EFFECT OF MANUFACTURING TEMPERATURE OF LAMINATED VENEER LUMBER ON DURATION OF LOAD BEHAVIOR

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To the Faculty of Washington State University and University of Idaho:

The members of the Committee appointed to examine the thesis of MELISSA ANN VERWEST find it satisfactory and recommend that it be accepted.

Chair

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ABSTRACT

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The structural properties of laminated veneer lumber (LVL) are influenced by several factors of the manufacturing process. While the effects of veneer quality and placement have been studied extensively, other manufacturing parameters have not been given adequate attention. The effect of manufacturing temperature on mechanical and duration of load properties of 38 mm by 89 mm by 2.44 m (nominal 2 in. by 4 in. by 8 ft) Douglas-fir laminated veneer lumber was investigated. Manufacturing temperatures common to the LVL production industry (149^{o}C (300^{o}F)), slightly higher than industry (171^{o}C (340^{o}F)), and much higher than industry (193^{o}C (380^{o}F)) were used for this study. It was found that the static load-displacement behavior was indeed affected by manufacturing temperature. Although affected, mechanical properties were not overly sensitive to manufacturing temperature differences.

Wood exhibits two separate yet related phenomena, which are creep and creep-rupture. Both phenomena define the time dependent behavior of wood. Over time, a sustained load causes an increase in deformation. This increase in deformation is known as creep. Creep-rupture, the eventual failure of the wood material, occurs because of the failure of the specimen

to sustain constant load over time due to increased deformation during that time (creep). Due to safety concerns, creep-rupture behavior is of more interest to code officials as well as building designers.

For load-duration behavior, no statistical significance was found with the duration of load deflections (initial, failure, and survival deflections) compared between temperature categories. Also, the exponential damage rate model (EDRM) was successfully used to model the behavior. Temperature effects were apparent but moderate between the low temperature and the higher temperatures. Calculated design adjustment factors from this study, based on the individual EDRM curves, were different than those from the Madison curve and thus different from current load-duration design adjustment factors used for solid sawn lumber.

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CHAPTER ONE

INTRODUCTION AND BACKGROUND

INTRODUCTION

As the timber industry changes, the demand for new products increases. Timber available nowadays is both smaller in diameter and lower in quality than in the past (McKeever, 1997). This fact, however, has not changed the increasing demand for wood seen year after year. To meet the demand and to combat the lower quality solid sawn lumber available, engineered wood products have become increasingly popular.

One such engineered wood product is laminated veneer lumber. This product is manufactured purposely to compete with solid sawn lumber (McKeever, 1997). Vlosky et al. (1994) reported that in 1992, North American production of structural LVL was 649 x 10^3 m^3 (275 million board feet). Production was expected to increase rapidly and projected production in 2002 was 2.34 x 10^6 m^3 (1000 million board feet) (Vlosky et al., 1994). The reported figure by McKeever (1997) for 1996 was 1.327 x 10^6 m^3 (565 million board feet). The increase had more than doubled in only four years. Clearly, laminated veneer lumber was gaining popularity and continues to do so.

As LVL gains popularity, the behavior of the product must be better understood. Currently, while general process is common knowledge, the details of the manufacturing process of laminated veneer lumber are proprietary. ASTM D5456 (1993), a standard for the evaluation of structural composite lumber products, specifically notes, "There is some potential for manufacturing variables to affect the properties of members that are loaded for sustained periods of time." Within the commentary of the standard (X1.2.2.1) it is stated,

> Generally, it is expected that composites as defined in this specification will perform similarly to other wood structural members when subjected to load for sustained periods. It is possible, however, that manufacturing procedures will adversely affect this performance.

Two of the manufacturing parameters that are suspected of causing adverse affects are low adhesive spread and improperly controlled time/temperature cycles.

Temperatures used during the manufacturing process surpass mere dehydration of the wood. In fact, common LVL production temperatures, 145^{o}C to 160^{o}C (293^{o}F to 320^{o}F), are relatively near the temperature associated with pyrolytic processes (200^{o}C). This is significant since, if wood is heated for prolonged periods of time, the elevated temperature changes may cause permanent damage. The result is a loss in weight and strength, and an actual degradation of the wood substance. Understanding how manufacturing temperature affects the duration of load response of LVL will help to refine the manufacturing process and further knowledge of laminated veneer lumber response performance under duration of load.

Time dependant behavior of structural composites is important because like many materials, wood is affected by two separate yet related phenomena, which are creep and creep-rupture. Both phenomena define the time dependant behavior of wood. Over time, a sustained load causes an increase in deformation. This increase in deformation is known as creep. Creep rupture, the eventual failure of the wood material, occurs because of the failure of the specimen to sustain constant load over time due to increased deformation during that time (creep). Due to safety concerns, creep-rupture behavior is of more interest to code officials as well as building designers.

The research and analysis within this thesis passes through several stages before the main objective is addressed. Conclusions made after each stage further the knowledge needed for the succeeding stages. First, a manufacturing process is developed and analyzed. Second, nondestructive techniques are examined to determine the best technique to predict mechanical properties. Third, full sized solid sawn lumber is subjected to the conditions of the manufacturing process with a focus on temperature. The solid sawn lumber is evaluated for both mechanical properties and load-duration behavior. Fourth, full sized laminated veneer lumber, manufactured with different temperatures, is evaluated for effects on mechanical properties. Fifth, the main objective, effects of elevated manufacturing temperature on load-duration behavior is addressed.

BACKGROUND

The multistage format of this research warranted research in several areas of study. This section is separated into subsections to provide attention to each pertinent area of study.

NONDESTRUCTIVE TESTING

Research involving vibrations in wood started as early as the mid seventeen hundreds due to the investigation of their use in musical instruments (Pellerin, 1965). A major initiation of nondestructive techniques for wood analysis was made by Jayne (1959). Jayne hypothesized that the mechanisms that controlled static behavior were the same as those that could be measured nondestructively in the form of energy storage and dissipation within wood. In the study, Jayne used transverse vibration on small clear wood specimens to verify the hypothesis of the relation between static properties and energy storage and dissipation. The result was a verification of the relationship between the static and the dynamic modulus of elasticity ($E_{dynamic}$). The hypothesis has prompted much research in the area of nondestructive techniques for testing strength and stiffness of wood members. Currently, there are three common techniques for nondestructive assessment: low load static bending (technique used for MSR lumber), transverse vibration, and stress wave propagation (Ross and Pellerin 1994).

The use of a longitudinal stress wave in wood evaluation has been investigated for over forty years (Gerhards, 1982). The majority of this research has involved the comparison of the dynamic modulus of elasticity to the static bending elasticity (E_{static}) in lumber specimens. The results have proven a strong correlation between the two moduli. For lumber, with a moisture content of twelve percent, Bell et al. (1954) reported a correlation coefficient of 0.98, with the dynamic modulus obtained from resonant frequency. Also using resonant frequency (Equation 1-1), Pellerin (1965) found the same correlation coefficient for construction lumber (numerous grades) with combined moisture contents of six and nine percent.

$$E_d = \frac{f_n^{\,2} \cdot w \cdot L^3}{C^2 \cdot I \cdot g} \qquad (1 - 1)$$

E_d = dynamic modulus of elasticity

C = constant (dependant upon the support conditions)

f_n = resonant frequency

w = beam weight

L = beam length

I = moment of inertia

g = acceleration due to gravity

Porter et al. (1972) had similar findings using a digital computer for determining a dynamic modulus. However, with a larger sample size and moisture content of ten percent, the correlation was lower at 0.90.

Simplification of the differential equation for wave propagation (Equation 1-2), has become a common way to determine the dynamic modulus of elasticity through the use of impact stress waves.

$$E_{dynamic} = \rho C^2 \qquad (1 - 2)$$

$E_{dynamic}$ = calculated dynamic modulus of elasticity

ρ = density

C = average longitudinal stress wave speed (three readings for this research)

Using this approach, Lanius et al. (1981) reported an even lower correlation coefficient of 0.824 for No. 1 and No. 2 Douglas-fir 50 mm by 150 mm (2 in. by 6 in.) with a seven percent moisture content. Gerhards (1982) summarized results of this relationship from several studies. The overall trend was a very high correlation of the two moduli (coefficients between 0.87 and 0.99). It was also noted that the correspondence between the moduli was not one-to-one. For Bell et al. (1954), the ratio of the dynamic to static modulus was 1.23, and for Porter et al. (1972), the ratio was 1.04. This trend of higher dynamic modulus values was also seen in the Pellerin (1965) and Lanius (1981) studies. In addition, Gerhards (1982) noted that the type of longitudinal stress wave, impact or ultrasonic instrumentation, did not yield different stress wave speeds.

Stress wave time techniques have been used to evaluate the same relationships for veneer sheets and more recently, laminated veneer lumber. Using the equation 1-2, Koch and Woodson, (1968) and Jung (1982) determined the $E_{dynamic}$ of individual veneer sheets. Koch and Woodson (1968) found a high correlation coefficient (0.94) between the stress wave modulus of elasticity and the static tension modulus of elasticity. Kimmel and Janowiak (1995) did not go as far as to calculate an $E_{dynamic}$ for veneer sheets but instead suggested that the ultrasonic propagation time was adequate to separate veneers for better mechanical performance of yellow-poplar and red maple LVL. Research done by Pu and Tang (1997) reported good correlation for solid sawn southern pine lumber but less accurate predictions for LVL of the same species. Their results also followed the solid sawn trend of nondestructive values being higher than static destructive bending values.

A difficulty in predicting beam stiffness in laminated veneer lumber is that the laminates will inherently have different properties. One technique to examine laminated sections is to use transformed sections analysis. This method involves transforming the geometry of the composite so that the new section has a constant stiffness. However, the calculation process is extensive. Another approach is to use the laminated beam theory (Timoshenko and Goodier, 1970). This theory makes a distinction between both horizontal and vertical laminates. The apparent bending modulus of elasticity is defined as the following (Equation 1-3 and 1-4):

$$E_{composite} = D \cdot \frac{12}{b \cdot t^3} \tag{1 - 3}$$

$$\text{where} \quad D = \sum_{i=1}^{n} b_i \cdot E_i \cdot \left(t_i \cdot d_i^2 \cdot \frac{t_i^3}{12} \right) \tag{1 - 4}$$

D = bending stiffness

E_i = dynamic modulus of elasticity for individual veneer sheets

<u>Vertical (edgewise) Orientation</u>

b = thickness of the section

b_i = thickness of the individual veneers

t = t_i = width of the beam

d_i = 0

<u>Horizontal (flatwise) Orientation</u>

b = b_i = width of the beam

t = thickness of the section

t_i = thickness of the individual veneers

d_i = distance from composite neutral axis to laminate neutral axis

The individual modulus of elasticity values for the veneer sheets, E_i, are found using longitudinal stress waves. An attempt at predicting the mechanical properties for parallel-laminated veneer members in edgewise bending was made by Jung (1982). The method was to predict the members' modulus of elasticity by averaging the dynamic moduli of the veneer sheets. Although robust and reportedly well correlated, this method neglects the contribution of both veneer and section dimensions. The overall trend also deviated from other findings in that the dynamic modulus of elasticity values were lower than the mechanical modulus of elasticity values.

Much consideration has also been given to the relationship between the modulus of elasticity (MOE) and the modulus of rupture (MOR). The aim has been to be able to predict the strength of a member by correlation of its dynamic modulus of elasticity. James (1964) provided regression analysis between modulus of rupture and both $E_{dynamic}$ and E_{static}. The correlation coefficients for clear Douglas-fir specimens, at a moisture content of twelve percent, were 0.908 and 0.926, respectively. For construction lumber, Pellerin (1965) found high correlation between the modulus of rupture and $E_{dynamic}$. For moisture contents of six and nine percent, the correlation coefficients were 0.89 and 0.90, respectively. In contrast, Jung (1982) found poor correlation between strength and stiffness for coast Douglas-fir parallel-laminated veneer. For edgewise bending, the mechanical MOE and the stress wave time predicted MOE had correlation coefficients of 0.609 and 0.553, respectively.

Predicting the mechanical properties of laminated veneer lumber could be done using any of the methods discussed above. Since there is uncertainty as to which method would best predict actual mechanical properties, experimentation was done to determine the predictive capability of the two methods.

TEMPERATURE EFFECTS

The strength of wood depends on its physical and chemical constitution. Chemically, wood is made up of three basic components: cellulose, hemicellulose, and lignin (Panshin and de Zeeuw, 1980). Heating causes these components to undergo changes such as shrinkage, expansion, dehydration, thermal degradation, and phase change. Schaffer (1973) summarized these changes in wood caused by thermal effects in Table 1-1.

Table 1-1: *Thermally Induced Changes in Dry Wood in an Inert Atmosphere (adapted from Schaffer 1973)*

Temperature ^oC	^oF	Thermal Induced Change
55	131	Natural lignin structure is altered. Hemicelluloses begin to soften.
70	158	Transverse shrinkage of wood begins.
110	230	Lignin slowly begins weight loss.
120	248	Hemicellulose content begins to decrease, a-cellulose begins to increase. Lignins begin to soften.
140	284	Bound water is free.
160	320	Lignin is melted and begins to reharden.
180	356	Hemicelluloses begin rapid weight loss after losing 4 percent. Lignin in torous flows.
200	392	Wood begins to lose weight rapidly. Phenolic resin begins to form. Cellulose dehydrates above this temperature.
210	410	Lignin hardens, resembles coke. Cellulose softens and depolymerizes. Endothermic reaction changes to exothermic.
225	437	Cellulose crystalinity decreases and recovers.
280	536	Lignin has reached 10 percent weight loss. Cellulose begins to lose weight.
288	550	Assumed wood charring temperature.
300	572	Hardboard softens irrecoverably.
320	608	Hemicelluloses have completed degradation.
370	698	Cellulose has lost 83 percent of initial weight.
400	752	Wood is completely carbonized.

Shape and size of the member and type of loading need to be considered simultaneously. This is because for short time exposures, the inner material of a large specimen would not be heated to the temperature of the surrounding medium (Wood Handbook, 1999). Therefore, it is possible that the immediate effect on the strength of the inner material is less than the surface material. However, the type of loading is important in determining if size may be of consequence. In the case of bending, the greatest stress is experienced by the outer fibers. This usually governs ultimate strength. Therefore, the fact the inner material may have experienced a lower temperature than the surface material due to short-term exposure is of little concern as far as temperature effect on member performance.

Temperature Effects on Mechanical Properties: General and Solid Sawn Lumber

There are two kinds of temperature effects; reversible and irreversible. For a temperature effect to be reversible, the temperature must be below 100^{o}C (212^{o}F) and temperature change must be immediate and quick. The Wood Handbook (1999) terms an immediate effect as "the change in properties that occurs when wood is quickly heated or cooled and then tested at that condition." Immediate effects have been shown to reduce both the modulus of elasticity and modulus of rupture with a linear relation to temperature (Gerhards, 1982; Wood Handbook, 1999). However, these effects tend to be reversible if the material is allowed to return to room temperature conditions and then tested.

Irreversible effects occur when wood is heated for a prolonged period of time. This long-term heating causes degradation of the wood and thus permanent damage. The result is a loss in weight and strength and a level of degradation of the wood substance. The degree of degradation and strength loss depends on factors including, but not limited to, heating medium, temperature, duration of exposure, and, species, size, and moisture content of the member involved. To test for permanent effects, the specimens must be conditioned back to room temperature conditions otherwise results are influenced by immediate effects. However, as Green and Evans (1994) noted, there is a lack of guidance to render a precise time at which to expect permanent strength loss. This is to say the time frames of "quick" and "prolonged" are not clearly defined.

There have been several studies on the effect of environmental conditions on mechanical properties of solid sawn lumber. Many of these studies center on the premise of manipulating environmental parameters for both conditioning of the specimens and for the duration of the tests being performed. For example, James (1961), tested the effect of elevated temperature and moisture content on the speed of sound and on the Youngs's modulus (using longitudinal vibration) of Douglas-fir. The testing procedure followed the conditions of immediate temperature effects. He found that a rise in temperature or moisture content caused a decrease in the speed of sound in the wood and a decrease in the modulus of elasticity. The Wood Handbook (1999) also cites increased moisture content or temperature as a source of decreased structural properties.

Schaffer (1973) studied the immediate effects on compressive and tensile strength (both parallel-to-the-grain) of Douglas-fir. Specimens, 25.4mm (1 in.) radial by 3.2 mm (0.125 in.) tangential and 254 mm (10 in.) long, were brought to equilibrium at the elevated temperatures within two minutes. The equilibrium temperature range tested was 25^{o}C to 275^{o}C (77^{o}F to 527^{o}F). Schaffer found that the immediate tensile strength was relatively insensitive to temperature until 170^{o}C (340^{o}F) while thermally induced changes had a more pronounced uniformed effect on compressive strength. For tensile strain at failure, an increase was apparent from 140^{o}C to 200^{o}C (284^{o}F to 392^{o}F) before a decrease at higher temperatures. Schaffer (1973) attributed this behavior to the softening and rehardening of the lignin that occurs at that temperature range (Table 5-1). The compressive strain at failure was found to decrease uniformly.

Gerhards (1982) presented a summary of all pertinent studies on the immediate effects on the mechanical properties of wood. From all the studies that dated back to 1936, only five studies involved extreme temperatures, that is, greater than environmental temperatures. None of these five studies examined the temperature effects on bending strength. Four of these studies examined the effects on modulus of elasticity but the largest specimen only had cross sectional dimensions of 20.1 mm by 20.1 mm (0.79 in. by 0.79 in.). For modulus of elasticity parallel to the grain with a moisture content of zero percent, only the study by Schaffer (1973) had data beyond 150^{o}C (302^{o}F). Although the overall data was represented by a decreasing linear relationship, the curve generated by passing through the average data showed no change in modulus of elasticity for the temperature range of 150^{o}C to 200^{o}C (302^{o}F to 392^{o}F). The relative modulus of elasticity, for this range, was less than a twenty-five percent decrease with 25^{o}C (77^{o}F) being the base temperature modulus of elasticity.

Gerhards (1982) also presented modulus of elasticity data involving extreme temperatures from Preusser (1968) but noted that the conditioning temperatures, sustained for an hour, were applied to specimens previously conditioned to twelve percent moisture content. Thus, moisture effects most likely compounded the data, especially at the higher temperatures.

According to Gerhards' (1982) comprehensive study, available data for bending strength was restricted to 125^{o}C (257^{o}F) for zero percent moisture content and 75^{o}C (167^{o}F) for equal or greater than eleven percent moisture content. All of the relationships support decreasing linear trends for both moisture content conditions. However, Gerhards (1982) concluded that bending strength, compressive strength parallel-to-the-grain (Schaffer, 1973), and tensile strength perpendicular-to-the-grain appear to experience the same immediate temperature effect. He also concluded that the temperature effects were greater at higher moisture contents.

In a more recent study, Fridley et al. (1992a) examined hygrothermal effects on the mechanical properties of select structural Douglas-fir 38 mm by 89 mm (nominal 2 in. by 4 in.). The specimens were conditioned to environmental conditions of varied relative humidity levels and temperature. Strong axis bending was performed at temperatures of 23^{o}C, 38^{o}C, and 54^{o}C (73^{o}F, 100^{o}F, and 130^{o}F). The results of this study showed that the modulus of rupture and the modulus of elasticity were affected by environmental hygrothermal conditions. At the same relative humidity, a rise in temperature caused a noticeable decrease in modulus of rupture. However, the modulus of elasticity showed very little change due to temperature increase. Models were developed but cautioned for use only with conditions of the study.

Irreversible effects, that is those associated with long-term temperature exposure and permanent damage, have been the focus of more recent studies. However, the temperature ranges of the published studies again do not reflect extreme temperatures. The main focus of these studies remains high end environmental temperatures.

In a study by LeVan et al. (1990), the bending properties of wood treated with fire retardant chemicals were examined at elevated temperatures. The research provided a control group of 305 mm (12 in.) long untreated Southern Pine with a cross-section of 15.9 mm (0.625 in.) tangential by 35 mm (1.375 in.) radial. The highest temperature of exposure was only 82^{o}C (180^{o}F). Permanent effects were of interest at varied times of exposure, the smallest of which was three days. After the time of exposure had elapsed, the specimens were reconditioned before testing at 23^{o}C (73^{o}F) with a moisture content of twelve percent. Since no baseline of zero exposure time was established for individual groups based on static tests (only the average of all groups being noted found from stress wave time), the shortest time that could be used for relative comparison was the three day exposure. Between the three and seven day exposures, it was concluded that the modulus of elasticity and the modulus of rupture showed no change. However, actual data recorded for this exposure range shows a 3.8 percent and 5.1 percent increase, respectively.

The study by LeVan et al. (1990) also gave insight to the mechanism that controls the degradation of wood. Through analysis of the chemical composition of the thermally exposed wood, she found that degradation of hemicelluloses was the major contributor to reduction of strength.

Green and Evans (1994) published the two-year results from a four-year study on the effects of ambient temperatures on flexural properties of lumber (nominal 2 in. by 4 in.). They tested MSR graded Spruce-Pine-Fir (SPF) and LVL of the species Douglas-fir, Southern Pine, and Yellow-poplar. The conditioning temperature was 66^{o}C (150^{o}F) and the shortest time of exposure tested was six months. Since Green and Evans (1994) were interested in permanent effects, before static tests were performed, all specimens were removed from the elevated temperature environment and reconditioned to 20^{o}C (68^{o}F). The results reported for SPF 1650F-1.5E revealed that although the mean modulus of elasticity decreased overall for the two year period, it actually increased 7.8 percent from zero to six months. SPF 2100F-1.8E hardly exhibited any change in modulus of elasticity mean value for the two year period and also increased from zero to six months (1.4 percent). Green and Evans (1994) concluded that for modulus of elasticity, the rate of degradation was independent of the first two year exposure. For modulus of rupture, both grades were reported to decrease (between five and nine percent) over the first six month period.

TEMPERATURE EFFECTS ON MECHANICAL PROPERTIES: SPECIFIC FOR LAMINATED VENEER LUMBER

Specific data on immediate temperature effects of LVL is not readily available. Most of the research of LVL has involved lay-up practices, veneer quality, species type, relative humidity, and nondestructive evaluation. ASTM D5456 (1993), a standard for evaluating structural composite lumber products, states that materials predicted to be exposed for sustained periods to temperatures not within the range of – 34^{o}C to 65^{o}F (-30^{o}F to 150^{o}F) should be evaluated for the effect of temperature. As of now, quality control for temperature is assured by the manufactures of the engineered wood product.

There have been several studies on the effect of environmental conditions on mechanical properties of solid sawn lumber (see section above). However, there exists little published research concerning this topic for laminated veneer lumber. The temperature ranges of the few published studies that do exist do not reflect manufacturing temperatures. The focus of these studies were high end environmental temperatures and char rates (near 300^{o}C (572^{o}F)).

In a study by Winandy (1991), the bending properties of plywood (veneer composed panels) treated with fire retardant chemicals were examined at elevated temperatures. The research provided a control group of 1.22 m by 2.44 m (4 ft by 8 ft) untreated Southern Pine N-grade plywood panel. The highest temperature of exposure was only 77^{o}C (170^{o}F). Permanent effects were of interest at varied times of exposure, the smallest of which was seven days. After the time of exposure had elapsed, the specimens were reconditioned before testing at 23^{o}C (74^{o}F) with a relative humidity (RH) of 65 percent (twelve percent moisture content). Since no baseline of zero exposure time with the same relative humidity was established for individual groups based on static bending tests, the shortest time that could be used for relative comparison was the seven day exposure. Actual data recorded for the exposure range of seven to fourteen days shows an increase in both modulus of elasticity and modulus of rupture values for different relative humidities of the temperature category 77^{o}C (170^{o}F). For an RH of 50 percent, a 6.7 percent increase for modulus of elasticity and a 4.9 percent increase for modulus of rupture was observed. For an RH of 79 percent, 4.6 percent and 4.9 percent increases, of the respective moduli, were observed.

As mentioned earlier, Green and Evans (1994) published the two-year results from a four-year study on the effects of ambient temperatures on flexural properties of LVL (nominal 2 in. by 4 in.). The results reported for all LVL species revealed that both the mean modulus of elasticity and mean modulus of rupture decreased overall for the two year period, and likewise decreased from zero to six months. However, both MOE and MOR, of all LVL species, showed an unexplained increase from six months to a year. For Douglas-fir LVL it was 6.2 percent and 3.0 percent, respectively. Green and Evans (1994) concluded that for modulus of elasticity, the rate of degradation was independent of the first two year exposure for both solid sawn lumber and LVL. For modulus of rupture, the amount of thermal degradation (over the two year period) for solid sawn lumber and LVL was concluded to be similar. Green and Evans (1994) suggested that a single mechanism might be responsible for the degradation of both solid sawn lumber and laminated veneer lumber. If the implications from Green and Evans (1994) are true, then the solid sawn lumber and LVL should exhibit similar behavior under the same thermal conditions. Since veneer is heated to high temperatures during the LVL production process, the effects of temperature increases would logically have a direct effect on the mechanical properties of the veneer, and ultimately, the LVL. In an unpublished study by Verwest (2000), Douglas-fir and Hemlock veneer coupons, 25.4 mm by 254 mm (1 in. by 10 in.), were subjected to elevated temperatures of 145^{o}C (293^{o}F) and 200^{o}C (392^{o}F). Room temperature, 25.4^{o}C (77.7^{o}F), was used as a control. The coupons were heated for thirty minutes (air circulation) in a Fisher Scientific oven and then allowed to return to equilibrium conditions. They were then tested for tensile fracture strength. The results of both species supported earlier findings on temperature effects, that is, the load and extension decreased as temperature increased.

White (2000) researched the rate of charring of laminated veneer lumber of several species. A standard fire endurance test was conducted at a temperature of 300^{o}C (572^{o}F). He related it to earlier studies of charring of solid sawn lumber by Schaffer (1967) and White (1988). Specimens were constructed with either five LVL members at 50 mm (1.97 in.) thick or six LVL members at 44 mm (1.73 in.) thick. Thus, specimens were either 250 mm or 264 mm (9.8 in. or 10.4 in.) high and 510 mm (20 in.) wide by 89 mm (3.5 in.) deep. White (2000) concluded that the charring of LVL may be considered comparable with solid sawn lumber. This research furthers the implication that the thermal effects experienced by solid sawn lumber are similar to those experienced by laminated veneer lumber.

Duration of Load

Numerous predictive models have been developed in relation to creep rupture, or duration of load (DOL) behavior, of wood. Such models include damage accumulation, strain energy (Fridley et al., 1992b), and fracture mechanics (Nielsen and Kousholt, 1980). The damage accumulation (DA) approach is the most popular modeling technique (Rosowsky and Fridley, 1995) and the model used in this research. Hence, the emphasis of this review is placed on previous research involving or relating to damage accumulation.

The first model related to the relationship between applied stress level and time-to-failure was developed by Wood (1951). Wood used constant bending loads located at the center span. These loads ranged from sixty to ninety-five percent of the strength found through static bending. The testing of the Douglas-fir small clear specimens resulted in data that was fitted to an empirical hyperbolic model curve. The model assumed a stress threshold of 18.3 percent. It was assumed that failure of a specimen would not occur below this threshold. The general form of the model is given in Equation 1-5a. Equation 1-5b presents the model calibrated by Wood (1951). Wood's (1951) model (Equation 1-5b) is commonly referred to as the "Madison curve." It is this curve that is the basis for the load-duration adjustment factors outlined in the National Design Specifications (NDS) for Wood Construction (AF & PA, 1997).

$$t_f = \frac{1}{A\left(\sigma - \sigma_o\right)^B} \qquad (1 - 5a)$$

$$\sigma = \frac{1.084}{t_f^{0.04635}} + 0.183 \qquad (1 - 5b)$$

t_f = time to failure in seconds

A, B = model constants determined from experimental data

σ = ratio of applied stress to ultimate stress (static test strength)

σ_o = stress threshold

The Madison curve can also be written in the format of damage accumulation. The definitions of the parameters A, B, σ, and σ_o defined above also apply to Equation 1-5c.

$$\frac{d\alpha}{dt} = A\left(\sigma - \sigma_o\right)^B \qquad (1 - 5c)$$

α = parameter of damage ranging from zero (no damage) to one (failure)

$d\alpha/dt$ = time rate of damage accumulation

Based on the Madison curve data of small clear Douglas-fir specimens under a constant bending load, Barrett and Foschi (1978a, 1978b) developed two damage accumulation models.

Each model assumed a stress threshold. The main difference from the Madison curve was the addition of a third model constant, C. The difference between the two new models was how the additional model constant was incorporated. All other parameters are previously defined. Barrett and Foschi (1978b) concluded that model II better represented the data.

Model I (Barrett and Foschi, 1978a)

$$\frac{d\alpha}{dt} = A(\sigma - \sigma_o)^B \cdot \alpha^C \qquad \text{if } \sigma > \sigma_o \tag{1 - 6a}$$

$$\frac{d\alpha}{dt} = 0 \qquad \text{if } \sigma \leq \sigma_o \tag{1 - 6b}$$

Model II (Barrett and Foschi, 1978b)

$$\frac{d\alpha}{dt} = A(\sigma - \sigma_o)^B + C\alpha \qquad \text{if } \sigma > \sigma_o \tag{1 - 7a}$$

$$\frac{d\alpha}{dt} = 0 \qquad \text{if } \sigma \leq \sigma_o \tag{1 - 7b}$$

Around the same time, Gerhards (1977, 1979) had also developed a damage accumulation model. The data used to derive the model came from tests on small clear specimens. Gerhards assumed that the lifetime of the member was an exponential function of the applied stress level. From this idea of exponential decay, Gerhards developed the Exponential Damage Rate Model (EDRM) given in Equation 1-8.

$$\frac{d\alpha}{dt} = \exp(-A + B\sigma) \tag{1 - 8}$$

Foschi and Yao (1986) developed a DA model similar to model II from Barrett and Foschi (1978b). However, instead of expressing damage accumulation in terms of a stress ratio, it was expressed as a function of actual applied stress. Also, an additional model constant, D, was added. An expression for their model is given in Equation 1-9. Foschi and Yao (1986) concluded that compared to the Barrett and Foschi (1978b) model II, the new model was a more accurate representation of the duration of load behavior of lumber.

$$\frac{d\alpha}{dt} = A\left(\tau - \tau_o\right)^B + C\alpha\left(\tau - \tau_o\right)^D \qquad (1 - 9)$$

τ = applied stress

τ_o = stress threshold

All other model parameters were defined previously

Gerhards and Link (1987) used full-sized 38 mm by 89 mm (2 in. by 4 in.) Douglas-fir lumber specimens to calibrate the EDRM. They concluded that the model also applied to full-sized lumber. Gerhards (1988) did further testing with the full-sized specimens in order to determine the effect of lumber grade on the duration of load behavior of Douglas-fir lumber. In direct disagreement of previous DA models developed by Wood (1951), Barrett and Foschi (1978a, 1978b), and Foschi and Yao (1986), Gerhards (1988) concluded that no evidence existed that would support a stress level threshold. He also noted that for loading at the same fraction of static strength, lower grades of lumber had lower load-durations. In addition, however, he stated that these differences might not be statistically significant. Finally, Gerhards (1988) found that for design loads that really exist for the design duration, the current allowable bending properties for lumber were nonconservative. Using calculated load-duration equations and the methods used to determine NDS adjustment factors, he proposed modifications to the factors. The resulting factors would consequentially lower design values for all design load-durations.

A study by Cai et al. (2000) compared the predictive capabilities of these four DA models (Wood, 1951; model II from Barrett and Foschi, 1978b; Gerhards, 1979; and Foschi and Yao, 1986). Small clear Southern Pine specimens were subjected to a five-day load sequence which varied stress levels daily. It was concluded that all of the DA models failed to consistently predict the time-to-failure. This was even more pronounced for lower stress levels and longer duration. Ultimately, it was concluded that, “the four DA models were about equal in their ability to simulate time-to-failure distribution” (Cai et al., 2000).

Temperature Effects on Duration of Load Behavior

There have been several studies on the effect of environmental conditions on creep-rupture of wood, both small clear and full-sized specimens. Similar to the conditions of mechanical testing, most of these studies center on the premise of manipulating environmental parameters for both conditioning of the specimens and for the duration of the tests being performed. Justifiably, environmental conditions simulated for testing have never been over 80°C (176°F). Although the testing temperatures were within the range for reversible effects, the long exposure time involved in creep-rupture testing would inevitably result in the temperature effects being classified as permanent.

Schniewind (1967) subjected small clear 10 mm by 20 mm by 220 mm (0.39 in. by 0.79 in. by 8.66 in.) Douglas-fir specimens to environmental conditions in order to determine the effects on creep-rupture. Both constant and cyclical temperature exposure environments were examined for the duration of the tests. It was concluded that the environmental effects on creep-rupture significantly reduced the life duration of the wood specimens. However, it was also noted that changes in size could alter the significance and change the results.

Building on this idea, Schniewind and Lyon (1973) tested larger specimens, although still clear, of 50.8 mm by 50.8 mm by 1.02 m (2 in. by 2 in. by 40 in.). The results showed that environmental effects were still present. However, it was concluded that as specimen size is increased, creep-rupture life during environmental changes would be similar to that of specimens in a constant environment.

In a study by Schaffer (1973), discussed earlier in this review, additional creep testing was performed for a two hour period. This study actually went beyond mere environmental temperatures and subjected specimens to temperature ranges of 25^{o}C to 275^{o}C (77^{o}F to 527^{o}F). The results showed that the compressive strength actually improved with duration of exposure, at a constant load, for the temperature range of 100^{o}C to 288^{o}C (212^{o}F to 550^{o}F). Consequentially, this is the temperature range starting after reversible temperature effects and ending before assumed wood charring temperature. The tensile strength showed no significant change in strength until 140^{o}C (284^{o}F) after which increased temperatures caused a decrease during exposure. Schaffer (1973) concluded that the increase seen in the long-term compression strength was credited to "the phenol-resin production of additional bonds with duration heating." For tensile strength, the decrease was caused by "the depolymerization of cellulose with duration of heating."

As was discussed previously, environmental changes in temperature and moisture content are known to affect mechanical properties, that is, short-term strength and stiffness. Fridley et al. (1989, 1990, 1991, 1992c, and 1992d) conducted several studies to determine the effect of environmental conditions on structural lumber. Again, "environmental" only included a temperature range of 23^{o}C to 54^{o}C (73^{o}F to 130^{o}F). Environmental conditions under consideration were constant and cyclical thermal effects and constant and cyclical moisture effects. Specimens, 38 mm by 89 mm by 2.44 m (nominal 2 in. by 4 in. by 8 ft), were Select Structural and No. 2 grade Douglas-fir. Fridley et al. (1989) concluded that for equal stress ratios, a trend of shorter time-to-failure for higher temperatures was observed. He also noted that the observed temperature effects were independent of relative humidity or moisture content effects. Further research by Fridley et al. (1992d) indicated that the effects brought on by constant hygrothermal conditioning could be predicted if the effects on short-term strength were accurately predicted.

No published data was available regarding the effect of temperature of any sort on duration of load behavior of laminated veneer lumber. However, if the implications from Green and Evans (1994) are true, that is similar degradation mechanism brought on by thermal changes, then the solid sawn lumber and LVL should exhibit similar behavior under the same thermal conditions.

Although much attention has been given to effects due to environmental conditions, there exists little research with respect to extreme temperatures. Since the manufacturing process of laminated veneer lumber demands the use of such temperatures, experimentation was performed in order to examine the mechanical and duration of load behavior of manufacturing temperature varied LVL.

Objectives

The main objective of this research was to determine how altered manufacturing temperature effects the duration of load response of laminated veneer lumber. Specific objectives are as follows:

1) Utilize different methods of experimental investigation to evaluate the structural properties of laminated veneer lumber,
2) Compare static and load-duration behaviors of laminated veneer lumber to those of solid sawn lumber subjected to the same manufacturing process, and
3) Assess the benefit or detriment of using higher manufacturing temperatures of laminated veneer lumber in industry.

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CHAPTER TWO

EXPERIMENTAL PROCEDURES

INTRODUCTION

The methodology for testing the duration of load behavior of wood and wood composites does not come from a published standard. Rather, experimental procedures used to evaluate duration of load behavior have been developed through numerous research studies on the topic. The generalized approach is as follows: First, the material to be tested is sorted into similar groups using modulus of elasticity as the primary sorting parameter. Static bending tests are then performed on a limited number of groups to determine bending strength and a governing statistical distribution. A predetermined percentage of the ultimate stress is then applied to the groups tested for load-duration via a constant load. Finally, deflections are monitored and time to failure is recorded. The research presented in this thesis follows this methodology and specific details regarding the approach are outlined in this chapter.

MATERIALS

Boise Cascade of Boise, Idaho provided all veneer and solid sawn lumber. All provided veneer was Douglas-fir (*Pseudotsuga menziesii*) and solid sawn lumber was Standard Douglas-fir larch. The veneer was rotary peeled and was cut into six hundred and sixty 1.25 m by 2.55 m (generous 4 ft x 8 ft) sheets. The average thickness of the veneer was 3.68 mm (0.145 in.). After arrival to Washington State University's Wood Materials and Engineering Laboratory, the veneer had to be cut in half lengthwise to 610 mm (2 ft) for processing purposes. The veneer was sorted using nondestructive longitudinal stress wave time techniques (Figure 2-1) and hot pressed at three predetermined temperatures to produce fifteen eleven-ply billets for each manufacturing temperature. Each billet was cut into six 2.44 m (8 ft) long, 38 mm by 89 mm (nominal 2 in. by 4 in.) laminated veneer lumber members. The Standard grade for the one hundred and eighty members of 38 mm by 89 mm (nominal 2 in. by 4 in.) solid sawn was chosen for the wide range in structural properties, that is, a high coefficient of variation (COV) of the material. Each member was 2.44 m (8 ft) in length.

MATERIAL SORT

NONDESTRUCTIVE TESTING

Nondestructive testing (NDT) was used to evaluate all the material. Figure 2-1 shows the typical setup for the nondestructive tests. Sonic propagation time was used to determine the dynamic modulus of elasticity ($E_{dynamic}$). Although sorting can be done using stress wave time alone, where a longer travel time indicates a lesser quality member, the calculation for dynamic modulus of elasticity also accounts for the density of the member. For wood and wood composites, the dynamic modulus of elasticity has been proven to correlate well to a static modulus of elasticity (E_{static}) from bending tests (Bell et al., 1954; James, 1964; Pellerin, 1965; Koch and Woodson, 1968; Lanius, 1981; Gerhards, 1982; Jung, 1982; Pu and Tang, 1997).

Figure 2-1: *Typical Nondestructive Test Setup (seen here for veneer sheet)*

To verify the nondestructive test calibration, the stress wave time testing was first performed on a 616 mm by 2.16 m (approximately 2 ft by 7 ft) by 1.19 mm (0.047 in.) thin steel plate. The steel was clamped down along its width. Accelerometers, containing piezoelectric material, were firmly attached to the clamps. A separate test was performed at each fifth point of the width. A sonic longitudinal stress wave was introduced into the steel via impact of a swung metal ball. A portable digital FLUKE oscilloscope displayed the excitation functions of the accelerometers. Since the stress-induced position was fixed, it was up to the operator to determine the signaled excitation of the receiving accelerometer. The difference in the excitation times was recorded as the time of flight of the stress wave in microseconds. Several sonic longitudinal waves were introduced per location to verify a consistent stress wave flight time. The stress wave times along the different width locations were averaged to obtain a representative stress wave time of the entire specimen. Keeping the wave propagation distance constant, the average longitudinal stress wave speed, C, was calculated. Specific measurements of width and thickness were taken in several locations with a caliper. The length and weight of the specimen were also recorded in order to determine specimen density. Knowing the specimen density and the wave speed, the following relationship was used to calculate the dynamic modulus of elasticity.

$$E_{dynamic} = \rho C^2 \tag{2 - 1}$$

$E_{dynamic}$ = calculated dynamic modulus of elasticity

ρ = density

C = average longitudinal stress wave speed (three readings)

Further explanation of this equation can be found in Appendix B. The calculated values of $E_{dynamic}$ for the steel plate were very close to the reference values (Table 2-1). The low percent difference of 0.6 percent gives strong indication that the test procedure was sound.

Table 2-1: *$E_{dynaminc}$ of Thin Steel Plate*

STEEL PLATE	Calculated	Reference*	% Difference**
Average C (m/s)	5235	5190	1.03
Average C (in./s)	206102	204000	
Average $C^2\rho$ (GPa)	202.8	207	0.6038
Average $C^2\rho$ (10^6 psi)	29.4	29.6	

*Reference value from Bray and Stanley, 1997
**% Difference calculated from unrounded psi values

SOLID SAWN

All solid sawn members were tested nondestructively to obtain an $E_{dynamic}$ for each specimen. The members were weighed and measured (one length, average of three widths, and average of three thicknesses). Each member was clamped down perpendicular to the width, that is, in a flatwise horizontal plank position. Stress waves were only introduced in one location, along the center of the width. An average of three stress wave times was taken.

The members were then sorted in order of ascending $E_{dynamic}$. Each $E_{dynamic}$ was assigned a random number. Because it was desired to keep the distributions the same for all temperature categories, every four ascending $E_{dynamic}$ values were arranged in ascending order of the random number and put into a temperature category based on the assigned random number. For example, the category no temperature received the $E_{dynamic}$ with the lowest random number, 149°C (300°F) received the $E_{dynamic}$ with the next ascending random number and so on for each set of four. Because the desired categories were not equal in sample size, every ninth $E_{dynamic}$ from the 193°C (380°F) group was picked off and randomly given to one of the other categories. The end result from this technique was forty-eight members each for the no temperature, 149°C

(300°F), and 171°C (340°F) categories and thirty-six members for the 193°C (380°F) category. An analysis of variance (ANOVA) was performed on the $E_{dynamic}$ values between the temperatures (Appendix E). The analysis showed no significant difference between the temperature categories. Figure 2-2 graphically supports the success of the distribution method.

Within the four temperature categories, it was necessary to separate each category into two equally distributed groups. One group was to be tested statically and the other group was to be tested under load-duration. The same technique for sorting into categories was employed for sorting into groups. However, in order to ensure the same distribution for each group, the first two $E_{dynamic}$ values were randomly distributed and then the next two values and so on until all categories were split into two even groups. This final sorting provided the sample sizes that were used in the tests [MOE-MOR/DOL]: no temperature [24/24], 149°C (300°F) [24/24], 171°C (340°F) [24/24], and 193°C (380°F) [18/18].

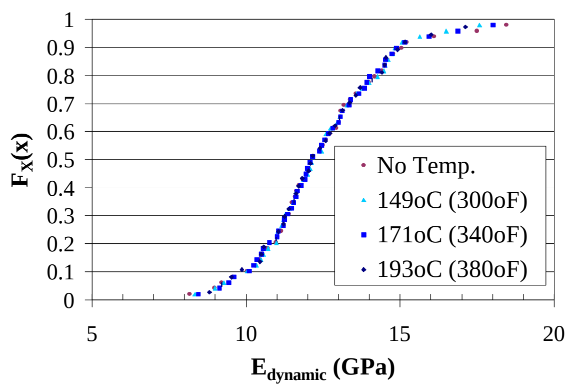


Figure 2-2: *Cumulative Distribution of Sorted Solid Sawn Lumber Sorted for Heated*

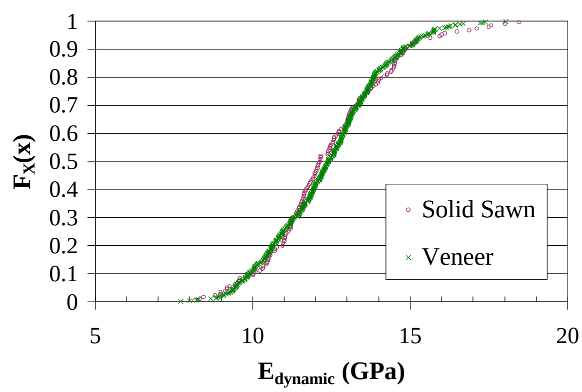


Figure 2-3: *Cumulative Distribution of $E_{dynamic}$ of Solid Sawn Lumber and Veneer*

VENEER

All veneers used in the production of laminated veneer lumber were tested nondestructively to obtain an $E_{dynamic}$ for each veneer sheet. The members were weighed and measured (average of three lengths, average of three widths, and average of four thicknesses). Each member was clamped down perpendicular to the width (flatwise). Stress waves were introduced to the third point locations along the width. The average of the three stress wave times at those locations was determined the stress wave time for the entire veneer sheet. It was desired that the veneer distribution mimic the solid sawn distribution. As is seen in Figure 2-3, the distributions are very similar. As a further check, an ANOVA was run on the two data sets and proved that no significant statistical difference existed between the two materials (Appendix E).

Several veneer sheets were needed for practice billets. These practice billets were needed to help establish additional manufacturing parameters. Sixty-nine sheets were randomly taken from the 660 sheets available. Additional practice sheets were selected based on the standard deviation of the stress wave times within each sheet. The material that was kept for manufacturing test specimens had the lowest standard deviations. The standard deviation of the retained veneer sheets (495 sheets) ranged from 0.00 μs to 27.71 μs.

The veneers were divided into groups of eleven based on ascending $E_{dynamic}$ values. The group with the lowest $E_{dynamic}$ was assigned to the temperature category of 149^{o}C (300^{o}F), the next ascending group of eleven was assigned to the next temperature and so on until all temperature categories had fifteen sets of eleven veneers. This sorting is not the common practice of the LVL industry, but the aim was to mimic the distribution of the solid sawn lumber for direct comparison of behavior. The unconventional sorting technique proved valid after ANOVA results suggested there was no significant statistical difference between the $E_{dynamic}$ values of all the temperature categories (Appendix E).

LVL BILLET PRODUCTION

All of the laminated veneer lumber (LVL) were manufactured at the Washington State University's Wood Materials and Engineering Laboratory. The LVL billets were produced with eleven piles. Each veneer was manually fed through a roller resin spreader to apply a single glueline (film) with a resin spread of 180.65 kg / 1000 m^2 (37 lb / 1000 ft^2). The adhesive for the fabrication was a liquid phenol-formaldehyde resin. A William & White Pressman hydraulic 1.22 m by 2.44 m (4 ft by 8 ft) platen hot press was used for making the 38 mm by 610 mm by 2.44 m (1.5 in. by 2 ft by 8 ft) billets. The pressing process was thickness controlled. Other parameters, such as time and pressure cycle, were experimentally determined. Because the manufacturing process, mainly temperature, was a key element of this research, pressing procedures are described in further detail in Chapter Three.

SPECIMEN SORT

After the billets were made, they were cut to dimension (nominal 2 in. by 4 in., 8 ft long). Six LVL specimens (nominal 2 in. by 4 in., 8 ft long) were cut from each billet. The specimens were labeled according to manufacturing temperature, billet number (1 through 15 where ascending number corresponds with ascending veneer $E_{dynamic}$ values), and letter *a* through *f* for location of specimen within the billet (*a* and *f* consisting of the edge-most billet material). All 269 LVL specimens were tested nondestructively, that is, the same as the solid sawn lumber were tested. However, because of the nature of the induced longitudinal stress wave, and the long travel distance, it was not possible to detect localized LVL manufacturing-induced failures such as delaminations. Because of this, each LVL was visually inspected as well and labeled as good, minor delaminations, or major delaminations. The location and extense of the delaminations was also recorded.

The sorting of the veneers ensured that the make-up of the LVL would be statistically the same. However, it was still necessary to sort the category temperatures into testing groups. This was done the same as the sorting of the solid sawn members. This final sorting provided the sample sizes that were used in the tests [MOE-MOR/DOL]: 149^{o}C (300^{o}F) [24/24], 171^{o}C (340^{o}F) [24/48], and 193^{o}C (380^{o}F) [19/19]. Since the production process had led to a high yield of LVL samples from the 171^{o}C (340^{o}F) category, the sample size of the duration of load test was doubled and split into two subcategories of the temperature (1 and 2). The addition of an entire DOL set of the same temperature would aid in determining the validity of the trends of load-duration behavior of the different temperatures.

Laminated beam theory was explored as another method to govern sorting values. The laminated beam theory was applied to both vertical and horizontal laminate orientations. Although this theory provided similar modulus of elasticity values as the nondestructive values, ultimately, sorting was performed based on the $E_{dynamic}$ of the LVL member. This ensured that all material sorting was done using values obtained from the same technique.

TEMPERATURE TREATED SOLID SAWN

To obtain comparison data, the solid sawn lumber was subjected to the same manufacturing temperatures that the LVL was produced with. In each temperature category, the members were sorted by ascending thicknesses. Twelve members were pressed simultaneously. The press schedule for the solid sawn was exactly the same as for the LVL billets except, instead of pressing to a thickness of 38 mm (1.5 in.), the press thickness was controlled by the maximum thickness of the solid sawn members for every group of twelve.

Thickness sorting was done to minimize the gap of air between the members and the top press platen and to ensure that no compression force was introduced to the solid sawn members. After the solid sawn lumber had been heat treated, the members were once again subjected to nondestructive testing.

STATIC BENDING TESTS

Static edgewise bending tests were performed to find a mechanical modulus of elasticity and modulus of rupture for all specimen categories. The modulus of elasticity, E_{static}, was used to compare to the nondestructive methods of determining stiffness: impact longitudinal stress wave time and laminated beam theory. The modulus of rupture was found to determine an ultimate flexural strength distribution for each test category. All of the test groups consisted of twenty-four members except the 193^{o}C (380^{o}F) temperature group which consisted of eighteen for solid sawn lumber and nineteen for LVL.

An Instron 4400R screw-driven test machine was used to perform all static edgewise bending tests on the simply supported beams. The procedures from ASTM D198 (1998), the standard test for determining structural lumber properties, were followed and the load-displacement data, time to failure, and maximum load were recorded by a computer data acquisition system (Labview, 1997). The ASTM standard states that the failure rate should be one that achieves maximum load in ten minutes but in no less than six minutes and no more than twenty minutes. A load rate of 3.3 mm/min (0.13 in./min) was determined to meet the provisions of the standard. All of the specimens were tested to failure. The displacement was measured at center span using a linear variable differential transformer (LVDT) (Appendix A). Using a spreader beam, the single point ramp load applied from the testing machine was evenly distributed into two point loads. The dimensions of the spreader beam were such that the two point loads were applied at third points, 610 mm (24 in.), in relation to the end reactions. This type of loading was consistent with the loading of the duration of load testing frames (see the section Load-Duration Tests in this Chapter). Finally, lateral bracing was applied in accordance with the ASTM standard to eliminate the concern of lateral-torsional buckling effects. The equations used for calculating E_{static} and modulus of rupture are 2-2 and 2-3, respectively: Further explanation of these equations is found in Appendix B. The actual static bending setup can be seen in Figure 2-4. A schematic of the testing setup can be seen in Figure 2-5.

$$E_{static} = \frac{P \cdot a}{4 \cdot b \cdot h^3 \cdot \Delta} \cdot \left(3 \cdot L^2 - 4 \cdot a^2\right) \qquad (2 - 2)$$

$$\sigma_r = \frac{M_{max} \cdot c}{I} \qquad (2 - 3)$$

E_{static} = apparent (no shear correction) modulus of elasticity found from static bending

P = load applied by the testing machine

a = distance from reaction point to the point load = 610 mm (24 in.)

b = cross sectional width

h = cross sectional height

L = span length

Δ = deflection measured at midspan

σ_r = bending strength

M_{max} = moment at midpoint

c = distance from neutral axis to outer fiber

I = moment of inertia about the axis of interest

Figure 2-4: *Typical Static Bending Test Setup Performed on the Instron 4400R*

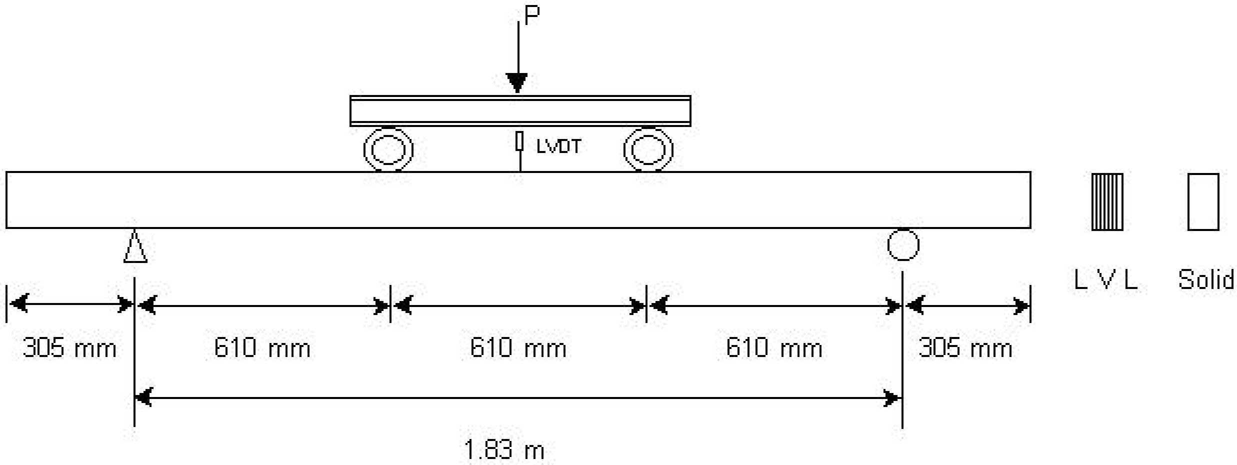


Figure 2-5: *Schematic of Static Bending Test Setup*

The solid sawn lumber without temperature treatment was considered the baseline material and used to validate the static bending test procedure results. ASTM D2915 (1994), a standard for evaluating structural lumber allowable properties, was followed. Using the baseline results, the modulus of elasticity and flexural bending design values were calculated. The design values calculated for the Standard & Better grade Douglas-fir Larch were higher but comparable to the NDS published design values: MOE = 9.81 GPa (1422881 psi) and parametric analysis F_b = 8.22 MPa (1193 psi). The higher values were expected because there are six other visually graded categories that are "better" than Standard grade. The closeness of these values to the design values confirms that the test procedure and calculations are sound. All equations used to determine both design values are found in Appendix B.

DETERMINATION OF LOADS

Using the maximum load obtained from the static bending tests, the modulus of rupture was calculated and used to determine loads for the load-duration tests. For the solid sawn members, since the members being tested were heat treated, the cross-sectional dimensions used in calculating the modulus of rupture were the dimensions found after heating. As expected, these cross-sectional dimensions were smaller than those before heating. For both LVL and solid sawn lumber, each temperature category was evaluated separately.

Several methods were used to determine which statistical distribution best represented the modulus of rupture data. The distributions analyzed were normal, lognormal, and 2-P Weibull. The first method was plotting the distributions on probability paper (Figure 2-7). This method was based on visual inspection for goodness of fit. The next method was to compare the coefficient of determination (r^2) values of the plots (Figure 2-7). This gave a quantitative result of goodness of fit, that is, the strength of the straight-line relationship of the data. Finally, the inverse CDF method was used (Figure 2-8). Both visual inspection and the standard error estimate of these inverse CDF plots were performed. After reviewing all of the above methods, it was clear that a lognormal distribution best represented the modulus of rupture data for all temperature categories of both solid sawn lumber and LVL. Examples of the probability plots and the inverse CDF plots are shown for the solid sawn no temperature category. All distribution fitting plots are found in Appendix B.

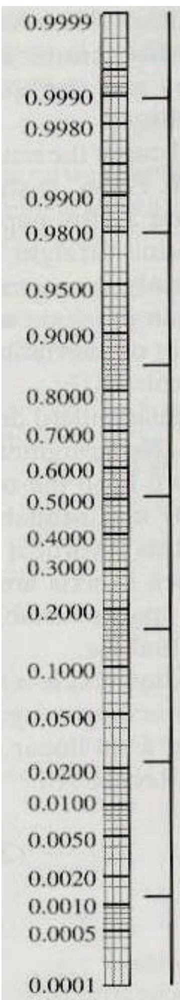


Figure 2-6: *Probability Axis for Figure 2-7*

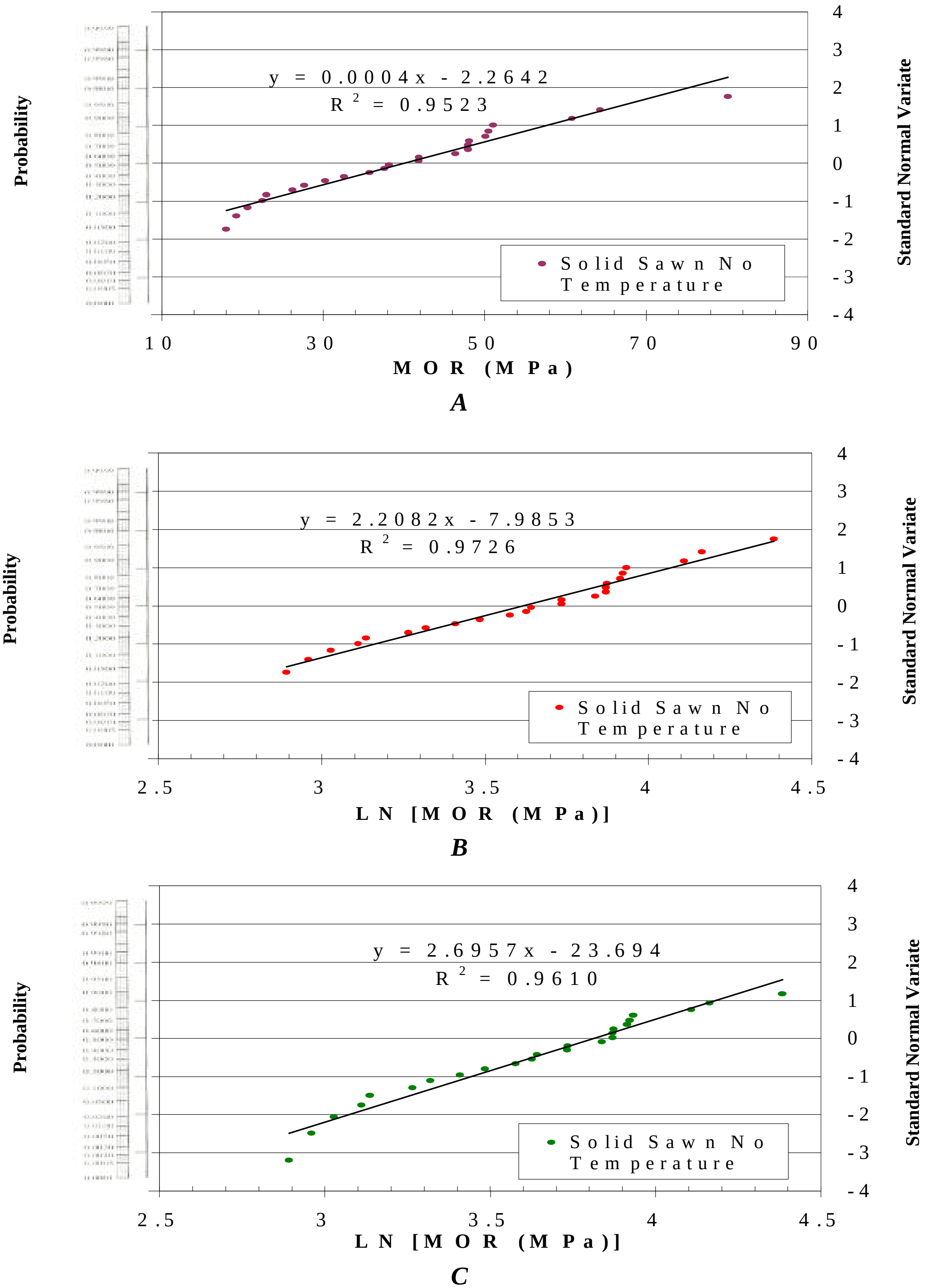
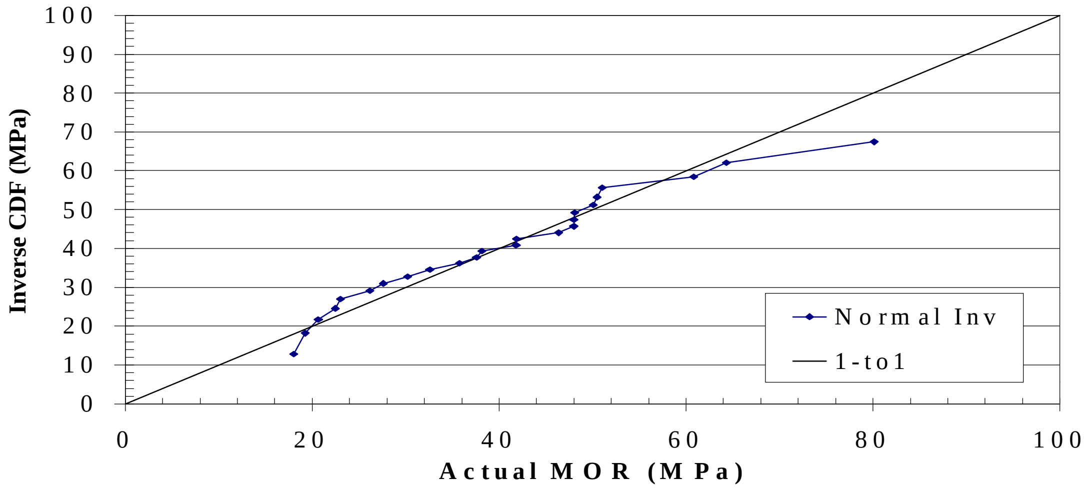
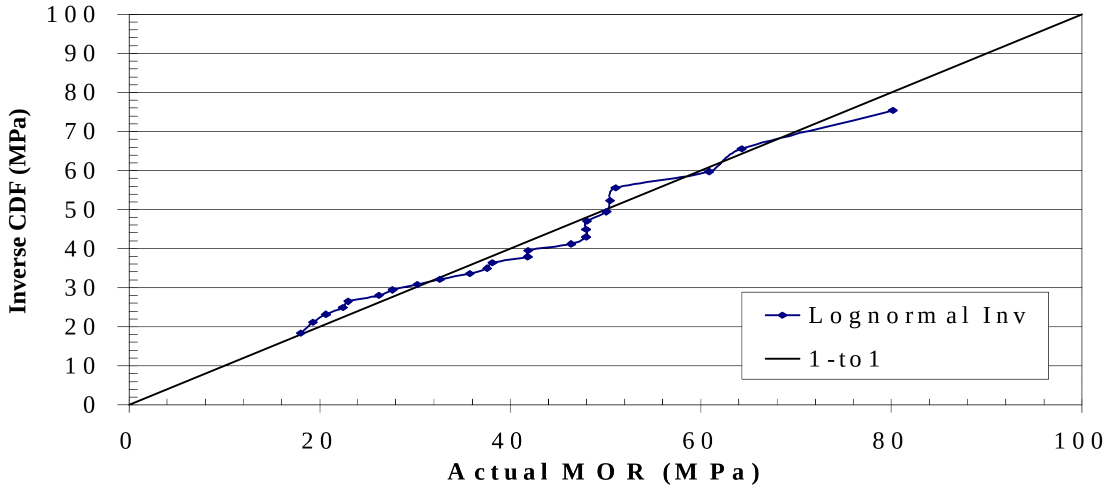


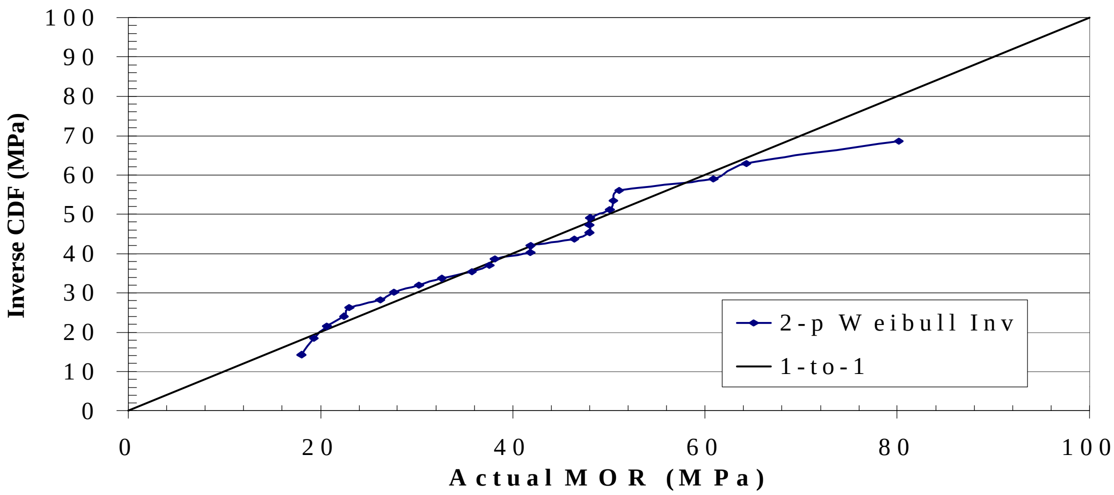
Figure 2-7: *Probability Plots: (A) Normal; (B) Lognormal; (C) 2-P Weibull Distributions*



A



B



C

Figure 2-8: *Inverse CDF Plots: (A) Normal; (B) Lognormal; (C) 2-P Weibull Distributions*

Once a lognormal distribution was determined as the best fitting distribution, the theoretical design values were found in accordance with ASTM D2915 (1994). This was done to compare temperature categories in the same manor that is done in practice. The general increase in F_b as temperature increased was a notable trend that was seen both for the solid sawn lumber and the laminated veneer lumber (Table 2-2). However, because it was desired to move beyond the lower tail data that governs the design values, the fifteenth percentile modulus of rupture was calculated from the lognormally distributed data. This value would be considered the applied stress used for the duration of load tests. Using the same equation that was used to calculate modulus of rupture from the static bending tests, the applied loads were back calculated out of the equation (Equation 2-4) using the applied stress values.

$$P = \frac{\left(2 \cdot \sigma_r \cdot I_x\right)}{a \cdot c} \qquad (2 - 4)$$

P = calculated applied load

σ_r = lognormally distributed 15th percentile modulus of rupture

I_x = moment of inertial for strong axis bending

a = distance from reaction point to the point load = 610 mm (24 in.)

c = distance from neutral axis to outer fiber

The actual values of modulus of rupture were obtained using the cross-sectional dimensions of the groups tested statically. When the loads were back calculated, the cross-sectional dimensions of the groups tested for load-duration behavior were used. This applied actual geometric properties of the group to the applied loads. This also explained the slight difference in applied loads for the two 171^{o}C (340^{o}F) load-duration groups. Two groups of 171^{o}C (340^{o}F) were used in order to provide a check within the duration of load testing. This is to say that essentially two groups from a similar population, one temperature category, should behave similarly under the same conditions of long-term testing.

Table 2-2: *Design Stress and Applied Stress*

<table>
<tr><th rowspan="2">Member & Temperature (^{o}C)</th><th colspan="2">F_b (MPa)</th><th rowspan="2">MOR (MPa) 15th percentile</th><th rowspan="2">Calculated Loads (N)</th></tr>
<tr><th>Nonparametric</th><th>Parametric</th></tr>
<tr><td>SS No Temp</td><td>8.58</td><td>8.22</td><td>25.61</td><td>4061</td></tr>
<tr><td>SS 149</td><td>8.59</td><td>8.68</td><td>28.01</td><td>4451</td></tr>
<tr><td>SS 171</td><td>7.94</td><td>9.67</td><td>30.56</td><td>4832</td></tr>
<tr><td>SS 193</td><td>12.52</td><td>10.90</td><td>34.02</td><td>5325</td></tr>
<tr><td>LVL 149</td><td>18.03</td><td>17.25</td><td>43.89</td><td>7172</td></tr>
<tr><td>LVL 171 - 1</td><td rowspan="2">16.92</td><td rowspan="2">19.35</td><td rowspan="2">49.65</td><td>8253</td></tr>
<tr><td>LVL 171 - 2</td><td>8251</td></tr>
<tr><td>LVL 193</td><td>19.32</td><td>19.15</td><td>50.08</td><td>8266</td></tr>
</table>

Load-Duration Tests

The second set of groups, one group per temperature category, was subjected to long-term loading to determine the load-duration response. All of the test groups consisted of twenty-four members, except the 193^{o}C (380^{o}F) temperature group which consisted of eighteen for solid sawn lumber and nineteen for LVL. The solid sawn lumber and laminated veneer lumber were both subjected to the constant load for forty-two days, when the last deflection data was obtained (except for the solid sawn 149^{o}C (300^{o}F) and 171^{o}C (340^{o}F) which had its last deflection data taken at thirty days). Although no more deflection data was taken, the laminated veneer lumber was observed for an additional forty-eight days for time-to-failure data (total of ninety days).

Test Frames

Four sets of testing frames were used. Each set consisted of twelve frames and each frame was designed to test two specimens at once (Figure 2-9 and Figure 2-10). The frames were specifically designed for strong axis bending load-duration tests. In a similar configuration as the static test setup, using a spreader beam, the single point load applied via a pulley and cable system was evenly distributed into two point loads. The dimensions of the spreader beam were such that the two point loads were applied at third points, 610 mm (24 in.), in relation to the supports. Lateral bracing was provided and the applied weights, made of steel and/or concrete, were hung from a 406.4 mm (16 in.) diameter pulley. Each pulley was individually calibrated by using a small load cell and applying known loads to the system (Appendix A). The actual mechanical advantage for each pulley was calculated by averaging the results from four known loads for each pulley. The minimum and maximum calculated mechanical advantages of the pulleys were 7.72:1 and 7.97:1, respectively. Belt friction of the pulleys was also calculated but was negligible so it was ignored.

Figure 2-9: *Duration of Load Test Frames*

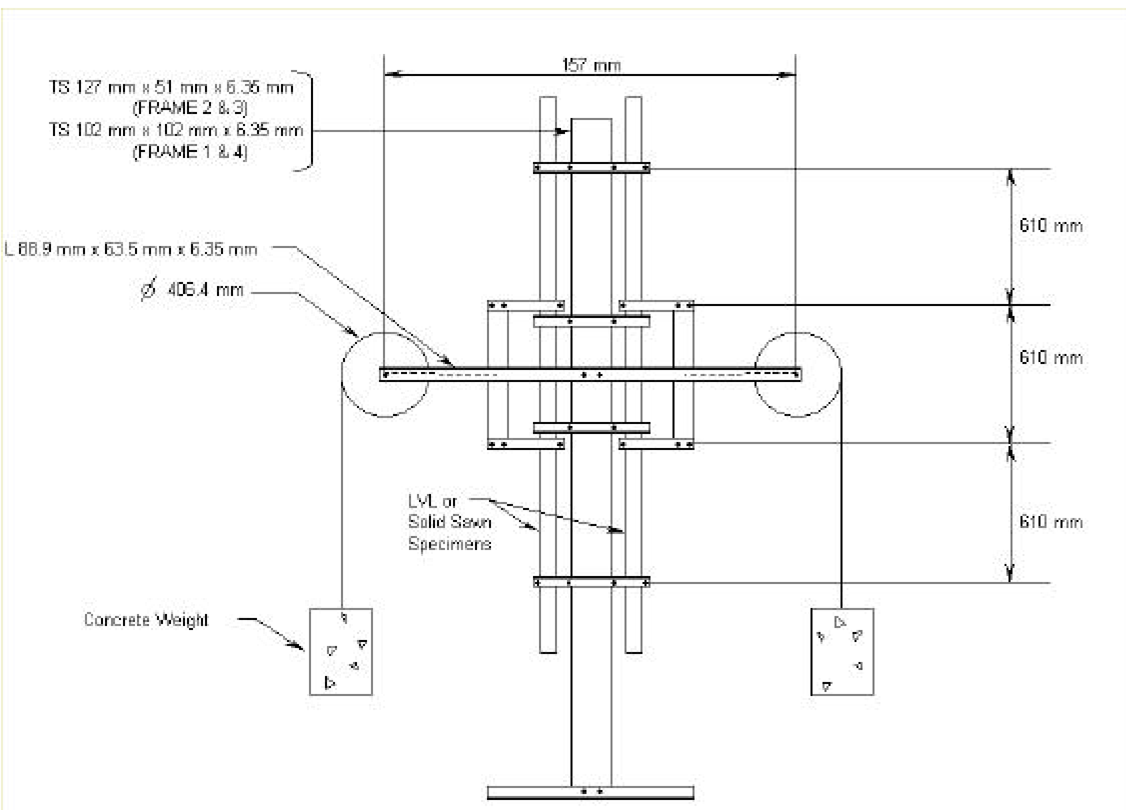


Figure 2-10: *Schematic of Duration of Load Test Frame*

DEFLECTION MEASUREMENTS

Only one set of testing frames was wired for measuring deflections via a data acquisition system. This allowed the center span deflection to be measured using voltage changes registered through a linear position transducer. However, because all frames were needed to test simultaneously, an alternative method for measuring deflections was used. A caliper was modified (Figure 2-11) so that it could easily be used to measure the distance from center span to the testing frame (Figure 2-12).

Figure 2-11: *Modified Caliper*

Figure 2-12: *Measuring Long-Term Deflection*

Because it was not possible to collect continuous data using the caliper, deflections were recorded at specific times relating to time of loading. These times were as follows: one minute, half hour (only for solid sawn), one hour, two hours, four hours, one day, four days, seven days, fourteen days, twenty-two days, thirty days (last collection for the solid sawn 149^{o}C (300^{o}F) and 171^{o}C (340^{o}F)), and forty-two days.

To verify the measurements obtained using the modified caliper, the linear position transducers were used. The collection rate for the transducers depended on the specimens being tested. For the solid sawn lumber, data was collected continuously for an hour and then every fifteen minutes but then reduced in order to compare to the caliper measurements. Data kept was collected continuously until one hour, then every fifteen minutes until twelve hours, then every hour until twenty-four hours, and then stop collection near eleven days. All of the important points of deflection were also kept, that is, points near specimen failure. For the laminated veneer lumber, the collection rate was altered during the actual data collection. For the first three days, the data was collected every thirty minutes, then every hour until six days, and finally every five hours until the end of data collection near sixteen days. The use of the data acquisition system allowed for examination of the trend of the early portion of the load-duration tests, the area that shows the most change. Expectedly, little difference was observed in the values collected from both methods (Figure 2-13).

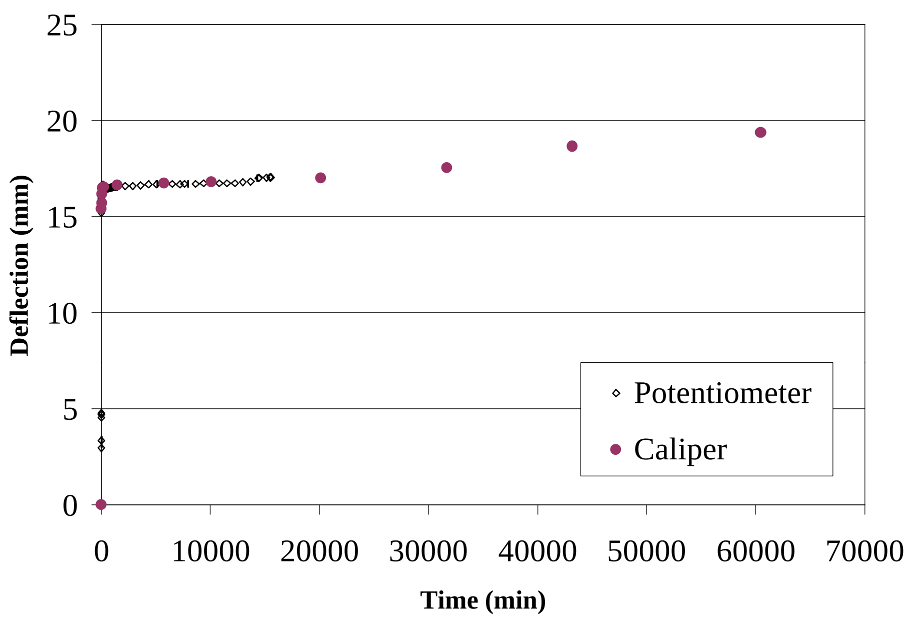


Figure 2-13: *Comparison of Deflection Collection Methods (FRAME 2, Channel 19 (No Temp Member # 97)*

RANK ORDER STATISTICS

Since the members used for the load-duration tests failed under sustained load, it was not possible to also retest the members for ultimate bending stress. In order to obtain an ultimate bending stress for the failed members, the rank order statistic method was used. This method uses the strength values found from the distribution fitting. Each specimen was ranked according to time of failure. The specimens were then assigned a lognormally distributed ultimate bending strength according to this ranking. That is to say, the first member to fail, considered the weakest, is assigned the lowest lognormal ultimate stress and so on. This ranking process was followed as the members broke until the end of testing, which was before all members had failed.

Nondestructive testing was done on all the members so there was information relating the load-duration specimens to each other but through modulus of elasticity, not bending strength. However, based on assumption that there is a positive correlation between stiffness and strength, the failure order of the members could be predicted relatively well. This proved useful in evaluating the load-duration behavior of the surviving members.

ENVIRONMENTAL TEMPERATURE AND RELATIVE HUMIDITY

Unlike past studies, the temperature variation considered herein was in the manufacturing process, *not* the test environment. The temperature of the respective testing environment was held relatively constant.

Static bending tests were performed in a temperature controlled room where the temperature range fluctuated between 21^{o}C (70^{o}F) and 23^{o}C (73^{o}F). Because the room was enclosed and environmentally controlled, the relative humidity was assumed to be constant (from the Wood Handbook (1999) page 12-5, near 30 percent to 40 percent for interior applications).

The testing room where the load-duration tests were performed was thermostat controlled at 21^{o}C (70^{o}F) with heating and cooling systems. Duration of load testing was primarily conducted during summer months so constant cooling was applied to the room and minimal heating was used to balance the environmental temperature. The relative humidity of the room was checked periodically with a Physio-Dyne heat stress meter. The average dry bulb reading was 23^{o}C (73^{o}F) and the average wet bulb reading was 13^{o}C (55^{o}F). This equates to a relative humidity of about 30 percent. There was very little fluctuation with these readings.

MOISTURE CONTENT

To obtain the moisture content of the veneer, sample 152.2 mm by 152.2 mm (6 in. by 6 in.) squares were cut from random veneer sheets. The specimens were oven-dried until an equilibrium weight was reached, per ASTM D4442 (1992). The average moisture content was calculated to be 5.52 percent with the maximum moisture content equaling 7 percent. For hot pressing, it is ideal to have the veneer moisture content range between 3 and 5 percent (Wood Handbook, 1999). To achieve a lower moisture content, the veneer was introduced to a temperature control room to reduce the moisture content. The room was conditioned at 100^{o}F and 14 percent relative humidity. These conditions drove down the equilibrium moisture content of the veneer to 3.3 percent.

It was not feasible to cut samples from the solid sawn members or the manufactured LVL. The solid sawn lumber had been surfaced dried at the mill and therefore was considered dry, that is, less than or equal to 19 percent moisture content. A Wagner capacitance type moisture meter was used to obtain a more accurate measure of 10 percent. No conditioning needed to be done since this moisture content was determined not to affect the stress wave time readings (Pellerin, 1965). After the solid sawn members were heated, moisture was noticeably driven out of the specimens. However, because the effects of the short-term heating were of interest, the specimens were allowed to return back to equilibrium of the testing facility before tests were performed. The moisture meter was also used to determine the moisture content of the

LVL. After being pressed at different temperatures and conditioned in the testing facility, the equilibrium moisture content of 10 percent was the same for all LVL members.

The nondestructive and static bending tests were performed at the same testing facility. However, the duration of load tests were performed at a different location at Washington State University. Because of this, the solid sawn and LVL specimens to be used for load-duration tests were conditioned in the new facility for at least a month before tests were run. The values for moisture content showed no appreciable difference from the 10 percent previously recorded. Confirmation of a consistent moisture content was made by again testing the specimens after failure.

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CHAPTER THREE

PRESSING PROCEDURE

INTRODUCTION

The general process of manufacturing laminated veneer lumber is well known. However, the specifics of the manufacturing process are left up to individual companies. Through trial and error, engineered wood manufacturing companies determine the details of the manufacturing process schedule and fine-tune them to optimize and improve their product. Products are then tested in accordance with ASTM D5456 (1993). Because most of the information is proprietary, only ranges of utilized pressing parameters are known.

Like in industry, practice attempts were made when manufacturing the billets. Parameters such as glue spread level, press time, pressure cycle, and temperature all had to be experimentally fine-tuned through trial and error. The end result was a press schedule that held time and thickness constant, regulated pressure cycles, and varied manufacturing temperature (Appendix C).

VENEER LAY-UP

Veneer quality is a processing variable that has been proven to affect laminated veneer lumber product. Quality control, such as visual grading or stress wave time, of the veneers allows for the manipulation and betterment of the development of an end product. This manipulation has led to a more uniform product with limited variation as compared to solid sawn lumber. However, other veneer parameters other than veneer quality also influence the LVL end properties. Among these are wood species, number of piles, veneer dimensions, and veneer location within the composite. Thus far, LVL studies have been very diverse in billet configurations (Laufenberg, 1983), involving species types, numbers of piles, lay-up techniques, and sorting schemes.

The current industry practice is to place higher grade veneer on the outside and lower quality veneer in the core of the billet. Studies from several researchers (Pu and Tang, 1997; Harding and Orange, 1998) have found this practice to vastly improve the quality of the LVL by increasing the modulus of elasticity. However, because it was desired to mimic the distribution of the solid sawn lumber, this practice was only followed within each billet. Because the sorting technique grouped the veneer in ascending order, the eleven dynamic modulus of elasticity ($E_{dynamic}$) values found within the billet (each veneer sheet) were arranged according to current industrial practice.

The very nature of rotary cutting causes checking in the veneer. The checked side is referred to as the loose side and the opposite, the tight side. The Wood Handbook (1999) suggests that the loose side be bonded to the tight side. In industry, this is followed so that the loose and tight faces are alternated from the core out with bottom and top faces exposing the tight side. This was the lay-up configuration of the veneers for this research.

ADHESIVE

It is important to choose the correct adhesive for the manufacturing of any wood product. Douglas-fir is known to "bond well with a fairly wide range of adhesives under a moderately wide range of bonding conditions" (Wood Handbook, 1999). The species type did not govern adhesive selection, so other factors were to determine the adhesive. Since the goal of this research was to compare manufacturing temperatures, a thermosetting adhesive, which would undergo irreversible chemical change, was needed. Because the application of this research is structural, it was desired for the adhesive to contribute to both stiffness and strength. A Phenolic adhesive was chosen. This is a typical adhesive used for softwood LVL production. A Phenolic adhesive is cured in a hot press with temperatures ranging 120^{o}C to 150^{o}C (250^{o}F to 300^{o}F) (Wood Handbook, 1999). Georgia-Pacific Resins, Inc. supplied the liquid phenol-formaldehyde resin (Appendix C).

VENEER MOISTURE CONTROL

The effectiveness of an adhesive does not depend on the adhesive alone. The wood being bonded must also be conditioned to maximize bonding with the adhesive. Because the adhesive was liquid, the wettability of the veneer was crucial. A simple drop test was done to examine the angle of the drop to the wood surface. Before the veneer had been dried (average moisture content (MC) = 5.5 percent), the wettability was moderate (about a 45^{o} drop angle). After the veneer had been conditioned to 3.3 percent MC, the wettability was improved, reducing the interface angle. Had the moisture been reduced any farther, there would not have been sufficient water within the wood to form intermolecular attraction with the water from the adhesive.

BILLET PRODUCTION

Billets were assembled one at a time. Each veneer was manually fed through a roller resin spreader (Figure 3-1) to apply a single glueline (film) with a resin spread of 180.65 kg / 1000 m^2 (37 lb / 1000 ft^2). The glue spread level was tested before each production day of LVL. A square 303.8 mm (1 ft) veneer section was sent through the glue spreader and weighed. The tolerance range for the resin was 16.7 grams to 16.8 grams. Approximate time from lay-up start-up to press start-up was ten minutes.

Figure 3-1: *Roller Resin Spreader*

Figure 3-2: *Williams & White Pressman Hydraulic Press*

PRESS SCHEDULE

LAMINATED VENEER LUMBER

A William & White Pressman hydraulic 1.22 m by 2.44 m (4 ft by 8 ft) platen hot press (Figure 3-2) was used for making the 38 mm by 610 mm by 2.44 m (1.5 in. by 2 ft by 8 ft) billets. However, before the billets could be pressed, a press schedule had to be developed. As stated earlier, practice billets were used to determine several of the parameters through experimentation. Upon investigation, a common range of temperatures was found to be 145^{o}C to 160^{o}C (293^{o}F to 320^{o}F) for this type of adhesive. The goal was to target temperatures near, greater, and much greater than common industrial practice. The only known parameters were the research driven temperatures of 149^{o}C (300^{o}F), 171^{o}C (340^{o}F), and 193^{o}C (380^{o}F) and thickness of 38 mm (1.5 in.). By knowing the temperatures, the first parameter that was determined was time. This was done by an analysis of the phenol-formaldehyde resin at the above specified temperatures. Using the resin characteristic charts (Appendix C), the point at which the resin properties reached equilibrium was found. This time was near twenty minutes for all temperatures.

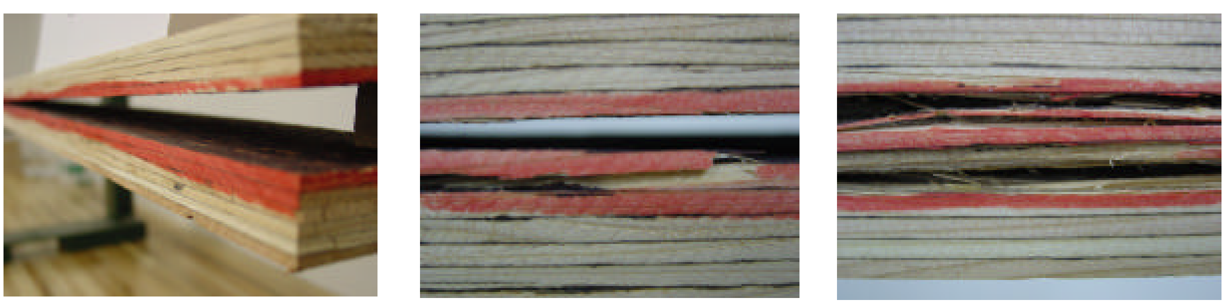
Under the conditions stated earlier, the type of adhesive was chosen. The single glueline method and resin spread level were determined from experience in LVL manufacturing. In order to determine a press cycle, thermocouples were used in two locations on practice billets: the core and between the second and third veneers from the surface. From their locations, the thermocouples provided data about the temperatures and gas pressures. From this information, a press schedule, common for all temperatures (except, of coarse, for temperature) was developed (Appendix C). The press cycle was based on a thickness cycle, which was based on a time cycle. After twenty-nine seconds, the end condition pressure was 6897 kPa (1000 psi) and then reduced to 1382 kPa (200 psi) after forty-four seconds and held constant until the end of the cycle at twenty minutes. It should be noted that the core temperature never reached the desired manufacturing temperature. It should also be noted that the actual averages billet thickness were larger than 38 mm (1.5 in.).

Solid Sawn Lumber

The solid sawn lumber was subjected to the same press schedule as the laminated veneer lumber except for thickness control, which was altered according to lumber thicknesses. Twelve members were placed on the platen at a time. The thickness of the press was determined by the maximum thickness of each set of twelve. Moisture content was not a concern because the width of the member was small enough to allow the escape of steam during pressing. Also, the sorting of the lumber (by thickness) prevented the members from being subjected to any pressure from the platens. It was observed that the higher the temperature, the more moisture was driven out onto the surface of the member. It was also observed that for all temperatures, heavy bleeding about the knots occurred. The severity also increased as temperature increased. Finally, color change was also noted, that is, as the temperature increased, the surface of the wood became darker.

Billet Failure

When using thermosetting adhesive, excess moisture can cause many problems, that essentially damage the wood product. One of these problems is termed “blow,” which is the separation along the bondline due to the release of pressure. This happens because the excess water, which has been sustained in liquid form due to the pressure, turns into steam upon release of that pressure and causes an explosion. Since the billet was over 910 mm (3 feet) square, full pressure was developed at the core of the billet (Norris, 1942). Because of this, even after what was learned with the experimental billets, blows were still a source of damage for many billets. In fact, it was the existence of multiple blows that limited the final sample size of the highest temperature category. What is unique is the observation that the type of blow was specific, yet different, between the temperatures at which the billet was pressed. The different blow failures can be seen in Figure 3-3.



A ***B*** ***C***

Figure 3-3: *LVL Manufacturing Blow Failures: (A) member 6e of 149°C (300°F); (B) member 4a of 171°C (340°F); (C) member 5b of 193°C (380°F).*

For manufacturing at 149^{o}C (300^{o}F), the blow failure was purely delamination (Figure 3-3A), where the adhesive and the wood did not bond properly. The blow failure for 171^{o}C (340^{o}F) (Figure 3-3B) was a combination of failures: clear delamination along the bond line and wood failure. The manufacturing temperature of 193^{o}C (380^{o}F) experienced the most blows. All of the blows at this temperature were pure wood failure that transcended bondlines (Figure 3-3C). This trend suggests that the adhesive did properly bond. However, the moisture from the manufacturing process was soaked into the wood causing the steam to blow the wood apart. Since billets manufactured at all temperatures experienced some sort of blow failure, the ratio of good and useable LVL to total LVL produced was calculated. "Good" LVL was defined as specimens with no blow failure and "useable" LVL included good LVL and minor failures determined not to affect the performance of the LVL. The results in Table 3-1 suggest that the best yield resulted from a manufacturing temperature of 171^{o}C (340^{o}F).

Table 3-1: *Manufacturing LVL Yield*

Total Expected*	Billets Made	LVL / Billet	Total LVL
	15	6	**90**
Temperature	149^{o}C (300^{o}F)	171^{o}C (340^{o}F)	193^{o}C (380^{o}F)
Total "good" LVL Additional "useable" LVL**	49 8	71 2	30 10
Optimistic "useable" Total	57	73	40
Percent of "good" LVL	54.44%	78.89%	33.33%
Percent of "useable" LVL	63.33%	81.11%	44.44%

*pertains to all temperatures
**only minor delaminations

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CHAPTER FOUR

Evaluating Prediction Methods for Stiffness and Strength: A Comparison of Nondestructive Evaluation and Laminated Beam Theory for Douglas-fir LVL

Abstract

The predictive capability of nondestructive stress wave testing for mechanical properties has been studied extensively. However, the laminated beam theory, based on stress wave time testing of individual veneers, has been given less attention. An experimental investigation was performed to assess the predictive capabilities of these two methods for modulus of elasticity and modulus of rupture. For Douglas-fir Larch Standard grade lumber, the dynamic modulus of elasticity showed good correlation with the static modulus of elasticity while correlation with modulus of rupture was poor. For Douglas-fir laminated veneer lumber, the nondestructive technique of calculating a dynamic modulus of elasticity proved to be the best predictive method overall. However, the laminated beam theory, which could be used to predict laminated veneer mechanical properties before manufacturing, also proved to be a good indicator.

Introduction

Nondestructive testing of wood products is unique from the testing of nonwood materials. This is because homogeneous isotropic materials, such as steel, are manufactured to specific material properties with practically no variance. Therefore, rather than testing for mechanical properties, nondestructive testing is used to detect localized defects in the material. In wood, however, “defects” are expected since the material is “manufactured” naturally. Because of this, nondestructive techniques are used to evaluate the mechanical properties of the naturally irregular wood.

Machine stress rating (MSR) is the most commonly used form of nondestructive testing for evaluating lumber. Longitudinal and transverse wave propagation can also be used to assess the structural properties of lumber. These methods, however, are not limited to solid sawn lumber alone. For laminated veneer lumber, the veneer sheets can be tested individually, before manufacture, in order to assess their mechanical properties. This can is done either visually or via stress wave propagation. The veneer sheets are then sorted according to their stiffness. The goal is to arrange the veneer sheets in such a way that the properties of the manufactured laminated veneer lumber are less variable (lower coefficient of variation, COV) and more predictable.

The veneer lay up is not the only factor that can affect the mechanical properties of the final product. Other factors include, but are not limited to, number of veneer piles, veneer quality, veneer dimensions, wood species, manufacturing variables, and end product dimensions. Examples of manufacturing variables are time, temperature, thickness, and pressure cycle. The development of these parameters is mainly proprietary, that is, not standardized, rather, defined by individual companies through experience. Because of this, the processing variables are not altered once end products meet standards. However, there is a potential to improve production if these variables can be further maximized. The variable examined in this research is processing temperature, however the actual effects of manufacturing temperature are discussed in later chapters. The reader is cautioned against drawing conclusions about the effects of manufacturing temperature from data presented in this chapter. This chapter serves only to establish a method that best predicts mechanical properties of the materials in question.

In order to determine the success of the predictability of the structural properties of the laminated veneer lumber manufactured at different temperatures, several techniques can be used, a few of which are a traditional static bending test, longitudinal stress wave propagation on the end product, and laminated beam theory. While there have been many studies relating modulus of elasticity from stress wave time to static bending, the effectiveness of the laminated beam theory has had little focus. This, no doubt, is in part because the latter technique is more rigorous and time consuming thus not as attractive to industrial applications. However, the technique does require the use of stress wave propagation of the veneer sheets and would provide a possible method for prediction of laminated veneer properties before processing. The following research examines the three above techniques and how their resultant modulus of elasticity values compare to each other. The correlation between these moduli of elasticity values and their respective moduli of rupture values was also examined.

BACKGROUND

A major initiation of nondestructive techniques for wood was made by Jayne (1959). Although research involving vibrations in wood had started as early as the mid seventeen hundreds (Pellerin, 1965), Jayne hypothesized that the mechanisms that controlled static behavior were the same as those that could be measured nondestructively in the form of energy storage and dissipation within wood. In the study, Jayne used transverse vibration on small clear wood specimens to verify the hypothesis of the relation between static properties and energy storage and dissipation. The result was a verification of the relationship between the static and the dynamic modulus of elasticity ($E_{dynamic}$). The hypothesis has prompted much research in the area of nondestructive techniques for testing strength and stiffness of wood members. Currently, there are three common techniques for nondestructive assessment: low load static bending (technique used for MSR lumber), transverse vibration, and stress wave propagation (Ross and Pellerin, 1994).

The use of a longitudinal stress wave in wood evaluation has been investigated for over forty years (Gerhards, 1982). The majority of this research has involved the comparison of the dynamic modulus of elasticity ($E_{dynamic}$) to the static bending elasticity (E_{static}) in lumber specimens. The results have proven a strong correlation between the two moduli. For lumber, moisture content of twelve percent, Bell et al. (1954) reported a correlation coefficient of 0.98, with the dynamic modulus obtained from resonant frequency. Also using resonant frequency (Equation 4-1), Pellerin (1965) found the same correlation coefficient for construction lumber (numerous grades) with combined moisture contents of six and nine percent.

$$E_d = \frac{f_n^2 \cdot w \cdot L^3}{C^2 \cdot I \cdot g} \qquad (4 - 1)$$

E_d = dynamic modulus of elasticity

C = constant (dependant upon the support conditions)

f_n = resonant frequency

w = beam weight

L = beam length

I = moment of inertia

g = acceleration due to gravity

Porter et al. (1972) had similar findings using a digital computer for determining a dynamic modulus. However, with a larger sample size and moisture content of 10 percent, the correlation was lower at 0.90.

Simplification of the differential equation for wave propagation (Equation 4-2), has become a common way to determine the dynamic modulus of elasticity through the use of impact stress waves.

$$E_{dynamic} = \rho C^2 \qquad (4 - 2)$$

$E_{dynamic}$ = calculated dynamic modulus of elasticity

ρ = density

C = average longitudinal stress wave speed (three readings)

Using this approach, Lanius et al. (1981) reported an even lower correlation coefficient of 0.824 for No. 1 and No. 2 Douglas-fir 50 mm by 150 mm (2 in. by 6 in.) with a seven percent moisture content. Gerhards (1982) summarized results of this relationship from several studies. The overall trend was a very high correlation of the two moduli (coefficients between 0.87 and 0.99). It was also noted that the correspondence between the moduli was not one-to-one. For Bell et al. (1954), the ratio of the dynamic to static modulus was 1.23, and for Porter et al. (1972), the ratio was 1.04. This trend of higher dynamic modulus values was also seen in the Pellerin (1965) and Lanius (1981) studies. In addition, Gerhards (1982) noted that the type of longitudinal stress wave, impact or ultrasonic instrumentation, did not yield different stress wave speeds.

Stress wave time techniques have been used to evaluate the same relationships for veneer sheets and more recently, laminated veneer lumber. Using the equation 4-2, Koch and Woodson, (1968) and Jung (1982) determined the $E_{dynamic}$ of individual veneer sheets. Koch and Woodson (1968) found a high correlation coefficient (0.94) between the stress wave modulus of elasticity and the static tension modulus of elasticity. Kimmel and Janowiak (1995) did not go as far as to calculate an $E_{dynamic}$ for veneer sheets but instead suggested that the ultrasonic propagation time was adequate to separate veneers for better mechanical performance of yellow-poplar and red maple LVL. Research done by Pu and Tang (1997) reported good correlation for solid sawn southern pine lumber but less accurate predictions for LVL of the same species. Their results also followed the solid sawn trend of nondestructive values being higher than static destructive bending values.

A difficulty in predicting beam stiffness in laminated veneer lumber is that the laminates will inherently have different properties. One technique to examine laminated sections is to use transformed sections analysis. This method involves transforming the geometry of the composite so that the new section has a constant stiffness. However, the calculation process is extensive. Another approach is to use the laminated beam theory (Timoshenko and Goodier, 1970). This theory makes a distinction between both horizontal and vertical laminates. The apparent bending modulus of elasticity is defined as the following (Equation 4-3 and 4-4):

$$E_{composite} = D \cdot \frac{12}{b \cdot t^3} \tag{4 - 3}$$

$$\text{where} \quad D = \sum_{i=1}^{n} b_i \cdot E_i \cdot \left(t_i \cdot d_i^2 \cdot \frac{t_i^3}{12} \right) \tag{4 - 4}$$

Since the variables of the bending stiffness, D, changes depending on the orientation of the laminates, the variables for both orientations are discussed in detail later in the chapter and defined in Appendix B. The individual modulus of elasticity values for the veneer sheets, E_i, are found using longitudinal stress waves. An attempt at predicting the mechanical properties for parallel-laminated veneer members in edgewise bending was made by Jung (1982). The method was to predict the members' modulus of elasticity by averaging the dynamic moduli of the veneer sheets. Although robust and reportedly well correlated, this method neglects the contribution of both veneer and section dimensions. The overall trend also deviated from other findings in that the dynamic modulus of elasticity values were lower than the mechanical modulus of elasticity values

Much consideration has also been given to the relationship between the modulus of elasticity (MOE) and the modulus of rupture (MOR). The aim has been to be able to predict the strength of a member by correlation of its dynamic modulus of elasticity. James (1964) provided regression analysis between modulus of rupture and both $E_{dynamic}$ and E_{static}. The correlation coefficients for clear Douglas-fir specimens, at a moisture content of twelve percent, were 0.908 and 0.926, respectively. For construction lumber, Pellerin (1965) found high correlation between the modulus of rupture and $E_{dynamic}$. For moisture contents of six and nine percent, the correlation coefficients were 0.89 and 0.90, respectively. In contrast, Jung (1982) found poor correlation between strength and stiffness for coast Douglas-fir parallel-laminated veneer. For edgewise bending, the mechanical MOE and the stress wave time predicted MOE had correlation coefficients of 0.609 and 0.553, respectively.

Predicting the mechanical properties of laminated veneer lumber could be done using either of the methods discussed above. Since there is uncertainty as to which method would best predict actual mechanical properties, experimentation was done to determine the predictive capability of the two methods.

MATERIALS

The laminated veneer lumber (LVL) was made from Douglas-fir (*Pseudotsuga menziesii*) veneer sheets and the solid sawn lumber was Standard Douglas-fir larch. The veneer was rotary peeled and was cut into six hundred and sixty 1.25 m by 2.55 m (generous 4 ft x 8 ft) sheets. The average thickness of the veneer was 3.68 mm (0.145 in.). After manufacture, each billet was cut into six 2.44 m (8 ft) long, 38 mm by 89 mm (nominal 2 in. by 4 in.) laminated veneer lumber members. The Standard grade for the one hundred and eighty members of 38 mm by 89 mm (nominal 2 in. by 4 in.) solid sawn was chosen for the wide range in structural properties, that is, a high COV of the material. Each member was 2.44 m (8 ft) in length.

METHODS

The objective was to determine the most effective method of predicting the mechanical properties of Douglas-fir LVL and Douglas-fir larch solid sawn lumber. Since the main goal centered on manufacturing temperatures, material had to be sorted into various temperature categories. Upon investigation, a common range of manufacturing temperatures was found to be 145^{o}C to 160^{o}C (293^{o}F to 320^{o}F). The goal was to target temperatures near, greater, and much greater than common industrial practice. The chosen temperatures were 149^{o}C (300^{o}F), 171^{o}C (340^{o}F), and 193^{o}C (380^{o}F). As a baseline, solid sawn members of the same species were subjected to the same press cycle as was used to manufacture the LVL.

First, the unheated solid sawn lumber and the veneer sheets had to be sorted. Laminated beam theory did not apply to this material so all nondestructive sorting was first done by impact longitudinal stress wave propagation. Once this was done, the solid sawn lumber was heat treated and the veneers were pressed into billets. The press schedule had to be established by using practice billets (Chapter Three). The processing variables were as follows:

LVL specific:

1. Resin: liquid phenol-formaldehyde;
2. Spread Level: single glueline of 180.65 kg / 1000 m^2 (37 lb / 1000 ft^2) via a roller spreader;

LVL and solid sawn lumber:

3. Press: hot platen hydraulic;
4. Press Temperatures: 149^{o}C (300^{o}F), 171^{o}C (340^{o}F), and 193^{o}C (380^{o}F);

5. Press Schedule: thickness controlled: 38 mm (1.5 in.), eleven piles for LVL and maximum thickness for every twelve solid sawn members;
6. Press Time: twenty minutes; and
7. Pressure Cycle: after twenty-nine seconds, the end condition pressure was 6897 kPa (1000 psi) and then reduced to 1382 kPa (200 psi) after forty-four seconds and held constant until the end of the cycle at twenty minutes.

After the laminated veneer lumber was manufactured, and the solid sawn lumber was heated, the modulus of elasticity was evaluated using longitudinal stress wave propagation and static edgewise bending. The laminated veneer lumber was also evaluated using the laminated beam theory. The static bending tests were also used to determine the modulus of rupture. All nondestructive and destructive testing was done at ten percent moisture content. Cumulative distributions were compared (Appendix D), correlation coefficients were found between the methods, and ANOVA's were performed on all relationships (Appendix E). The overall effectiveness of the different methods was determined.

MATERIAL SORT

The sorting of the material was crucial for examining the effect of manufacturing temperature on the mechanical properties of the laminated veneer lumber. Solid sawn members and veneer had to be sorted. All initial sorting techniques were based on the dynamic modulus of elasticity. Because of additional duration of load testing, supplementary sorting (using the method determined through this study) was performed but is not discussed here. Therefore, not all material was used for this study.

Solid Sawn

All unheated solid sawn members were tested nondestructively to obtain an $E_{dynamic}$ (from Equation 4-2) for each specimen. The members were weighed and measured (one length, average of three widths, and average of three thicknesses). Each member was clamped down perpendicular to the width, that is, in a flatwise horizontal plank position. Impact longitudinal stress waves were only introduced in one location along the width, the center. An average of three stress wave times was taken.

The members were then sorted in order of ascending $E_{dynamic}$. A pseudo random sort (Chapter Two) was used to divide the members into the four temperature categories (one of the categories being no temperature). An analysis of variance (ANOVA) was performed on the $E_{dynamic}$ values between the temperatures (Appendix E). The analysis showed no statistical difference between the temperature categories.

Veneer

All veneers used in the production of laminated veneer lumber were tested nondestructively to obtain an $E_{dynamic}$ (from Equation 4-2) for each veneer sheet. The members were weighed and measured (average of three lengths, average of three widths, and average of four thicknesses). Each member was clamped down perpendicular to the width (flatwise). Impact longitudinal stress waves were introduced to the third point locations along the width. The average of the three stress wave times at those locations was determined as the stress wave time for the entire veneer sheet. The veneers were divided into groups of eleven based on ascending $E_{dynamic}$ values. The group with the lowest $E_{dynamic}$ was assigned to the temperature category of 149^{o}C (300^{o}F), the next ascending group of eleven was assigned to the next temperature and so on until all temperature categories had fifteen sets of eleven veneers. This sorting is not the common practice in industry but the aim here was to mimic the distribution of the solid sawn lumber. The unconventional sorting technique proved valid after ANOVA results suggested there was no significant statistical difference between the $E_{dynamic}$ values of all the temperature categories (Appendix E). The validity of this technique is graphically represented in Figure 4-1.

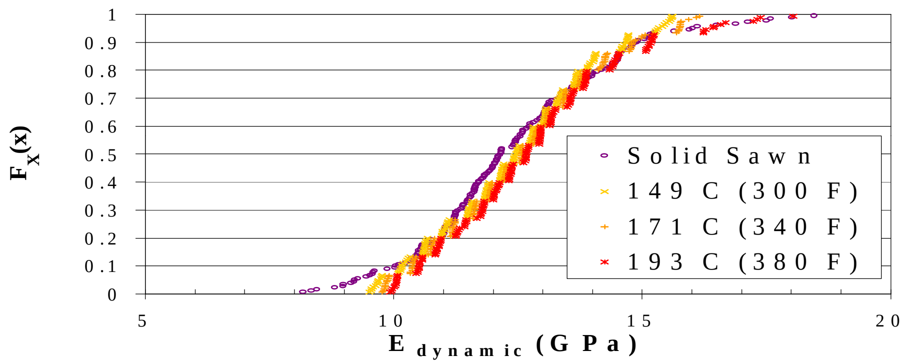


Figure 4-1: *Cumulative Distribution of $E_{dynamic}$ of Sorted Veneers and Solid Sawn Lumber*

DETERMINATION OF MODULUS OF ELASTICITY

The materials evaluated for modulus of elasticity, through various techniques, were the unheated solid sawn lumber, heat treated solid sawn lumber, veneer sheets, and manufactured laminated veneer lumber. Because of the nature of some of the materials, not all materials were evaluated with all techniques. Table 4-1 presents a test matrix for the study of correlation between modulus of elasticity values determined using the different methods. When testing correlation between the nondestructive methods and static bending, only the specimens that were destructively tested were included in the compared nondestructive population. However, with the laminated beam theory, some methods required all useable data to be considered.

Table 4-1: *Test Matrix for Obtaining Modulus for Elasticity Values*

Material	Temperature (^oC)*	Test Type		
		Impact Longitudinal Stress Waves	Laminated Beam Theory	Static Edgewise Bending
Unheated Solid Sawn Lumber	No Temp	48	NA	24
	149	48	NA	----
	171	48	NA	----
	193	36	NA	----
Heated Solid Sawn Lumber	149	48	NA	24
	171	48	NA	24
	193	36	NA	18
Veneer	No Temp	495	NA	NA
LVL	149	57	57	24
	171	73	73	24
	193	40	40	19

*temperatures in ^oF are 300, 340, and 380

IMPACT LONGITUDINAL STRESS WAVES

The nondestructive technique used to evaluate all test material was impact longitudinal stress wave propagation (Equation 4-2). The solid sawn lumber was nondestructively tested before it was heat treated. Sorting before the applied heat ensured that the temperature categories had similar distributions before alterations. After heating, the new $E_{dynamic}$ of the heat treated solid sawn lumber was calculated. The veneer sheets were also tested to obtain an $E_{dynamic}$. This value was the basis for sorting and would also be used for the laminated beam theory application. The $E_{dynamic}$ value is an apparent modulus of elasticity, that is, not corrected for shear contributions.

After the billets were made at the three manufacturing temperatures, they were cut to dimension (nominal 2 in. by 4 in., 8 ft long). Six LVL specimens of such dimensions were cut from each billet. The specimens were labeled according to manufacturing temperature, billet number (1 through 15 where ascending number corresponds with ascending veneer $E_{dynamic}$

values), and letter *a* through *f* for location of specimen within the billet (*a* and *f* consisting of the edge-most billet material). All 269 LVL specimens were tested nondestructively. However, because of the nature of the induced longitudinal stress wave, and the long travel distance, it was not possible to detect localized LVL manufacturing induced failures such as delaminations. Because of this, each LVL was visually inspected as well and labeled as good, minor delaminations, or major delaminations. The location and amount of delamination was also recorded. The sorting of the veneers ensured that the make-up of the LVL would be statistically not different.

LAMINATED BEAM THEORY

Since this theory deals with laminates that have different modulus of elasticity values, it did not apply to the solid sawn members. The laminated beam theory was calculated for both horizontal and vertical laminate orientations (Appendix B). The modulus of elasticity values that were calculated were apparent values, that is not corrected for shear. The $E_{dynamic}$ of the individual veneer sheets, E_i, had already been found through sorting practices.

For horizontal laminates, the modulus of elasticity changes with respect to the depth of the beam because of the varying veneer $E_{dynamic}$ values. This orientation would simulate flatwise bending. Applying Equation 4-4 for this orientation, the width of the beam was termed b. Because the LVL is cut to dimension, the width of the individual veneer sheets, b_i, was equal to the section width, b. Also, d_i, the distance from the composite neutral axis to the laminate neutral axis, was applicable for the horizontal orientation. The individual veneer thicknesses were termed t_i. However, the depth of the beam, or thickness, varied according to what is considered the "section" thickness. It is assumed that "section" refers to the actual cross section of the laminated veneer member. Calculations using the average thickness of the LVL member as the definition for section were termed $E_{composite\text{-}horz}$. However, the laminated veneer lumber was cut from larger "sections," that is the billets. The laminated beam theory was applied to reflect average billet dimensions of thickness. The calculations using the average thicknesses from all useable LVL members that came from the same billet, essentially, average billet thickness, were termed $E_{billet\text{-}horz}$. Finally, the most simplistic approach was to use the anticipated press thickness of 38 mm (1.5 in.) as the section thickness. This was examined because the actual press thickness was 38.6 mm (1.52 in.), which was slightly greater than the expected thickness of 38 mm (1.5 in.). This approach was termed $E_{expected\text{-}horz}$. Because the last two approaches use dimensions of the entire billet, only one value per billet was obtained leading to the assumption that all of the LVL cut from that billet would possess the same properties. Because of this, the LVL actually used in the static bending tests could not be differentiated, therefore, the last two approaches encompass all "useable" LVL data rather than just the members being tested statically.

A similar analysis of the vertical laminate orientation was also done. This orientation would simulate edgewise bending. In this case, because the laminates were vertical, there was no change in modulus of elasticity with respect to the depth of the beam and therefore, d_i was equal to zero. The width of the beam was now the depth and therefore termed t. Because the individual veneer widths were cut to dimension of the section, t_i equaled t. The thicknesses of the individual veneers were now termed b_i and the thickness of the section was termed b. The simplified equation for this orientation became Equation 4-5.

$$E = \frac{\sum_{i=1}^{n} b_i \cdot E_i}{b} \qquad (4 - 5)$$

The same three options for "section" thickness were explored. The nomenclature for the vertical laminate orientation was then $E_{composite\text{-}vert}$, $E_{billet\text{-}vert}$, and $E_{expected\text{-}vert}$.

Static Bending Tests

Static edgewise bending tests were performed to find an actual modulus of elasticity and modulus of rupture for all specimen categories. The static modulus of elasticity was used to compare to the nondestructive methods of determining stiffness: impact longitudinal stress wave time and laminated beam theory.

An Instron 4400R screw-driven test machine was used to perform all static bending tests on the simply supported beams. The procedures from ASTM D198 (1998), the standard test for determining structural lumber properties, were followed and the load-displacement data, time to failure, and maximum load were recorded by a computer data acquisition system (Labview, 1997). The ASTM standard states that the failure rate should be one that achieves maximum load in ten minutes but in no less than six minutes and no more than twenty minutes. A load rate of 3.3 mm/min (0.13 in./min) was determined to meet the provisions of the standard. All of the specimens were tested to failure. The displacement was measured at center span using a linear variable differential transformer (LVDT) (Appendix A). Using a spreader beam, the single point ramp load applied from the testing machine was evenly distributed into two point loads. The dimensions of the spreader beam were such that the two point loads were applied at third points, 610 mm (24 in.), in relation to the end reactions. Finally, lateral bracing was applied in accordance with the ASTM standard to eliminate the concern of lateral-torsional buckling effects. The actual static bending setup can be seen in Chapter Two. The equation used for static bending modulus of elasticity was (Equation 4-6):

$$E_{static} = \frac{P \cdot a}{4 \cdot b \cdot h^3 \cdot \Delta} \cdot \left(3 \cdot L^2 - 4 \cdot a^2\right) \tag{4 - 6}$$

For the solid sawn members, since the members being tested were heat treated, the cross-sectional dimensions used in calculating both moduli were the altered dimensions found after heating. As expected, these cross-sectional dimensions were smaller than those before heating.

The solid sawn lumber without temperature treatment was considered the baseline material and used to validate the static bending test procedure results. ASTM D2915 (1994), the standard for evaluating structural lumber allowable properties, was followed. Using the baseline results, the modulus of elasticity was calculated. The design value calculated for the Standard & Better grade Douglas-fir Larch was E_{static} = 9.81 GPa (1422881 psi). This was higher but very comparable to the NDS (AF & PA, 1997) published design value of 9.65 GPa (1400000 psi). The higher value was expected because there are six other visually graded categories that are "better" than Standard grade. All equations used to determine the apparent modulus of elasticity are found in Appendix B.

DETERMINATION OF MODULUS OF RUPTURE

Using the same static bending technique described in the above section, the modulus of rupture was found to determine an ultimate flexural strength distribution for each test category. The equation used (Equation 4-7) was derived from Equation 2-3, where all variables are defined (Appendix B).

$$\sigma_r = \frac{\frac{P_{max}}{2} \cdot a \cdot c}{I_x} \tag{4 - 7}$$

Again, the solid sawn lumber without temperature treatment was considered the baseline material. ASTM D2915 (1994), the standard for evaluating structural lumber allowable properties, was followed. Using the baseline results, the flexural bending design value was calculated. The design value calculated using a parametric approach, F_b = 8.22 MPa (1193 psi), for the Standard & Better grade Douglas-fir Larch was higher than the NDS published design value of 3.96 MPa (575 psi). Again, the higher values were expected. All equations used to determine the modulus of rupture are found in Appendix B.

RESULTS

EFFECT OF TESTING TECHNIQUES FOR MODULUS OF ELASTICITY

The first step was to evaluate the results from the various methods. One way this was done was through analysis of variation (ANOVA) tests with α equal to 0.05. This determined if there existed any statistical difference between the distributions of the methods of evaluating modulus of elasticity (Appendix E). Cumulative distributions were also visually analyzed for comparison of curve shape (Appendix D). In conjunction with these distributions was the comparing of the mean values. Finally, the correlation coefficients, between methods, were found. As was seen in Table 4-1, the solid sawn lumber was limited to just one nondestructive test method. Therefore, the analysis was simplified to just testing the predictive capability of the wave propagation for the static modulus of elasticity. The four temperature categories were examined independently. The ANOVA tests revealed that all categories, except 193^{o}C (380^{o}F) which had a P-value of 0.07 (α = 0.05), were statistically different (Appendix E). From the cumulative distribution graph (Figure 4-2), it can be seen that the high temperature distribution curves for E_{static} and $E_{dynamic}$ are closest and best parallel each other. Graphical comparison of the mean values (Figure 4-3), shows that the $E_{dynamic}$ value (only specimens tested statically) was always larger than the E_{static} value. This supports the earlier published findings on this relationship, that is a lack of one-to-one correspondence. The range of ratios of dynamic to static modulus of elasticity values was 1.11 to 1.27. Although it was now established that the majority of the distributions were different, it was still necessary to analyze their correlation since that would be most helpful for predictions. As seen in Figure 4-4, the correlation coefficients for all categories were high with a range of 0.795 to 0.926. Although no specific discussion about the difference between temperatures is presented here, it is surprising that the correlation coefficient found for the unheated sample set was notably lower (0.795) than previously published values.

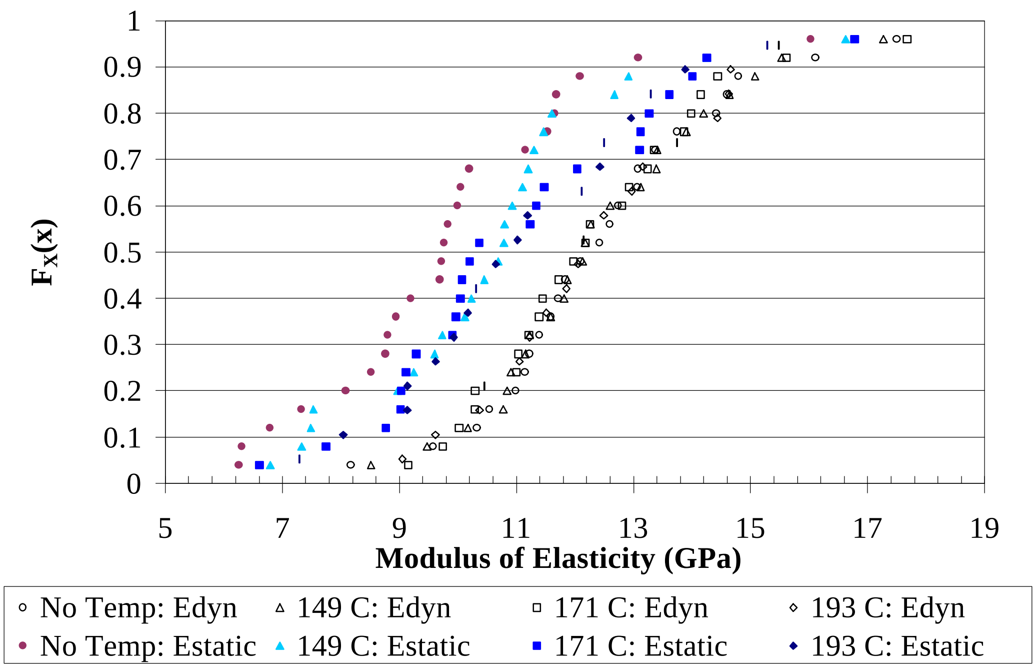


Figure 4-2: *Cumulative Distribution for MOE Methods of Solid Sawn Lumber*

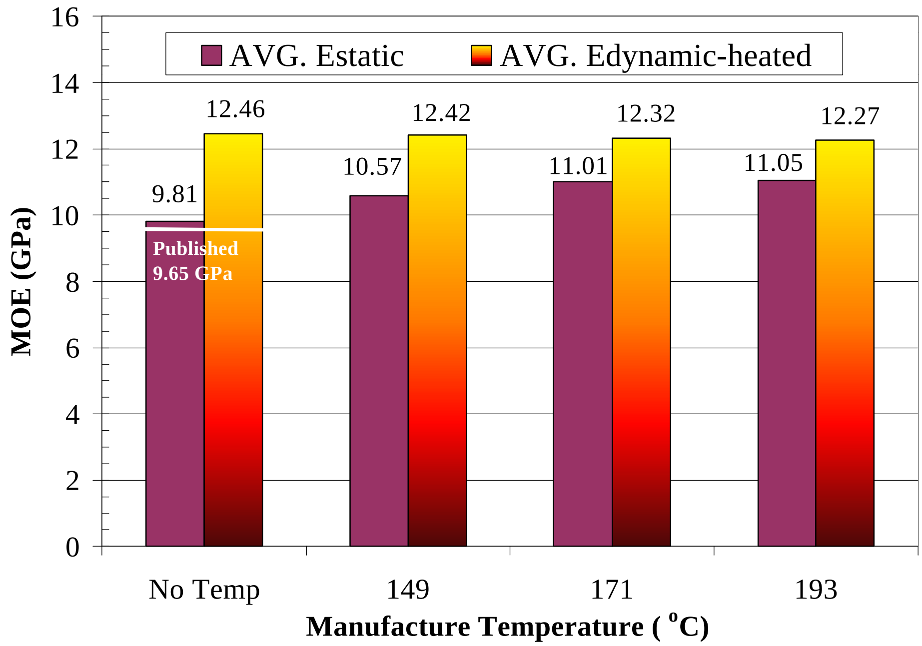


Figure 4-3: *Comparison of Means of MOE Methods for Solid Sawn Lumber*

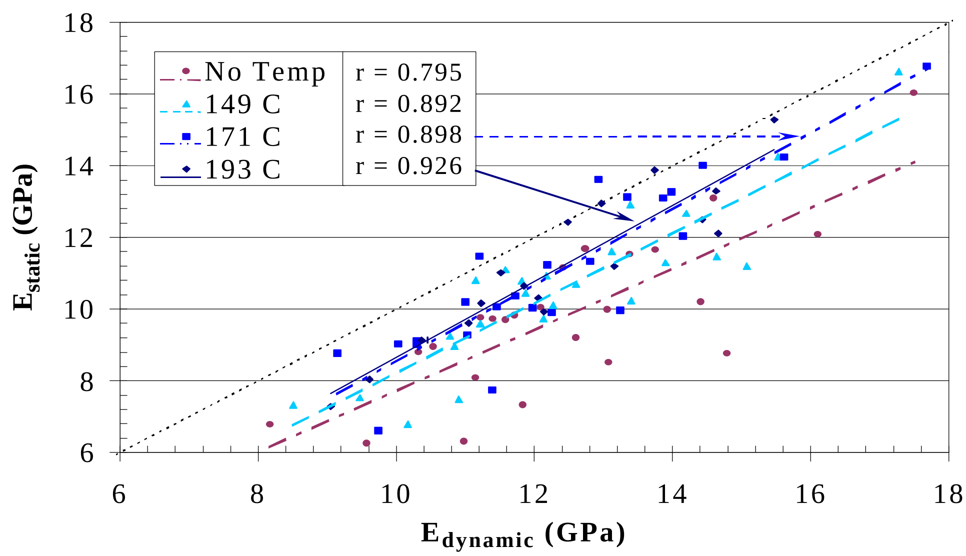
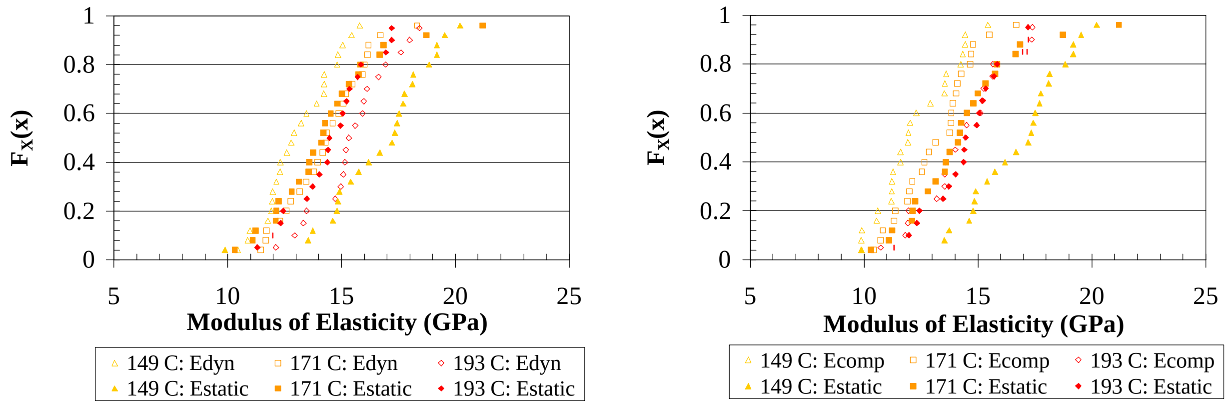


Figure 4-4: *Correlation of Edynamic and Estatic for Solid Sawn Lumber*

Evaluation of the different techniques for laminated veneer lumber was much more involved. Because of this, only samples of graphical representation are shown here. All other graphical results (CDF's and correlations) can be found in Appendix D. First, ANOVA tests were performed. When comparing nondestructive methods to E_{static}, only the members that made up the static population were used, except for E_{billet} and $E_{expected}$, which included all useable members. As expected, the vertical (edgewise) and horizontal (flatwise) values were statistically different from each other for all methods and all temperatures, with higher horizontal values. All ANOVA results are in Appendix E. It is important to note that the values obtained from the static bending tests for the LVL manufactured at 149^{o}C (300^{o}F) were unusually high. This is because there was not a distinct linear elastic region on the load-displacement curves from the static testing. Because of this, results for this temperature are cautioned for use in determining a superior predictive method. For example, the ANOVA results revealed that all predictive MOE's were statistically different from E_{static}. However, for the higher two temperatures, all values were statistically not different. Because of the large discrepancy, the temperature category 149^{o}C (300^{o}C) is excluded from the following discussion comparisons to E_{static} (however, it is still included in the graphical results). Presented in Figure 4-5 are two of the better methods of prediction according to the ANOVA results. Upon investigation of the cumulative distribution curves for all methods, it was seen that the $E_{dynamic}$ curve shapes were closest to and best paralleled the E_{static} curves.



A *B*

Figure 4-5: *Cumulative Distributions for MOE Methods of LVL: (A) $E_{dynamic}$ compared to E_{static}; (B) $E_{composite\text{-}vert}$ compared to E_{static}*

Investigation of the mean values (Figure 4-6) for each method revealed that the $E_{dynamic}$ value (members of the static tests only) and all horizontal orientation MOE values were always larger than the E_{static} value. In the case of $E_{dynamic}$, this follows both the response of the solid sawn lumber and published findings. However, the ratios of dynamic to static modulus of elasticity values, 1.002 and 1.063, were much closer to a one-to-one relationship between the mean values than were the ratios of the solid sawn lumber. The horizontal MOE also provided good estimates and were expected to be overestimates because they should predict flatwise bending. All the MOE values from the vertical laminated beam theory were lower than the E_{static} values but still provided good estimates. All dynamic to static modulus of elasticity ratios are found in Table 4-2. Because all of the methods were not statistically different and the ratios were near one, it was necessary to analyze the correlation of the data within the populations.

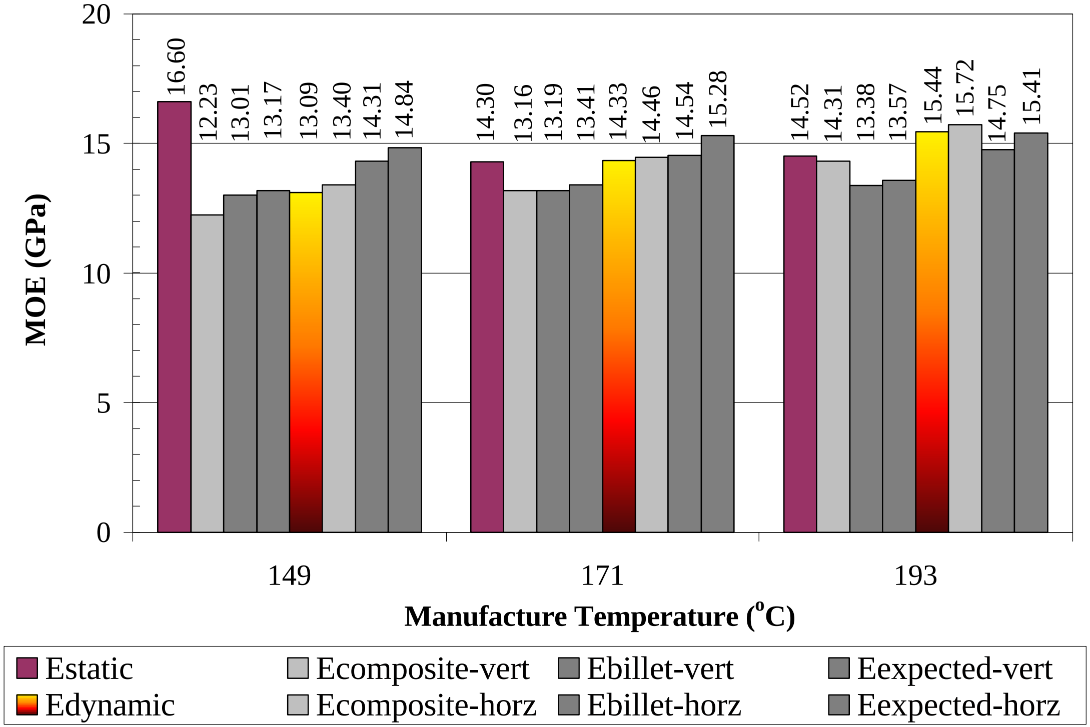


Figure 4-6: *Comparison of Means of MOE Methods for LVL*

Table 4-2: *Modulus of Elasticity Mean Ratios*

Temp.	E_{static}	$\frac{E_{composite\text{-}vert}}{E_{static}}$	$\frac{E_{billet\text{-}horz}}{E_{static}}$	$\frac{E_{expected\text{-}horz}}{E_{static}}$
149°C	16.60	0.737	0.784	0.793
171°C	14.30	0.920	0.922	0.938
193°C	14.52	0.986	0.921	0.935

Temp.	$\frac{E_{dynamic}}{E_{static}}$	$\frac{E_{composite\text{-}horz}}{E_{static}}$	$\frac{E_{billet\text{-}horz}}{E_{static}}$	$\frac{E_{expected\text{-}horz}}{E_{static}}$
149°C	0.789	0.807	0.862	0.894
171°C	1.002	1.011	1.017	1.090
193°C	1.063	1.083	1.016	1.061

To examine the distributions on a micro level, the correlation between specimen's destructive and nondestructive modulus of elasticity values was analyzed. The distributions were graphed (Figure 4-7) and the correlation coefficients (r) were found (Table 4-3). Overall, correlation coefficient values were lower than those found for the solid sawn lumber. This was the same trend as was reported by Pu and Tang (1997) for the southern pine species. To determine the best overall correlation, each method was ranked from 1 to 3 per temperature, with 1 being the best correlation. From this, the overall rank was then determined. Overall (not including 149°C) the $E_{dynamic}$ and vertical MOE values provided the best correlations to E_{static}. The major difference was that $E_{dynamic}$ was an overestimate and vertical MOE's were underestimates.

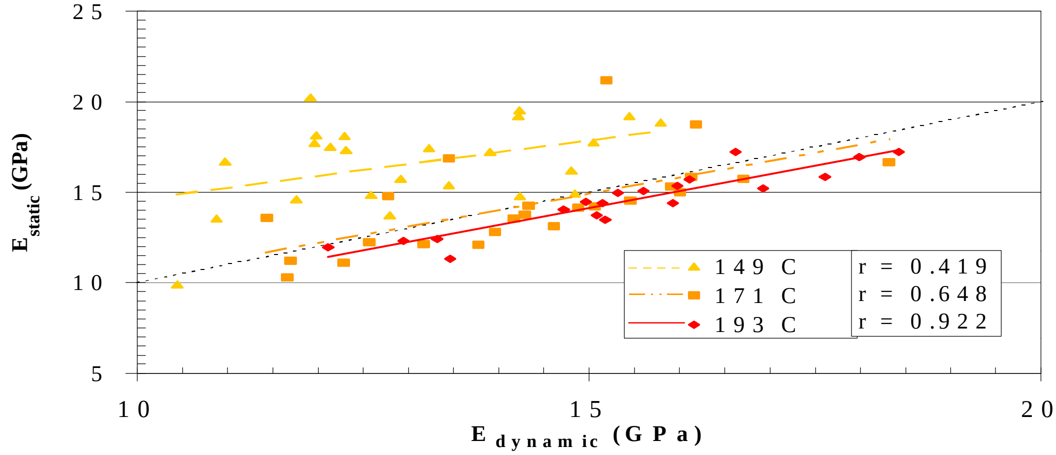
Table 4-3: *Correlation Coefficients of MOE Methods for LVL*

Temp.	$E_{dynamic}$			$E_{composite-vert}$			$E_{billet-vert}$			$E_{expected-vert}$		
	r^2	r	rank	r^2	r	rank	r^2	r	rank	r^2	r	rank
149°C	0.1756	0.4190	4	0.1604	0.4005	7	0.1627	0.4034	6	0.1633	0.4041	5
171°C	0.4203	0.6483	1	0.3427	0.5854	6	0.3479	0.5898	5	0.3526	0.5938	3
193°C	0.8508	0.9224	2	0.8562	0.9253	1	0.85	0.9220	3	0.8416	0.9174	4
overall			1			2b			3			2a

Temp.	$E_{composite-horz}$			$E_{billet-horz}$			$E_{expected-horz}$		
	r^2	R	rank	r^2	r	rank	r^2	r	rank
149°C	0.1779	0.4218	3	0.1862	0.4315	2	0.1892	0.4350	1
171°C	0.3335	0.5775	7	0.3525	0.5937	4	0.3631	0.6026	2
193°C	0.8366	0.9147	5	0.8247	0.9081	6	0.7982	0.8934	7
overall			6			5			4

r^2 = coefficient of determination

r = correlation coefficient



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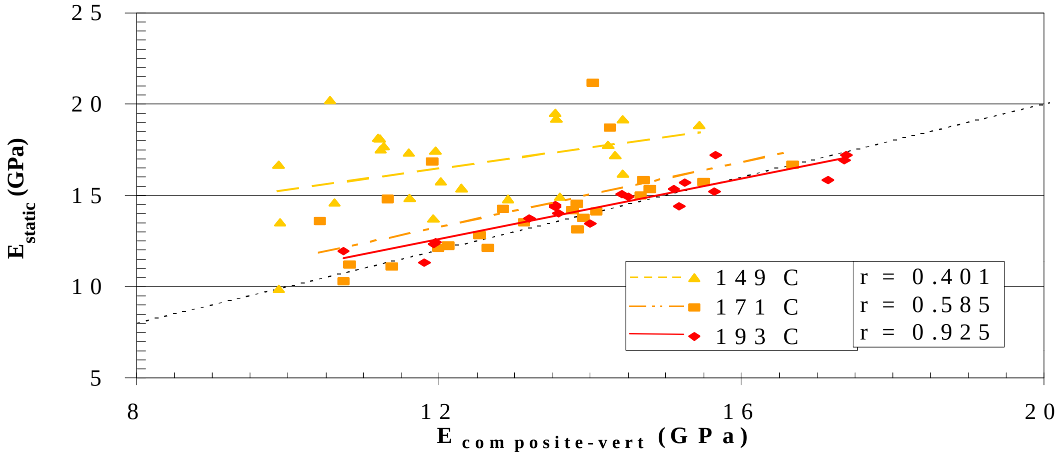

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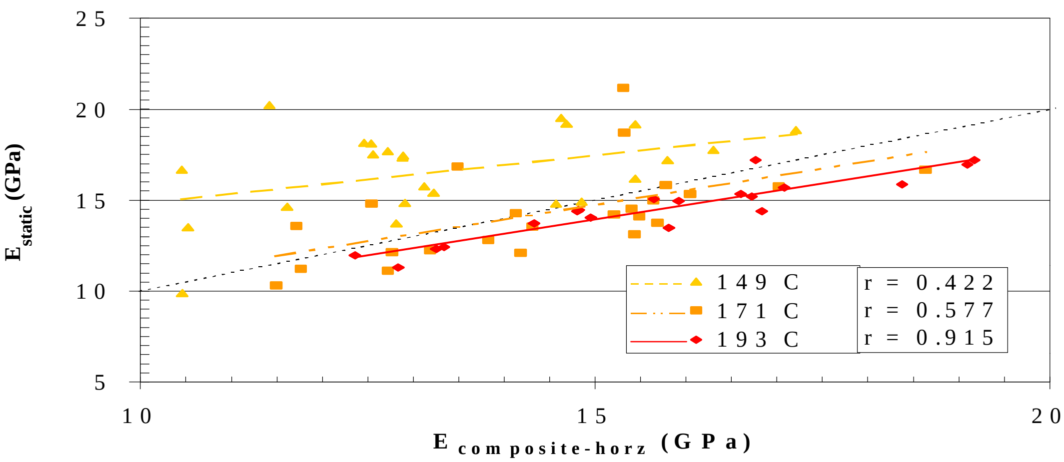

C

Figure 4-7: *Correlation of MOE Methods for LVL: (A) $E_{dynamic}$ vs. E_{static}; (B) $E_{composite\text{-}vert}$ (edgewise) vs. E_{static} (edgewise); (C) $E_{composite\text{-}horz}$ (flatwise) vs E_{static} (edgewise)*

Continuing the investigation on a member by member basis, because of the sorting technique used with the veneer and the unconventional lay-up practice of ascending veneer $E_{dynamic}$ values, the usefulness of veneer sorting based on modulus of elasticity could be assessed. Recalling that for each temperature, the lowest veneer $E_{dynamic}$ values made up billet one and the highest values made up billet fifteen, the properties of the LVL from the billets should mimic this ascending behavior no matter what method was used to determine modulus of elasticity. Table 4-4 uses the 171^{o}C (340^{o}F members of static and DOL set one) temperature as an example to show that this was indeed the case for all temperatures.

Table 4-4: *Influence of Veneer Sorting Technique on LVL Properties*

Number	MOR (MPa)	E_{dyn} (GPa)	E_{static} (GPa)	E_{comp-h} (GPa)	$E_{billet-h}$ (GPa)	E_{exp-h} (GPa)	E_{comp-v} (GPa)	$E_{billet-v}$ (GPa)	E_{exp-v} (GPa)
1b	43.86	11.43	13.59	11.72	11.82	12.52	10.42	10.45	10.65
2d	35.53	11.70	11.22	11.76	11.74	12.44	10.82	10.81	11.02
2f	43.63	11.66	10.31	11.49	11.74	12.44	10.73	10.81	11.02
3c	52.48	12.28	11.10	12.72	12.69	13.30	11.37	11.36	11.54
3d	60.34	12.78	14.80	12.54	12.69	13.30	11.32	11.36	11.54
4c	52.51	13.45	16.85	13.49	13.60	14.20	11.91	11.94	12.11
5d	55.69	12.57	12.25	13.18	13.11	13.68	12.12	12.10	12.22
5e	54.17	13.17	12.13	12.77	13.11	13.68	11.99	12.10	12.22
6a	51.28	13.78	12.10	14.18	14.00	14.55	12.64	12.59	12.75
6e	57.34	13.96	12.81	13.82	14.00	14.55	12.54	12.59	12.75
7c	66.64	14.33	14.27	14.13	14.06	14.87	12.84	12.82	13.07
8c	66.20	14.17	13.54	14.31	14.44	14.81	13.13	13.17	13.28
10a	61.83	14.29	13.76	15.69	15.47	16.11	13.91	13.84	14.03
10b	58.50	15.46	14.53	15.40	15.47	16.11	13.82	13.84	14.03
10e	65.89	15.06	14.20	15.21	15.47	16.11	13.76	13.84	14.03
10f	61.31	14.61	13.13	15.43	15.47	16.11	13.83	13.84	14.03
11a	61.19	14.88	14.13	15.48	15.44	16.21	14.08	14.07	14.30
11c	59.94	15.19	21.18	15.31	15.44	16.21	14.03	14.07	14.30
12d	75.51	16.18	18.72	15.32	15.48	16.45	14.26	14.31	14.60
13c	87.66	16.13	15.84	15.77	16.00	17.04	14.71	14.78	15.09
13d	72.16	16.00	15.01	15.64	16.00	17.04	14.66	14.78	15.09
13e	71.87	15.90	15.33	16.04	16.00	17.04	14.79	14.78	15.09
14a	76.15	16.71	15.75	17.02	16.93	17.84	15.50	15.47	15.75
15a	77.31	18.32	16.66	18.63	18.77	20.08	16.67	16.72	17.10

EFFECT OF TESTING TECHNIQUES FOR MODULUS OF RUPTURE

There is a known correlation between modulus of rupture and modulus of elasticity for lumber. All methods that consisted of all specimens that were tested destructively (this excludes the E_{billet} and $E_{expected}$ data sets) were analyzed to assess the correlation of stiffness and strength.

For the solid sawn lumber, the E_{static} and $E_{dynamic}$ values were compared with the modulus of rupture. Some correlation was seen with the E_{static} (Figure 4-8) but very low values were found with the $E_{dynamic}$ (Table 4-5). Correlation was strongest at low to moderate strengths and much more dispersed at the higher strengths. All the values found were considerably lower than the cited published correlations from James (1964) and Pellerin (1965).

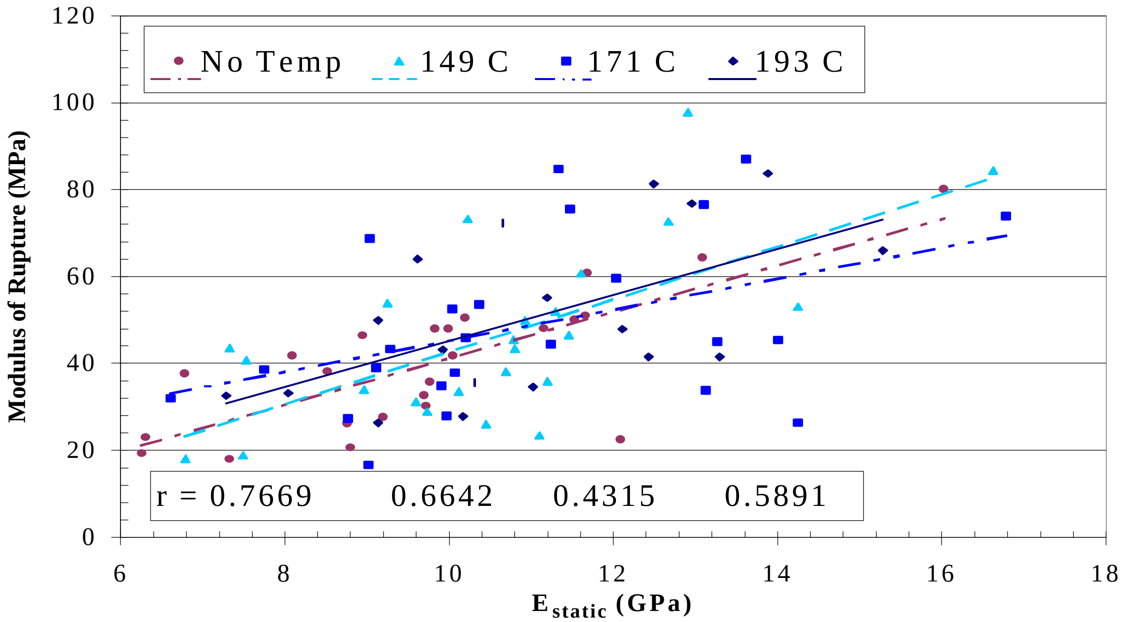

Figure 4-8: *Correlation of E_{static} and MOR for Solid Sawn Lumber*

Table 4-5: *Correlation Coefficients of MOR and MOE for Solid Sawn Lumber*

Temp.	E_{static}		$E_{dynamic}$	
	r^2	r	r^2	r
No Temp	0.5881	0.7669	0.2331	0.4828
149°C	0.4411	0.6642	0.3006	0.5483
171°C	0.1862	0.4315	0.0847	0.2910
193°C	0.3470	0.5891	0.2953	0.5434

For laminated veneer lumber, the MOR correlation was examined with E_{static}, $E_{dynamic}$, $E_{composit-horz}$, and $E_{composite-vert}$. Each temperature was examined independently. Because all MOR values seemed reasonable for all temperatures, all temperature categories were included in the determination of correlation. Overall, the correlations for the LVL were much better than those of the solid sawn lumber. They were also notably better than those found by Jung (1982), who had obtained a predictive MOE from averaging the stress wave time MOE's from the veneer sheets. For all temperatures, E_{static} had the worst correlation. Two of the best methods of predicting modulus of elasticity also had the best correlations to modulus of rupture. Figure 4-9 shows one of these methods, $E_{dynamic}$. The range of correlation coefficients for these methods, $E_{dynamic}$ and $E_{compsite-vert}$, were 0.852 to 0.943 (Table 4-6).

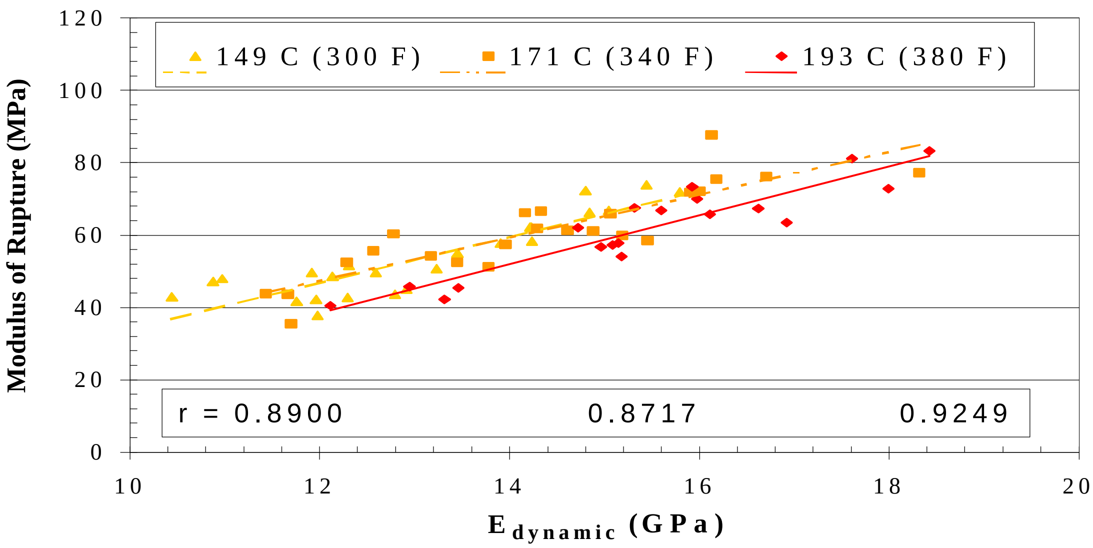

Figure 4-9: *Correlation of $E_{dynamic}$ and MOR for LVL*

Table 4-6: *Correlation Coefficients of MOR and MOE for LVL*

Temp.	E_{static}			$E_{dynamic}$			$E_{composite-vert}$			$E_{composite-horz}$		
	r^2	r	rank	r^2	R	rank	r^2	r	rank	r^2	r	rank
149°C	0.117	0.3418	4	0.792	0.8900	1	0.767	0.8758	2	0.695	0.8339	3
171°C	0.326	0.5712	4	0.760	0.8717	1	0.726	0.8522	2	0.662	0.8138	3
193°C	0.777	0.8816	4	0.855	0.9249	3	0.890	0.9432	1	0.872	0.9338	2
overall			4			1			2			3

CONCLUSIONS

Again, the reader is cautioned against drawing conclusions about the effects of manufacturing temperature from data presented in this chapter. Neither enough data nor discussion is presented to draw such conclusions. This chapter serves only to establish a method that best predicts mechanical properties of the materials in question.

The results, which examine the nondestructive techniques for determining modulus of elasticity, provided several conclusions regarding the predicting stiffness and strength. Although specific reasonability of these predictions varied, many of the conclusions were the same for both solid sawn lumber and laminated veneer lumber.

It is concluded that the mechanical modulus of elasticity of clear Douglas-fir larch and Douglas-fir LVL can be predicted with reasonable accuracy using the nondestructive evaluation of the modulus of elasticity, $E_{dynamic}$. Although the predictive $E_{dynamic}$ values were overestimates of E_{static}, that is a lack of a one-to-one relationship for both materials, the correlation coefficients were high and were within an acceptable range.

Specifically, for the solid sawn lumber, the ANOVA results showed that for each temperature, except for the 193^{o}C (380^{o}F), $E_{dynamic}$ was statistically different from E_{static}. However, there was still a very high correlation between the two. The statistical difference was merely registering the fact that the $E_{dynamic}$ was overestimating the E_{static}.

The ANOVA results for the LVL showed that all of the methods for predicting modulus of elasticity were statistically not different from E_{static}, except for the 149^{o}C (300^{o}F) temperature. This concludes that there is a closer one-to-one relationship between nondestructive and destructive MOE values for LVL than for the solid sawn lumber. There was also a high correlation between all of the methods and E_{static}. However, overall, the correlations were much broader than the solid sawn lumber.

For the laminated beam theory, it can be concluded that the vertical laminate orientation does better predict the static edgewise bending over the horizontal laminate orientation. Although the distributions were similar, the higher predicted values and the lower correlation coefficients of the horizontal laminate orientation lead to the conclusion that it would better predict flatwise bending.

Breaking down the different approaches for assessing the section thickness for application of the laminated beam theory (composite, billet, and expected) leads to the conclusion that slight changes in geometric thickness do have an effect on the predictive modulus of elasticity. However, these changes are small. $E_{expected\text{-}vert}$ was a very good prediction for E_{static}. This is important because unlike all of the other nondestructive evaluations, this value does not need dimensions found after manufacturing, if pressing is thickness controlled. This leads to the conclusion that the modulus of elasticity of the LVL can be predicted reasonably accurately before manufacturing, provided the individual veneer $E_{dynamic}$ values were calculated, and the LVL dimensions are true to those of the prediction.

For the LVL, the sorting techniques had been based on the $E_{dynamic}$ of the individual veneers. It can be concluded that the LVL, a product of nondestructive sorting of veneers according to modulus of elasticity, will reflect the sorting procedure of the veneer for destructive and nondestructive MOE evaluation and for modulus of rupture. Therefore, because of the predictive accuracy of $E_{expected}$ and because the mechanical properties reflect the segregation of the veneer groups, producers of LVL can easily design products with particular properties.

For solid sawn lumber, the correlation between $E_{dynamic}$ and modulus of rupture was fairly poor. However, the correlation for LVL was high for all nondestructive methods. This leads to the conclusion that nondestructive modulus of elasticity is a good indicator of strength for laminated veneer lumber.

Finally, through experimentation and statistical analysis, it was concluded that overall, the best method for predicting the modulus of elasticity of LVL was $E_{dynamic}$. This method also provided the best overall correlation with modulus of rupture. However, the laminated beam theory should not be discounted because of distribution similarity and a relatively high observed correlation.

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CHAPTER FIVE

EFFECT OF EXTREME ELEVATED TEMPERATURE ON STRUCTURAL PROPERTIES AND DURATION OF LOAD BEHAVIOR OF DOUGLAS-FIR LARCH SOLID SAWN LUMBER

ABSTRACT

Wood material is subjected to extreme elevated temperatures during the manufacturing of wood composites, such as laminated veneer lumber. Despite this fact, there has been very little published research with regard to the effects of temperatures, exceeding mere environmental conditions, for a short duration of time. An investigation was performed on full-sized Douglas-fir Larch Standard grade lumber specimens to determine such effects on mechanical properties and duration of load behavior. It was found that the mechanical properties slightly increased as temperature increased. However, the increases were not statistically significant.

For load-duration behavior, some statistical significance was found for the differences of both initial and survival deflections compared between temperature categories. Also, the exponential damage rate model (EDRM) was successfully used to model the load-duration behavior. Such behavior was only severely affected for short-term load durations (less than five years). Calculated load-duration adjustment factors from this study, based on the individual EDRM curves, were different than those from the Madison curve and thus different from current load-duration design adjustment factors used for solid sawn lumber.

INTRODUCTION

Wood is subjected to elevated temperatures in several service situations. Such situations are commercial attics and special industrial applications such as wooden structures above ovens or dryers. Because of this, the effect of varied temperature on both solid sawn lumber and composite lumber has been given some attention. Recently, there has been interest in long-term effects of elevated environmental temperature. Effects of extended exposure time for both mechanical properties and load-duration behavior have been studied. Both water and air heating mediums have been used for these studies. Generally, results have supported a decrease in mechanical properties and load-duration performance as the result of elevated temperatures.

However, in the manufacturing of laminated veneer lumber, wood material is subjected to higher temperature extremes than the mere environmental conditions. Although previous tests have focused on both immediate and permanent temperature effects, the test procedures used were very much unlike the conditions that wood is subjected to during the pressing procedure. First, the exposure time is much less than most tests done to determine elevated environmental effects. Second, the temperatures used in the pressing cycle are much more elevated than environmental exposure temperatures. Third, after pressed specimens are exposed to the elevated temperatures of the manufacturing process they return to equilibrium conditions and will go into service where temperatures are much less, even if elevated environmental temperatures are present. Therefore, the short time high temperature exposure becomes part of the history of the solid sawn member.

There is a lack of understanding of the effect of temperature exposure much higher than environmental conditions. In conjunction with this, there is a lack of research regarding short-term (less than an hour) exposure of wood material to any temperature increase where the specimens are reconditioned to room temperature conditions. Understanding of elevated temperature effects on wood material is crucial for the manufacturing of composite material. Despite this, LVL manufacturing temperature itself has been given little attention. The temperature range in industry is based on the cure temperature of the adhesive and experience in laminated veneer manufacturing. Thus, the focus if this research was to focus on the mechanical and durational effects of short-term extreme temperature exposure of solid wood material.

BACKGROUND

It was necessary to do extensive research into several aspects of this study. This section is broken down into subsections in order to differentiate and compare previous published research. The following subsections are temperature effects, temperature effects on mechanical properties, duration of load, and temperature effects on duration of load behavior.

TEMPERATURE EFFECTS

The strength of wood depends on its physical and chemical constitution. Chemically, wood is made up of three basic components: cellulose, hemicellulose, and lignin (Panshin and de Zeeuw, 1980). Heating causes these components to undergo changes such as shrinkage, expansion, dehydration, thermal degradation, and phase change. Schaffer (1973) summarized these changes in wood caused by thermal effects in Table 5-1.

Table 5-1: *Thermally Induced Changes in Dry Wood in an Inert Atmosphere (adapted from Schaffer 1973)*

Temperature °C	°F	Thermal Induced Change
55	131	Natural lignin structure is altered. Hemicelluloses begin to soften.
70	158	Transverse shrinkage of wood begins.
110	230	Lignin slowly begins weight loss.
120	248	Hemicellulose content begins to decrease, a-cellulose begins to increase. Lignins begin to soften.
140	284	Bound water is free.
160	320	Lignin is melted and begins to reharden.
180	356	Hemicelluloses begin rapid weight loss after losing 4 percent. Lignin in torous flows.
200	392	Wood begins to lose weight rapidly. Phenolic resin begins to form. Cellulose dehydrates above this temperature.
210	410	Lignin hardens, resembles coke. Cellulose softens and depolymerizes. Endothermic reaction changes to exothermic.
225	437	Cellulose crystalinity decreases and recovers.
280	536	Lignin has reached 10 percent weight loss. Cellulose begins to lose weight.
288	550	Assumed wood charring temperature.
300	572	Hardboard softens irrecoverably.
320	608	Hemicelluloses have completed degradation.
370	698	Cellulose has lost 83 percent of initial weight.
400	752	Wood is completely carbonized.

Shape and size of the member and type of loading need to be considered simultaneously. This is because for short time exposures, the inner material of a large specimen would not be heated to the temperature of the surrounding medium (Wood Handbook, 1999). Therefore, it is possible that the immediate effect on the strength of the inner material is less than the surface material. However, the type of loading is important in determining if size may be of consequence. In the case of bending, the greatest stress is experienced by the outer fibers. This usually governs ultimate strength. Therefore, the fact the inner material may have experienced a lower temperature than the surface material due to short-term exposure is of little concern as far as temperature effect on member performance.

TEMPERATURE EFFECTS ON MECHANICAL PROPERTIES

There are two kinds of temperature effects; reversible and irreversible. For a temperature effect to be reversible, the temperature must be below 100^{o}C (212^{o}F) and temperature change must be immediate and quick. The Wood Handbook (1999) terms an immediate effect as "the change in properties that occurs when wood is quickly heated or cooled and then tested at that condition." Immediate effects have been shown to reduce both the modulus of elasticity and modulus of rupture with a linear relation to temperature (Gerhards, 1982; Wood Handbook, 1999). However, these effects tend to be reversible if the material is allowed to return to room temperature conditions and then tested.

Irreversible effects occur when wood is heated for a prolonged period of time. This long-term heating causes degradation of the wood and thus permanent damage. The result is a loss in weight and strength and a level of degradation of the wood substance. The degree of degradation and strength loss depends on factors including, but not limited to, heating medium, temperature, duration of exposure, and, species, size, and moisture content of the member involved. To test for permanent effects, the specimens must be conditioned back to room temperature conditions otherwise results are influenced by immediate effects. However, as Green and Evans (1994) noted, there is a lack of guidance to render a precise time at which to expect permanent strength loss. This is to say the time frames of "quick" and "prolonged" are not clearly defined.

There have been several studies on the effect of environmental conditions on mechanical properties of solid sawn lumber. Many of these studies center on premise of manipulating environmental parameters for both conditioning of the specimens and for the duration of the tests being performed. For example, James (1961), tested the effect of elevated temperature and moisture content on the speed of sound and on the Youngs's modulus (using longitudinal vibration) of Douglas-fir. The testing procedure followed the conditions of immediate temperature effects. He found that a rise in temperature or moisture content caused a decrease in the speed of sound in the wood and a decrease in the modulus of elasticity. The Wood Handbook (1999) also cites increased moisture content or temperature as a source of decreased structural properties.

Schaffer (1973) studied the immediate effects on compressive and tensile strength (both parallel-to-the-grain) of Douglas-fir. Specimens, 25.4mm (1 in.) radial by 3.2 mm (0.125 in.) tangential and 254 mm (10 in.) long, were brought to equilibrium at the elevated temperatures within two minutes. The equilibrium temperature range tested was 25^{o}C to 275^{o}C (77^{o}F to 527^{o}F). Schaffer found that the immediate tensile strength was relatively insensitive to temperature until 170^{o}C (340^{o}F) while thermally induced changes had a more pronounced uniformed effect on compressive strength. For tensile strain at failure, an increase was apparent from 140^{o}C to 200^{o}C (284^{o}F to 392^{o}F) before a decrease at higher temperatures. Schaffer attributed this behavior to the softening and rehardening of the lignin that occurs at that temperature range (Table 5-1). The compressive strain at failure was found to decrease uniformly.

Gerhards (1982) presented a summary of all pertinent studies on the immediate effects on the mechanical properties of wood. From all the studies that dated back to 1936, only five studies involved extreme temperatures, that is, greater than environmental temperatures. None of these five studies examined the temperature effects on bending strength. Four of these studies examined the effects on modulus of elasticity but the largest specimen only had cross sectional dimensions of 20.1 mm by 20.1 mm (0.79 in. by 0.79 in.). For modulus of elasticity parallel to the grain with a moisture content of zero percent, only the study by Schaffer (1973) had data beyond 150°C (302°F). Although the overall data was represented by a decreasing linear relationship, the curve generated by passing through the average data showed no change in modulus of elasticity for the temperature range of 150°C to 200°C (302°F to 392°F). The relative modulus of elasticity, for this range, was less than a twenty-five percent decrease with 25°C (77°F) being the base temperature modulus of elasticity.

Gerhards (1982) also presented modulus of elasticity data involving extreme temperatures from Preusser (1968) but noted that the conditioning temperatures, sustained for an hour, were applied to specimens previously conditioned to twelve percent moisture content. Thus, moisture effects most likely compounded the data, especially at the higher temperatures.

According to Gerhards' (1982) comprehensive study, available data for bending strength was restricted to 125°C (257°F) for zero percent moisture content and 75°C (167°F) for equal or greater than eleven percent moisture content. All of the relationships support decreasing linear trends for both moisture content conditions. However, Gerhards concluded that bending strength, compressive strength parallel-to-the-grain (Schaffer, 1973), and tensile strength perpendicular-to-the-grain appear to experience the same immediate temperature effect. He also concluded that the temperature effects were greater at higher moisture contents.

In a more recent study, Fridley et al. (1992b) examined hygrothermal effects on the mechanical properties of select structural Douglas-fir 38 mm by 89 mm (nominal 2 in. by 4 in.). The specimens were conditioned to environmental conditions of varied relative humidity levels and temperature. Strong axis bending was performed at temperatures of 23°C, 38°C, and 54°C (73°F, 100°F, and 130°F). The results of this study showed that the modulus of rupture and the modulus of elasticity were affected by environmental hygrothermal conditions. At the same relative humidity, a rise in temperature caused a noticeable decrease in modulus of rupture.

However, the modulus of elasticity showed very little change due to temperature increase. Models were developed but cautioned for use only with conditions of the study.

Irreversible effects, that is those associated with long-term temperature exposure and permanent damage, have been the focus of more recent studies. However, the temperature ranges of the published studies again do not reflect extreme temperatures. The main focus of these studies remains high end environmental temperatures.

In a study by LeVan et al. (1990), the bending properties of wood treated with fire retardant chemicals were examined at elevated temperatures. The research provided a control group of 305 mm (12 in.) long untreated Southern Pine with a cross-section of 15.9 mm (0.625 in.) tangential by 35 mm (1.375 in.) radial. The highest temperature of exposure was only 82^{o}C (180^{o}F). Permanent effects were of interest at varied times of exposure, the smallest of which was three days. After the time of exposure had elapsed, the specimens were reconditioned before testing at 23^{o}C (73^{o}F) with a moisture content of twelve percent. Since no baseline of zero exposure time was established for individual groups based on static tests (only the average of all groups being noted found from stress wave time), the shortest time that could be used for relative comparison was the three day exposure. Between the three and seven day exposures, it was concluded that the modulus of elasticity and the modulus of rupture showed no change. However, actual data recorded for this exposure range shows a 3.8 percent and 5.1 percent increase, respectively.

The study by LeVan et al. (1990) also gave insight to the mechanism that controls the degradation of wood. Through analysis of the chemical composition of the thermally exposed wood, they found that degradation of hemicelluloses was the major contributor to reduction of strength.

Green and Evans (1994) published the two-year results from a four-year study on the effects of ambient temperatures on flexural properties of lumber (nominal 2 in. by 4 in.). They tested MSR graded Spruce-Pine-Fir (SPF) and LVL of the species Douglas-fir, Southern Pine, and Yellow-poplar. The conditioning temperature was 66^{o}C (150^{o}F) and the shortest time of exposure tested was six months. Since Green and Evans (1994) were interested in permanent effects, before static tests were performed, all specimens were removed from the elevated temperature environment and reconditioned to 20^{o}C (68^{o}F). The results reported for SPF 1650F-1.5E revealed that although the mean modulus of elasticity decreased overall for the two year period, it actually increased 7.8 percent from zero to six months. SPF 2100F-1.8E hardly exhibited any change in modulus of elasticity mean value for the two year period and also increased from zero to six months (1.4 percent). Green and Evans (1994) concluded that for modulus of elasticity, the rate of degradation was independent of the first two year exposure. For modulus of rupture, both grades were reported to decrease (between five and nine percent) over the first six month period.

The nonexistence of research reflecting the conditions of the manufacturing process, extremely short exposure times of extremely high exposure temperatures, warrants the investigation of such conditions. Also, full size members subjected to extreme temperatures needs to be studied. Thus, research was conducted to determine the effects of the manufacturing process conditions on full size wood material.

Duration of Load

Numerous predictive models have been developed in relation to creep rupture, or duration of load (DOL) behavior, of wood. Such models include damage accumulation, strain energy (Fridley et al., 1992c), and fracture mechanics (Nielsen and Kousholt, 1980). The damage accumulation (DA) approach is the most popular modeling technique (Rosowsky and Fridley, 1995) and is the model used in this research. Hence, the emphasis of this review is placed on previous research involving or relating to damage accumulation.

The first model related to the relationship between applied stress level and time-to-failure was developed by Wood (1951). Wood used constant bending loads located at the center span. These loads ranged from sixty to ninety-five percent of the strength found through static bending. The testing of the Douglas-fir small clear specimens resulted in data that was fitted to an empirical hyperbolic model curve. The model assumed a stress threshold of 18.3 percent. It was assumed that failure of a specimen would not occur below this threshold. The general form of the model is given in Equation 5-1a. Equation 5-1b presents the model calibrated by Wood. Wood's (1951) model (Equation 5-1b) is commonly referred to as the "Madison curve." It is this curve that is the basis for the load-duration adjustment factors outlined in the National Design Specifications (NDS) for Wood Construction (AF & PA, 1997).

$$t_f = \frac{1}{A\left(\sigma - \sigma_o\right)^B} \qquad (5 - 1a)$$

$$\sigma = \frac{1.084}{t_f^{0.04635}} + 0.183 \qquad (5 - 1b)$$

t_f = time to failure in seconds

A, B = model constants determined from experimental data

σ = ratio of applied stress to ultimate stress (static test strength)

σ_o = stress threshold

The Madison curve can also be written in the format of damage accumulation. The definitions of the parameters A, B, σ, and σ_o defined above also apply to Equation 5-1c.

$$\frac{d\alpha}{dt} = A(\sigma - \sigma_o)^B \qquad (5 - 1c)$$

α = parameter of damage ranging from zero (no damage) to one (failure)

$d\alpha/dt$ = time rate of damage accumulation

Based on the Madison curve data of small clear Douglas-fir specimens under a constant bending load, Barrett and Foschi (1978a, 1978b) developed two damage accumulation models. Each model assumed a stress threshold. The main difference from the Madison curve was the addition of a third model constant, C. The difference between the two new models was how the additional model constant was incorporated. All other parameters are previously defined. Barrett and Foschi (1978b) concluded that model II better represented the data.

Model I (Barrett and Foschi, 1978a)

$$\frac{d\alpha}{dt} = A(\sigma - \sigma_o)^B \cdot \alpha^C \qquad \text{if}\ \sigma > \sigma_o \qquad (5 - 2a)$$

$$\frac{d\alpha}{dt} = 0 \qquad \text{if}\ \sigma \leq \sigma_o \qquad (5 - 2b)$$

Model II (Barrett and Foschi, 1978b)

$$\frac{d\alpha}{dt} = A(\sigma - \sigma_o)^B + C\alpha \qquad \text{if}\ \sigma > \sigma_o \qquad (5 - 3a)$$

$$\frac{d\alpha}{dt} = 0 \qquad \text{if}\ \sigma \leq \sigma_o \qquad (5 - 3b)$$

Around the same time, Gerhards (1977, 1979) had also developed a damage accumulation model. The data used to derive the model came from tests on small clear specimens. Gerhards assumed that the lifetime of the member was an exponential function of the applied stress level. From this idea of exponential decay, Gerhards developed the Exponential Damage Rate Model (EDRM) given in Equation 5-4.

$$\frac{d\alpha}{dt} = \exp(-A + B\sigma) \tag{5 - 4}$$

Foschi and Yao (1986) developed a DA model similar to model II from Barrett and Foschi (1978b). However, instead of expressing damage accumulation in terms of a stress ratio, it was expressed as a function of actual applied stress. Also, an additional model constant, D, was added. An expression for their model is given in Equation 5-5. Foschi and Yao (1986) concluded that compared to the Barrett and Foschi (1978b) model II, the new model was a more accurate representation of the duration of load behavior of lumber.

$$\frac{d\alpha}{dt} = A(\tau - \tau_o)^B + C\alpha(\tau - \tau_o)^D \tag{5 - 5}$$

τ = applied stress

τ_o = stress threshold

All other model parameters were defined previously

Gerhards and Link (1987) used full-sized 38 mm by 89 mm (2 in. by 4 in.) Douglas-fir lumber specimens to calibrate the EDRM. They concluded that the model also applied to full-sized lumber. Gerhards (1988) did further testing with the full-sized specimens in order to determine the effect of lumber grade on the duration of load behavior of Douglas-fir lumber. In direct disagreement of previous DA models developed by Wood (1951), Barrett and Foschi (1978a, 1978b), and Foschi and Yao (1986), Gerhards (1988) concluded that no evidence existed that would support a stress level threshold. He also noted that for loading at the same fraction of static strength, lower grades of lumber had lower load-durations. In addition, however, he stated that these differences might not be statistically significant. The EDRM regression equations for the different grades tested are given in Equations 5-5a, 5-5b, and 5-5c.

$$LN(t_f) = 27.4382 - 24.7090\text{SL} \qquad (5 - 6a)$$

$$LN(t_f) = 25.9539 - 24.0309\text{SL} \qquad (5 - 6b)$$

$$LN(t_f) = 23.6222 - 21.7119\text{SL} \qquad (5 - 6c)$$

t_f = time to failure in minutes

SL = ratio of applied stress to ultimate stress (static test strength)

Finally, Gerhards (1988) found that for design loads that really exist for the design duration, the current allowable bending properties for lumber were nonconservative. Using these load-duration equations and the methods used to determine NDS adjustment factors he proposed modifications to the factors. The resulting factors would consequentially lower design values for all design load-durations.

A study by Cai et al. (2000) compared the predictive capabilities of these four DA models (Wood, 1951; model II from Barrett and Foschi, 1978b; Gerhards, 1979; and Foschi and Yao, 1986). Small clear Southern Pine specimens were subjected to a five-day load sequence which varied stress levels daily. It was concluded that all of the DA models failed to consistently predict the time-to-failure. This was even more pronounced for lower stress levels and longer duration. Ultimately, it was concluded that, “the four DA models were about equal in their ability to simulate time-to-failure distribution” (Cai et al., 2000).

Temperature Effects on Duration of Load Behavior

There have been several studies on the effect of environmental conditions on creep-rupture of wood, both small clear and full-sized specimens. Similar to the conditions of mechanical testing, most of these studies center on the premise of manipulating environmental parameters for both conditioning of the specimens and for the duration of the tests being performed. Justifiably, environmental conditions simulated for testing have never been over 80°C (176°F). Although the testing temperatures were within the range for reversible effects, the long exposure time involved in creep-rupture testing would inevitably result in the temperature effects being classified as permanent.

Schniewind (1967) subjected small clear 10 mm by 20 mm by 220 mm (0.39 in. by 0.79 in. by 8.66 in.) Douglas-fir specimens to environmental conditions in order to determine the effects on creep-rupture. Both constant and cyclical temperature exposure environments were examined for the duration of the tests. It was concluded that the environmental effects on creep-rupture significantly reduced the life duration of the wood specimens. However, it was also noted that changes in size could alter the significance and change the results.

Building on this idea, Schniewind and Lyon (1973) tested larger specimens, although still clear, of 50.8 mm by 50.8 mm by 1.02 m (2 in. by 2 in. by 40 in.). The results showed that environmental effects were still present. However, it was concluded that as specimen size is increased, creep-rupture life during environmental changes would be similar to that of specimens in a constant environment.

In a study by Schaffer (1973), discussed earlier in this review, additional creep testing was performed for a two hour period. This study actually went beyond mere environmental temperatures and subjected specimens to temperature ranges of 25°C to 275°C (77°F to 527°F). The results showed that the compressive strength actually improved with duration of exposure, at a constant load, for the temperature range of 100°C to 288°C (212°F to 550°F). The tensile strength showed no significant change in strength until 140°C (284°F) after which increased temperatures caused a decrease during exposure. Schaffer (1973) concluded that the increase seen in the long-term compression strength was credited to “the phenol-resin production of additional bonds with duration heating.” For tensile strength, the decrease was caused by “the depolymerization of cellulose with duration of heating.”

As was discussed previously, environmental changes in temperature and moisture content are known to affect mechanical properties, that is, short-term strength and stiffness. Fridley et al. (1989, 1990, 1991, 1992d and 1992e) conducted several studies to determine the effect of environmental conditions on structural lumber. Again, “environmental” only included a temperature range of 23^{o}C to 54^{o}C (73^{o}F to 130^{o}F). Environmental conditions under consideration were constant and cyclical thermal effects and constant and cyclical moisture effects. Specimens, 38 mm by 89 mm by 2.44 m (nominal 2 in. by 4 in. by 8 ft), were Select Structural and No. 2 grade Douglas-fir. Fridley et al. (1989) concluded that for equal stress ratios, a trend of shorter time-to-failure for higher temperatures was observed. He also noted that the observed temperature effects were independent of relative humidity or moisture content effects. Further research by Fridley et al. (1992e) indicated that the effects brought on by constant hygrothermal conditioning could be predicted if the effects on short-term strength were accurately predicted.

The lack of research on the load-duration behavior of wood material with a history of exposure to any extreme condition leads to uncertainty of performance. Therefore, research was conducted to evaluate the load-duration behavior of wood material possessing a history of short-term exposure to extreme temperatures.

MATERIALS

Boise Cascade of Boise, Idaho provided all solid sawn lumber. All lumber was Standard grade Douglas-fir Larch. The Standard grade for the one hundred and eighty members of 38 mm by 89 mm (nominal 2 in. by 4 in.) solid sawn was chosen for the wide range in structural properties, that is, a high coefficient of variation (COV) of the material. Each member was 2.44 m (8 ft) in length.

METHODS

The objective was two fold: To determine the effect of LVL manufacturing temperature on the mechanical properties and duration of load (DOL) behavior of solid sawn Douglas-fir Larch. The temperature effects of the processing procedure would, by definition, not be reversible. This is because although the exposure time is "short," the exposure temperature is above 100^{o}C (212^{o}F). Also, these effects would not technically be immediate because, although "quick," extreme temperature exposure was not the condition at the time of testing. Specimens were reconditioned back to room temperature conditions. Therefore, the conditions of the manufacturing process are more of a measure of permanent effects. Although solid sawn lumber is not normally subjected to such conditions, it was important to determine the effect on such material for the sake of comparison to LVL. Thus, the solid sawn lumber would serve as a comparison material. Since the main goal centered on manufacturing temperatures, material had to be sorted into various temperature categories. Upon investigation, a common range of LVL manufacturing temperatures was found to be 145^{o}C to 160^{o}C (293^{o}F to 320^{o}F). The goal was to target temperatures near, greater, and much greater than common industrial practice. The chosen temperatures were 149^{o}C (300^{o}F), 171^{o}C (340^{o}F), and 193^{o}C (380^{o}F).

First, the unheated solid sawn lumber had to be sorted. Nondestructive sorting was done by impact longitudinal stress wave propagation. After this was done, the solid sawn lumber was heat treated. The press schedule had to be established according to several factors and by using practice billets (Chapter Three). The processing variables for solid sawn lumber were as follows:

1. Press: hot platen hydraulic;
2. Press Temperatures: 149°C (300°F), 171°C (340°F), and 193°C (380°F);
3. Press Schedule: thickness controlled for maximum thickness of every twelve solid sawn members;
4. Press Time: twenty minutes; and
5. Pressure Cycle: after twenty-nine seconds, the end condition pressure was 6897 kPa (1000 psi) and then reduced to 1382 kPa (200 psi) after forty-four seconds and held constant until the end of the cycle at twenty minutes.

After the solid sawn lumber was heated, the material was allowed to return to equilibrium conditions (moisture content (MC) = 10%) before further testing was done. The modulus of elasticity was again evaluated using longitudinal stress wave propagation and also, static edgewise bending. The static bending tests were also used to determine the modulus of rupture. The effectiveness of the predictive capability of $E_{dynamic}$ values was evaluated (Chapter Four) and the effect of the manufacturing temperature on the mechanical properties was analyzed.

For the second phase, the solid sawn lumber was tested using long-term loading. A known stress was applied to each specimen. Stress ratios were assigned on a member by member basis and time to failure and deflection data were recorded. The effect of manufacturing temperature on the duration of load behavior was analyzed.

SPECIMEN SORT

All unheated solid sawn members were tested nondestructively to obtain an $E_{dynamic}$ (from Equation 2-1) for each specimen. The members were weighed and measured (one length, average of three widths, and average of three thicknesses). Impact longitudinal stress waves were only introduced in one location along the width, the center. An average of three stress wave times was taken.

The members were then sorted in order of ascending $E_{dynamic}$. A pseudo random sort (Chapter Two) was used to divide the members into the four temperature categories (one of the categories being no temperature). All categories consisted of forty-eight members, except for the high temperature category, which only had thirty-six members. An analysis of variance (ANOVA) was performed on the $E_{dynamic}$ values between the temperatures (Appendix E). The analysis showed no statistical difference between the temperature categories.

Within the temperature categories, it was necessary to separate the members into two equally distributed groups. One group was to be tested statically and the other group was to be tested under load-duration. The same technique for sorting into categories was employed for sorting into groups (Chapter Two). This final sorting provided the sample sizes that were used in the tests [MOE-MOR/DOL]: no temperature [24/24], 149^{o}C (300^{o}F) [24/24], 171^{o}C (340^{o}F) [24/24], and 193^{o}C (380^{o}F) [18/18].

Each category was heated to the determined temperature and nondestructive stress wave time was again used to determine E_{dynmic}. ANOVA results (Appendix E) showed no significant statistical difference between the newly determined $E_{dynamic}$ values of the temperature categories.

STATIC BENDING TESTS

Static edgewise bending tests were performed to find actual modulus of elasticity and modulus of rupture values for all specimen categories. The static modulus of elasticity, E_{static}, was used to monitor temperature effects on stiffness and to compare to the nondestructive method, E_{dyamic}, which had been used for sorting. Twenty-four members of each temperature category, except the 193^{o}C (380^{o}F), were tested for mechanical properties. The high temperature category only contained eighteen members.

An Instron 4400R screw-driven test machine was used to perform all static bending tests on the simply supported beams. The procedures from ASTM D198 (1998), the standard test for determining structural lumber properties, were followed and the load-displacement data, time to failure, and maximum load were recorded by a computer data acquisition system (Labview, 1997). A load rate of 3.3 mm/min (0.13 in./min) was determined to meet the provisions of the standard. All of the specimens were tested to failure. The displacement was measured at center span using a linear variable differential transformer (LVDT) (Appendix A). Using a spreader beam, the single point ramp load applied from the testing machine was evenly distributed into two point loads. The dimensions of the spreader beam were such that the two point loads were applied at third points, 610 mm (24 in.), in relation to the end reactions. Finally, lateral bracing was applied in accordance with the ASTM standard to eliminate the concern of lateral-torsional buckling effects. The actual static bending setup can be seen in Chapter Two. The equation used for static bending modulus of elasticity was Equation 2-2.

For the solid sawn members, since the members being tested were heat treated, the cross-sectional dimensions used in calculating E_{static} were the altered dimensions found after heating and reconditioning. These cross-sectional dimensions were, for the most part, smaller than those before heating (Table 5-2). Since moisture content was essentially returned to the conditions before heating, the loss in dimension and in mass may not be from shrinkage due to simple moisture loss alone. This is explained later in this chapter.

Table 5-2: *Cross-Section Dimension Changes from Temperature Effects*

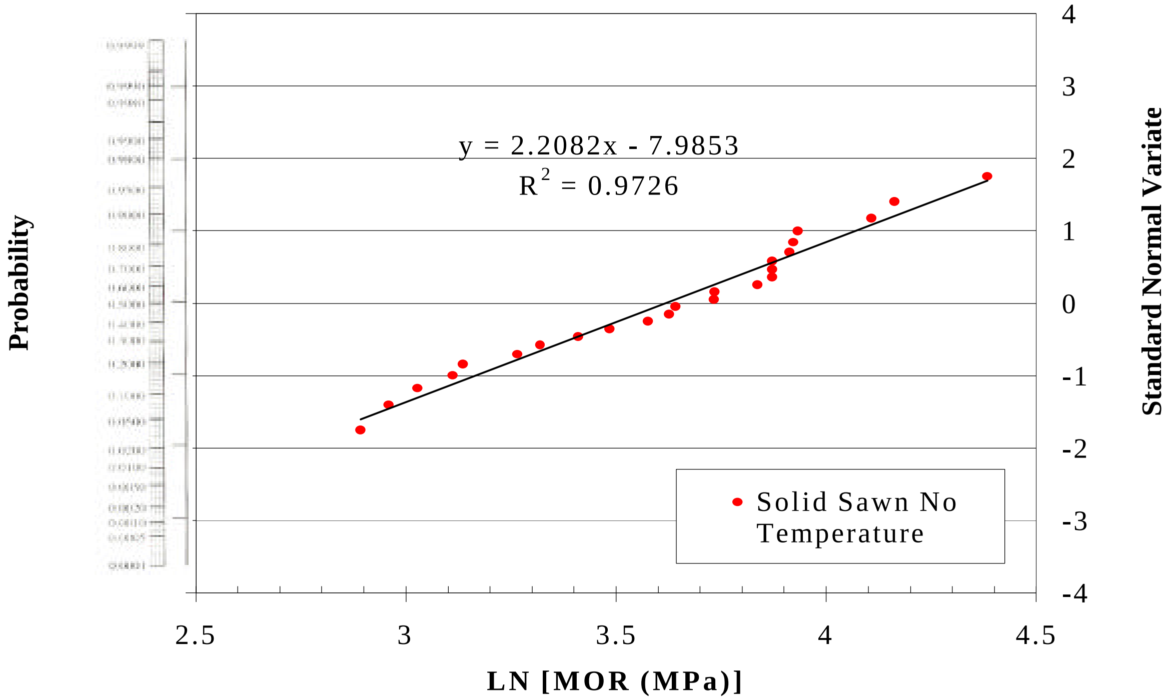
dimensions in mm	Unheated			Heated			Percent Difference		
Temperature	Width	Thick	Mass (g)	Width	Thick	Mass (g)	Width	Thick	Mass
149°C (300°F)	88.16	37.72	9.21	87.95	37.66	9.08	-0.23	-0.16	-1.45
171°C (340°F)	87.90	37.59	9.27	87.44	37.62	9.04	-0.53	0.10	-2.43
193°C (380°F)	87.82	37.64	9.39	87.22	37.56	9.09	-0.69	-0.23	-3.15

Static bending tests were performed in a temperature controlled room where the temperature range fluctuated between 21°C (70°F) and 23°C (73°F). The relative humidity was determined to be in the proximity range of thirty percent to forty percent.

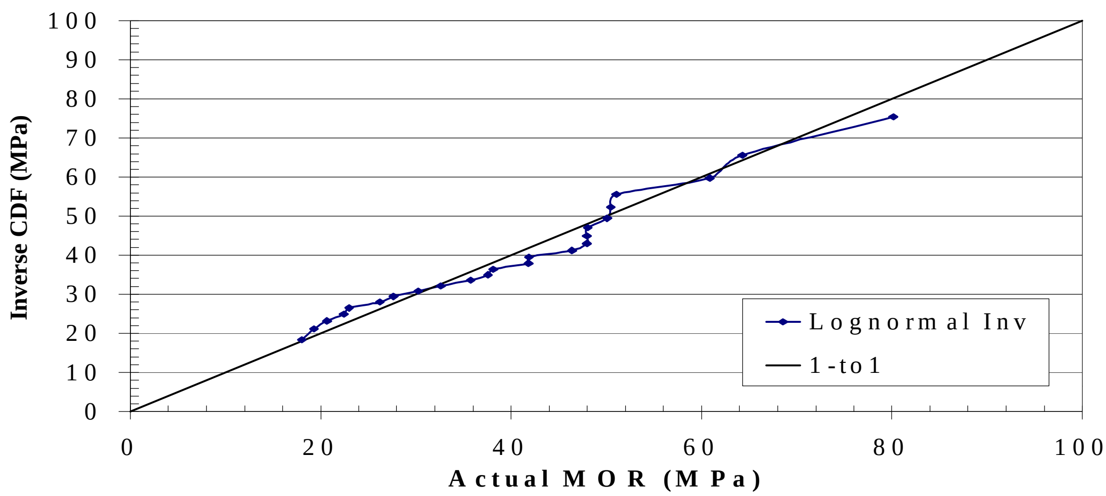
DETERMINATION OF LOADS

Using the maximum load obtained from the static bending tests, the modulus of rupture was calculated and used to determine loads for the load-duration tests. Again, the cross-sectional dimensions used in calculating the modulus of rupture were the dimensions found after heating. Each temperature category was evaluated separately.

Several methods were used to determine which statistical distribution best represented the modulus of rupture data. The distributions analyzed were normal, lognormal, and 2-P Weibull. The first methods were plotting the distributions on probability paper and comparing the coefficients of determination (r^2) (Figure 5-1A). These methods were based on visual inspection and quantitative results for goodness of fit. Also, the inverse cumulative distribution function (CDF) method was used (Figure 5-1B). Both visual inspection and the standard error estimate of these plots were performed. After reviewing all of the above methods, it was clear that a lognormal distribution best represented the modulus of rupture data for all temperature categories of the solid sawn lumber. Examples of the lognormal probability plots and the lognormal inverse CDF plots are shown for the solid sawn no temperature category (Figure 5-1). Distribution fitting plots for all temperatures are found in Appendix B.



A



B

Figure 5-1: *MOR Best Fit Lognormal Distribution: (A) Probability Plot and r^2; (B) Inverse CDF*

Once a lognormal distribution was determined as the best fitting distribution, the theoretical design values, F_b, were found in accordance with ASTM D2915 (1994) (Table 5-3). This was done to compare temperature categories in the same manor that is done in practice. However, because it was desired to move beyond the lower tail data that governs the design values, the fifteenth percentile modulus of rupture was calculated from the lognormally distributed data. This value would be considered the applied stress used for DOL testing. Using the same equation that was used to calculate modulus of rupture from the static bending tests, the applied loads were back calculated out of the equation (Equation 2-4) using the applied stress values.

Table 5-3: *Design Stress and Applied Stress for Solid Sawn Lumber*

Temperature ^{o}C (^{o}F)	F_b (MPa)		MOR (MPa) 15^{th} percentile	Calculated Loads (N)
	Nonparametric	Parametric		
No Temp	8.58	8.22	25.61	4061
149 (300)	8.59	8.68	28.01	4451
171 (340)	7.94	9.67	30.56	4832
193 (380)	12.52	10.90	34.02	5325

The actual values of modulus of rupture were obtained using the cross-sectional dimensions of the groups tested statically. When the loads were back calculated, the cross-sectional dimensions of the groups tested for load-duration behavior were used. This applied actual geometric properties of the group to the applied loads.

LOAD-DURATION TESTS

The second set of groups, one group per temperature category, was subjected to long-term loading to determine the response. The sample size was the same as that of the static tests, that is, all of the test groups consisted of twenty-four members except the 193^{o}C (380^{o}F) temperature group which consisted of eighteen members. The solid sawn lumber was subjected to a constant load for forty-two days, when the last deflection data was obtained (except for the solid sawn 149^{o}C (300^{o}F) and 171^{o}C (340^{o}F) which had its last deflection data taken at thirty days). Because of time constraints, the members had to be unloaded before the majority of the members had failed.

Four sets of testing frames were used. Each set consisted of twelve frames and each frame was designed to test two specimens at once. The frames were specifically designed for strong axis bending load-duration tests. The actual load-duration setup can be seen in Chapter Two. In a similar configuration as the static test setup, using a spreader beam, the single point load applied via a pulley and cable system was evenly distributed into two point loads. The dimensions of the spreader beam were such that the two point loads were applied at third points, 610 mm (24 in.), in relation to the supports. Lateral bracing was provided and the applied weights, made of steel and/or concrete, were hung from a 406.4 mm (16 in.) diameter pulley. Each pulley was individually calibrated by using a small load cell and applying known loads to the system (Appendix A). The actual mechanical advantage for each pulley was calculated by averaging the results from four known loads for each pulley. The minimum and maximum calculated mechanical advantages of the pulleys were 7.72:1 and 7.97:1, respectively.

A modified caliper was used to collect deflection data. Because it was not possible to collect continuous data using the caliper, deflections were recorded at specific times relating to time of loading. These times were as follows: one minute, half hour, one hour, two hours, four hours, one day, four days, seven days, fourteen days, twenty-two days, thirty days (last collection for the solid sawn 149^{o}C (300^{o}F) and 171^{o}C (340^{o}F)), and forty-two days.

Since the members used for the load-duration tests failed under sustained load, it was not possible to also retest the members for ultimate bending stress. In order to obtain an ultimate bending stress for the failed members, the rank order statistic method was used. This method uses the strength values found from the distribution fitting. Each specimen was ranked according to time of failure. The specimens were then assigned a lognormally distributed ultimate bending strength according to this ranking. That is to say, the first member to fail, considered the weakest, is assigned the lowest lognormal ultimate stress and so on. This ranking process was followed as the members broke until the end of testing, which was before all members had failed.

Nondestructive testing was done on all the members so there was information relating the load-duration specimens to each other but, through modulus of elasticity, not bending strength. However, based on assumption that there is a positive correlation between stiffness and strength, the failure order of the members could be predicted relatively well. This proved useful in evaluating the load-duration behavior of the surviving members.

The testing room where the load-duration tests were performed was thermostat controlled at 21^{o}C (70^{o}F) with heating and cooling systems. Duration of load testing was primarily conducted during summer months so constant cooling was applied to the room and minimal heating was used to balance the environmental temperature. The relative humidity was monitored and essentially remained at a constant thirty percent.

RESULTS

THERMALLY INDUCED DEGRADATION

Since the decrease in specimen cross-sectional dimension and in mass were permanent and above the temperature range for reversible effects, it is possible that a chemical change of the wood involving degradation of the wood substances caused a permanent loss of dimension and mass (Table 5-1). This resulted in decreased density (calculated mass divided by volume) of the material. Since pressure was not applied to the solid sawn lumber, the decrease was purely thermally induced (degradation and moisture reduction). Examination of the percent difference of the average values of the densities, Table 5-4, shows an increase of average density loss as temperature increases. However, ANOVA results found no significant statistical difference between the temperature categories (unheated or heated) or between the unheated and heated densities within each temperature group (Appendix E). Although the densities were found to be statistically similar, the practicality of the loss of over two percent being solely attributed to thermal degradation is questionable, especially since the exposure time was very short. Moisture effects may be playing a roll in the differences.

Table 5-4: *Densities of Unheated and Heated Solid Sawn Lumber*

ρ (kg/m^3)	UNHEATED			HEATED			% Difference
Temperature	Minimum	Average	Maximum	Minimum	Average	Maximum	of Average
No Temp	405.58	513.47	699.52	405.58	513.47	699.52	0.00
149°C (300°F)	409.74	515.45	621.64	402.84	509.28	616.40	-1.21
171°C (340°F)	424.00	519.62	628.99	414.82	509.58	613.71	-1.97
193°C (380°F)	412.91	527.72	644.78	402.31	515.32	623.50	-2.41

LOAD-DISPLACEMENT CURVES

The data acquisition system continuously recorded both loads and deflections for each statically tested solid sawn member. This data was used to plot a load-displacement curve for each specimen (Appendix F). The shapes of the load-displacement curves were typical within each temperature category but slightly different between categories. As is shown in Figure 5-2A, the no temperature members had a very linear relationship between load and displacement for all load levels. For the 149°C (300°F), low level loads were distinctly not linearly related to deflections (Figure 5-2B). The rise in manufacturing temperature to 171°C (340°F) shows the load-displacement curve had become more linear again in the low load region (Figure 5-2C). Finally, the curve became fully linear again for members of the 193°C (380°F) temperature category (Figure 5-2D).

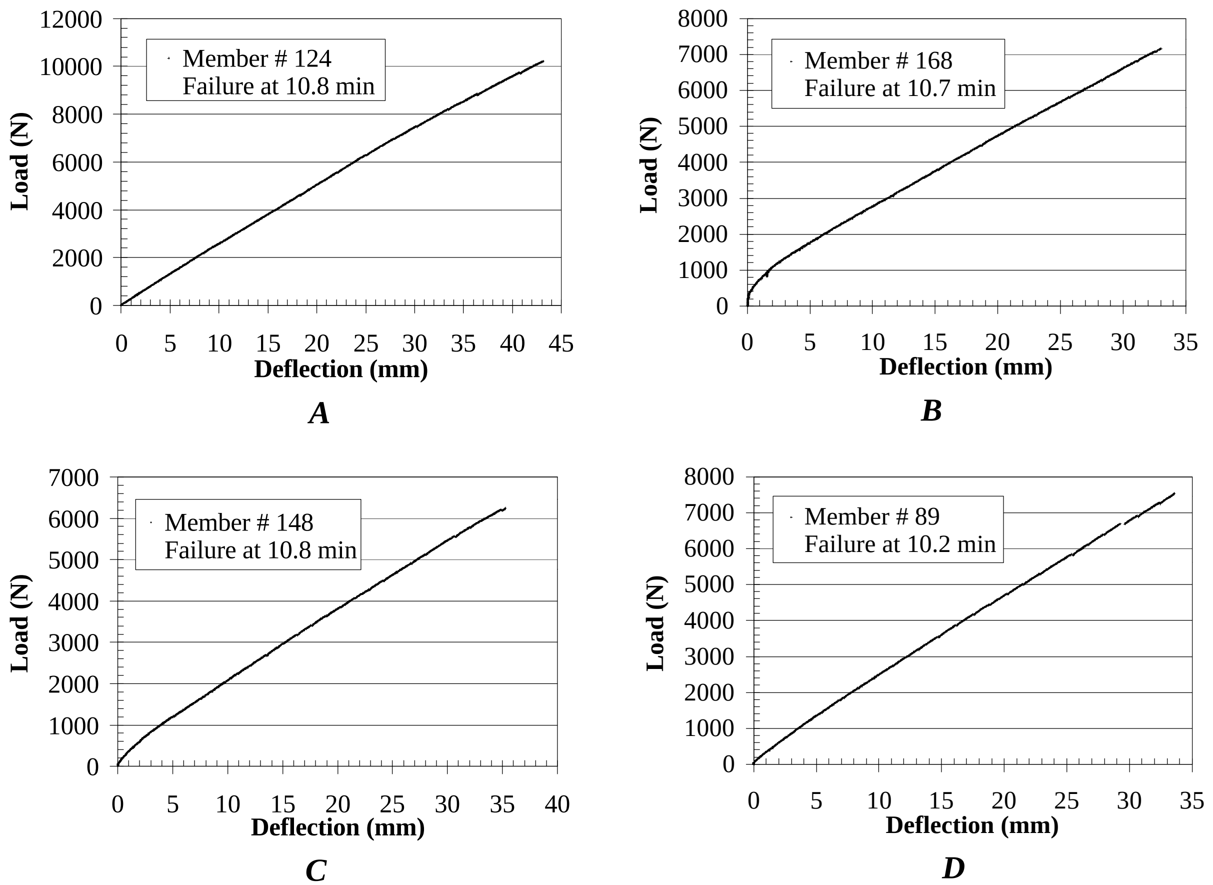


Figure 5-2: *Typical Load-Displacement Curves for Solid Sawn Lumber: (A) No Temperature; (B) 149°C (300°F); (C) 171°C (340°F); (D) 193°C (380°F)*

Determination of deflection at peak load became a problem with the two higher temperature categories. This is because a few of the specimens in these categories deflected more than the range of the LVDT (past two inches). Deflection summary data is provided in Table 5-5. From this table it can be seen that on average, as temperature increases, deflection increases. The range, however, is relatively small. Using the better estimate, the difference of the range values was slightly less than 5 mm (0.20 in.). The ANOVA results (Appendix E) showed no statistically significant difference between the maximum static deflections of the different temperature groups. Also provided in Table 5-5, are the average peak loads for all temperature categories. Like deflection, as the temperature increased, the peak load increased. The difference from no temperature to 193°C (380°F) is almost 1.55 kN (350 lbf).

Table 5-5: *Average Static Deflections and Peak Loads for Solid Sawn Lumber*

	Accurate Reading	Deflection At Peak Load	Surpassed LVDT	Better Estimate*	Peak Load
Temperature	n	Δ (mm)	NA	Δ (mm)	(kN)
No Temp	24	35.42	0	-----	6.346
149°C (300°F)	24	36.85	0	-----	7.326
171°C (340°F)	20	34.48	4	38.03	7.663
193°C (380°F)	15	37.28	3	40.40	7.885

*Better Estimate includes the maximum deflections recorded for those members that surpassed the LVDT

MECHANICAL PROPERTIES

From the load-displacement curves, it was evident that temperature history was having an effect on the response of the solid sawn lumber and, ultimately, lumber's mechanical properties.

After the solid sawn lumber had been heated and reconditioned to equilibrium conditions, the members were again tested using impact longitudinal stress wave. The results showed a slight decrease from original unheated $E_{dynamic}$ values (including values from specimens tested both statically and long-term). The decrease in $E_{dynamic}$ values was small but became greater as temperature increased (0.32%, 1.05%, and 1.21 %). Using the load and deflection data of the low load linear region, E_{static} was computed. The average values are found in Table 5-6 and graphically shown in Figure 5-3. The solid sawn lumber without temperature treatment was considered the baseline material and used to validate the results from the static bending test procedure. ASTM D2915 (1994), the standard for evaluating structural lumber allowable properties, was followed. The design value calculated for the Standard & Better grade Douglas-fir Larch was E_{static} = 9.81 GPa (1422881 psi). This was higher but very comparable to the NDS (AF & PA, 1997) published design value of 9.65 GPa (1400000 psi). The higher value was expected because there are six other visually graded categories that are “better” than Standard grade. All equations used to determine the apparent modulus of elasticity are located in Appendix B.

Table 5-6: *Mean Values and Coefficient of Variation for Moduli of Solid Sawn Lumber*

	Unheated SSL		Heated Solid Sawn Lumber					
	$E_{dynamic}$* (GPa)		$E_{dynamic}$* (GPa)		E_{static} (GPa)		MOR (MPa)	
Temperature	Mean	COV % (n)	Mean	COV % (n)	Mean	COV % (n)	Mean	COV % (n)
No Temp	12.46	16.70 (48)	12.46	16.70 (48)	9.81	22.76 (24)	40.11	38.95 (24)
149°C (300°F)	12.40	15.71 (48)	12.36	15.45 (48)	10.57	20.98 (24)	46.05	44.00 (24)
171°C (340°F)	12.42	16.01 (48)	12.29	15.92 (48)	11.01	21.55 (24)	48.79	40.45 (24)
193°C (380°F)	12.39	15.51 (36)	12.24	15.37 (36)	11.05	19.02 (24)	50.72	37.30 (24)

*$E_{dynamic}$ values include specimens tested both statically and long-term

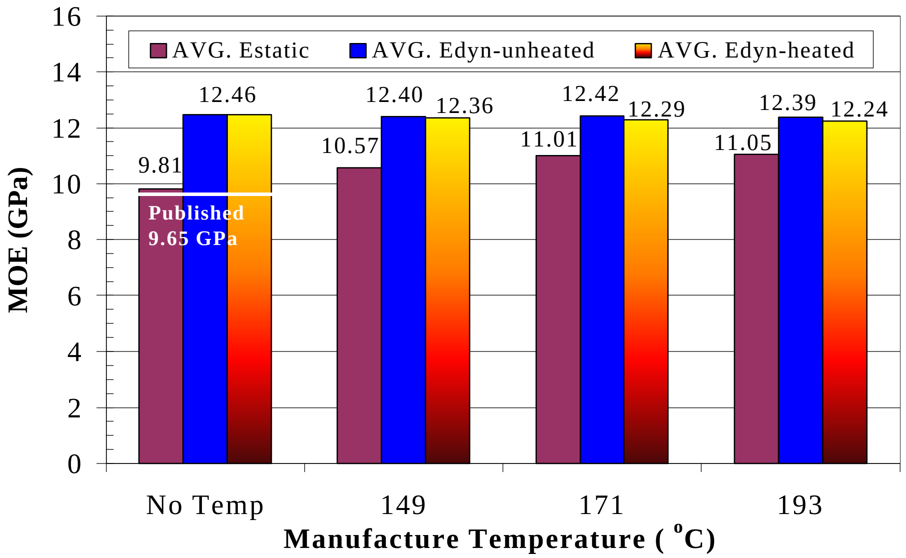


Figure 5-3: *Comparison of Means of MOE for Solid Sawn Lumber*

It was observed that as the manufacturing temperature increased the mechanical modulus of elasticity increased. The difference of range values was 1.24 GPa (180000 psi). ANOVA results (Appendix E), however, showed that there was no significant statistical difference between the E_{static} of the temperature categories. However, between both the no temperature - 171°C (340°F) and no temperature - 193°C (380°F) temperature categories, a P-value (α = 0.05) of near 0.08 was observed. This suggests there may be a trend towards these data sets being statistically different.

The same observation, an increase in temperature yields an increase in moduli, was made for modulus of rupture data (Table 5-6). The difference in range values was 10.61 MPa (1540 psi). Again, ANOVA results showed no significant statistical difference between modulus of rupture values for different temperature categories. However, the P-value for the comparison of no temperature to 193°C (380°F) was 0.053, which indicates that there may be a trend toward these temperatures being significantly different.

To further investigate these trends, the static deflections at peak load (Better Estimate) were compared with their respective strength. Correlation coefficients were found for this relationship for each temperature. Overall, the correlation was fairly good (Figure 5-4). The slopes off the trendlines were similar (except for 149°C (300°F) and they had a similar elevation location. This suggests that the correlation trend between the deflection and strength is similar for all temperatures.

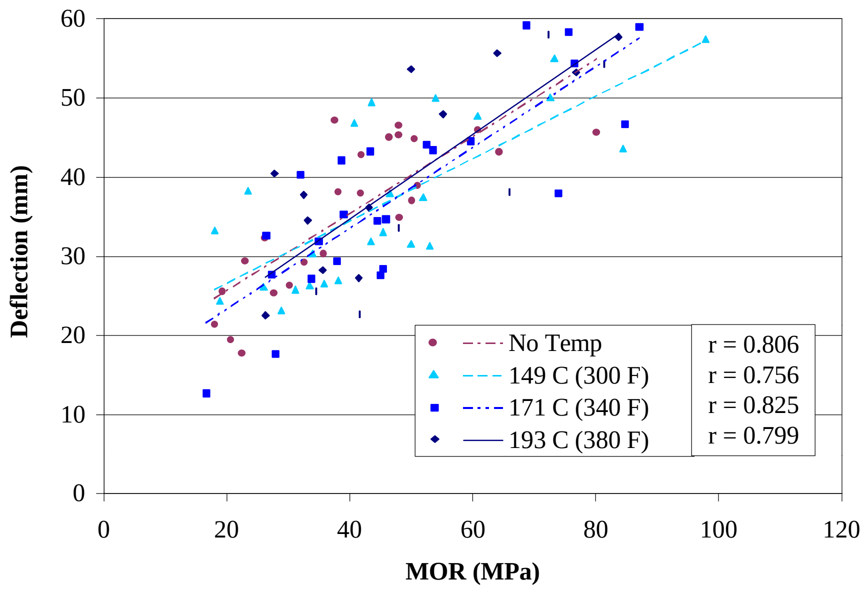


Figure 5-4: *Correlation of Static Deflection and Modulus of Rupture for Solid Sawn Lumber*

Using the no temperature value as the base value for all properties (similar to Gerhards 1982), the relative values per property per temperature were calculated based on the average values (Table 5-7). The relationships between temperature and their respective percent increase for all properties, maximum static deflection, maximum load, E_{static} and modulus of rupture, were represented with both a linear and a second order polynomial trendline. These relationships are shown in Figure 5-5. Because the values of $E_{dynamic}$ (heated) did not show much fluctuation, they were not included in Figure 5-5.

Table 5-7: *Relative Solid Sawn Lumber Properties Based on No Temperature (%)*

Temperature	$E_{dynamic}$*	Deflection	Load	E_{static}	MOR
No Temp	100.0	100.0	100.0	100.0	100.0
149°C (300°F)	99.2	104.0	115.4	107.8	114.8
171°C (340°F)	98.6	107.4	120.8	112.3	121.7
193°C (380°F)	98.2	114.1	124.2	112.7	126.5

*$E_{dynamic}$ values include specimens tested both statically and long-term

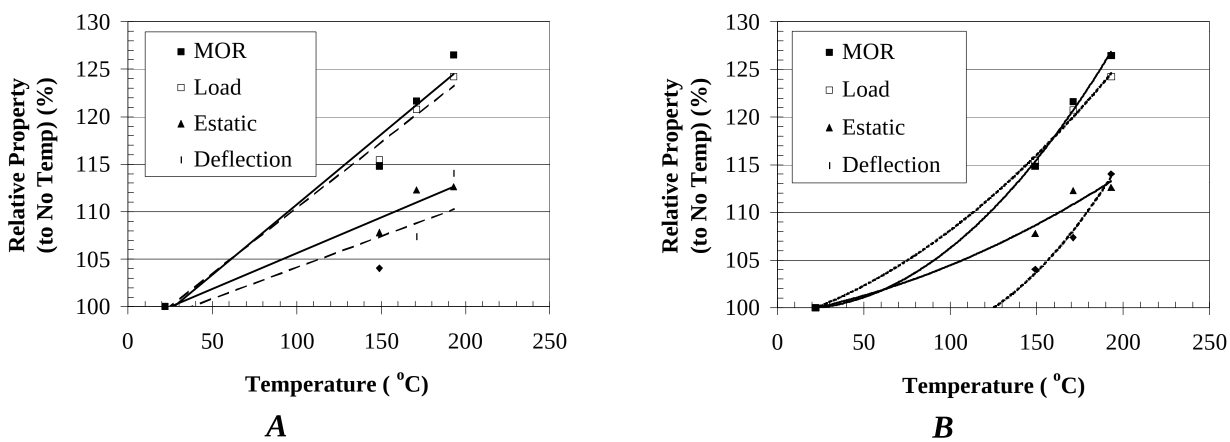


Figure 5-5: *Relative Mechanical Properties of Solid Sawn Lumber due to Elevated Temperature Exposure of Twenty Minutes (Tested at Room Temperature Conditions): (A) Linear Fit; (B) Second Order Polynomial Fit*

The obvious cause of increased mechanical properties would be that short-term heating to higher temperatures causes a loss in moisture content. However, this possibility was minimized because the testing of all specimens was done at equilibrium room temperature conditions with all specimens having been reconditioned to ten percent moisture content. Published literature supports a linear decrease in mechanical properties for immediate temperature effects. However, because the temperatures used were above 100°C (212°F), the conditions of reversible effects, and thus immediate effects, are violated. The data might be better compared with permanent effects.

The shortest time exposure for comparison was the three to seven day exposure from the research by LeVan (1990). The 3.8 percent and 5.1 percent increase in modulus of elasticity and modulus of rupture, respectively, had been concluded to be inconsequential. However, the higher percent increase in modulus of rupture follows the trends seen in Figure 5-5. The percent increases for the 82°C (180°F) also fit relatively well to the linear model and very well to the second order polynomial model. This is interesting given that the time of exposure of the published data was longer than for the data of Figure 5-5. The second order polynomial curve fit for the deflection data actually falls below 100 percent from 22°C (72°F) until about 130°C (266°F). It is doubtful that this is valid. More data for the temperatures that fall within this range given the short exposure time are needed to properly fit the curve. Essentially, this is true for all of the property curves.

DURATION OF LOAD BEHAVIOR

The phenomenon known as creep rupture, or load-duration behavior, was the focus of the research. Of specific interest were the effects of laminated veneer lumber manufacturing temperature on the load-duration behavior of solid sawn lumber. Specific analysis of the related phenomenon creep was not performed, however, DOL deflection behavior was examined.

By definition, creep rupture occurs because of the failure of the specimen to sustain constant load over time due to increased deformation during that time. In order to examine duration of load behavior, the modulus of rupture values were used to determine the sustained loads. These MOR values, found from static testing, showed an increase with increase of temperature. Logically, the lognormal distributions, used to determine the applied loads for the load-duration tests, reflected this trend. ANOVA results showed no significant statistical difference between modulus of rupture values between different temperature categories, except for the comparison of no temperature and 193°C (380°F). Also, the P-value ($\alpha = 0.05$) for the comparison of no temperature and 171°C (340°F) was 0.08, which indicates that there may be a trend toward these temperatures being significantly different. In order to avoid the lower tail region of the strength distribution, applied stress levels were based on the 15th percentile. Using the 15th percentile lognormal modulus of rupture values, the applied loads were calculated (Table 5-8) and adjusted using the mechanical advantages of the pulleys of the test frames.

Table 5-8: *Applied Loads for Solid Sawn Lumber*

Temperature	No Temp	149°C	171°C	193°C
FRAME	2	3	4	1
Applied load (N)	4061	4451	4832	5325
PULLY MECHANICAL ADVANTAGE RANGE				
Maximum	7.94	7.95	7.97	7.96
Minimum	7.75	7.74	7.76	7.72

DURATION OF LOAD BEHAVIOR: DEFLECTION ANALYSIS

Although specific analysis of creep was not performed, deflection measurements were taken with a digital caliper. From these measurements, displacement-time curves were generated for each specimen tested. Examination of this graphical representation of creep behavior provides insight into the overall load-duration behavior of the specimens. Figure 5-6 illustrates a typical curve for all temperatures. The arrow near the last deflection measurement represents survival past the duration of the test. An example depicting a non-failing member was shown because survival after six weeks was the most typical case for all solid sawn lumber temperature categories. Deflection-time plots for all specimens are presented in Appendix G.

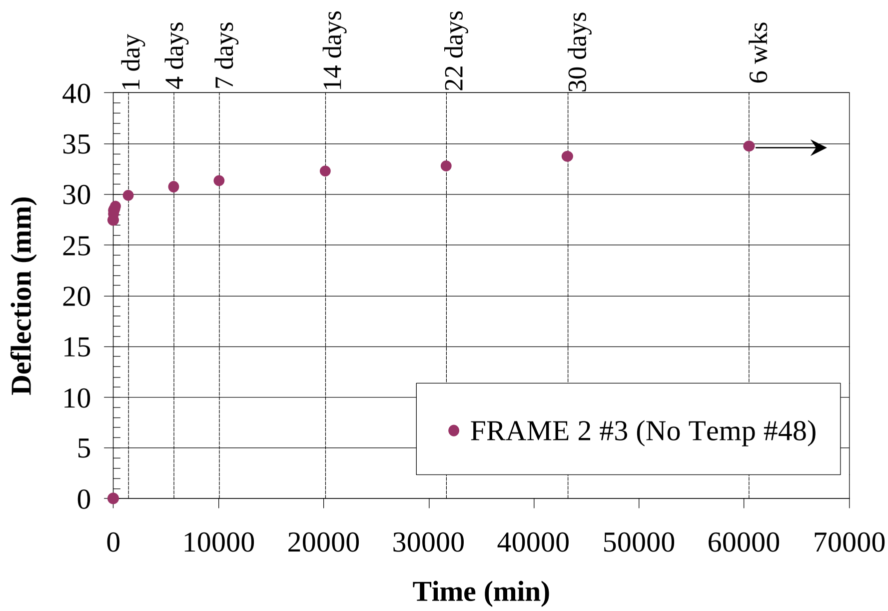


Figure 5-6: *Typical Displacement-Time Curve for All Temperatures*

The shapes of the deflection-time curves were similar to those of other Douglas-fir solid sawn lumber trends found by Fridley et al. (1992a). Similar meaning that there was an initial elastic deflection region followed by a primary creep phase region followed by a secondary creep phase region. The duration of these regions was comparable to those previously reported. However, for all temperature categories, there was a high number of surviving specimens after six weeks. Because of this and because deflection data was collected manually, the trend for the final stage of creep, tertiary, could not be obtained. A summary of the number of failures and survivals for each temperature is provided in Table 5-9. The reason for a high number of ramp failures for the 171°C (340°F) temperature group was unexplained.

Table 5-9: *Number of Failures and Survivals for Each Temperature Category for Solid Sawn Lumber(after six weeks of observation)*

Temperature	Ramp Failure	DOL Failure	Survivor	Total
No Temp	5	5	14	24
149^{o}C (300^{o}F)	2	6	16	24
171^{o}C (340^{o}F)	9	3	12	24
193^{o}C (380^{o}F)	5	4	9	18

Three DOL deflection stages were examined: initial, failure (less than 43200 min), and survival (equal to 43200 min). Initial deflection data, obtained at one minute after load was applied, has the sample size of the total number of specimens minus those lost due to ramp failures. ANOVA was performed to compare the distribution of deflections. For each temperature category, each DOL deflection stage was compared to the respective maximum static deflection. For all temperatures, the static deflection and the failure DOL deflection were not statistically significantly different. Contrarily, the static deflection and initial DOL deflection were statistically different for all temperatures. Survival results varied depending upon temperature (Appendix E). For the no temperature and 149^{o}C (300^{o}F) categories, the static deflection was statistically significantly different from the survival DOL deflections. For the higher temperature categories, 171^{o}C (340^{o}F) and 193^{o}C (380^{o}F), the opposite was true.

ANOVA was also performed for the three DOL deflection stages compared between temperature categories. Results between failure deflections of different temperature categories showed no statistically significant difference suggesting that the failure DOL deflection behavior was similar for all temperature categories. The results for initial and survival deflections between temperature groups showed no difference except when the high temperature, 193^{o}C (380^{o}F), was involved (Appendix E). Expanding on the ANOVA results, mean deflection values were compared to detect possible trends (Table 5-10 and Figure 5-7). Although the high temperature, 193^{o}C (380^{o}F) had the highest deflection average for all DOL deflection stages, there was not a definite trend for either the initial or failure deflections. However, there was a slight increase for the survival deflections. Recall that this stage contained the most samples for all temperatures. An increase between range values was about 7 mm (0.28 in.). The trend, although increasing, was not similar to that of the static deflections.

Table 5-10: *Average DOL Deflection Values*

Temperature	Initial Δ	Failure Δ	Survival Δ
No Temp	24.04	33.10	26.07
149°C	23.13	27.84	26.50
171°C	24.46	28.30	28.56
193°C	28.57	39.04	33.24

All deflection values are in mm

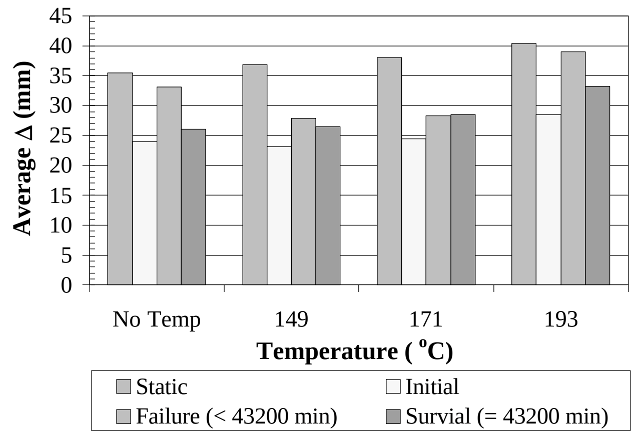


Figure 5-7: *Bar Graph of Average DOL Deflection Values*

To investigate possible correlation, the DOL deflections were compared with their respective strength. Correlation coefficients were found for this relationship for each temperature. Because a large number of data points were survivals, their assigned strength had to be predicted. This was done using the dynamic modulus of elasticity ($E_{dynamic}$). However, as was seen in Chapter Four, the correlation between $E_{dynamic}$ and modulus of rupture was not very strong. Therefore, the predictive capability of the $E_{dynamic}$ for the rank order of the assigned modulus of rupture was only moderately reliable. Figure 5-8 shows the combined data of the ranked modulus of rupture and the predicted modulus of rupture according to the respective $E_{dynamic}$. Overall, there was evidence of some correlation (Table 5-11) with the no temperature category having the best correlation. The slopes off the trendlines were similar. This suggests that the correlation trend is similar for all temperature categories.

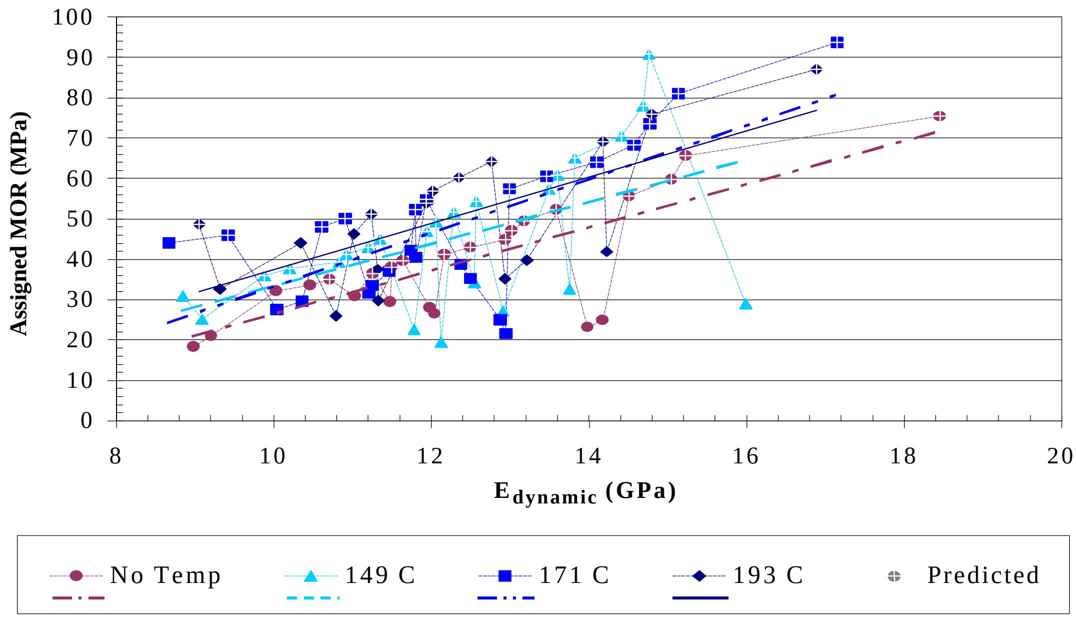


Figure 5-8: *Correlation of $E_{dynamic}$ and Rank Order Modulus of Rupture for Solid Sawn Lumber*

Table 5-11: *Coefficients of Determination and Correlation Coefficients for Assigned Modulus of Rupture*

	Initial Δ		Survival Δ		$E_{dynamic}$	
Temperature	r^2	r	r^2	r	r^2	r
No Temp	0.6903	0.8308	0.5832	0.7637	0.6179	0.7861
149°C	0.2472	0.4972	0.3653	0.6044	0.2795	0.5287
171°C	0.5210	0.7218	0.5439	0.7375	0.5037	0.7097
193°C	0.3914	0.6256	0.6316	0.7947	0.4651	0.6820

The correlations between the modulus of rupture and the DOL deflections were not as strong as were the MOR correlations with the static deflections. In fact, the low correlation coefficients of 149°C (300°F) suggest there may be very little correlation at all. The MOR correlation trends with the initial (Figure 5-9) and combined survival deflections (Figure 5-10) are decreasing trends. The data points are connected in order to track increasing MOR. Although this is the opposite as what was seen for static deflections, it stands to reason. Since the initial and survival DOL deflections are the result of a constant sustained load, at any given time, the stronger members would deflect less than would the weaker members, which were closer to failure. Because of the lack of failure DOL deflection data, no conclusions could be made as to the overall correlation behavior. Consequently, these deflections were not graphically represented.

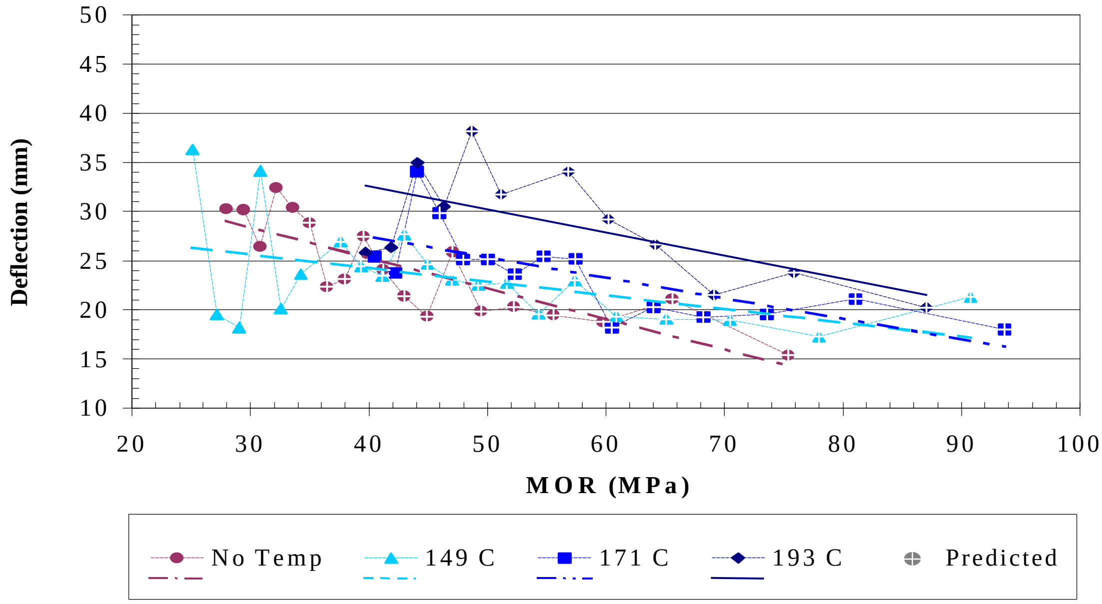


Figure 5-9: *Correlation of Initial DOL Deflection and Modulus of Rupture for Solid Sawn Lumber*

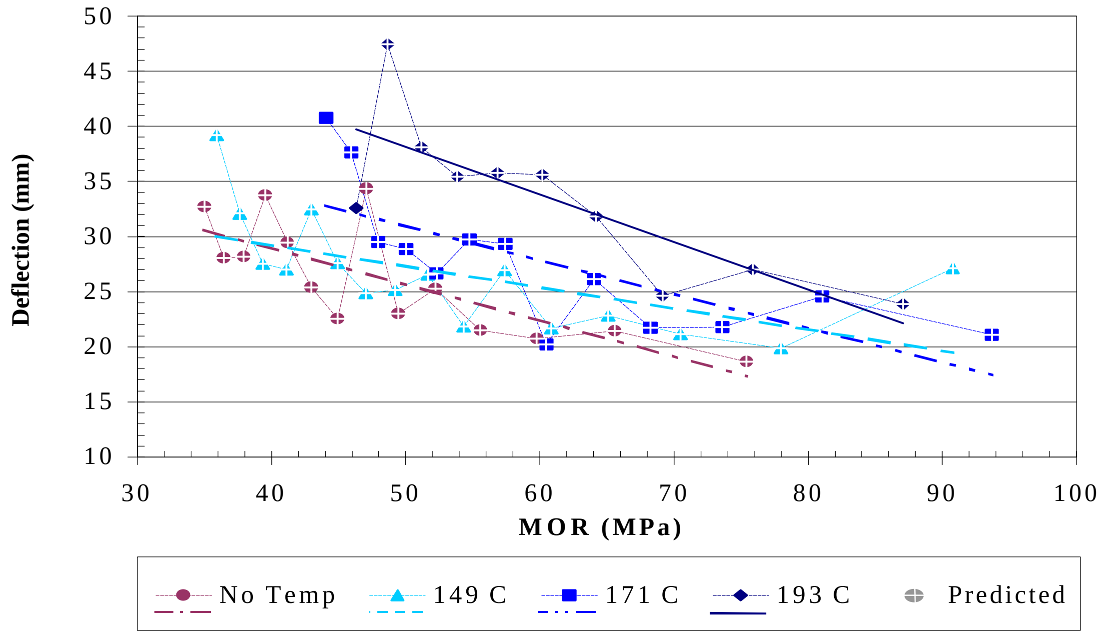


Figure 5-10: *Correlation of Survival DOL Deflections and Modulus of Rupture for Solid Sawn Lumber*

As stated earlier, the predictive capabilities of the $E_{dynamic}$ values were not proven to be as reliable as desired. Even though some correlation existed with the survival DOL deflections, since most of the correlation findings were predicted, possible observations, such as some slope similarity, were not substantiated.

DURATION OF LOAD BEHAVIOR: DAMAGE ACCUMULATION

There are several methods to assess the duration of load behavior of wood. The damage accumulation (DA) approach is the most popular (Rosowsky and Fridley, 1995) and the approach of greater confidence (Fridley, 1992) since it is so widely used. The damage accumulation is related to the applied stress level. The approach for evaluation of duration of load behavior is to plot the applied stress ratio (SR) versus the time to failure. For this research, the SR was determined using the lognoramally distributed modulus of rupture values as the ultimate stresses (as the denominator), assigned to specimens using rank order statistics. The 15^{th} percentile value of the distribution was the applied stress and used as the numerator of the stress ratio.

The focus of the study was to determine the effect of manufacturing temperature on duration of load behavior. Since it was not of interest to compare the performance of the different DA models, only one model was used to analyze the DOL behavior of the solid sawn lumber. Some support of this reasoning was found from Cai et al. (2000). It had been found that four common DA models were similar in their predictive capabilities for small clear specimens tested at high stress ratios applied for short durations. Selection of the DA model was based on similarities between the test specimens used to develop the model and those of this research.

The Exponential Damage Rate Model (EDRM) developed by Gerhards (1977, 1979) was a model based on small clear Douglas-fir specimens. However, using data from 38 mm by 89 mm by 2.44 m (nominal 2 in. by 4 in., 8 ft long) Douglas-fir lumber, the model was later calibrated by Gerhards and Link (1987). Expanding on this study, Gerhards (1988) provided calibrated models for several grades conditioned at and tested in an environment of 23^{o}C (73^{o}F) and 50 percent relative humidity. Since the test specimens and testing conditions of the studies by Gerhards were similar to some aspects of this research, Gerhards' EDRM (Equation 5-4) was used to model the load-duration behavior.

Least squares regression fit of the data to Gerhards' EDRM was performed on each temperature category only for the data points obtained for failures under sustained load (Table 5-9). Excluding both the large amount of survivals, after six weeks, and the expected ramp failures, only a limited amount of data points were left available for regression analysis. Model constants are provided in Table 5-12A. The goodness of fit of the model was evaluated from calculated coefficient of determination and standard error of the estimate (Table 5-12B) and visual inspection of Figure 5-11.

Table 5-12: *EDRM: (A) Model Constants; (B) Coefficient of Determination and Standard Error*

Temperature	A	B
No Temp	47.8650	48.7163
149^{o}C	32.8310	26.5253
171^{o}C	77.4847	95.5857
193^{o}C	60.5772	69.0393

A

Temperature	r^2	Standard Error
No Temp	0.819	1.595
149^{o}C	0.908	1.047
171^{o}C	0.986	0.490
193^{o}C	0.900	1.492

B

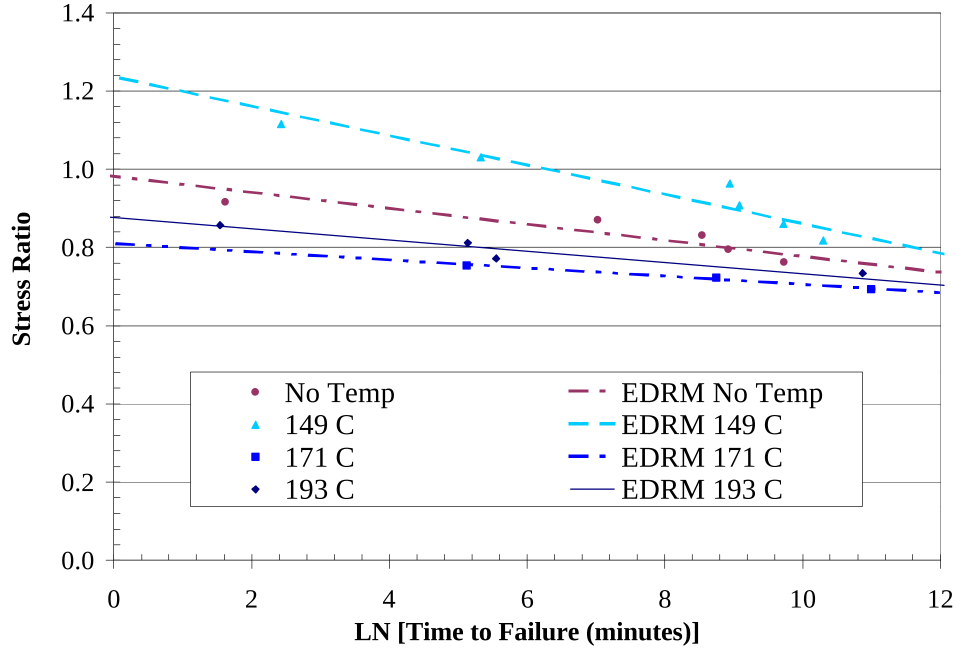


Figure 5-11; *Time-to-Failure Plot for All Temperature Categories of Solid Sawn Lumber*

The results in Table 5-12B, high coefficients of determination and low standard errors, show that the linear fit, on the natural log scale, of the Gerhards' EDRM model is good. Figure 5-11 provides visual verification of the goodness of fit. It is also apparent that, for the overall behavior, the limited data does not follow the shape characteristic of a hyperbolic model, such as that of Wood (1951).

To compare the regression lines of the temperature categories, methods for testing the hypothesis of equality for population regression coefficients and elevations were performed (Zar, 1996). Each test involved the use of the t distribution in a manor analogous to the testing for difference between two mean populations. The validity of the t test assumes two basic theoretical assumptions of the sample populations; both are randomly obtained from a normal distribution and there are equal variances between both populations. However, the t test has been proven to be quite robust and can withstand considerable departures from the theoretical assumptions (Zar, 1996). This is especially true if the sample sizes are equal or nearly equal.

This was important because the nearly equal small sample sizes, for all temperature categories, of the regression data make determining normality difficult. Nonetheless, cumulative distributions were graphed, to determine normality, and variances were calculated. Visually, it was determined that the trend of the samples (sigmoid curve) was reasonably close enough to normality. Also, the variance values, although not equal, were close in value. Because of the robustness of the test and because violation of the theoretical assumptions was not apparent, the t test was deemed reliable for the hypothesis tests of slope and elevation equality.

All regression analysis was performed at a 95 percent confidence level ($\alpha = 0.05$). Only two temperature regression lines were compared at a time. All regression analysis is provided in Appendix H. These sets of comparisons of all temperature EDRM regression lines indicated that the hypothesis of slope equality was rejected. This suggests that the data of the sample populations do not represent a common population. Since the specimens involved were indeed all originally from a common population, the manufacturing temperature exposure clearly has an effect on the duration of load performance of solid sawn lumber. However, examination of Figure 5-11 indicates that the EDRM regression lines converge as time increases. Because of this, it is necessary to evaluate for what time frame the manufacturing temperature is most affecting the load-duration behavior.

For reference, the Douglas-fir No.3 EDRM developed by Gerhards (1988) and the Madison curve (Wood, 1951) were graphed with the EDRM curves for all temperature categories (Figure 5-12). The Madison curve was included because the derived values are the basis for the load-duration design factors of the National Design Specification (NDS) for Wood Construction (AF&PA, 1997). The time to failure span was only meant to be representative of the actual time for the duration of load tests, which was about six weeks (11 on a natural log scale).

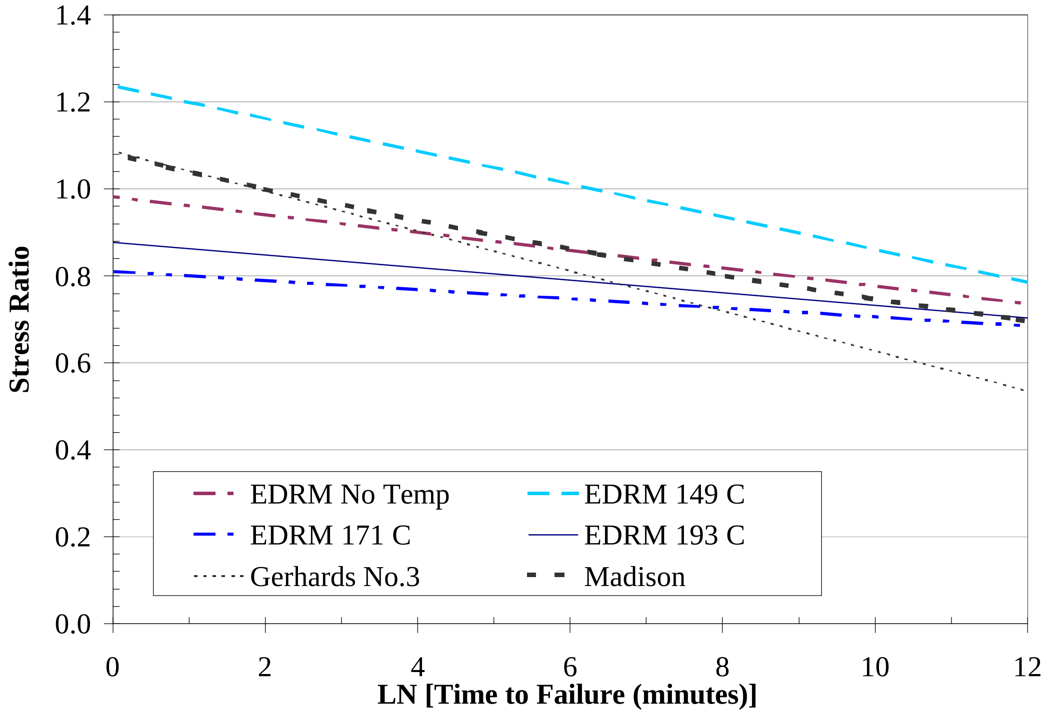


Figure 5-12: *EDRM Comparison for Solid Sawn Lumber (Duration of Testing)*

Examination of Figure 5-12 reveals that the EDRM curves of the different temperature categories were not very similar to the Gerhards (1988) No.3 model. However, the Madison curve (Wood, 1951), although not representative of the entire data set (discussed earlier), seemed to provide a good fit for the long-term tail region of all temperature categories. This suggests that the effects of short-term exposure to manufacturing temperatures may be minimal, if any, for long-term duration of load. However, it was already determined that the EDRM curves were different. This suggests that the manufacturing temperature exposure had more of an affect for the shorter load-durations. Also, it is necessary to extrapolate and examine the long-term behavior used in design, such as ten and fifty years.

Upon examination of the two reference EDRM curves, it is apparent that they both cross the 100 percent stress ratio line near seven minutes. This would correspond to a realistic failure time for the static ramp load tests. Contrarily, the EDRM curves of the temperature categories found through least squares regressions did not cross the 100 percent stress ratio at failure times reflective of their respective ramp loading static tests, which averaged between 10.7 and 12.8 minutes. In fact, for the temperature of 149^{o}C (300^{o}F), the intersection was unrealistically located at a high failure time for the static ramp failure time while the other temperature categories started below the 100 percent line, which is also unrealistic. However, similar discrepancies can be seen in data presented by Fridley et al. (1989 and 1991). These unrealistic results for the short duration of time suggest that the Gerhards' EDRM does not accurately model the values of this response. However, this inaccuracy should not discount the EDRM as a viable model for long-term behavior. The short-term behavior of the material can be determined using static testing methods. It is reasonable to accept these discrepancies because the damage accumulation is different for ramp loading than for a constant applied load. For a ramp load, the DA increases exponentially with stress level and culminates near the ultimate stress. Contrarily, for a constant applied stress, there is a constant rate of DA.

In order to better assess the differences between temperature categories, stress levels were predicted for common load-durations (Table 5-13). There was no detectable trend from one temperature category to the next. However, the 149^{o}C (300^{o}F) had the highest stress levels for durations less than ten years. The 171^{o}C (340^{o}F) category had all but one of the lowest predicted stress levels. Although the validity of the actual stress level along the EDRM regression is questionable for the short-term durations (discussed earlier), the actual load-duration data supports the relationship seen between the temperature categories. For extrapolated long-term behavior (five, ten, and fifty years), the stress levels of all temperature categories were very comparable to each other and to the NDS values. This supports the earlier suggestion that the effect of short-term manufacturing temperature exposure is minor for long-term loads. The decreasing trend between the difference of maximum and minimum stress levels (for temperature categories only) as constant load-duration increases is represented as percentages in Table 5-13. Figure 5-13 graphically demonstrates the extrapolated EDRM regressions.

Table 5-13: *Predicted Stress Levels for Heat Treated Solid Sawn Lumber*

Constant Load Duration	Madison Curve	Standard Grade Heat Treated Douglas-fir				Max. - Min. Difference
		No Temp	149^{o}C	171^{o}C	193^{o}C	
Ten Minutes	0.989	0.935	1.151	0.787	0.844	36.4%
One Day	0.823	0.833	0.964	0.735	0.772	22.9%
One Week	0.768	0.793	0.890	0.714	0.744	17.6%
Two Months	0.712	0.749	0.808	0.691	0.712	11.7%
Five Years	0.635	0.679	0.680	0.656	0.663	2.4%
Ten Years	0.621	0.665	0.654	0.649	0.653	1.6%
Fifty Years	0.589	0.632	0.594	0.632	0.630	3.8%

Lowest Temperature Category Values
Highest Temperature Category Values

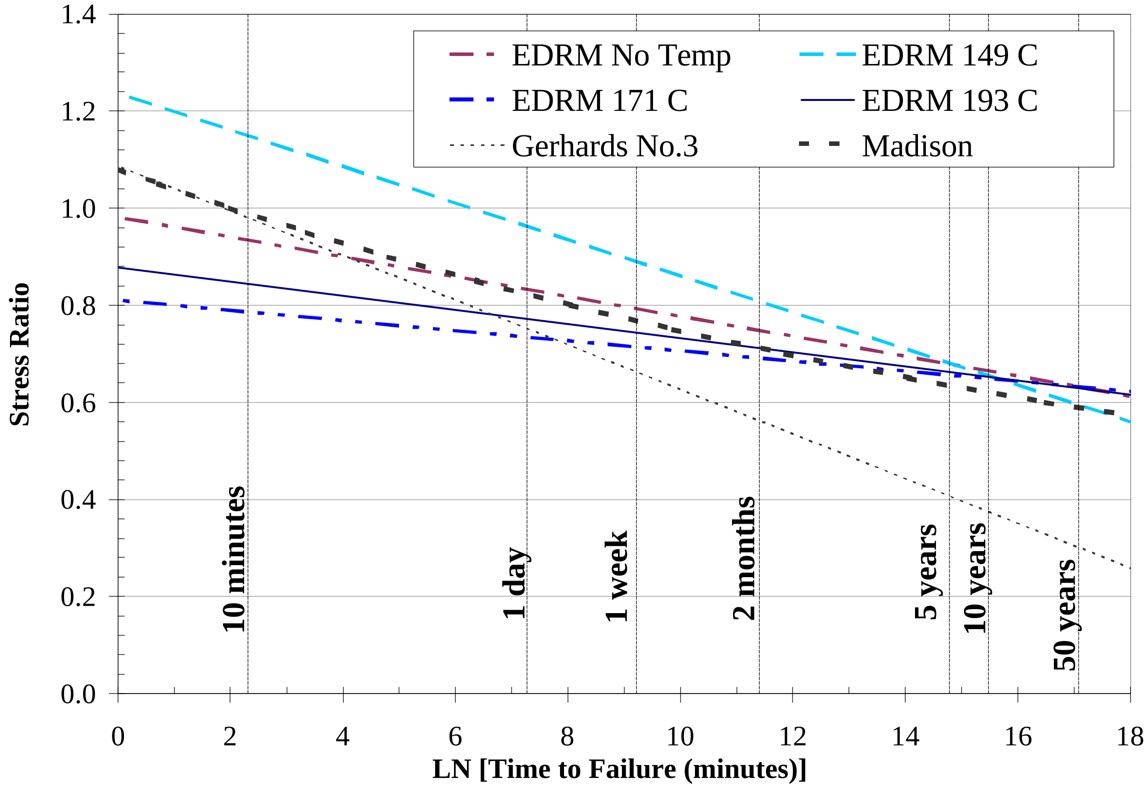


Figure 5-13: *EDRM Comparisons for Solid Sawn Lumber (Extrapolated Design Duration)*

Current load-duration design factors of the NDS are the result of the procedures of ASTM D245 (1993), the standard for establishing allowable properties for visually graded lumber. The equation used to determine the published value for the allowable bending strength is Equation 5-6.

$$F_b = \frac{x_{05}}{2.1} \qquad (5 - 7)$$

F_b = allowable bending strength

x_{05} = parametric or nonparametric (commonly 5th percent exclusion) strength value

Example calculations are provided in Appendix B. The denominator factor of 2.1 is the product of a 1.6 load-duration factor (based on ten years) and a 1.3 end use factor. Since the allowable bending strength equation is based on ten years, the load-duration adjustment factor for ten years is 1.0. Stress ratios are found via interpolation along the model curve and then normalized per temperature category by the respective ten year stress ratio (Table 5-13). The resulting values are the respective adjustment factors.

Load-duration adjustment factors were calculated for all of the EDRM curves of the temperature categories. Table 5-14 contains the current load-duration adjustment factors (AF & PA 1997) from the Madison curve and the calculated load-duration adjustment factors for each temperature category. These factors are also presented graphically in Figure 5-14.

Table 5-14: *Calculated Load-Duration Adjustment Factors (Normalized to 10 Year Duration)*

Constant Load Duration	Madison Curve (NDS)	Standard Grade Heat Treated Douglas-fir			
		No Temp	149°C	171°C	193°C
Ten Minutes	1.59 (1.60)	1.41	1.76	1.21	1.29
One Day	1.33	1.25	1.47	1.13	1.18
One Week	1.24 (1.25)	1.19	1.36	1.10	1.14
Two Months	1.15	1.13	1.23	1.07	1.09
Five Years	1.02	1.02	1.04	1.01	1.02
Ten Years	1.00	1.00	1.00	1.00	1.00
Fifty Years	0.95 (0.90)	0.95	0.91	0.97	0.96

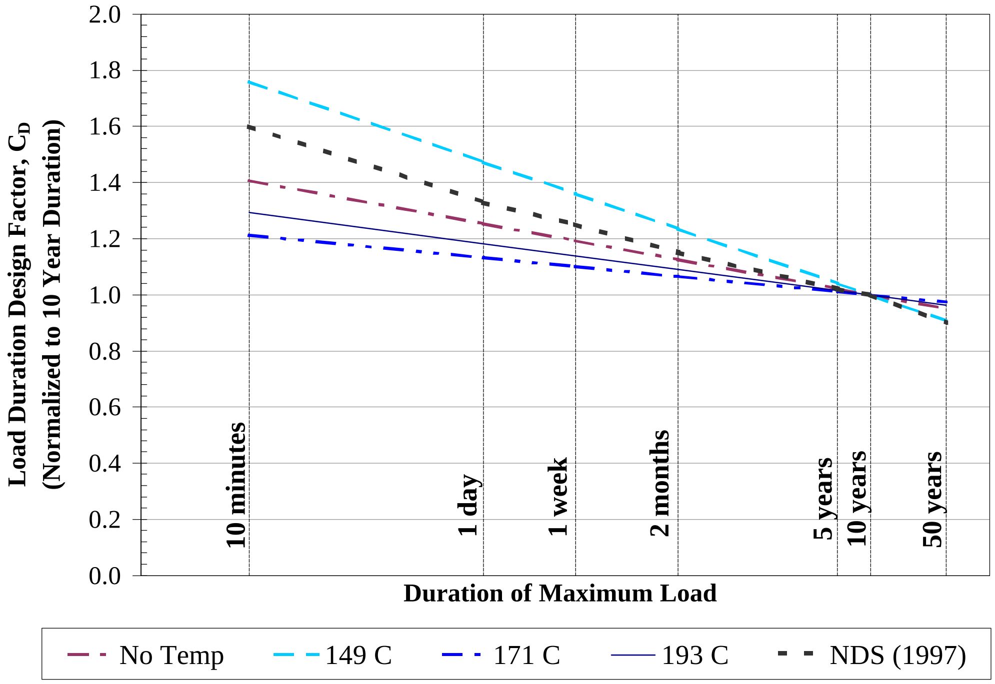


Figure 5-14: *Calculated Load-Duration Adjustment Factors*

It is apparent that the Madison curve load-duration adjustment factors are not appropriate for representation of the EDRM curves found for all temperature categories, including the control (no temperature). It should be noted that the majority of the temperature categories, save the 149°C (300°F) category, had calculated load-duration adjustment factors lower than those of the Madison curve. Also, the differences in predicted stress ratio and consequently load-duration adjustment factors were most severe for the short-term load-durations (less than five years).

CONCLUSIONS

The experimental results of this research gave insight to the mechanical and duration of load behavior of solid sawn wood material after short-term exposure to extreme temperatures. The trend of degradation of wood material increased as temperature increased. Although not shown to be statistically significant, the degradation was attributed to the thermally induced chemical change of the wood substance that is associated with the temperature range used in the research and possible moisture content influence.

It was observed that short-term extreme temperature exposure caused changes in the load-displacement relationship. This was most apparent for the 149^{o}C (300^{o}F) temperature category. Deflection and failure load both increased as temperature increased. However, it was determined that the differences in maximum static deflection were statistically not significant.

The dynamic modulus of elasticity, found via longitudinal stress wave time, was determined to be the same before and after heating for all temperature categories. It was also determined to be the same between all temperature categories. The static modulus of elasticity, while still shown to be statistically not different, showed a trend of an increased modulus as temperature increased. Although there is evidence of a trend, and a second order polynomial fit can be well applied to the trend, statistically it can be concluded that the modulus of elasticity is not effected by short-term (twenty minutes) extreme temperatures. The observations and conclusions made for static modulus of elasticity can also be applied to modulus of rupture. It can also be concluded that short-term extreme temperature exposure does not affect the correlation between strength and static deflection.

Although analysis was performed on the duration of load deflections (initial, failure, and survival), there was not enough data to substantiate any conclusions.

It was concluded that the exponential damage rate model (EDRM) was a good fit to all temperature categories. Regression analysis of equality of slope and elevation revealed that all temperature category EDRM curves were not the same. It was observed that the slope of the curves were different from existing EDRM curves (Gerhards 1988) for solid sawn lumber. The short-term duration showed the most difference in load-duration behavior for all temperature categories. It was concluded that the load-duration adjustment factors of the Madison curve (Wood, 1951) did not adequately represent the EDRM curves of this research overall. However, the Madison curve represented long duration periods, five to fifty years, well for all temperature categories. Essentially, it can be concluded that the short-term exposure to extreme elevated temperatures has virtually no effect on duration of load behavior of solid sawn lumber.

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CHAPTER SIX

EFFECT OF MANUFACTURING TEMPERATURE ON STRUCTURAL PROPERTIES OF DOUGLAS-FIR LAMINATED VENEER LUMBER

ABSTRACT

The structural properties of laminated veneer lumber (LVL) are influenced by several factors of the manufacturing process. While the effects of veneer quality and placement have been studied extensively, other parameters have not been given adequate attention. The effect of manufacturing temperatures on mechanical properties of Douglas-fir laminated veneer lumber were investigated. Manufacturing temperature common to the LVL production industry (149^{o}C (300^{o}F)), slightly higher than industry (171^{o}C (340^{o}F)), and much higher than industry (193^{o}C (380^{o}F)) were used. It was found that the static load-displacement behavior was indeed affected by manufacturing temperature. Although affected, mechanical properties were not overly sensitive to manufacturing temperature differences.

INTRODUCTION

How a material performs under static loading conditions determines the design values of that material. In the case of wood composite materials, more than just the material itself can affect the overall performance. This is a concern because during the manufacturing of wood composites, wood material is subjected to many processing parameters such as increased pressure, exposure to and bonding with adhesives, and rapid temperature and moisture changes. The effects of these processing parameters become a part of the wood composites' history and could potentially effect the wood composites' static performance thus affecting the design values.

In the case of laminated veneer lumber, processing parameters are determined by LVL manufacturing companies based on the cure temperature of the adhesive and experience in laminated veneer manufacturing. The products are produced and mechanically evaluated for quality control. In order to better understand the mechanical behavior and response of the LVL, it is important to evaluate the actual effects of the variation of these parameters as opposed to simply determining design values. Understanding such effects would aid in product refinement. Given the many parameters that exist for LVL manufacturing, this research targeted only the effects of manufacturing temperatures. Published data, involving short-term exposures of extreme temperatures, is very limited for wood material so subsequent testing on solid sawn lumber (Chapter Five) was performed to provide insight involving such effects. In order to study these effects, full-sized laminated veneer lumber was statically tested.

BACKGROUND

TEMPERATURE

The strength of wood depends on its physical and chemical constitution. Chemically, wood is made up of three basic components: cellulose, hemicellulose, and lignin (Panshin and de Zeeuw, 1980). Heating causes these components to undergo changes such as shrinkage, expansion, dehydration, thermal degradation, and phase change. Schaffer (1973) summarized these changes in wood caused by thermal effects in Table 6-1.

Table 6-1: *Thermally Induced Changes in Dry Wood in an Inert Atmosphere (adapted from Schaffer 1973)*

Temperature °C	°F	Thermal Induced Change
55	131	Natural lignin structure is altered. Hemicelluloses begin to soften.
70	158	Transverse shrinkage of wood begins.
110	230	Lignin slowly begins weight loss.
120	248	Hemicellulose content begins to decrease, a-cellulose begins to increase. Lignins begin to soften.
140	284	Bound water is free.
160	320	Lignin is melted and begins to reharden.
180	356	Hemicelluloses begin rapid weight loss after losing 4 percent. Lignin in torous flows.
200	392	Wood begins to lose weight rapidly. Phenolic resin begins to form. Cellulose dehydrates above this temperature.
210	410	Lignin hardens, resembles coke. Cellulose softens and depolymerizes. Endothermic reaction changes to exothermic.
225	437	Cellulose crystalinity decreases and recovers.
280	536	Lignin has reached 10 percent weight loss. Cellulose begins to lose weight.
288	550	Assumed wood charring temperature.
300	572	Hardboard softens irrecoverably.
320	608	Hemicelluloses have completed degradation.
370	698	Cellulose has lost 83 percent of initial weight.
400	752	Wood is completely carbonized.

Shape and size of the member and type of loading need to be considered simultaneously. This is because for short time exposures, the inner material of a large specimen would not be heated to the temperature of the surrounding medium (Wood Handbook, 1999). Therefore, it is possible that the immediate effect on the strength of the inner material is less than the surface material. However, the type of loading is important in determining if size may be of consequence. In the case of bending, the greatest stress is experienced by the outer fibers. This usually governs ultimate strength. Therefore, the fact the inner material may have experienced a lower temperature than the surface material due to short-term exposure is of little concern as far as temperature effect on member performance, but is still an issue with LVL production.

TEMPERATURE EFFECTS ON MECHANICAL PROPERTIES

There are two kinds of temperature effects; reversible and irreversible. For a temperature effect to be reversible, the temperature must be below 100^{o}C (212^{o}F) and temperature change must be immediate and quick. The Wood Handbook (1999) terms an immediate effect as "the change in properties that occurs when wood is quickly heated or cooled and then tested at that condition." Immediate effects have been shown to reduce both the modulus of elasticity and modulus of rupture of solid sawn lumber with a linear relation to temperature (Gerhards, 1982; Wood Handbook, 1999). However, these effects tend to be reversible if the material is allowed to return to room temperature conditions and then tested.

Immediate temperature effects on solid sawn lumber have been well studied. Most of these studies center on the premise of manipulating environmental parameters for both conditioning of the specimens and for the duration of the tests being performed. According to a comprehensive study by Gerhards' (1982) on immediate effects on solid sawn lumber, available data for bending strength was restricted to 125^{o}C (257^{o}F) for zero percent moisture content and 75^{o}C (167^{o}F) for equal or greater than eleven percent moisture content. All of the relationships support decreasing linear trends for both moisture content conditions. Gerhards concluded that bending strength, compressive strength parallel-to-the-grain (Schaffer, 1973), and tensile strength perpendicular-to-the-grain appear to experience the same immediate temperature effect. He also concluded that the temperature effects were greater at higher moisture contents.

Specific data on immediate temperature effects of LVL is not readily available. Most of the research of LVL has involved lay-up practices, veneer quality, species type, relative humidity, and nondestructive evaluation. ASTM D5456 (1993), a standard for evaluating structural composite lumber products, states that materials predicted to be exposed for sustained periods to temperatures not within the range of -34^{o}C to 65^{o}F (-30^{o}F to 150^{o}F) should be evaluated for the effect of temperature. As of now, quality control for temperature is assured by the manufactures of the engineered wood product.

Irreversible effects occur when wood is heated for a prolonged period of time. This long-term heating causes degradation of the wood and thus permanent damage. The result is a loss in weight and strength and a level of degradation of the wood substance. The degree of degradation and strength loss depends on factors including, but not limited to, heating medium, temperature, duration of exposure, and, species, size, and moisture content of the member involved. To test for permanent effects, the specimens must be conditioned back to room temperature conditions otherwise results are influenced by immediate effects. However, as Green and Evans (1994) noted, there is a lack of guidance to render a precise time at which to expect permanent strength loss. This is to say the time frames of “quick” and “prolonged” are not clearly defined.

There have been several studies on the effect of environmental conditions on mechanical properties of solid sawn lumber. However, there exists little published research concerning this topic for laminated veneer lumber. The temperature ranges of the few published studies that do exist do not reflect manufacturing temperatures. The focus of these studies were high end environmental temperatures and char rates (near 300^{o}C (572^{o}F)).

In a study by Winandy (1991), the bending properties of plywood (veneer composed panels) treated with fire retardant chemicals were examined at elevated temperatures. The research provided a control group of 1.22 m by 2.44 m (4 ft by 8 ft) untreated Southern Pine N-grade plywood panel. The highest temperature of exposure was only 77^{o}C (170^{o}F). Permanent effects were of interest at varied times of exposure, the smallest of which was seven days. After the time of exposure had elapsed, the specimens were reconditioned before testing at 23^{o}C (74^{o}F) with a relative humidity (RH) of 65 percent (twelve percent moisture content). Since no baseline of zero exposure time with the same relative humidity was established for individual groups based on static bending tests, the shortest time that could be used for relative comparison was the seven day exposure. Actual data recorded for the exposure range of seven to fourteen days shows an increase in both modulus of elasticity and modulus of rupture values for different relative humidities of the temperature category 77^{o}C (170^{o}F). For an RH of 50 percent, a 6.7 percent increase for modulus of elasticity and a 4.9 percent increase for modulus of rupture was observed. For an RH of 79 percent, 4.6 percent and 4.9 percent increases, of the respective moduli, were observed.

Green and Evans (1994) published the two-year results from a four-year study on the effects of ambient temperatures on flexural properties of lumber (nominal 2 in. by 4 in.). They tested MSR graded Spruce-Pine-Fir (SPF) and LVL 2.0E of the species Douglas-fir, Southern Pine, and Yellow-poplar. The conditioning temperature was 66^{o}C (150^{o}F) and the shortest time of exposure tested was six months. Since Green and Evans (1994) were interested in permanent effects, before static bending tests were performed, all specimens were removed from the elevated temperature environment and reconditioned to 20^{o}C (68^{o}F). The results reported for all LVL species revealed that both the mean modulus of elasticity and mean modulus of rupture decreased overall for the two year period, and likewise decreased from zero to six months. However, both MOE and MOR, of all LVL species, showed an unexplained increase from six months to a year. For Douglas-fir LVL it was 6.2 percent and 3.0 percent, respectively. Green and Evans (1994) concluded that for modulus of elasticity, the rate of degradation was independent of the first two year exposure for both solid sawn lumber and LVL. For modulus of rupture, the amount of thermal degradation (over the two year period) for solid sawn lumber and

LVL was concluded to be similar. Green and Evans (1994) suggested that a single mechanism might be responsible for the degradation of both solid sawn lumber and laminated veneer lumber.

A previous study by LeVan et al. (1990) had given insight to the mechanism that controls the degradation of wood. Through analysis of the chemical composition of the thermally exposed wood, they found that degradation of hemicelluloses was the major contributor to reduction of strength. If the implications from Green and Evans (1994) are true, then the solid sawn lumber and LVL should exhibit similar behavior under the same thermal conditions.

Since veneer is heated to high temperatures during the LVL production process, the effects of temperature increases would logically have a direct effect on the mechanical properties of the veneer, and ultimately, the LVL. In an unpublished study by Verwest (2000), Douglas-fir and Hemlock veneer coupons, 25.4 mm by 254 mm (1 in. by 10 in.), were subjected to elevated temperatures of 145^{o}C (293^{o}F) and 200^{o}C (392^{o}F). Room temperature, 25.4^{o}C (77.7^{o}F), was used as a control. The coupons were heated for thirty minutes (air circulation) in a Fisher Scientific oven and then allowed to return to equilibrium conditions. They were then tested for tensile fracture strength. The results of both species supported earlier findings on temperature effects, that is the load and extension decreased as temperature increased. Table 6-2 summarizes the results. Both species exhibited a very linear relationship between tensile fracture strength and temperature.

Table 6-2: *Average Fracture Strength and Extension of Heat Treated Veneer Coupons*

	Douglas-fir			Hemlock		
Temperature [^{o}C (^{o}F)]	25.4 (77.7)	145 (293)	200 (392)	25.4 (77.7)	145 (293)	200 (392)
Average Fracture Strength [N (lbf)]	4567.9 (1026.9)	3313.5 (744.9)	2240.6 (503.7)	2750.8 (618.4)	1842.0 (414.1)	1380.7 (310.4)
Extension [mm (in.)]	2.49 (0.098)	1.98 (0.078)	1.32 (0.052)	1.60 (0.063)	1.09 (0.043)	0.914 (0.036)

White (2000) researched the rate of charring of laminated veneer lumber of several species. A standard fire endurance test was conducted at a temperature of 300°C (572°F). He related it to earlier studies of charring of solid sawn lumber by Schaffer (1967) and White (1988). Specimens were constructed with either five LVL members at 50 mm (1.97 in.) thick or six LVL members at 44 mm (1.73 in.) thick. Thus, specimens were either 250 mm or 264 mm (9.8 in. or 10.4 in.) high and 510 mm (20 in.) wide by 89 mm (3.5 in.) deep. White (2000) concluded that the charring of LVL may be considered comparable with solid sawn lumber. This research furthers the implication that the thermal effects experienced by solid sawn lumber are similar to those experienced by laminated veneer lumber.

The nonexistence of research reflecting the conditions of the manufacturing process, extremely short exposure times of extremely high exposure temperatures, warrants the investigation of such conditions. Also, full size members subjected to extreme temperatures needs to be studied. Thus, research was conducted to determine the effects of the LVL manufacturing process temperature on mechanical properties of full size laminated veneer lumber material.

MATERIALS

Boise Cascade of Boise, Idaho provided all veneer used for this research. All provided veneer was Douglas-fir (*Pseudotsuga menziesii*). The veneer was rotary peeled and was cut into six hundred and sixty 1.25 m by 2.55 m (generous 4 ft x 8 ft) sheets. The average thickness of the veneer was 3.68 mm (0.145 in.). After arrival to Washington State University's Wood Materials and Engineering Laboratory, the veneer had to be cut in half lengthwise to 610 mm (2 ft) for processing purposes. The veneer was sorted using nondestructive longitudinal stress wave time techniques and hot pressed at three predetermined temperatures to produce fifteen eleven-ply billets for each temperature. Each billet was cut into six 2.44 m (8 ft) long, 38 mm by 89 mm (nominal 2 in. by 4 in.) laminated veneer lumber members.

METHODS

The objective was two fold: To determine the effect of LVL manufacturing temperature on the mechanical properties and duration of load behavior of Douglas-fir LVL. Only the effects on the mechanical properties are addressed in this chapter. The effects on DOL behavior are discussed in Chapter Seven. The temperature effects of the processing procedure would, by definition, not be reversible. This is because although the exposure time is "short," the exposure temperature is above 100^{o}C (212^{o}F). Also, these effects would not technically be immediate because, although "quick," extreme temperature exposure was not the condition at the time of testing. Specimens were reconditioned back to room temperature conditions. Therefore, the conditions of the manufacturing process are more of a measure of permanent effects. Since the main goal centered on manufacturing temperatures, the veneer material had to be sorted into various temperature categories. Upon investigation, a common range of LVL manufacturing temperatures was found to be 145^{o}C to 160^{o}C (293^{o}F to 320^{o}F). The goal was to target temperatures near, greater, and much greater than common industrial practice. The chosen temperatures were 149^{o}C (300^{o}F), 171^{o}C (340^{o}F), and 193^{o}C (380^{o}F).

First, the veneer had to be sorted. Nondestructive sorting was done by impact longitudinal stress wave propagation. After this was done, veneers were pressed with a liquid resin into billets. The press schedule had to be established according to several factors and by using practice billets (Chapter Three). The processing variables for the laminated veneer lumber were as follows:

1. Resin: liquid phenol-formaldehyde;

2. Spread Level: single glueline of 180.65 kg / 1000 m^2 (37 lb / 1000 ft^2) via a roller spreader;
3. Press: hot platen hydraulic;
4. Press Temperatures: 149°C (300°F), 171°C (340°F), and 193°C (380°F);
5. Press Schedule: thickness controlled to 38 mm (1.5 in.) utilizes eleven piles;
6. Press Time: twenty minutes; and
7. Pressure Cycle: after twenty-nine seconds, the end condition pressure was 6897 kPa (1000 psi) and then reduced to 1382 kPa (200 psi) after forty-four seconds and held constant until the end of the cycle at twenty minutes.

After the laminated veneer lumber was manufactured, the material was allowed to return to equilibrium conditions (moisture content (MC) = 10%) before further testing was done. The modulus of elasticity was evaluated using longitudinal stress wave propagation ($E_{dynamic}$) and also, static edgewise bending (E_{static}). The static bending tests were also used to determine the modulus of rupture. The effectiveness of the predictive capability of the dynamic modulus of elasticity and of the MOE determined form the laminated beam theory values was evaluated (Chapter Four). It had been concluded that $E_{dynamic}$ provided the best predictive values to E_{static}. This also ensured that all material sorting was done using values obtained from the same technique, $E_{dynamic}$. The effect of the LVL manufacturing process temperature on the mechanical properties of laminated veneer lumber was analyzed.

SPECIMEN SORT

VENEER

All veneers used in the production of laminated veneer lumber were tested nondestructively to obtain an $E_{dynamic}$ (from Equation 2-1) for each veneer sheet. The members were weighed and measured (average of three lengths, average of three widths, and average of four thicknesses). Each member was clamped down perpendicular to the width (flatwise). Impact longitudinal stress waves were introduced to the third point locations along the width. The average of the three stress wave times at those locations was determined as the stress wave time for the entire veneer sheet. The veneers were divided into groups of eleven based on ascending $E_{dynamic}$ values. The group with the lowest $E_{dynamic}$ was assigned to the temperature category of 149°C (300°F), the next ascending group of eleven was assigned to the next temperature and so on until all temperature categories had fifteen sets of eleven veneers. This sorting is not the common practice by the LVL industry, but the aim here was to mimic the distribution of the solid sawn lumber. The unconventional sorting technique proved valid after ANOVA results suggested there was no significant statistical difference between the $E_{dynamic}$ values of all the temperature categories (Appendix E). The validity of this technique is graphically represented in Figure 6-1.

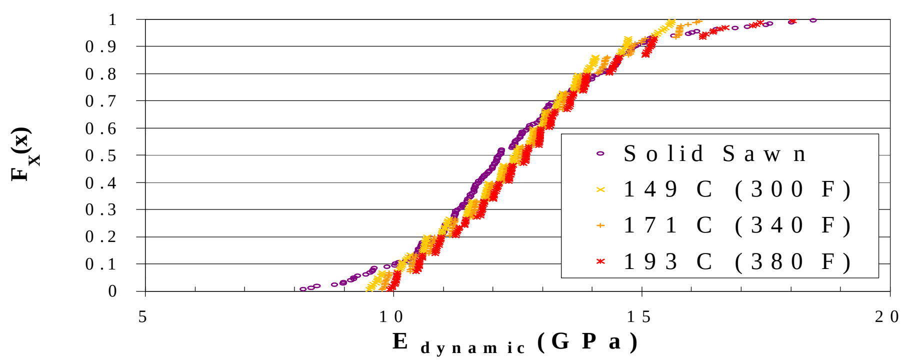


Figure 6-1: *Cumulative Distribution of $E_{dynamic}$ of Sorted Veneers and Solid Sawn Lumber*

LAMINATED VENEER LUMBER

After the billets were made, they were cut to dimension (nominal 2 in. by 4 in., 8 ft long) into six LVL specimens per billet. The specimens were labeled according to manufacturing temperature, billet number (1 through 15 where ascending number corresponds with ascending veneer $E_{dynamic}$ values), and letter *a* through *f* for location of specimen within the billet (*a* and *f* consisting of the edge-most billet material). All 269 LVL specimens were tested nondestructively. However, because of the nature of the induced longitudinal stress wave, and the long travel distance, it was not possible to detect localized LVL manufacturing-induced failures such as delaminations. Because of this, each LVL was visually inspected as well and labeled as good, minor delaminations, or major delaminations. The location and extense of the delaminations was also recorded.

The sorting of the veneer assured similar property dispersion among all temperatures. However, because of manufacturing blow failures for all temperatures, this assurance was compromised. Discussion of the effect of manufacturing temperature on specimen sorting is provided later in this Chapter. Despite manufacturing failures, it was still necessary to sort the category temperatures into two equally distributed testing groups. One group was to be tested statically and the other group was to be tested under load-duration. In order to ensure the same distribution for each group, a pseudo random sort (Chapter Two) was used to divide the members into the testing groups. Each temperature category was ordered according to ascending $E_{dynamic}$. The first two $E_{dynamic}$ values (three value increments of random sorting for 171^{o}C (340^{o}F)), from the ascending data, were randomly distributed and then the next two values and so on until the entire temperature category was split into two even groups (three even groups for 171^{o}C (340^{o}F)). An analysis of variance (ANOVA) was performed on the $E_{dynamic}$ values between the groups (Appendix E). The analysis showed no statistical difference between the MOE-MOR and DOL groups. This final sorting provided the sample sizes that were used in the tests [MOE-MOR/DOL]: 149°C (300°F) [24/24], 171°C (340°F) [24/48], and 193°C (380°F) [19/19]. Since the production process had led to a high yield of LVL samples from the 171°C (340°F) category, the sample size of the duration of load test was doubled and split into two subcategories of the temperature (1 and 2). The addition of an entire DOL set of the same temperature would aid in determining the validity of the trends of load-duration behavior of the different temperatures.

STATIC BENDING TESTS

Static edgewise bending tests were performed to find an actual modulus of elasticity and modulus of rupture values for all specimen categories. The static modulus of elasticity, E_{static}, was used to monitor temperature effects on stiffness and to compare to the nondestructive method, E_{dyamic}, which had been used for sorting. Twenty-four members of each temperature category, except the 193°C (380°F) which had nineteen members, were tested for mechanical properties.

An Instron 4400R screw-driven test machine was used to perform all static bending tests on the simply supported beams. The procedures from ASTM D198 (1998), the standard test for determining structural lumber properties, were followed and the load-displacement data, time to failure, and maximum load were recorded by a computer data acquisition system (Labview, 1997). A load rate of 3.3 mm/min (0.13 in./min) was determined to meet the provisions of the standard. All of the specimens were tested to failure. The displacement was measured at center span using a linear variable differential transformer (LVDT) (Appendix A). Using a spreader beam, the single point ramp load applied from the testing machine was evenly distributed into two point loads. The dimensions of the spreader beam were such that the two point loads were applied at third points, 610 mm (24 in.), in relation to the end reactions. Finally, lateral bracing was applied in accordance with the ASTM standard to eliminate the concern of lateral-torsional buckling effects. The actual static bending setup can be seen in Chapter Two. The equation used for static bending modulus of elasticity was Equation 2-2.

Static bending tests were performed in a temperature controlled room where the temperature range fluctuated between 21^{o}C (70^{o}F) and 23^{o}C (73^{o}F). The relative humidity was determined to be in the proximity range of thirty percent to forty percent.

RESULTS

TEMPERATURE EFFECTS ON THE MANUFACTURING PROCESS

Sorting of the veneers ensured that the make-up of the LVL would be statistically similar. However, billets manufactured at all temperatures experienced various types of "blow failures" that resulted in the loss of material. The ratio of good and useable LVL to total LVL produced was calculated. "Good" LVL was defined as data with no blow failure and "useable" LVL included good LVL and minor failures determined not to affect the performance of the LVL. Results from Table 6-3 suggest that a temperature of 171^{o}C (340^{o}F) provided the best yield.

Table 6-3: *Manufacturing LVL Yield*

Total Expected*	Billets Made	LVL / Billet	Total LVL
	15	6	**90**
Temperature	149^{o}C (300^{o}F)	171^{o}C (340^{o}F)	193^{o}C (380^{o}F)
Total "good" LVL Additional "useable" LVL**	49 8	71 2	30 10
Optimistic "useable" Total	57	73	40
Percent of "good" LVL	54.44%	78.89%	33.33%
Percent of "useable" LVL	63.33%	81.11%	44.44%

*pertains to all temperatures
**only minor delaminations

For manufacturing at 149°C (300°F), the blow failure was purely delamination, where the adhesive and the wood did not properly bond. The blow failure for 171°C (340°F) was a combination of failures: clear delamination along the bond line and wood failure. The manufacturing temperature of 193°C (380°F) experienced the most blows. All of the blows at this temperature were pure wood failure that transcended bondlines.

Further investigation shows that blow failure types were not the only entities unique to manufacturing temperature. It was quite apparent that veneer quality was a factor for temperature dependant manufacturing failures. Figure 6-2 demonstrates this finding through the use of cumulative percent of frequency. Frequency, in this case, refers to the number of members used from a given billet for both static and duration of load testing.

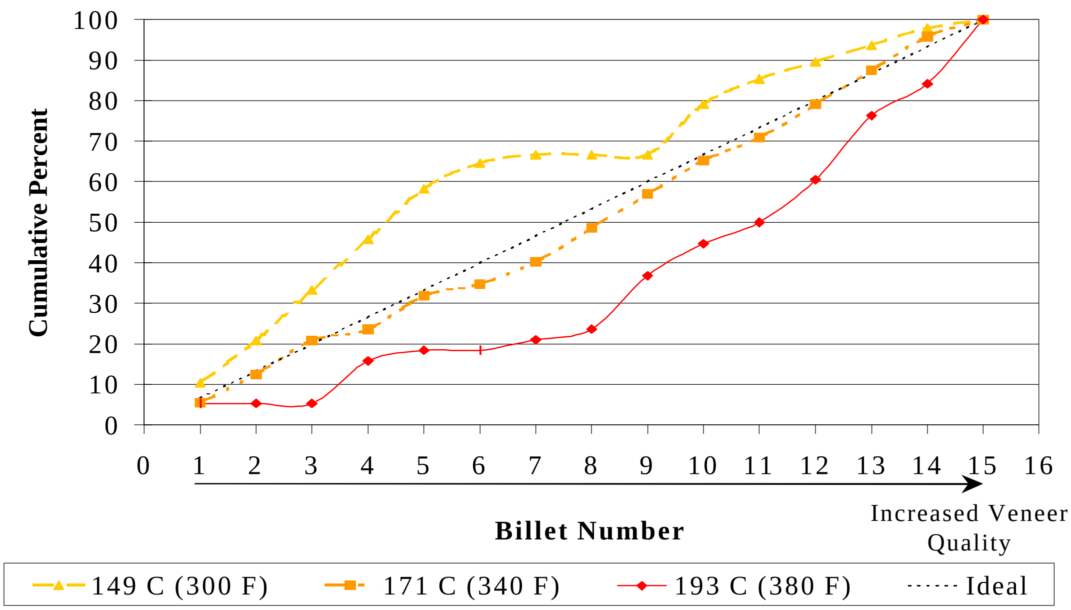


Figure 6-2: *Cumulative Percent of Frequency of Billet Number Used for Testing*

Through examination of the cumulative percentage curves for each temperature (Figure 6-2), it is clear that although the laminated veneer lumber had been manufactured to possess similar distributions, the manufacturing failures clearly compromised this deliberation. Ideally, the curves should be straight lines. Such a line would represent equal member selection from all billets. The 171^{o}C (340^{o}F) temperature category was very close to an ideal representation of the billets. This was a direct result of a large yield from all the billets. The shape of the 149^{o}C (300^{o}F) curve indicates that most of the members used for testing came from the lower billet numbers while none of the middle billet numbers were represented. An even more sever case was seen for the 193^{o}C (380^{o}F) temperature category, that is, a large portion of the material came from higher billet numbers and thus, better quality veneers.

Unfortunately, this was a situation that could not be controlled. Despite the adverse effects on similar property distribution for all temperatures, the trend of the failures did provide some insight. For a 149^{o}C (300^{o}F) manufacturing temperature, blows were more prevalent in the billets made of higher quality veneers. Because these blow failures were pure delamination, the adhesive was not able to bond properly to the higher grade veneers, that is those with less voids, checks, and general imperfections. Since a poor bond was present, usually in the middle layers, the steam pressure was able to blow the billet apart along the poor bondline. For the highest temperature of 193^{o}C (380^{o}F), the billet failures were very concentrated for those made up of lower veneer quality. The billet failure type was pure wood failure. Billets made of lower quality veneer did not posses the strength to withstand the greater amount of steam pressure associated with higher temperatures and thus the wood was blown apart. All temperatures had relatively low yields from billets six and seven. This suggests that this is the turning point from low quality to high quality where delaminations and wood failures are both actively occurring.

For the laminated veneer members, a greater amount of densification as temperature was increased was a concern, especially after knowing that the veneer make-up of the members to be tested from the temperature categories was varied. Examination of all manufactured members showed that densification of the material was not very temperature dependant (Table 6-4). An

ANOVA was performed and indicated significant statistical difference between only the densities of the 171°C (340°F) and 193°C (380°F) temperature categories (Appendix E). However, examination of only the members to be tested showed that density was more of an issue (Table 6-4). This was supported by ANOVA results that showed opposite findings from the tests run with all manufactured members. Figure 6-3 shows the pattern of densities as billet numbers increase. It also shows where the concentrations of selected members for testing for the low and high temperatures are located.

Table 6-4: *Densities of Laminated Veneer Lumber*

ρ (kg/m^3)	TESTED MEMBERS				ALL MEMBERS			
Temperature	n	Minimum	Average	Maximum	n	Minimum	Average	Maximum
149°C (300°F)	89	473.69	540.66	604.00	48	473.69	524.12	590.46
171°C (340°F)	90	494.30	549.78	629.04	48	494.30	551.31	629.04
193°C (380°F)	90	483.92	537.98	606.39	38	494.74	557.49	606.39

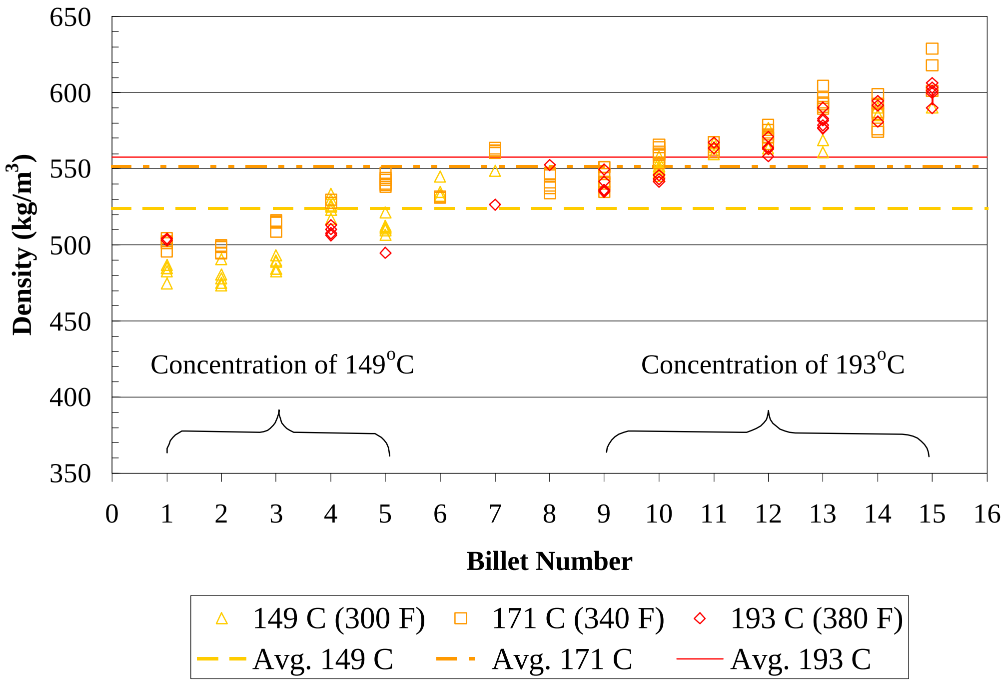
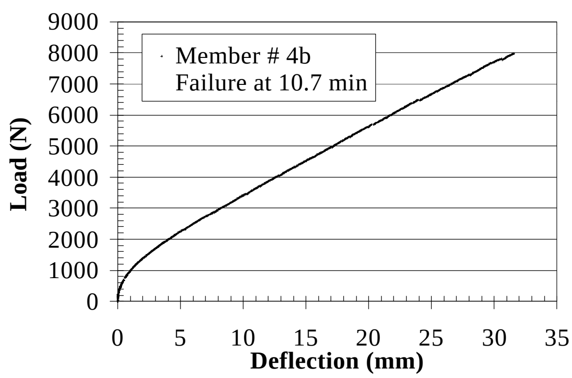


Figure 6-3: *Density Chart for Laminated Veneer Lumber*

LOAD-DISPLACEMENT CURVES

The data acquisition system (Labview, 1997) continuously recorded both loads and deflections for each statically tested laminated veneer lumber. This data was used to plot a load-displacement curve for each specimen (Appendix F). The shapes of the load-displacement curves were typical within each temperature category but slightly different between categories. As is seen in Figure 6-4A, for the 149°C (300°F) temperature category, low level loads were distinctly not linearly related to deflections. The rise in manufacturing temperature to 171°C (340°F) shows the load-displacement curve had become practically linear in the low load region (Figure 6-4B). Finally, the curve was fully linear for members of the 193°C (380°F) temperature category (Figure 6-4C).



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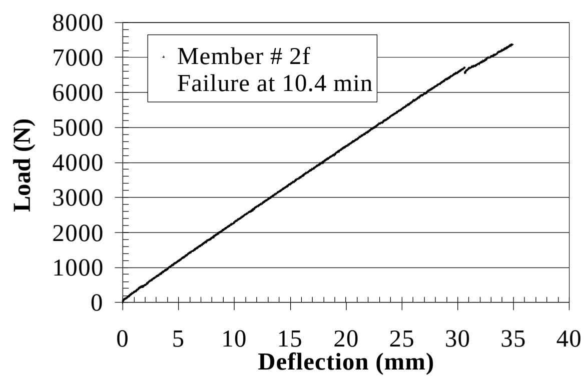

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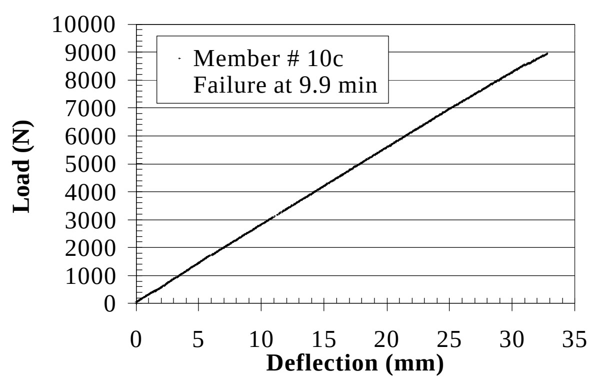

C

Figure 6-4: *Typical Load-Displacement Curves for Laminated Veneer Lumber: (A) 149°C (300°F); (B) 171°C (340°F); (C) 193°C (380°F)*

Deflection at peak load was determined for each temperature. Deflection summary data is provided in Table 6-5. There was no trend in the deflection data. However, the ANOVA results (Appendix E) showed a statistically significant difference between the maximum static deflections of 149°C (300°F) and 171°C (340°F) temperature groups. Also provided in Table 6-5, are the average peak loads for all temperature categories. It was observed that as the temperature increased, the peak load increased. The difference from 149°C (300°F) to 193°C (380°F) is 1.38 kN (310 lbf). However, because of the sorting issues, the validity of the increase is cautioned.

Table 6-5: *Average Static Deflections and Peak Loads for Laminated Veneer Lumber*

	Sample Size	Deflection At Peak Load	Peak Load
Temperature	n	Δ (mm)	(kN)
149°C (300°F)	24	35.60	8.839
171°C (340°F)	24	39.87	10.199
193°C (380°F)	19	37.24	10.218

MECHANICAL PROPERTIES

From the load-displacement curves, it was evident that temperature history was having an effect on the response of the laminated veneer lumber and, ultimately, lumber's mechanical properties.

After the laminated veneer lumber had been manufactured and reconditioned to equilibrium conditions, the members were tested using impact longitudinal stress waves to obtain a dynamic modulus of elasticity ($E_{dynamic}$). The laminated beam theory was also explored as an option to predict mechanical modulus of elasticity but it was found that overall, $E_{dynamic}$ best represented the E_{static} values (Chapter Four). The average values are found in Table 6-6 and graphically shown in Figure 6-5. A comparison of all LVL produced revealed a slight increase in $E_{dynamic}$ value as temperature increased. ANOVA results (Appendix E) showed a significant statistical difference between the low and high temperature categories. As expected, due to the influence of failures during manufacture, the $E_{dynamic}$ value increase was greater for the members actually used for static and duration of load testing. For these members, the ANOVA results showed significant statistical difference between all temperature categories.

Table 6-6: *Mean Values and Coefficient of Variation for Moduli of Laminated Veneer Lumber*

	ALL MEMBERS		TESTED MEMBERS					
	$E_{dynamic}$ (GPa)		$E_{dynamic}$* (GPa)		E_{static} (GPa)		MOR (MPa)	
Temperature	Mean	COV (n)	Mean	COV (n)	Mean	COV (n)	Mean	COV (n)
149°C (300°F)	13.85	11.37 (89)	13.09	11.44 (48)	16.60	14.20 (24)	53.67	20.15 (24)
171°C (340°F)	14.27	12.43 (90)	14.32	12.08 (72)	14.30	17.23 (24)	61.21	19.63 (24)
193°C (380°F)	14.53	11.70 (90)	15.48	10.91 (38)	14.52	11.83 (19)	61.74	20.02 (19)

*$E_{dynamic}$ values include specimens tested both statically and long-term

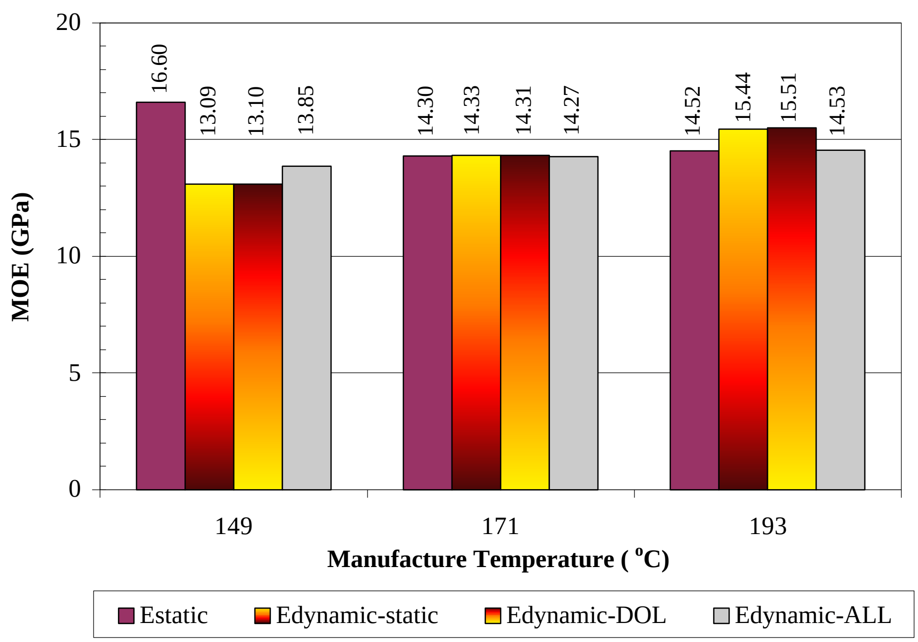

Figure 6-5: *Comparison of Means of MOE for Laminated Veneer Lumber*

Using the load and deflection data of the low load linear region, E_{static} was computed. ASTM D2915 (1994), a standard for evaluating structural lumber allowable properties, was followed. Design values were calculated for all temperature categories of Douglas-fir LVL and consequentially were the same as E_{static} (Table 6-6). All equations used to determine the apparent modulus of elasticity (not shear corrected) are found in Appendix B. The design values found were all higher than those usually associated with LVL products, that is a range of 12.41 GPa to 13.79 GPa (1800000 psi to 2000000 psi). However, because of the nonlinear region for the low loads for the 149^{o}C (300^{o}F) temperature category, the calculated E_{static} is unrealistically high. The value is also very different from the respective $E_{dynamic}$ value.

The same observation, an increase in temperature yields an increase in moduli ($E_{dynamic}$), was made for modulus of rupture (MOR) data (Table 6-6). The difference in range values was 8.08 MPa (1172 psi). ANOVA results showed significant statistical difference between modulus of rupture values involving the temperature category 149^{o}C (300^{o}F).

The modulus of rupture was needed for the duration of load analysis. Because of this, probability methods were used to determine the statistical distribution that best represented the actual MOR values. Once a lognormal distribution was determined as the best fitting distribution, the theoretical design values, F_b, were found in accordance with ASTM D2915 (1994) (Table 6-7). Since a distribution was known, both parametric and nonparametric approaches could be used (sample calculations found in Appendix B). This was done to compare temperature categories in the same manor that is done in practice. The calculated parametric design values compared well with the design value range that is commonly associated with LVL; 17.92 MPa to 20.68 MPa (2600 psi to 3000 psi).

Table 6-7: *Design Stress for Laminated Veneer Lumber*

Temperature °C (°F)	F_b (MPa)	
	Nonparametric	Parametric
149 (300)	18.03	17.25
171 (340)	16.92	19.35
193 (380)	19.32	19.15

To further investigate these possible trends, the static deflections at peak load were compared with their respective strength. Correlation coefficients were found for this relationship for each temperature. Overall, the correlation was good (Figure 6-6). The slopes off the trendlines were similar and they had a similar elevation location. This suggests that the correlation trend between the deflection and strength is similar for all temperatures.

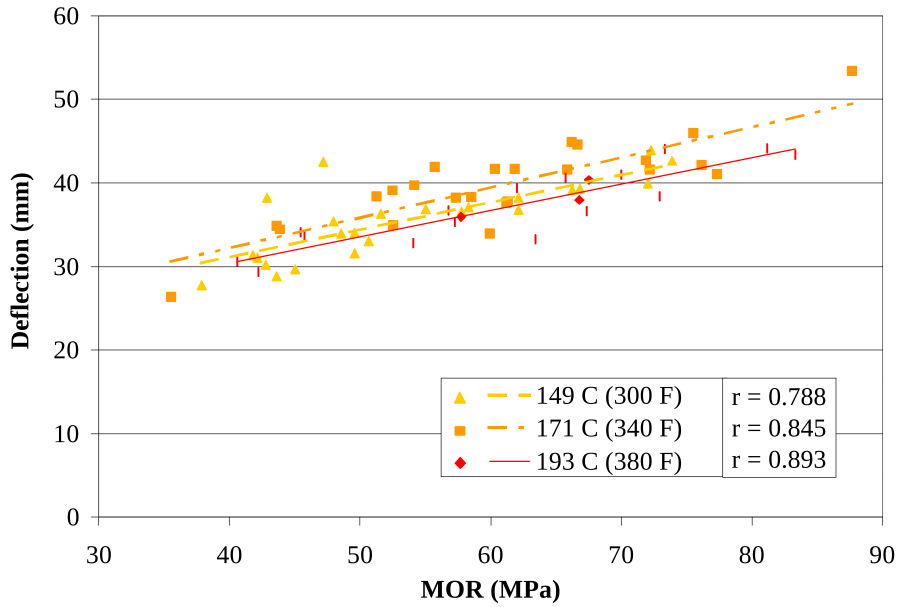

Figure 6-6: *Correlation of Static Deflection and Modulus of Rupture for Laminated Veneer Lumber*

Using the 149°C (300°F) temperature category value as the base value for all properties, the relative values per property per temperature were calculated based on the average values (except for the allowable stress, F_b). These relative values are found in Table 6-8. The low temperature was chosen as the reference value because the temperature is similar to what is currently used in industry. The relative relationships between temperatures for all properties, $E_{dynamic}$ (tested members and all members), maximum static deflection, maximum load, modulus of rupture, and, allowable strength show that the temperature categories of 171°C (340°F) and 193°C (380°F) were very similar relative to the base temperature. Because of the unrealistic high E_{static} value for 149°C (300°F), relative values were not found for the property E_{static}.

Table 6-8: *Relative Laminated Veneer Lumber Properties Based on 149°C (300°F) Temperature (%)*

	TESTED MEMBERS					ALL MEMBERS
Temperature	$E_{dynamic}$*	Deflection	Load	MOR	F_b (parametric)	$E_{dynamic}$
149°C (300°F)	100.0	100.0	100.0	100.0	100.0	100.0
171°C (340°F)	109.4	112.0	115.4	114.1	112.2	103.0
193°C (380°F)	118.2	104.6	115.6	115.1	111.0	104.9

*$E_{dynamic}$ values include specimens tested both statically and long-term

It should be noted that the percent increase from the base temperature to the higher temperatures was, in most cases, significant. However, the skew on sorting similarity is quite apparent when the two $E_{dynamic}$ values are compared (Table 6-8). Although increasing, the $E_{dynamic}$ average values found from all the members that were stress wave time tested had much smaller percent increases when compared to the $E_{dynamic}$ average values found from the “useable” members which made up the specimens for static and duration of load testing. Because of this, specific conclusions regarding the type of relationship between the manufacturing temperature and the mechanical properties can not be drawn with confidence.

Despite these shortcomings, the fact remains that overall, mechanical properties appear to improve as manufacturing temperature increases, if only slightly. The obvious cause of increased mechanical properties would be that short-term heating to higher temperatures causes a loss in moisture content. However, this possibility of moisture loss was minimized because the testing of all specimens was done at equilibrium room temperature conditions with all specimens having been reconditioned to ten percent moisture content. Published literature supports a linear decrease in mechanical properties for immediate temperature effects. However, because the temperatures used were above 100^{o}C (212^{o}F), the conditions of reversible effects, and thus immediate effects, are violated. The data might be better compared with permanent effects.

CONCLUSIONS

The experimental results of this research gave insight to the mechanical behavior of laminated veneer lumber (LVL) produced at different manufacturing temperatures.

It was observed that all manufacturing temperature categories experienced billet failures. However, the types of billet failures (delamination, wood failure, and a combination of the two) were concluded to be temperature dependent. The veneer quality was found to be a factor for temperature dependant manufacturing failures. It was concluded that lower quality veneers experienced less billet failures when manufactured at 149^{o}C (300^{o}F), while higher quality veneers experienced less billet failure when manufactured at the 193^{o}C (380^{o}F). As far as material yield, a manufacturing temperature of 171^{o}C (340^{o}F) was concluded to be superior.

Manufacturing temperature caused changes in the load-displacement relationship of the laminated veneer lumber. This was most apparent for the 149^{o}C (300^{o}F) temperature category. Ultimate load increased as temperature increased. Although some significant difference was found between temperature categories, no trend was observed for static deflection. However, because of the skew of material yield, interpretation of the results are cautioned.

The dynamic modulus of elasticity, found via longitudinal stress wave time, was determined to be statistically different for all tested temperature categories. However, only a difference was observed between the low and high temperature categories when all members were compared. Hence, it was concluded that the skew of material yield had an affect on the material used for *testing*.

The static modulus of elasticity and modulus of rupture were both found to be statistically different between temperature categories except between 171^{o}C (340^{o}F) and 193^{o}C (380^{o}F). For the *tested members*, it was concluded that the two high temperature categories were similar with regard to mechanical properties and both were different from the low temperature category. This conclusion also held true for parametric allowable strength design values.

The correlation between strength and static deflection was relatively high and increased as temperature increased. Through observation of the slopes of the best-fit lines, it was concluded, for the *tested members*, that the trend of correlation was similar for all temperature categories.

Since there exists a material skew, specific conclusions regarding the type of relationship between the manufacturing temperature and the mechanical properties can not be drawn with full confidence. However, because the material skew was indeed a product of manufacturing at different temperatures, general conclusions could be drawn. One such conclusion is that the optimal manufacturing temperature, which is not as sensitive to veneer quality, is higher than what is currently used in industry. Also, if indeed the trends (seen with tested members) of increased mechanical properties with increased manufacturing temperatures is valid, the sacrifice in material yield is not worth the slight mechanical property gain.

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CHAPTER SEVEN

EFFECT OF MANUFACTURING TEMPERATURE ON DURATION OF LOAD OF DOUGLAS-FIR LAMINATED VENEER LUMBER

ABSTRACT

Several factors of the laminated veneer lumber (LVL) manufacturing process influence the behavior of the final product. While the effects of veneer quality and placement on mechanical properties have been studied extensively, the effects of processing parameters on duration of load behavior have not been explored. Manufacturing temperature effects on load-duration behavior of Douglas-fir laminated veneer lumber were investigated. Temperature common to the LVL industry (149^{o}C (300^{o}F)), slightly higher than industry (171^{o}C (340^{o}F)), and much higher than industry (193^{o}C (380^{o}F)) were used. For load-duration behavior, no statistical significance was found between duration of load deflections (initial, failure, and survival). Also, the exponential damage rate model (EDRM) was successfully used to model the behavior. Temperature effects were apparent but moderate between the low temperature and the higher temperatures. Calculated design adjustment factors from this study, based on the individual EDRM curves, were different than those from the Madison curve and thus different from current load-duration design adjustment factors used for solid sawn lumber.

INTRODUCTION

Wood exhibits two separate yet related phenomena, which are creep and creep-rupture. Both phenomena define the time dependant behavior of wood. Over time, a sustained load causes an increase in deformation. This increase in deformation is known as creep. Creep rupture, the eventual failure of the wood material, occurs because of the failure of the specimen to sustain constant load over time due to increased deformation during that time (creep). Due to safety concerns, creep-rupture behavior is of more interest to code officials and building designers.

Among other things, material make-up is a factor that affects creep-rupture. As the timber resource changes, the materials available for consumption changes. These wood materials are being maximized by the production of wood composite materials. Laminated veneer lumber is one such wood composite product. In the case of wood composite material, more than just the wood material itself can affect the overall performance. This is a concern because during the manufacturing of wood composites, wood material is subjected to many processing parameters such as increased pressure, exposure to and bonding with adhesives, and rapid temperature and moisture changes. The effects of these processing parameters become a part of the wood composites' history and could potentially affect the wood composites' duration of load performance.

In the case of laminated veneer lumber, processing parameters are determined by LVL manufacturing companies based on the cure temperature of the adhesive and experience in laminated veneer manufacturing. The products are produced and mechanically evaluated for quality control. In order understand the load-duration behavior and response of the LVL, it is important to evaluate the actual effects of the variation of these parameters. Understanding such effects would aid in product refinement. Given the many parameters that exist for LVL manufacturing, this research targeted only the effects of manufacturing temperatures. Published material, involving short-term exposures of extreme temperatures, is very limited for wood material so subsequent testing on solid sawn lumber (Chapter Five) was performed to provide insight involving such effects. Mechanical testing of laminated veneer lumber, crucial for determining load-duration testing parameters, was presented in Chapter Six. In order to study manufacturing temperature effects, full-sized laminated veneer lumber was tested long-term.

BACKGROUND

TEMPERATURE

The strength of wood depends on its physical and chemical constitution. Chemically, wood is made up of three basic components: cellulose, hemicellulose, and lignin (Panshin and de Zeeuw, 1980). Heating causes these components to undergo changes such as shrinkage, expansion, dehydration, thermal degradation, and phase change. Schaffer (1973) summarized these changes in wood caused by thermal effects in Table 7-1.

Table 7-1: *Thermally Induced Changes in Dry Wood in an Inert Atmosphere (adapted from Schaffer 1973)*

Temperature ^{o}C	^{o}F	Thermal Induced Change
55	131	Natural lignin structure is altered. Hemicelluloses begin to soften.
70	158	Transverse shrinkage of wood begins.
110	230	Lignin slowly begins weight loss.
120	248	Hemicellulose content begins to decrease, a-cellulose begins to increase. Lignins begin to soften.
140	284	Bound water is free.
160	320	Lignin is melted and begins to reharden.
180	356	Hemicelluloses begin rapid weight loss after losing 4 percent. Lignin in torous flows.
200	392	Wood begins to lose weight rapidly. Phenolic resin begins to form. Cellulose dehydrates above this temperature.
210	410	Lignin hardens, resembles coke. Cellulose softens and depolymerizes. Endothermic reaction changes to exothermic.
225	437	Cellulose crystalinity decreases and recovers.
280	536	Lignin has reached 10 percent weight loss. Cellulose begins to lose weight.
288	550	Assumed wood charring temperature.
300	572	Hardboard softens irrecoverably.
320	608	Hemicelluloses have completed degradation.
370	698	Cellulose has lost 83 percent of initial weight.
400	752	Wood is completely carbonized.

Shape and size of the member and type of loading need to be considered simultaneously. This is because for short time exposures, the inner material of a large specimen would not be heated to the temperature of the surrounding medium (Wood Handbook, 1999). Therefore, it is possible that the immediate effect on the strength of the inner material is less than the surface material. However, the type of loading is important in determining if size may be of consequence. In the case of bending, the greatest stress is experienced by the outer fibers. This usually governs ultimate strength. Therefore, the fact the inner material may have experienced a lower temperature than the surface material due to short-term exposure is of little concern as far as temperature effect on member performance, but is still an issue with LVL production.

Duration of Load

Numerous predictive models have been developed in relation to creep rupture, or duration of load (DOL) behavior, of wood. Such models include damage accumulation, strain energy (Fridley et al., 1992b), and fracture mechanics (Nielsen and Kousholt, 1980). The damage accumulation (DA) approach is the most popular modeling technique (Rosowsky and Fridley, 1995) and the model used in this research. Hence, the emphasis of this review is placed on previous research involving or relating to damage accumulation.

The first model related to the relationship between applied stress level and time-to-failure was developed by Wood (1951). Wood used constant bending loads located at the center span. These loads ranged from sixty to ninety-five percent of the strength found through static bending. The testing of the Douglas-fir small clear specimens resulted in data that was fitted to an empirical hyperbolic model curve. The model assumed a stress threshold of 18.3 percent. It was assumed that failure of a specimen would not occur below this threshold. The general form of the model is given in Equation 7-1a. Equation 7-1b presents the model calibrated by Wood.

Wood's (1951) model (Equation 7-1b) is commonly referred to as the "Madison curve." It is this curve that is the basis for the load-duration adjustment factors outlined in the National Design Specifications (NDS) for Wood Construction (AF & PA, 1997).

$$t_f = \frac{1}{A\left(\sigma - \sigma_o\right)^B} \tag{7 - 1a}$$

$$\sigma = \frac{1.084}{t_f^{0.04635}} + 0.183 \tag{7 - 1b}$$

t_f = time to failure in seconds

A, B = model constants determined from experimental data

σ = ratio of applied stress to ultimate stress (static test strength)

σ_o = stress threshold

The Madison curve can also be written in the format of damage accumulation. The definitions of the parameters A, B, σ, and σ_o defined above also apply to Equation 7-1c.

$$\frac{d\alpha}{dt} = A\left(\sigma - \sigma_o\right)^B \tag{7 - 1c}$$

α = parameter of damage ranging from zero (no damage) to one (failure)

$d\alpha/dt$ = time rate of damage accumulation

Based on the Madison curve data of small clear Douglas-fir specimens under a constant bending load, Barrett and Foschi (1978a, 1978b) developed two damage accumulation models. Each model assumed a stress threshold. The main difference from the Madison curve was the addition of a third model constant, C. The difference between the two models was how the additional model constant was incorporated. All other parameters are previously defined. Barrett and Foschi (1978b) concluded that model II better represented the data.

Model I (Barrett and Foschi, 1978a)

$$\frac{d\alpha}{dt} = A\left(\sigma - \sigma_o\right)^B \cdot \alpha^C \qquad \text{if}\, \sigma > \sigma_o \tag{7 - 2a}$$

$$\frac{d\alpha}{dt} = 0 \qquad \text{if}\, \sigma \le \sigma_o \tag{7 - 2b}$$

Model II (Barrett and Foschi, 1978b)

$$\frac{d\alpha}{dt} = A\left(\sigma - \sigma_o\right)^B + C\alpha \qquad \text{if}\, \sigma > \sigma_o \tag{7 - 3a}$$

$$\frac{d\alpha}{dt} = 0 \qquad \text{if}\, \sigma \le \sigma_o \tag{7 - 3b}$$

Around the same time, Gerhards (1977, 1979) had also developed a damage accumulation model. The data used to derive the model came from tests on small clear specimens. Gerhards assumed that the lifetime of the member was an exponential function of the applied stress level. From this idea of exponential decay, Gerhards developed the Exponential Damage Rate Model (EDRM) given in Equation 7-4.

$$\frac{d\alpha}{dt} = \exp\left(-A + B\sigma\right) \tag{7 - 4}$$

Foschi and Yao (1986) developed a DA model similar to model II from Barrett and Foschi (1978b). However, instead of expressing damage accumulation in terms of a stress ratio, it was expressed as a function of actual applied stress. Also, an additional model constant, D, was added. An expression for their model is given in Equation 7-5. Foschi and Yao (1986) concluded that compared to the Barrett and Foschi (1978b) model II, the new model was a more accurate representation of the duration of load behavior of lumber.

$$\frac{d\alpha}{dt} = A\left(\tau - \tau_o\right)^B + C\alpha\left(\tau - \tau_o\right)^D \tag{7 - 5}$$

τ = applied stress

τ_o = stress threshold

All other model parameters were defined previously

Gerhards and Link (1987) used full-sized 38 mm by 89 mm (2 in. by 4 in.) Douglas-fir lumber specimens to calibrate the EDRM. They concluded that the model also applied to full-sized lumber. Gerhards (1988) did further testing with the full-sized specimens in order to determine the effect of lumber grade on the duration of load behavior of Douglas-fir lumber. In direct disagreement of previous DA models developed by Wood (1951), Barrett and Foschi (1978a, 1978b), and Foschi and Yao (1986), Gerhards (1988) concluded that no evidence existed that would support a stress level threshold. He also noted that for loading at the same fraction of static strength, lower grades of lumber had lower load-durations. In addition, however, he stated that these differences might not be statistically significant. The EDRM regression equations for the different grades tested are given in Equations 7-5a, 7-5b, and 7-5c.

$$LN(t_f) = 27.4382 - 24.7090SL \tag{7 - 6a}$$

$$LN(t_f) = 25.9539 - 24.0309SL \tag{7 - 6b}$$

$$LN(t_f) = 23.6222 - 21.7119SL \tag{7 - 6c}$$

t_f = time to failure in minutes

SL = ratio of applied stress to ultimate stress (static test strength)

Finally, Gerhards (1988) found that for design loads that really exist for the design duration, the current allowable bending properties for lumber were nonconservative. Using these load-duration equations and the methods used to determine NDS adjustment factors he proposed modifications to the factors. The resulting factors would consequentially lower design values for all design load-durations.

A study by Cai et al. (2000) compared the predictive capabilities of these four DA models (Wood, 1951; model II from Barrett and Foschi, 1978b; Gerhards, 1979; and Foschi and Yao, 1986). Small clear Southern Pine specimens were subjected to a five-day load sequence which varied stress levels daily. It was concluded that all of the DA models failed to consistently predict the time-to-failure. This was even more pronounced for lower stress levels and longer duration. Ultimately, it was concluded that, “the four DA models were about equal in their ability to simulate time-to-failure distribution” (Cai et al., 2000).

TEMPERATURE EFFECTS ON DURATION OF LOAD BEHAVIOR

There have been several studies on the effect of environmental conditions on creep-rupture of wood, both small clear and full-sized specimens. Similar to the conditions of mechanical testing, most of these studies center on the premise of manipulating environmental parameters for both conditioning of the specimens and for the duration of the tests being performed. Justifiably, environmental conditions simulated for testing have never been over 80^{o}C (176^{o}F). Although the testing temperatures were within the range for reversible effects, the long exposure time involved in creep-rupture testing would inevitably result in the temperature effects being classified as permanent.

Schniewind (1967) subjected small clear 10 mm by 20 mm by 220 mm (0.39 in. by 0.79 in. by 8.66 in.) Douglas-fir specimens to environmental conditions in order to determine the effects on creep-rupture. Both constant and cyclical temperature exposure environments were examined for the duration of the tests. It was concluded that the environmental effects on creep-rupture significantly reduced the life duration of the wood specimens. However, it was also noted that changes in size could alter the significance and change the results.

Building on this idea, Schniewind and Lyon (1973) tested larger specimens, although still clear, of 50.8 mm by 50.8 mm by 1.02 m (2 in. by 2 in. by 40 in.). The results showed that environmental effects were still present. However, it was concluded that as specimen size is increased, creep-rupture life during environmental changes would be similar to that of specimens in a constant environment.

In a study by Schaffer (1973), discussed earlier in this review, additional creep testing was performed for a two hour period. This study actually went beyond mere environmental temperatures and subjected specimens to temperature ranges of 25^{o}C to 275^{o}C (77^{o}F to 527^{o}F). The results showed that the compressive strength actually improved with duration of exposure, at a constant load, for the temperature range of 100^{o}C to 288^{o}C (212^{o}F to 550^{o}F). Consequentially, this is the temperature range starting after reversible temperature effects and ending before assumed wood charring temperature. The tensile strength showed no significant change in strength until 140^{o}C (284^{o}F) after which increased temperatures caused a decrease during exposure. Schaffer (1973) concluded that the increase seen in the long-term compression strength was credited to “the phenol-resin production of additional bonds with duration heating.” For tensile strength, the decrease was caused by “the depolymerization of cellulose with duration of heating.”

As was discussed previously, environmental changes in temperature and moisture content are known to affect mechanical properties, that is, short-term strength and stiffness. Fridley et al. (1989, 1990, 1991, 1992c and 1992d) conducted several studies to determine the effect of environmental conditions on structural lumber. Again, “environmental” only included a temperature range of 23°C to 54°C (73°F to 130°F). Environmental conditions under consideration were constant and cyclical thermal effects and constant and cyclical moisture effects. Specimens, 38 mm by 89 mm by 2.44 m (nominal 2 in. by 4 in. by 8 ft), were Select Structural and No. 2 grade Douglas-fir. Fridley et al. (1989) concluded that for equal stress ratios, a trend of shorter time-to-failure for higher temperatures was observed. He also noted that the observed temperature effects were independent of relative humidity or moisture content effects. Further research by Fridley et al. (1992d) indicated that the effects brought on by constant hygrothermal conditioning could be predicted if the effects on short-term strength were accurately predicted.

No published data was available regarding the effect of temperature of any sort on duration of load behavior of laminated veneer lumber. However, if the implications from Green and Evans (1994) are true, that is similar degradation mechanism brought on by thermal changes, then the solid sawn lumber and LVL should exhibit similar behavior under the same thermal conditions.

While veneer lay-up has been given much attention, the lack of research of other manufacturing parameters, such as manufacturing temperature, of LVL could lead to uncertainty of performance. Therefore, research was conducted to evaluate the load-duration behavior of laminated veneer lumber at varied manufacturing temperatures.

MATERIALS

Boise Cascade of Boise, Idaho provided all veneer used for this research. All provided veneer was Douglas-fir (*Pseudotsuga menziesii*). The veneer was rotary peeled and was cut into six hundred and sixty 1.25 m by 2.55 m (generous 4 ft x 8 ft) sheets. The average thickness of the veneer was 3.68 mm (0.145 in.). After arrival to Washington State University's Wood Materials and Engineering Laboratory, the veneer had to be cut in half lengthwise to 610 mm (2 ft) for processing purposes. The veneer was sorted using nondestructive longitudinal stress wave time techniques and hot pressed at three predetermined temperatures to produce fifteen eleven-ply billets for each temperature. Each billet was cut into six 2.44 m (8 ft) long, 38 mm by 89 mm (nominal 2 in. by 4 in.) laminated veneer lumber members.

METHODS

The objective was two fold: To determine the effect of LVL manufacturing temperature on the mechanical properties and duration of load behavior of Douglas-fir LVL. The effects on the mechanical properties were addressed earlier in Chapter Six. The effects on DOL behavior are discussed in this chapter. The temperature effects of the processing procedure would, by definition, not be reversible. This is because although the exposure time is "short," the exposure temperature is above 100^{o}C (212^{o}F). Also, these effects would not technically be immediate because, although "quick," extreme temperature exposure was not the condition at the time of testing. Specimens were conditioned back to room temperature conditions. Therefore, the conditions of the manufacturing process are more of a measure of permanent effects. Since the main goal centered on manufacturing temperatures, the veneer material had to be sorted into various temperature categories. Upon investigation, a common range of LVL manufacturing temperatures was found to be 145^{o}C to 160^{o}C (293^{o}F to 320^{o}F). The goal was to target temperatures near, greater, and much greater than common industrial practice. The chosen temperatures were 149^{o}C (300^{o}F), 171^{o}C (340^{o}F), and 193^{o}C (380^{o}F).

First, the veneer had to be sorted. Nondestructive sorting was done by impact longitudinal stress wave propagation. After this was done, veneers were pressed with a liquid resin into billets. The press schedule had to be established according to several factors and by using practice billets (Chapter Three). The processing variables for the laminated veneer lumber were as follows:

1. Resin: liquid phenol-formaldehyde;
2. Spread Level: single glueline of 180.65 kg / 1000 m^2 (37 lb / 1000 ft^2) via a roller spreader;
3. Press: hot platen hydraulic;
4. Press Temperatures: 149°C (300°F), 171°C (340°F), and 193°C (380°F);
5. Press Schedule: thickness controlled to 38 mm (1.5 in.) utilizes eleven piles;
6. Press Time: twenty minutes; and
7. Pressure Cycle: after twenty-nine seconds, the end condition pressure was 6897 kPa (1000 psi) and then reduced to 1382 kPa (200 psi) after forty-four seconds and held constant until the end of the cycle at twenty minutes.

After the laminated veneer lumber was manufactured, the material was allowed to return to equilibrium conditions (moisture content (MC) = 10%) before further testing was done. The dynamic modulus of elasticity ($E_{dynamic}$) was evaluated using longitudinal stress wave propagation and also, static edgewise bending (E_{static}). The static bending tests were also used to determine the modulus of rupture.

For the second phase, the solid sawn lumber was tested using long-term loading. A known stress was applied to each specimen. Stress ratios were assigned on a member by member basis and time to failure and deflection data were recorded. The effect of LVL manufacturing temperature on the duration of load behavior was analyzed.

SPECIMEN SORT

VENEER

All veneers used in the production of laminated veneer lumber were tested nondestructively to obtain an $E_{dynamic}$ (from Equation 2-1) for each veneer sheet. The members were weighed and measured (average of three lengths, average of three widths, and average of four thicknesses). Each member was clamped down perpendicular to the width (flatwise). Impact longitudinal stress waves were introduced to the third point locations along the width. The average of the three stress wave times at those locations was determined as the stress wave time for the entire veneer sheet. The veneers were divided into groups of eleven based on ascending $E_{dynamic}$ values. The group with the lowest $E_{dynamic}$ was assigned to the temperature category of 149°C (300°F), the next ascending group of eleven was assigned to the next temperature and so on until all temperature categories had fifteen sets of eleven veneers. This sorting is not the common practice in industry but the aim here was to mimic the distribution of the solid sawn lumber. The unconventional sorting technique proved valid after ANOVA results suggested there was no significant statistical difference between the $E_{dynamic}$ values of all the temperature categories (Appendix E). The validity of this technique is graphically represented in Figure 7-1.

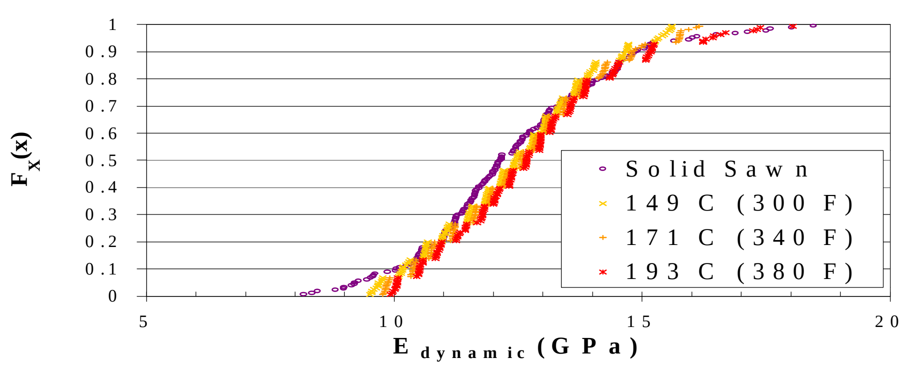


Figure 7-1: *Cumulative Distribution of $E_{dynamic}$ of Sorted Veneers and Solid Sawn Lumber*

LAMINATED VENEER LUMBER

After the billets were made, they were cut to dimension (nominal 2 in. by 4 in., 8 ft long) into six LVL specimens per billet. The specimens were labeled according to manufacturing temperature, billet number (1 through 15 where ascending number corresponds with ascending veneer $E_{dynamic}$ values), and letter *a* through *f* for location of specimen within the billet (*a* and *f* consisting of the edge-most billet material). All 269 LVL specimens were tested nondestructively. However, because of the nature of the induced longitudinal stress wave, and the long travel distance, it was not possible to detect localized LVL manufacturing-induced failures such as delaminations. Because of this, each LVL was visually inspected as well and labeled as good, minor delaminations, or major delaminations. The location and extent of the delaminations was also recorded.

The sorting of the veneer assured similar property dispersion among all temperatures. However, because of manufacturing blow failures for all temperatures, this assurance was compromised. Discussion of the effect of manufacturing temperature on specimen sorting is provided later in this Chapter. Despite manufacturing failures, it was still necessary to sort the category temperatures into two equally distributed testing groups. One group was to be tested statically and the other group was to be tested under load-duration. In order to ensure the same distribution for each group, a pseudo random sort (Chapter Two) was used to divide the members into the testing groups. Each temperature category was ordered according to ascending $E_{dynamic}$. The first two $E_{dynamic}$ values (three value increments of random sorting for 171^{o}C (340^{o}F)), from the ascending data, were randomly distributed and then the next two values and so on until the entire temperature category was split into two even groups (three even groups for 171^{o}C (340^{o}F)). An analysis of variance (ANOVA) was performed on the $E_{dynamic}$ values between the groups (Appendix E). The analysis showed no statistical difference between the MOE-MOR and DOL groups. This final sorting provided the sample sizes that were used in the tests [MOE-MOR/DOL]: 149^{o}C (300^{o}F) [24/24], 171^{o}C (340^{o}F) [24/48], and 193^{o}C (380^{o}F) [19/19]. Since the production process had led to a high yield of LVL samples from the 171^{o}C (340^{o}F) category, the sample size of the duration of load test was doubled and split into two subcategories of the temperature (1 and 2). The addition of an entire DOL set of the same temperature would aid in determining the validity of the trends of load-duration behavior of the different temperatures.

STATIC BENDING TESTS

Static edgewise bending tests were performed to find an actual modulus of elasticity and modulus of rupture values for all specimen categories. The static modulus of elasticity, E_{static}, was used to monitor temperature effects on stiffness and to compare to the nondestructive method, E_{dyamic}, which had been used for sorting. Twenty-four members of each temperature category, except the 193^{o}C (380^{o}F) which had nineteen members, were tested for mechanical properties.

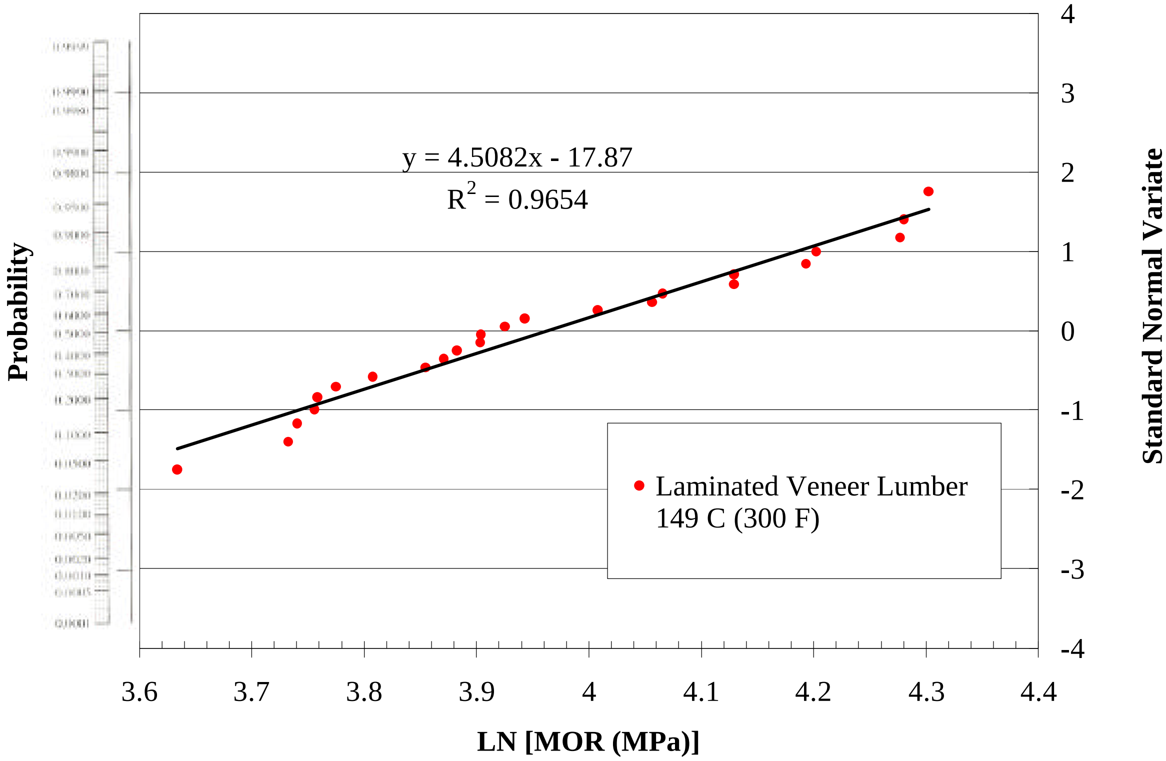
An Instron 4400R screw-driven test machine was used to perform all static bending tests on the simply supported beams. The procedures from ASTM D198 (1998), the standard test for determining structural lumber properties, were followed and the load-displacement data, time to failure, and maximum load were recorded by a computer data acquisition system (Labview, 1997). A load rate of 3.3 mm/min (0.13 in./min) was determined to meet the provisions of the standard. All of the specimens were tested to failure. The displacement was measured at center span using a linear variable differential transformer (LVDT) (Appendix A). Using a spreader beam, the single point ramp load applied from the testing machine was evenly distributed into two point loads. The dimensions of the spreader beam were such that the two point loads were applied at third points, 610 mm (24 in.), in relation to the end reactions. Finally, lateral bracing was applied in accordance with the ASTM standard to eliminate the concern of lateral-torsional buckling effects. The actual static bending setup can be seen in Chapter Two. The equation used for static bending modulus of elasticity was Equation 2-2.

Static bending tests were performed in a temperature controlled room where the temperature range fluctuated between 21°C (70°F) and 23°C (73°F). The relative humidity was determined to be in the proximity range of thirty percent to forty percent.

DETERMINATION OF LOADS

Using the maximum load obtained from the static bending tests, the modulus of rupture was calculated and used to determine loads for the load-duration tests. Each temperature category was evaluated separately.

Several methods were used to determine which statistical distribution best represented the modulus of rupture data. The distributions analyzed were normal, lognormal, and 2-P Weibull. The first methods were plotting the distributions on probability paper and comparing the coefficients of determination (r^2) (Figure 7-2A). These methods were based on visual inspection and quantitative results for goodness of fit. Also, the inverse cumulative distribution function (CDF) method was used (Figure 7-2B). Both visual inspection and the standard error estimate of these plots were performed. After reviewing all of the above methods, it was clear that a lognormal distribution best represented the modulus of rupture data for all temperature categories of the laminated veneer lumber. Examples of the lognormal probability plots and the lognormal inverse CDF plots are shown for the laminated veneer lumber 149°C (300°F) temperature category (Figure 7-2). Distribution fitting plots for all temperatures are found in Appendix B.



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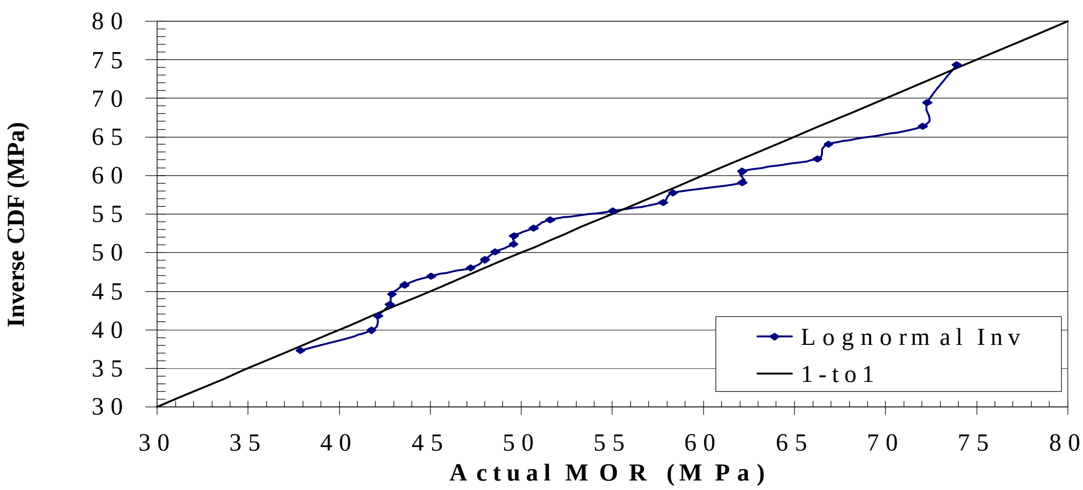

B

Figure 7-2: *MOR Best Fit Lognormal Distribution: (A) Probability Plot and r^2; (B) Inverse CDF*

Once a lognormal distribution was determined as the best fitting distribution, the theoretical design values, F_b, were found in accordance with ASTM D2915 (1994) (Table 5-3). This was done to compare temperature categories in the same manor that is done in practice.

However, because it was desired to move beyond the lower tail data that governs the design values, the fifteenth percentile modulus of rupture was calculated from the lognormally distributed data. This value would be considered the applied stress used for the duration of load tests. Using the same equation that was used to calculate modulus of rupture from the static bending tests, the applied loads were back calculated out of the equation (Equation 2-4) using the applied stress values.

Table 7-2: *Design Stress and Applied Stress for Laminated Veneer Lumber*

Temperature (^{o}C)	F_b (MPa)		MOR (MPa) 15^{th} percentile	Calculated Loads (N)
	Nonparametric	Parametric		
LVL 149	18.03	17.25	43.89	7172
LVL 171 - 1	16.92	19.35	49.65	8253
LVL 171 - 2				8251
LVL 193	19.32	19.15	50.08	8266

The actual values of modulus of rupture were obtained using the cross-sectional dimensions of the groups tested statically. When the loads were back calculated, the cross-sectional dimensions of the groups tested for load-duration behavior were used. This applied actual geometric properties of the group to the applied loads.

LOAD-DURATION TESTS

The second set of groups, one group per temperature category, was subjected to long-term loading to determine the response. The sample size was the same as that of the static tests, that is, all of the test groups consisted of twenty-four members except the 193°C (380°F) temperature group which consisted of nineteen members. The laminated veneer lumber was subjected to a constant load for forty-two days, when the last deflection data was obtained. Although no more deflection data was taken, the laminated veneer lumber was observed for an additional forty-eight days for time-to-failure data (total of ninety days).

Four sets of testing frames were used. Each set consisted of twelve frames and each frame was designed to test two specimens at once. The frames were specifically designed for strong axis bending load-duration tests. The actual load-duration setup can be seen in Chapter Two. In a similar configuration as the static test setup, using a spreader beam, the single point load applied via a pulley and cable system was evenly distributed into two point loads. The dimensions of the spreader beam were such that the two point loads were applied at third points, 610 mm (24 in.), in relation to the supports. Lateral bracing was provided and the applied weights, made of steel and/or concrete, were hung from a 406.4 mm (16 in.) diameter pulley. Each pulley was individually calibrated by using a small load cell and applying known loads to the system (Appendix A). The actual mechanical advantage for each pulley was calculated by averaging the results from four known loads for each pulley. The minimum and maximum calculated mechanical advantages of the pulleys were 7.72:1 and 7.97:1, respectively.

A modified caliper was used to collect deflection data. Because it was not possible to collect continuous data using the caliper, deflections were recorded at specific times relating to time of loading. These times were as follows: one minute, one hour, two hours, four hours, one day, four days, seven days, fourteen days, twenty-two days, thirty days, and forty-two days.

Since the members used for the load-duration tests failed under sustained load, it was not possible to also retest the members for ultimate bending stress. In order to obtain an ultimate bending stress for the failed members, the rank order statistic method was used. This method uses the strength values found from the distribution fitting. Each specimen was ranked according to time of failure. The specimens were then assigned a lognormally distributed ultimate bending strength according to this ranking. That is to say, the first member to fail, considered the weakest, is assigned the lowest lognormal ultimate stress and so on. This ranking process was followed as the members broke until the end of testing, which was before all members had failed.

Nondestructive testing was done on all the members so there was information relating the load-duration specimens to each other but through modulus of elasticity, not bending strength. However, based on assumption that there is a positive correlation between stiffness and strength, the failure order of the members could be predicted relatively well. This proved useful in evaluating the load-duration behavior of the surviving members.

The testing room where the load-duration tests were performed was thermostat controlled at 21^{o}C (70^{o}F) with heating and cooling systems. Duration of load testing was primarily conducted during summer months so constant cooling was applied to the room and minimal heating was used to balance the environmental temperature. The relative humidity was monitored and essentially remained at a constant thirty percent.

RESULTS

The sorting of the veneers ensured that the make-up of the LVL would be statistically the same. However, billets manufactured at all temperatures experienced various types of "blow failures" that resulted in the loss of material. The ratio of good and useable LVL to total LVL produced was calculated. "Good" LVL was defined as data with no blow failure and "useable" LVL included good LVL and minor failures determined not to affect the performance of the LVL. The results in Table 7-3 suggest that the best yield resulted from a manufacturing temperature of 171^{o}C (340^{o}F).

Table 7-3: *Manufacturing LVL Yield*

Total Expected*	Billets Made	LVL / Billet	Total LVL
	15	6	**90**
Temperature	149°C (300°F)	171°C (340°F)	193°C (380°F)
Total "good" LVL	49	71	30
Additional "useable" LVL**	8	2	10
Optimistic "useable" Total	57	73	40
Percent of "good" LVL	54.44%	78.89%	33.33%
Percent of "useable" LVL	63.33%	81.11%	44.44%

*pertains to all temperatures
**only minor delaminations

Veneer quality was found to be a factor for temperature dependant manufacturing failures. An in depth discussion about this finding is provided in Chapter Six. Although sorting of the veneer had been used to manufacture LVL with similar distributions per temperature, the manufacturing failures compromised this deliberation. Ideally, LVL selection should represent equal member selection from all billets. However, because the manufacturing failures were temperature dependent, LVL selection was only equal for the 171°C (340°F) temperature category. The members that made up the testing temperature category of 149°C (300°F) were comprised of LVL pulled mainly from billets 1 through 5. Contrarily, LVL mainly from billets 9 through 15 was pulled for testing for the 193°C (380°F) temperature category. Unfortunately, this was a situation that could not be controlled. Consequently, because of the sorting issues, the validity of the increases seen for mechanical properties and in modulus of rupture was cautioned (Chapter Six). However, for the duration of load tests, the increase in the 15th percentile modulus of rupture, and thus applied stress, is inconsequential since analysis was done in terms of stress ratios.

DURATION OF LOAD BEHAVIOR

The phenomenon known as creep rupture, or load-duration behavior, was the focus of the research. Of specific interest were the effects of manufacturing temperature on the load-duration behavior of laminated veneer lumber. Specific analysis of the related phenomenon creep was not performed, however, DOL deflection behavior was examined.

By definition, creep rupture occurs because of the failure of the specimen to sustain constant load over time due to increased deformation during that time. In order to examine duration of load behavior, the lognormal modulus of rupture values were used to determine the sustained loads. ANOVA results showed significant statistical difference between modulus of rupture values when compared to the temperature category of 149^{o}C (300^{o}F). As stated above, however, the validity of this increase is questionable but inconsequential. In order to avoid the lower tail region of the strength distribution, applied stress levels were based on the 15th percentile. Using the 15th percentile lognormal modulus of rupture values, the applied loads were calculated (Table 7-4) and adjusted using the mechanical advantages of the pulleys of the test frames.

Table 7-4: *Applied Loads for Laminated Veneer Lumber*

Temperature	149^{o}C	171^{o}C - 1	171^{o}C - 2	193^{o}C
FRAME	2	3	3 & 4	4
Applied load (N)	7172	8253	8251	8266
PULLY MECHANICAL ADVANTAGE RANGE				
Maximum	7.94	7.95	7.97	7.96
Minimum	7.75	7.74	7.76	7.72

A summary of the number of failures and survivals for each temperature is provided in Table 7-5. The performance of the members for all temperatures was very similar for ninety days of observation. This confirms the fact that the trend seen in manufacturing failures did not affect the outcome of the load-duration tests. Figure 7-3 indicates which billet numbers made up the failure and survivor categories. The billet numbers are represented by the space between the horizontal gridlines. Those data points occupying that space are from said billet. Clearly, the unconventional method of billet lay-up had an impact on how the LVL members from the respective billet performed under a sustained load. The significance of such performance is discussed later in this chapter.

Table 7-5: *Number of Failures and Survivals for Each Temperature Category for Laminated Veneer Lumber (after ninety days of observation)*

Temperature	Ramp Failure	DOL Failure	Survivor	Total
149°C	7	13	4	24
171°C - 1	7	14	3	24
171°C - 2	7	14	3	24
193°C	4	10	5	19

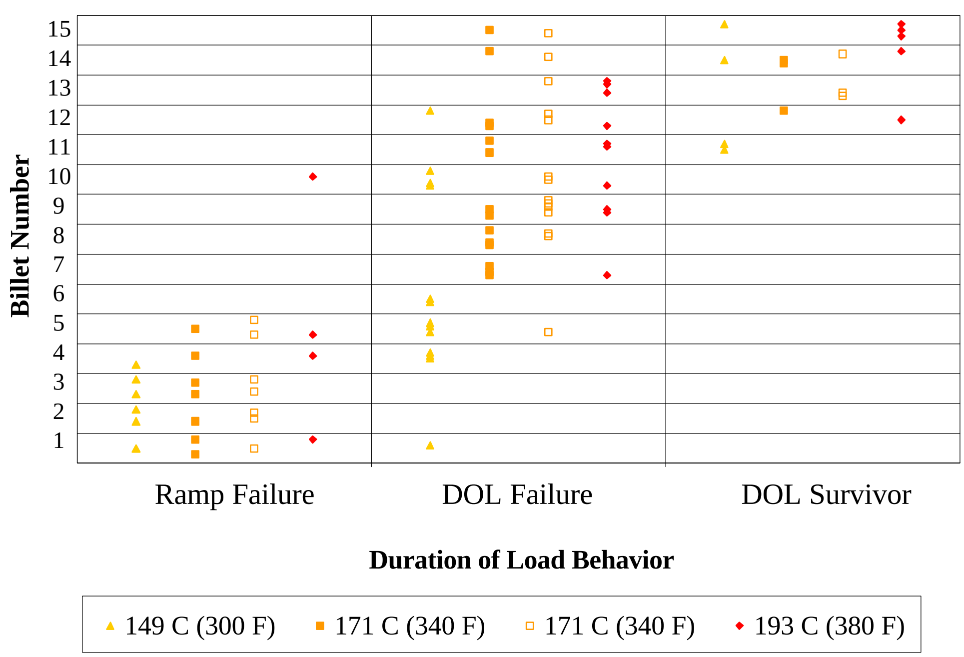

Figure 7-3: *Relationship Between Billet Number and Duration of Load Behavior*

Although specific analysis of creep was not performed, deflection measurements were taken with a digital caliper. From these measurements, displacement-time curves were generated for each specimen tested. Examination of this graphical representation of creep behavior provides insight into the overall load-duration behavior of the specimens. Figure 7-4 illustrates a typical curve for all temperatures. The arrow near the last deflection measurement represents survival past the duration of the test. Deflection-time plots for all specimens are presented in Appendix G.

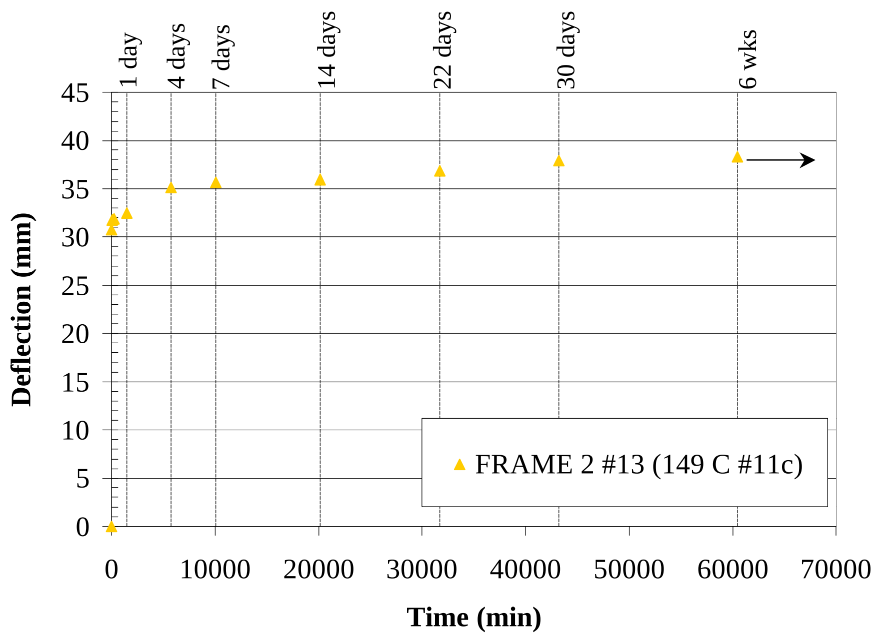

Figure 7-4: *Typical Displacement-Time Curve for All Temperatures*

The shapes of the deflection-time curves were similar to those of Douglas-fir solid sawn lumber trends found by Fridley et al. (1992a). Similar meaning that there was an initial elastic deflection region followed by a primary creep phase region followed by a secondary creep phase region. The duration of these regions was comparable to those previously reported for solid sawn lumber. Most members failed within the six week time period. However, since deflection data was collected manually, the trend for the final stage of creep, tertiary, could not be obtained.

Three DOL deflection stages were examined: initial, failure (less than 60480 min), and survival (equal to 60480 min). Initial deflection data, obtained at one minute after load was applied, has the sample size of the total number of specimens minus those lost due to ramp failures (Table 7-5). ANOVA was performed to compare the distribution of deflections. For each temperature category, each DOL deflection stage was compared to the respective maximum static deflection. For all temperatures, the static deflections were not statistically significantly different from neither the failure nor the survival DOL deflections. Contrarily, the static deflection and initial DOL deflection were statistically different for all temperatures.

ANOVA was also performed for the three DOL deflection stages compared between temperature groups. Results between all temperature categories for all DOL deflections showed no statistical significant difference for all DOL deflections (except failure DOL deflection between 171^{o}C (340^{o}F) - 1 and 193^{o}C (380^{o}F) temperature categories). These results suggested that DOL deflection behavior was similar for all temperature categories. Expanding on the ANOVA results, mean deflection values were compared (Table 7-6 and Figure 7-5). There was no indication of a manufacturing temperature effect on any of the DOL deflections.

Table 7-6: *Average DOL Deflection Values*

Temperature	Initial Δ	Failure Δ	Survival Δ
149°C	33.63	38.43	36.42
171°C - 1	33.76	40.70	37.36
171°C - 2	32.88	36.64	37.74
193°C	33.18	37.32	37.13

All deflection values are in mm

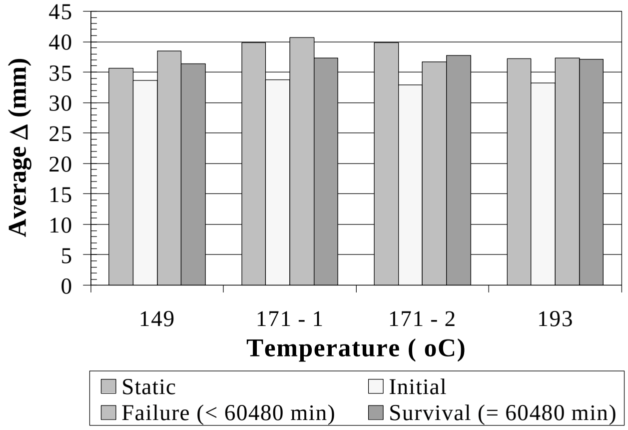

Figure 7-5: *Bar Graph of Average DOL Deflection Values*

To investigate possible correlation, the DOL deflections were compared with their respective strength. Correlation coefficients were found for this relationship for each temperature. For the few members that were survivals, their assigned strength had to be predicted. This was done using the dynamic modulus of elasticity ($E_{dynamic}$). As was seen in Chapter Four, the correlation between $E_{dynamic}$ and modulus of rupture was strong. Therefore, the predictive capability of the $E_{dynamic}$ for the rank order of the assigned modulus of rupture was respectively reliable. There was strong correlation for all temperature categories (Table 7-7) with the 149°C (300°F) category having the best correlation. Figure 7-6 shows the combined data of the ranked modulus of rupture and the predicted modulus of rupture according to the respective $E_{dynamic}$. The slopes off the trendlines were similar. This suggests that the correlation trend is similar for all temperature categories.

Table 7-7: *Coefficients of Determination and Correlation Coefficients for $E_{dynamic}$*

	Assigned MOR		Time to Failure	
Temperature	r^2	r	r^2	r
149°C	0.8893	0.9430	0.7763	0.8811
171°C - 1	0.8042	0.8968	0.6568	0.8104
171°C - 2	0.7832	0.8850	0.7235	0.8506
193°C	0.8767	0.9363	0.6005	0.7749

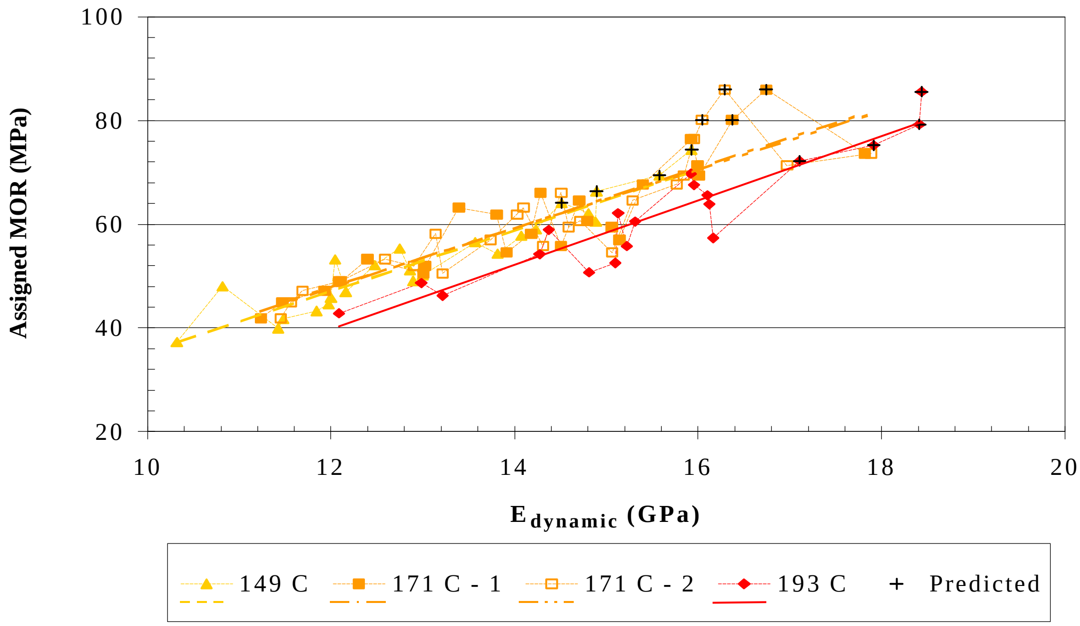

Figure 7-6: *Correlation of $E_{dynamic}$ and Rank Order Modulus of Rupture for Laminated Veneer Lumber*

Since the $E_{dynamic}$ values were so well correlated to the assigned modulus of rupture values, the predictive capability of the $E_{dynamic}$ values was taken one step further to time to failure. Table 7-7 shows that overall, the correlations were good. Because of the known positive correlation between modulus of rupture and modulus of elasticity, this relationship was anticipated. However, the fact that the predictive modulus of elasticity, $E_{dynamic}$, was able to correlate so well to failure times was rather significant. This insinuates that time to failure could be reasonably predicted using nondestructive techniques. Figure 7-7 graphically displays the relationship.

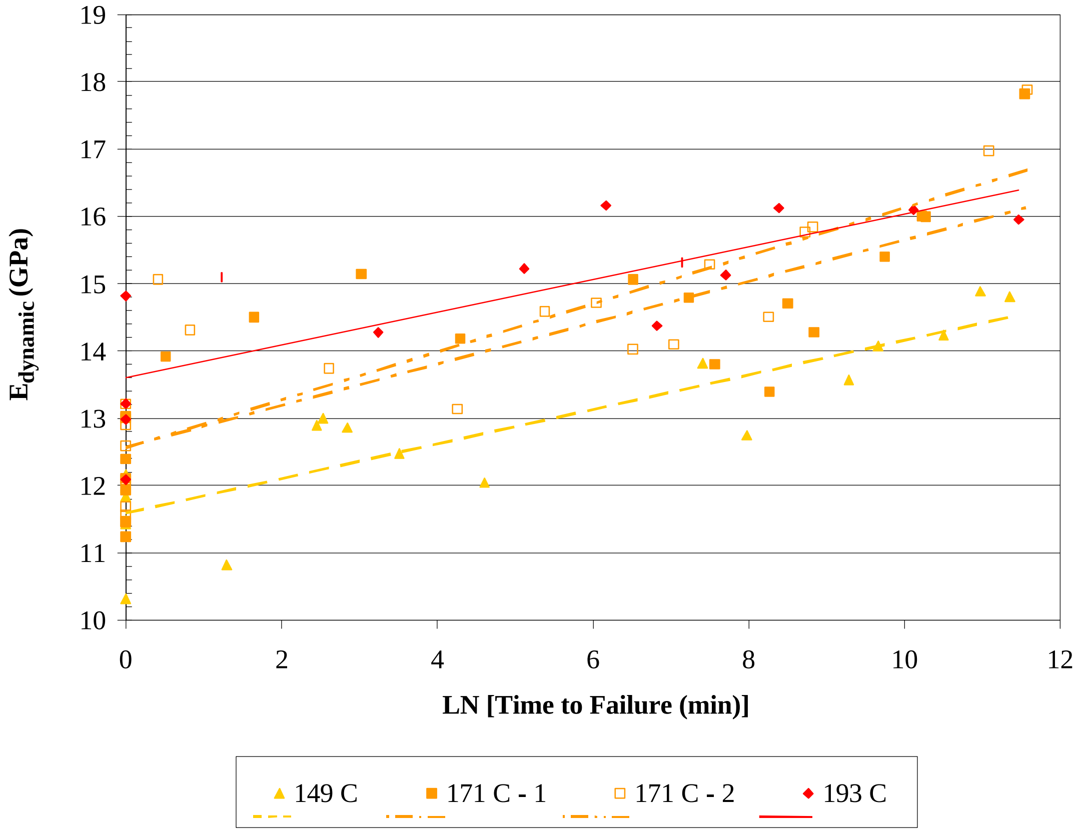

Figure 7-7: *Correlation of $E_{dynamic}$ and Time to Failure for Laminated Veneer Lumber*

To continue on with the examination of the DOL deflections, the concept of the good predictive capabilities of $E_{dynamic}$ was utilized. Because correlations had been proven to be good for both assigned MOR and time to failure, the predicted behavior of the members allowed the initial DOL deflections of surviving members to be included in the deflection analysis.

Table 7-8: *Coefficients of Determination and Correlation Coefficients for Assigned Modulus of Rupture*

	Initial Δ		Failure Δ	
Temperature	r^2	r	r^2	r
149°C	0.7327	0.8560	0.0195	0.1396
171°C - 1	0.6222	0.7888	0.0537	0.2317
171°C - 2	0.4134	0.6430	0.2065	0.4544
193°C	0.6676	0.8171	0.4158	0.6448

Overall, there was evidence of some correlation between the modulus of rupture and the initial DOL deflections (Table 7-8). However, the coefficients of determination for failure DOL deflections are all low. This suggested that there was no correlation at all. Figure 7-8 and Figure 7-9 graphically display the MOR correlation with the initial and failure DOL deflections, respectively. The data points are connected in order to track increasing MOR. For the initial deflection, although the decreasing trend was the opposite as what was seen for static deflections, it stands to reason. Since the initial DOL deflections are the result of a constant sustained load, at any given time, the stronger members would deflect less than would the weaker members, which were closer to failure. Since almost all members failed, no conclusions could be made as to the overall correlation behavior for survival DOL deflections. Consequently, these deflections were not graphically represented.

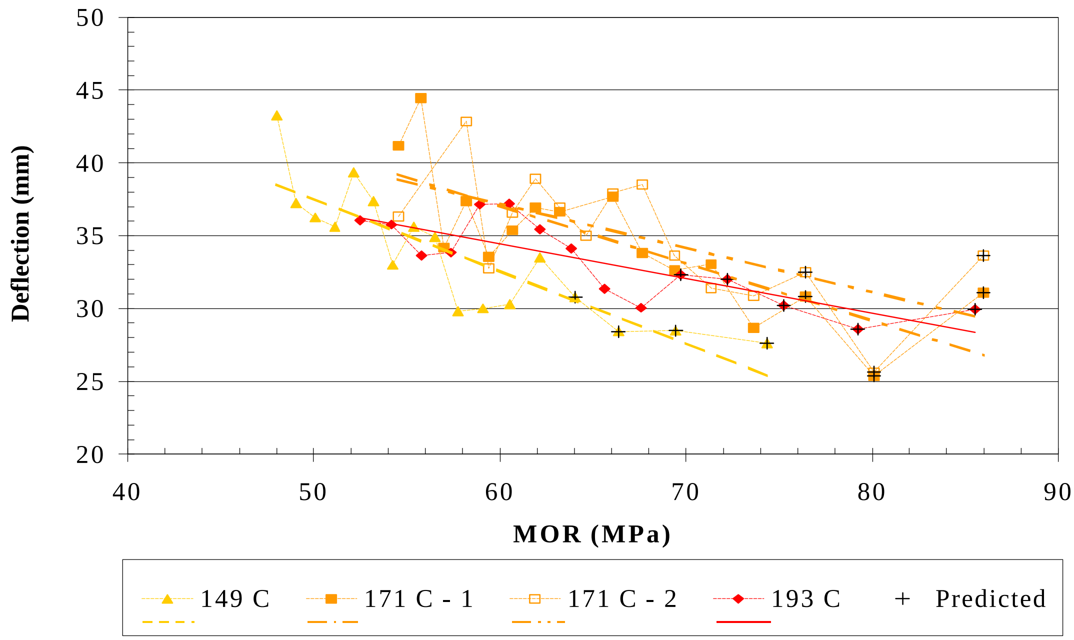

Figure 7-8: *Correlation of Initial DOL Deflection and Modulus of Rupture for Laminated Veneer Lumber*

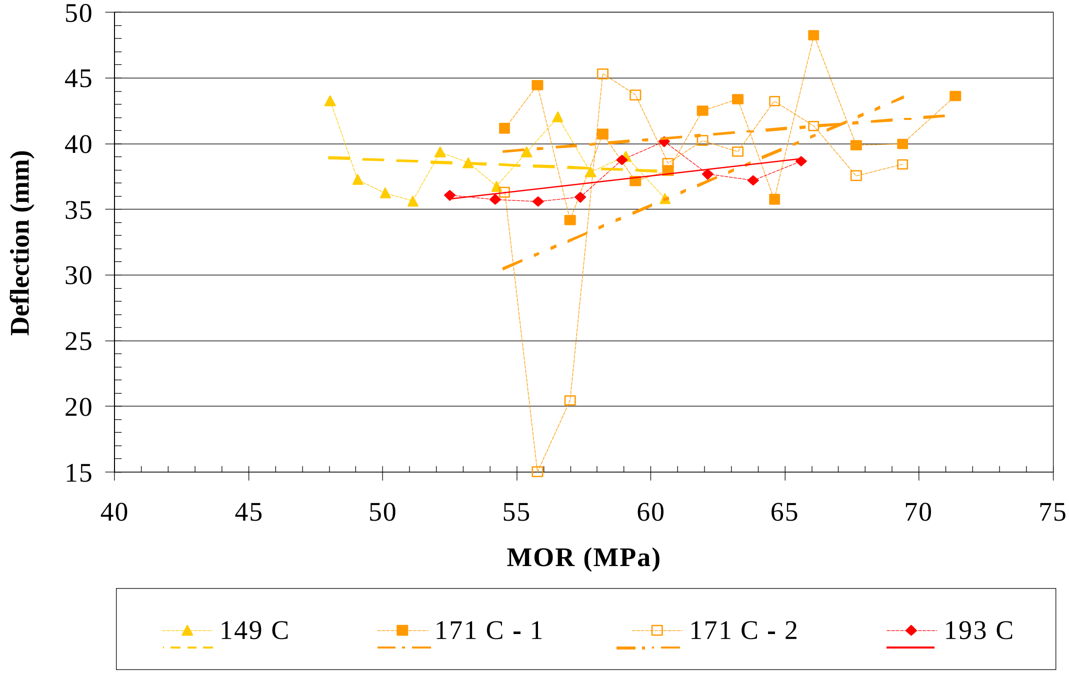

Figure 7-9: *Correlation of Failure DOL Deflections and Modulus of Rupture for Laminated Veneer Lumber*

The slopes of the best fit lines for all temperatures were similar for the MOR correlation with the initial DOL deflections. Also, with the exception of a few outliers for the 171°C (340°F) - 2 category, most failure deflections were similar to the mean values, that is, low standard deviation. These findings suggest that LVL manufacturing temperature does not have any effect on the duration of load initial and failure deflections.

Duration of Load Behavior: Damage Accumulation

There are several methods to assess the duration of load behavior of wood. The damage accumulation (DA) approach is the most popular (Rosowsky and Fridley, 1995) and the approach of greater confidence (Fridley, 1992) since it is so widely used. The damage accumulation is related to the applied stress level. The approach for evaluation of duration of load behavior is to plot the applied stress ratio (SR) versus the time to failure. For this research, the SR was determined using the lognoramally distributed modulus of rupture values as the ultimate stresses (as the denominator), assigned to specimens using rank order statistics. The 15^{th} percentile value of the distribution was the applied stress and used as the numerator of the stress ratio.

The focus of the study was to determine the effect of manufacturing temperature on duration of load behavior of laminated veneer lumber. Since it was not of interest to compare the performance of the different DA models, only one model was used to analyze the DOL behavior of the solid sawn lumber. Some support of this reasoning was found from Cai et al. (2000). It had been found that four common DA models were similar in their predictive capabilities for small clear specimens tested at high stress ratios applied for short durations. However, since all DA models have been developed using small clear and or full sized solid sawn lumber, selection of the DA model could not be based on similarities between the test specimens used to develop the model and those of this research. However, subsequent testing with solid sawn Douglas-fir Larch lumber had led to the choice of the Exponential Damage Rate Model (EDRM) developed by Gerhards (1977, 1979) (Chapter Five). For congruency with the analysis, Gerhards' EDRM was used.

Least squares regression fit of the data to Gerhards' EDRM was performed on each temperature category only for the data points obtained for failures under sustained load (Table 7-5). Excluding both the expected ramp failures and the few survivors, over half of all specimens for each temperature were available for regression analysis. Model constants are provided in Table 7-9A. The goodness of fit of the model was evaluated from calculated coefficient of determination and standard error of the estimate (Table 7-9B) and visual inspection of Figure 7-10.

Table 7-9: *EDRM: (A) Model Constants; (B) Coefficient of Determination and Standard Error*

Temperature	A	B
149°C	51.0229	55.0124
171°C - 1	42.3376	44.5307
171°C - 2	42.4134	45.4511
193°C	42.4753	42.4343

A

Temperature	r^2	Standard Error
149°C	0.956	0.814
171°C - 1	0.931	0.931
171°C - 2	0.964	0.674
193°C	0.964	0.615

B

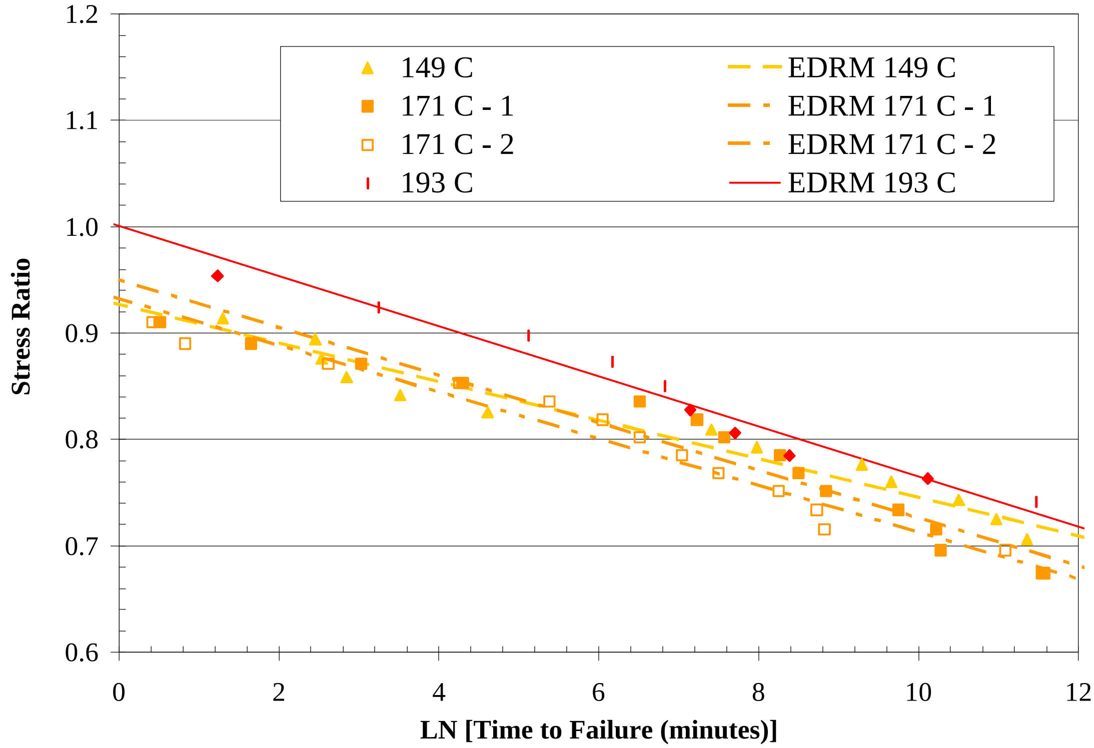

Figure 7-10; *Time-to-Failure Plot for All Temperature Categories of Laminated Veneer Lumber*

The results in Table 7-9B, high coefficients of determination and low standard errors, show that the linear fit, on the natural log scale, of the Gerhards' EDRM model is good. Figure 7-10 provides visual verification of the goodness of fit. It is also apparent that, for the overall behavior, the limited data does not follow the shape characteristic of a hyperbolic model, such as that of Wood (1951).

To compare the regression lines of the temperature categories, methods for testing the hypothesis of equality for population regression coefficients and elevations were performed (Zar, 1996). Each test involved the use of the t distribution in a manor analogous to the testing for difference between two mean populations. The validity of the t test assumes two basic theoretical assumptions of the sample populations; both are randomly obtained from a normal distribution and there are equal variances between both populations. However, the t test has been proven to be quite robust and can withstand considerable departures from the theoretical assumptions (Zar, 1996). This is especially true if the sample sizes are equal or nearly equal. Sample sizes were indeed nearly equal. Nonetheless, cumulative distributions were graphed, to determine normality, and variances were calculated. Visually, it was determined that the trend of the samples (sigmoid curve) was reasonably close enough to normality. Also, the variance values, although not equal, were close in value. Because of the robustness of the test and because violation of the theoretical assumptions was not apparent, the t test was deemed reliable for the hypothesis tests of slope and elevation equality.

All regression analysis was performed at a 95 percent confidence level ($\alpha = 0.05$). Only two temperature regression lines were compared at a time. All regression analysis is provided in Appendix H. As was expected, the two 171°C (340°F) temperature subcategories had both equal slopes and equal elevations. Their close equality heightened confidence in the other temperature EDRM models. The hypothesis of both slope and elevation equality was also accepted between the temperature categories 171°C (340°F) - 1 and 193°C (380°F) and 171°C (340°F) - 2 and 193°C (380°F). However, when the temperature category 149°C (300°F) was involved in these sets of comparisons of EDRM regression lines, the hypothesis of slope equality was rejected. This suggests that the data of the sample population of 149°C (300°F) dose not represent a common population with the other temperature categories. However, because of the compromised sorting due to the manufacture failures, ANOVA results comparing the E_{static} of all temperatures had shown significant statistical difference between populations when the 149^{o}C (300^{o}F) temperature category was involved. Yet, it should be noted that the ANOVA results comparing the $E_{dynamic}$ of all manufactured LVL did show a difference between temperature categories 149^{o}C (300^{o}F) and 193^{o}C (380^{o}F). This was significant because all manufactured LVL did indeed come from a common population of veneer. Thus, it is possible that the manufacturing temperature exposure may have an effect on the duration of load performance of laminated veneer lumber.

Since the EDRM regressions of the 171^{o}C (340^{o}F) - 1 & 2 and 193^{o}C (380^{o}F) represented a common population, EDRM constants were found using multi regression analysis. In equation form the "Common" EDRM was:

$$LN(t_f) = 42.3776 - 44.2581SL \qquad (7 - 7)$$

t_f = time to failure in minutes

SL = ratio of applied stress to ultimate stress

Figure 7-11 shows where the Common EDRM is located in relation to the populations that it embodied.

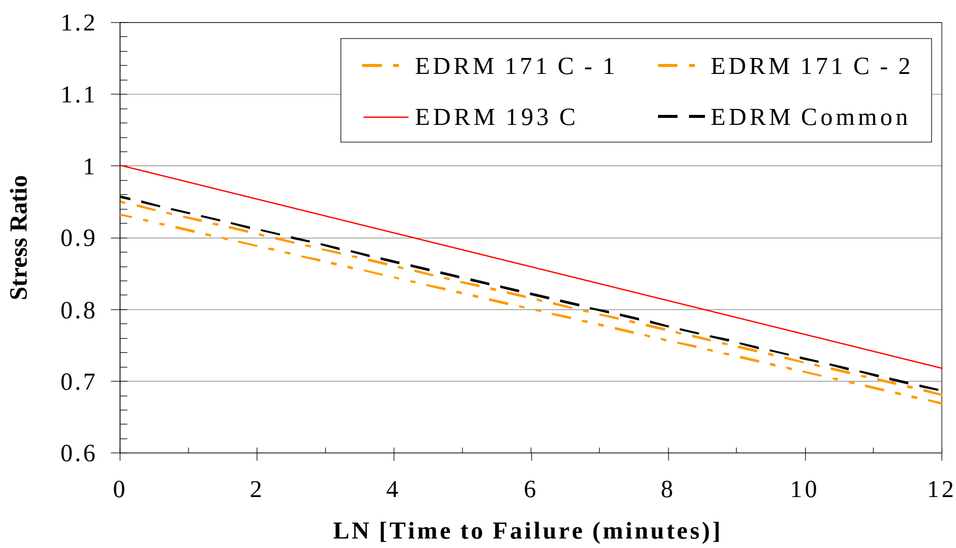

Figure 7-11: *Common EDRM Representing 171^{o}C (340^{o}F) - 1 & 2 and 193^{o}C (380^{o}F)*

For reference, the Douglas-fir Select Structural EDRM developed by Gerhards (1988) and the Madison curve (Wood, 1951) were graphed with the EDRM curves for all temperature categories (Figure 7-12). The Madison curve was included because the derived values are the basis for the load-duration design factors of the National Design Specification (NDS) for Wood Construction (AF & PA, 1997). The time to failure span was only meant to be representative of the actual time for the duration of load tests, which was about six weeks (11 on a natural log scale).

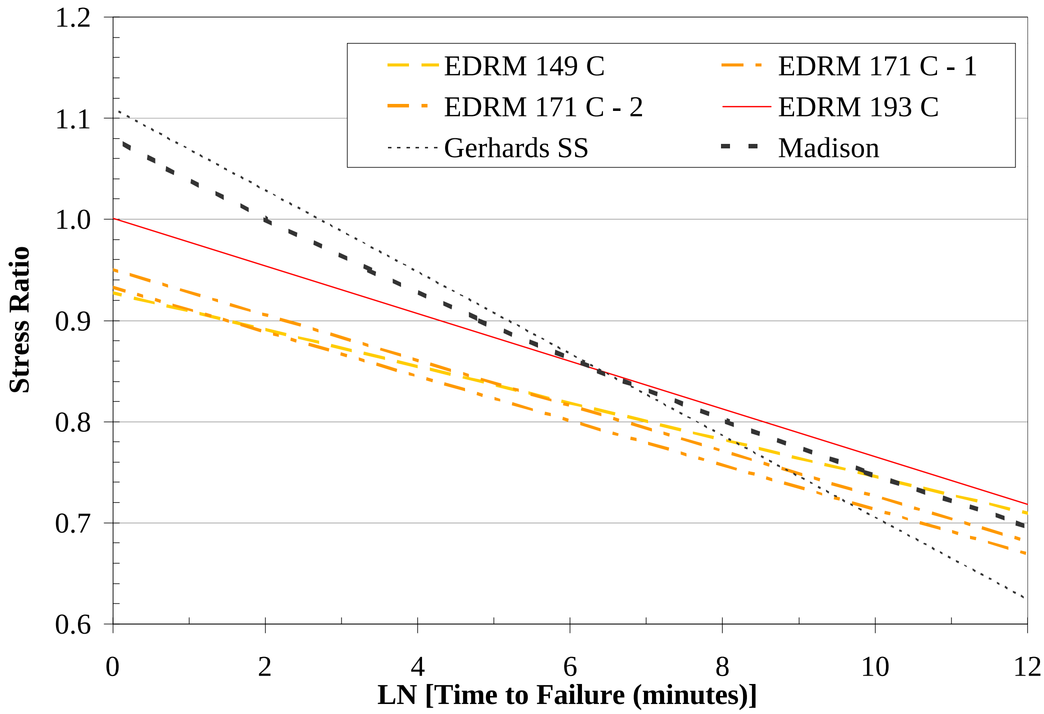

Figure 7-12: *EDRM Comparison for Laminated Veneer Lumber (Duration of Testing)*

Examination of Figure 7-12 reveals that the EDRM curves of the different temperature categories were not very similar to the Gerhards (1988) SS model. However, the Madison curve (Wood, 1951), although not representative of the entire data set (discussed earlier), seemed to provide a good fit for the long-term tail region of all temperature categories. This suggests that the effects of short-term exposure to manufacturing temperatures may be minimal, if any, for long-term duration of load. This made it necessary to extrapolate and examine the long-term behavior used in design, such as ten and fifty years.

Upon examination of the two reference EDRM curves, it is seen that they cross the 100 percent stress ratio line between seven and sixteen minutes. This would correspond to a fairly realistic failure time for the static ramp load tests. Contrarily, the EDRM curves of the temperature categories found through least squares regressions did not cross the 100 percent stress ratio at failure times reflective of their respective ramp loading static tests, which averaged between 10.9 and 11.8 minutes. In fact, the 193^{o}C (380^{o}F) temperature category started at 100 percent and all other temperature categories started below the 100 percent line, which is unrealistic. However, similar discrepancies can be seen in data presented by Fridley et al. (1989 and 1991). These unrealistic results for the short duration of time suggest that Gerhards' EDRM does not accurately model the values of this response. However, this inaccuracy should not discount the EDRM as a viable model for long-term behavior. The short-term behavior of the material can be determined using static testing methods. It is reasonable to accept these discrepancies because the damage accumulation is different for ramp loading than for a constant applied load. For a ramp load, the DA increases exponentially with stress level and culminates near the ultimate stress. Contrarily, for a constant applied stress, there is a constant rate of DA.

In order to better assess the differences between temperature categories, stress levels were predicted for common load-durations (Table 7-10). There was no detectable trend from one temperature category to the next. However, the 193^{o}C (380^{o}F) contained all of the highest stress levels for the short-term duration and the 149^{o}C (300^{o}F) had the highest stress levels for durations five years and greater. The 171^{o}C (340^{o}F) - 2 category contained all of the lowest predicted stress levels. Although the validity of the actual stress level along the EDRM regression is questionable for the short-term durations (discussed earlier), the actual load-duration data supports the relationship seen between the temperature categories. Stress levels for all temperatures are comparable to each other for the entire duration. For extrapolated long-term behavior (5, 10, and 50 years), the stress levels of all temperature categories were very comparable to the NDS values. The fall and rise difference of maximum and minimum stress levels (for temperature categories only) as constant load-duration increases is represented as percentages in Table 7-10. Figure 7-13A graphically demonstrates the extrapolated EDRM regressions for all temperatures. Figure 7-13B represents the data using the Common EDRM regression.

Table 7-10: *Predicted Stress Levels for Laminated Veneer Lumber*

Constant Load Duration	Madison Curve	Douglas-fir Laminated Veneer Lumber					Max. - Min. Difference
		149°C	171°C - 1	171°C - 2	193°C	Common	
Ten Minutes	0.989	0.886	0.899	0.883	0.947	0.905	6.4%
One Day	0.823	0.795	0.787	0.773	0.830	0.793	5.6%
One Week	0.768	0.760	0.744	0.730	0.784	0.749	5.3%
Two Months	0.712	0.720	0.695	0.682	0.732	0.700	5.0%
Five Years	0.635	0.659	0.619	0.608	0.653	0.624	5.1%
Ten Years	0.621	0.646	0.603	0.593	0.636	0.608	5.3%
Fifty Years	0.589	0.617	0.567	0.557	0.598	0.571	6.0%

Lowest Temperature Category Values
Highest Temperature Category Values

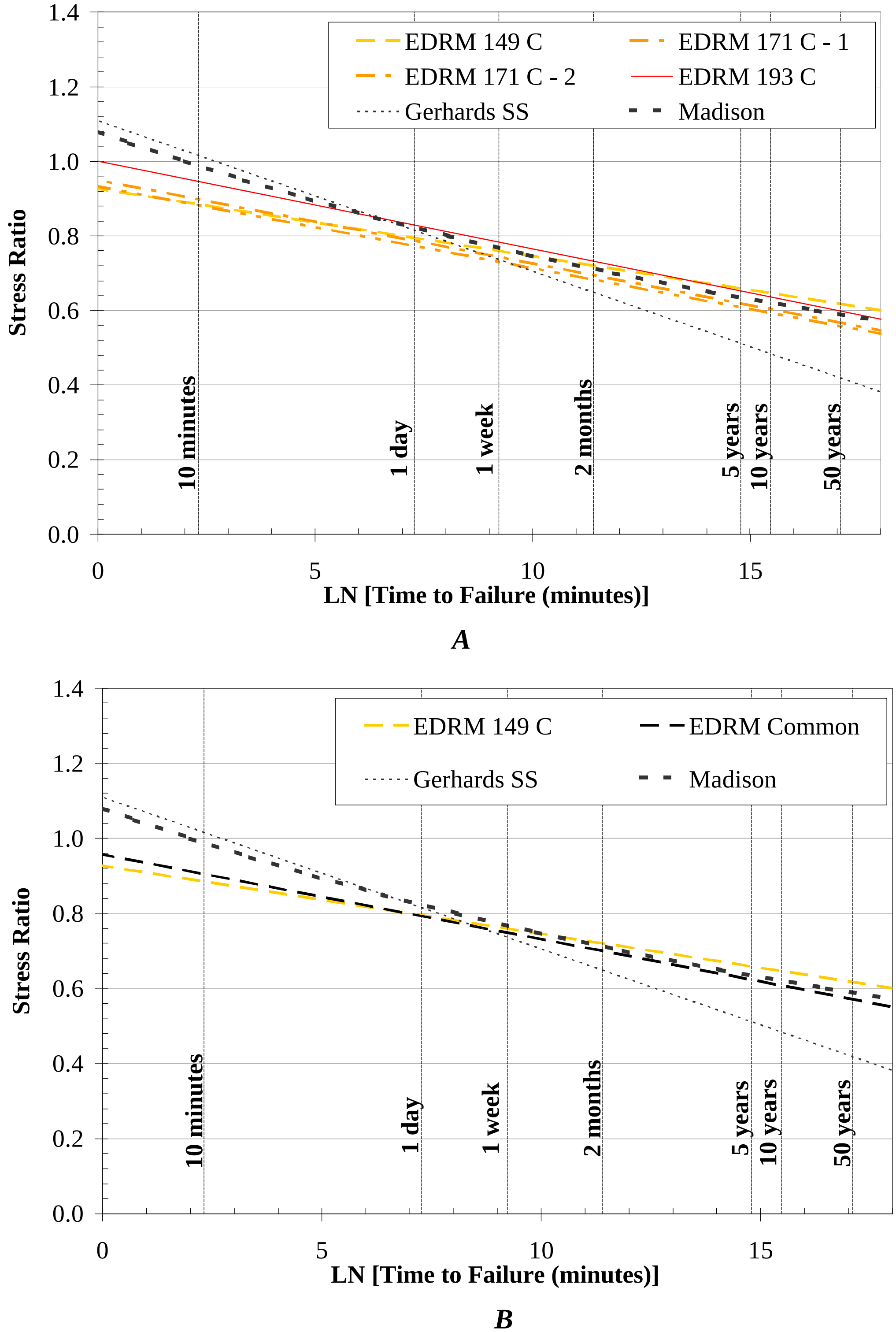

Figure 7-13: *EDRM Comparison for Laminated Veneer Lumber (Extrapolated Design Duration): (A) All Temperatures; (B) 149°C (300°F) and Common Regression*

Current load-duration design factors of the NDS are the result of the procedures of ASTM D245 (1993), a standard for establishing allowable properties for visually graded lumber. The equation used to determine the published value for the allowable bending strength is given in Equation 7-8.

$$F_b = \frac{x_{05}}{2.1} \qquad (7 - 8)$$

F_b = allowable bending strength

x_{05} = parametric or nonparametric (commonly 5th percent exclusion) strength value

Example calculations are provided in Appendix B. The denominator factor of 2.1 is the product of a 1.6 load-duration factor (based on ten years) and a 1.3 end use factor. Since the allowable bending strength equation is based on ten years, the load-duration adjustment factor for ten years is 1.0. Stress ratios are found via interpolation along the model curve and then normalized by the ten year stress ratio (Table 7-10). The resulting values are the respective adjustment factors.

Load-duration factors were calculated for all the EDRM curves of the temperature categories. Table 7-11 contains the current load-duration adjustment factors (AF & PA 1997) from the Madison curve and the calculated load-duration adjustment factors for each temperature category. These factors are also presented graphically in Figure 7-14.

Table 7-11: *Calculated Load-Duration Adjustment Factors (Normalized to 10 Year Duration)*

Constant Load Duration	Madison Curve (NDS)	Douglas-fir Laminated Veneer Lumber				
		149°C	171°C - 1	171°C - 2	193°C	Common
Ten Minutes	1.59 (1.60)	1.371	1.490	1.489	1.488	1.490
One Day	1.33	1.231	1.305	1.305	1.304	1.305
One Week	1.24 (1.25)	1.176	1.233	1.232	1.232	1.233
Two Months	1.15	1.115	1.152	1.151	1.151	1.152
Five Years	1.02	1.019	1.026	1.026	1.026	1.026
Ten Years	1.00	1.000	1.000	1.000	1.000	1.000
Fifty Years	0.95 (0.90)	0.955	0.940	0.940	0.940	0.940

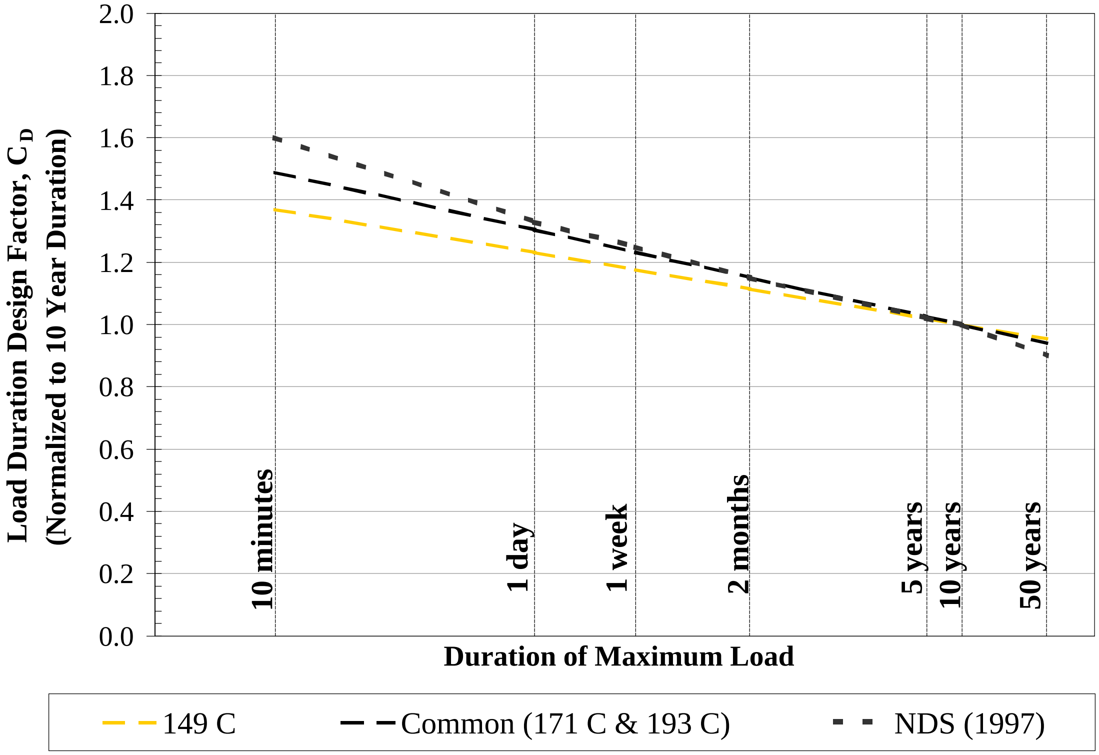

Figure 7-14: *Calculated Load-Duration Adjustment Factors*

The Madison curve load-duration adjustment factors are not appropriate for representation of the EDRM curves found for all temperature categories. It should be noted that during the duration of less than two months, all of the temperature categories had calculated load-duration adjustment factors lower than those of the Madison curve. However, the Madison curve did provide good representation of the duration periods greater than two months. Therefore, the differences in predicted stress ratio and consequently load-duration adjustment factors were most severe for the short-term load-durations (less than two months).

CONCLUSIONS

The experimental results of this research gave insight to the duration of load behavior of laminated veneer lumber (LVL) produced at different manufacturing temperatures.

It was observed that all manufacturing temperature categories experienced billet failures. However, the types of billet failures (delamination, wood failure, and a combination of the two) were concluded to be temperature dependent. The veneer quality was found to be a factor for temperature dependant manufacturing failures. It was concluded that lower quality veneers experienced less billet failures when manufactured at 149^{o}C (300^{o}F), while higher quality veneers experienced less billet failure when manufactured at the 193^{o}C (380^{o}F). As far as material yield, a manufacturing temperature of 171^{o}C (340^{o}F) was concluded to be superior.

The dynamic modulus of elasticity, found via longitudinal stress wave time, was determined to be statistically different for all tested temperature categories. However, only a difference was observed between the low and high temperature categories when all members were compared. Hence, it was concluded that the skew of material yield had an affect on the material used for testing. However, for duration of load testing, this skew was determined to be inconsequential because ratios of stress were used for comparison.

Analysis was performed on the duration of load (DOL) deflections (initial, failure, and survival). It was concluded that manufacturing temperature of LVL had no effect on the DOL deflections.

Veneer quality was found to have a substantial impact on when a LVL member would fail. Because of this fact, the predictive dynamic modulus of elasticity was able to correlate rather well to failure times. This insinuates that time to failure could be reasonably predicted using nondestructive techniques.

It was concluded that the exponential damage rate model (EDRM) was a very good fit to all temperature categories. Regression analysis of equality of slope and elevation revealed that the two high temperature categories had both similar slopes and elevations of their respective

EDRM curves. It was observed that the slope of all of the temperature EDRM curves were not similar to existing EDRM curves (Gerhards, 1988) for solid sawn lumber. It was concluded that the load-duration adjustment factors of the Madison curve (Wood, 1951) did not adequately represent the EDRM curves of this research overall. However, the Madison curve (Wood, 1951) represented long durational periods, roughly two months to fifty years, well for all temperature categories. Essentially, it can be concluded that the manufacturing temperature in the range of 149^{o}C to 193^{o}C (300^{o}F to 380^{o}F) has no effect on the duration of load behavior of laminated veneer lumber.

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CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

The conclusions from the research effort detailed in proceeding chapters are presented here. Conclusions are broken into sections based on the focus as follows: Nondestructive Testing, Solid Sawn Lumber, and Laminated Veneer Lumber. Recommendations for future research are given following the presentation of the conclusions.

NONDESTRUCTIVE TESTING CONCLUSIONS

The results, which examine the nondestructive techniques for determining modulus of elasticity, provided several conclusions regarding the prediction of stiffness and strength. Although levels of reasonability of these predictions varied, many of the conclusions were the same for both solid sawn lumber and laminated veneer lumber.

It is concluded that the mechanical modulus of elasticity of clear Douglas-fir Larch and Douglas-fir LVL can be predicted with reasonable accuracy using the nondestructive evaluation of the modulus of elasticity, $E_{dynamic}$. Although the predictive $E_{dynamic}$ values were overestimates of E_{static}, that is a lack of a one-to-one relationship for both materials, the correlation coefficients were high and were within an acceptable range.

Specifically, for the solid sawn lumber, the ANOVA results showed that for each temperature, except for the 193^{o}C (380^{o}F), $E_{dynamic}$ was statistically different from E_{static}. However, there was still a very high correlation between the two. The statistical difference was merely registering the fact that the $E_{dynamic}$ was overestimating the E_{static}.

The ANOVA results for the LVL showed that all of the methods for predicting modulus of elasticity were statistically not different from E_{static}, except for the 149°C (300°F) temperature. This concludes that there is a closer one-to-one relationship between nondestructive and destructive MOE values for LVL than for the solid sawn lumber. There was also a high correlation between all of the methods and E_{static}. However, overall, the correlations were much broader than the solid sawn lumber.

For the laminated beam theory, it can be concluded that the vertical laminate orientation does better predict the static edgewise bending over the horizontal laminate orientation. Although the distributions were similar, the higher predicted values and the lower correlation coefficients of the horizontal laminate orientation lead to the conclusion that it would better predict flatwise bending.

Breaking down the different approaches for assessing the section thickness for application of the laminated beam theory (composite, billet, and expected) leads to the conclusion that slight changes in geometric thickness do have an effect on the predictive modulus of elasticity. However, these changes are small. $E_{expected\text{-}vert}$ was a very good prediction for E_{static}. This is important because unlike all of the other nondestructive evaluations, this value does not need dimensions found after manufacturing, if pressing is thickness controlled. This leads to the conclusion that the modulus of elasticity of the LVL can be predicted reasonably accurately before manufacturing, provided the individual veneer $E_{dynamic}$ values were calculated, and the LVL dimensions are true to those of the prediction.

For the LVL, the sorting techniques had been based on the $E_{dynamic}$ of the individual veneers. It can be concluded that the LVL, a product of nondestructive sorting of veneers according to modulus of elasticity, will reflect the sorting procedure of the veneer for destructive and nondestructive MOE evaluation and for modulus of rupture. Therefore, because of the predictive accuracy of $E_{expected}$ and because the mechanical properties reflect the segregation of the veneer groups, producers of LVL can easily design products with particular properties.

For solid sawn lumber, the correlation between $E_{dynamic}$ and modulus of rupture was fairly poor. However, the correlation for LVL was high for all nondestructive methods. This leads to the conclusion that nondestructive modulus of elasticity is a good indicator of strength for laminated veneer lumber.

Finally, through experimentation and statistical analysis, it was concluded that overall, the best method for predicting the modulus of elasticity of LVL was $E_{dynamic}$. This method also provided the best overall correlation with modulus of rupture. However, the laminated beam theory should not be discounted because of distribution similarity and a relatively high correlation was observed.

SOLID SAWN LUMBER CONCLUSIONS

The experimental results of this research gave insight to the mechanical and duration of load behavior of solid sawn wood material after short-term exposure to extreme temperatures. Conclusions found were somewhat contradictory to other traditional temperature studies, which suggest decrease in structural properties and in time to failure. However, other studies were done at much lower environmental temperatures. These environmental temperatures, at highest, merely approached the beginning of degradation of wood, i.e. chemical alteration.

MECHANICAL PROPERTIES CONCLUSIONS

The trend of degradation of wood material increased as temperature increased. Although not shown to be statistically significant, the degradation was attributed to the thermally induced chemical change of the wood substance that is associated with the temperature range used in the research and possible moisture content influence.

It was observed that short-term extreme temperature exposure caused changes in the load-displacement relationship. This was most apparent for the 149^{o}C (300^{o}F) temperature category. Deflection and failure load both increased as temperature increased. However, it was determined that the differences in maximum static deflection were statistically not significant.

The dynamic modulus of elasticity, found via longitudinal stress wave time, was determined to be the same before and after heating for all temperature categories. It was also determined to be the same between all temperature categories. The static modulus of elasticity, while still shown to be statistically not different, showed a trend of an increased modulus as temperature increased. Although there is evidence of a trend, and a second order polynomial fit can be well applied to the trend, statistically it can be concluded that the modulus of elasticity is not effected by short-term (twenty minutes) extreme temperatures. The observations and conclusions made for static modulus of elasticity can also be applied to modulus of rupture. It can also be concluded that short-term extreme temperature exposure does not affect the correlation between strength and static deflection.

LOAD-DURATION CONCLUSIONS

It was concluded that the exponential damage rate model (EDRM) was a good fit to all temperature categories. Regression analysis of equality of slope and elevation revealed that all temperature category EDRM curves were not the same. It was observed that the slope of the curves were different from existing EDRM curves (Gerhards 1988) for solid sawn lumber. The short-term duration showed the most difference in load-duration behavior for all temperature categories. It was concluded that the load-duration adjustment factors of the Madison curve

(Wood, 1951) did not adequately represent the EDRM curves of this research overall. However, the Madison curve represented long duration periods, five to fifty years, well for all temperature categories. Essentially, it can be concluded that the short-term exposure to extreme elevated temperatures has virtually no effect on duration of load behavior of solid sawn lumber.

Laminated Veneer Lumber Conclusions

LVL has proven to be “stronger” than it’s solid sawn counterparts. The main reasons this is true is due to practical elimination of localized weak spots such as knots and also due to the adhesives used. No beneficial or detrimental reasoning has been given to the actual chemical alteration of the wood. If the implications from Green (1994) are true, that is a common mechanism controlling degradation spurred on by thermal changes, then the solid sawn lumber and LVL should exhibit similar behavior under the same thermal conditions. While this was not entirely seen to be true, several similarities did exist. It is true that not all wood composite products are produced through heating, a major cause of chemical alteration. However, in the case of LVL, hot pressing is the common practice. Raising the temperature does not necessarily have a detrimental effect on the LVL product. The experimental results of this research gave insight to the mechanical behavior and duration of load behavior of laminated veneer lumber (LVL) produced at different manufacturing temperatures.

Pressing Conclusions

It was observed that all manufacturing temperature categories experienced billet failures. However, the types of billet failures, delamination, wood failure, and a combination of the two, were concluded to be temperature dependent. The veneer quality was found to be a factor for temperature dependant manufacturing failures. It was concluded that lower quality veneers experienced less billet failures when manufactured at 149^{o}C (300^{o}F), while higher quality veneers experienced less billet failure when manufactured at the 193^{o}C (380^{o}F). As far as material yield, a manufacturing temperature of 171^{o}C (340^{o}F) was concluded to be superior.

Mechanical Properties Conclusions

Manufacturing temperature caused changes in the load-displacement relationship of the laminated veneer lumber. This was most apparent for the 149^{o}C (300^{o}F) temperature category. Load increased as temperature increased. Although some significant difference was found between temperature categories, no trend was observed for static deflection. However, because of the skew of material yield, results were cautioned.

The dynamic modulus of elasticity, found via longitudinal stress wave time, was determined to be statistically different for all tested temperature categories. However, only a difference was observed between the low and high temperature categories when all members were compared. Hence, it was concluded that the skew of material yield had an affect on the material used for *testing*.

The static modulus of elasticity and modulus of rupture were both found to be statistically different between temperature categories except between 171^{o}C (340^{o}F) and 193^{o}C (380^{o}F). For the *tested members*, it was concluded that the two high temperature categories were similar with regard to mechanical properties and both were different from the low temperature category. This conclusion also held true for parametric allowable strength design values.

The correlation between strength and static deflection was relatively high and increased as temperature increased. Through observation of the slopes of the best-fit lines, it was concluded, for the *tested members*, that the trend of correlation was similar for all temperature categories.

Since there exists a material skew, specific conclusions regarding the type of relationship between the manufacturing temperature and the mechanical properties can not be drawn with confidence. However, because the material skew was indeed a product of manufacturing at different temperatures, general conclusions could be drawn. One such conclusion is that the optimal manufacturing temperature, which is not as sensitive to veneer quality, is higher than what is currently used in industry. Also, if indeed the trends (seen with tested members) of increased mechanical properties with increased manufacturing temperatures is valid, the sacrifice in material yield is not worth the slight mechanical property gain.

Load-Duration Conclusions

For duration of load testing, the *testing* material skew was determined to be inconsequential because ratios of stress were used for comparison. Analysis was performed on the duration of load (DOL) deflections (initial, failure, and survival). It was concluded that manufacturing temperature of LVL had no effect on the DOL deflections.

Veneer quality was found to have a substantial impact on when a LVL member would fail. Because of this fact, the predictive dynamic modulus of elasticity was able to correlate rather well to failure times. This insinuates that time to failure could be reasonably predicted using nondestructive techniques.

It was concluded that the exponential damage rate model (EDRM) was a very good fit to all temperature categories. Regression analysis of equality of slope and elevation revealed that the two high temperature categories had both similar slopes and elevations of their respective EDRM curves. It was observed that the slope of all of the temperature EDRM curves were not similar to existing EDRM curves (Gerhards, 1988) for solid sawn lumber. It was concluded that the load-duration adjustment factors of the Madison curve (Wood, 1951) did not adequately represent the EDRM curves of this research overall. However, the Madison curve (Wood, 1951) represented long durational periods, roughly two months to fifty years, well for all temperature categories. Essentially, it can be concluded that the manufacturing temperature in the range of 149^{o}C to 193^{o}C (300^{o}F to 380^{o}F) has no effect on the duration of load behavior of laminated veneer lumber.

RECOMMENDATIONS

The focus time period for this research was ninety days. Since actual design periods are longer that ninety days, the data was extrapolated. It was within this extrapolated time period that the temperature effects were determined to be negligible. It is recommended that actual longer test periods should be implemented in order to validate the extrapolated data.

For the modeling of the long-term behavior, the exponential damage rate model (EDRM) was found to be a very good fit for both solid sawn and laminated veneer lumber. Although the model was a good fit, it failed to represent the actual short-term behavior observed during static testing. This is not the only research that has encountered this issue. Therefore, it is recommended that an effort be made to refine the model to better represent the short-term duration behavior so that it coincides with actual tested short-term behavior.

Results of the experiments only pertained to the temperatures tested. Although an effort was made to create a model involving a broader temperature range, it is recommend that an effort be made to test more temperatures in order to fill in missing data and refine the presented model. Not only is it imperative to test more temperatures, the overwhelming lack of research involving extreme temperatures makes it necessary to test higher than environmental temperatures. Thermally induced chemical changes within the wood material make the knowledge of wood behavior when exposed to high temperatures invaluable to the wood composite industry.

Expanding upon this, it is recommended that the exploration of chemical changes within the wood material be looked at in greater detail. Thus far, only strong speculation has been made as to what controls thermal degradation. Also, it is recommended that the exploration of chemical occurrences within the resin be studied in relation with the wood material.

The aim of this investigation was to target a specific stress level. However, it is important to designers to have further knowledge of behavior at other stress levels. Therefore, it is recommended that a wider range of stress levels be used to further define the load-duration behavior of the manufactured laminated veneer lumber.

Experimentation was done to determine the effect of a manufacturing parameter on the performance of laminated veneer lumber. It has already been shown that veneer quality is an important parameter and this study portrayed the effects of manufacturing temperature. There are, however, more parameters that need attention, such as time and pressure. It is recommended that other manufacturing parameters, such as these, are studied in order to determine both the mechanical and durational effects. Further testing could help provide more refined products and improve the product economically if more manufacturing parameters are streamlined.

APPENDIX A

Additional Equipment List

INTRODUCTION

Not all the equipment used was depicted within the main document. This appendix serves to list the relevant equipment used for this research. Pictures are provided for pertinent test set-ups.

EQUIPMENT USED FOR TESTING

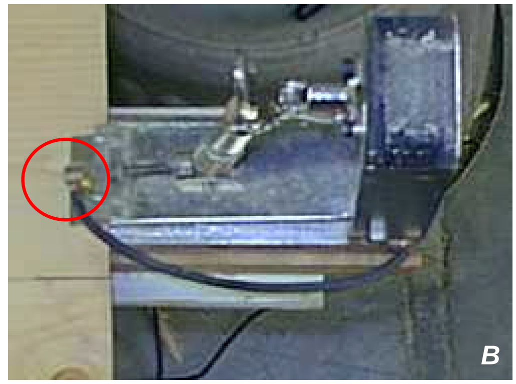
(visuals are provided for some devices not pictured in the main document)

Item*†	Purpose	Manufacturer	Model	Serial #	WSU #	Other
Portable Digital Oscilloscope	NDT Stress Wave Time	FLUKE	97 50MHz SCOPEMETER	NA	324814	A 50V AC 10:1PROBE 100mus/DIV SINGLE Trig:A B 50mV AC 10:1 PROBE
Accelerometer: Impact side	Stress Wave Time	Columbia	3021	1283	NA	Hexagonal Width: 0.630 in
Accelerometer: Receiver side	Stress Wave Time	Columbia	302 - S	4332	NA	Hexagonal Width: 0.630 in
Electronic digital caliper	Dimensions	Fowler & NSK	MAX-CAL	398345	NA	Precision = 0.001 in
Contractor Grade tape measure	Dimension (length)	Stanley	NA	33-445	NA	
Scale	Weights	Mettler	PC 24	NA	259415	Calibrated until 12/2001
Capacitance Moisture meter	Moisture content	Wagner	NA	NA	NA	Less accurate below 5%
Oven	Moisture content	Fisher Scientific	NA	NA	355291	Temp. range: 20°C - 220°C
Williams & White Press (4' x 8')	LVL manufacture	Pressman	NA	NA	NA	Hydraulic platens: max=400°F
Roller Glue Spreader	LVL manufacture	National Standards	NA	NA	NA	Single or double line
Screw machine	Static Bending	Instron	# 4400R	P2118	370139	
Load Cell	Static Bending	Instron	NA	NA	NA	Static Rating +/- 150 kN Weight 17,5 kg
LVDT	Static Bending	SENSORTEC	# 060-3618-02	L2573200	NA	Range +/-1.00 inches EXC_VAC @ 5kHz
S-Load Cell	Pulley Calibration	Interface	SSM-AJ-500	C99233	NA	Capacity = 500 lbf
Micron Smart Meter MM 50	Pulley Calibration	National Standards	47170 (BR.A)	NA	NA	Last calibrated 3/22/2000
PHYSIO-DYNE Heat Stress Meter	Relative Humidity	Environment Tectonics	RP 250	NA	NA	wet-dry bulb chart provided
Electronic digital caliper (modified)	DOL Deflections	NA	NA	NA	NA	Precision = 0.001 in
Linear Position Transducer	DOL Deflections	UniMeasure	LX-PA 10	NA	NA	Accurate +/- 0.05 in (for 10 in)

*items in ***bold italics*** are pictured here in Appendix A

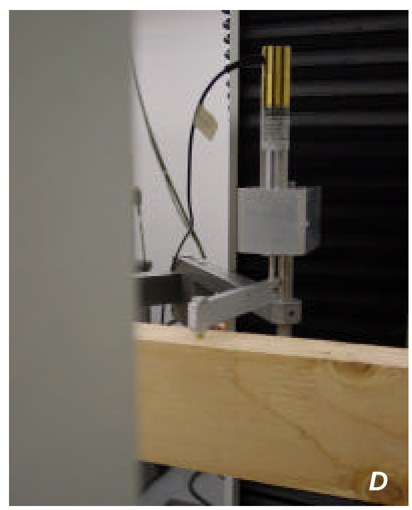
† items in *italics* are pictured in the main document

Equipment for Nondestructive Tests



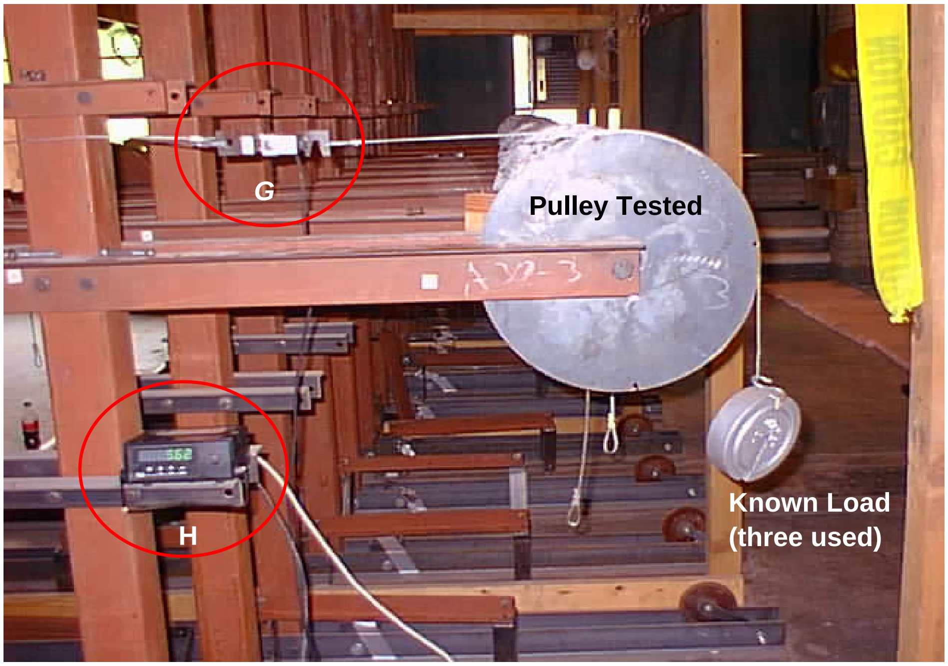
A. *Clamp System & Accelerometer: Receiver Side*
B. *Clamp System & Accelerometer: Impact Side*

Equipment for Static Bending Tests



C. *Load Cell*
D. *LVDT*
E. *Pin Support*
F. *Roller Support*

EQUIPMENT FOR PULLEY CALIBRATION



G. S-Load Cell
H. Micron Smart Box MM50

EQUIPMENT FOR LOAD-DURATION DEFLECTION

I. Linear Position Transducer

APPENDIX B

METHODS EQUATIONS

INTRODUCTION

The main document presents several equations and graphical representation pertaining to methodology. However, most of these equations require a more detailed understanding for application. The methods equations are presented in order of appearance within the main document. Presentation of example equations for calculation of equivalent published values is also provided within this appendix.

STRESS WAVE TIME

Mass conversions:

All weights were measured in grams:

$weight_{gm} := gm \qquad 1 \cdot gm = 2.204622622 \times 10^{-3}\,lb$

(all specimen masses (gm) were multiplied by 2.204622622 x 10³)

$weight_{lb} := weight_{gm} \cdot \left(2.204622622 \times 10^{-3}\right)$

$weight_{lb} = 4.86 \times 10^{-6}\,lb$

Density conversions:

$length := in \qquad width := in \qquad thickness := in$

$Volume := length \cdot width \cdot thickness \qquad Volume = 1\,in^3$

$\rho := \dfrac{weight_{lb}}{Volume} \quad \dfrac{lb}{in^3}$ (NOT a true measure of density)

However, because density is a mass to volume calculation NOT weight to volume, it was necessary to convert the "density" calculated into a force relation. In doing so, Modulus of Elasticity can be determined from equations that relate propagation speed with density.

F = mass x acceleration

$mass := \dfrac{lb \cdot s^2}{ft} \qquad acceleration := g \quad acceleration = 386.089\,\dfrac{in}{s^2}$

Combining these equations will yield a measure of force in pounds. However, it is necessary to keep the density denominator units as per inches cubed. The conversion factor used is then:

$$\text{conversion} := \frac{lb \cdot s^2}{ft \cdot 32.2} \cdot \frac{1 \cdot ft}{12 \cdot in}$$

$$\rho_{force} := \frac{4.86 \times 10^{-6}}{\text{Volume}} \cdot \text{conversion} \qquad \rho_{force} = 1.26 \times 10^{-8} \frac{lb \cdot s^2}{in^4}$$

Essentially, divide "density" by gravity: $\frac{\rho}{g} = 1.26 \times 10^{-8} \frac{lb \cdot s^2}{in^4} = \rho_{force}$

(gravity in inches/second^2)

MODULUS OF ELASTICITY FOUND FOR ROD (PLANE) WAVE SPEED

Stress Wave Time is in microseconds: $\mu := 10^{-6}$

$$SWT := \mu \cdot s$$

Wave speed, C_L, is measured with relation to a fixed distance from a source accelerometer to a receiving accelerometer in which the wave travels in a finite amount of time:

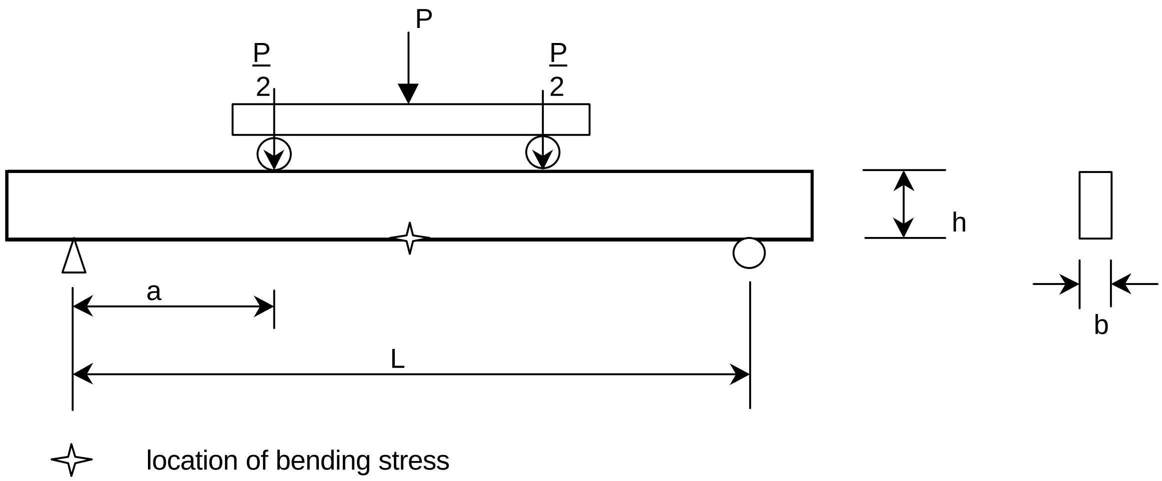
$$\text{distance} := ft \qquad C_L := \frac{\text{distance}}{SWT}$$

Modulus of Elasticity is denoted as $E_{dynamic}$ and is a function of stress wave time and density:

$$E_{dynamic} := C_L^2 \cdot \rho_{force} \qquad E_{dynamic} := psi$$

STATIC BENDING TESTS

Simple Beam - Two equal concentrated loads symmetrically placed



$a := 24 \cdot in$ $L := 72 \cdot in$ $h := 3.5 \cdot in$ $b := 1.5 \cdot in$

(nominal)

Modulus of Rupture: The maximum load carrying capacity of a beam.

$$\sigma_r = \frac{M_{max} \cdot c}{I}$$

M_{max} = Moment at midpoint (and theoretically between load points)

$M_{max} = \frac{P_{max}}{2} \cdot a$ (P_{max} dependent on the test) (where P is in lb)

c = distance of outer fiber from neutral axis $c := \frac{h}{2}$

I = moment of inertia for the cross section (I_x) $I_x := \frac{b \cdot h^3}{12}$

$$\sigma_r = \frac{\frac{P_{max}}{2} \cdot a \cdot c}{I_x}$$

Modulus of Elasticity: Because of the availability of deflection and load, evaluate by use of the beam deflection theory.

$$\Delta y = \frac{\frac{\Delta P}{2}\cdot a}{24\cdot E\cdot I_x}\cdot\left(3\cdot L^2 - 4\cdot a^2\right)$$

rearrange to solve for E . . .

$$E = \frac{\Delta P}{\Delta y}\cdot\frac{a}{48\cdot I_x}\cdot\left(3\cdot L^2 - 4\cdot a^2\right) \quad \text{(where P is in lb and y is in inches)}$$

Thus, E (apparent) can be calculated using the slope of the linear portion of the P-y curve.

To verify the Two-Point Loading Rectangular Beam equation found in the ASTM D198, substitute in equation for I_x:

$$E_{apparent} = \frac{P\cdot a}{4\cdot b\cdot h^3\cdot\Delta}\cdot\left(3\cdot L^2 - 4\cdot a^2\right) \qquad \text{Two-Point Loading Rectangular Beam}$$

Because a = $^1/_3$L, the equation may be reduced to. . .

$$E_{apparent} = \frac{P\cdot L^3}{4.7\cdot b\cdot h^3\cdot\Delta} \qquad \text{Third-Point Loading Rectangular Beam}$$

The equation for two-point loading was used to reduce rounding error (constant = 4.7)

For numerical evaluation, average increments taken in the lower load range to ensure increments were in the elastic region.

For graphical evaluation, the specific data points were plotted over the P-y curves. R^2 was calculated for the portion said to be linear. Linear region was confirmed if $R^2 \geq 0.9897$ (the lowest value encountered - LVL 300ºF).

COMPARISON TO PUBLISHED VALUE

This check was done to compare the Modulus of Elasticity found through static bending for the Solid Sawn (Standard) No Temperature to the published value.

To standardize the apparent Modulus of Elasticity found through third-point static bending to the conditions governing the published design values, use the conversion equation in ASTM D2915:

$$E_{ai2} = \frac{1 + K_1 \cdot \left(\frac{h_1}{L_1}\right)^2 \cdot \left(\frac{E}{G}\right)}{1 + K_2 \cdot \left(\frac{h_2}{L_2}\right)^2 \cdot \left(\frac{E}{G}\right)} \cdot Eai$$

E_a = apparent MOE (not shear corrected)

h = depth of beam

L = span of beam

E = Shear free MOE

G = Modulus of Rigidity

K_i = tabulated factors for adjusting apparent MOE of simply supported beams

$E_{published}$ is based on a uniformly distributed load and a $^L/_h$ ratio of 21:1

Historically, for solid sawn wood, it is assumed that G is $^1/_{16}$ of E.

K_1 = 0.939 for load concentrated at third points

K_2 = 0.960 for uniformly distributed load

$$E_{ai2} = E_{published} = \frac{1 + 0.939 \cdot \left(\frac{1}{21}\right)^2 \cdot (16)}{1 + 0.960 \cdot \left(\frac{1}{21}\right)^2 \cdot (16)} \cdot E_{static}$$

$E_{published} = \quad 0.999 \cdot E_{static}$

No adjustment required

As explained by the standard, the uniform load configuration may be closely approximated by applying loads at the third points of the span. This only applies if the $^{L}/_{h}$ ratio is the same.

Therefore, the apparent Modulus of Elasticity found through static bending for the Solid Sawn (Standard) No Temperature does not require adjustment in order to compare it to the published value.

$$E_{staticAVG} := 1422881 \cdot \frac{lb}{in^2} \quad \approx \quad E_{published} := 1400000 \cdot \frac{lb}{in^2}$$

Published values based on average apparent MOE

DERIVATION OF SHEAR ADJUSTMENT

Apparent values of MOE are of primary concern. The apparent MOE attributes all deflection to moment. Because of this, all comparisons of MOE are comparisons of the apparent MOE. However, if shear had been considered, an adjustment factor would have been applied . . .

For a simply-supported beam with two symmetric point loads (P/2) at a distance *a* (where *a* = a fraction < $^{1}/_{2}$) from the supports

$$\Delta = \frac{P \cdot L^3}{48 \cdot E \cdot I} \cdot \left(3a - 4 \cdot a^3\right) \cdot \left[1 + \frac{2.4 \cdot \left(\frac{E}{G}\right) \cdot \left(\frac{d}{L}\right)^2}{\left(3 - 4 \cdot a^2\right)} \right]$$

In the case of third point loading, a = $^{1}/_{3}$

$$\Delta = \frac{P \cdot L^3}{48 \cdot E_{true} \cdot I} \cdot \left(1 - \frac{4}{27}\right) \cdot \left[1 + \frac{2.4 \cdot \left(\frac{E}{G}\right) \cdot \left(\frac{d}{L}\right)^2}{\left(3 - \frac{4}{9}\right)} \right]$$

$$\Delta = \frac{23\cdot\left(P\cdot L^3\right)}{1296\cdot E_{true}\cdot\left(\frac{b\cdot h^3}{12}\right)}\cdot\left[1+\frac{21.6\cdot\left(\frac{E}{G}\right)\cdot\left(\frac{d}{L}\right)^2}{23}\right]$$

For Douglas Fir, an $^{E}/_{G}$ = 16 is assumed Span to depth ratio = 21:1 $\frac{72\cdot in}{3.5\cdot in} = 20.57143$

$$\Delta = \frac{P\cdot L^3}{\frac{108}{23}\cdot E_{true}\cdot\left(b\cdot h^3\right)}\cdot\left[1+\frac{21.6\cdot(16)\cdot\left(\frac{1}{21}\right)^2}{23}\right]$$

$$\Delta = \frac{P\cdot L^3}{4.7\cdot E_{true}\cdot\left(b\cdot h^3\right)}\ [1.034] \qquad \text{OR} \qquad E_{true} = \frac{P\cdot L^3}{4.7\cdot\left(b\cdot h^3\right)\cdot\Delta}\ [1.034]$$

Comparing back to ASTM D198 . . .

$$E_{apparent} = \frac{P\cdot L^3}{4.7\cdot b\cdot h^3\cdot\Delta}$$

Therefore, for the loading condition . . .

$$E_{true} = E_{apparent}\cdot 1.034$$

Again, this adjustment was not applied to any of the MOE values. Therefore, all the MOE values analyzed were apparent MOE values.

MODULUS OF RUPTURE DISTRIBUTION DETERMINATION

PROBABILITY PLOTS

Estimate the distribution parameters - plotting the data on probability scales and using the least squares method to estimate the best fit parameters (ALL CALCULATIONS DEMONSTRATED ARE FOR SOLID SAWN NO TEMPERATURE).

Normal Distribution

x-axis: yield strength data, x

y-axis: $\Phi^{-1}(p_i)$

y = 0.0004x - 2.2642 (from graph)

Lognormal Distribution

x-axis: y = ln(x)

y-axis: $\Phi^{-1}(p_i)$

y = 2.2082x - 18976 (from graph)

$$p_i = \frac{i}{n+1}$$

2-p Weibull Distribution

A transformation of the $F_X(x)$ equation must be performed in order to obtain an appropriate set of plotting scales

$$F_X(x) = 1 - e^{-\left(\frac{x}{k}\right)^{\beta}}$$

$$\ln(1 - F_X(x)) = -\left(\frac{x}{k}\right)^{\beta}$$

$$\ln(-\ln(1 - F_X(x))) = \beta\cdot\ln(x) - \beta\cdot\ln(k)$$

x-axis: $y = \ln(x)$ y-axis: $z = \ln(-\ln(1 - F_X(x)))$ $b = -\beta\cdot\ln(k)$

z = by + b -----> y = 2.6957x - 23.694 (from graph) therefore: $\beta := 2.6957$

also, b = -23.694 = -βln(k)

$$k := e^{\frac{-23.694}{-\beta}}$$ therefore: $k = 6.565 \times 10^{3}$

Although these values are reasonable, a more numerical approach can be used . . .

2-P Weibull beta - K solver

Determining the scale and shape parameters for the 2-P Weibull Distribution:

$\mu_{Mu} := 5817.472 \qquad \sigma_{Mu} := 2265.990$

Using a solving block . . .

Start with seed values where k is marginally greater than β and both values are > one

$\beta := 2 \qquad k := 100$ [guess values]

Given

$$\mu_{Mu} = k\cdot\Gamma\left(1+\frac{1}{\beta}\right)$$ [Eqn. 2.71a] (Nowak and Collins,2000)

$$\sigma_{Mu} = \sqrt{k^2\cdot\left[\Gamma\left(1+\frac{2}{\beta}\right)-\left(\Gamma\left(1+\frac{1}{\beta}\right)\right)^2\right]}$$ [Eqn. 2.71b] (Nowak and Collins, 2000)

$$\mathrm{Find}(\beta,k) = \begin{pmatrix} 2.776792 \\ 6.535217\times 10^3 \end{pmatrix}$$

If either of the above values had been negative, the "guess values" would have been changed.

Coefficient of Determination

Which distribution(s) best represent the data - based on resulting R^2 values?

Normal Distribution: $R^2 = 0.9523$

Lognormal Distribution: $R^2 = 0.9726$

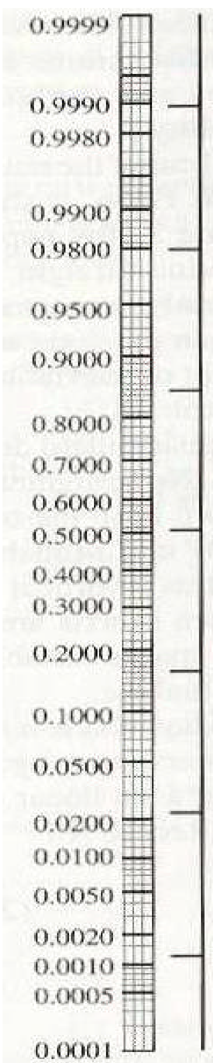
2-p Weibull Distribution: $R^2 = 0.9610$

Based on the above values, the lognormal distribution best fits the data set, that is its R^2 value is nearest to 1. It may be helpful to check another method as well.

Plots

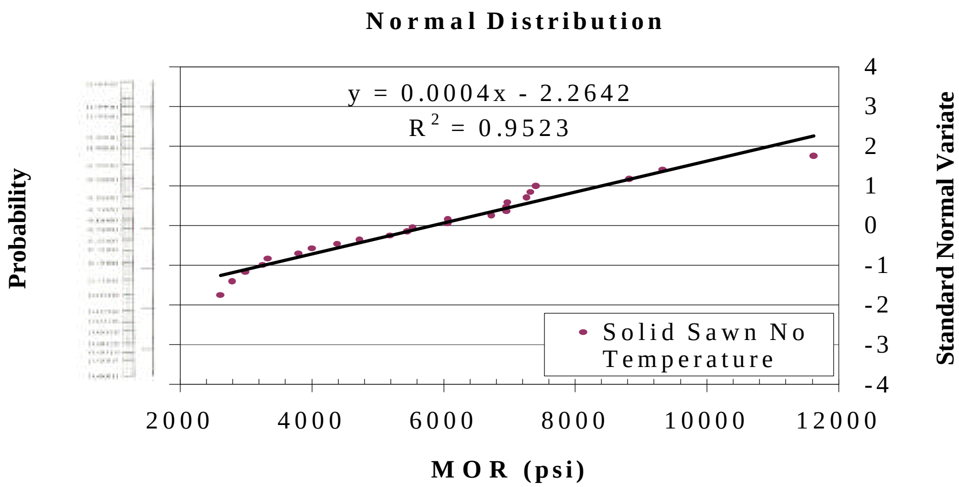
Visual examination of goodness of fit and comparison of the coefficients of determination were both used to determine the best fitting distribution. Plots are provided for all tested distributions for each temperature category.

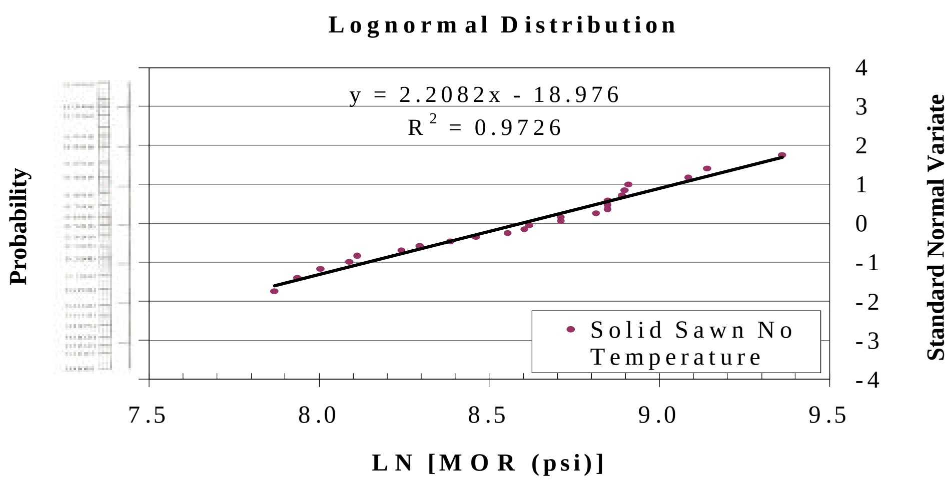
The scale on the left is a probability scale. The gridlines of the standard normal variate scale should coincide with the rightmost hash marks of the probability scale.

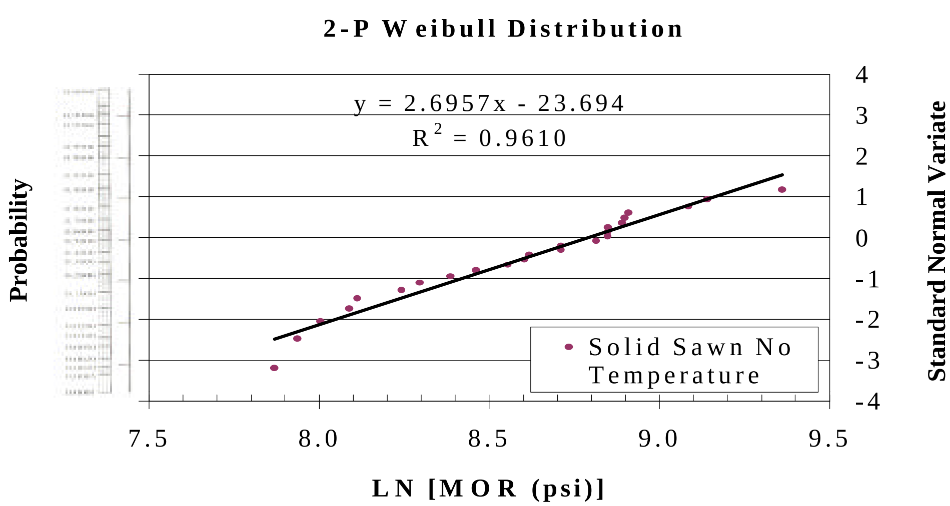


← Rightmost Hash Marks

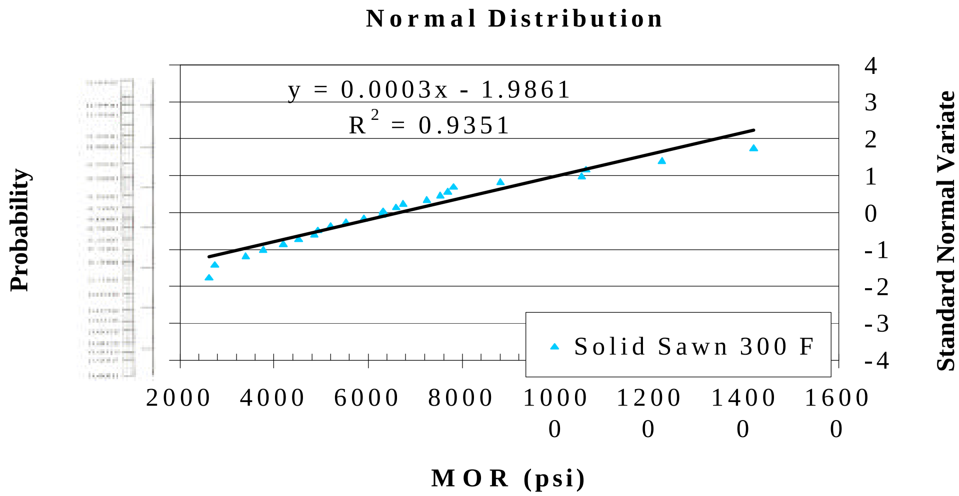
SOLID SAWN LUMBER: NO TEMPERATURE

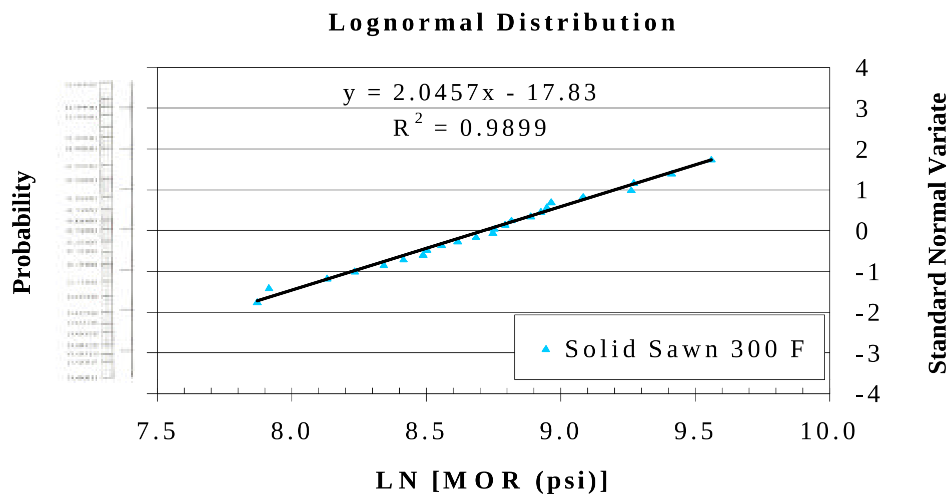


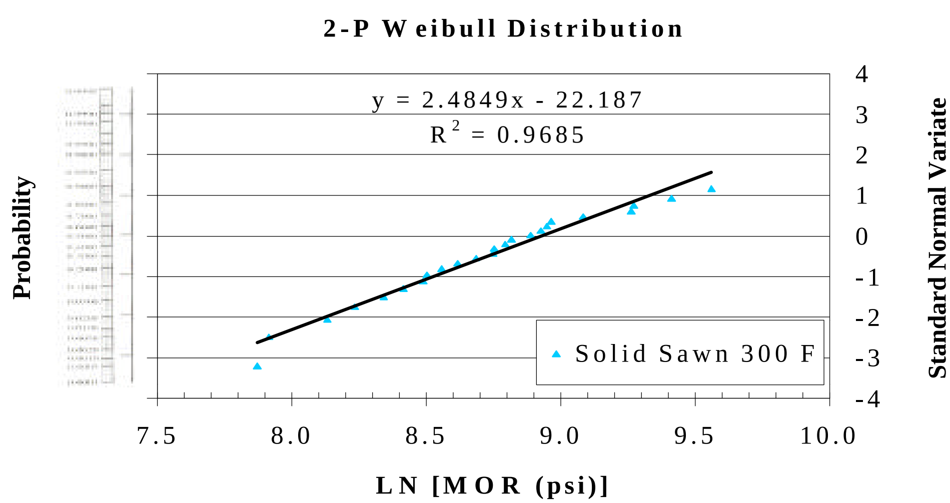




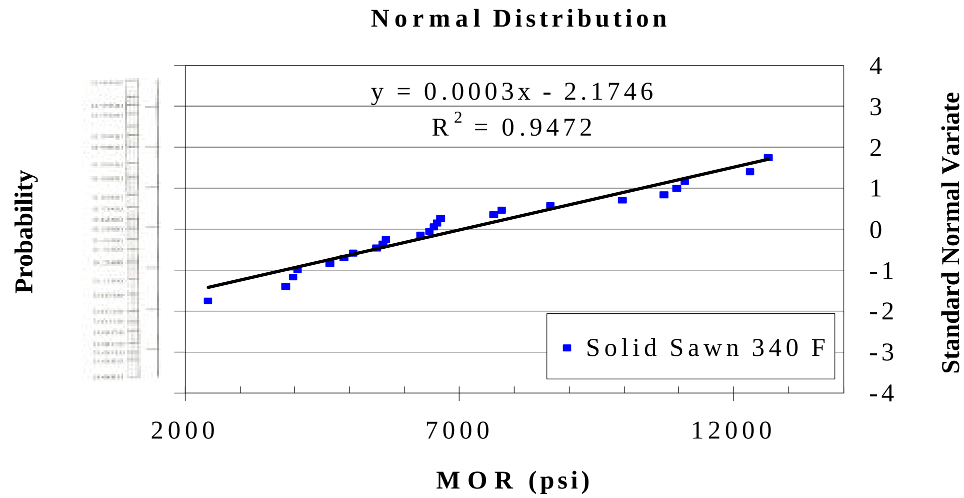
SOLID SAWN LUMBER: 300°F

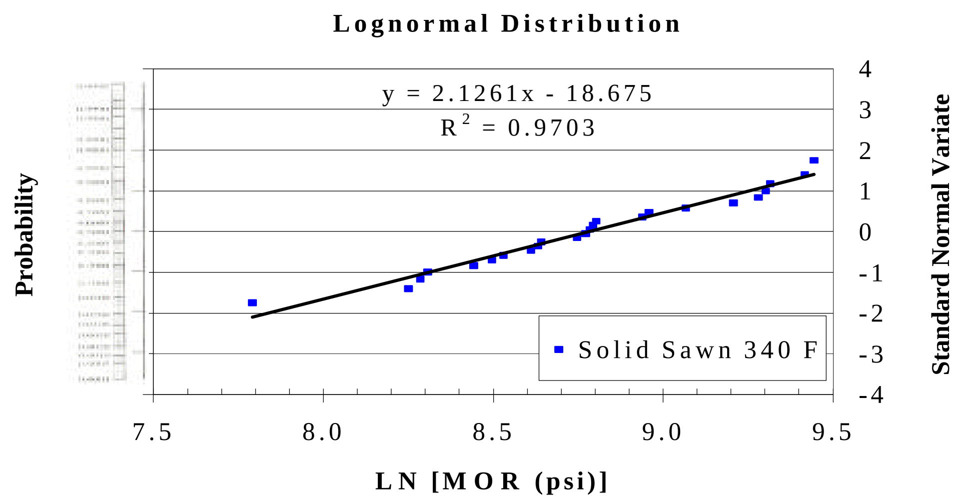


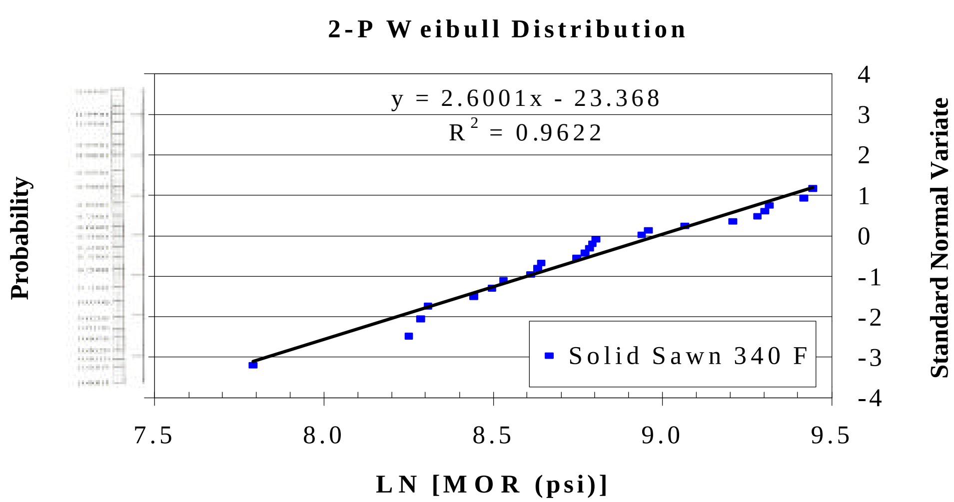




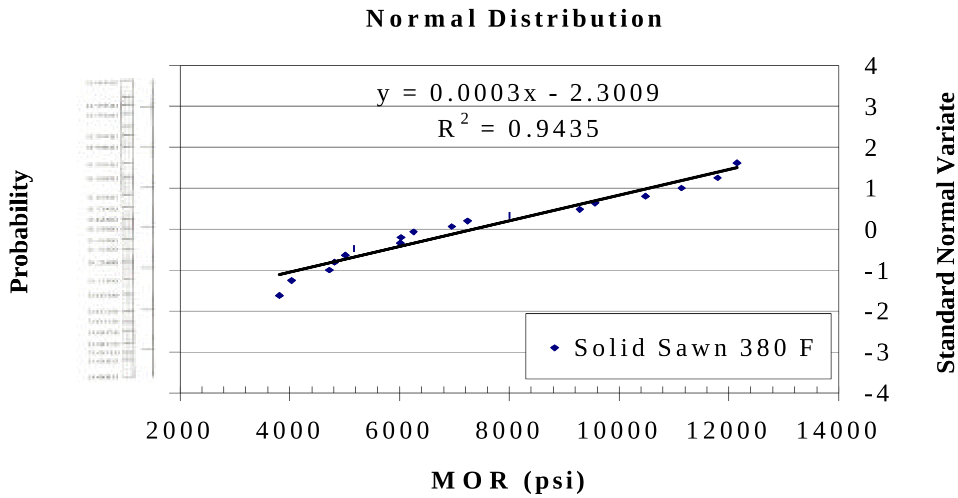
SOLID SAWN LUMBER: 340^{O}F

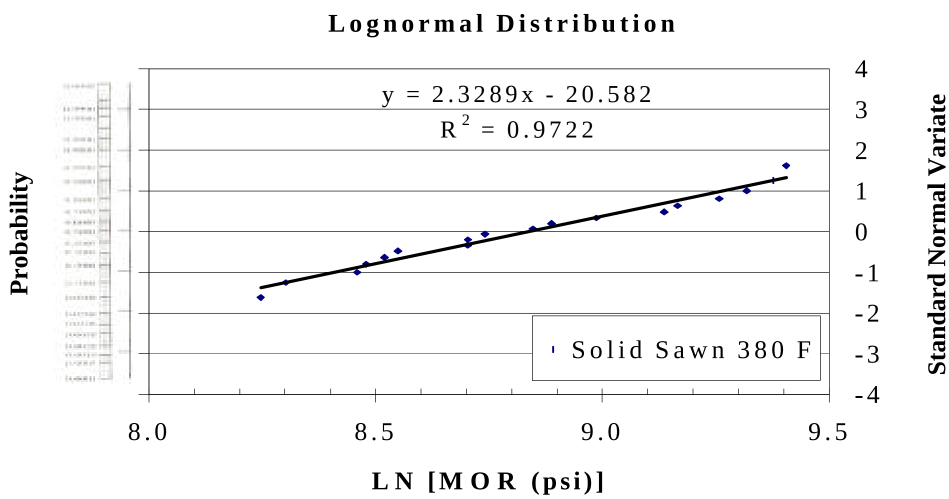


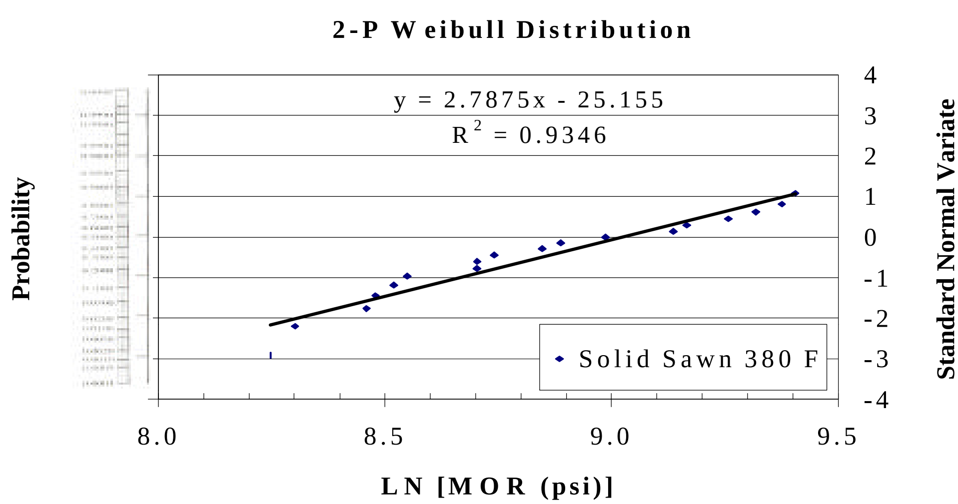




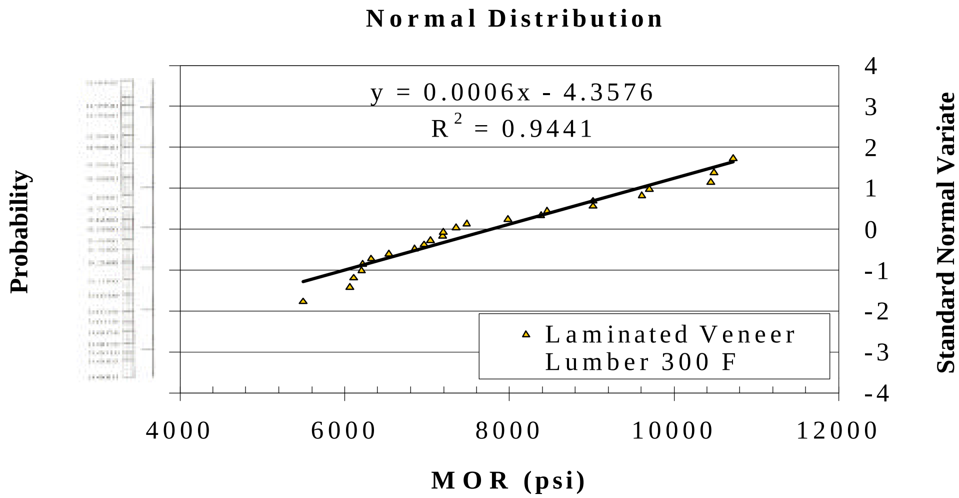
SOLID SAWN LUMBER: 380°F

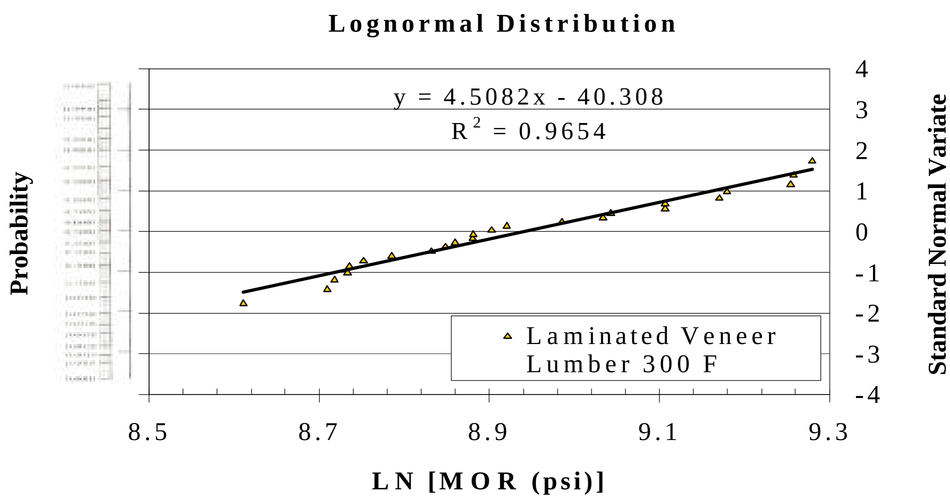


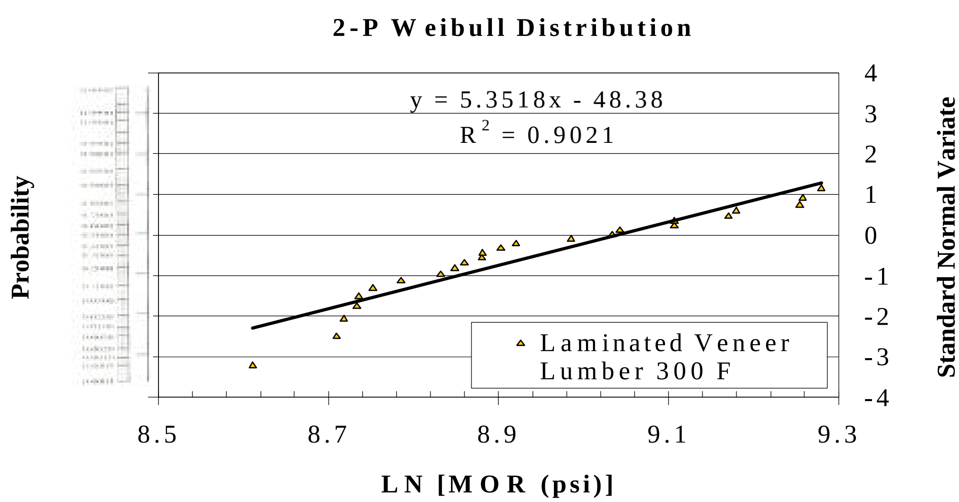




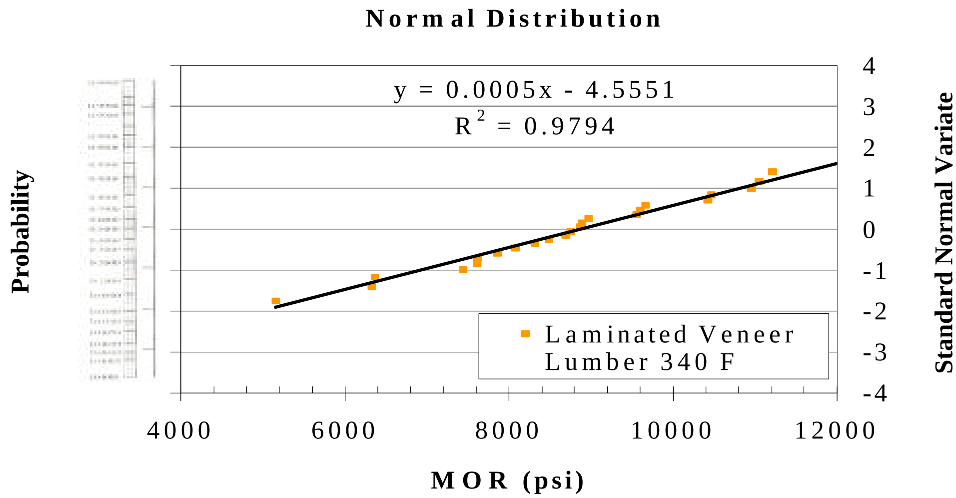
LAMINATED VENEER LUMBER: 300^{O}F

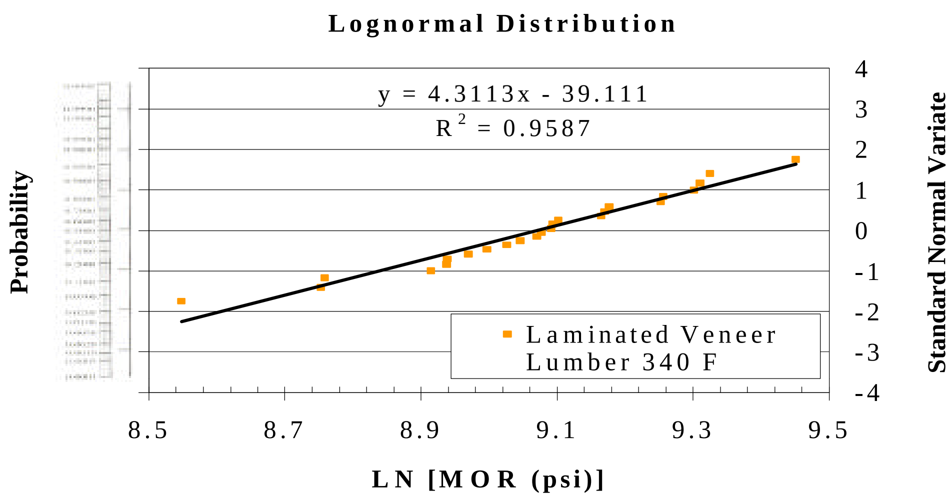


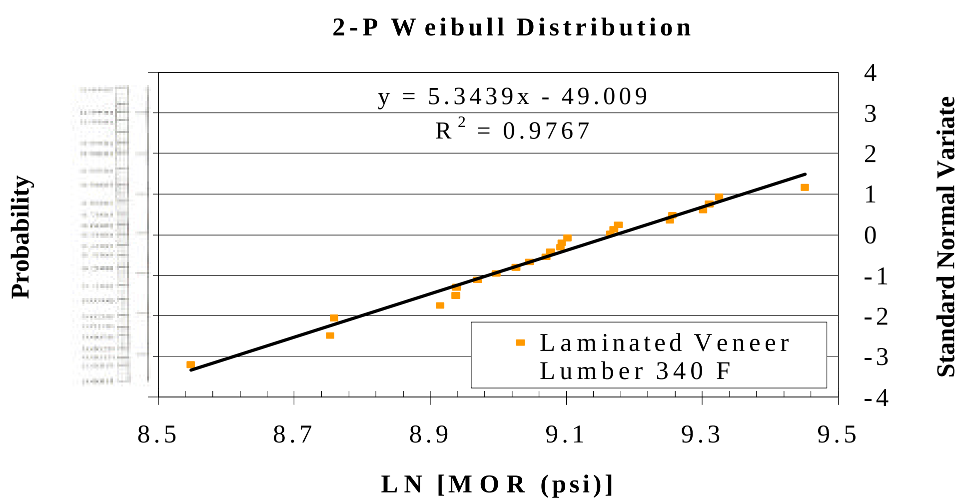




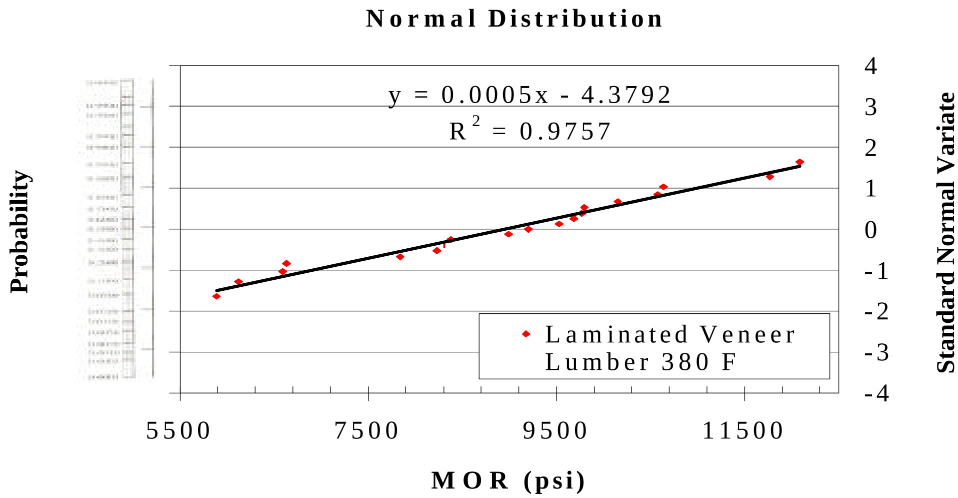
LAMINATED VENEER LUMBER: 340°F

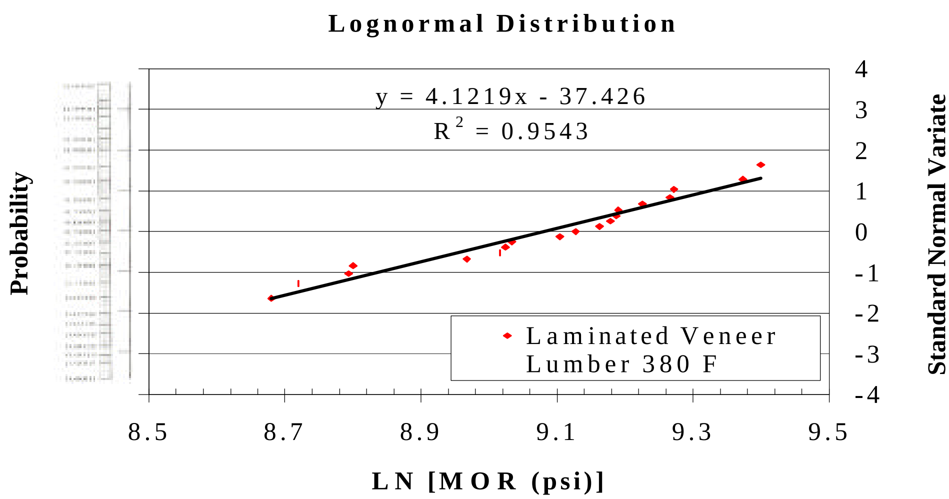


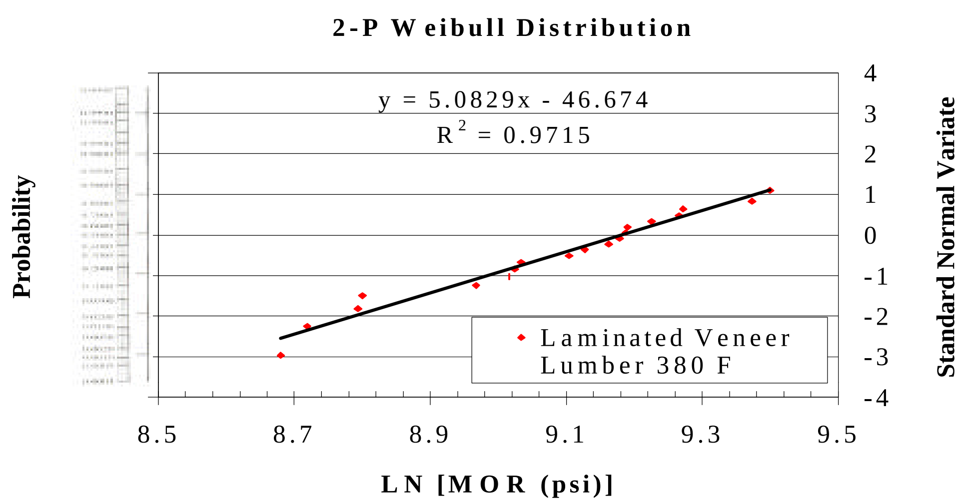




LAMINATED VENEER LUMBER: 380°F







INVERSE CDF

The inverse CDF method allows the comparison between the actual data and the estimated data. Thus, the ideal distribution would have an inverse CDF that follows a 1-to-1 relationship.

$$F_X^{-1}(F_X(x_i)) = F_X^{-1}\left(\frac{i}{n+1}\right)$$

The inverse CDF was estimated (y-axis values) using the following . . .

Normal Distribution (from excel)
NORMINV (p_i, μ_x, σ_x)

Lognormal Distribution (from excel)
LOGINV (p_i, μ_y, σ_y)

2-p Weibull Distribution (solving for x from $F_X(x)$)

$$x = \kappa(-\ln(1-F_X(x)))^{1/\beta}$$

$$x = 6535.217 \cdot \left(-\ln\left(1-p_i\right)\right)^{\frac{1}{2.777}}$$

Regression analysis performed between the actual data and the distribution data. The Intercept and X-Variable Standard Error were compared . . .

	Normal Distribution	*Lognormal Distribution*	*2-p Weibull Distribution*
Intercept	316.9	234.9	277.7
X-Variable	0.052	0.038	0.452

Also, the standard error estimate was calculated: $\sqrt{\frac{\left(1-r^2\right)\cdot(n-1)}{(n-2)}}$

Normal Distribution

$$\sqrt{\frac{\left(1-0.9523^2\right)\cdot(24-1)}{(24-2)}} = 0.312$$

Lognormal Distribution

$$\sqrt{\frac{\left(1-0.9718^2\right)\cdot(24-1)}{(24-2)}} = 0.241$$

2-p Weibull Distribution

$$\sqrt{\frac{\left(1-0.962^2\right)\cdot(24-1)}{(24-2)}} = 0.279$$

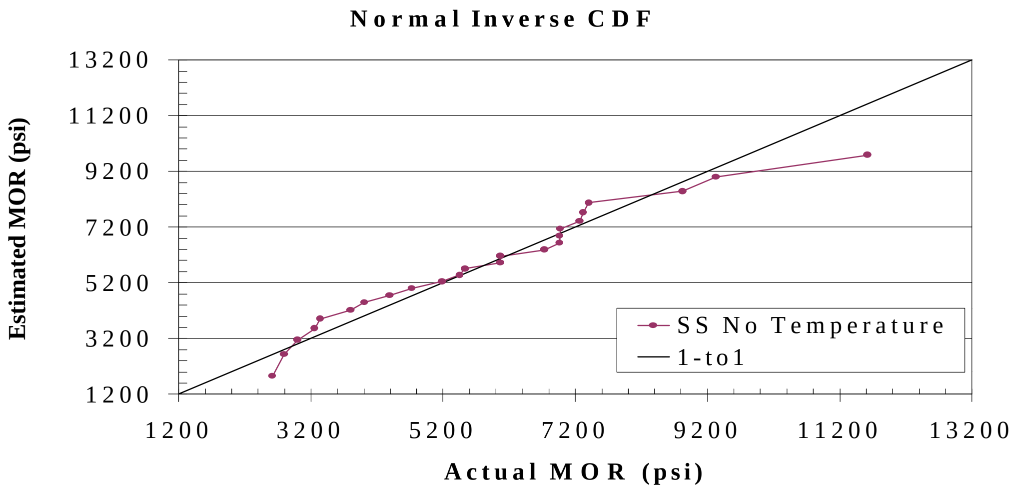
Based on the above values, the lognormal distribution best fits the data set, that is the standard error values are the lowest. In fact, a lognormal distribution proved to be the best fit for all test categories.

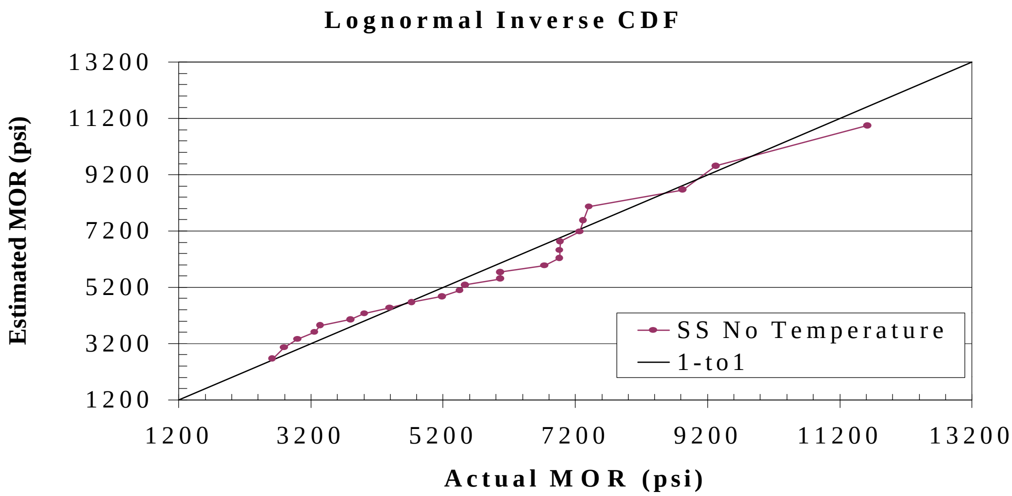
USE A LOGNORMAL DISTRIBUTION

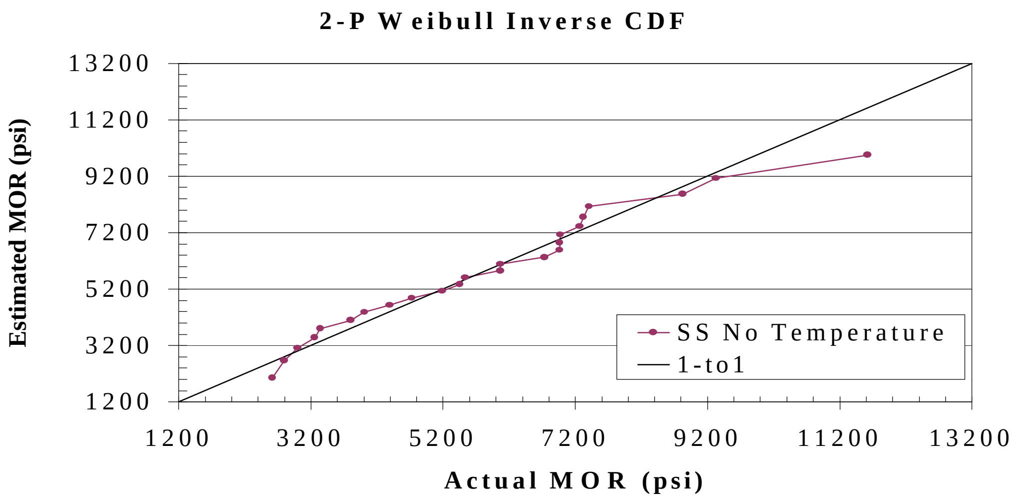
Plots

Inverse CDF plots are provided for all tested distributions for all temperature categories.

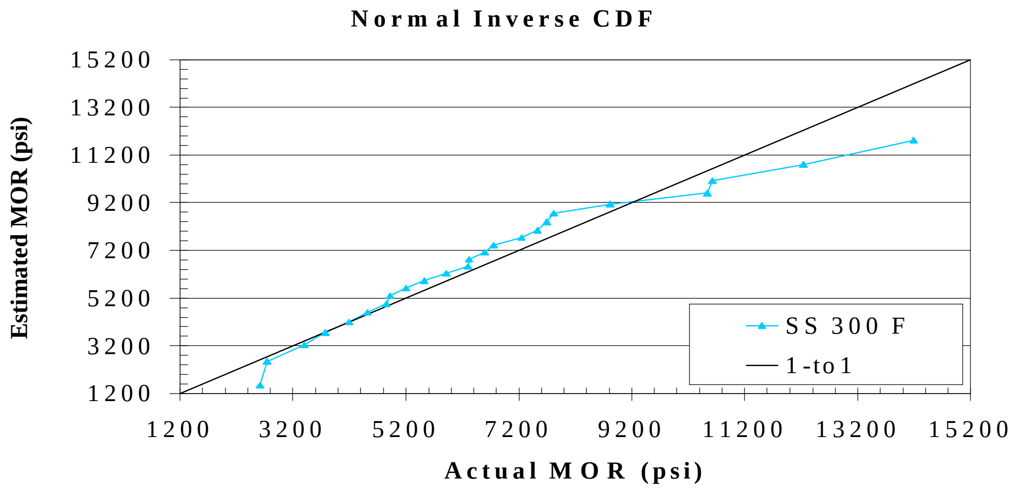
SOLID SAWN LUMBER: NO TEMPERATURE

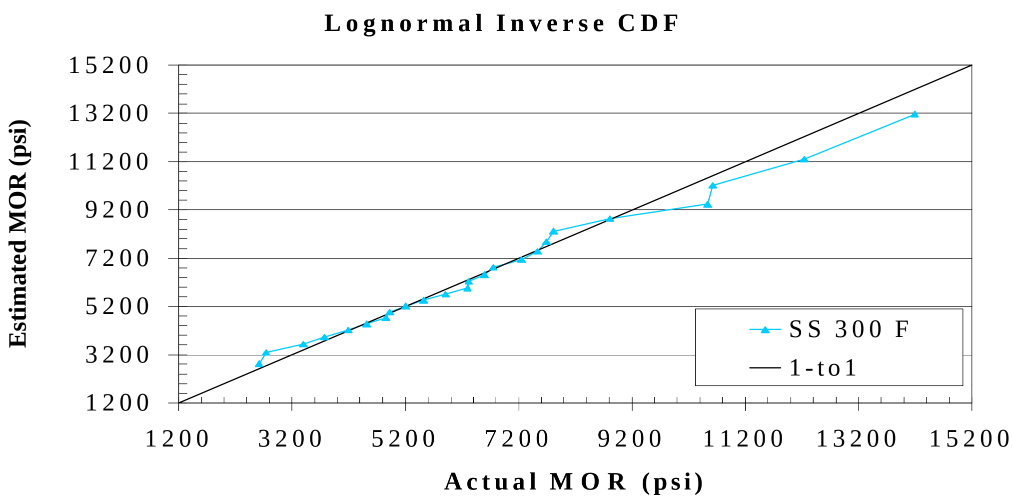


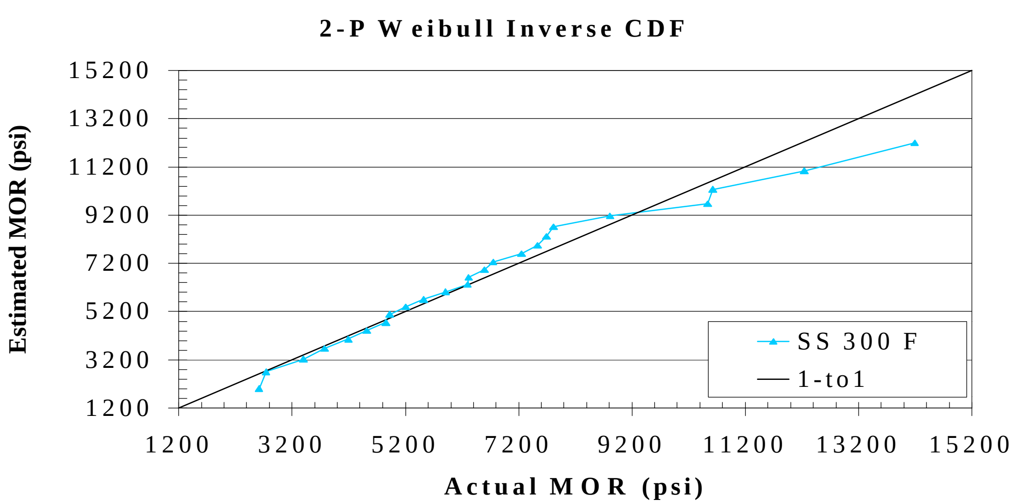




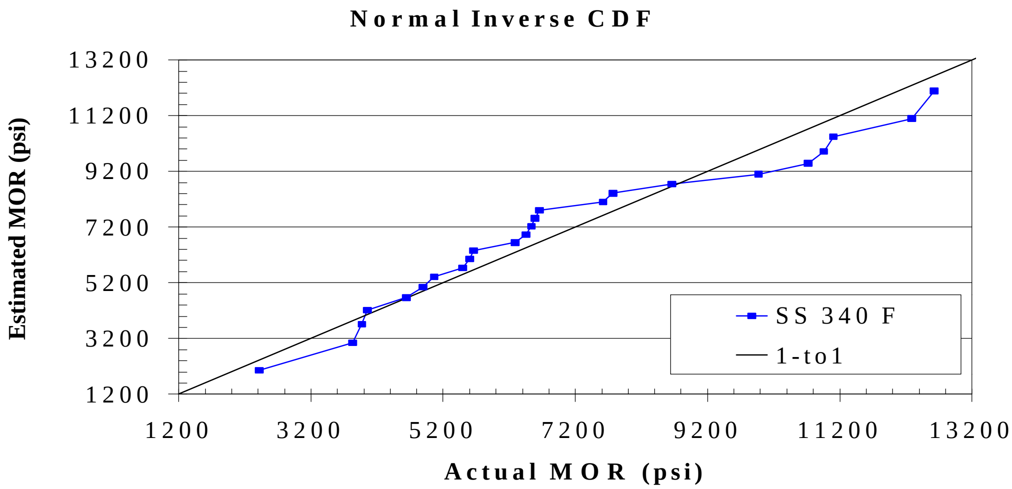
SOLID SAWN LUMBER: 300^{O}F

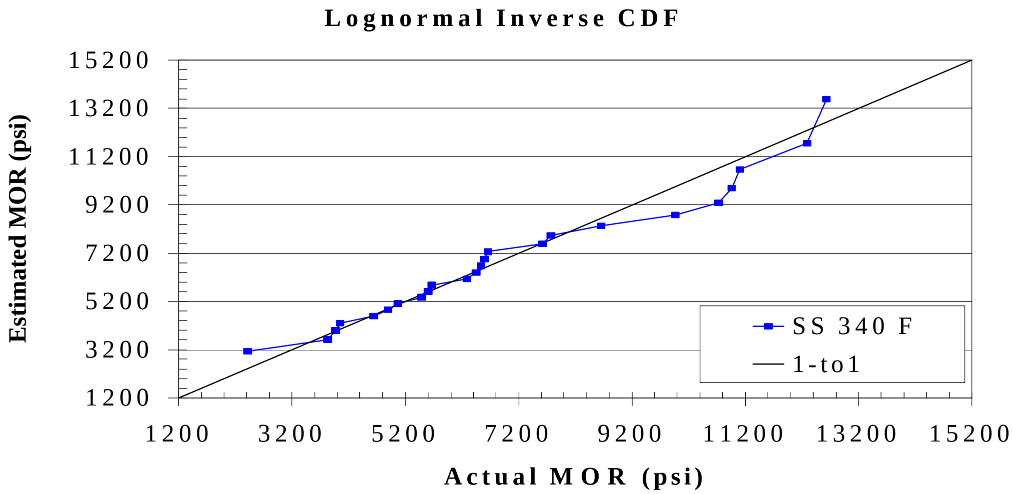


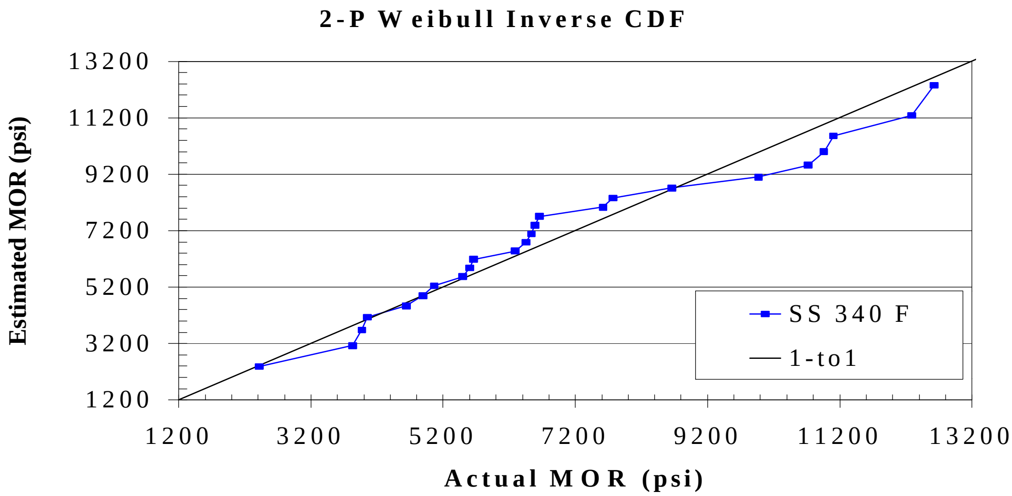




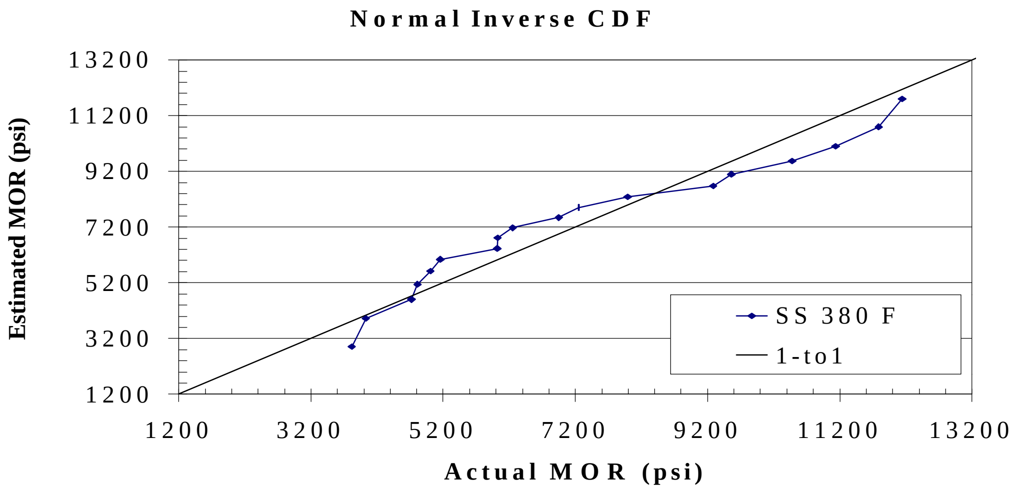
SOLID SAWN LUMBER: 340°F

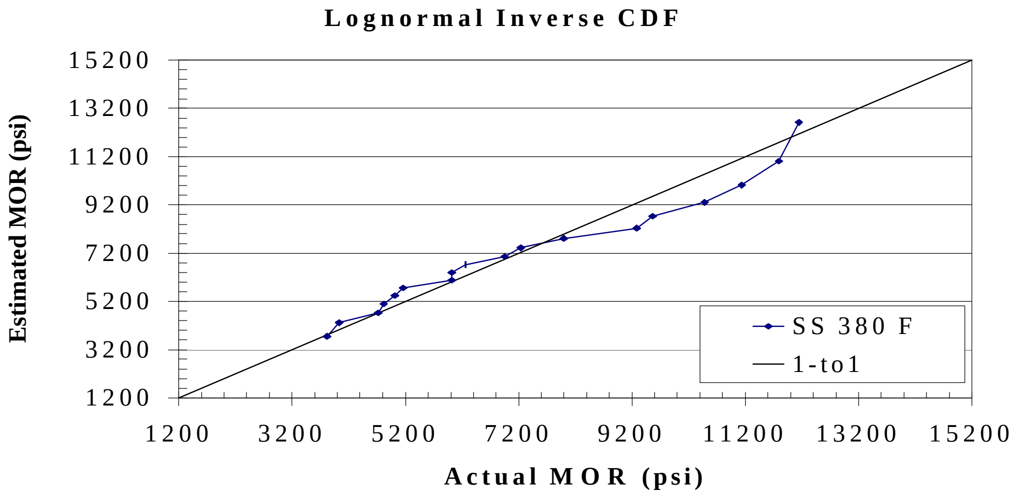


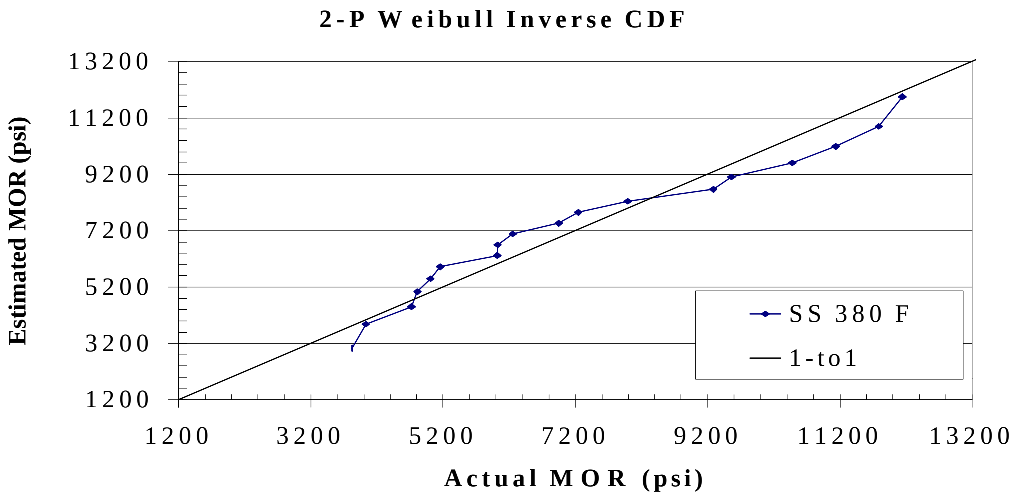




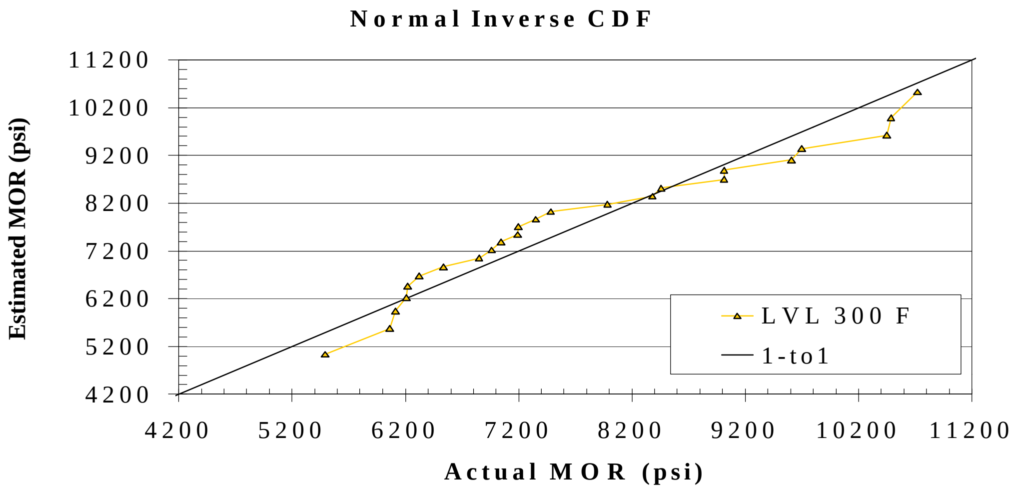
Solid Sawn Lumber: 380°F

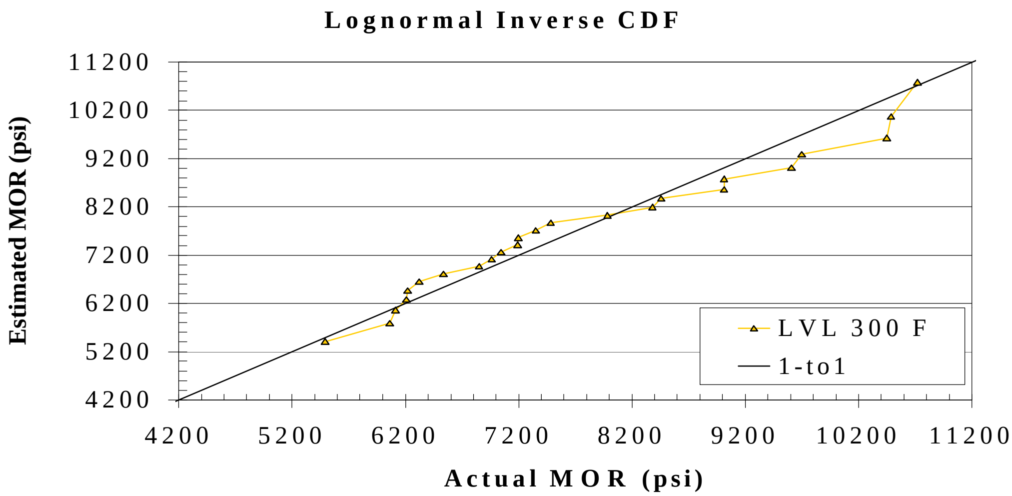


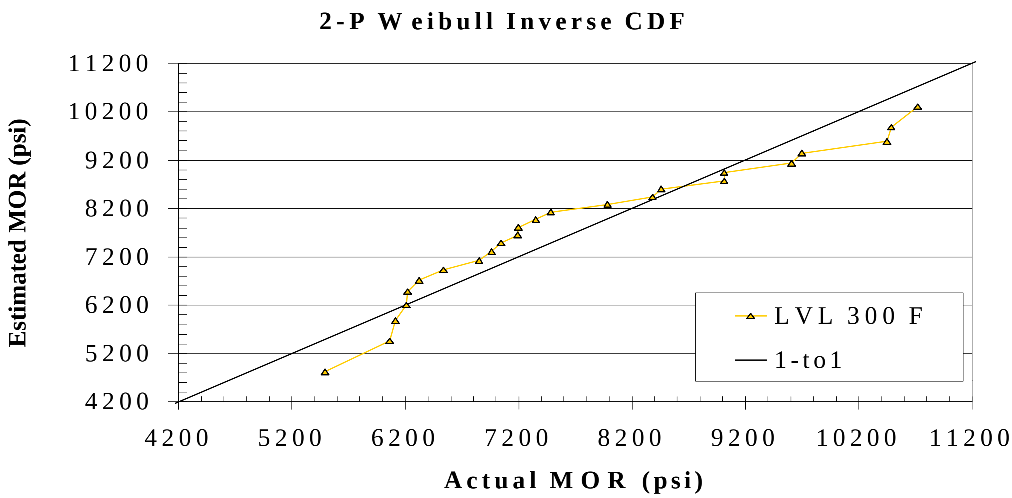




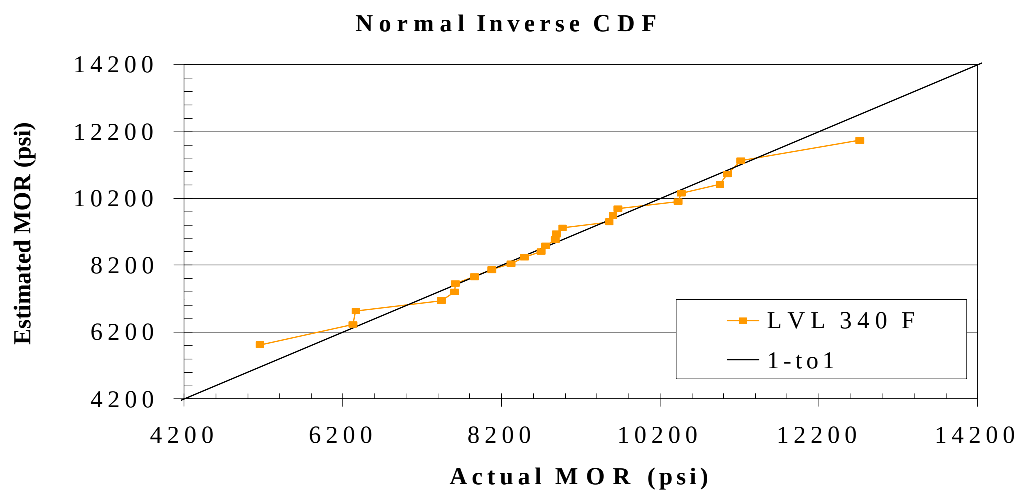
LAMINATED VENEER LUMBER: 300^{O}F

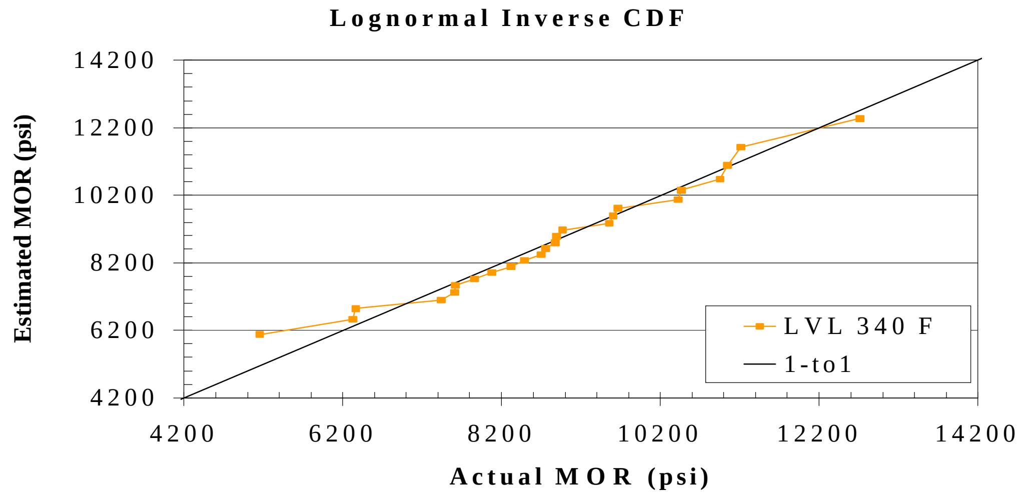


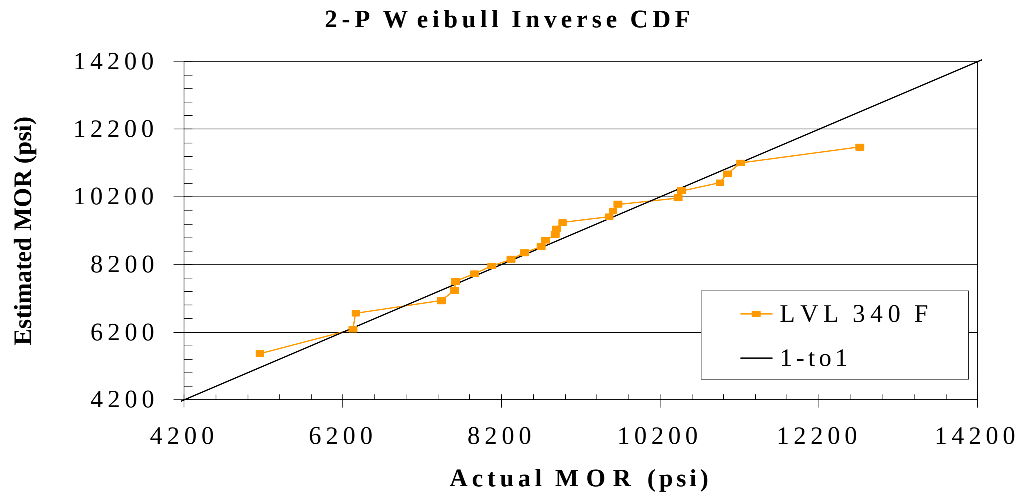




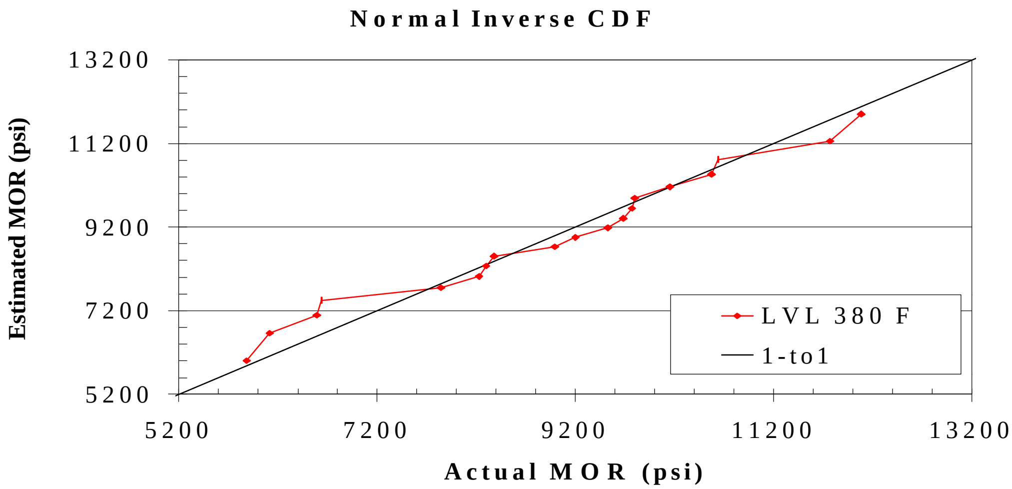
LAMINATED VENEER LUMBER: 340°F

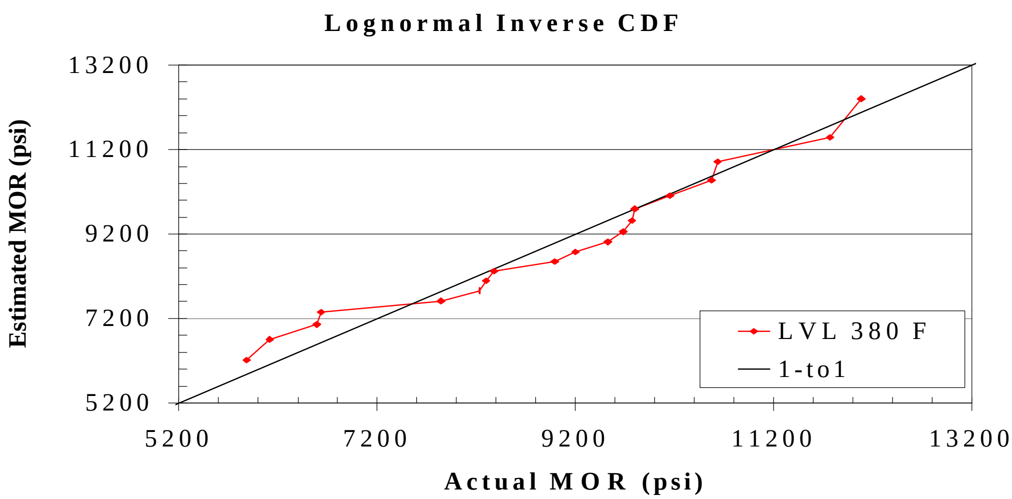


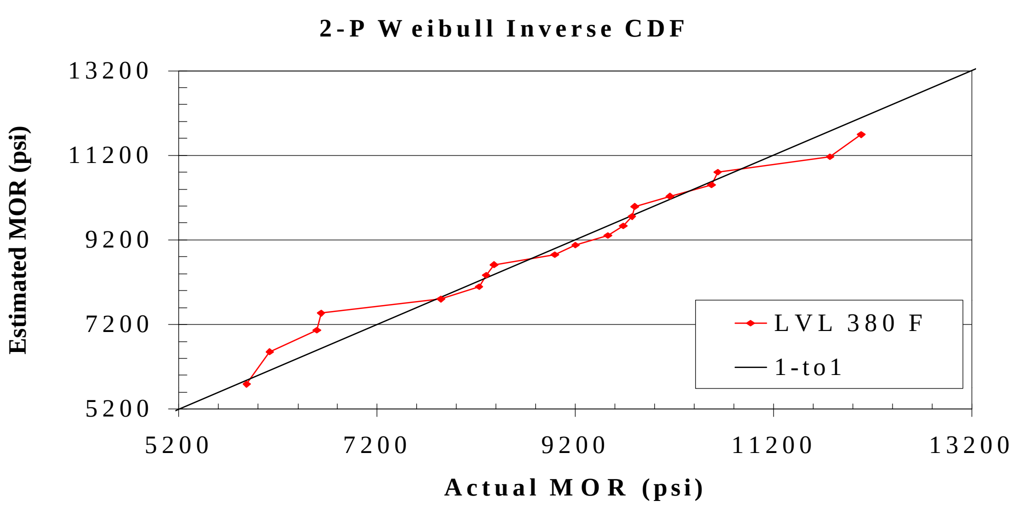




LAMINATED VENEER LUMBER: 380^{O}F







ALLOWABLE BENDING STRESS

Wood design values are based on the fifth percentile value rather than mean values. Because of this, it is necessary to determine a five percent tolerance limit with 75% confidence for strength properties.

For the MOR values obtained from static testing, the above three distributions were used to try and fit the data. It was found that the lognormal distribution best represented the MOR data. Since the distribution is known, a parametric approach can be used. A nonparametric approach was also performed for comparison.

Parametric Approach

5% exclusion limit with a parametric tolerance limit at 75% confidence for bending strength data (lognormal distribution assumed):

Sample size = 24 $\quad X_{bar} := 8.593382904 \quad s := 0.403611178$

Find the sample size, n, in TABLE 3 from ASTM D2915

For a 5% tolerance limit (exclusion), use 1-p = 0.95

Find the appropriate K value: $\quad K := 1.901$

Use the equation: $\quad MOR_{0575} := X_{bar} - K \cdot s \quad MOR_{0575} = 7.826$

Convert the value into a non-log value: $\quad x_{05} := e^{MOR_{0575}} \quad x_{05} = 2505.185$

For a design value, the end use factor (1.3) and the load duration factor (1.6) are taken into account:

$$F_b := \frac{x_{05}}{2.1} \qquad F_b = 1192.945 \ \frac{lb}{in^2}$$ for edgewise bending

Nonparametric Approach

5% exclusion limit with a nonparametric tolerance limit at 75% confidence for bending strength data (no distribution assumed):

Find the sample size, n, in TABLE 2 from ASTM D2915

Sample size = 24 $X_{bar} := 5817.472$ $s := 2265.990$

Since N < 28, the order statistic 1, the lowest value, must be used $MOR_{NP} := 2614.726$

For a design value, the end use factor (1.3) and the load duration factor (1.6) are taken into account: $F_b := \frac{MOR_{NP}}{2.1}$ $F_b = 1245.108\ \frac{lb}{in^2}$ for edgewise bending

NDS design value for Standard grade dimension lumber: $F_b := 575 \cdot \frac{lb}{in^2}$

The design value found using the parametric approach was lower than that of the nonparametric approach. This was not expected since the reverse is usually true, that is, the nonparametric approach is usually more conservative. However, both values were larger than the NDS design value for Standard grade dimension lumber. This is not surprising because the lumber was graded as Standard or Better and because Standard grade is inclusive of a wide range of material which drives down the published design values. However, there are six visually graded categories that are "better" that Standard grade. This could potentially increase experimentally found design values. A larger sample size of Standard grade would provide calculated design values closer to the published design values.

LAMINATED BEAM THEORY

Use the bending stiffness (D) to compute the apparent Bending Modulus of Elasticity:

$$E = D \cdot \frac{12}{b \cdot t^3}$$

E = Apparent Bending Modulus of Elasticity

D = bending stiffness (a product of material and geometric properties)

b = width of the section (depending on orientation)

t = thickness of the section (depending on orientation)

where D is computed for the composite with respect to the neutral axis:

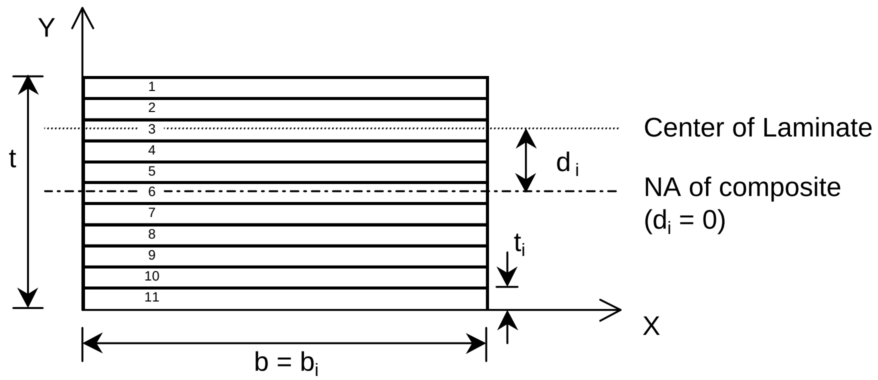
$$D = \sum_{i=1}^{n} \int_{y_{i-1}}^{y} b_i \cdot E_i \cdot y^2 \, dy$$

$$D = \sum_{i=1}^{n} b_i \cdot E_i \cdot \left[t_i \cdot \left(y_i - y_o\right)^2 + \frac{t_i^{\,3}}{12} \right]$$

Use a coordinate system where the neutral axis coincides with the origin:

$$D = \sum_{i=1}^{n} b_i \cdot E_i \cdot \left(t_i \cdot d_i^{\,2} + \frac{t_i^{\,3}}{12} \right)$$

HORIZONTAL LAMINATES - there exists a change in E with respect to depth in the beam



b_i = width of individual veneers (cut to dimension so constant) = b

E_i = Modulus of Elasticity for individual veneers

t_i = thickness of individual veneers

t = thickness of composite section

d_i = distance between the composite neutral axis and the individual laminate

Substituting the equation for bending stiffness for horizontal laminates into the equation for apparent Bending Modulus of Elasticity (flatwise bending):

$$E = \frac{12}{b \cdot t^3} \cdot \sum_{i=1}^{n} b_i \cdot E_i \cdot \left(t_i \cdot d_i^2 + \frac{t_i^3}{12} \right)$$

Since b = bi, section width does not have an effect on the apparent E:

$$E = \frac{12}{t^3} \cdot \sum_{i=1}^{n} E_i \cdot \left(t_i \cdot d_i^2 + \frac{t_i^3}{12} \right)$$

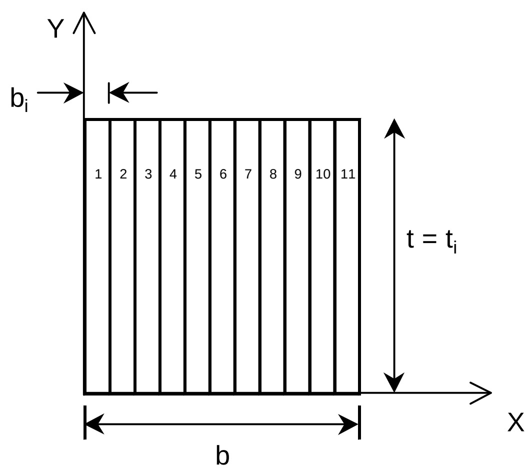
where several options for t, to represent "section" thickness, were used:

$E_{composite\text{-}horz}$: t = average thickness of the LVL member (caliper measurements)

$E_{billet\text{-}horz}$: t = average thickness of the entire billet (caliper measurements)

$E_{expected\text{-}horz}$: t = expected press controlled thickness of 1.5 inches (assumed dimension)

VERTICAL LAMINATES - there exists NO change in E with respect to depth in the beam



b_i = thickness of individual veneers

b = thickness of composite section

E_i = Modulus of Elasticity for individual veneers

t_i = width of individual veneers (cut to dimension so constant) = t

Because the laminates are vertical, there is no change in E with respect to the depth of the beam so $d_i = 0$:

$$D = \sum_{i=1}^{n} \frac{b_i t^3}{12} \cdot E_i$$

$$D = \frac{t^3}{12} \cdot \sum_{i=1}^{n} b_i E_i$$

Substituting the equation for bending stiffness for vertical laminates into the equation for apparent Bending Modulus of Elasticity (edgewise bending):

$$E = \left(\frac{t^3}{12} \cdot \sum_{i=1}^{n} b_i E_i \right) \cdot \frac{12}{b \cdot t^3}$$

$$E = \frac{\sum_{i=1}^{n} b_i E_i}{b}$$

where several options for b, to represent section edgewise width ("section" thickness), were used:

$E_{composite}$: b = average thickness of the LVL member (caliper measurements)

E_{billet}: b = average thickness of the entire billet (caliper measurements)

$E_{expected}$: b = expected press controlled thickness of 1.5 inches (assumed dimension)

REFERENCES

Hoyle, R.J., and Woeste, F.E. (1989). Wood Technology in the Design of Structures, 5th Ed. Iowa State University Press, Ames, Iowa.

Nowak, A.S., and Collins, K.R. (2000). Reliability of Structures. McGraw-Hill Book Co. New York, NY.

Timoshenko, S. P., and Goodier, J. N. (1970). Theory of Elasticity, 3rd Ed. McGraw-Hill Book Co. New York, NY. 291-315.

APPENDIX C

RESIN SPECIFICATIONS AND PRESSING PLOTS

INTRODUCTION

The Williams & White Press from Pressman has the capability of monitoring several variables of the manufacturing process. When thermocouples are used, that is in the case of a practice billet, core temperature and core gas pressure per thermocouple can be monitored. Typically, one thermocouple was placed in the center of the billet and another was positioned near the surface veneers. Thermocouples #1 and #2 were not necessarily located in the same respective position for each practice billet. Mat pressure and mat thickness were two parameters that were monitored for both practice and test billets.

Resin specifications are provided. The phenol-formaldehyde resin was analyzed for cure time. From this analysis, plots were produced. The results depicted on these plots aided in the determination of the press time for the veneer billets.

PRESS SCHEDULE

PressMAN v7.8 Press Control rel. 06/14/2000 SK Software Copyright 1990-2000

Proj. Ref.: Temp All	Date......: 11-17-2000	Time......: 12:58:13
Prod. Ref.:	Panel ID..: All	File Name.: MEL-LVL2.REG
Press ID..: WSUWW	Mat Length: 101.5 in.	Mat Width.: 24.0 in.
Density...: 40.00 lb/ft3	Thickness.: 1.500 in.	Caul Thick: 0.000 in.
Units.....: IMPERIAL	Pressure..: MAT	Position..: THICKNESS

SEG.	CONTROL	SETPOINT	SEG. TIME	END CONDITION	EVENTS
1	FASTPOSN	-2.000 in./s	21 s	POSITION <= 2.250 in.	1 1
2	POSITION	50.00 %	1 s		2
3	POSITION	50.00 %	5 s		2
4	POSITION	1.750 in.	2 s	PRESSURE >= 1000.4 psi	
5	POSITION	1.540 in.	15 s	PRESSURE >= 200.4 psi	
6	POSITION	1.530 in.	120 s		
7	POSITION	1.500 in.	240 s		
8	POSITION	1.485 in.	240 s		
9	POSITION	1.470 in.	515 s		
10	PRESSURE	0.0 psi	70 s		
11	FASTPOSN	32.767 in.	30 s		1
12					
13					
14					
15					
16					
17					
18					
19					
20					

EVENT Listing:

EVENT 1: Fast Position Control	EVENT 2: Not Used
EVENT 3: Follow Density Rate Profile	EVENT 4: Not Used
EVENT 5: Begin Steam Injection Program	EVENT 6: Run Steam Injection Program
EVENT 7: Not Used	EVENT 8: Not Used
EVENT 9: Decelerate from Set Rate to 0	EVENT 10: Accelerate from 0 to Set Rate
EVENT 11: Setpoint is Given as Rate	EVENT 12: PID Control is Manual

PRESS PRESSURE/POSITION PID PARAMETERS	LOOP 1 PRESSURE	LOOP 2 POSITION	LOOP 3 FAST POSTN	LOOP 4 NOT USED
Gain	3.00 %	40.00 %	15.00 %	N/A
Reset	0.20 %	2.00 %	0.00 %	N/A
Rate	0.00 %	0.00 %	0.00 %	N/A
Bias	50.00 %	50.00 %	50.00 %	N/A
Dead Band	0.00 %	0.00 %	0.00 %	N/A

Solid Sawn Lumber

149°C (300°F)

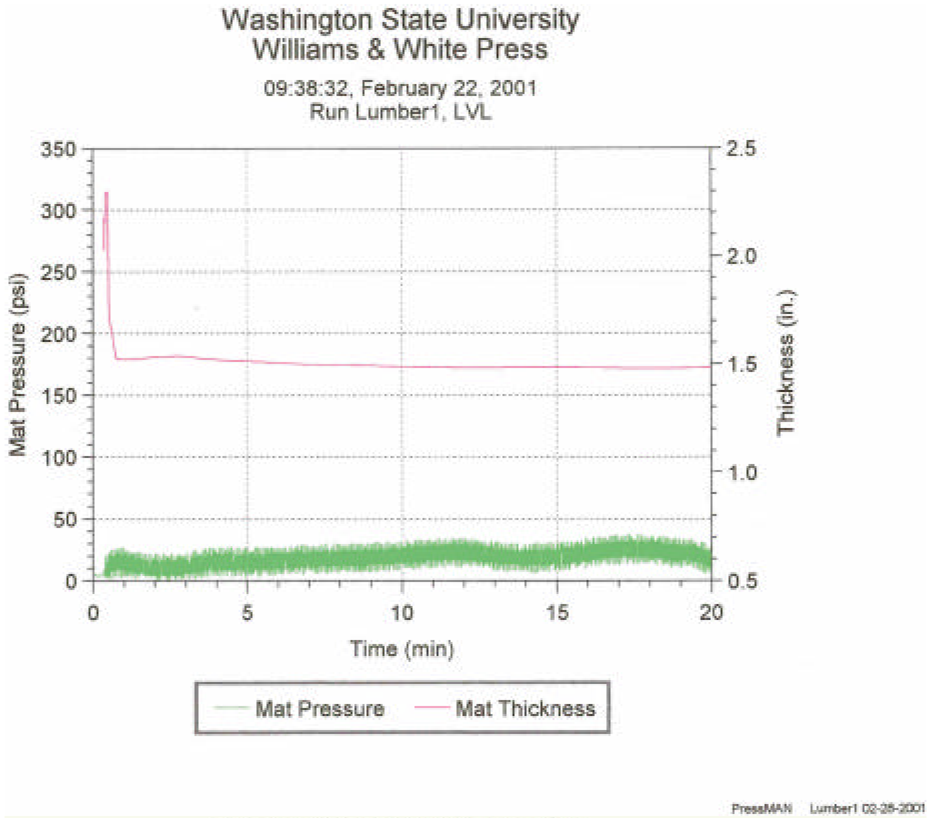
Day Heated:	February 22, 2001
Number of Plots:	4
Appendix Pages:	270 and 271

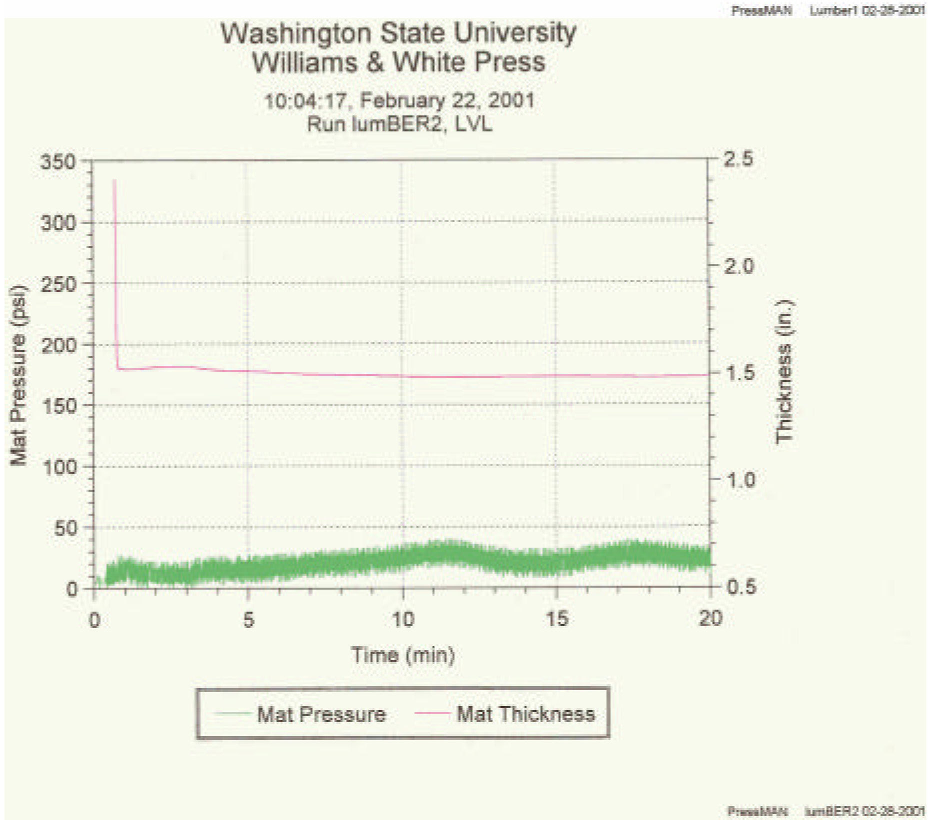
171°C (340°F)

Day Heated:	February 28, 2001
Number of Plots:	4
Appendix Pages:	272 and 273

193°C (380°F)

Day Heated:	February 27, 2001
Number of Plots:	3
Appendix Pages:	274 and 275


Washington State University
Williams & White Press
09:38:32, February 22, 2001
Run Lumber1, LVL
Mat Pressure (psi)
Thickness (in.)
Time (min)
Mat Pressure
Mat Thickness
PressMAN Lumber1 02-28-2001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Williams & White Press
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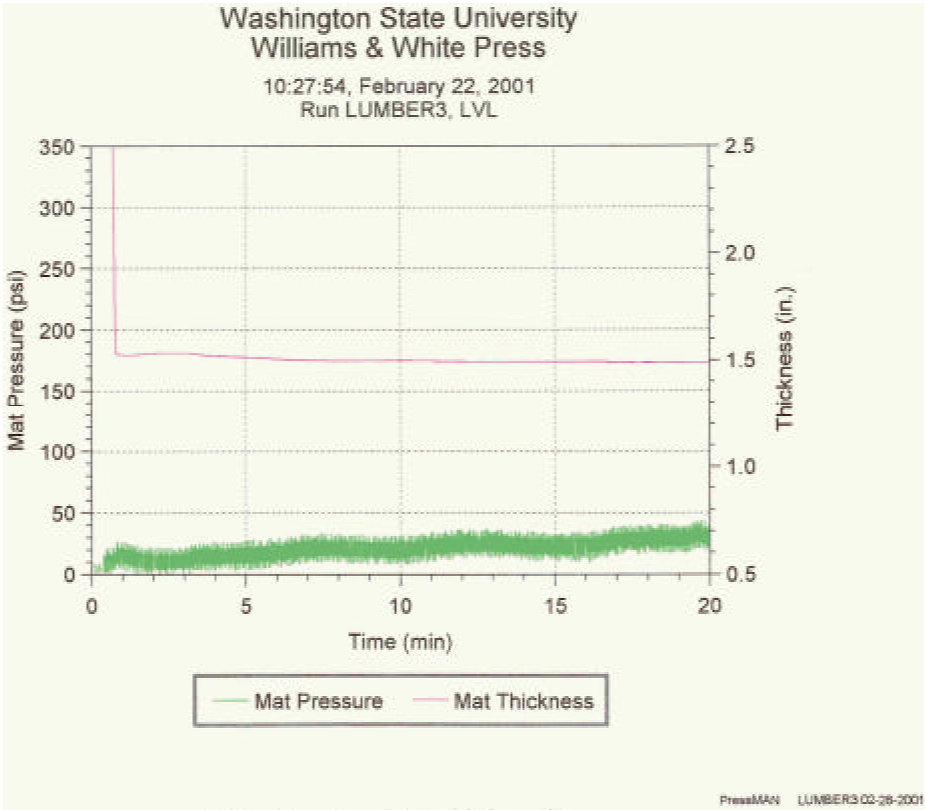
Run lumBER2, LVL
Mat Pressure (psi)
Thickness (in.)
Time (min)
Mat Pressure
Mat Thickness
PressMAN lumBER2 02-28-2001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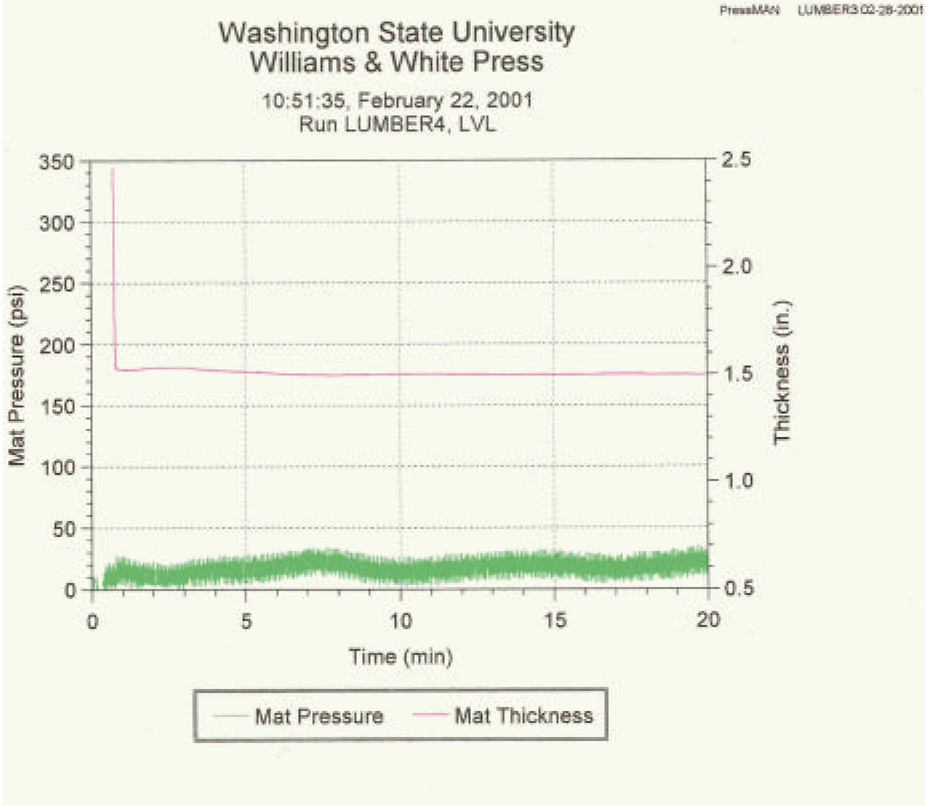
Mat Pressure (psi)
Thickness (in.)
Time (min)
Mat Pressure
Mat Thickness
PressMAN LUMBER3 02-28-2001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Williams & White Press
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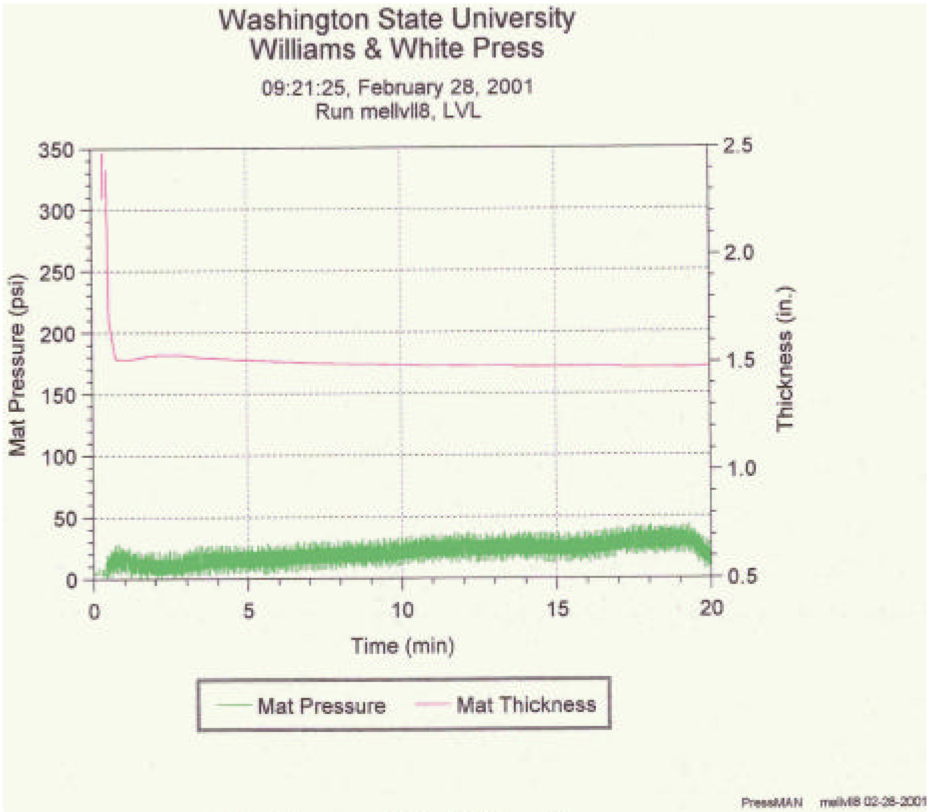
Mat Pressure (psi)
Thickness (in.)
Time (min)
Mat Pressure
Mat Thickness
PressMAN LUMBER4 02-28-2001


Washington State University
Williams & White Press
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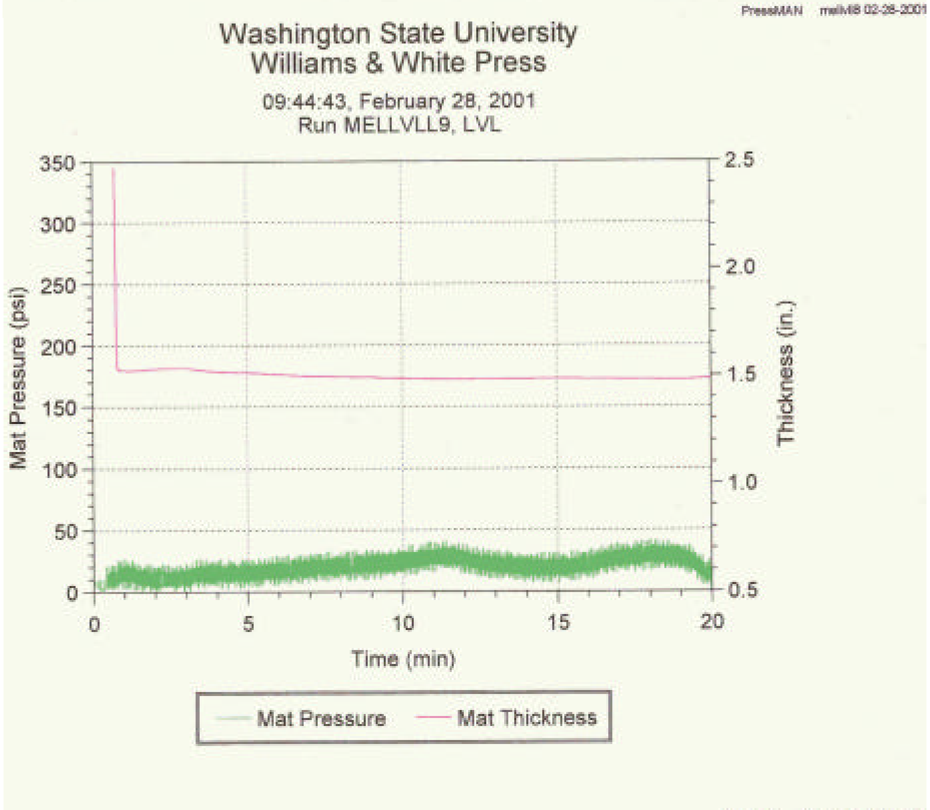
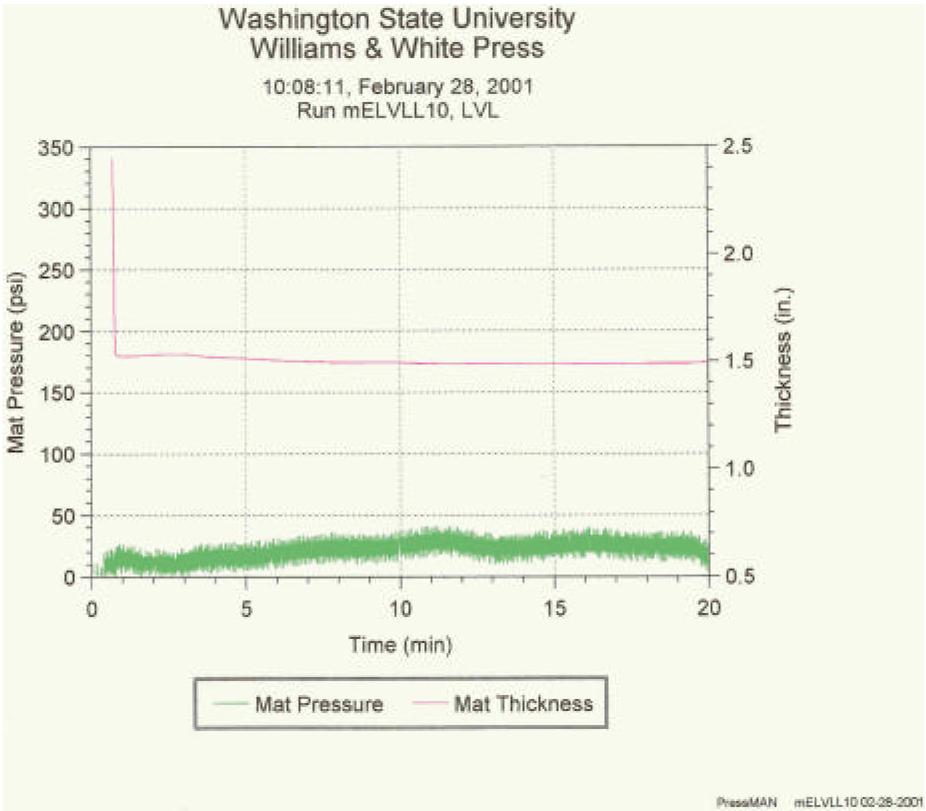
Run mellvll8, LVL
Mat Pressure (psi)
Thickness (in.)
Time (min)
Mat Pressure
Mat Thickness
PressMAN mellvll8 02-28-2001


Washington State University
Williams & White Press
09:44:43, February 28, 2001
Run MELLVLL9, LVL
Mat Pressure (psi)
Thickness (in.)
Time (min)
Mat Pressure
Mat Thickness
PressMAN MELLVLL9 02-28-2001


Washington State University
Williams & White Press
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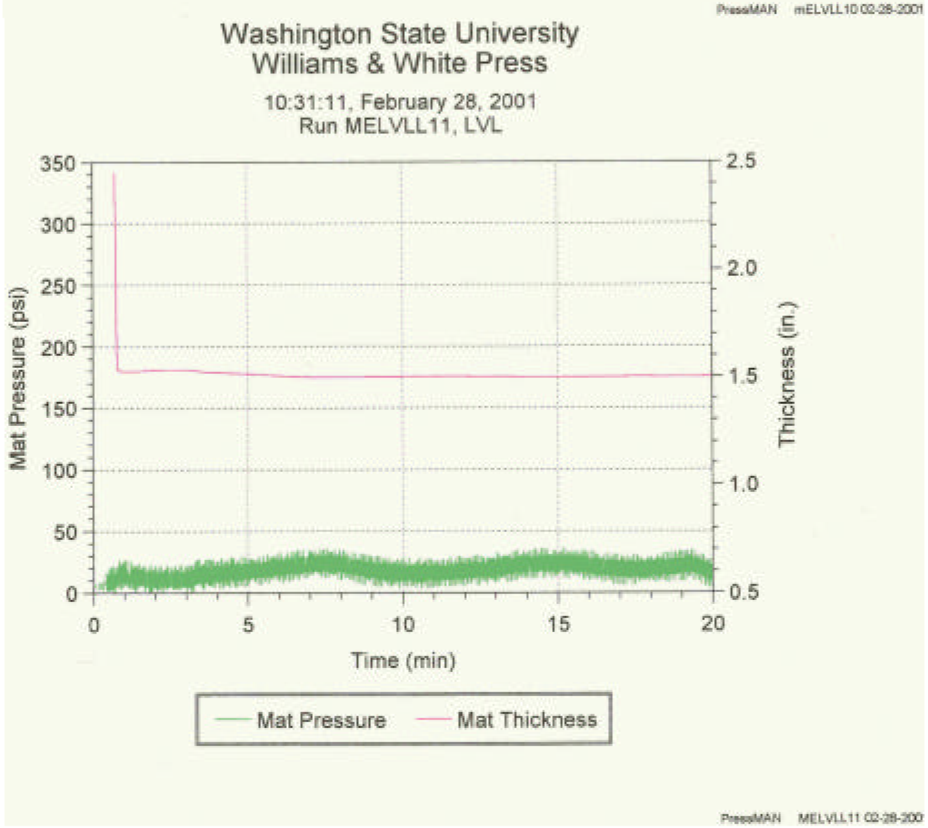
Mat Pressure (psi)
Thickness (in.)
Time (min)
Mat Pressure
Mat Thickness
PressMAN mELVLL10 02-28-2001


Washington State University
Williams & White Press
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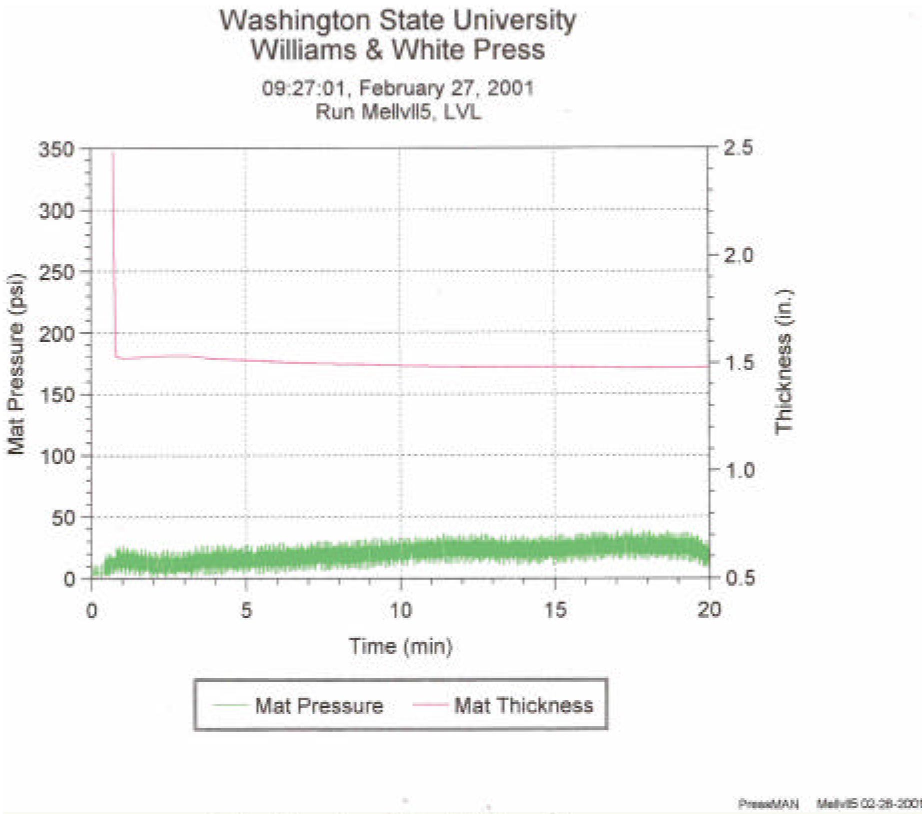
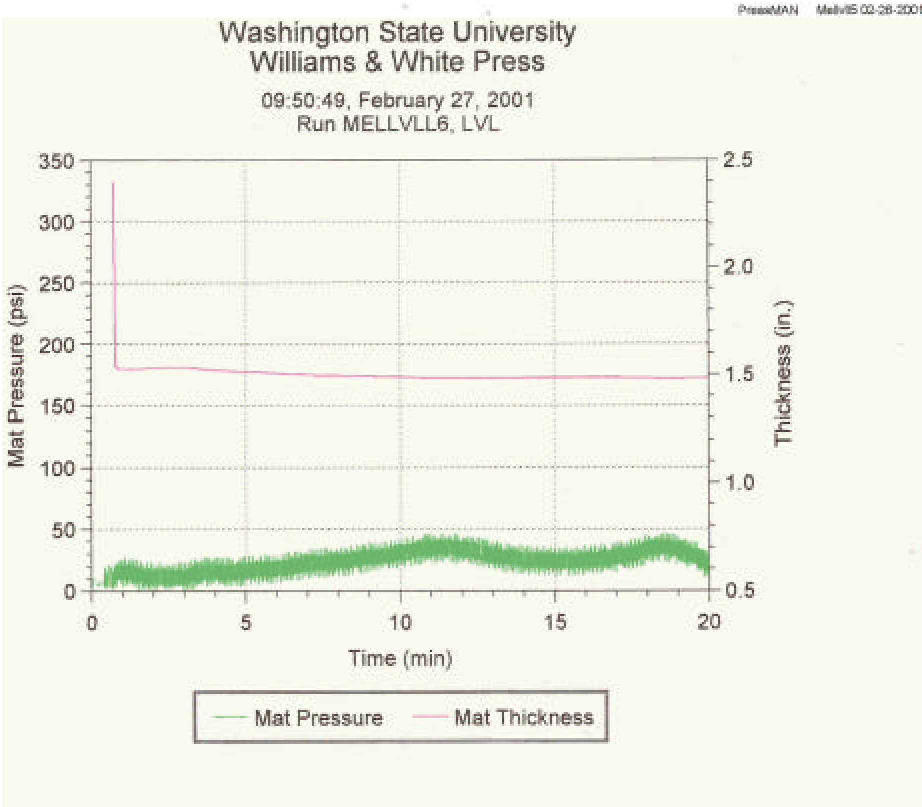
Mat Pressure (psi)
Thickness (in.)
Time (min)
Mat Pressure
Mat Thickness
PressMAN MELVLL11 02-28-200


Washington State University
Williams & White Press
09:27:01, February 27, 2001
Run Mellvll5, LVL
Mat Pressure (psi)
Thickness (in.)
350
300
250
200
150
100
50
0
2.5
2.0
1.5
1.0
0.5
0
5
10
15
20
Time (min)
Mat Pressure
Mat Thickness
PressMAN
Mellvll5 02-28-2001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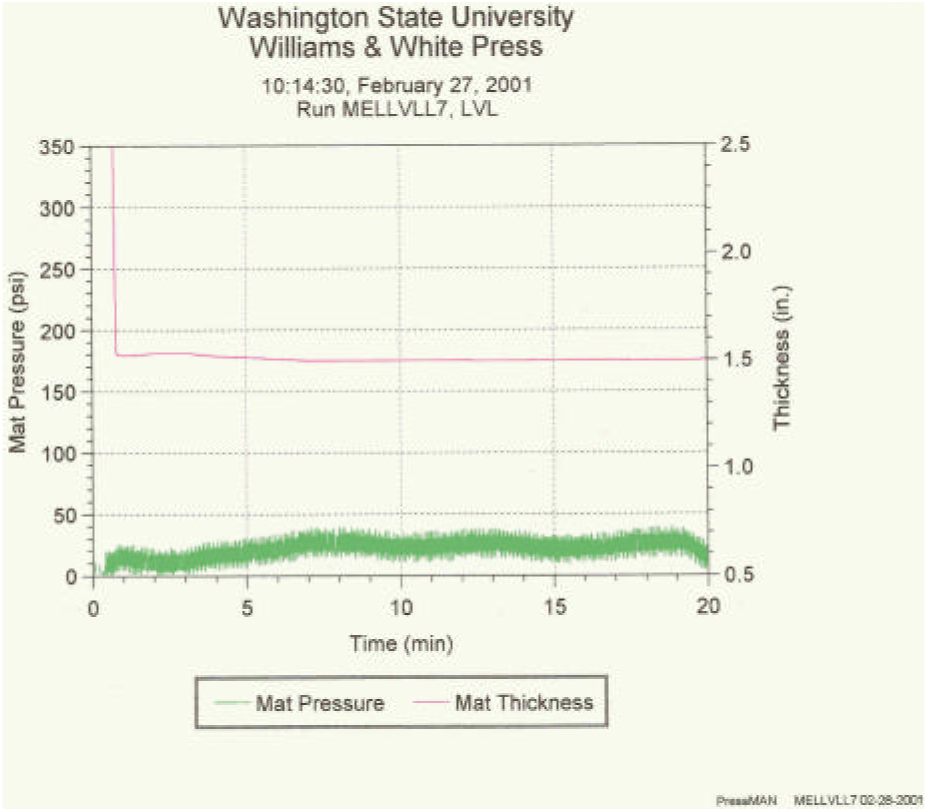
Williams & White Press
09:50:49, February 27, 2001
Run MELLVLL6, LVL
Mat Pressure (psi)
Thickness (in.)
350
300
250
200
150
100
50
0
2.5
2.0
1.5
1.0
0.5
0
5
10
15
20
Time (min)
Mat Pressure
Mat Thickness
PressMAN
MELLVLL6 02-28-2001


Washington State University
Williams & White Press
10:14:30, February 27, 2001
Run MELLVLL7, LVL
Mat Pressure (psi)
Thickness (in.)
Time (min)
Mat Pressure
Mat Thickness
PressMAN MELLVLL7 02-28-2001

Georgia-Pacific

Georgia-Pacific Resins, Inc.
A wholly owned subsidiary of
Georgia-Pacific Corporation

NFPA Ratings
Flammability 0
Health 2
Reactivity 0
Specific

Material Safety Data Sheet

GP® 275A39 RESI-MIX® Engineered Wood Adhesive

Section 1. Chemical Product and Company Identification

Product / Trade Name	GP® 275A39 RESI-MIX® Engineered Wood Adhesive
Synonyms	RPMX 275A39
Chemical Family	Phenol-Formaldehyde Resin
Chemical Formula	$(C_6H_6O \cdot CH_2O)_x \cdot xNa$
Manufacturer	**Georgia-Pacific Resins, Inc.** 2883 Miller Road Decatur, GA 30035 (770) 593-6874 (Non-Emergency Phone)

Emergency Phone (24 hours): CHEMTREC 1-800-424-9300

Section 2. Composition and Information on Ingredients

Hazardous Components	CAS #	% by Weight	ACGIH TLV ™	OSHA PEL
Formaldehyde	50-00-0	< 0.1	CEIL: 0.3 ppm	TWA: 0.75 ppm STEL: 2 ppm

TWAs are 8 hour exposures unless otherwise noted. STELs are 15 minute exposures unless otherwise noted.

Section 3. Hazards Identification

HMIS

Health Hazard	2
Fire Hazard	0
Reactivity	0
Personal Protection	

Note: Personal protective equipment (PPE) is related to conditions of use. Determination of PPE is the responsibility of the employer. Refer to *Section 8* **(Exposure Controls / Personal Protection)** of this MSDS for recommendations.

Emergency Overview

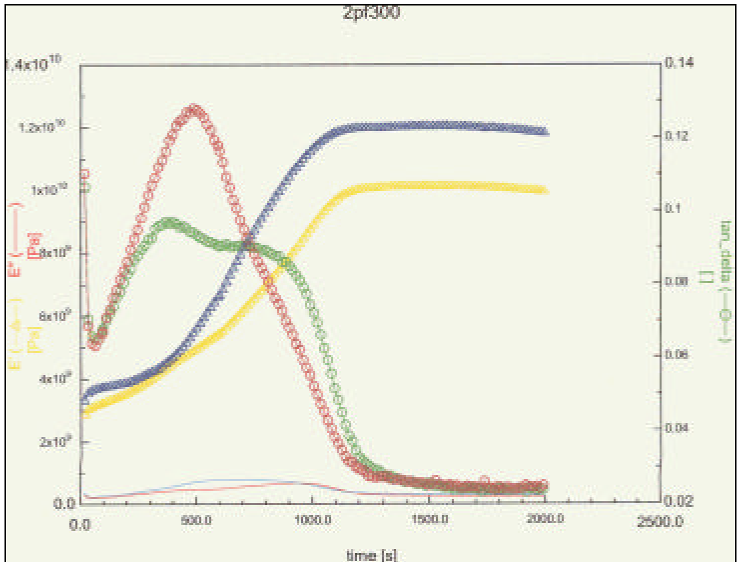
Light to dark brown viscous liquid with a slight phenolic odor.

Eye irritation or injury may result from exposure to this product.

Potential Health Effects

Eye Contact Contact with liquid or mist can cause moderate to severe eye irritation or injury. Prolonged exposure to vapors released from hot or curing product may cause mild to moderate eye irritation. Symptoms may include redness, watering, itching, or a burning sensation in the eyes.

Continued on Next Page **Effective Date:** 07/03/2000


2pf300
E' (—▲—) [Pa]
E'' (——) [Pa]
tan_delta (—O—) []
time [s]
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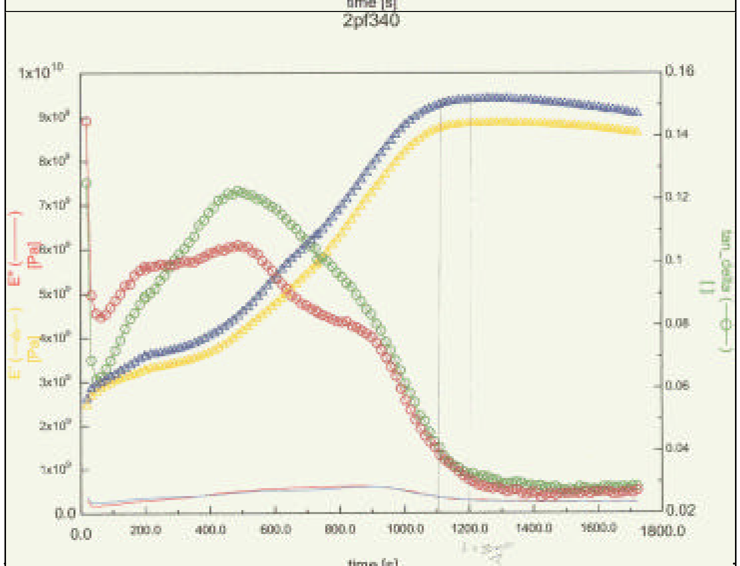
500.0
1000.0
1500.0
2000.0
2500.0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E'' (——) [Pa]
tan_delta (—O—) []
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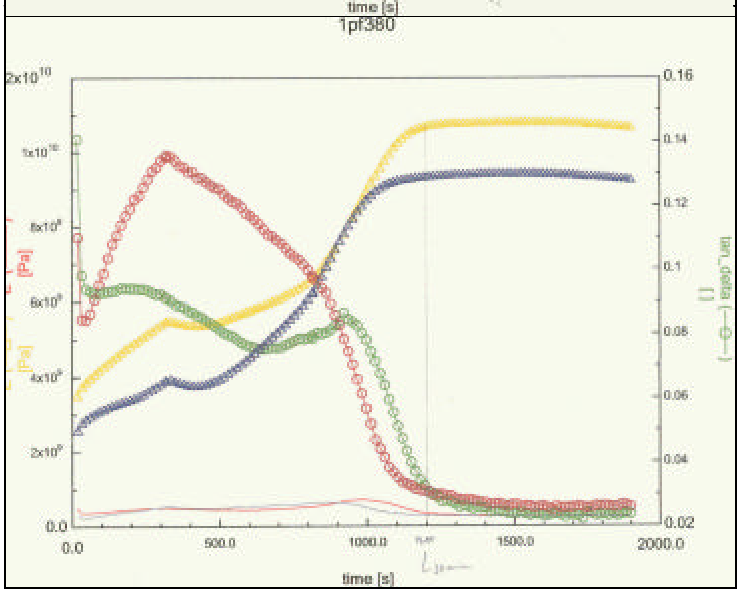
800.0
1000.0
1200.0
1400.0
1600.0
1800.0


1pf380
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E'' (——) [Pa]
tan_delta (—O—) []
time [s]
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500.0
1000.0
1500.0
2000.0

Laminated Veneer Lumber

149^{O}C (300^{O}F)

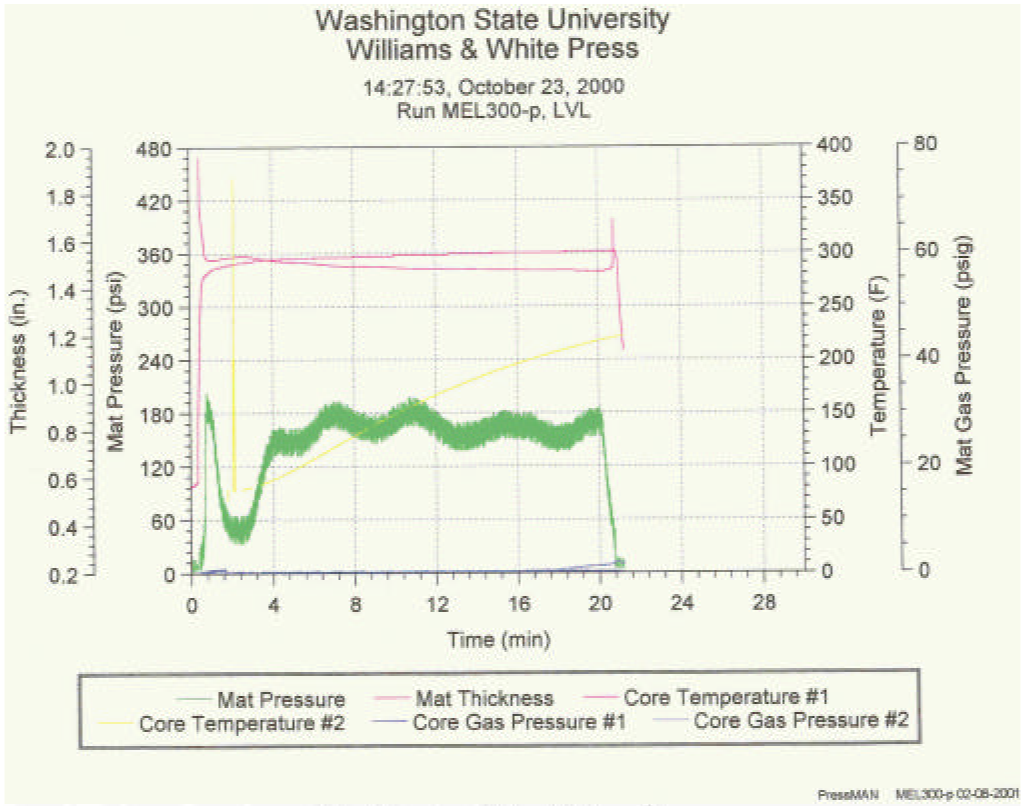
Manufactured from:	October 31, 2000 until November 1, 2000
Practice Billet:	MEL300-p, LVL
Test Billets:	300-n (n = 1 through 15)
Appendix Pages:	279 - 286

171^{O}C (340^{O}F)

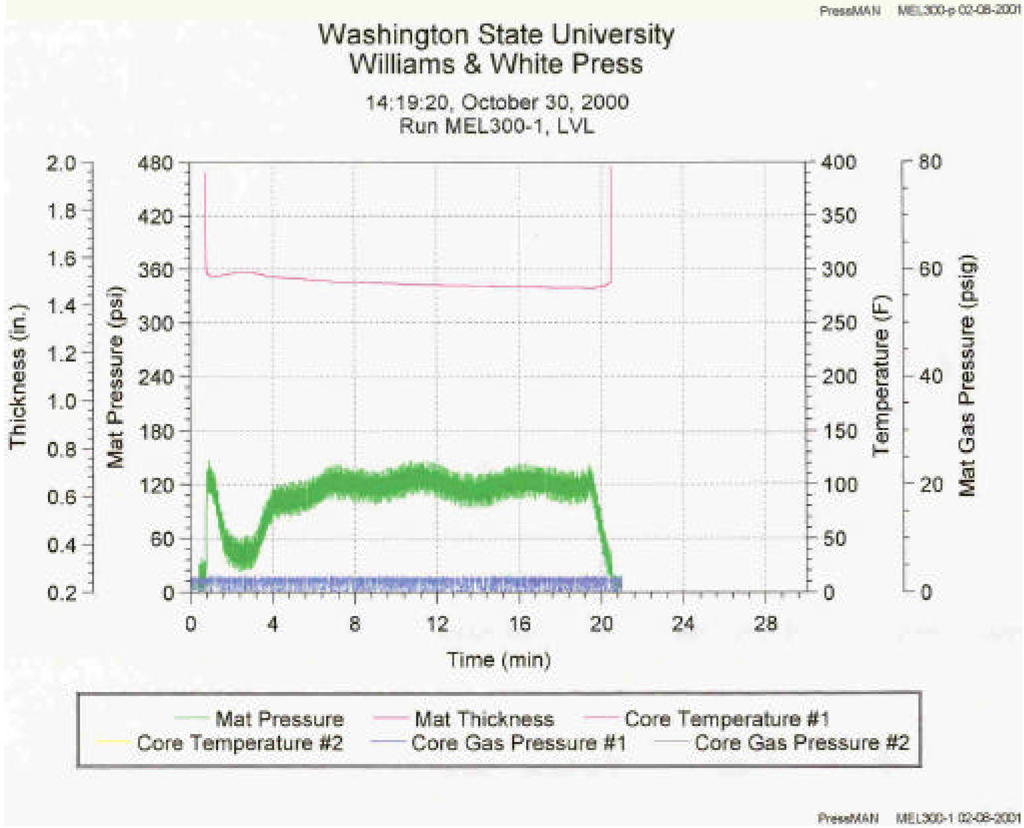
Manufactured from:	November 2, 2000 until November 14, 2000
Practice Billet:	EL340-2, LVL
Test Billets:	340--n (n = 1 through 15)
Appendix Pages:	287 - 294

193^{O}C (380^{O}F)

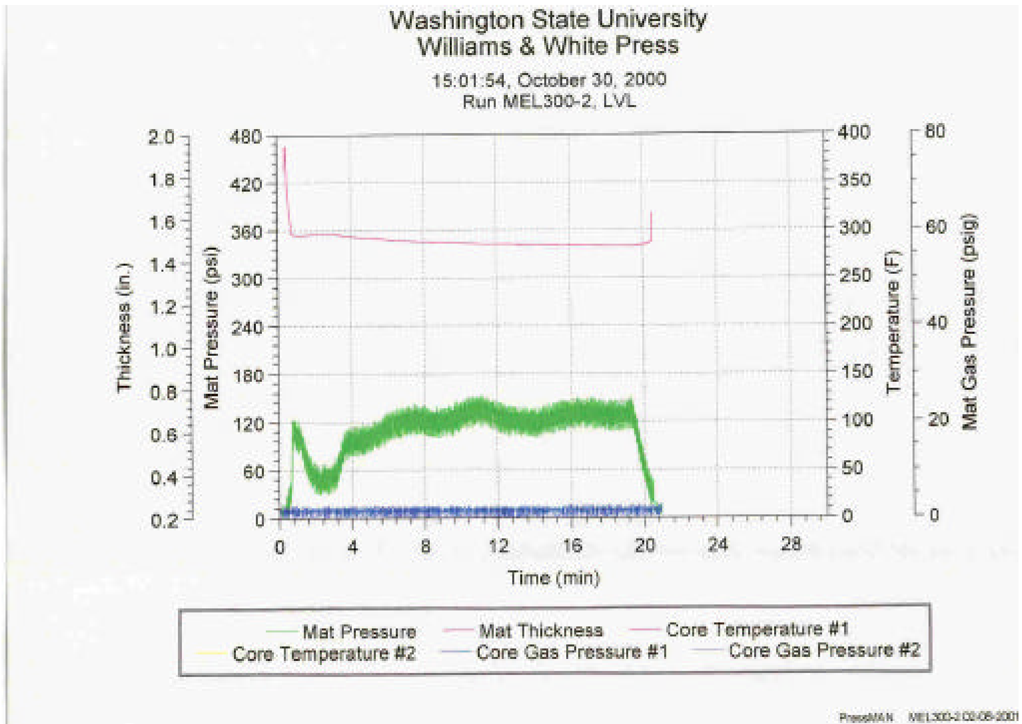
Manufactured from:	November 16, 2000 until November 20, 2000
Practice Billet:	MEL380-1, LVL
Test Billets:	380--n (n = 1 through 15)
Appendix Pages:	295 - 302



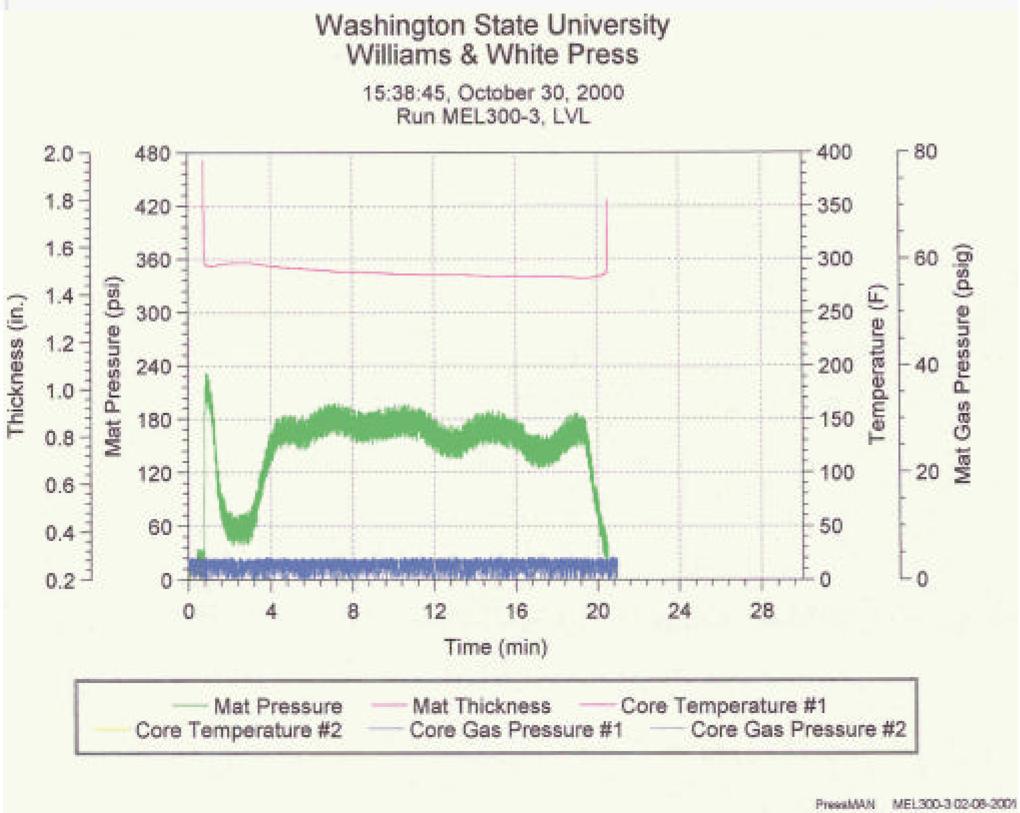
Washington State University
Williams & White Press
14:27:53, October 23, 2000
Run MEL300-p, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN MEL300-p 02-08-2001



Washington State University
Williams & White Press
14:19:20, October 30, 2000
Run MEL300-1, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN MEL300-1 02-08-2001



Washington State University
Williams & White Press
15:01:54, October 30, 2000
Run MEL300-2, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2



Washington State University
Williams & White Press
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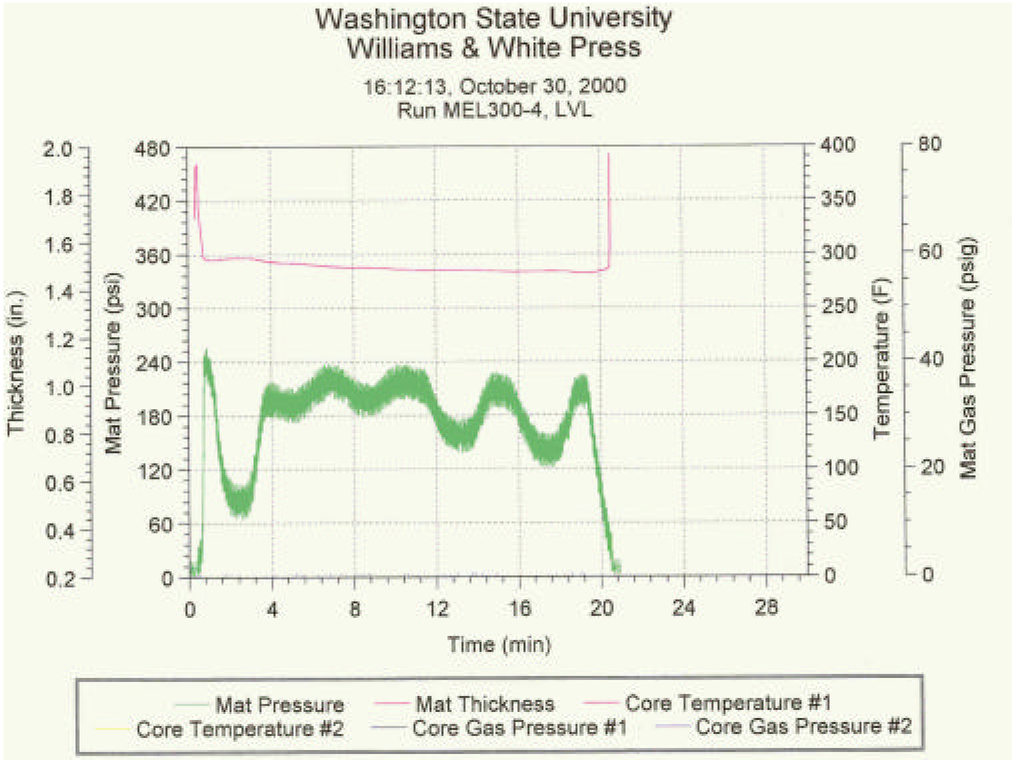
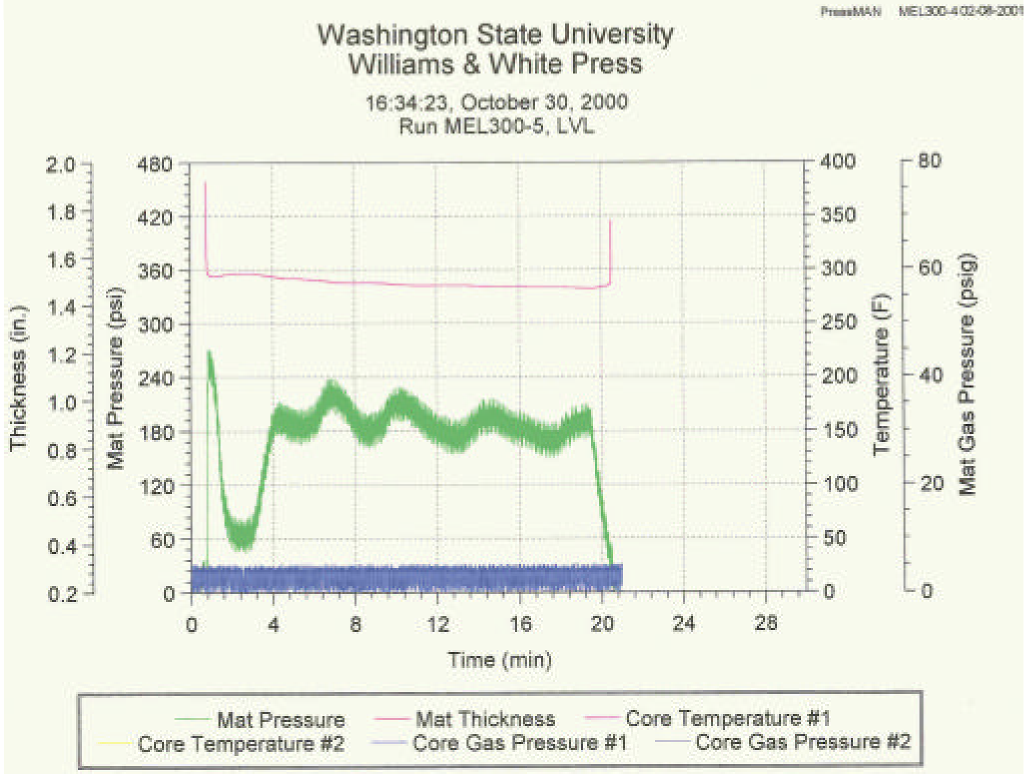
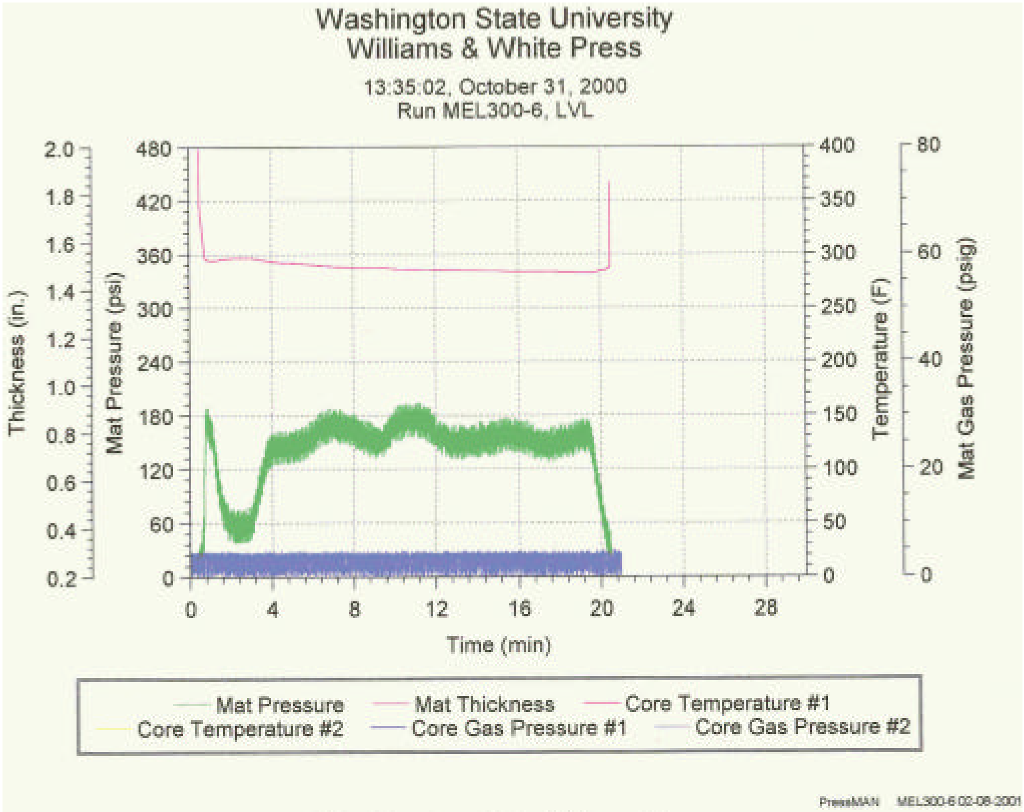
Run MEL300-3, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2



PressMAN MEL300-4 02-08-2001



PressMAN MEL300-5 02-08-2001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Williams & White Press
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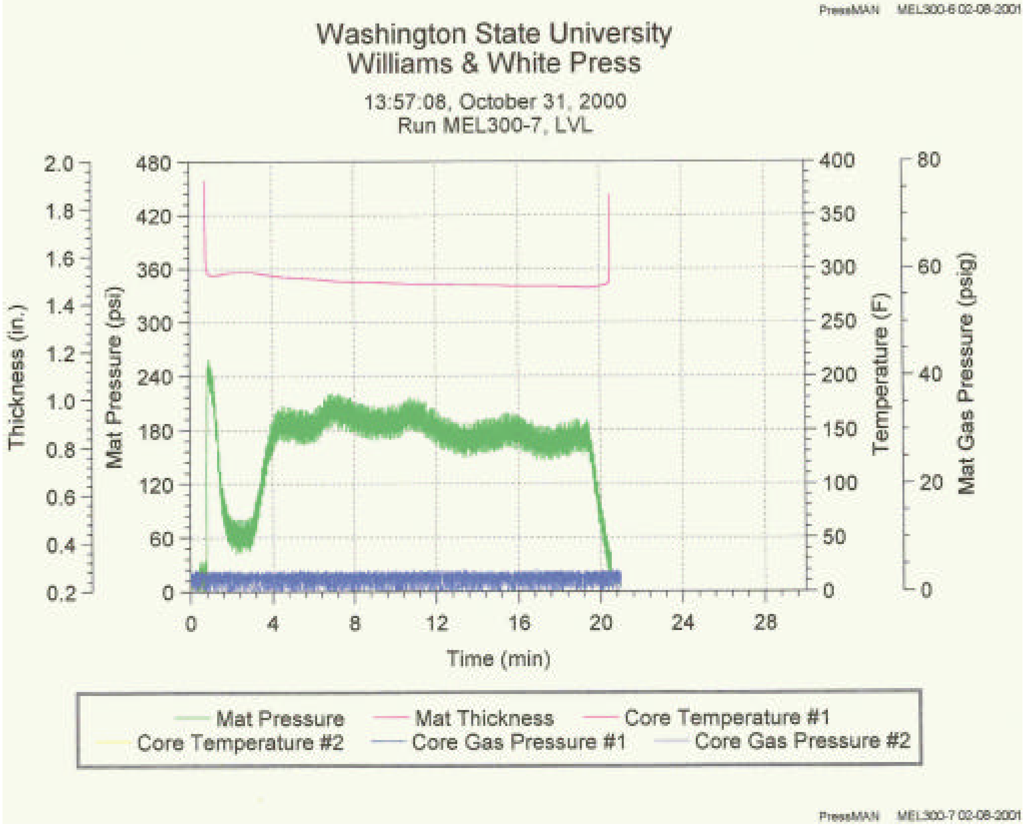
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN MEL300-6 02-08-2001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Williams & White Press
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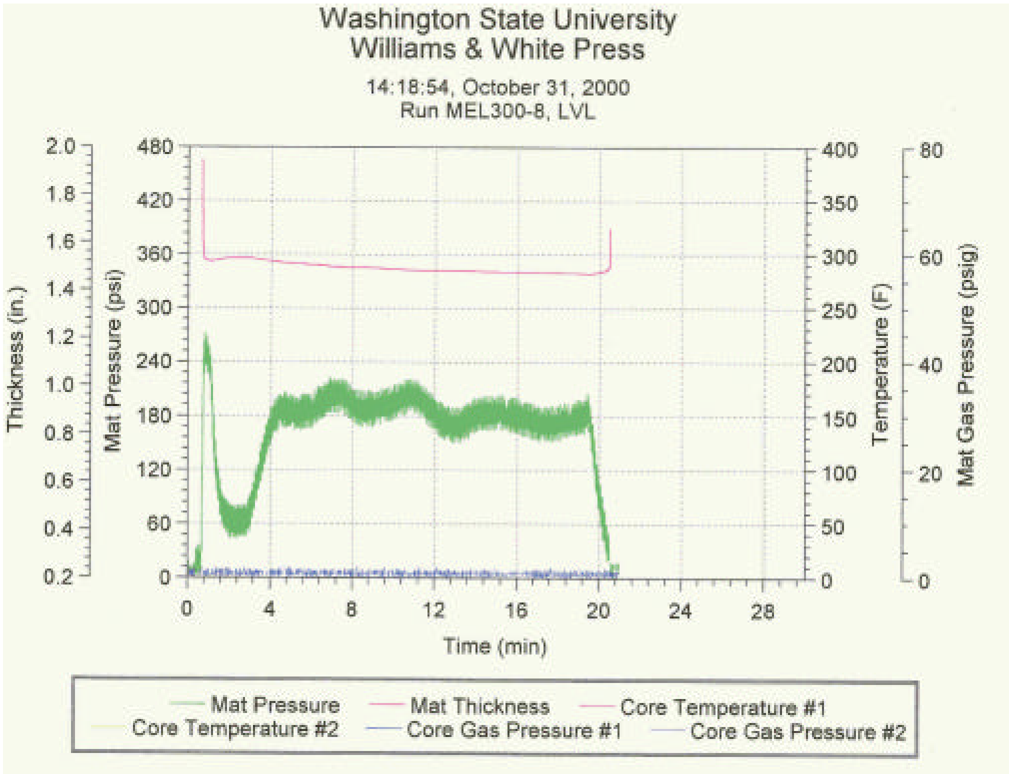
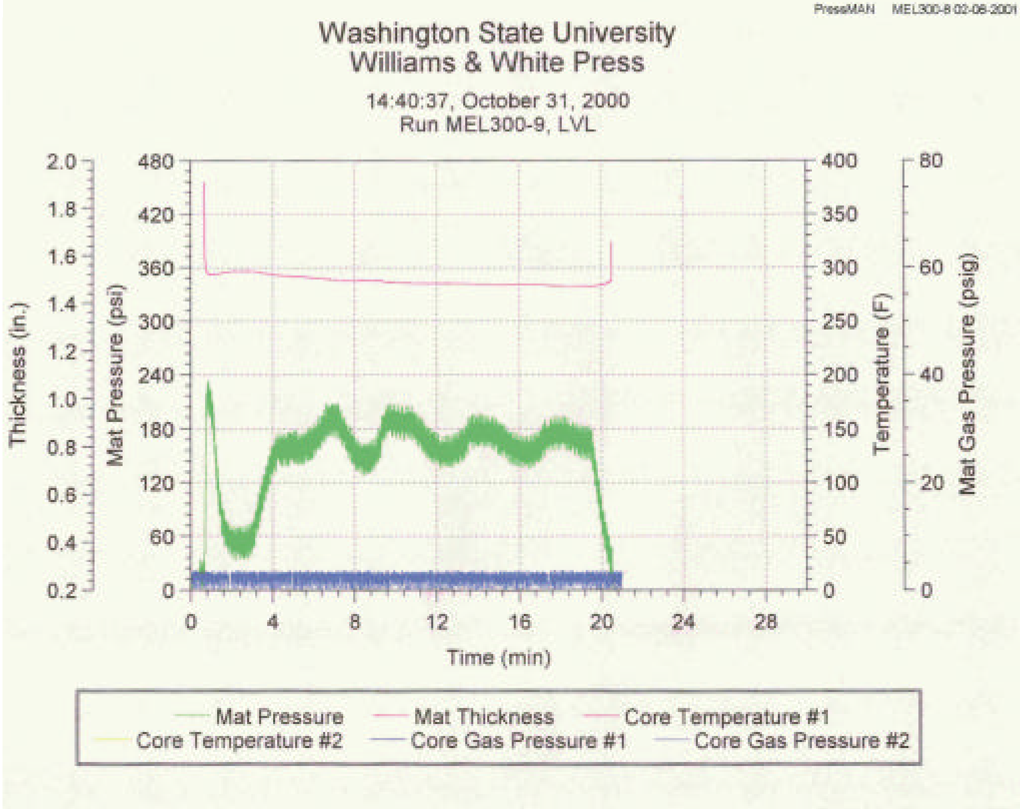
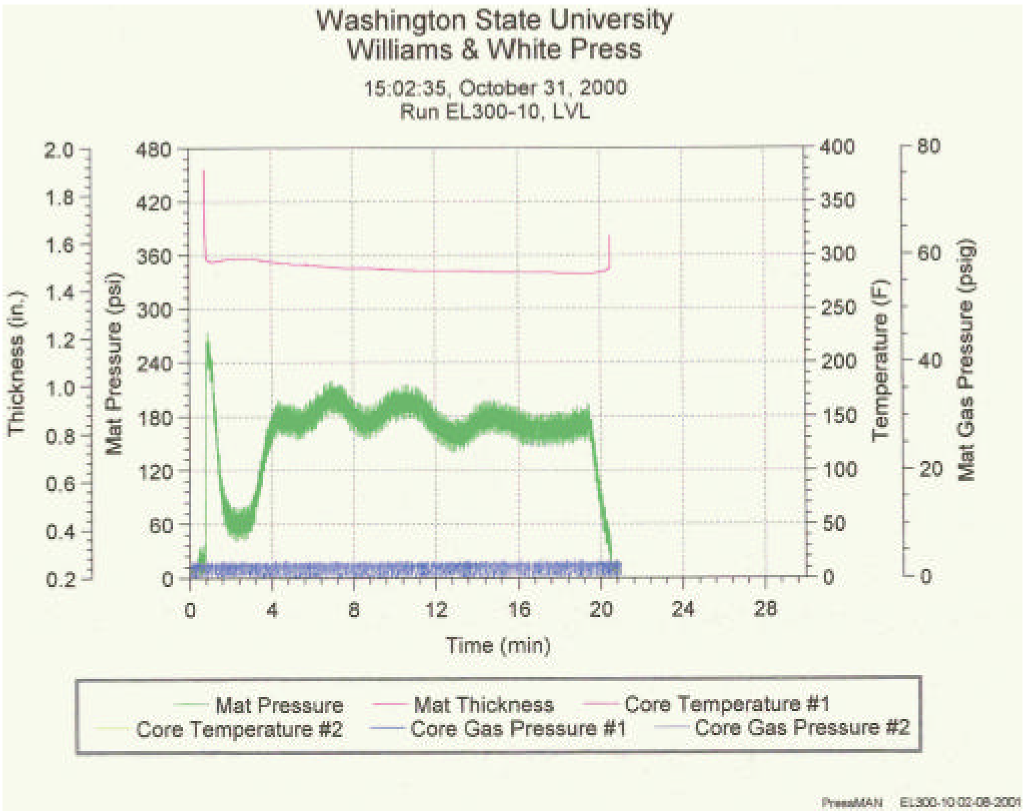
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN MEL300-7 02-08-2001



PressMAN MEL300-8 02-08-2001



PressMAN MEL300-9 02-08-2001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Williams & White Press
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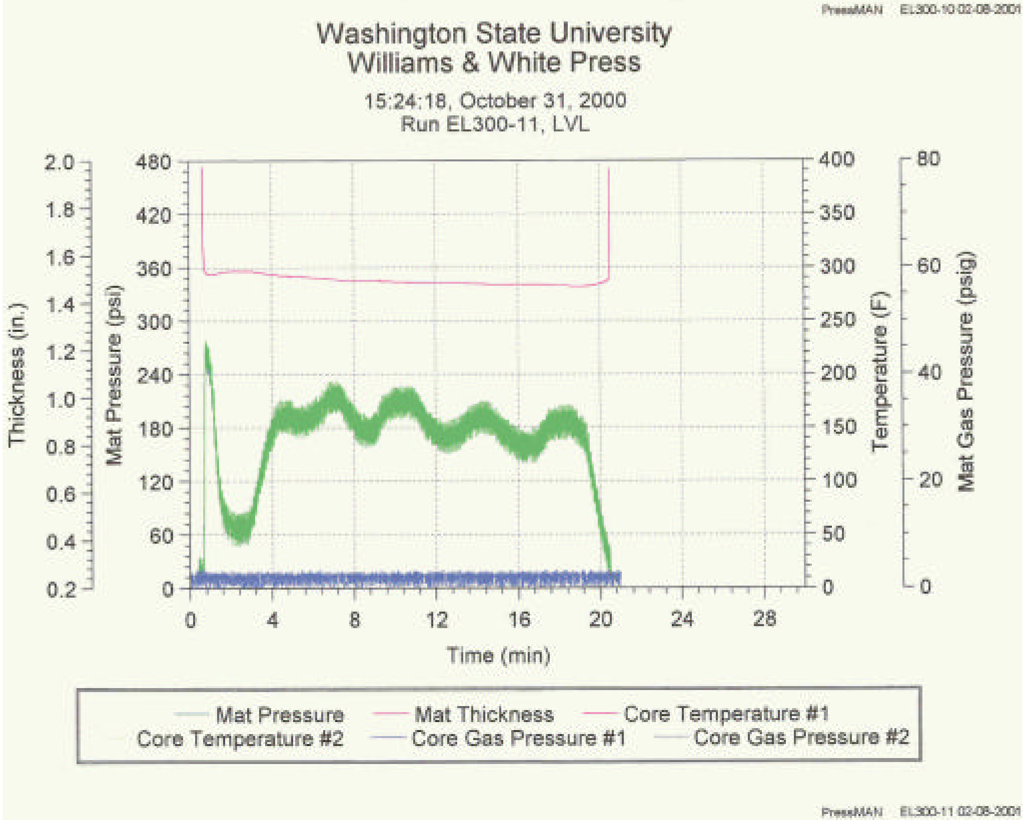
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN EL300-10 02-08-2001


Washington State University
Williams & White Press
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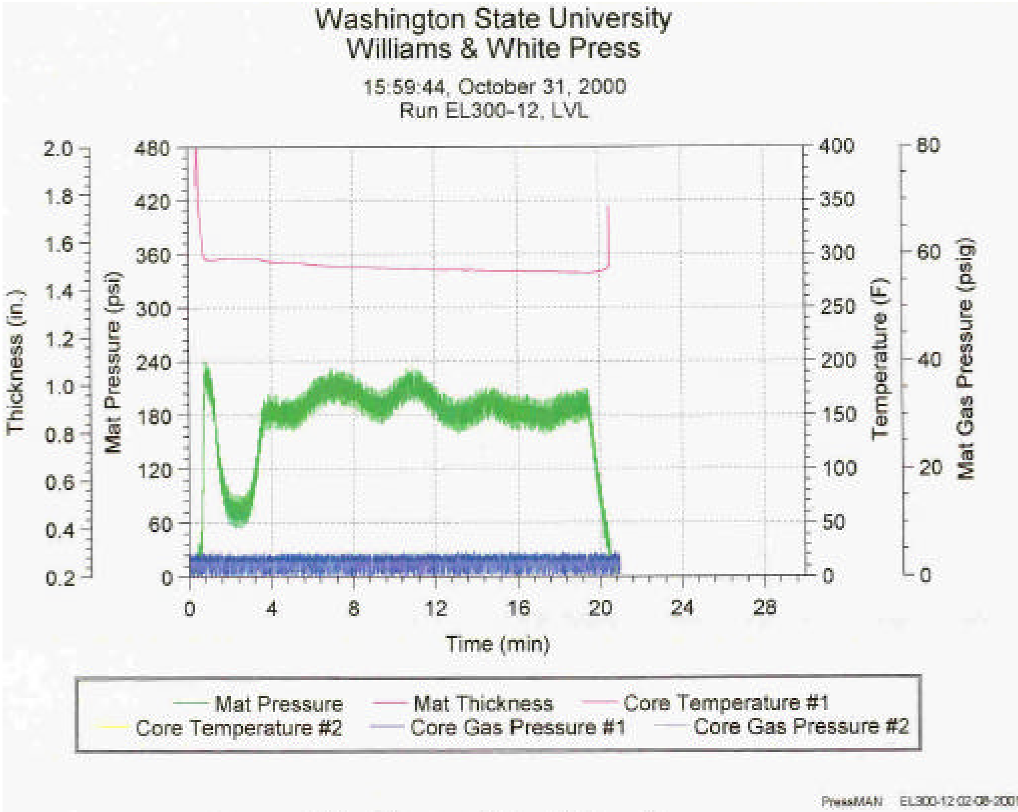
Run EL300-11, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN EL300-11 02-08-2001



Washington State University
Williams & White Press
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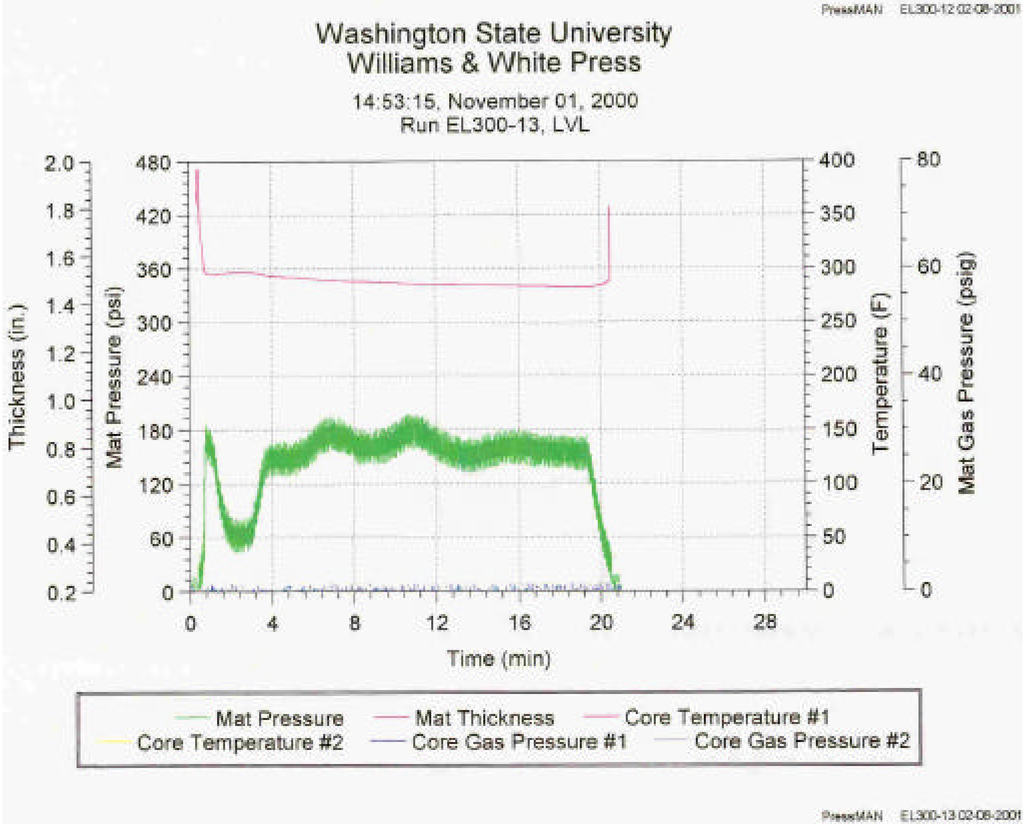
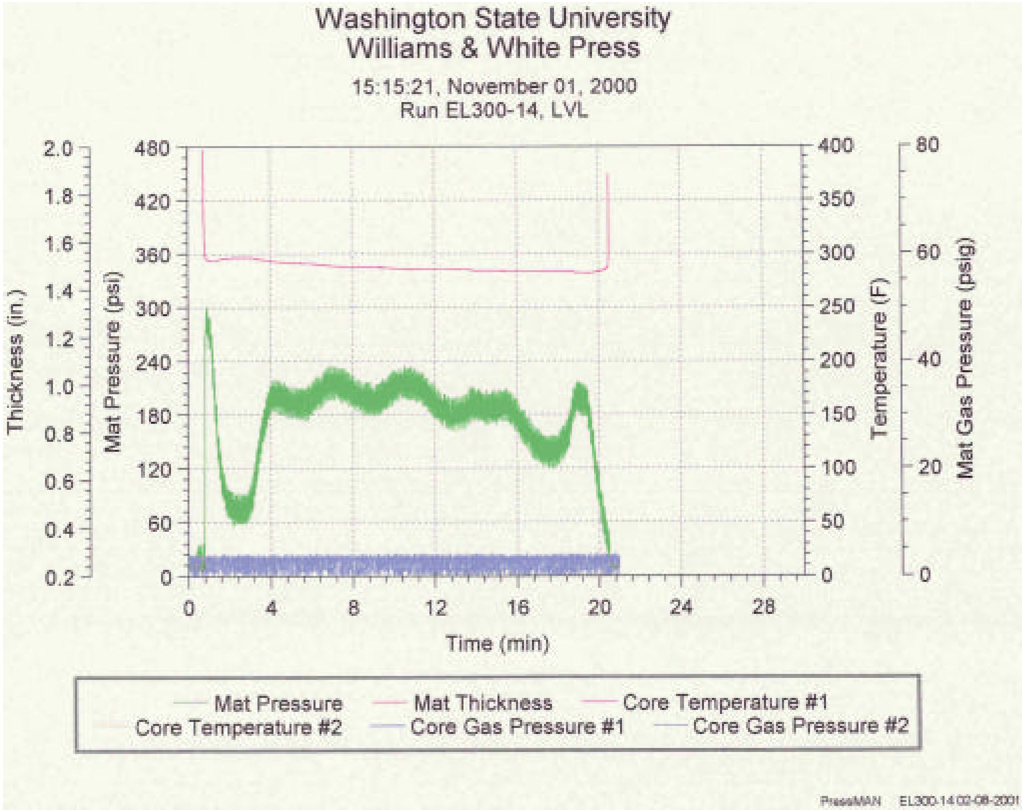
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN EL300-12 02-08-2001



Washington State University
Williams & White Press
14:53:15, November 01, 2000
Run EL300-13, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN EL300-13 02-08-2001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Williams & White Press
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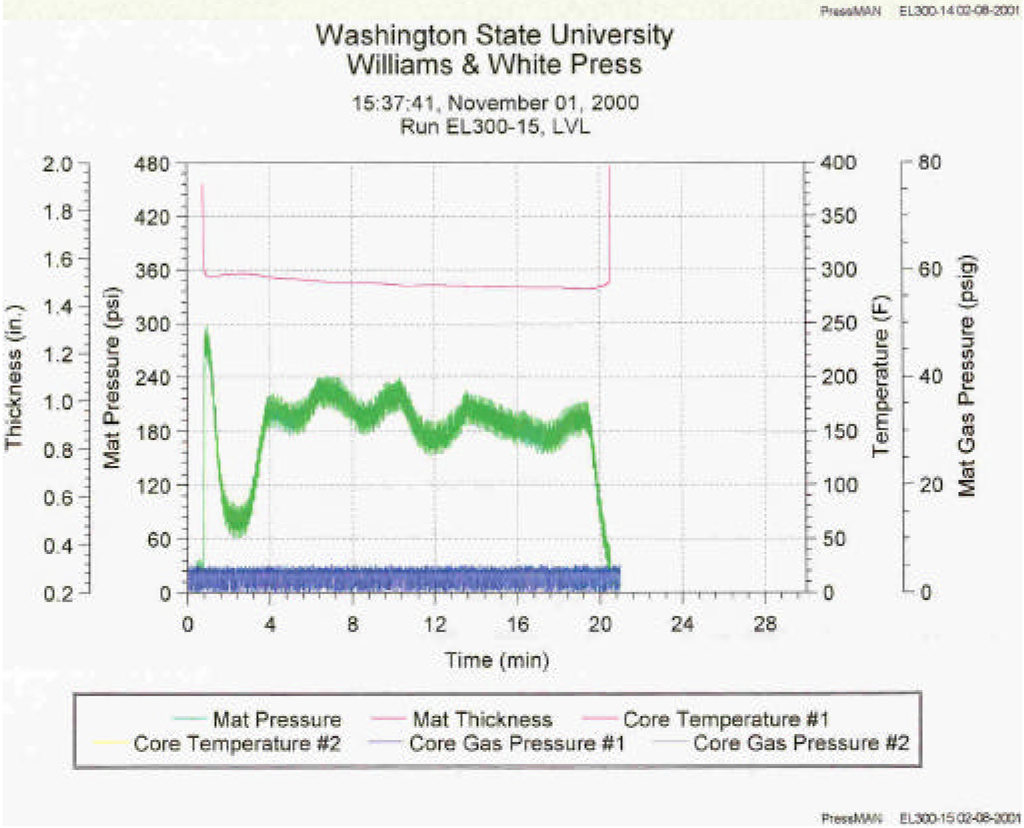
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN EL300-14 02-08-2001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Williams & White Press
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Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN EL300-15 02-08-2001

Washington State University
Williams & White Press

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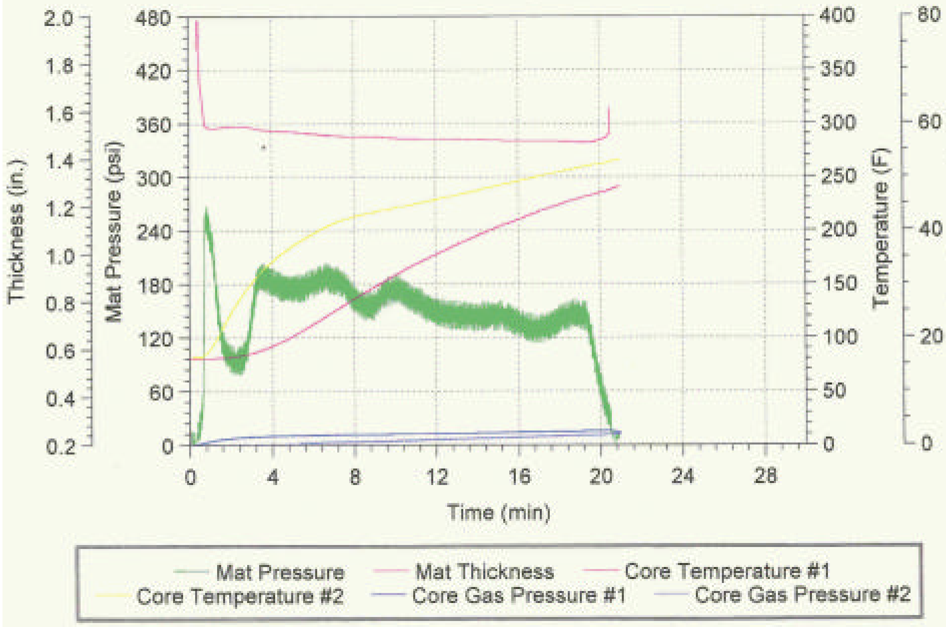
Run EL340-2, LVL



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Washington State University
Williams & White Press

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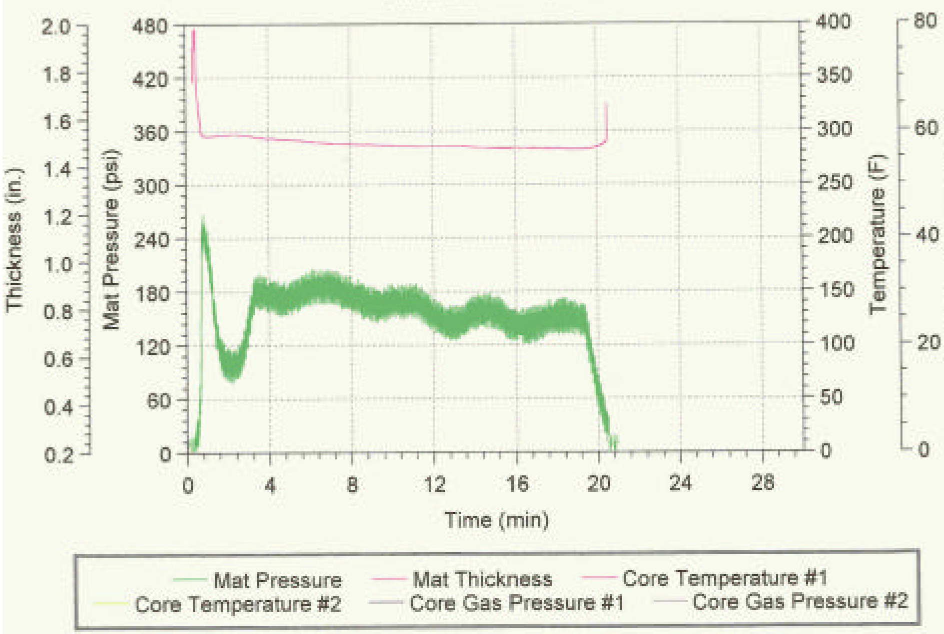

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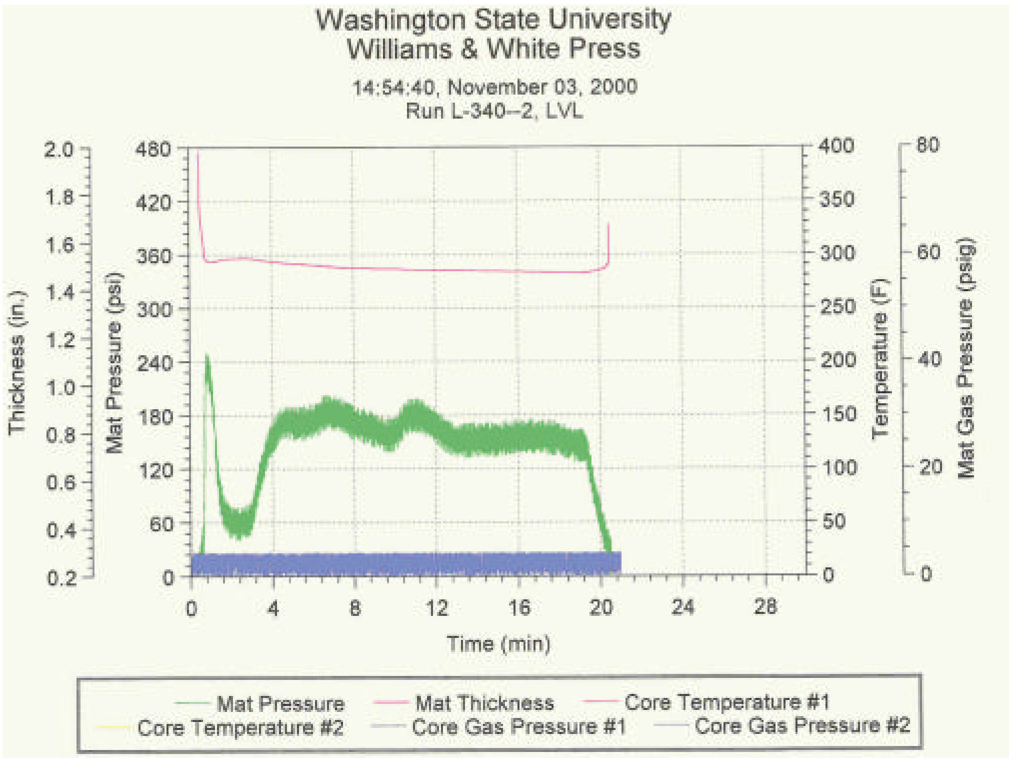

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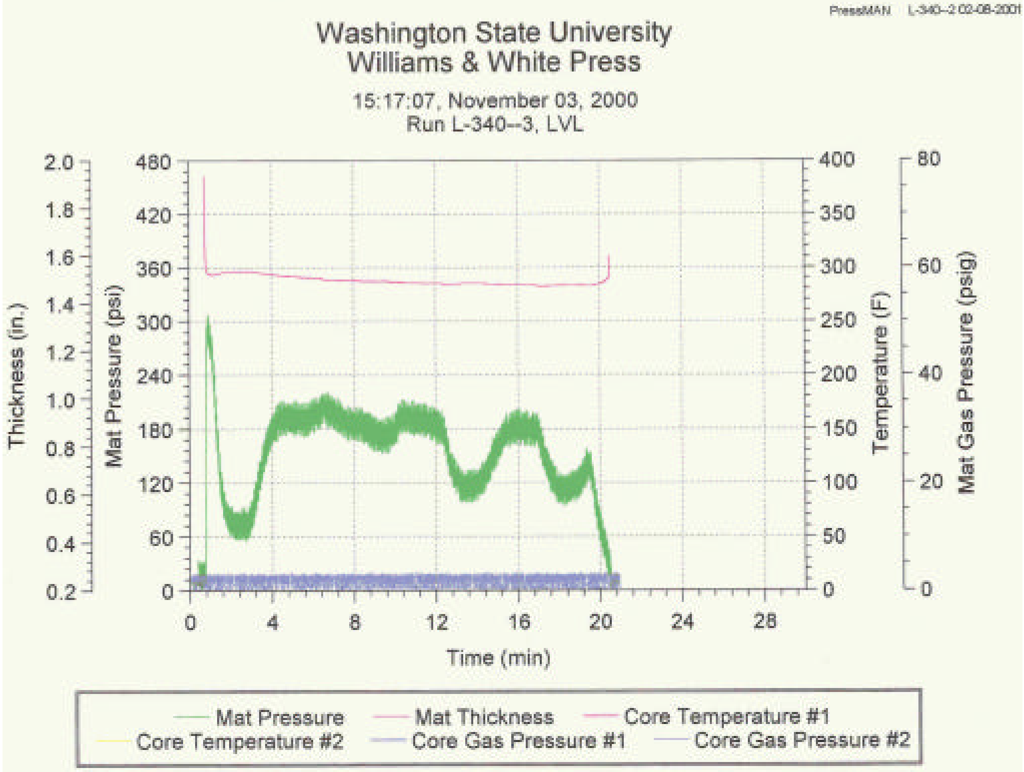

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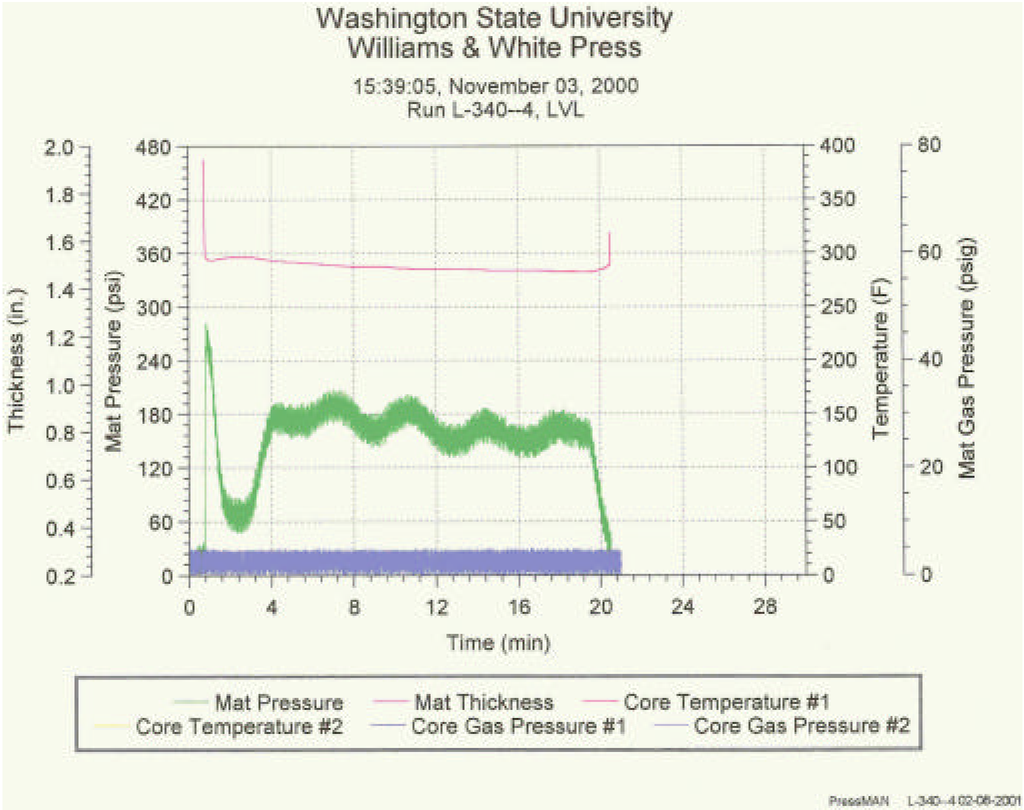
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Williams & White Press
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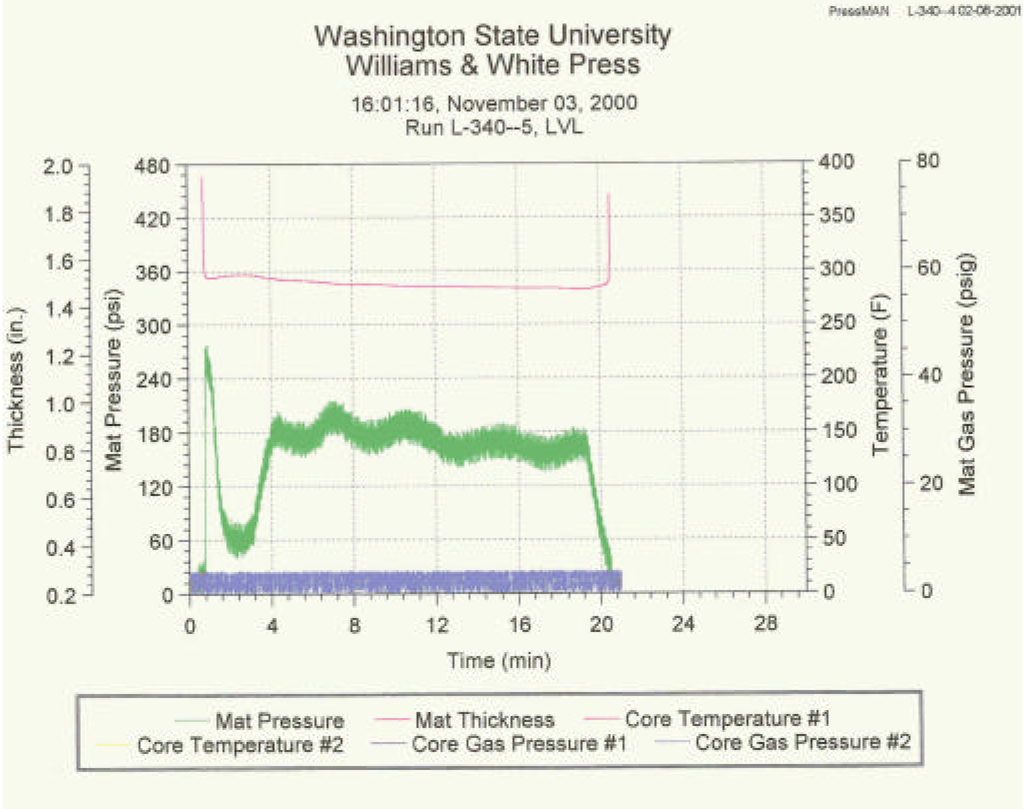
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L-340--4 02-08-2001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Williams & White Press
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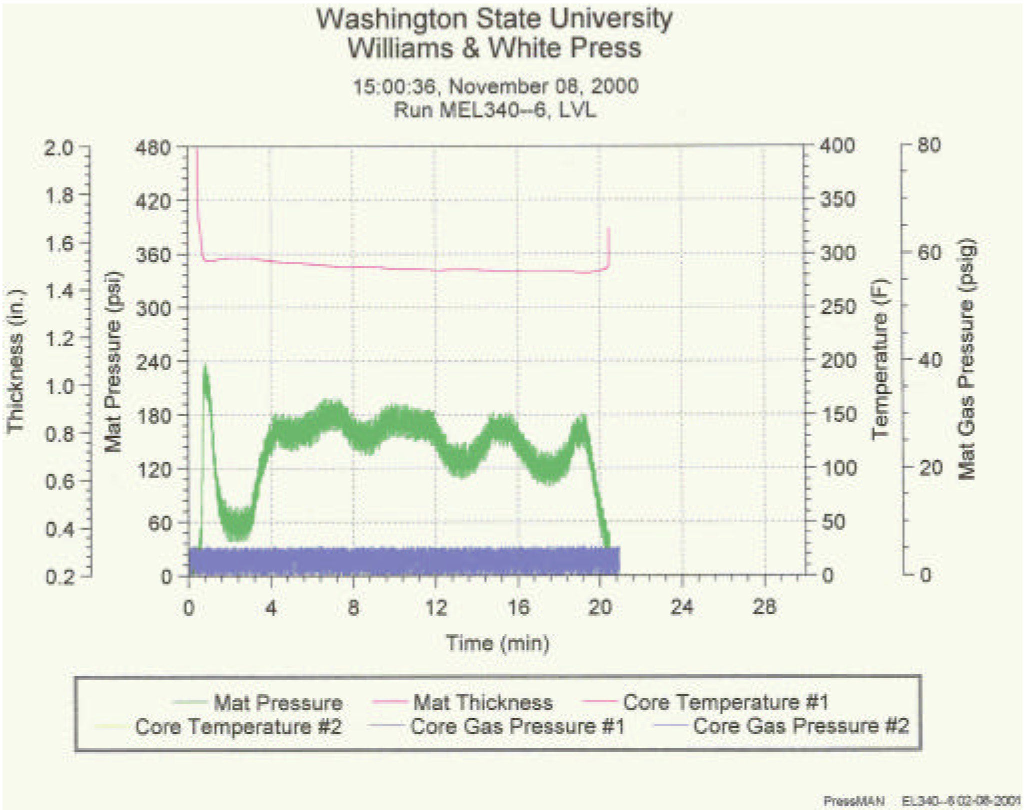
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L-340--5 02-08-2001



Washington State University
Williams & White Press
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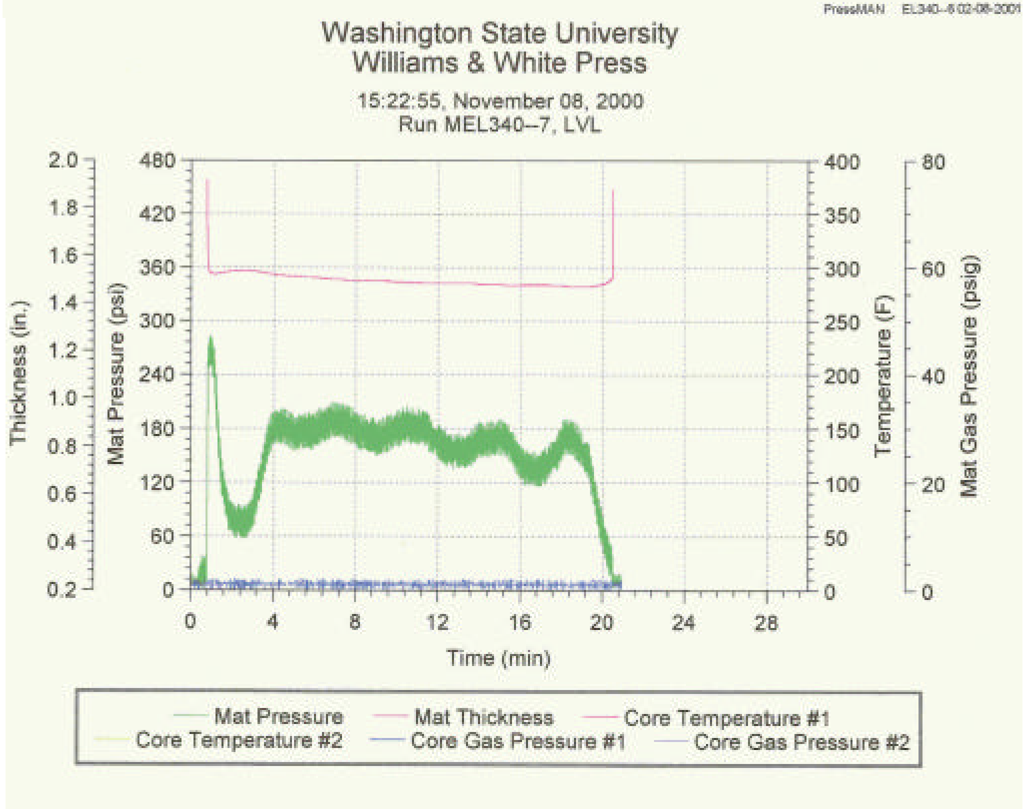
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN EL340--6 02-08-2001



Washington State University
Williams & White Press
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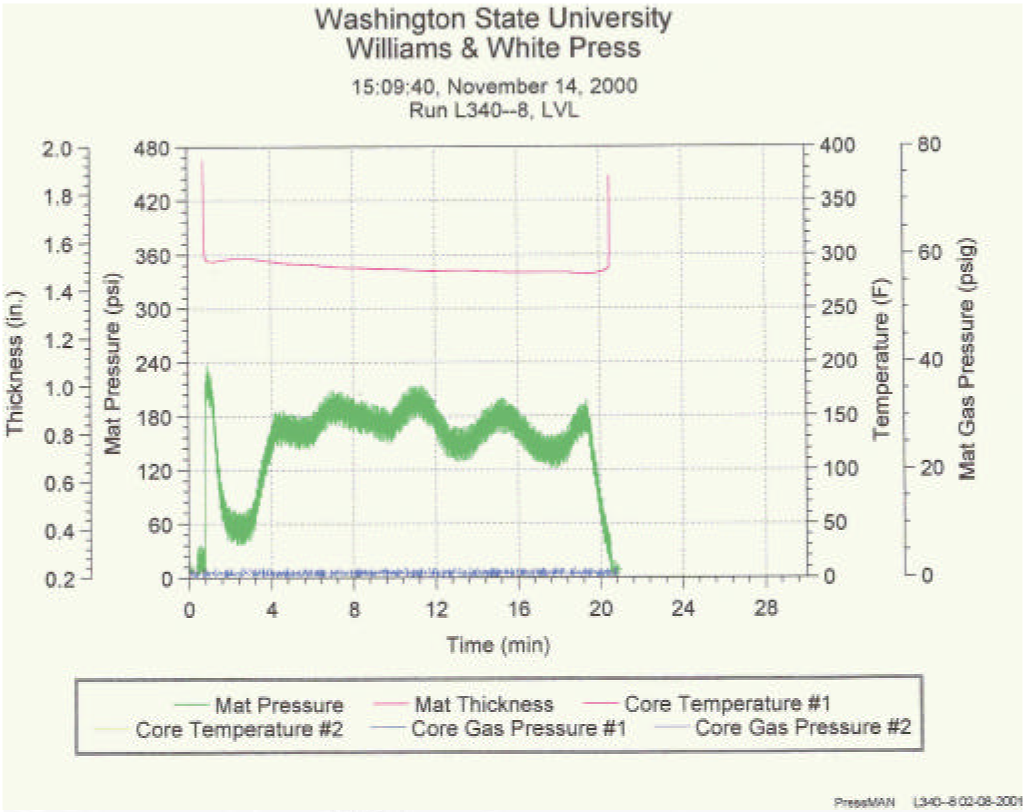
Run MEL340--7, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN EL340--7 02-08-2001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Williams & White Press
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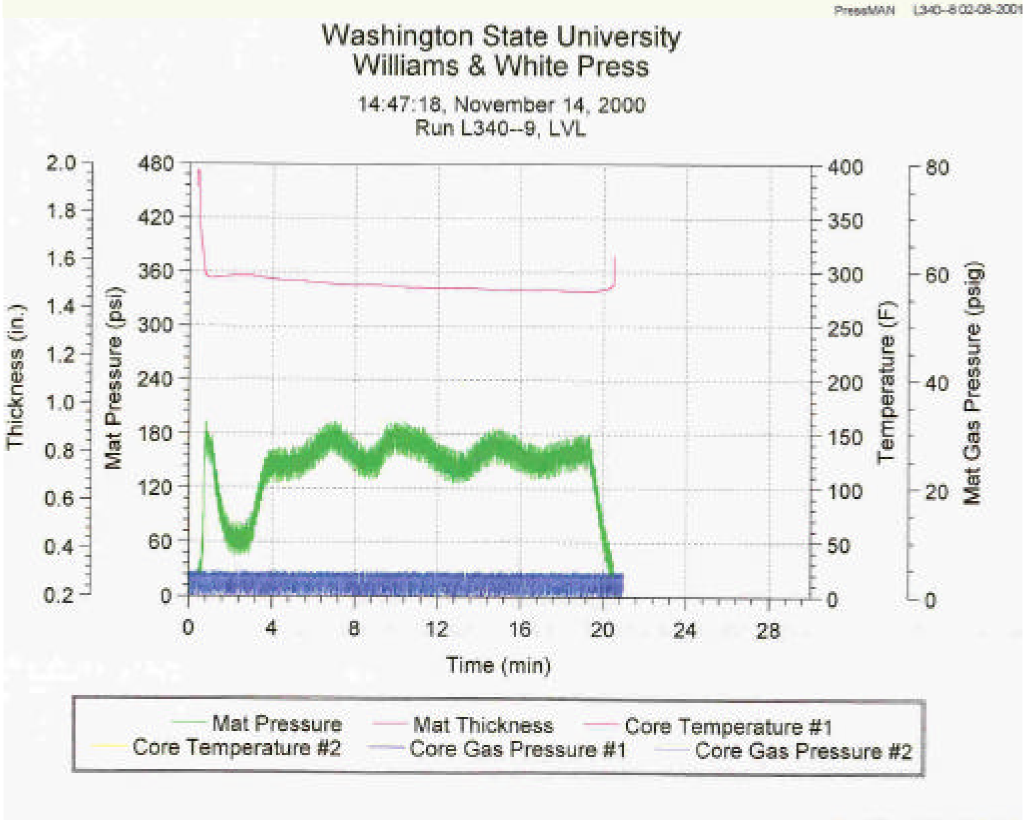
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L340--8 02-08-2001


Washington State University
Williams & White Press
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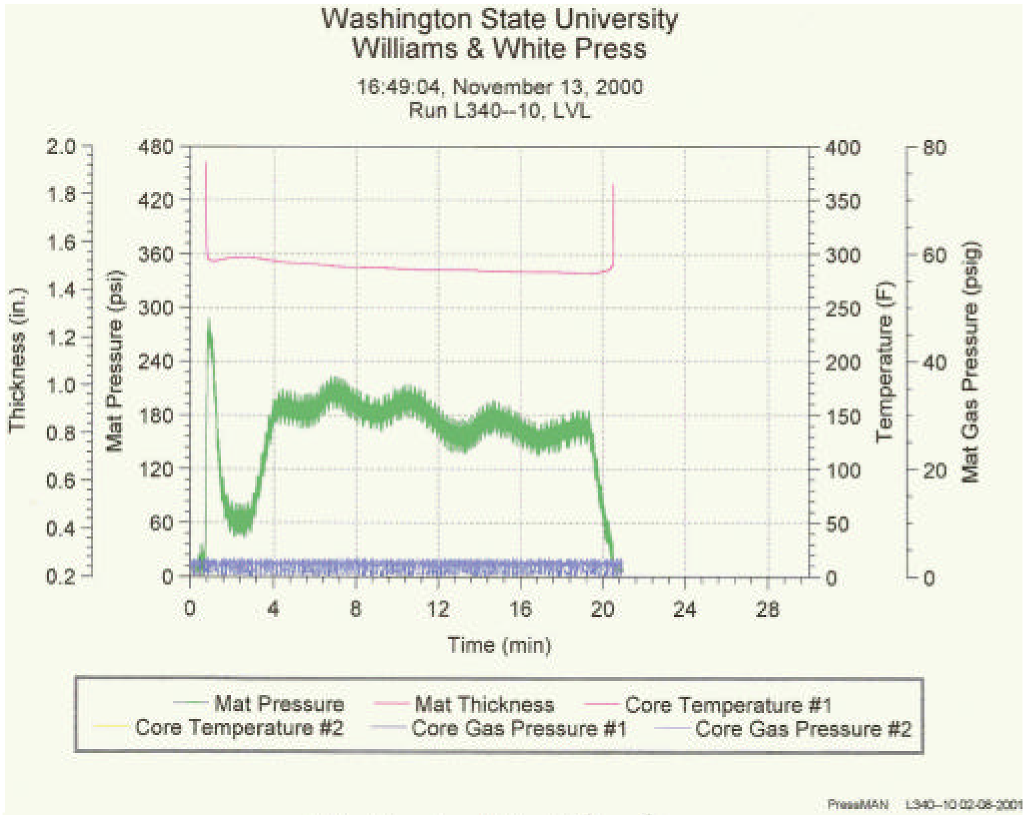
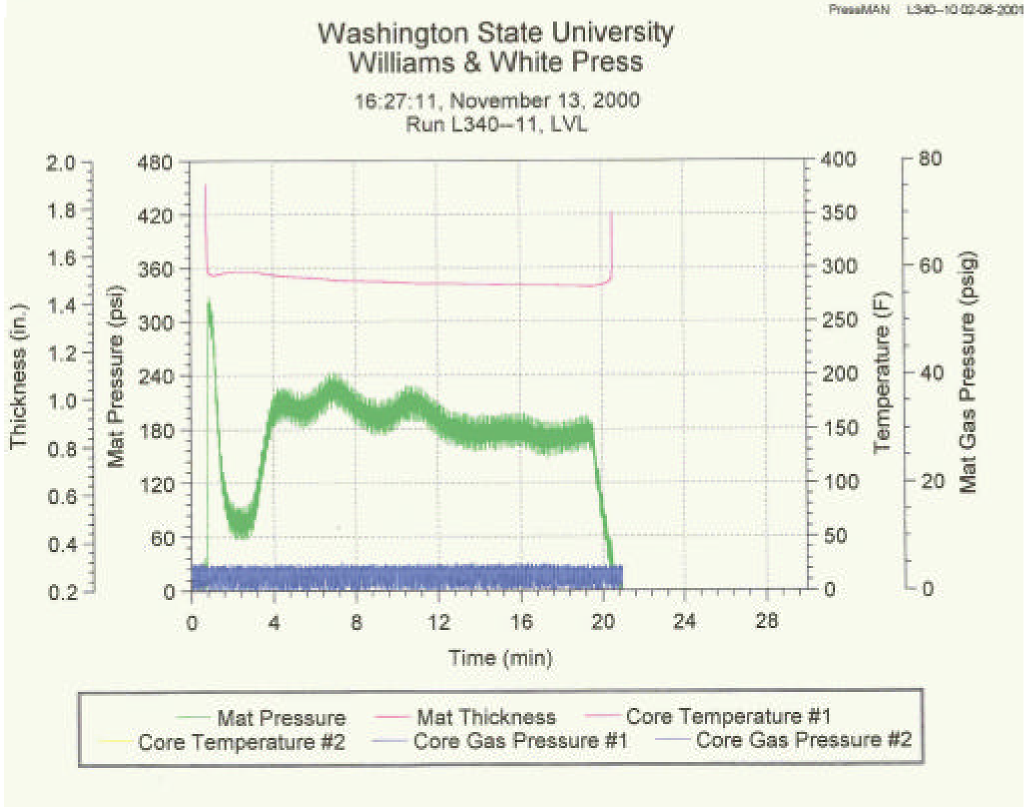
Run L340--9, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L340--9 02-08-2001


Washington State University
Williams & White Press
16:49:04, November 13, 2000
Run L340--10, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L340--10 02-08-2001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Williams & White Press
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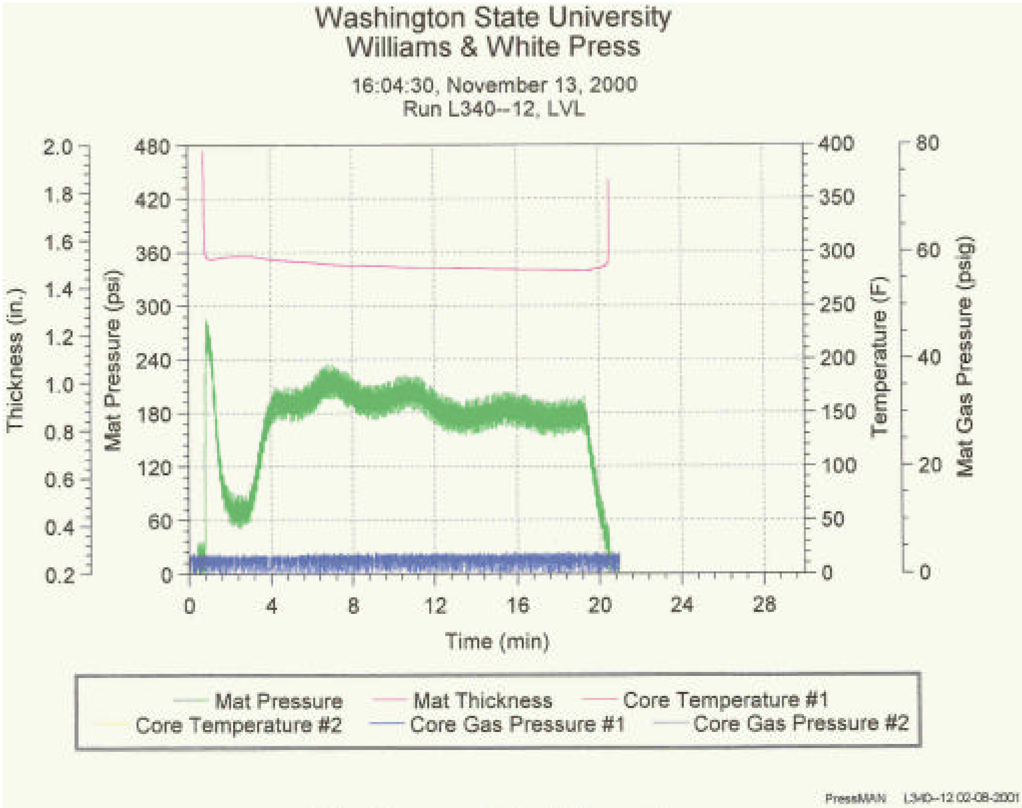
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L340--11 02-08-2001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Williams & White Press
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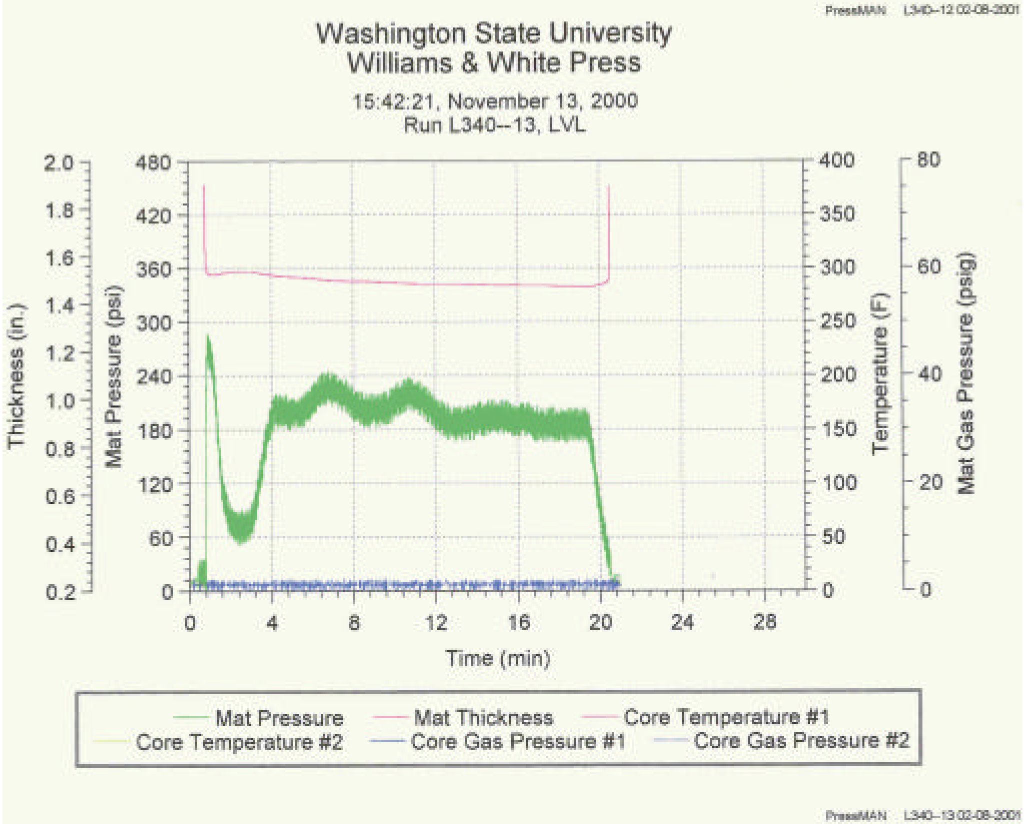
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L340--12 02-08-2001


Washington State University
Williams & White Press
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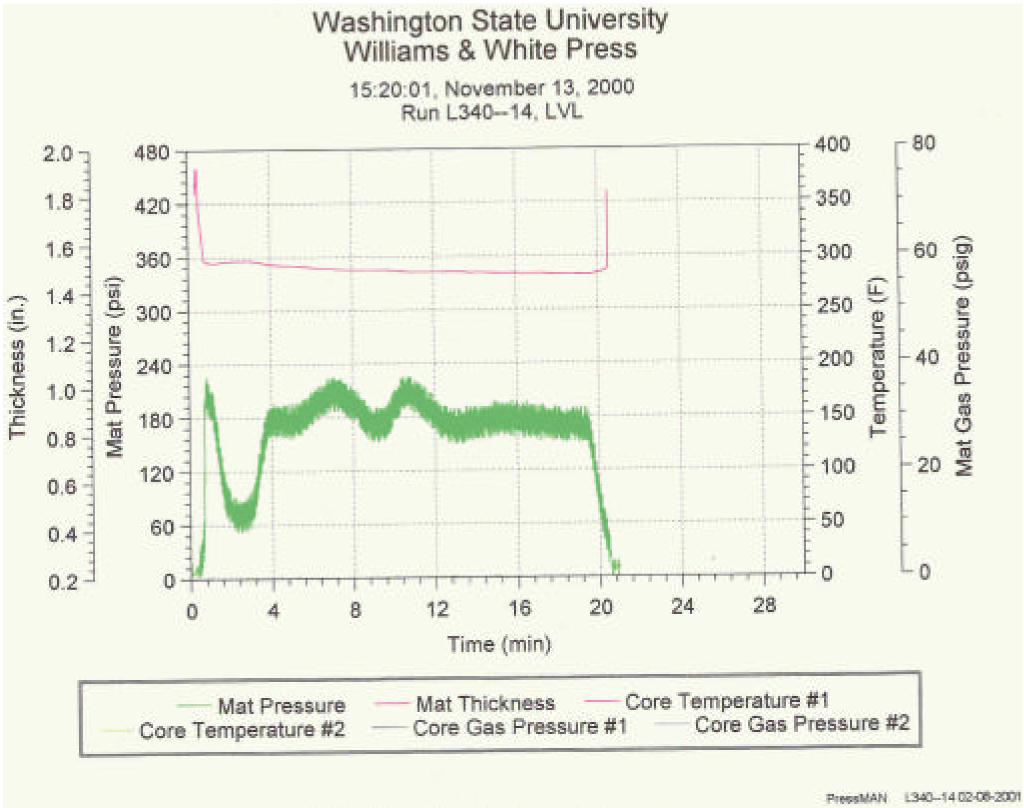
Run L340--13, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L340--13 02-08-2001



Washington State University
Williams & White Press
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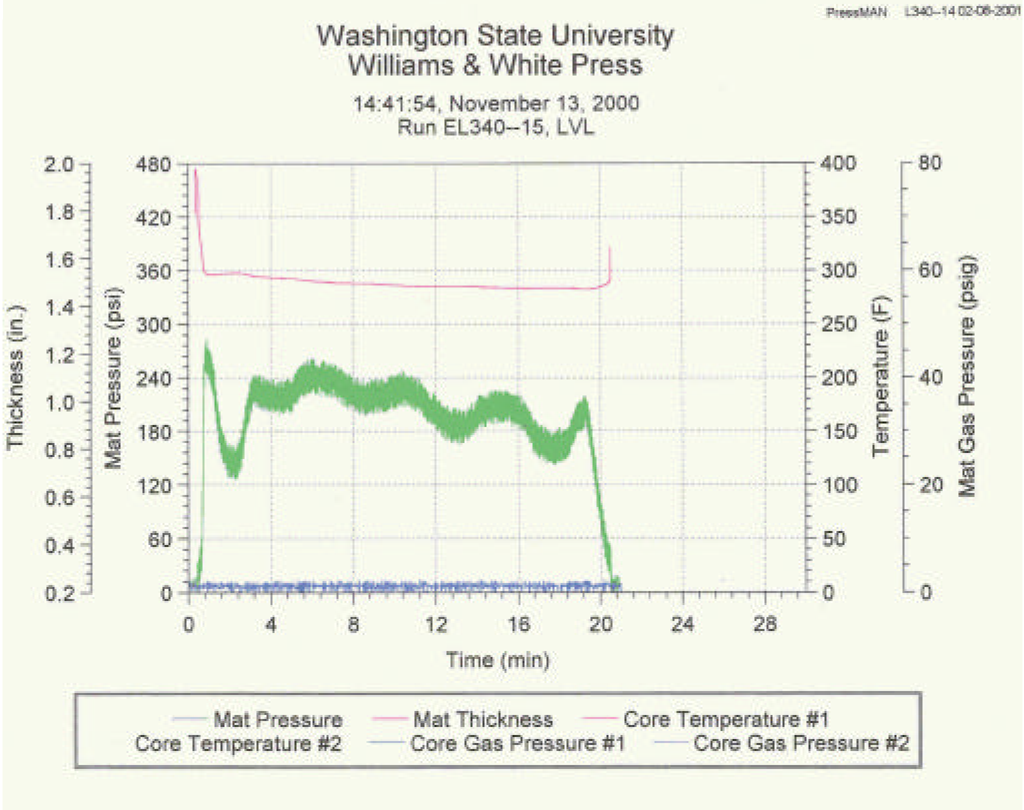
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L340--14 02-08-2001



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Williams & White Press
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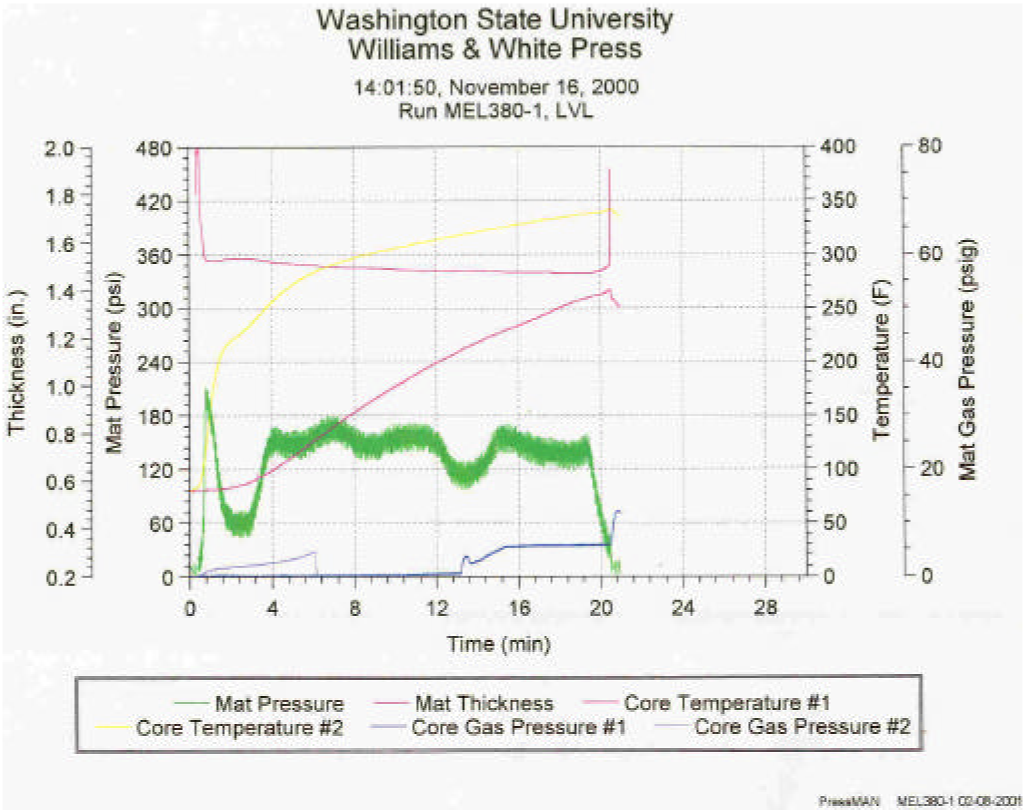
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L340--15 02-08-2001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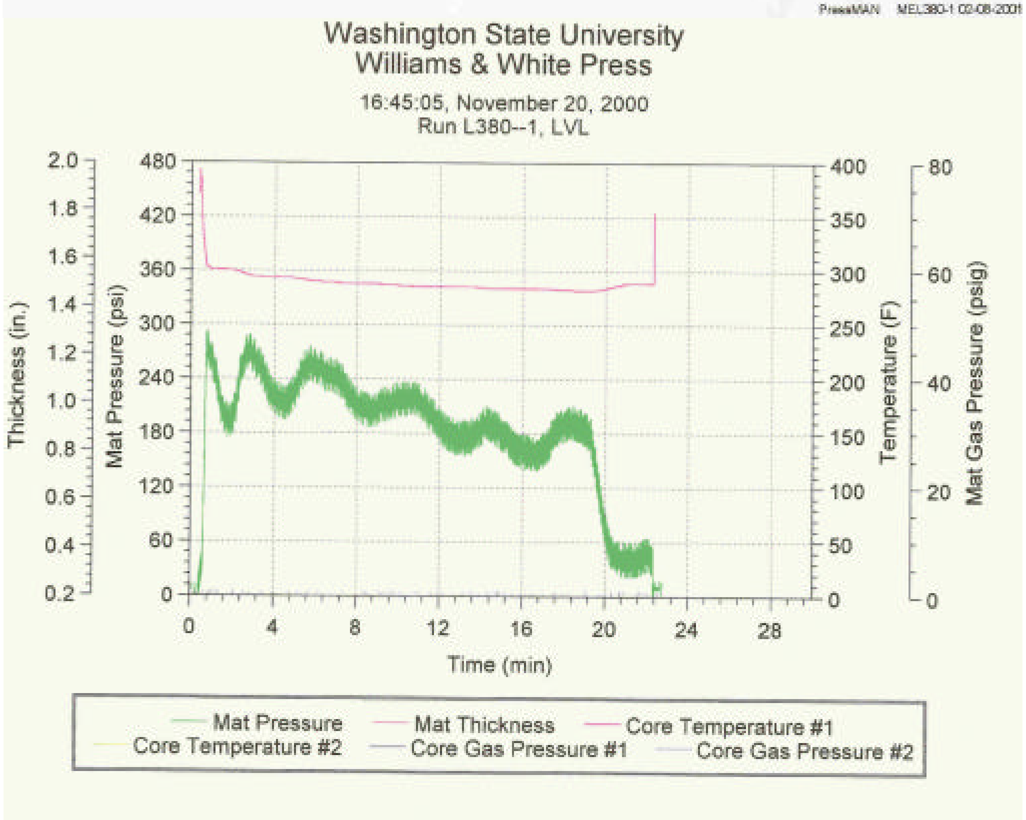
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN MEL380-1 02-08-2001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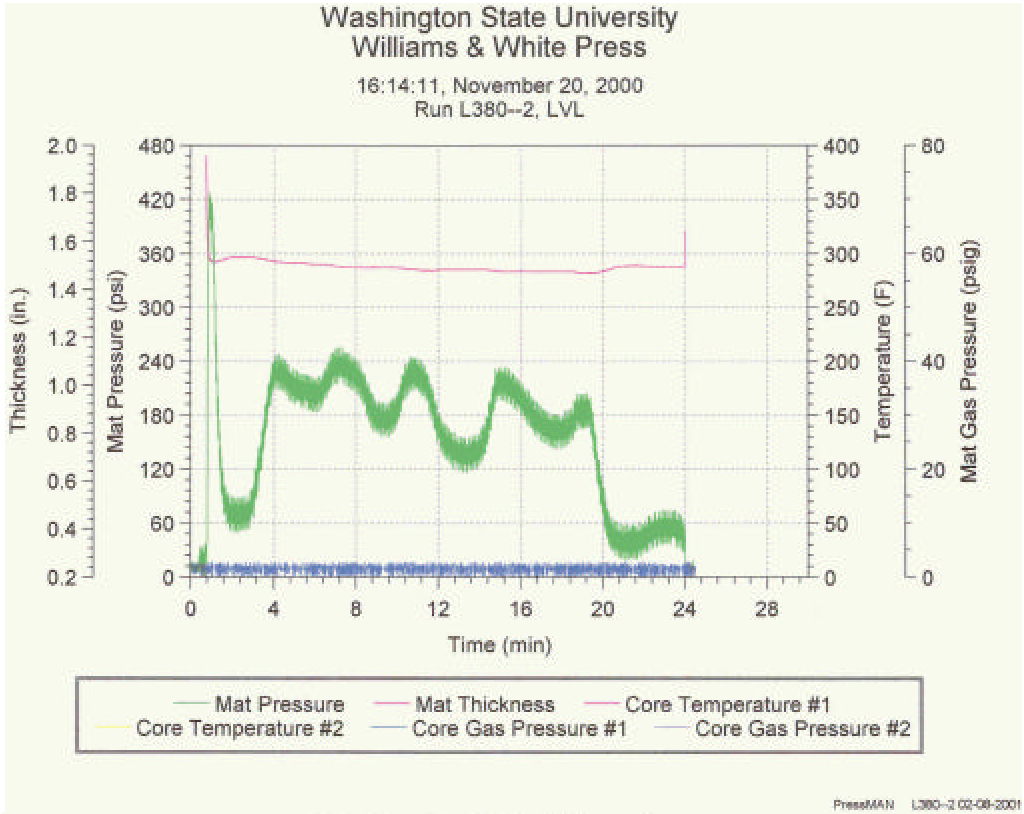
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--1 02-08-200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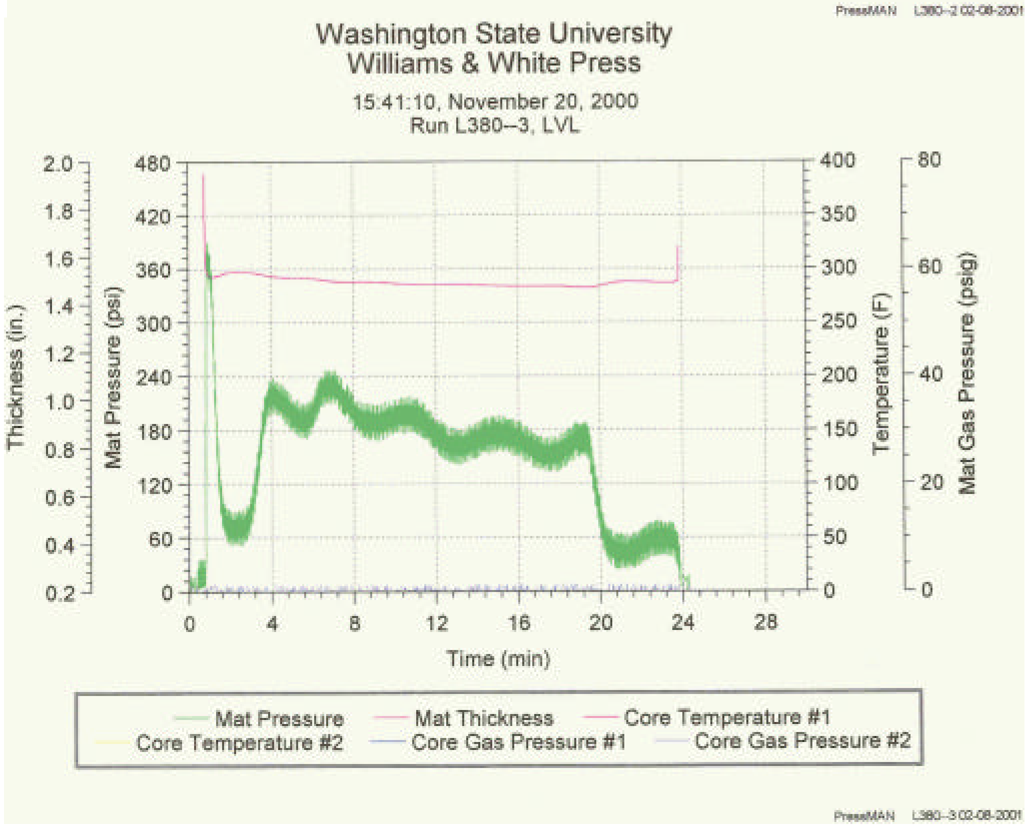
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--2 02-08-2001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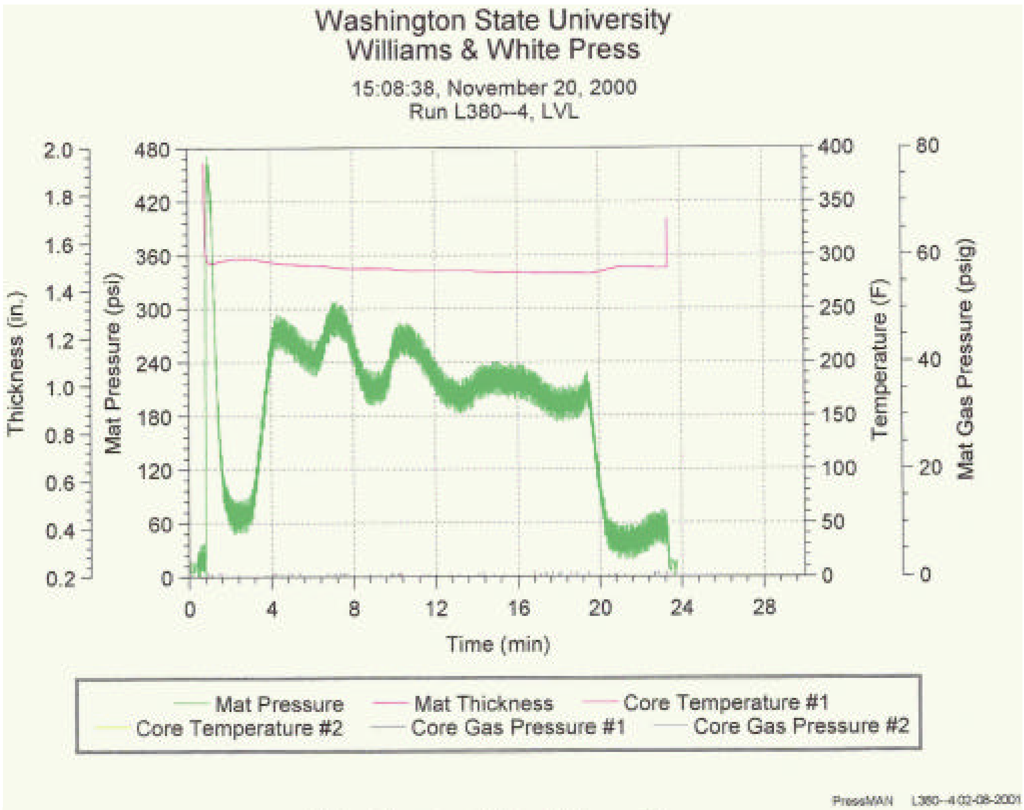
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--3 02-08-2001



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Williams & White Press
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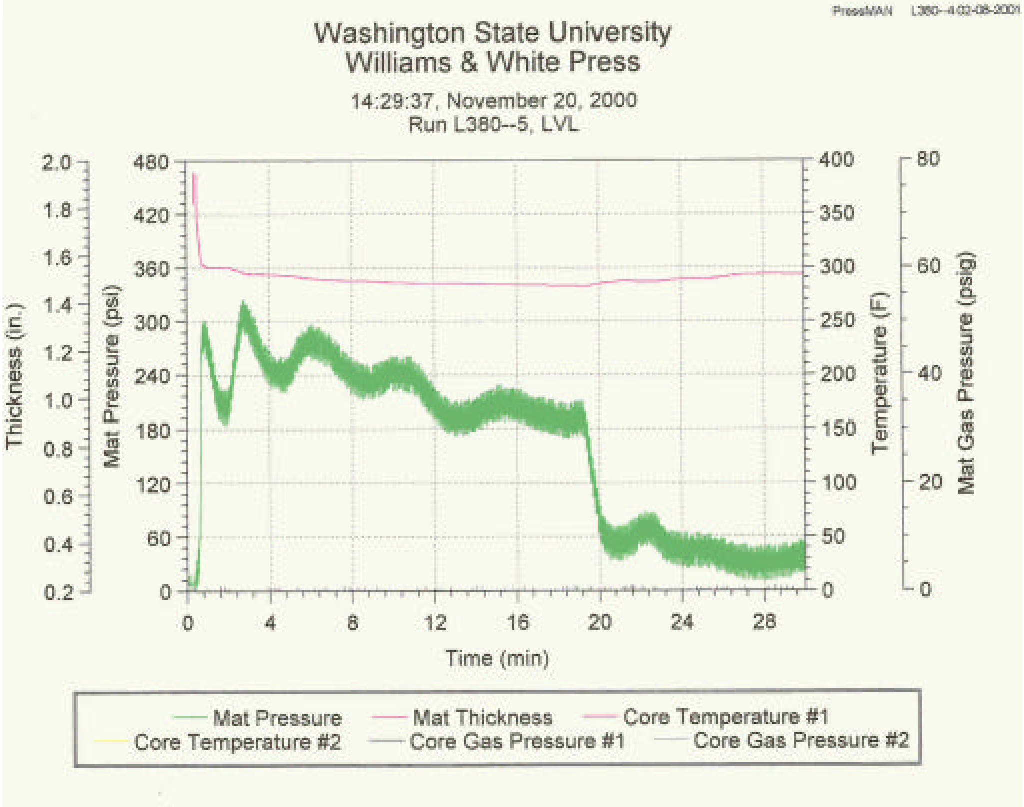
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--4 02-08-2001



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Williams & White Press
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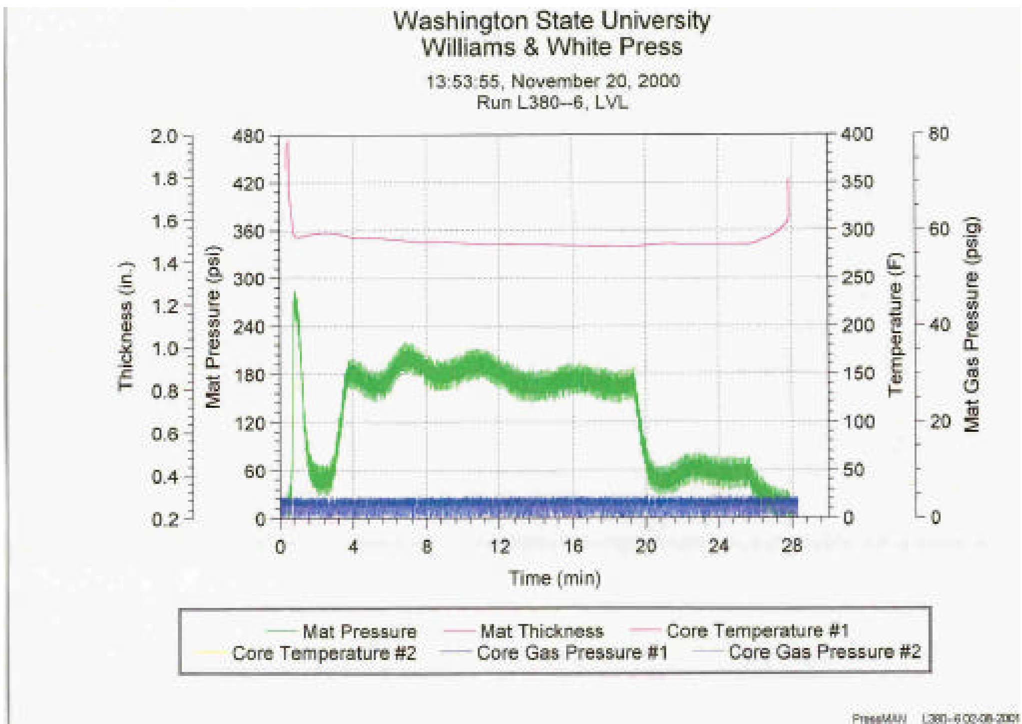
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--5 02-08-2001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Williams & White Press
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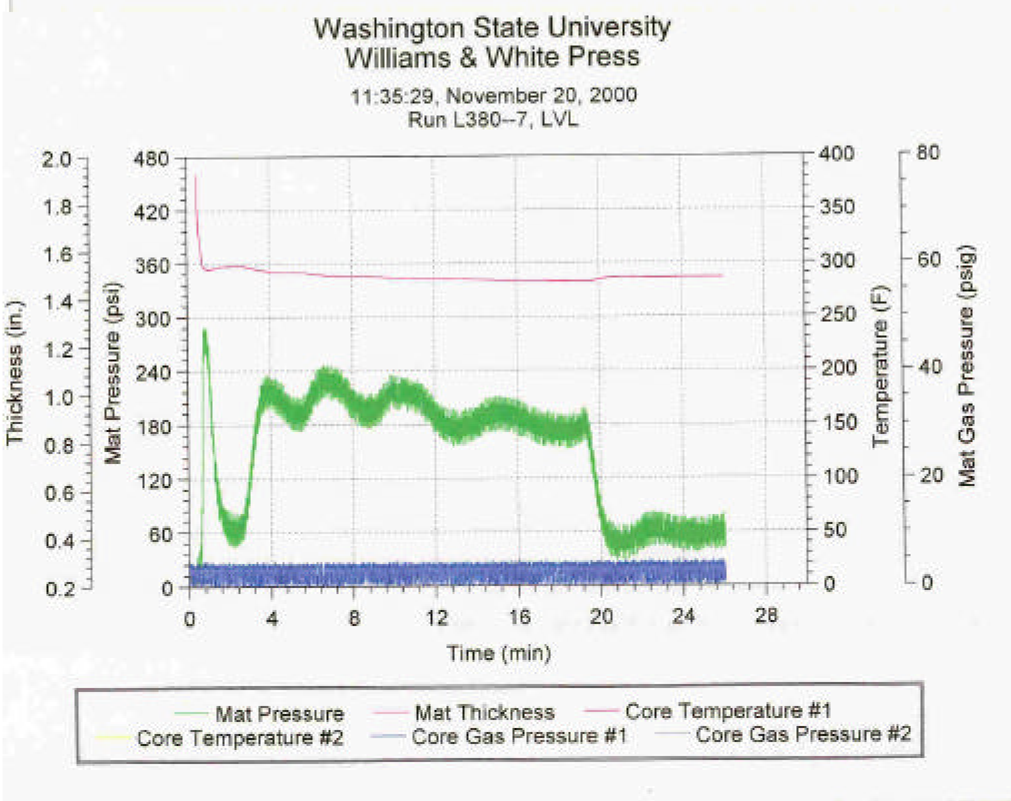
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--6 02-08-2001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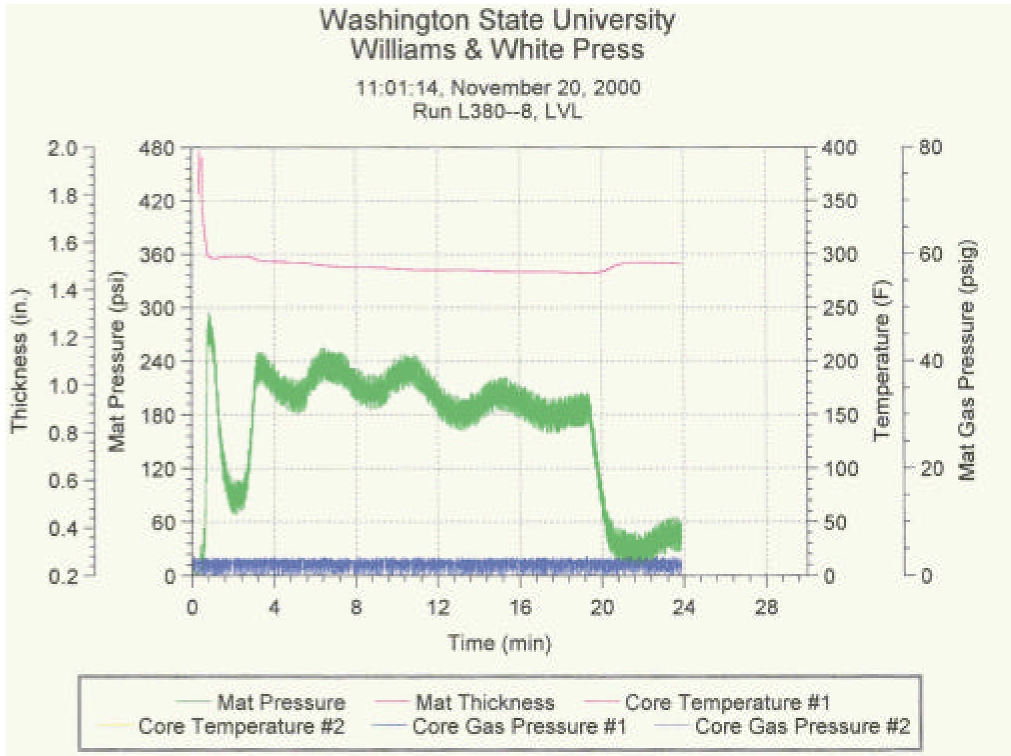
Run L380--7, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--7 02-08-2001



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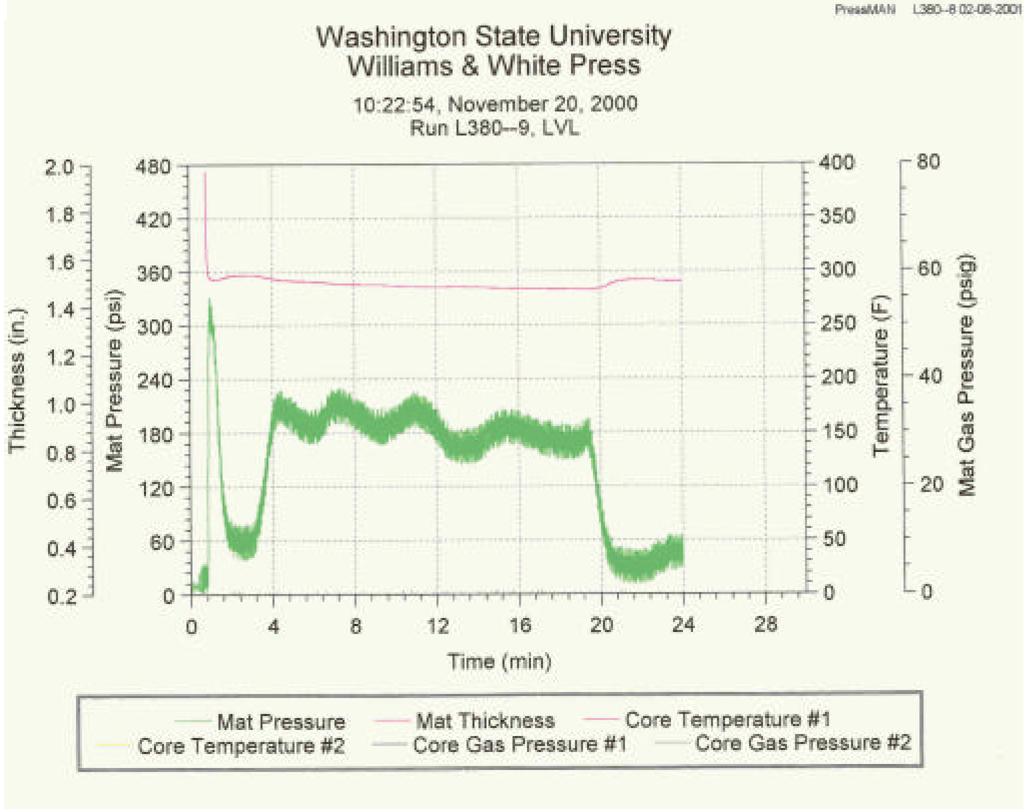

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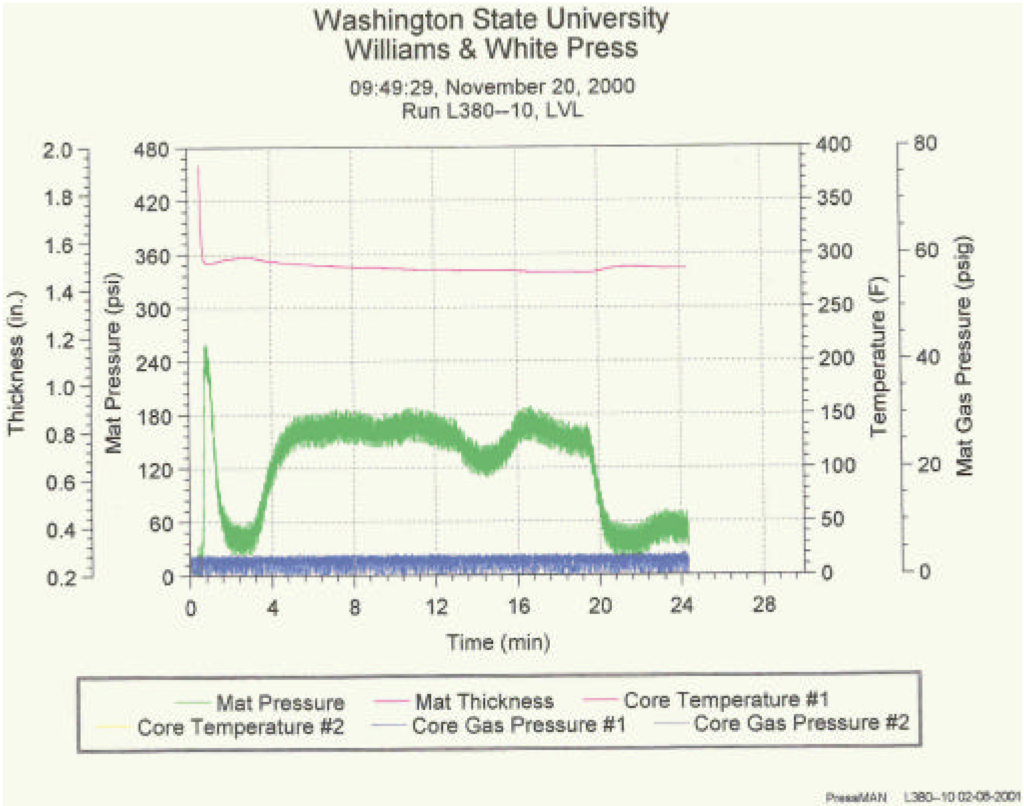
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Williams & White Press
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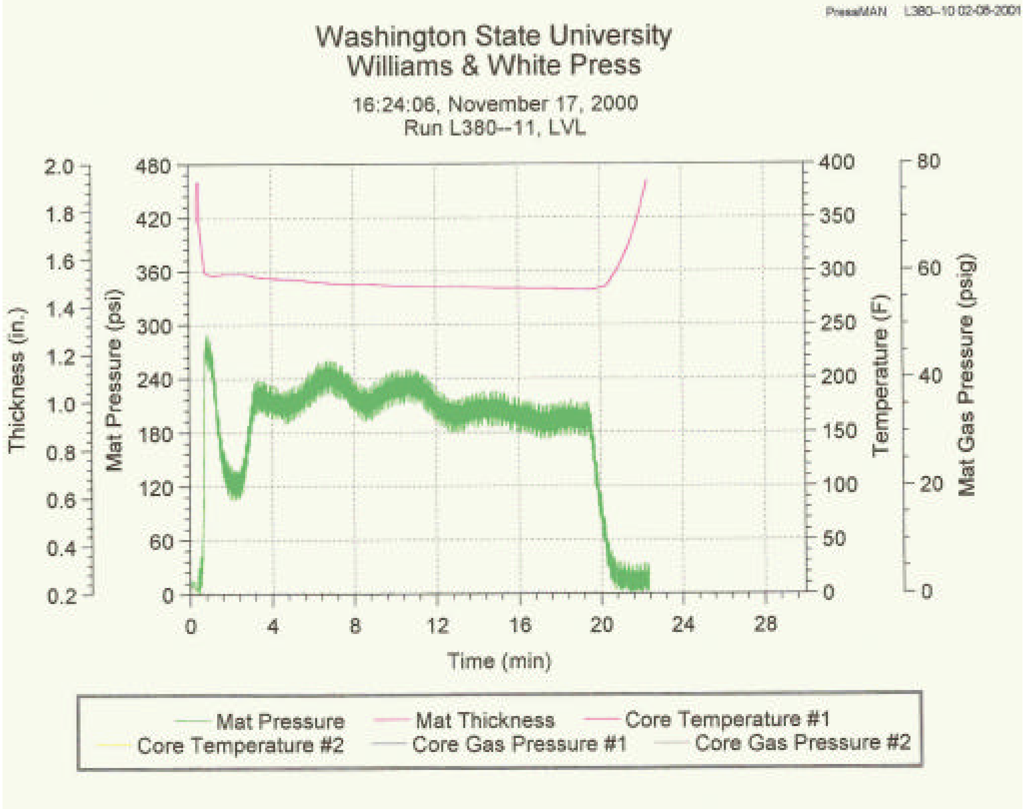
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--10 02-08-2001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Williams & White Press
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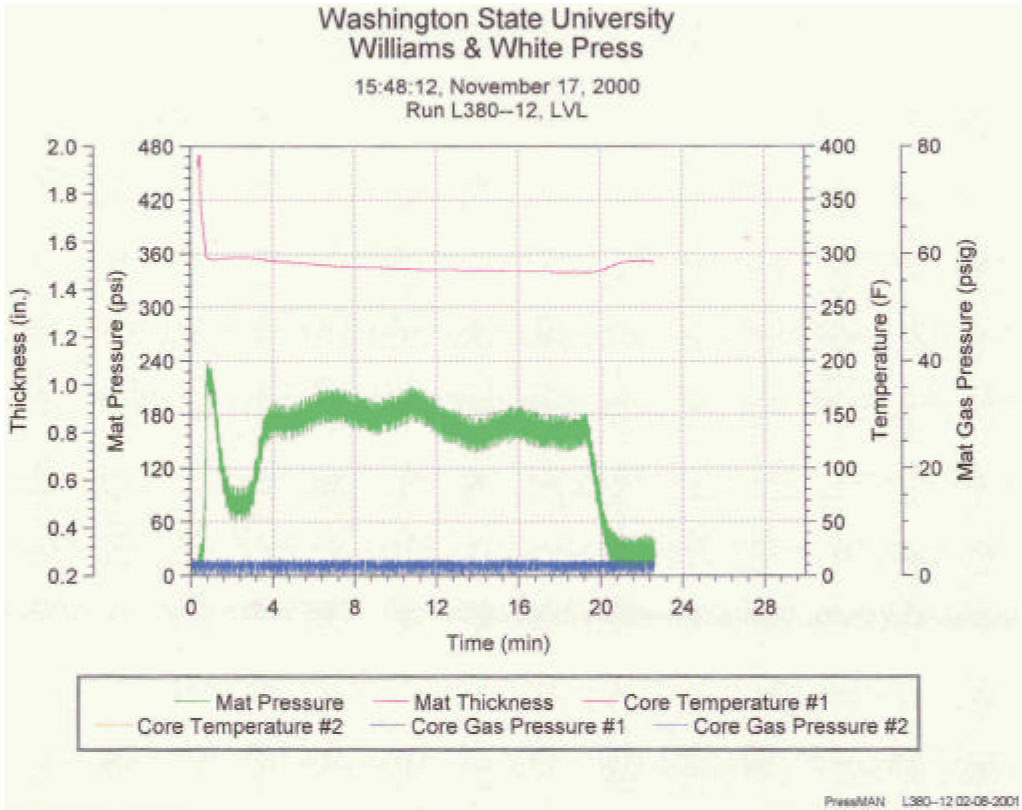
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--11 02-08-2001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Williams & White Press
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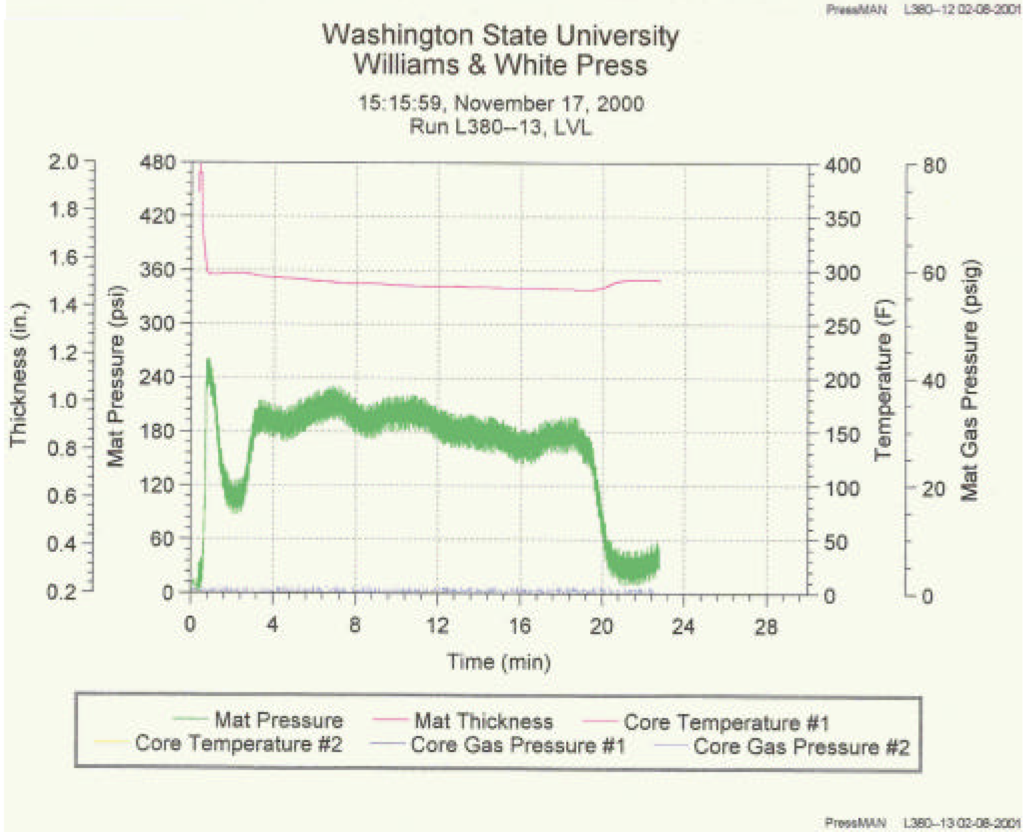
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--12 02-08-2001


Washington State University
Williams & White Press
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Thickness (in.)
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Temperature (F)
Mat Gas Pressure (psig)
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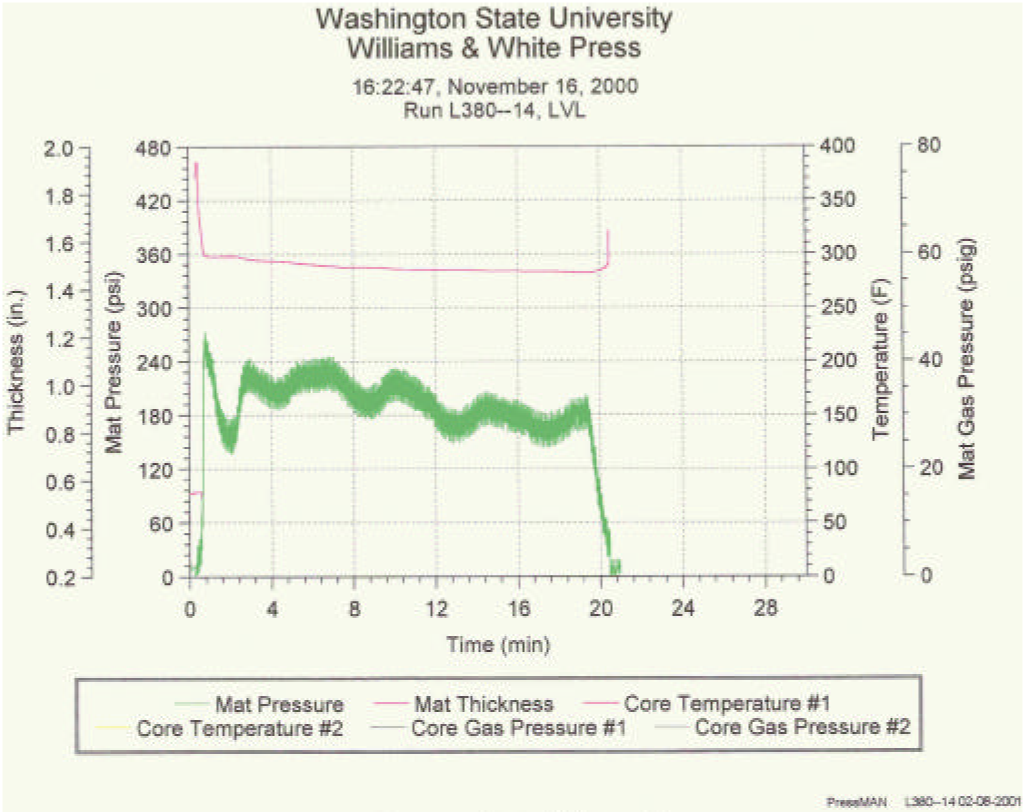
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--13 02-08-2001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Williams & White Press
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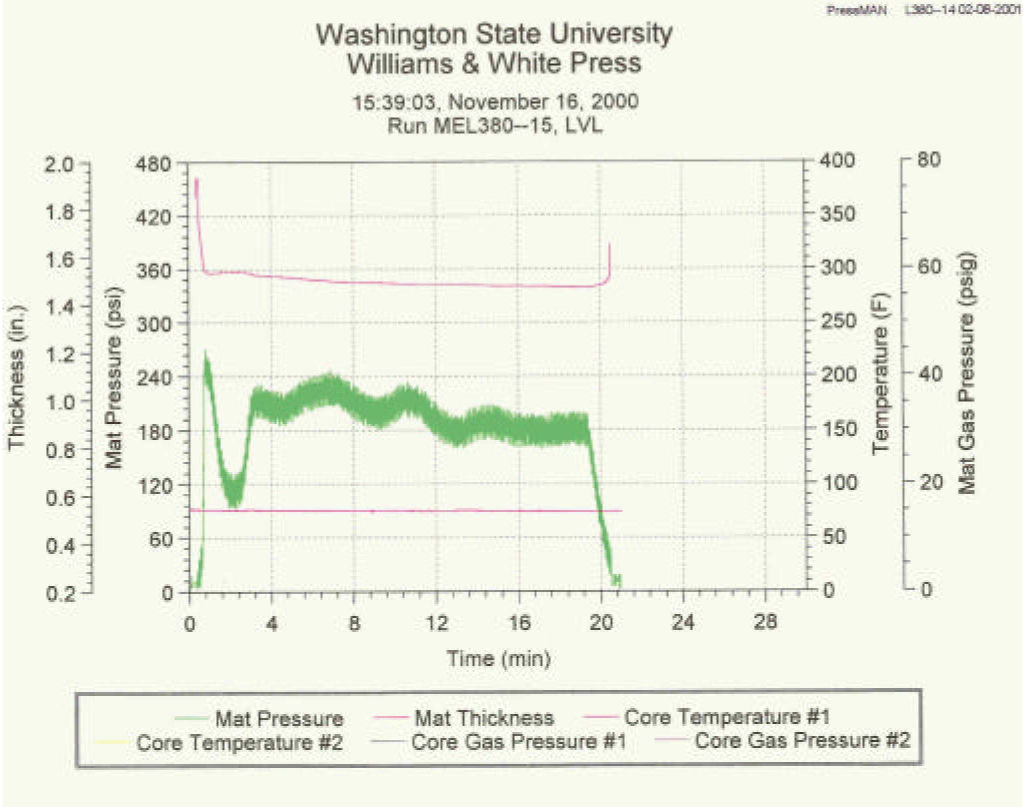
Run L380--14, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--14 02-08-2001


Washington State University
Williams & White Press
15:39:03, November 16, 2000
Run MEL380--15, LVL
Thickness (in.)
Mat Pressure (psi)
Temperature (F)
Mat Gas Pressure (psig)
Time (min)
Mat Pressure
Mat Thickness
Core Temperature #1
Core Temperature #2
Core Gas Pressure #1
Core Gas Pressure #2
PressMAN L380--15 02-08-2001

APPENDIX D

CUMULATIVE DISTRIBUTION FUNCTIONS

INTRODUCTION

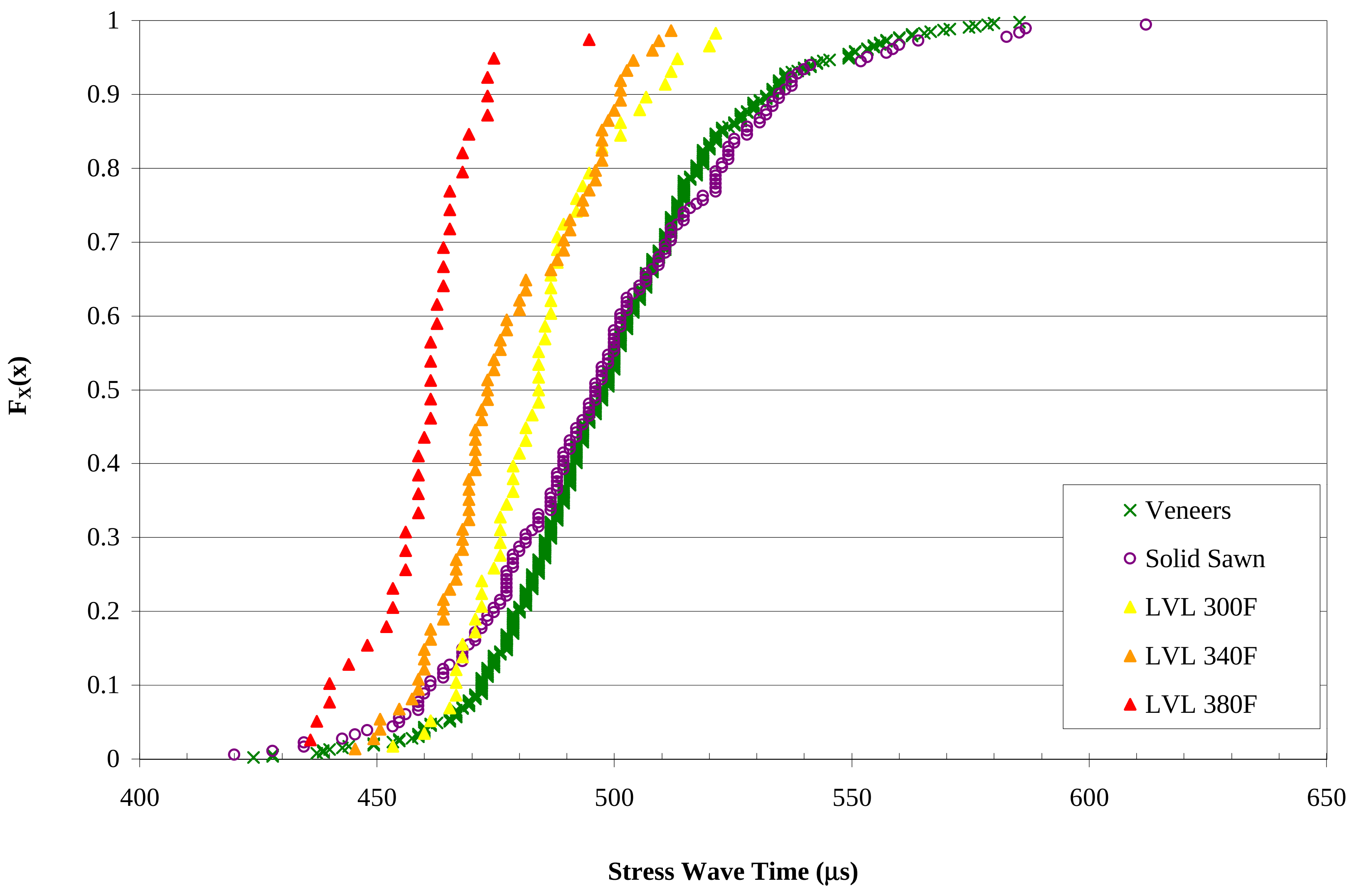
Cumulative distribution functions (CDFs) were used extensively to graphically determine if given populations possessed similar or dissimilar distributions. This method was imperative to the justification of specimen sorting techniques. Because the value of the CDF was found in its comparative ability, plots within this appendix represent two or more populations.

CDFs were also used to help determine the best nondestructive predictive method for the static modulus of elasticity for laminated veneer lumber. CDFs representing populations of dynamic modulus of elasticity and calculated modulus of elasticity values from the laminated beam theory are provided in this appendix. Accompanying these CDFs are correlation graphs for the nondestructive testing (NDT) techniques. Charts depicting the percent difference between several of the different NDT techniques are also provided. Actual calculated values for all the nondestructive techniques are also located within this appendix.

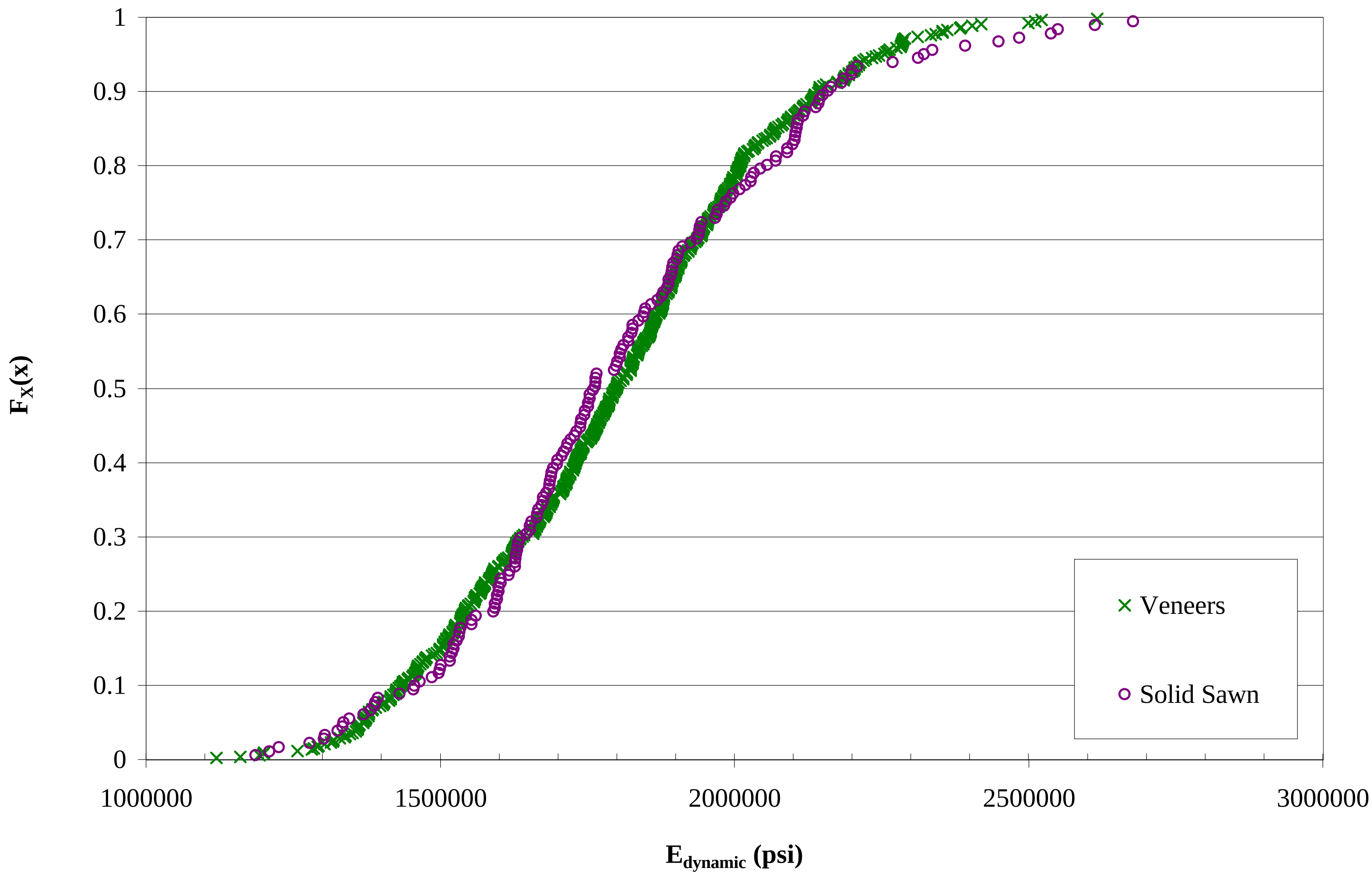
POPULATION COMPARISONS

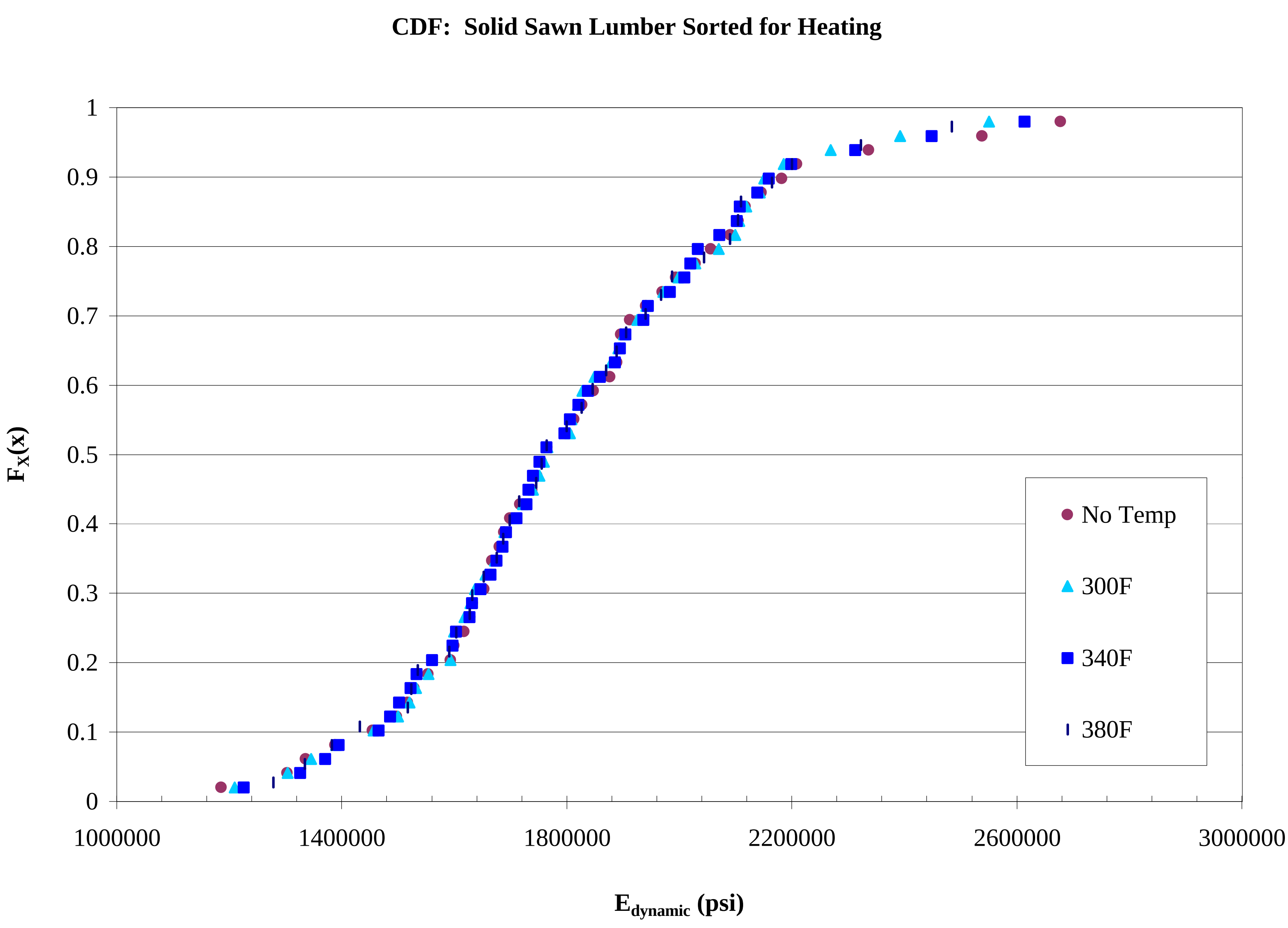
Appendix Pages: 306 - 317

CDF: Stress Wave Time of Veneer, Solid Sawn Lumber, and Laminated Veneer Lumber (useable)

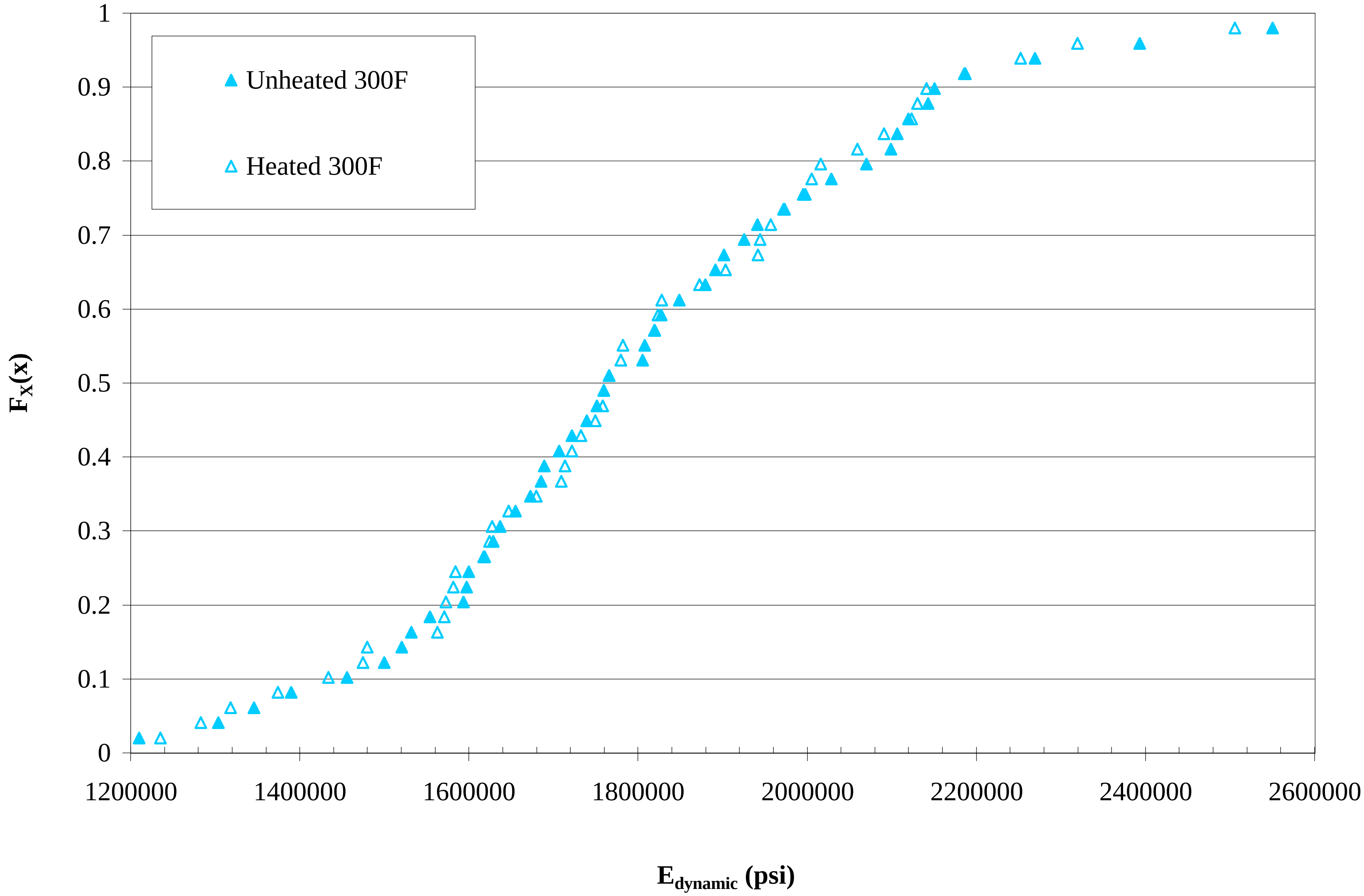


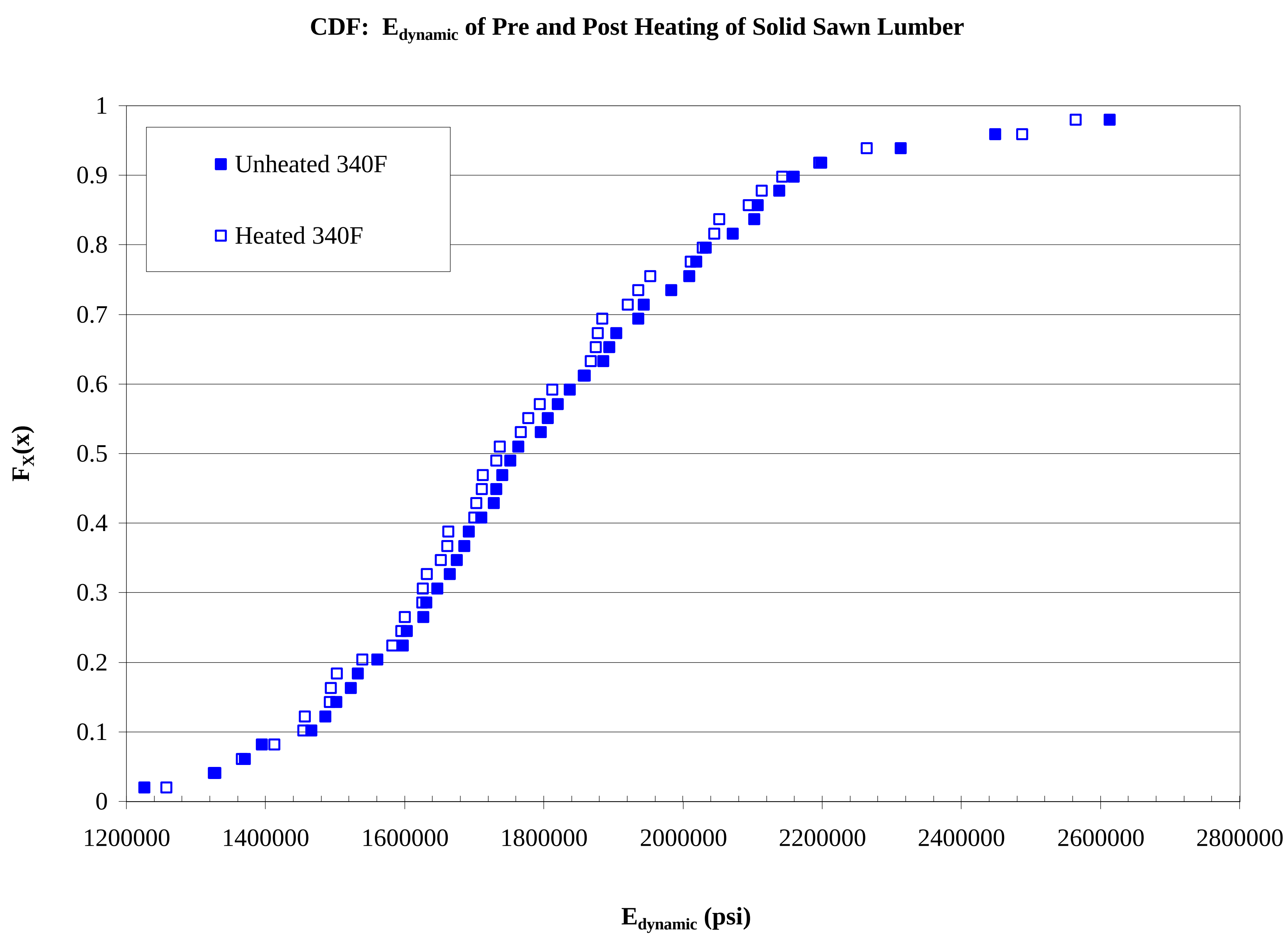
CDF: $E_{dynamic}$ of Veneers and Unheated Solid Sawn Lumber




CDF: Solid Sawn Lumber Sorted for Heating
$F_X(x)$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1000000
1400000
1800000
2200000
2600000
3000000
$E_{dynamic}$ (psi)
No Temp
300F
340F
380F

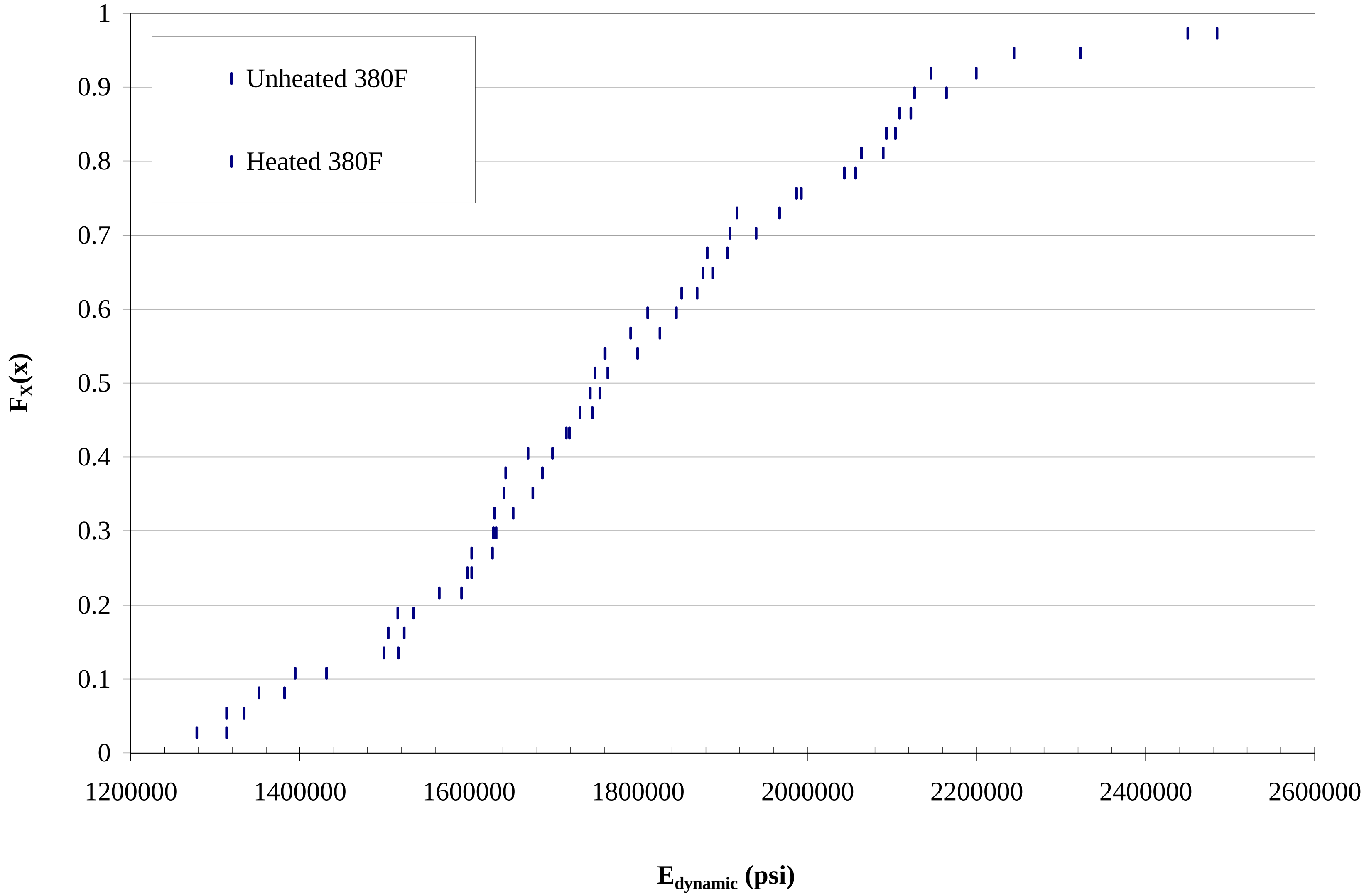
CDF: $E_{dynamic}$ of Pre and Post Heating of Solid Sawn Lumber



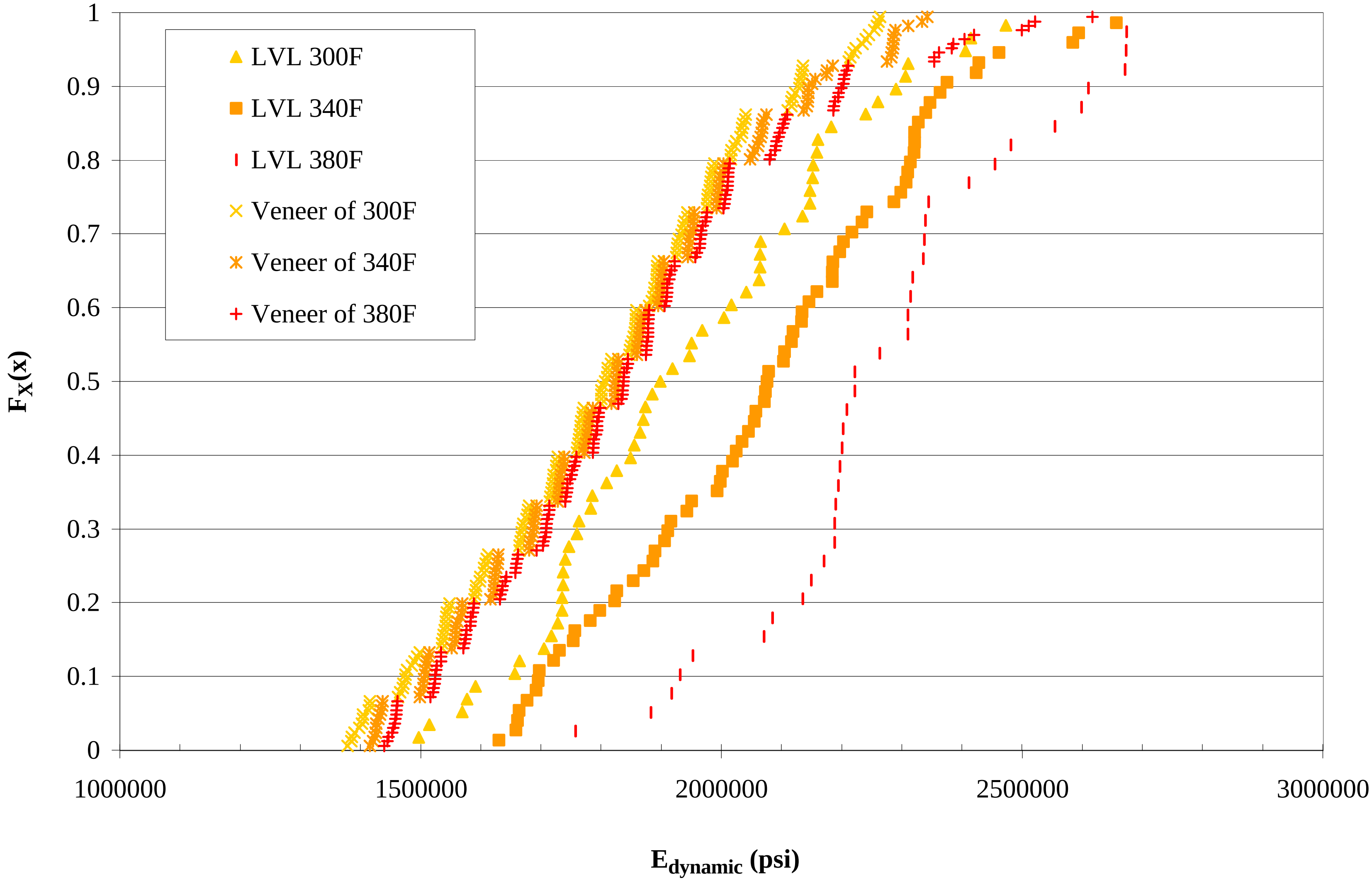


CDF: $E_{dynamic}$ of Pre and Post Heating of Solid Sawn Lumber
Unheated 340F
Heated 340F
$F_X(x)$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1200000
1400000
1600000
1800000
2000000
2200000
2400000
2600000
2800000
$E_{dynamic}$ (psi)

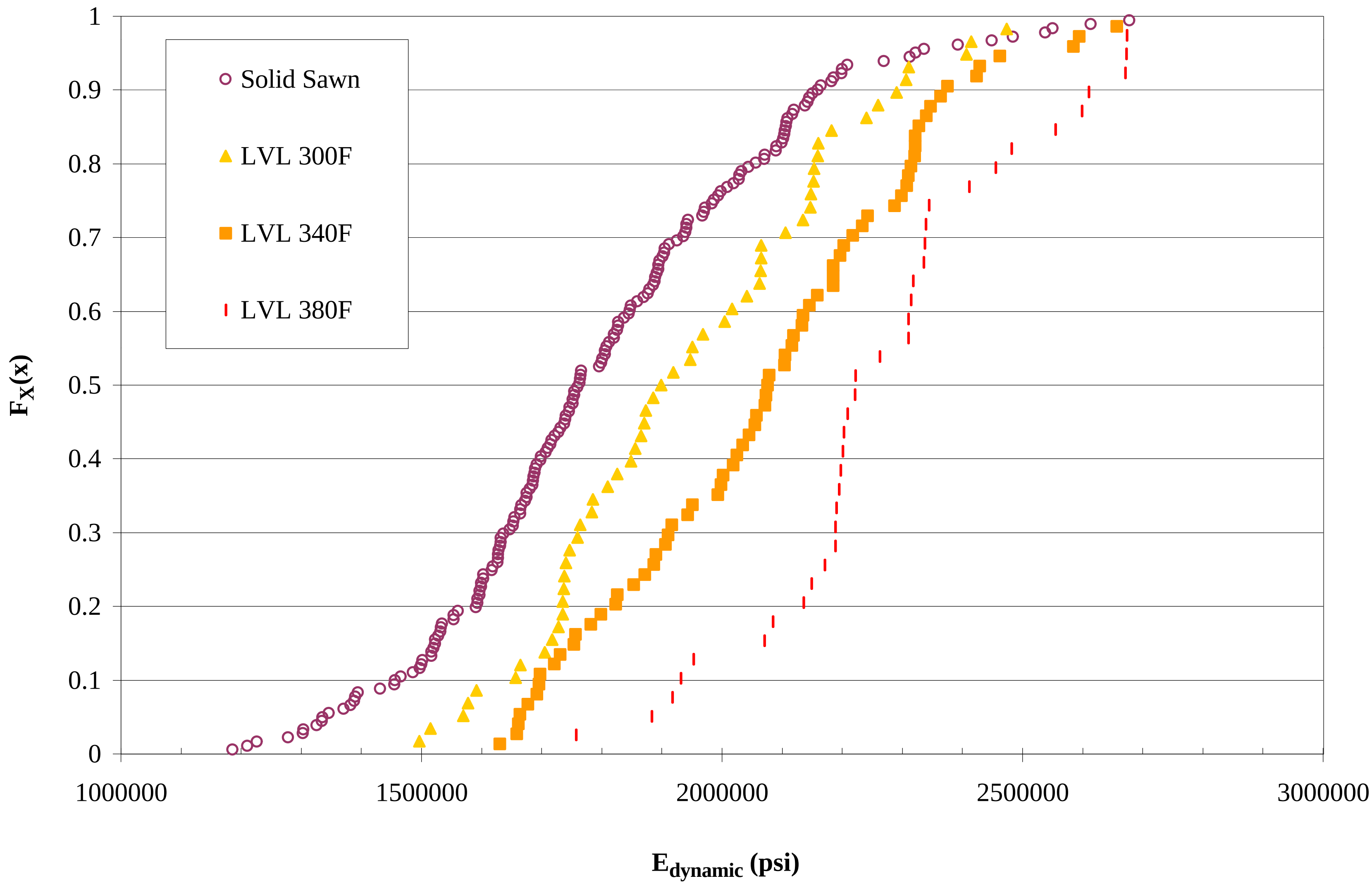
CDF: $E_{dynamic}$ of Pre and Post Heating of Solid Sawn Lumber

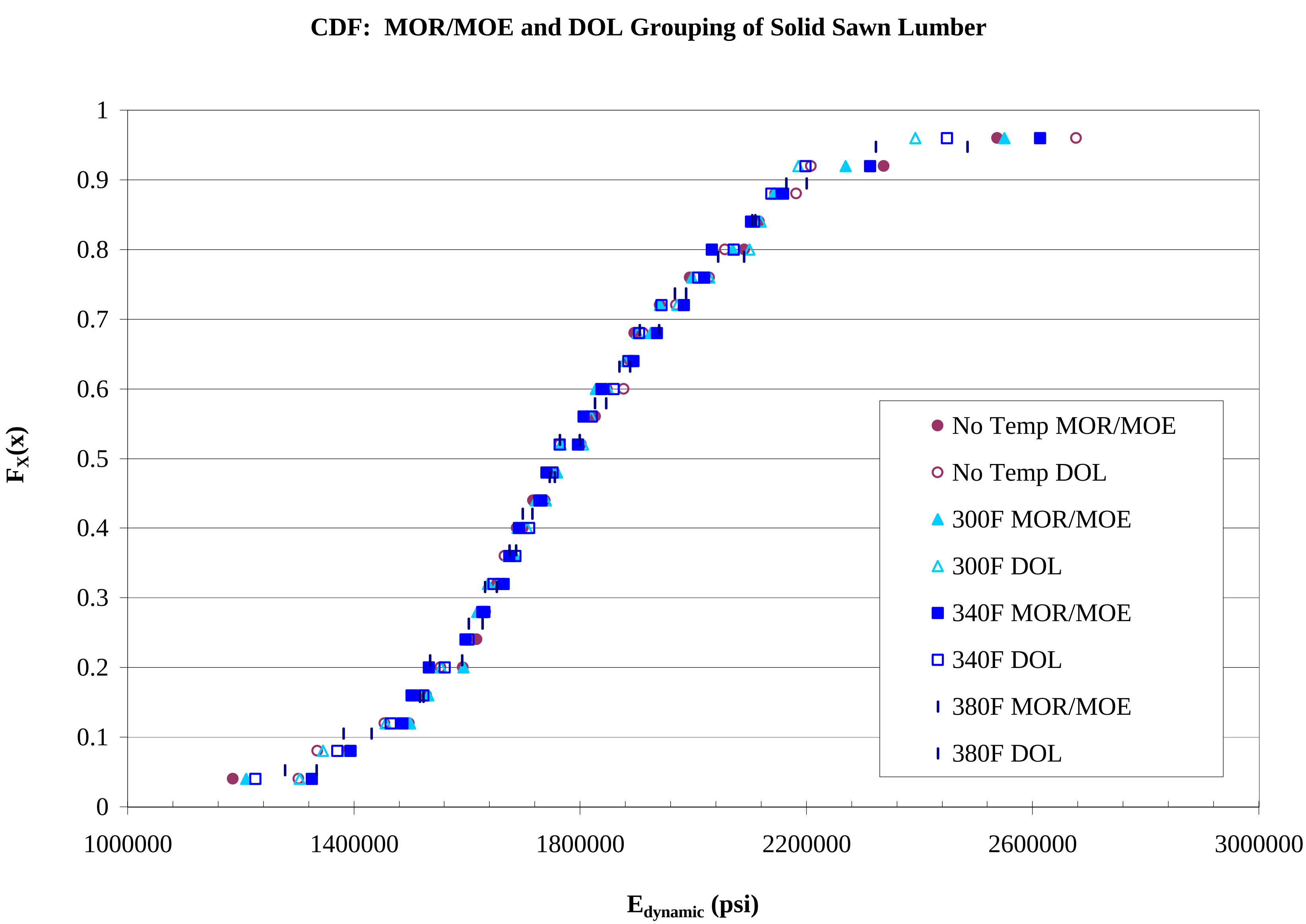


CDF: $E_{dynamic}$ of Veneers and Laminated Veneer Lumber (useable)

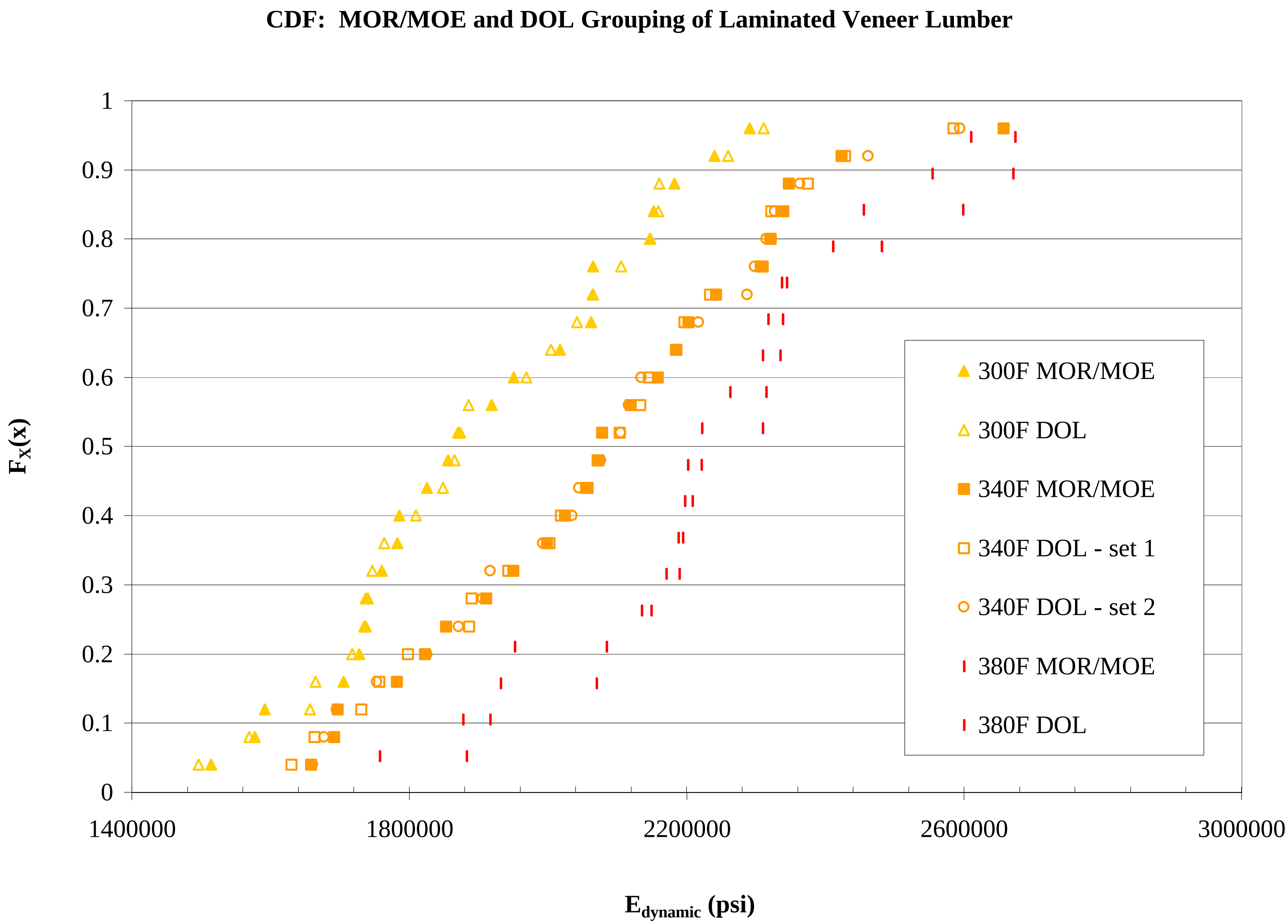


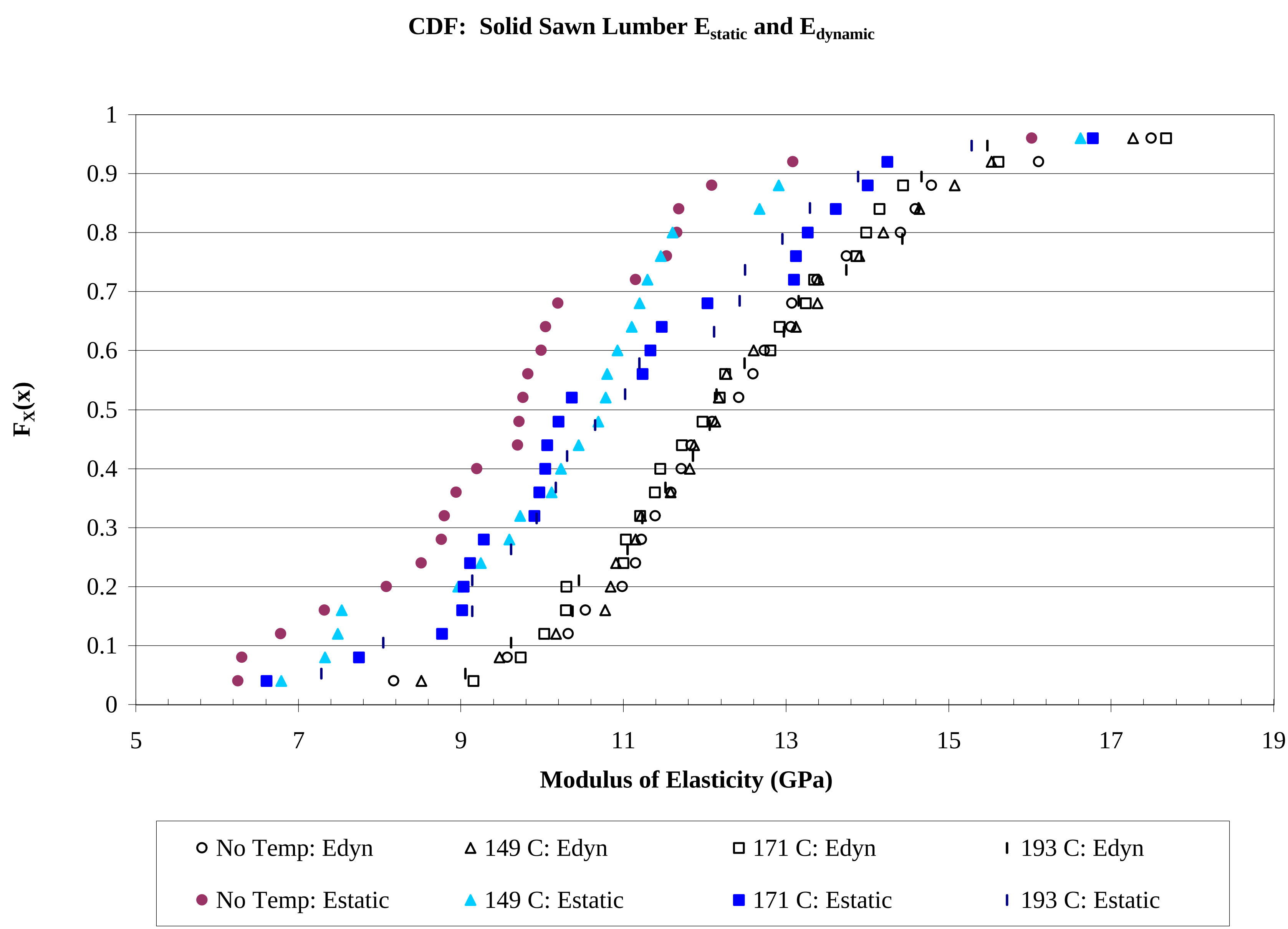
CDF: $E_{dynamic}$ of Solid Sawn Lumber and Laminated Veneer Lumber (useable)

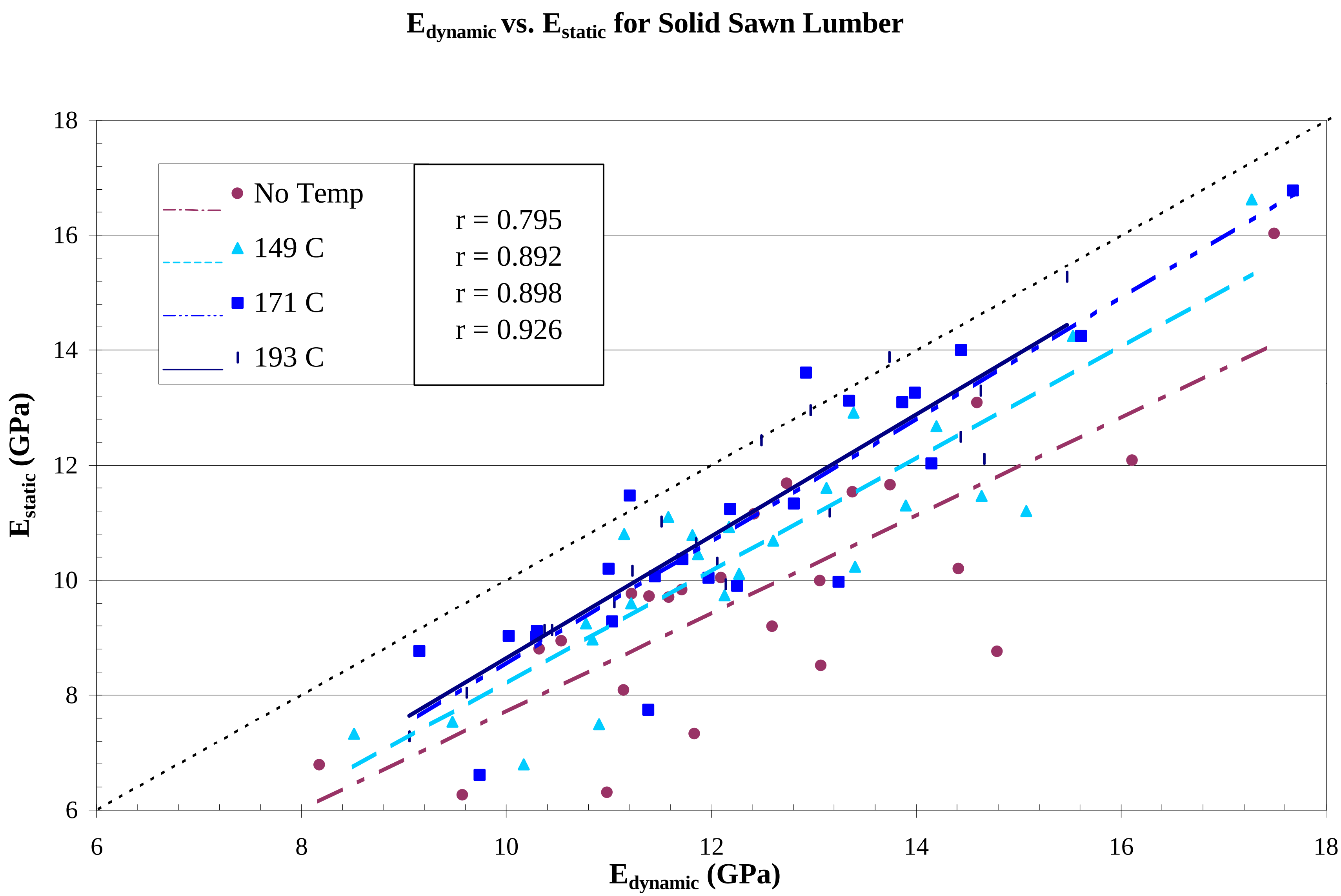




CDF: MOR/MOE and DOL Grouping of Solid Sawn Lumber
$F_X(x)$
$E_{dynamic}$ (psi)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1000000
1400000
1800000
2200000
2600000
3000000
No Temp MOR/MOE
No Temp DOL
300F MOR/MOE
300F DOL
340F MOR/MOE
340F DOL
380F MOR/MOE
380F DOL


CDF: MOR/MOE and DOL Grouping of Laminated Veneer Lumber
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Fx(x)
1400000
1800000
2200000
2600000
3000000
Edynamic (psi)
300F MOR/MOE
300F DOL
340F MOR/MOE
340F DOL - set 1
340F DOL - set 2
380F MOR/MOE
380F DOL


CDF: Solid Sawn Lumber E_static and E_dynamic
F_X(x)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
7
9
11
13
15
17
19
Modulus of Elasticity (GPa)
No Temp: Edyn
149 C: Edyn
171 C: Edyn
193 C: Edyn
No Temp: Estatic
149 C: Estatic
171 C: Estatic
193 C: Estatic



E dynamic vs. E static for Solid Sawn Lumber
No Temp
149 C
171 C
193 C
r = 0.795
r = 0.892
r = 0.898
r = 0.926
E static (GPa)
E dynamic (GPa)
18
16
14
12
10
8
6
6
8
10
12
14
16
18

NONDESTRUCTIVE PREDICTIVE POPULATIONS

CUMULATIVE DISTRIBUTION FUNCTIONS AND CORRELATION GRAPHS

Appendix Pages: 319 - 332

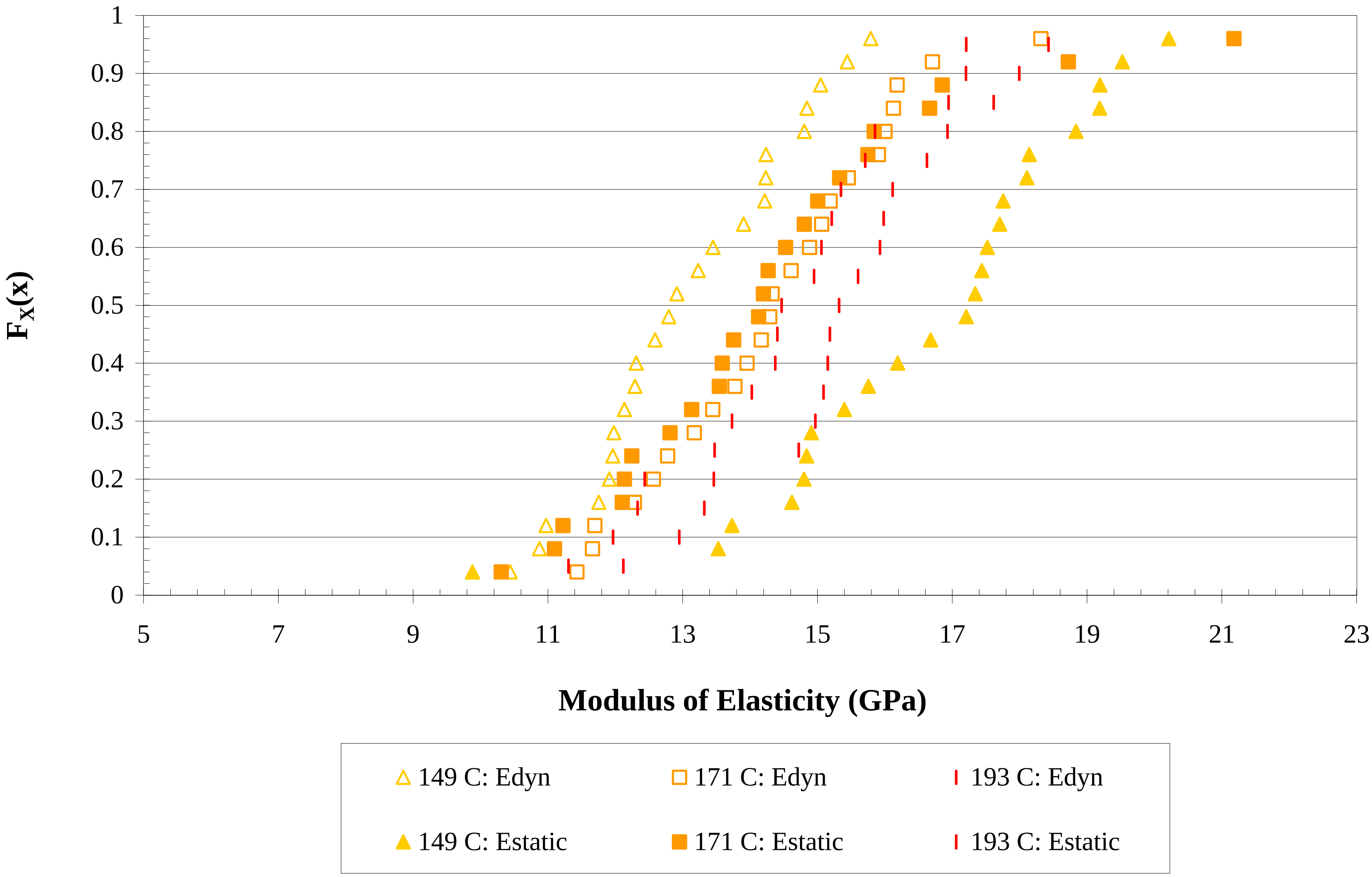
COMPARATIVE CHARTS

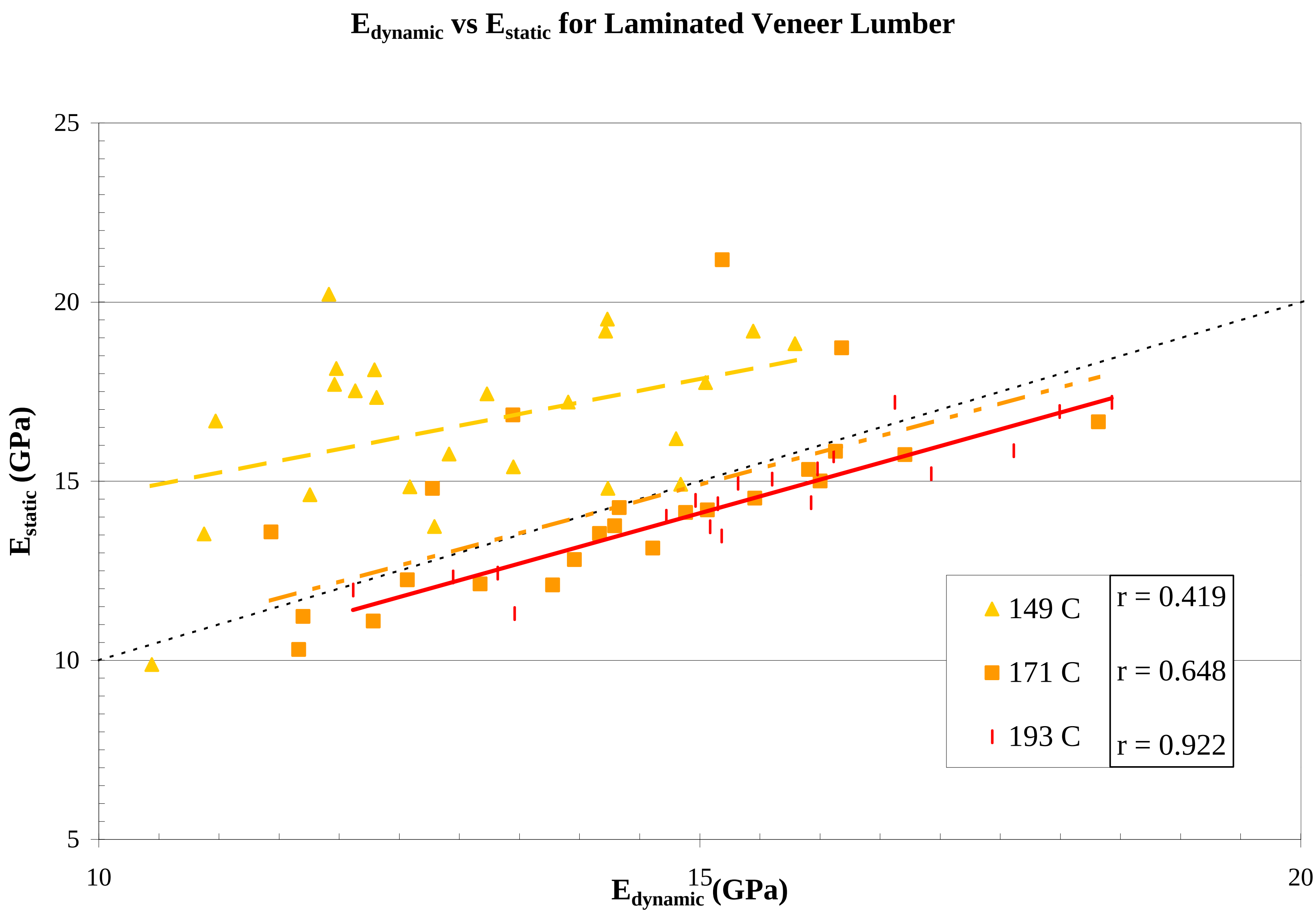
Appendix Pages: 333 - 337

DATA

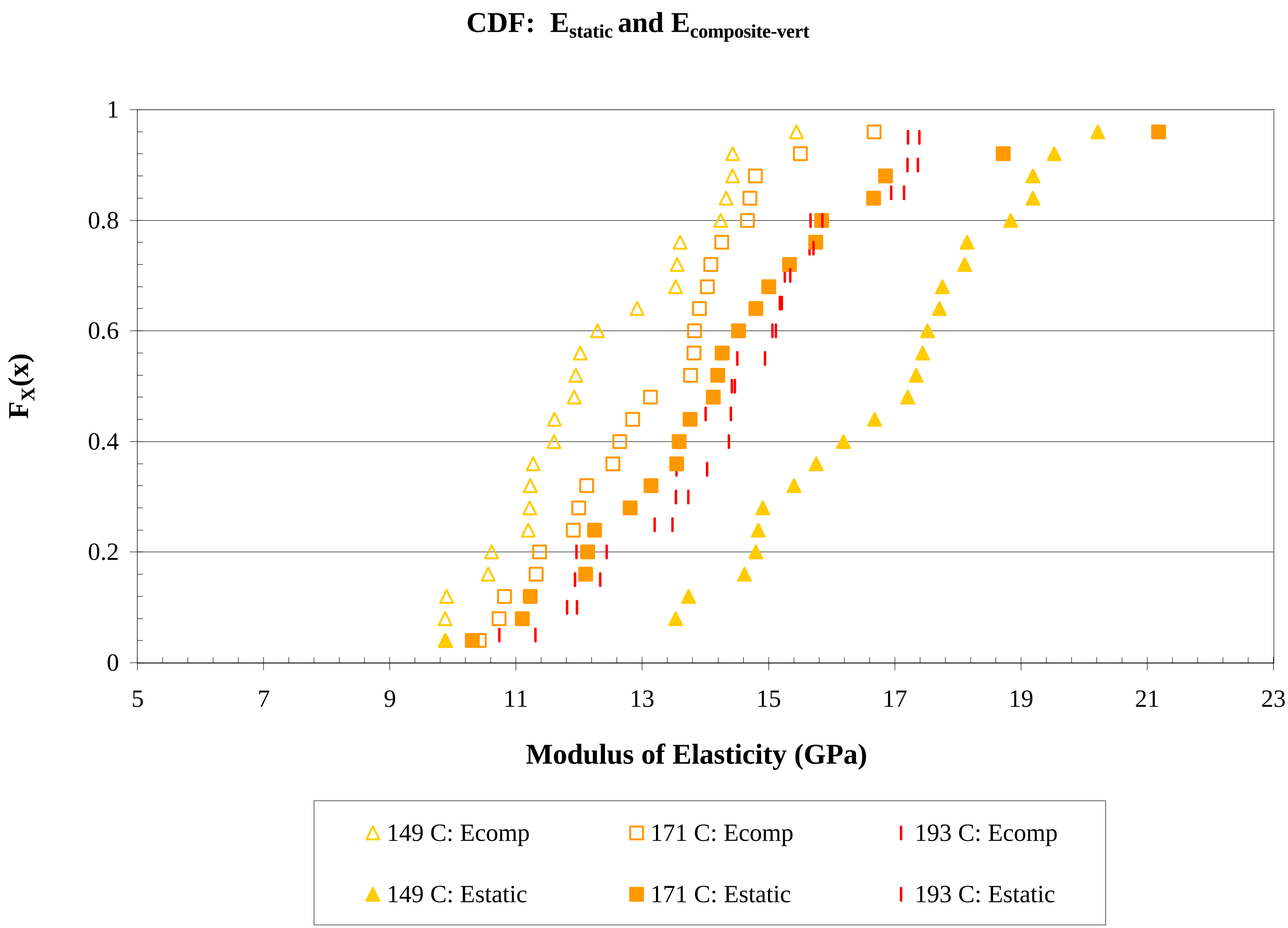
Appendix Pages: 338 - 343

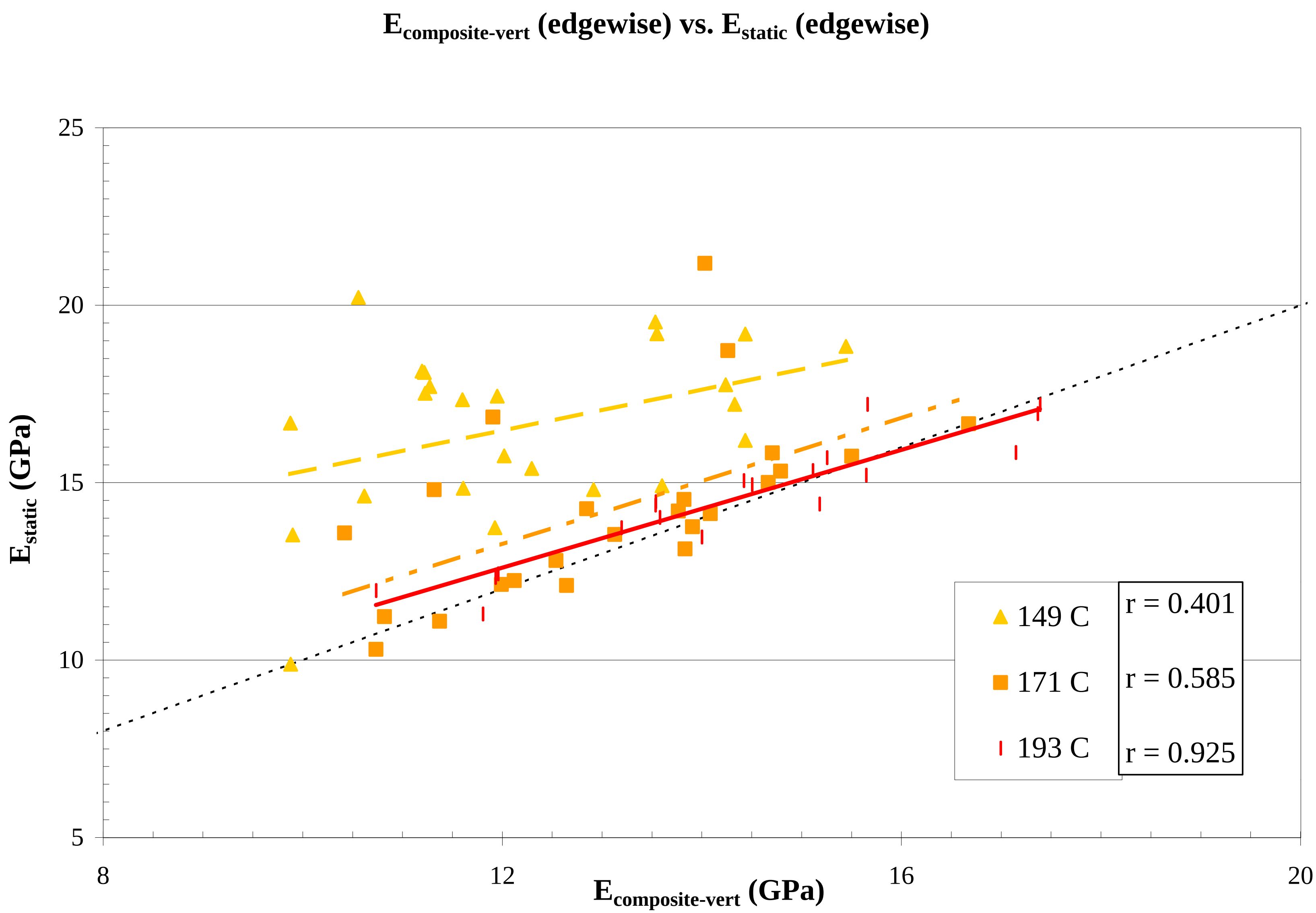
CDF: Laminated Veneer Lumber E_{static} and $E_{dynamic}$



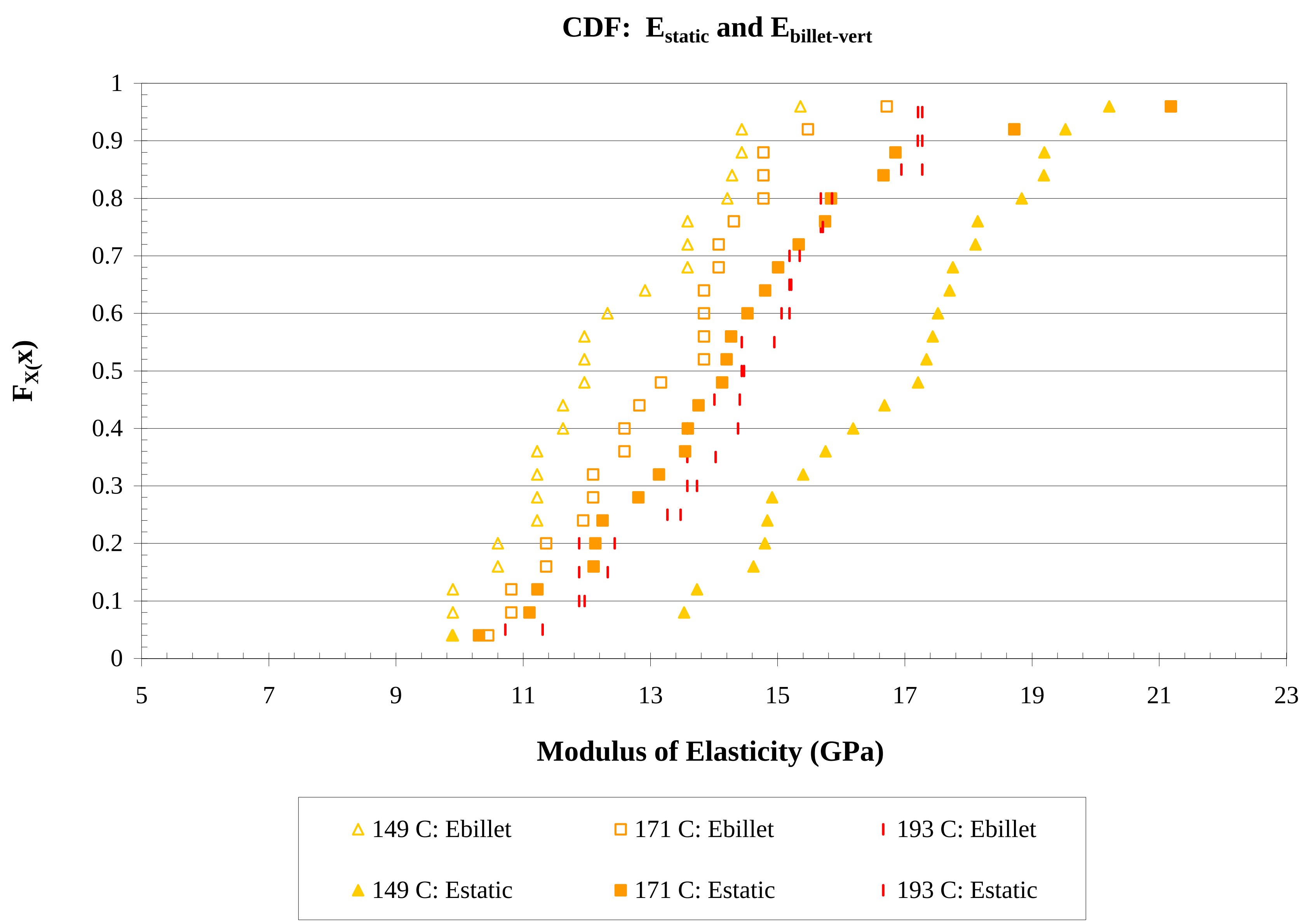


$E_{dynamic}$ vs E_{static} for Laminated Veneer Lumber
25
20
15
10
5
E_{static} (GPa)
10
15
20
$E_{dynamic}$ (GPa)
149 C
171 C
193 C
r = 0.419
r = 0.648
r = 0.922

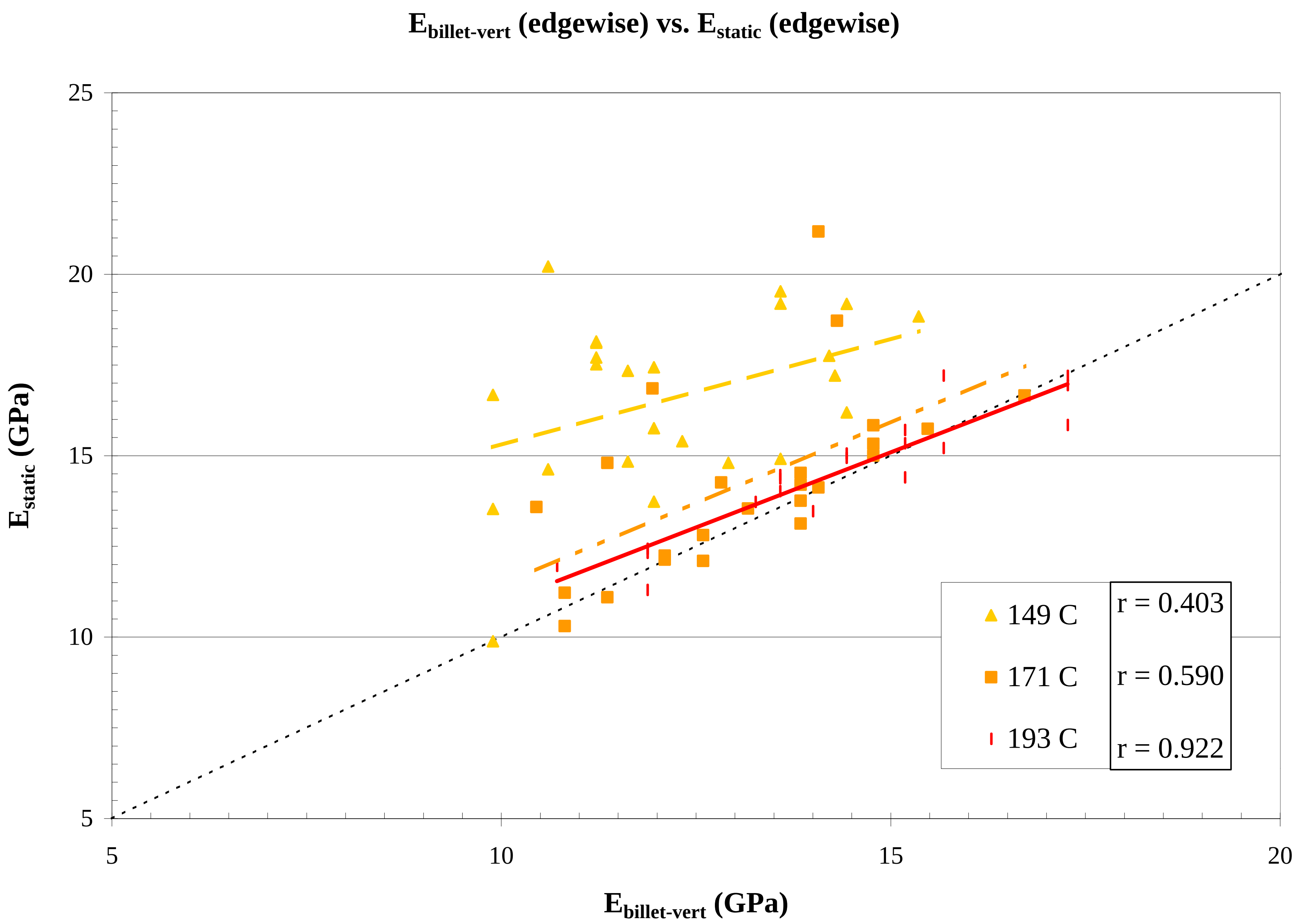

CDF: E_{static} and $E_{composite\text{-}vert}$
$F_X(x)$
0
0.2
0.4
0.6
0.8
1
5
7
9
11
13
15
17
19
21
23
Modulus of Elasticity (GPa)
149 C: Ecomp
171 C: Ecomp
193 C: Ecomp
149 C: Estatic
171 C: Estatic
193 C: Estatic



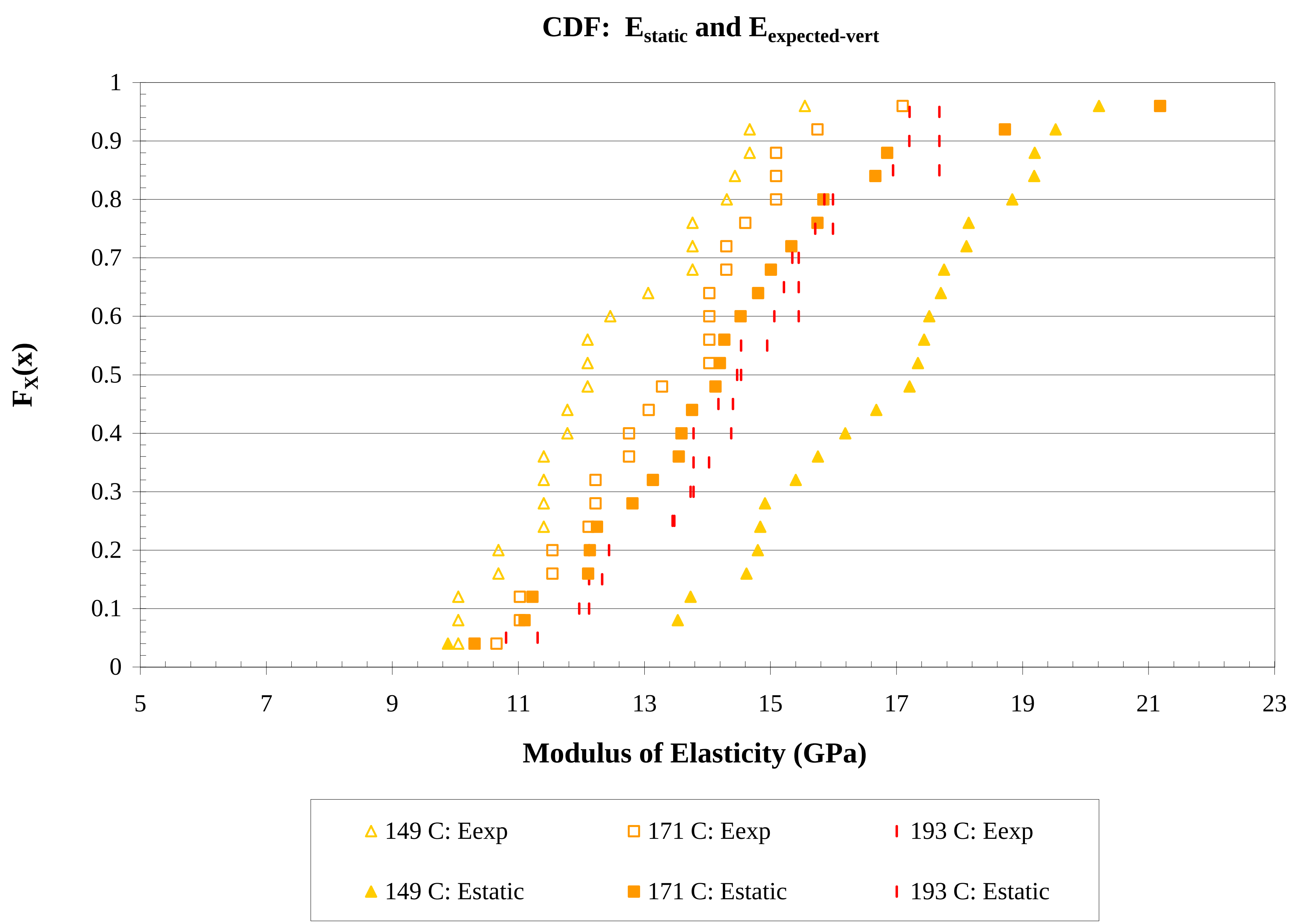
E composite-vert (edgewise) vs. E static (edgewise)
25
20
15
10
5
8
12
16
20
E static (GPa)
E composite-vert (GPa)
149 C
171 C
193 C
r = 0.401
r = 0.585
r = 0.925



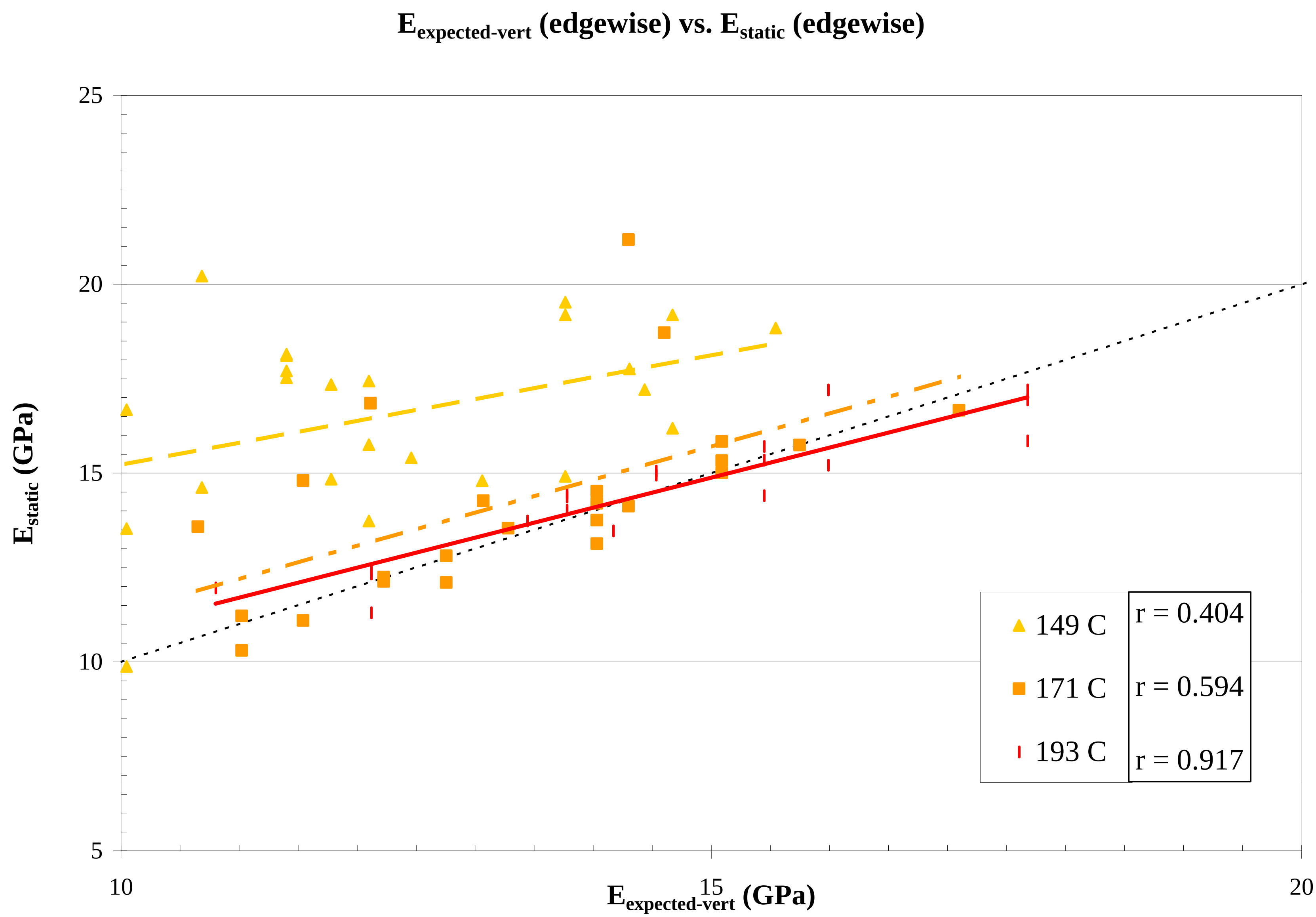
CDF: E_{static} and $E_{billet\text{-}vert}$
$F_{X}(x)$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
7
9
11
13
15
17
19
21
23
Modulus of Elasticity (GPa)
149 C: Ebillet
171 C: Ebillet
193 C: Ebillet
149 C: Estatic
171 C: Estatic
193 C: Estatic



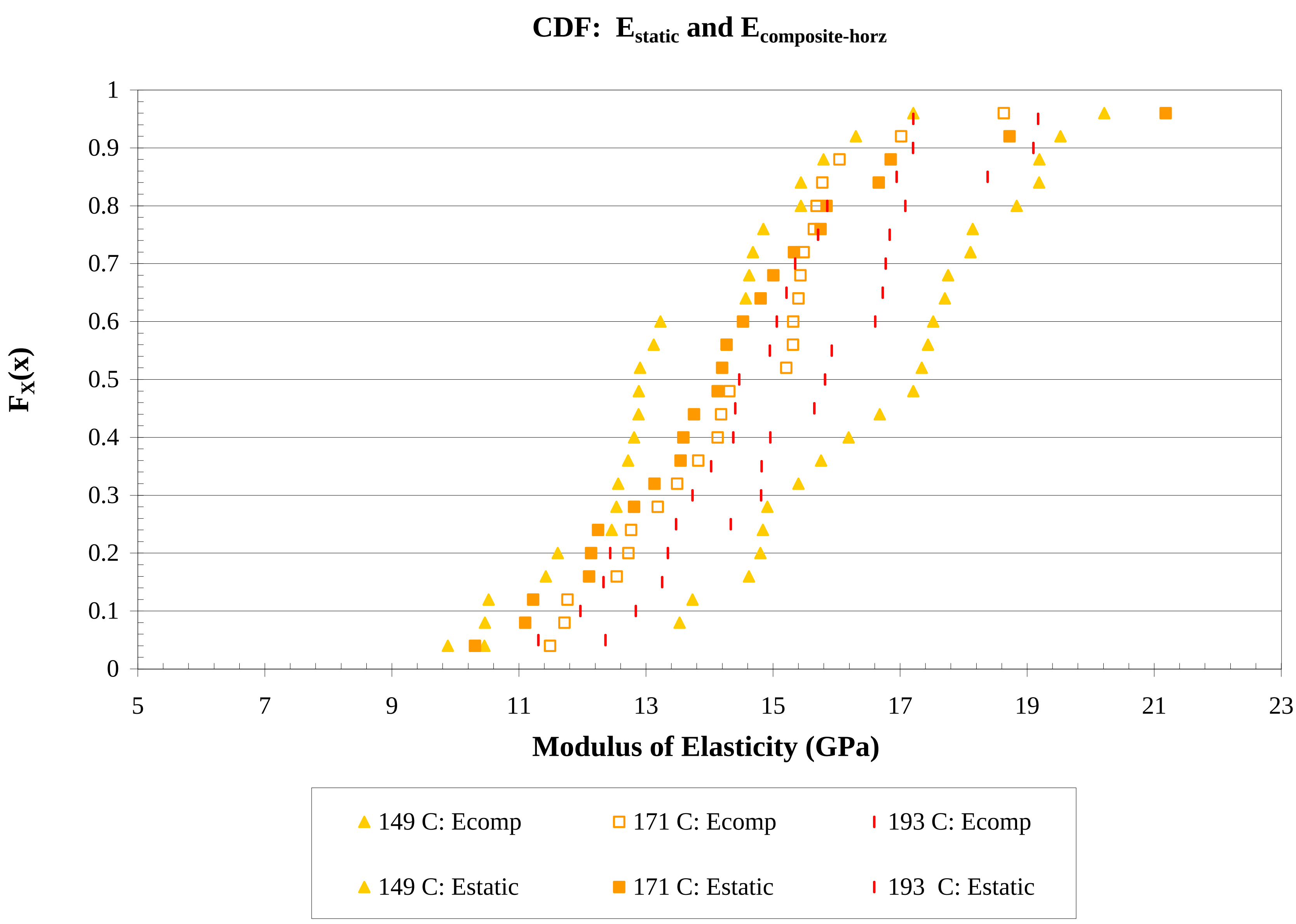
E billet-vert (edgewise) vs. E static (edgewise)
25
20
15
10
5
5
10
15
20
E static (GPa)
E billet-vert (GPa)
149 C
171 C
193 C
r = 0.403
r = 0.590
r = 0.922



CDF: E_{static} and $E_{expected\text{-}vert}$
$F_X(x)$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
5
7
9
11
13
15
17
19
21
23
Modulus of Elasticity (GPa)
149 C: Eexp
171 C: Eexp
193 C: Eexp
149 C: Estatic
171 C: Estatic
193 C: Estatic

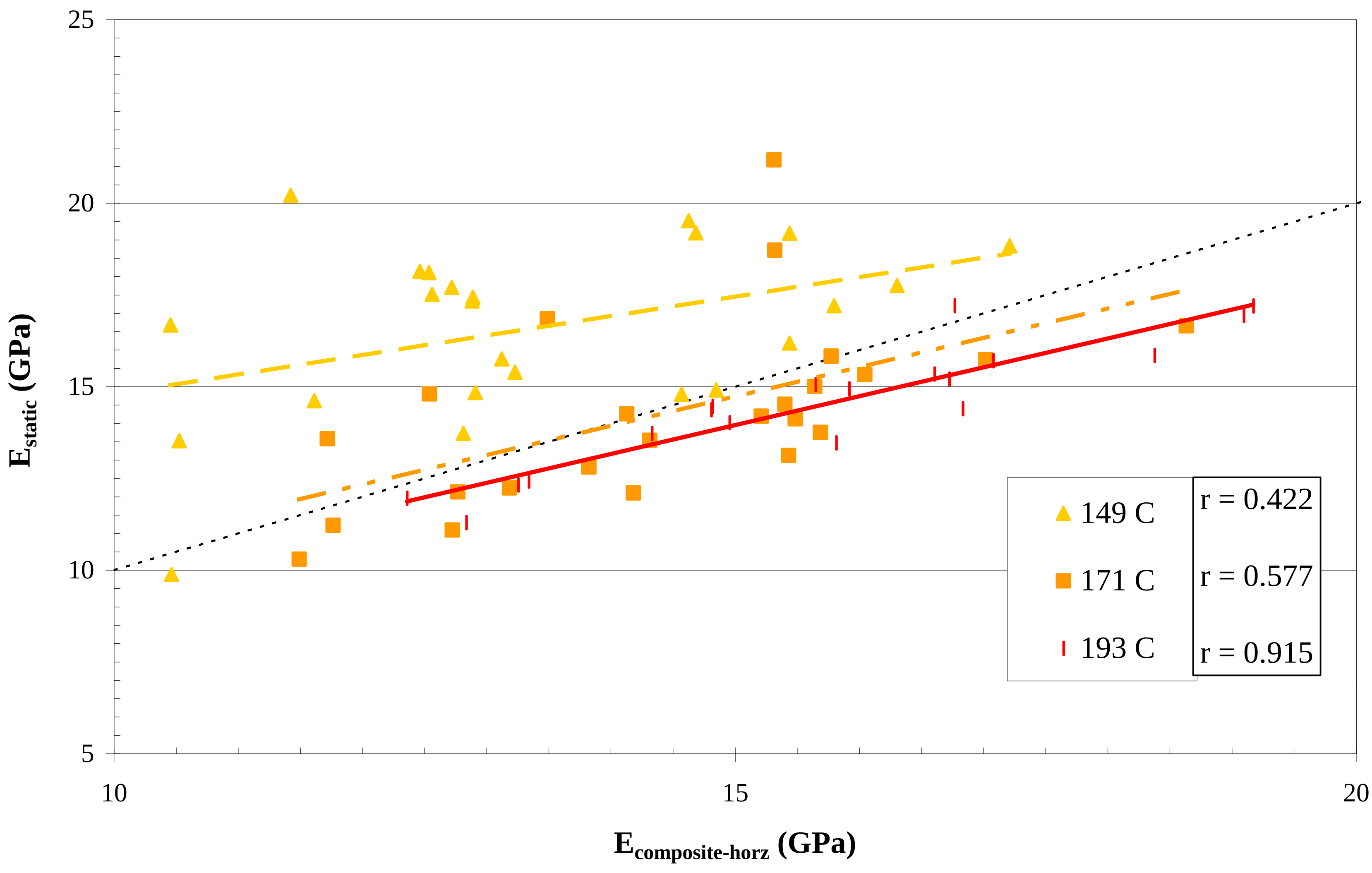


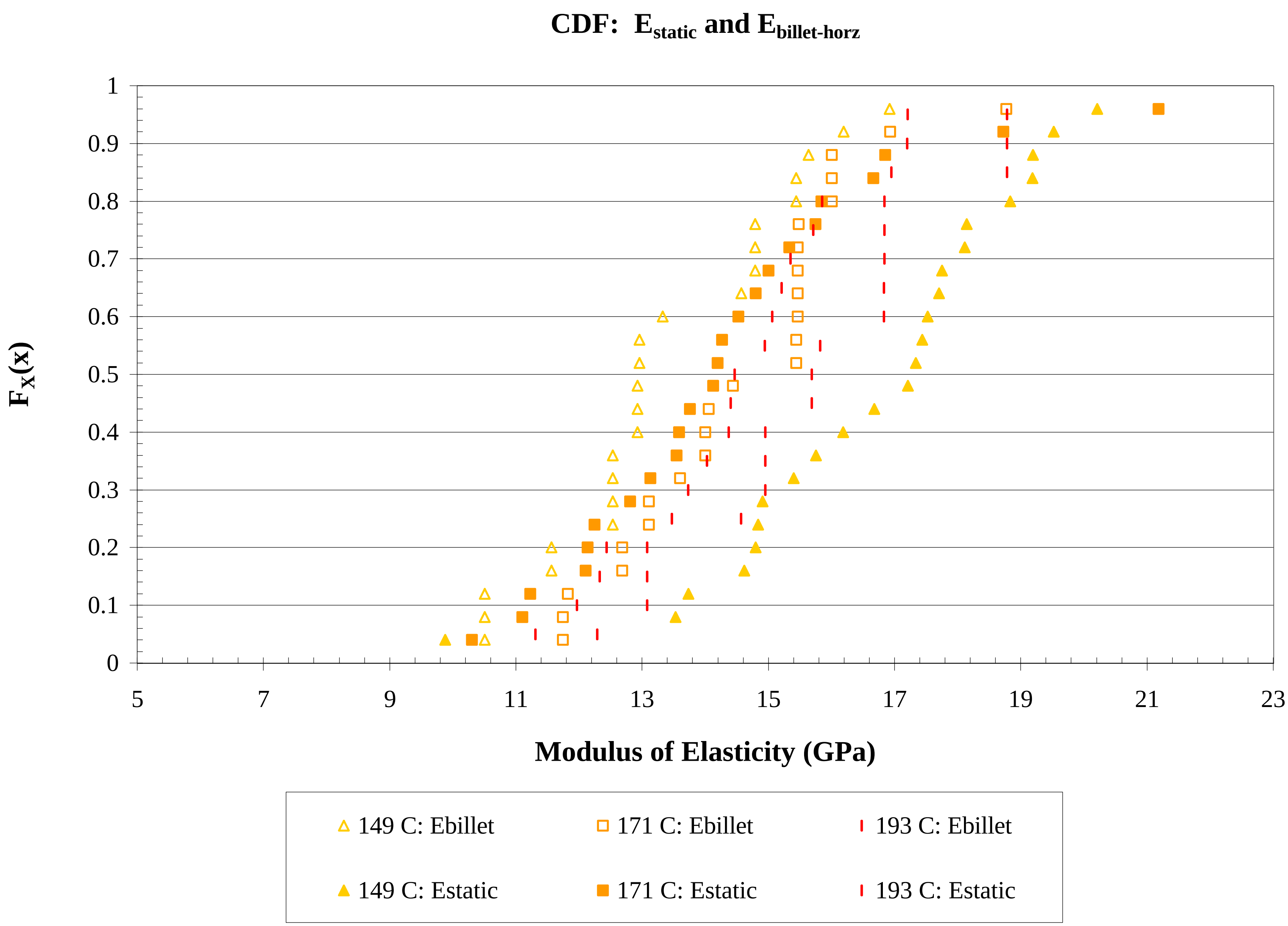
$E_{expected\text{-}vert}$ (edgewise) vs. E_{static} (edgewise)
25
20
15
10
5
E_{static} (GPa)
10
15
20
$E_{expected\text{-}vert}$ (GPa)
149 C
171 C
193 C
r = 0.404
r = 0.594
r = 0.917



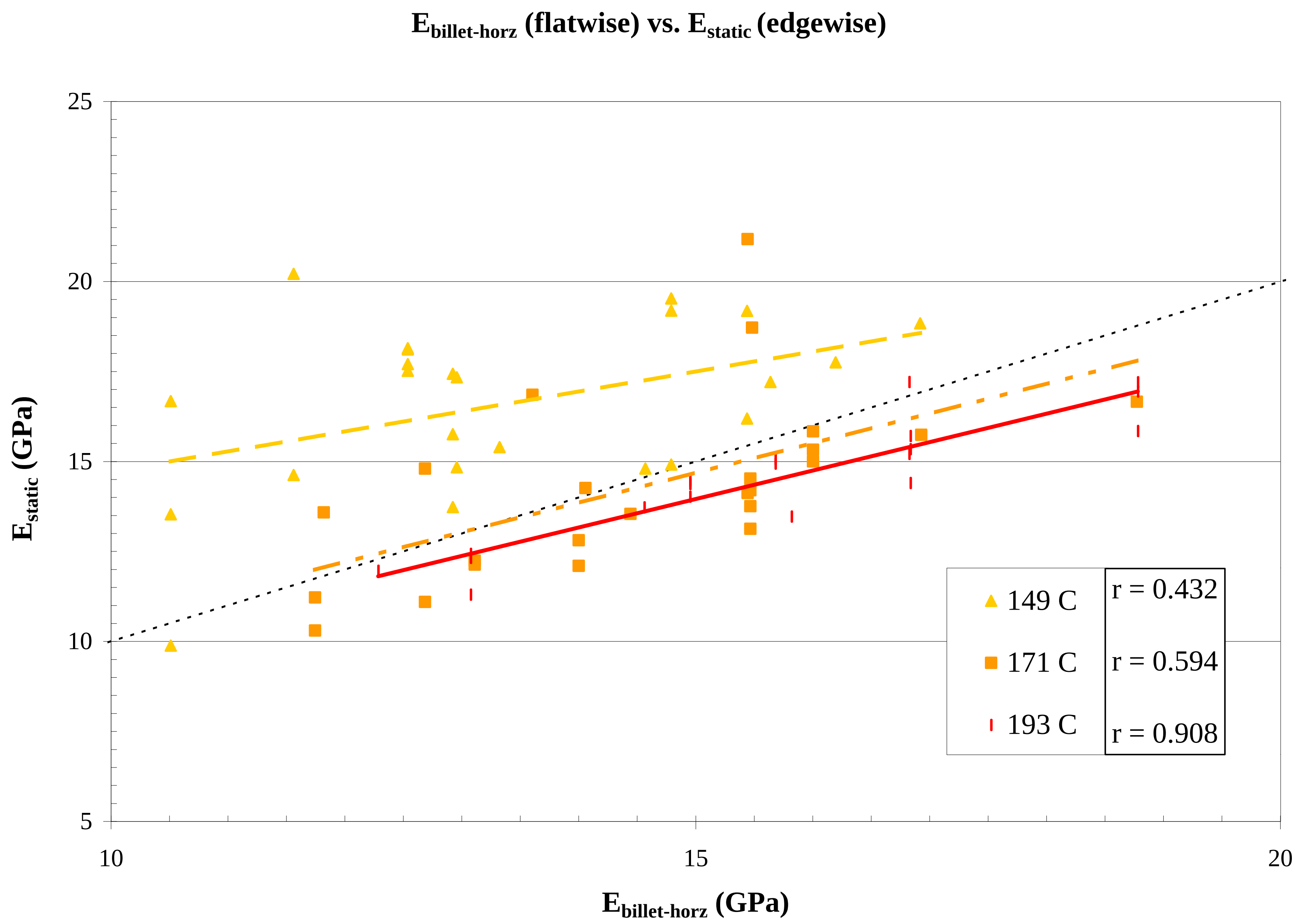
CDF: E_{static} and $E_{composite\text{-}horz}$
$F_X(x)$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
7
9
11
13
15
17
19
21
23
Modulus of Elasticity (GPa)
149 C: Ecomp
171 C: Ecomp
193 C: Ecomp
149 C: Estatic
171 C: Estatic
193 C: Estatic

$E_{composite\text{-}horz}$ **(flatwise) vs.** E_{static} **(edgewise)**

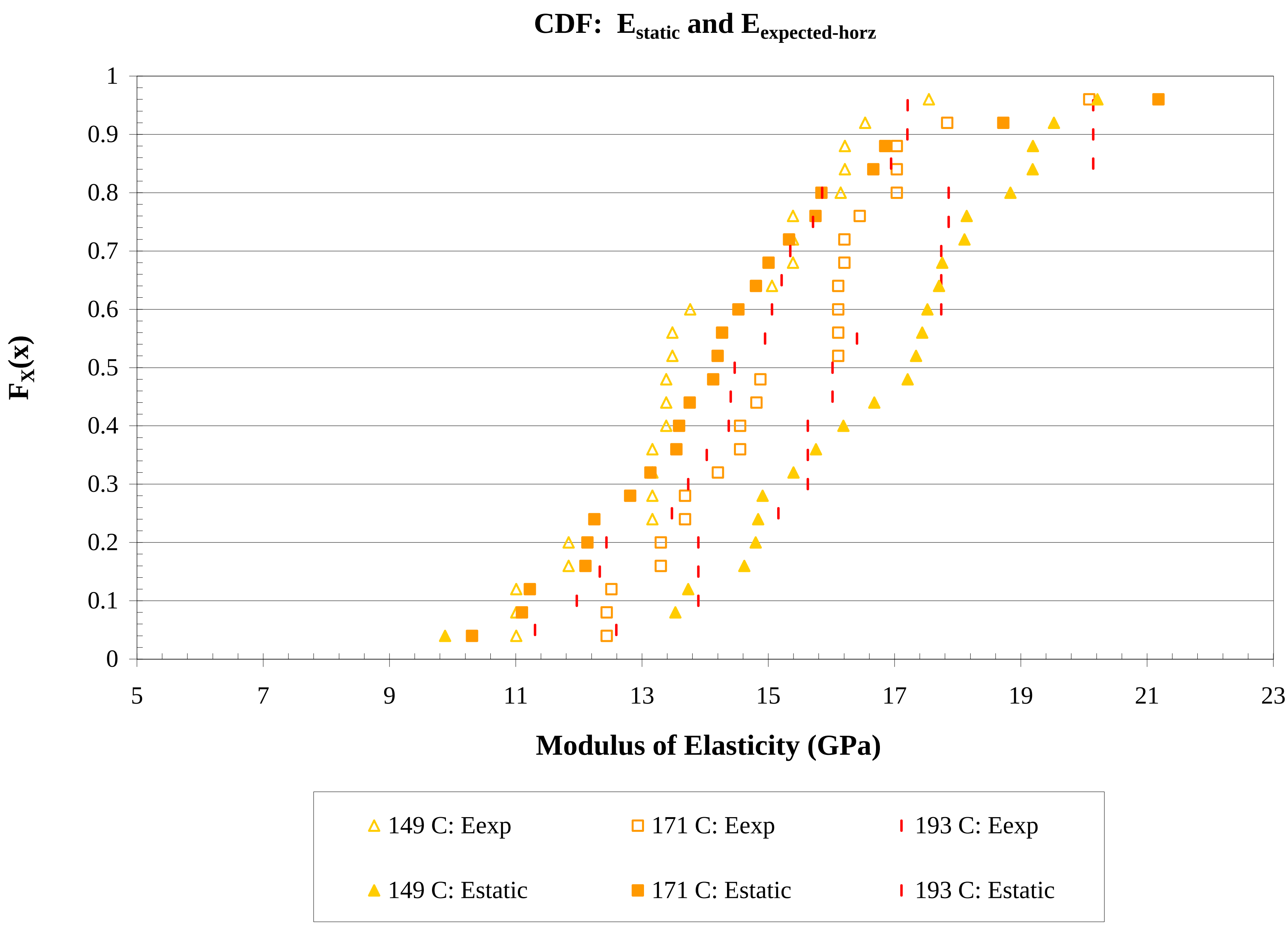


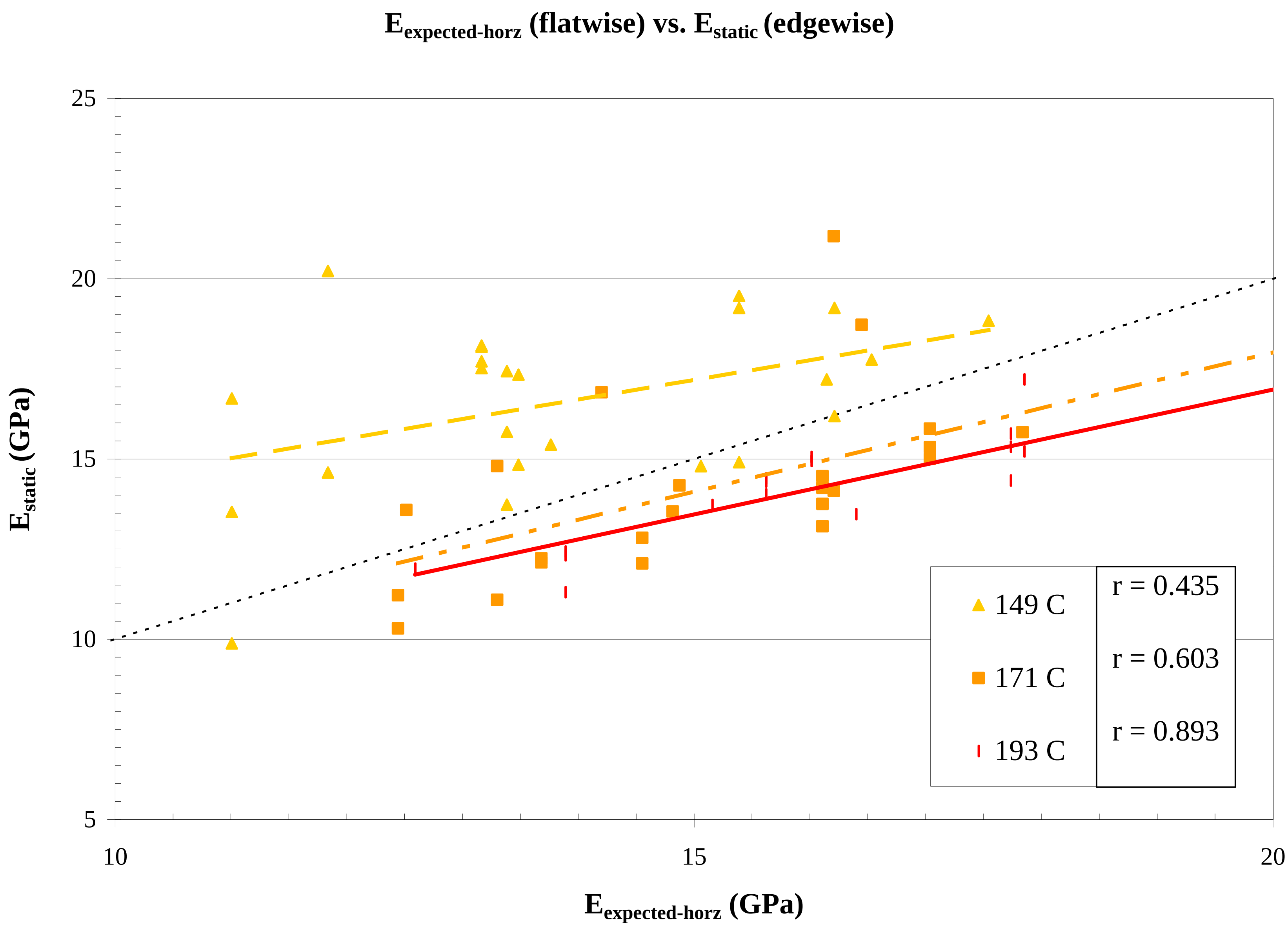


CDF: E_{static} and $E_{billet\text{-}horz}$
$F_X(x)$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
7
9
11
13
15
17
19
21
23
Modulus of Elasticity (GPa)
149 C: Ebillet
171 C: Ebillet
193 C: Ebillet
149 C: Estatic
171 C: Estatic
193 C: Estatic



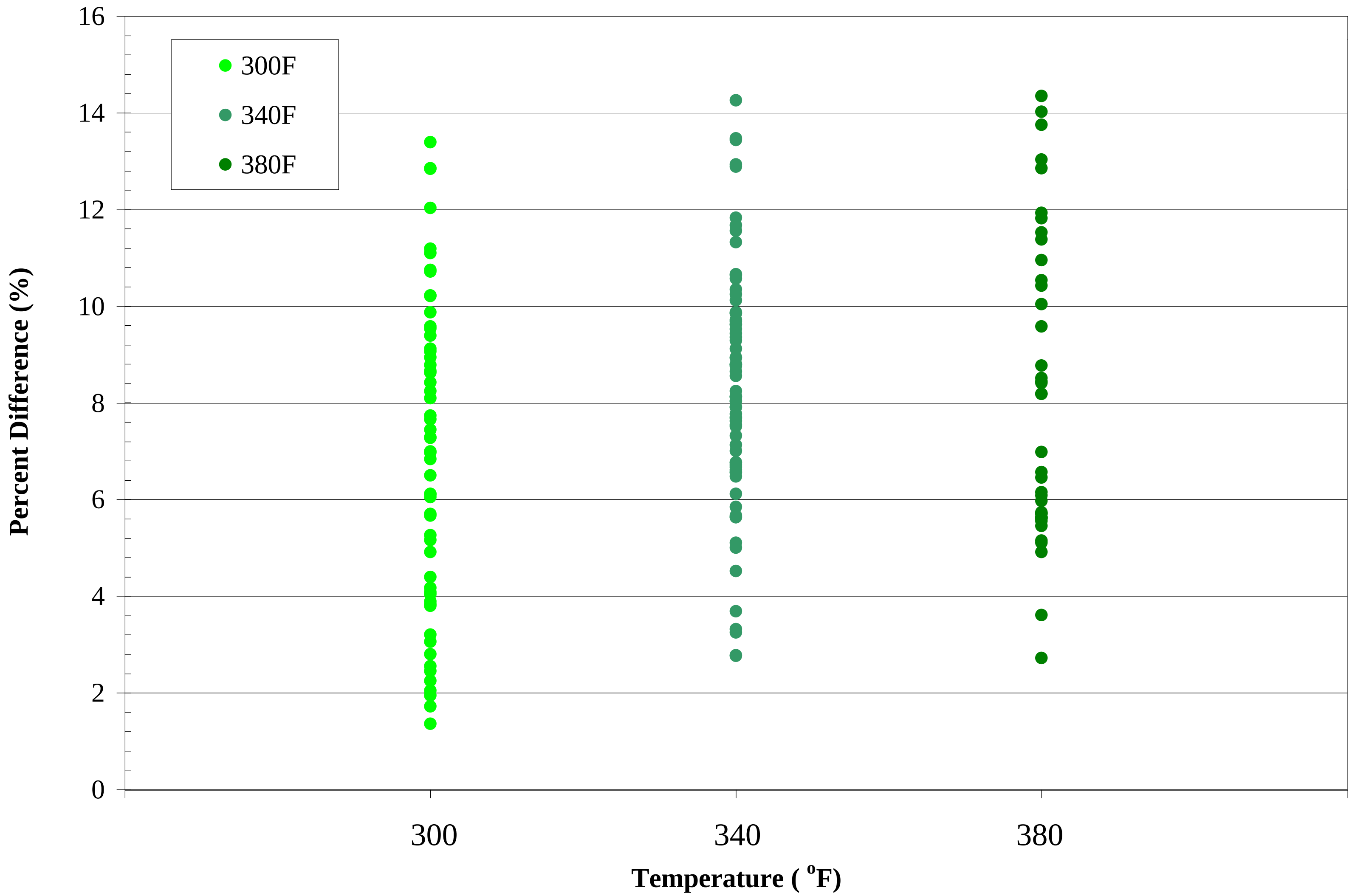
E billet-horz (flatwise) vs. E static (edgewise)
25
20
15
10
5
10
15
20
E billet-horz (GPa)
E static (GPa)
149 C
171 C
193 C
r = 0.432
r = 0.594
r = 0.908


CDF: E static and E expected-horz
Fx(x)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
7
9
11
13
15
17
19
21
23
Modulus of Elasticity (GPa)
149 C: Eexp
171 C: Eexp
193 C: Eexp
149 C: Estatic
171 C: Estatic
193 C: Estatic

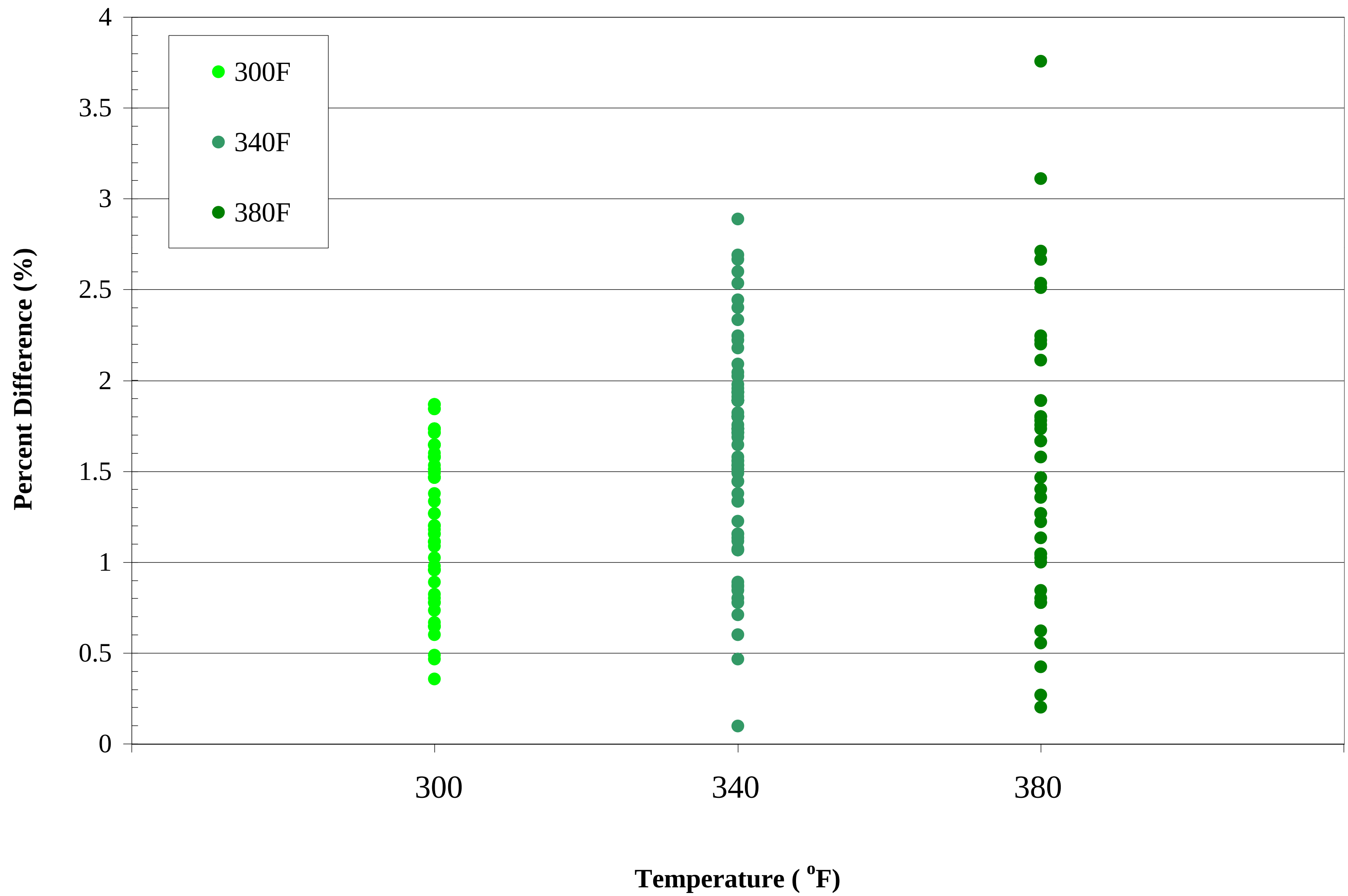


$E_{expected\text{-}horz}$ (flatwise) vs. E_{static} (edgewise)
E_{static} (GPa)
$E_{expected\text{-}horz}$ (GPa)
25
20
15
10
5
10
15
20
149 C
171 C
193 C
r = 0.435
r = 0.603
r = 0.893

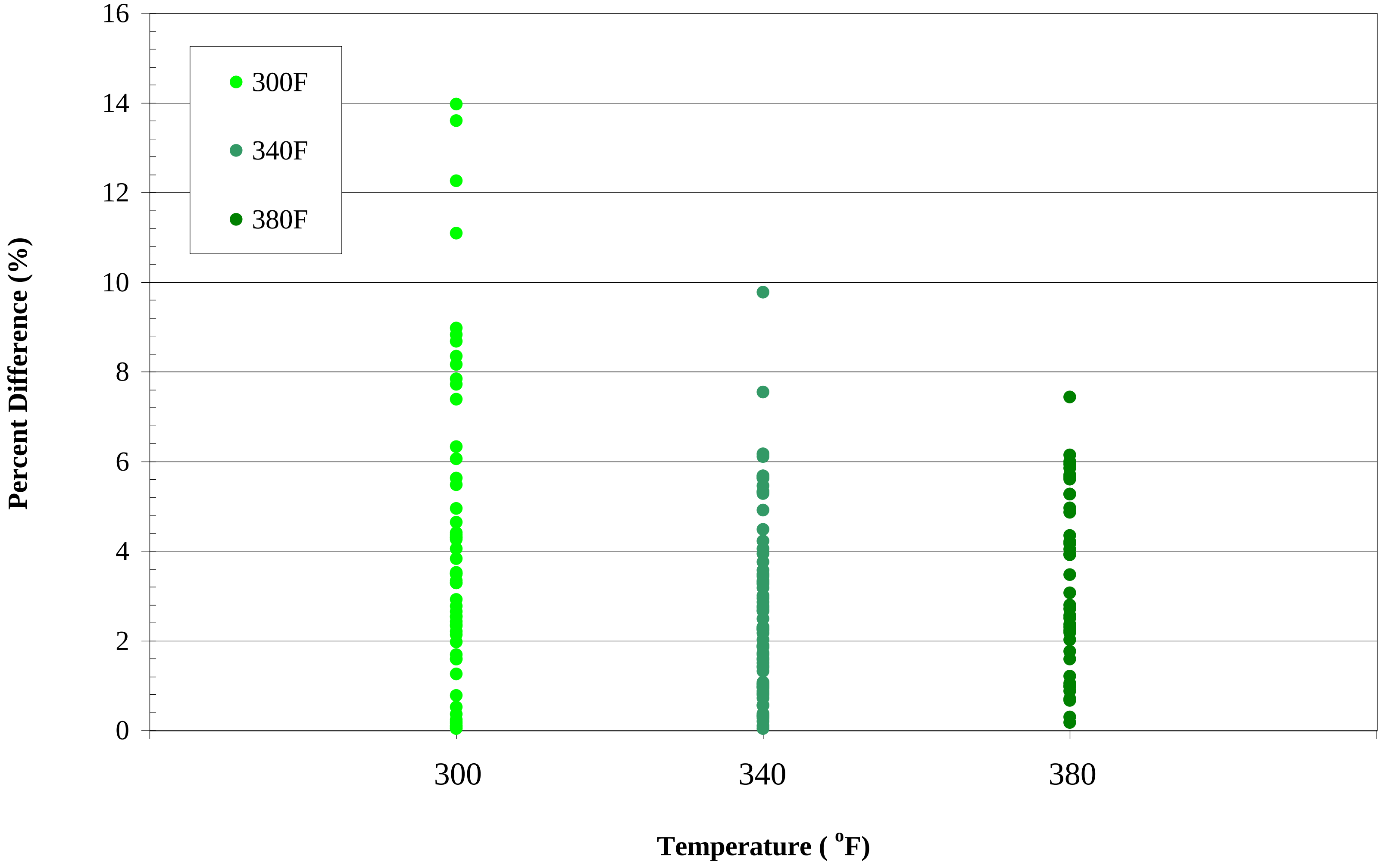
Percent Difference of MOE: Stress Wave Time vs. Vertical Laminated Beam Theory (Based on Temperature)



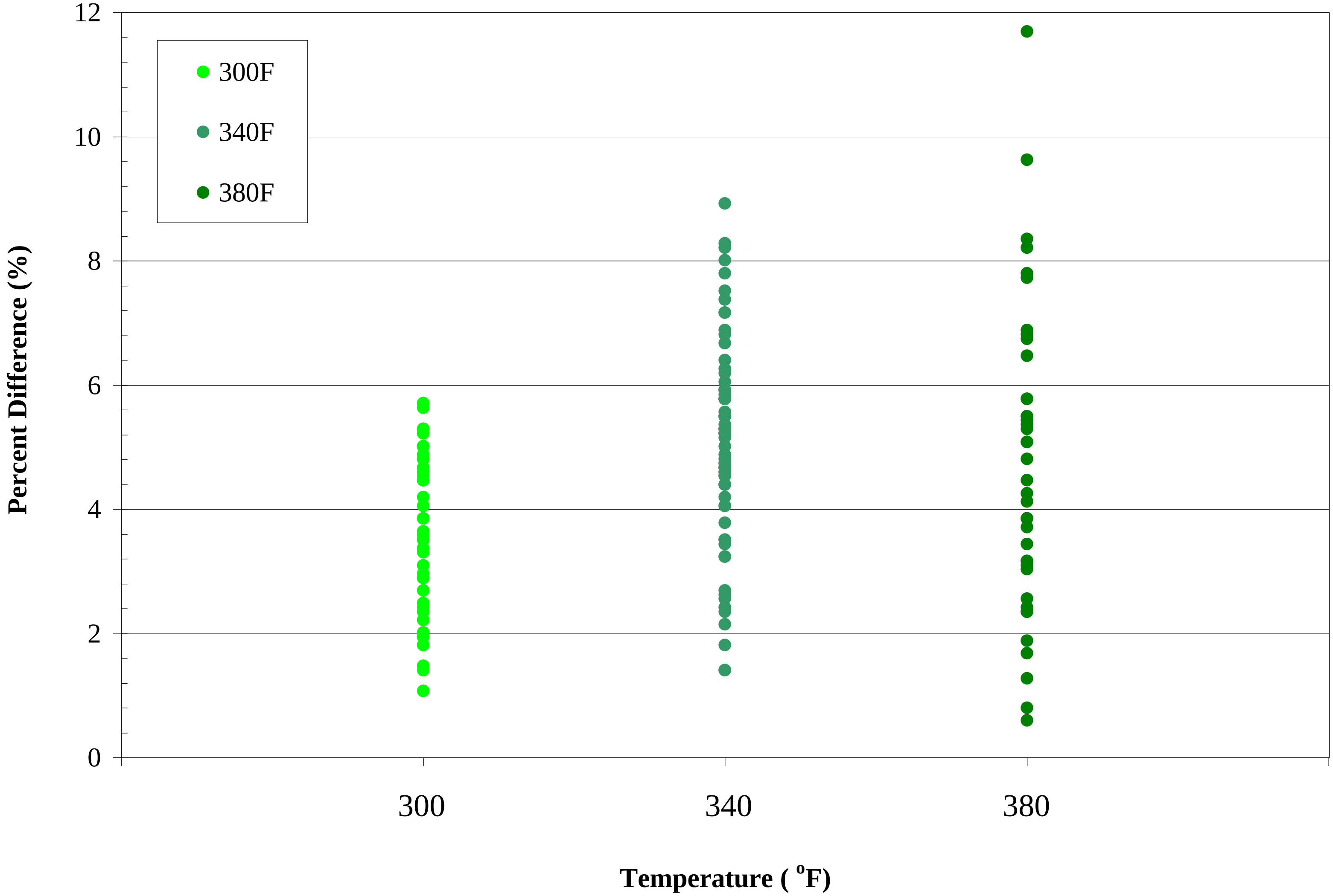
Percent Difference of MOE from The Vertical Laminated Theory: Actual Thickness of LVL vs Expected Thickness of 1.5in (Based on Temperature)

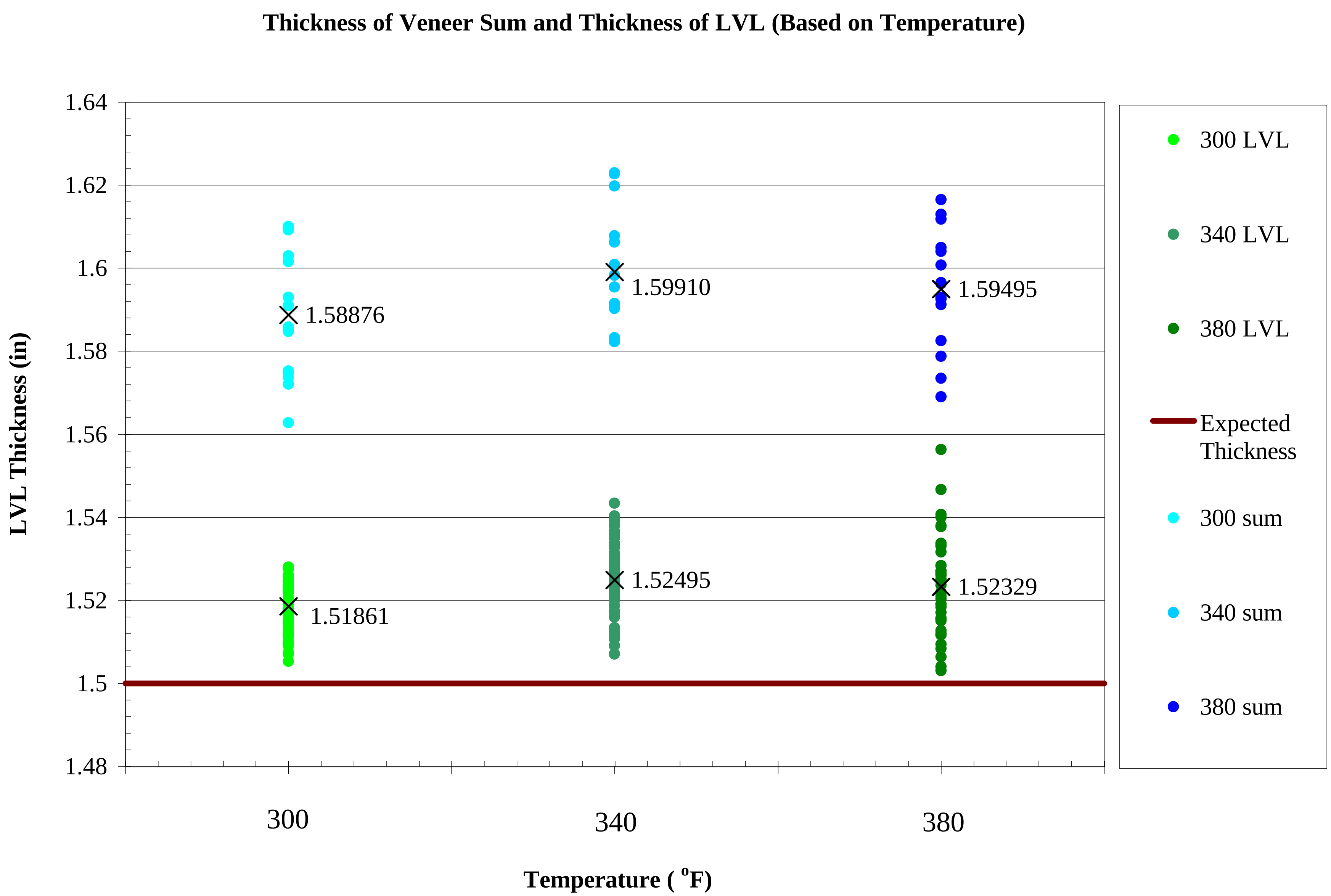


Percent Difference of MOE: Stress Wave Time vs. Horizontal Laminated Beam Theory (Based on Temperature)



Percent Difference of MOE from The Horizontal Laminated Theory: Actual Thickness of LVL vs Expected Thickness of 1.5in (Based on Temperature)




Thickness of Veneer Sum and Thickness of LVL (Based on Temperature)
LVL Thickness (in)
1.64
1.62
1.6
1.58
1.56
1.54
1.52
1.5
1.48
1.58876
1.59910
1.59495
1.51861
1.52495
1.52329
300
340
380
Temperature (°F)
300 LVL
340 LVL
380 LVL
Expected Thickness
300 sum
340 sum
380 sum

MODULUS OF ELASTICITY: DYNAMIC, COMPOSITE, AND EXPECTED (VERTICAL & HORIZONTAL)

300°F					
Billet/LVL #	$E_{dynamic}$ (psi)	$E_{composite-vert}$ (psi)	$E_{expected-vert}$ (psi)	$E_{composite-horz}$ (psi)	$E_{expected-horz}$ (psi)
1a	1577502.12	1435821.06	1457517.92	1526528.00	1596781.60
1b	1514656.54	1432997.73	1457517.92	1517540.62	1596781.60
1c	1496543.24	1441818.12	1457517.92	1545735.75	1596781.60
1d	1569342.11	1432684.71	1457517.92	1516546.38	1596781.60
1e	1591603.28	1432684.71	1457517.92	1516546.38	1596781.60
2a	1728138.30	1531477.95	1549855.69	1656702.07	1717061.90
2b	1656880.30	1544364.61	1549855.69	1698876.05	1717061.90
2c	1664607.71	1537894.29	1549855.69	1677612.37	1717061.90
2d	1705428.45	1539931.68	1549855.69	1684288.69	1717061.90
2e	1735086.10	1537555.25	1549855.69	1676503.08	1717061.90
2f	1740332.93	1534848.28	1549855.69	1667663.89	1717061.90
3a	1763737.22	1623663.26	1653971.64	1806424.11	1909483.92
3b	1737259.80	1624017.54	1653971.64	1807606.84	1909483.92
3c	1783155.14	1627213.03	1653971.64	1818298.03	1909483.92
3d	1760021.94	1628280.99	1653971.64	1821880.49	1909483.92
3e	1735017.31	1635077.42	1653971.64	1844789.37	1909483.92
3f	1737017.80	1625791.26	1653971.64	1813536.01	1909483.92
4a	1717798.72	1694736.37	1708670.87	1908313.08	1955772.90
4b	1825830.18	1683972.60	1708670.87	1872182.77	1955772.90
4c	1809685.08	1681027.31	1708670.87	1862376.51	1955772.90
4d	1746639.12	1692498.11	1708670.87	1900762.06	1955772.90
4e	1870315.12	1682130.59	1708670.87	1866045.81	1955772.90
4f	1785597.58	1682866.91	1708670.87	1868497.37	1955772.90
5a	1873381.57	1743562.76	1755186.51	1903095.64	1941411.86
5b	1865217.19	1731332.59	1755186.51	1863328.29	1941411.86
5c	1918991.84	1733232.23	1755186.51	1869468.43	1941411.86
5d	1848740.43	1735898.74	1755186.51	1878110.02	1941411.86
5e	1885351.92	1735136.05	1755186.51	1875635.57	1941411.86
5f	1855635.38	1729815.87	1755186.51	1858435.53	1941411.86
6a	1898400.89	1790064.03	1807169.08	1940183.79	1996335.55
6b	2004069.97	1788882.73	1807169.08	1936345.22	1996335.55
6c	1968520.33	1786132.41	1807169.08	1927427.86	1996335.55
6d	1950812.94	1783390.54	1807169.08	1918565.17	1996335.55
6f	1947208.65	1790064.03	1807169.08	1940183.79	1996335.55
7b	2065051.08	1873487.32	1894303.84	2113194.43	2184419.80
9a	2134751.31	1957439.04	1969183.68	2184814.14	2224377.23
10a	2064747.44	1983793.08	1996577.53	2189701.16	2232308.79
10b	2041540.43	1965135.36	1996577.53	2128497.50	2232308.79
10c	2152895.08	1972902.70	1996577.53	2153836.50	2232308.79
10d	2064330.06	1962988.61	1996577.53	2121529.49	2232308.79
10e	2062237.24	1965565.28	1996577.53	2129894.77	2232308.79
10f	2147796.73	1971603.88	1996577.53	2149585.50	2232308.79
11c	2105246.74	2065088.57	2075184.56	2363313.13	2398144.79
11d	2182629.80	2065545.35	2075184.56	2364881.70	2398144.79

11e	2160392.32	2052380.33	2075184.56	2319950.67	2398144.79
12a	2016936.75	2078657.53	2093901.02	2291180.91	2341957.44
12e	2152014.21	2061377.07	2093901.02	2234512.95	2341957.44
12f	2159160.73	2075452.55	2093901.02	2280599.27	2341957.44
13d	2240194.27	2093727.58	2128157.77	2239477.86	2351785.52
13f	2147153.28	2093727.58	2128157.77	2239477.86	2351785.52
14c	2260008.34	2221678.27	2254756.59	2434448.45	2544814.18
14d	2290660.11	2240318.98	2254756.59	2496241.82	2544814.18
14f	2306425.95	2221191.91	2254756.59	2432849.99	2544814.18
15b	2473249.40	2374160.03	2392625.72	2687938.36	2751145.99
15c	2406330.93	2348781.79	2392625.72	2602659.49	2751145.99
15e	2310848.84	2358041.12	2392625.72	2633561.46	2751145.99
15f	2415033.25	2349294.29	2392625.72	2604363.54	2751145.99

340°F					
Billet/LVL #	$E_{dynamic}$ (psi)	$E_{composite-vert}$ (psi)	$E_{expected-vert}$ (psi)	$E_{composite-horz}$ (psi)	$E_{expected-horz}$ (psi)
1a	1630190.51	1516377.91	1545020.61	1716271.34	1815375.33
1b	1658221.78	1511433.20	1545020.61	1699536.42	1815375.33
1c	1660805.31	1516377.91	1545020.61	1716271.34	1815375.33
1e	1721263.58	1517370.74	1545020.61	1719644.66	1815375.33
1f	1663707.10	1517701.97	1545020.61	1720771.06	1815375.33
2b	1730392.73	1571326.02	1598911.52	1712960.57	1804769.56
2c	1695172.72	1587621.77	1598911.52	1766808.97	1804769.56
2d	1696914.41	1569269.76	1598911.52	1706244.55	1804769.56
2e	1677043.95	1557381.35	1598911.52	1667759.30	1804769.56
2f	1691609.06	1557044.33	1598911.52	1666676.81	1804769.56
3a	1756462.17	1655256.92	1674016.50	1864858.41	1928984.90
3b	1753443.54	1645494.59	1674016.50	1832057.10	1928984.90
3c	1781809.83	1649457.90	1674016.50	1845327.00	1928984.90
3d	1853093.74	1641550.28	1674016.50	1818914.13	1928984.90
3e	1798202.92	9.00	1674016.50	1828460.13	1928984.90
3f	1825774.36	1651265.73	1674016.50	1851401.14	1928984.90
4c	1950295.79	1727046.33	1756981.80	1956557.87	2060072.58
4d	1889607.05	1736910.83	1756981.80	1990275.98	2060072.58
5a	1916548.06	1753665.11	1773224.71	1898463.34	1984530.18
5b	1905841.25	1751747.28	1773224.71	1892241.59	1984530.18
5c	1886148.94	1771508.20	1773224.71	1957004.07	1984530.18
5d	1822690.12	1757899.16	1773224.71	1912247.51	1984530.18
5e	1910549.20	1739194.04	1773224.71	1851852.30	1984530.18
5f	1871395.08	1754433.42	1773224.71	1900959.68	1984530.18
6a	1998201.10	1834167.29	1850063.41	2057054.72	2111003.01
6e	2024402.11	1818542.02	1850063.41	2004929.14	2111003.01
7a	1942688.41	1850207.28	1895434.57	2006716.44	2157502.18
7b	2002085.07	1860295.65	1895434.57	2039720.98	2157502.18
7c	2078403.46	1863140.14	1895434.57	2049091.82	2157502.18
7d	2133043.90	1866810.15	1895434.57	2061224.57	2157502.18
8a	2071275.55	1917169.28	1926116.06	2118974.81	2148779.11
8b	2057137.15	1909987.28	1926116.06	2095249.95	2148779.11
8c	2054722.93	1904112.98	1926116.06	2075977.08	2148779.11
8d	2075918.42	1905787.66	1926116.06	2081459.41	2148779.11
8e	2045075.93	1911250.78	1926116.06	2099410.86	2148779.11
8f	2018462.34	1910829.43	1926116.06	2098022.67	2148779.11
9a	2145652.67	1938914.55	1969075.44	2098720.47	2198192.17
9b	2134303.79	1935949.20	1969075.44	2089105.92	2198192.17
9c	2103647.16	1934258.78	1969075.44	2083638.25	2198192.17
9d	1992832.43	1938914.55	1969075.44	2098720.47	2198192.17
9e	2034683.98	1935949.20	1969075.44	2089105.92	2198192.17
9f	2116421.86	1957331.45	1969075.44	2159094.81	2198192.17
10a	2072878.71	2017130.08	2035060.13	2275336.33	2336552.90
10b	2241982.97	2004765.89	2035060.13	2233751.58	2336552.90
10c	2104609.21	2013581.92	2035060.13	2263350.38	2336552.90
10d	2184954.76	2008283.02	2035060.13	2245528.81	2336552.90
10e	2184887.63	1996461.87	2035060.13	2206108.86	2336552.90
10f	2119051.55	2006083.37	2035060.13	2238158.37	2336552.90

11a	2158527.33	2042761.69	2074084.03	2245891.72	2350794.94
11b	2184553.97	2039191.21	2074084.03	2234135.71	2350794.94
11c	2202890.97	2035189.31	2074084.03	2221008.07	2350794.94
11f	2196608.01	2046793.46	2074084.03	2259216.03	2350794.94
12a	2233491.37	2069636.46	2117927.98	2226289.87	2385794.71
12b	2320258.60	2077757.99	2117927.98	2252601.62	2385794.71
12c	2287230.69	2072787.28	2117927.98	2236473.27	2385794.71
12d	2346984.54	2068289.05	2117927.98	2221944.47	2385794.71
12e	2217195.88	2077757.99	2117927.98	2252601.62	2385794.71
12f	2309896.39	2087771.29	2117927.98	2285326.56	2385794.71
13a	2363226.12	2155945.01	2188523.73	2362444.69	2471168.70
13b	2327217.81	2143743.32	2188523.73	2322560.11	2471168.70
13c	2339469.76	2133064.07	2188523.73	2288022.61	2471168.70
13d	2320938.44	2127074.90	2188523.73	2268803.92	2471168.70
13e	2307056.34	2145144.15	2188523.73	2327116.14	2471168.70
13f	2298094.60	2155473.14	2188523.73	2360893.86	2471168.70
14a	2423308.97	2248545.42	2284022.47	2468420.27	2587111.97
14b	2428465.28	2246088.53	2284022.47	2460337.69	2587111.97
14c	2374916.00	2243637.01	2284022.47	2452290.36	2587111.97
14d	2461838.62	2240702.23	2284022.47	2442679.83	2587111.97
14e	2314448.62	2241679.63	2284022.47	2445877.75	2587111.97
14f	2321710.02	2247070.64	2284022.47	2463566.48	2587111.97
15a	2656724.43	2418631.74	2479903.74	2702561.54	2913203.49
15b	2594348.16	2430219.26	2479903.74	2741591.37	2913203.49
15c	2584656.51	2425465.51	2479903.74	2725534.37	2913203.49

380°F					
Billet/LVL #	$E_{dynamic}$ (psi)	$E_{composite\text{-}vert}$ (psi)	$E_{expected\text{-}vert}$ (psi)	$E_{composite\text{-}horz}$ (psi)	$E_{expected\text{-}horz}$ (psi)
1a	1757216.71	1557090.65	1566779.22	1792608.68	1826279.34
1f	1753029.37	1550925.31	1566779.22	1771399.24	1826279.34
4a	1931559.43	1734276.77	1757785.85	1934920.63	2014678.86
4b	1952131.91	1712129.08	1757785.85	1861733.21	2014678.86
4d	1916940.33	1714355.51	1757785.85	1869005.59	2014678.86
4f	1877808.07	1730482.68	1757785.85	1922249.28	2014678.86
5a	1882996.39	1791628.49	1836618.27	1976285.82	2128935.85
7a	2084891.45	1869393.84	1874378.89	2039377.12	2055735.68
8a	2200310.45	1934254.10	1949728.14	2146620.55	2198552.70
8f	2188138.19	1913582.69	1949728.14	2078530.50	2198552.70
9a	2135178.14	1969520.46	1998406.76	2169078.13	2265924.19
9b	2070245.61	1961358.87	1998406.76	2142224.08	2265924.19
9c	2189794.91	1990004.52	1998406.76	2237463.16	2265924.19
9d	2197155.92	1963071.48	1998406.76	2147840.57	2265924.19
9e	2170427.57	1963500.09	1998406.76	2149247.76	2265924.19
10a	2221327.23	2027039.72	2055418.28	2281601.37	2378776.47
10c	2202036.83	2030599.83	2055418.28	2293644.10	2378776.47
10d	2149072.15	2035067.60	2055418.28	2308817.00	2378776.47
11d	2194348.66	2075711.86	2093240.10	2317189.74	2376388.98
11e	2208222.10	2081675.24	2093240.10	2337218.53	2376388.98
11f	2188111.12	2071603.35	2093240.10	2303457.53	2376388.98
12a	2314471.54	2085994.95	2107782.01	2251586.80	2322875.94
12b	2221822.61	2103574.86	2107782.01	2308994.25	2322875.94
12c	2309461.75	2091514.67	2107782.01	2269507.82	2322875.94
12d	2262724.57	2091514.67	2107782.01	2269507.82	2322875.94
13a	2317573.12	2191784.06	2240490.37	2408375.74	2572528.51
13b	2344519.91	2202316.88	2240490.37	2443263.87	2572528.51
13c	2337046.96	2212465.81	2240490.37	2477197.61	2572528.51
13d	2309961.18	2201835.92	2240490.37	2441663.48	2572528.51
13e	2335165.75	2191307.69	2240490.37	2406805.74	2572528.51
13f	2338583.01	2212465.81	2240490.37	2477197.61	2572528.51
14a	2454981.98	2269343.08	2319268.63	2425796.90	2589447.59
14b	2410990.86	2271318.57	2319268.63	2432137.47	2589447.59
14f	2481377.50	2281247.83	2319268.63	2464174.00	2589447.59
15a	2670881.77	2496475.40	2564157.62	2696704.77	2922036.83
15b	2554336.04	2486790.80	2564157.62	2665442.30	2922036.83
15c	2598659.91	2471344.89	2564157.62	2616083.52	2922036.83
15d	2609644.79	2518818.88	2564157.62	2769761.36	2922036.83
15e	2673768.94	2535422.83	2564157.62	2824897.67	2922036.83
15f	2672758.66	2522122.25	2564157.62	2780673.08	2922036.83

MODULUS OF ELASTICITY: BILLET (VERTICAL & HORIZONTAL)

	300°F			340°F			380°F		
	Avg. Width (in)	Avg. Thick. (in)		Avg. Width (in)	Avg. Thick. (in)		Avg. Width (in)	Avg. Thick. (in)	
Billet	LVL $t_{section}$	LVL $b_{section}$	$E_{billet\text{-}vert}$ (psi)	LVL $t_{section}$	LVL $b_{section}$	$E_{billet\text{-}vert}$ (psi)	LVL $t_{section}$	LVL $b_{section}$	$E_{billet\text{-}vert}$ (psi)
1	3.500867	1.523333	1435192.70	3.495400	1.528867	1515848.94	3.482000	1.509333	1554001.87
2	3.448944	1.511889	1537668.24	3.499267	1.529133	1568448.76	3.481347	1.522470	1608541.73
3	3.516778	1.524556	1627331.62	3.502111	1.523778	1647894.32	3.481347	1.522470	1653480.22
4	3.435056	1.520000	1686188.36	3.493833	1.521667	1731964.54	3.505333	1.532778	1722756.47
5	3.471167	1.517611	1734818.45	3.482389	1.521444	1754689.68	3.484000	1.537667	1791628.49
6	3.455133	1.516333	1787702.98	3.461167	1.519500	1826321.23	3.481347	1.522470	1829184.66
7	3.479333	1.516667	1873487.32	3.493000	1.528500	1860092.81	3.502667	1.504000	1869393.84
8	3.481347	1.522470	1882309.30	3.477333	1.512778	1909847.00	3.498167	1.520167	1923862.87
9	3.486333	1.509000	1957439.04	3.470056	1.522333	1940188.20	3.500133	1.522067	1969434.20
10	3.461667	1.520000	1970306.77	3.486500	1.520444	2007695.98	3.479222	1.518111	2030897.08
11	3.479556	1.510333	2060986.65	3.478083	1.524333	2040974.89	3.470333	1.512222	2076321.92
12	3.473222	1.516000	2071801.80	3.495722	1.530556	2075646.30	3.479917	1.510500	2093130.10
13	3.480833	1.524667	2093727.58	3.498056	1.531611	2143354.52	3.469611	1.526222	2201996.22
14	3.481333	1.518222	2227694.23	3.494278	1.526333	2244616.97	3.451333	1.529889	2273957.91
15	3.483083	1.522333	2357524.79	3.496000	1.534111	2424762.84	3.467778	1.535444	2504966.20
Billet	LVL $b_{section}$	LVL $t_{section}$	$E_{billet\text{-}horz}$ (psi)	LVL $b_{section}$	LVL $t_{section}$	$E_{billet\text{-}horz}$ (psi)	LVL $b_{section}$	LVL $t_{section}$	$E_{billet\text{-}horz}$ (psi)
1	3.500867	1.523333	1524524.68	3.495400	1.528867	1714475.84	3.482000	1.509333	1781961.89
2	3.448944	1.511889	1676872.74	3.499267	1.529133	1703567.97	3.481347	1.522470	1793592.83
3	3.516778	1.524556	1818695.61	3.502111	1.523778	1840084.21	3.481347	1.522470	1816190.47
4	3.435056	1.520000	1879582.69	3.493833	1.521667	1973320.90	3.505333	1.532778	1896616.85
5	3.471167	1.517611	1874605.83	3.482389	1.521444	1901792.76	3.484000	1.537667	1976285.82
6	3.455133	1.516333	1932516.77	3.461167	1.519500	2030768.96	3.481347	1.522470	2008462.95
7	3.479333	1.516667	2113194.43	3.493000	1.528500	2039053.83	3.502667	1.504000	2039377.12
8	3.481347	1.522470	2048369.24	3.477333	1.512778	2094788.31	3.498167	1.520167	2112209.74
9	3.486333	1.509000	2184814.14	3.470056	1.522333	2102859.05	3.500133	1.522067	2168793.13
10	3.461667	1.520000	2145345.69	3.486500	1.520444	2243560.20	3.479222	1.518111	2294651.49
11	3.479556	1.510333	2349258.22	3.478083	1.524333	2240003.43	3.470333	1.512222	2319233.42
12	3.473222	1.516000	2268585.60	3.495722	1.530556	2245740.42	3.479917	1.510500	2274770.59
13	3.480833	1.524667	2239477.86	3.498056	1.531611	2321296.66	3.469611	1.526222	2442196.79
14	3.481333	1.518222	2454278.38	3.494278	1.526333	2455505.08	3.451333	1.529889	2440625.98
15	3.483083	1.522333	2631831.88	3.496000	1.534111	2723166.23	3.467778	1.535444	2724313.86

APPENDIX E

ANALYSIS OF VARIANCE (ANOVA) RESULTS

INTRODUCTION

Analysis of variation (ANOVA) results were used to determine statistical significance, or lack thereof, between many populations such as temperatures, mechanical properties, and static and duration of load deflections. All ANOVA charts are set up the same. The far left column provides the sample size of the respective populations (n_1/n_2). The next two (in some cases three) columns name the populations being compared. The following column houses the F value and the next column, the $F\alpha$ (F critical) value. The next column represents the relationship between F and $F\alpha$ (greater than or less than). The following column houses the P value and the next column represents the relationship (greater than or less than) between the P value and the test α ($\alpha = 0.05$). Based on the analysis, the furthest most column on the right states if the populations tested are either statistically different or statistically not different.

ANOVA SUMMARY: SOLID SAWN LUMBER - COMPARING MOE AND COMPARING TEMPERATURES

Comparison of Modulus of Elasticity Values

	Edynamic (Static and DOL Tests): Unheated vs. Heated								
(48 / 48)	No Temp	Unheated	Unheated	0	3.9423043	**F=0**	1	**P=1**	Statistically EXACT
(48 / 48)	SS 300°F	Unheated	Heated	0.01522	3.94230	**F<Fα**	0.90209	**P>>α**	Statistically NOT Different
(48 / 48)	SS 340°F	Unheated	Heated	0.11680	3.94230	**F<Fα**	0.73330	**P>>α**	Statistically NOT Different
(36 / 36)	SS 380°F	Unheated	Heated	0.11200	3.97779	**F<Fα**	0.73888	**P>>α**	Statistically NOT Different
	Edynamic vs. Estatic (for Static Tests)								
(24 / 24)	No Temp	Edynamic	Estatic	18.11550	4.05174	**F>Fα**	0.00010	**P<<α**	Statistically Different
(24 / 24)	SS 300°F	Edynamic	Estatic	9.04800	4.05174	**F>Fα**	0.00425	**P<<α**	Statistically Different
(24 / 24)	SS 340°F	Edynamic	Estatic	4.27387	4.05174	**F>Fα**	0.04436	**P<α**	Statistically Different
(18 / 18)	SS 380°F	Edynamic	Estatic	3.43663	4.13002	**F<Fα**	0.07246	**P>α**	Statistically NOT Different

Comparison of Temperatures

	Edynamic from SWT - Before Heated (for DOL Tests)					0.92827	= average P value	
(24 / 24)	No Temp	SS 300°F	0.01437	4.05174	**F<Fα**	0.90510	**P>>α**	Statistically NOT Different
(24 / 24)	No Temp	SS 340°F	0.02658	4.05174	**F<Fα**	0.87120	**P>>α**	Statistically NOT Different
(24 / 18)	No Temp	SS 380°F	0.00262	4.08474	**F<Fα**	0.95942	**P>>α**	Statistically NOT Different
(24 / 24)	SS 300°F	SS 340°F	0.00222	4.05174	**F<Fα**	0.96263	**P>>α**	Statistically NOT Different
(24 / 18)	SS 300°F	SS 380°F	0.00365	4.08474	**F<Fα**	0.95214	**P>>α**	Statistically NOT Different
(24 / 18)	SS 340°F	SS 380°F	0.01044	4.08474	**F<Fα**	0.91914	**P>>α**	Statistically NOT Different
	Edynamic from SWT - After Heated (for DOL Tests)					0.82491	= average P value	
(24 / 24)	No Temp	SS 300°F	0.08485	4.05174	**F<Fα**	0.77214	**P>>α**	Statistically NOT Different
(24 / 24)	No Temp	SS 340°F	0.12501	4.05174	**F<Fα**	0.72527	**P>>α**	Statistically NOT Different
(24 / 18)	No Temp	SS 380°F	0.15809	4.08474	**F<Fα**	0.69303	**P>>α**	Statistically NOT Different
(24 / 24)	SS 300°F	SS 340°F	0.00579	4.05174	**F<Fα**	0.93969	**P>>α**	Statistically NOT Different
(24 / 18)	SS 300°F	SS 380°F	0.02277	4.08474	**F<Fα**	0.88082	**P>>α**	Statistically NOT Different
(24 / 18)	SS 340°F	SS 380°F	0.00603	4.08474	**F<Fα**	0.93850	**P>>α**	Statistically NOT Different

	Edynamic from SWT - Before Heated (for Static Tests)					0.90264	= average P value	
(24 / 24)	No Temp	SS 300^{o}F	0.00467	4.05174	**F<Fα**	0.94580	**P>>α**	Statistically NOT Different
(24 / 24)	No Temp	SS 340^{o}F	0.00200	4.05174	**F<Fα**	0.96456	**P>>α**	Statistically NOT Different
(24 / 18)	No Temp	SS 380^{o}F	0.03167	4.08474	**F<Fα**	0.85965	**P>>α**	Statistically NOT Different
(24 / 24)	SS 300^{o}F	SS 340^{o}F	0.01289	4.05174	**F<Fα**	0.91011	**P>>α**	Statistically NOT Different
(24 / 18)	SS 300^{o}F	SS 380^{o}F	0.01304	4.08474	**F<Fα**	0.90966	**P>>α**	Statistically NOT Different
(24 / 18)	SS 340^{o}F	SS 380^{o}F	0.04892	4.08474	**F<Fα**	0.82608	**P>>α**	Statistically NOT Different

	Edynamic from SWT - After Heated (for Static Tests)					0.85630	= average P value	
(24 / 24)	No Temp	SS 300^{o}F	0.00470	4.05174	**F<Fα**	0.94563	**P>>α**	Statistically NOT Different
(24 / 24)	No Temp	SS 340^{o}F	0.05330	4.05174	**F<Fα**	0.81844	**P>>α**	Statistically NOT Different
(24 / 18)	No Temp	SS 380^{o}F	0.09273	4.08474	**F<Fα**	0.76232	**P>>α**	Statistically NOT Different
(24 / 24)	SS 300^{o}F	SS 340^{o}F	0.02694	4.05174	**F<Fα**	0.87033	**P>>α**	Statistically NOT Different
(24 / 18)	SS 300^{o}F	SS 380^{o}F	0.05893	4.08474	**F<Fα**	0.80944	**P>>α**	Statistically NOT Different
(24 / 18)	SS 340^{o}F	SS 380^{o}F	0.00745	4.08474	**F<Fα**	0.93166	**P>>α**	Statistically NOT Different

	Estatic from Graphical Slope (Heated)							
(24 / 24)	No Temp	SS 300^{o}F	1.41808	4.05174	**F<Fα**	0.23983	**P>α**	Statistically NOT Different
(24 / 24)	No Temp	SS 340^{o}F	3.27342	4.05174	**F<Fα**	0.07695	**P>α**	Statistically NOT Different
(24 / 18)	No Temp	SS 380^{o}F	3.33955	4.08474	**F<Fα**	0.07510	**P>α**	Statistically NOT Different
(24 / 24)	SS 300^{o}F	SS 340^{o}F	0.43676	4.05174	**F<Fα**	0.51199	**P>>α**	Statistically NOT Different
(24 / 18)	SS 300^{o}F	SS 380^{o}F	0.49484	4.08474	**F<Fα**	0.48585	**P>α**	Statistically NOT Different
(24 / 18)	SS 340^{o}F	SS 380^{o}F	0.00285	4.08474	**F<Fα**	0.95771	**P>>α**	Statistically NOT Different

	Actual Modulus of Rupture							
(24 / 24)	No Temp	SS 300^{o}F	1.29363	4.05174	**F<Fα**	0.26127	**P>α**	Statistically NOT Different
(24 / 24)	No Temp	SS 340^{o}F	2.85871	4.05174	**F<Fα**	0.09765	**P>α**	Statistically NOT Different
(24 / 18)	No Temp	SS 380^{o}F	3.96480	4.08474	**F<Fα**	0.05332	**P>α**	Statistically NOT Different
(24 / 24)	SS 300^{o}F	SS 340^{o}F	0.22636	4.05174	**F<Fα**	0.63649	**P>>α**	Statistically NOT Different
(24 / 18)	SS 300^{o}F	SS 380^{o}F	0.57969	4.08474	**F<Fα**	0.45090	**P>α**	Statistically NOT Different
(24 / 18)	SS 340^{o}F	SS 380^{o}F	0.10191	4.08474	**F<Fα**	0.75121	**P>>α**	Statistically NOT Different

	Lognormal Modulus of Rupture							
(24 / 24)	No Temp	SS 300^{o}F	1.43847	4.05174	**F<Fα**	0.23653	**P>α**	Statistically NOT Different
(24 / 24)	No Temp	SS 340^{o}F	3.19399	4.05174	**F<Fα**	0.08050	**P>α**	Statistically NOT Different
(24 / 18)	No Temp	SS 380^{o}F	4.63272	4.08474	**F>Fα**	0.03746	**P<α**	Statistically Different
(24 / 24)	SS 300^{o}F	SS 340^{o}F	0.29299	4.05174	**F<Fα**	0.59092	**P>>α**	Statistically NOT Different
(24 / 18)	SS 300^{o}F	SS 380^{o}F	0.73288	4.08474	**F<Fα**	0.39705	**P>α**	Statistically NOT Different
(24 / 18)	SS 340^{o}F	SS 380^{o}F	0.10942	4.08474	**F<Fα**	0.74254	**P>>α**	Statistically NOT Different

Comparison of Density

	Density - Before Heated							
(48 / 48)	No Temp	SS 300°F	0.03313	3.94230	**F<Fα**	0.85596	**P>>α**	Statistically NOT Different
(48 / 48)	No Temp	SS 340°F	0.37700	3.94230	**F<Fα**	0.54070	**P>>α**	Statistically NOT Different
(48 / 36)	No Temp	SS 380°F	1.40614	3.95738	**F<Fα**	0.23912	**P>α**	Statistically NOT Different
(48 / 48)	SS 300°F	SS 340°F	0.18141	3.94230	**F<Fα**	0.67114	**P>>α**	Statistically NOT Different
(48 / 36)	SS 300°F	SS 380°F	1.08674	3.95738	**F<Fα**	0.30026	**P>α**	Statistically NOT Different
(48 / 36)	SS 340°F	SS 380°F	0.57096	3.95738	**F<Fα**	0.45204	**P>α**	Statistically NOT Different

	Density - After Heated							
(48 / 48)	No Temp	SS 300°F	0.15275	3.94230	**F<Fα**	0.69680	**P>>α**	Statistically NOT Different
(48 / 48)	No Temp	SS 340°F	0.15479	3.94230	**F<Fα**	0.69489	**P>>α**	Statistically NOT Different
(48 / 36)	No Temp	SS 380°F	0.02417	3.95738	**F<Fα**	0.87683	**P>>α**	Statistically NOT Different
(48 / 48)	SS 300°F	SS 340°F	0.00099	3.94230	**F<Fα**	0.97501	**P>>α**	Statistically NOT Different
(48 / 36)	SS 300°F	SS 380°F	0.27858	3.95738	**F<Fα**	0.59906	**P>>α**	Statistically NOT Different
(48 / 36)	SS 340°F	SS 380°F	0.30524	3.95738	**F<Fα**	0.58212	**P>>α**	Statistically NOT Different

	Density: Unheated vs. Heated								
(48 / 48)	SS 300°F	Unheated	Heated	0.34355	3.94230	**F<Fα**	0.55919	**P>>α**	Statistically NOT Different
(48 / 48)	SS 340°F	Unheated	Heated	1.32684	3.94230	**F<Fα**	0.25229	**P>α**	Statistically NOT Different
(36 / 36)	SS 380°F	Unheated	Heated	0.95011	3.97779	**F<Fα**	0.33305	**P>α**	Statistically NOT Different

ANOVA SUMMARY: VENEER

Comparison of Temperatures per Dynamic Modulus of Elasticity

	Veneer Sheets							
(165 / 165)	LVL 300^{o}F	LVL 340^{o}F	0.74647	3.86996	**F<Fα**	0.38823	**P>α**	Statistically NOT Different
(165 / 165)	LVL 300^{o}F	LVL 380^{o}F	3.46775	3.86996	**F<Fα**	0.06347	**P>α**	Statistically NOT Different
(165 / 165)	LVL 340^{o}F	LVL 380^{o}F	1.05247	3.86996	**F<Fα**	0.30569	**P>α**	Statistically NOT Different

Comparison of Modulus of Elasticity

	Solid Sawn Compared to Veneers							
(180 / 495)	Solid Sawn	Veneers	1.26125	3.85532	**F<Fα**	0.26182	**P>α**	Statistically NOT Different

ANOVA SUMMARY: LAMINATED VENEER LUMBER - COMPARING MOE

Comparing Only Members Used for Testing

	300°F - Static & DOL Tests							
(48 / 48)	Edynamic (psi)	Ecomposite-vert (psi)	6.29207	3.94230	**F>Fα**	0.01384	**P<α**	Statistically Different
(48 / 15)	Edynamic (psi)	Ebillet-vert (psi)	0.03308	3.99849	**F<Fα**	0.85628	**P>>α**	Statistically NOT Different
(48 / 15)	Edynamic (psi)	Eexpected-vert (psi)	0.02510	3.99849	**F<Fα**	0.87464	**P>>α**	Statistically NOT Different
(48 / 15)	Ecomposite-vert (psi)	Ebillet-vert (psi)	2.12128	3.99849	**F<Fα**	0.15039	**P>α**	Statistically NOT Different
(48 / 15)	Ecomposite-vert (psi)	Eexpected-vert (psi)	3.13142	3.99849	**F<Fα**	0.08179	**P>α**	Statistically NOT Different
(15 / 15)	Ebillet-vert (psi)	Eexpected-vert (psi)	0.05884	4.19598	**F<Fα**	0.81011	**P>>α**	Statistically NOT Different
(48 / 48)	Edynamic (psi)	Ecomposite-horz (psi)	1.24728	3.94230	**F<Fα**	0.26692	**P>α**	Statistically NOT Different
(48 / 15)	Edynamic (psi)	Ebillet-horz (psi)	6.31214	3.99849	**F>Fα**	0.01465	**P<α**	Statistically Different
(48 / 15)	Edynamic (psi)	Eexpected-horz (psi)	12.61760	3.99849	**F>Fα**	0.00074	**P<α**	Statistically Different
(48 / 15)	Ecomposite-horz (psi)	Ebillet-horz (psi)	2.09341	3.99849	**F<Fα**	0.15305	**P>α**	Statistically NOT Different
(48 / 15)	Ecomposite-horz (psi)	Eexpected-horz (psi)	5.49486	3.99849	**F>Fα**	0.02235	**P<α**	Statistically Different
(15 / 15)	Ebillet-horz (psi)	Eexpected-horz (psi)	0.47765	4.19598	**F<Fα**	0.49518	**P>α**	Statistically NOT Different

	300°F - Static Tests							
(24 / 24)	Estatic (psi)	Edynamic (psi)	37.93033	4.05174	**F>Fα**	1.67E-07	**P<<α**	Statistically Different
(24 / 24)	Estatic (psi)	Ecomposite-horz (psi)	27.29403	4.05174	**F>Fα**	4.12E-06	**P<<α**	Statistically Different
(24 / 24)	Estatic (psi)	Ecomposite-vert (psi)	55.73841	4.05174	**F>Fα**	1.83E-09	**P<<α**	Statistically Different
(24 / 24)	Ecomposite-vert (psi)	Ecomposite-horz (psi)	5.25986	4.05174	**F>Fα**	0.02644	**P<α**	Statistically Different
(24 / 15)	Estatic (psi)	Ebillet-horz (psi)	9.60279	4.10546	**F>Fα**	0.00370	**P<α**	Statistically Different
(24 / 15)	Estatic (psi)	Ebillet-vert (psi)	25.70230	4.10546	**F>Fα**	0.00001	**P<<α**	Statistically Different
(24 / 15)	Estatic (psi)	Eexpected-horz (psi)	5.57333	4.10546	**F>Fα**	0.02362	**P<α**	Statistically Different
(24 / 15)	Estatic (psi)	Eexpected-vert (psi)	23.34643	4.10546	**F>Fα**	0.00002	**P<<α**	Statistically Different

	340°F - Static & DOL Tests							
(48 / 48)	Edynamic (psi)	Ecomposite-vert (psi)	14.96045	3.90779	**F>Fα**	0.00017	**P<α**	Statistically Different
(48 / 15)	Edynamic (psi)	Ebillet-vert (psi)	5.29797	3.95320	**F>Fα**	0.02380	**P<α**	Statistically Different
(48 / 15)	Edynamic (psi)	Eexpected-vert (psi)	3.41301	3.95320	**F<Fα**	0.06816	**P>α**	Statistically NOT Different
(48 / 15)	Ecomposite-vert (psi)	Ebillet-vert (psi)	0.01146	3.95320	**F<Fα**	0.91499	**P>>α**	Statistically NOT Different
(48 / 15)	Ecomposite-vert (psi)	Eexpected-vert (psi)	0.12967	3.95320	**F<Fα**	0.71966	**P>>α**	Statistically NOT Different
(15 / 15)	Ebillet-vert (psi)	Eexpected-vert (psi)	0.11507	4.19598	**F<Fα**	0.73697	**P>>α**	Statistically NOT Different
(48 / 48)	Edynamic (psi)	Ecomposite-horz (psi)	0.60849	3.90779	**F<Fα**	0.43665	**P>α**	Statistically NOT Different
(48 / 15)	Edynamic (psi)	Ebillet-horz (psi)	0.19241	3.95320	**F<Fα**	0.66203	**P>>α**	Statistically NOT Different
(48 / 15)	Edynamic (psi)	Eexpected-horz (psi)	3.61043	3.95320	**F<Fα**	0.06081	**P>α**	Statistically NOT Different
(48 / 15)	Ecomposite-horz (psi)	Ebillet-horz (psi)	0.00027	3.95320	**F<Fα**	0.98700	**P>>α**	Statistically NOT Different
(48 / 15)	Ecomposite-horz (psi)	Eexpected-horz (psi)	2.04357	3.95320	**F<Fα**	0.15652	**P>α**	Statistically NOT Different
(15 / 15)	Ebillet-horz (psi)	Eexpected-horz (psi)	1.06043	4.19598	**F<Fα**	0.31193	**P>α**	Statistically NOT Different

	340°F - Static Tests							
(24 / 24)	Estatic (psi)	Edynamic (psi)	0.00272	4.05174	**F<Fα**	0.95861	**P>>α**	Statistically NOT Different
(24 / 24)	Estatic (psi)	Ecomposite-horz (psi)	0.06692	4.05174	**F<Fα**	0.79703	**P>>α**	Statistically NOT Different
(24 / 24)	Estatic (psi)	Ecomposite-vert (psi)	3.58973	4.05174	**F<Fα**	0.06443	**P>α**	Statistically NOT Different
(24 / 24)	Ecomposite-vert (psi)	Ecomposite-horz (psi)	7.04750	4.05174	**F>Fα**	0.01087	**P<α**	Statistically Different
(24 / 15)	Estatic (psi)	Ebillet-horz (psi)	0.10078	4.10546	**F<Fα**	0.75268	**P>>α**	Statistically NOT Different
(24 / 15)	Estatic (psi)	Ebillet-vert (psi)	2.32432	4.10546	**F<Fα**	0.13587	**P>α**	Statistically NOT Different
(24 / 15)	Estatic (psi)	Eexpected-horz (psi)	1.65435	4.10546	**F<Fα**	0.20636	**P>α**	Statistically NOT Different
(24 / 15)	Estatic (psi)	Eexpected-vert (psi)	1.48001	4.10546	**F<Fα**	0.23148	**P>α**	Statistically NOT Different

	380°F - Static & DOL Tests							
(48 / 48)	Edynamic (psi)	Ecomposite-vert (psi)	7.78022	3.97023	**F>Fα**	0.00671	**P<α**	Statistically Different
(48 / 15)	Edynamic (psi)	Ebillet-vert (psi)	15.90788	4.03040	**F>Fα**	0.00021	**P<α**	Statistically Different
(48 / 15)	Edynamic (psi)	Eexpected-vert (psi)	12.83003	4.03040	**F>Fα**	0.00076	**P<α**	Statistically Different
(48 / 15)	Ecomposite-vert (psi)	Ebillet-vert (psi)	3.09063	4.03040	**F<Fα**	0.08474	**P>α**	Statistically NOT Different
(48 / 15)	Ecomposite-vert (psi)	Eexpected-vert (psi)	1.93835	4.03040	**F<Fα**	0.16989	**P>α**	Statistically NOT Different
(15 / 15)	Ebillet-vert (psi)	Eexpected-vert (psi)	0.08482	4.19598	**F<Fα**	0.77301	**P>>α**	Statistically NOT Different
(48 / 48)	Edynamic (psi)	Ecomposite-horz (psi)	0.59868	3.97023	**F<Fα**	0.44155	**P>α**	Statistically NOT Different
(48 / 15)	Edynamic (psi)	Ebillet-horz (psi)	1.85794	4.03040	**F<Fα**	0.17885	**P>α**	Statistically NOT Different
(48 / 15)	Edynamic (psi)	Eexpected-horz (psi)	0.01461	4.03040	**F<Fα**	0.90427	**P>>α**	Statistically NOT Different
(48 / 15)	Ecomposite-horz (psi)	Ebillet-horz (psi)	3.25804	4.03040	**F<Fα**	0.07698	**P>α**	Statistically NOT Different
(48 / 15)	Ecomposite-horz (psi)	Eexpected-horz (psi)	0.41931	4.03040	**F<Fα**	0.52019	**P>>α**	Statistically NOT Different
(15 / 15)	Ebillet-horz (psi)	Eexpected-horz (psi)	0.82164	4.19598	**F<Fα**	0.37244	**P>α**	Statistically NOT Different

	380°F - Static Tests							
(19 / 19)	Estatic (psi)	Edynamic (psi)	2.77352	4.11316	**F<Fα**	0.10452	**P>α**	Statistically NOT Different
(19 / 19)	Estatic (psi)	Ecomposite-horz (psi)	3.93195	4.11316	**F<Fα**	0.05505	**P>α**	Statistically NOT Different
(19 / 19)	Estatic (psi)	Ecomposite-vert (psi)	0.12752	4.11316	**F<Fα**	0.72311	**P>>α**	Statistically NOT Different
(19 / 19)	Ecomposite-vert (psi)	Ecomposite-horz (psi)	4.92458	4.11316	**F>Fα**	0.03287	**P<α**	Statistically Different
(19 / 15)	Estatic (psi)	Ebillet-horz (psi)	0.13145	4.14909	**F<Fα**	0.71932	**P>>α**	Statistically NOT Different
(19 / 15)	Estatic (psi)	Ebillet-vert (psi)	3.54098	4.14909	**F<Fα**	0.06899	**P>α**	Statistically NOT Different
(19 / 15)	Estatic (psi)	Eexpected-horz (psi)	1.84702	4.14909	**F<Fα**	0.18363	**P>α**	Statistically NOT Different
(19 / 15)	Estatic (psi)	Eexpected-vert (psi)	2.36390	4.14909	**F<Fα**	0.13400	**P>α**	Statistically NOT Different

Comparing All "Useable" Members

	Ecomposite-vert* (from laminated beam theory) compared Edynamic								
(57 / 57)	300°F	Ecomposite	Edynamic	6.01403	3.92583	**F>Fα**	0.01574	**P<α**	Statistically Different
(73 / 73)	340°F	Ecomposite	Edynamic	15.00050	3.90685	**F>Fα**	0.00016	**P<α**	Statistically Different
(40 / 40)	380°F	Ecomposite	Edynamic	8.73545	3.96346	**F>Fα**	0.00413	**P<α**	Statistically Different

*Ecomposite-horz not examined because Ecomposite-vert should match edgewise bending, that which Edynamic was used to sort for

ANOVA SUMMARY: LAMINATED VENEER LUMBER - COMPARING TEMPERATURES

Comparing Only Members Used for Testing

	Edynamic from SWT (for Static Tests)							
(24 / 24)	LVL 300°F	LVL 340°F	6.93777	4.05174	**F>Fα**	0.01146	**P<α**	Statistically Different
(24 / 19)	LVL 300°F	LVL 380°F	23.31019	4.07854	**F>Fα**	0.00002	**P<<α**	Statistically Different
(24 / 19)	LVL 340°F	LVL 380°F	4.37876	4.07854	**F>Fα**	0.04262	**P<α**	Statistically Different

	Edynamic from SWT (for DOL Tests)							
(24 / 24)	LVL 300°F	LVL 340°F-1	6.47000	4.05174	**F>Fα**	0.01440	**P<α**	Statistically Different
(24 / 24)	LVL 300°F	LVL 340°F-2	6.63160	4.05174	**F>Fα**	0.01330	**P<α**	Statistically Different
(24 / 19)	LVL 300°F	LVL 380°F	23.49188	4.07854	**F>Fα**	0.00002	**P<<α**	Statistically Different
(24 / 24)	LVL 340°F-1	LVL 340°F-2	0.00182	4.05174	**F<Fα**	0.96614	**P>>α**	Statistically NOT Different
(24 / 19)	LVL 340°F-1	LVL 380°F	5.11002	4.07854	**F>Fα**	0.02916	**P<α**	Statistically Different
(24 / 19)	LVL 340°F-2	LVL 380°F	4.87554	4.07854	**F>Fα**	0.03289	**P<α**	Statistically Different

	Estatic from Graphical Slope							
(24 / 24)	LVL 300°F	LVL 340°F	10.95207	4.05174	**F>Fα**	0.00182	**P<α**	Statistically Different
(24 / 19)	LVL 300°F	LVL 380°F	10.40823	4.07854	**F>Fα**	0.00247	**P<α**	Statistically Different
(24 / 19)	LVL 340°F	LVL 380°F	0.11160	4.07854	**F<Fα**	0.74003	**P>>α**	Statistically NOT Different

	Density (Static & DOL Tests)							
(48 / 48)	LVL 300°F	LVL 340°F	18.93237	3.92149	**F>Fα**	0.00003	**P<<α**	Statistically Different
(48 / 48)	LVL 300°F	LVL 380°F	20.07118	3.95457	**F>Fα**	0.00002	**P<<α**	Statistically Different
(38 / 38)	LVL 340°F	LVL 380°F	0.89969	3.92902	**F<Fα**	0.34498	**P>α**	Statistically NOT Different

	Actual Modulus of Rupture							
(24 / 24)	LVL 300°F	LVL 340°F	5.22353	4.05174	**F>Fα**	0.02694	**P<α**	Statistically Different
(24 / 19)	LVL 300°F	LVL 380°F	5.21430	4.07854	**F>Fα**	0.02765	**P<α**	Statistically Different
(24 / 19)	LVL 340°F	LVL 380°F	0.02046	4.07854	**F<Fα**	0.88695	**P>>α**	Statistically NOT Different

	Lognormal Modulus of Rupture							
(24 / 24)	LVL 300°F	LVL 340°F	6.24436	4.05174	**F>Fα**	0.01609	**P<α**	Statistically Different
(24 / 19)	LVL 300°F	LVL 380°F	6.29560	4.07854	**F>Fα**	0.01615	**P<α**	Statistically Different
(24 / 19)	LVL 340°F	LVL 380°F	0.01940	4.07854	**F<Fα**	0.88992	**P>>α**	Statistically NOT Different

Comparison of All Members Produced

	Edynamic							
(89 / 90)	LVL 300°F	LVL 340°F	2.77642	3.89454	**F<Fα**	0.09743	**P>α**	Statistically NOT Different
(89 / 90)	LVL 300°F	LVL 380°F	7.78035	3.89454	**F>Fα**	0.00586	**P<α**	Statistically Different
(90 / 90)	LVL 340°F	LVL 380°F	1.05113	3.89423	**F<Fα**	0.30664	**P>α**	Statistically NOT Different

	Density							
(89 / 90)	LVL 300°F	LVL 340°F	3.10193	3.89454	**F<Fα**	0.07993	**P>α**	Statistically NOT Different
(89 / 90)	LVL 300°F	LVL 380°F	0.26102	3.89454	**F<Fα**	0.61006	**P>>α**	Statistically NOT Different
(90 / 90)	LVL 340°F	LVL 380°F	5.46783	3.89423	**F>Fα**	0.02048	**P<α**	Statistically Different

ANOVA SUMMARY: SOLID SAWN LUMBER & LVL - TESTED MEMBERS FOR MOE/MOR VS DOL

Comparison Would Yeild No Difference if Sorted Properly

	Solid Sawn Edynamic from SWT - Before Heated						0.90083	= average P value	
(24 / 24)	No Temp	MOR/MOE	DOL	0.00002	4.05174	**F<Fα**	0.99617	**P>>α**	Statistically NOT Different
(24 / 24)	SS 300°F	MOR/MOE	DOL	0.00214	4.05174	**F<Fα**	0.96327	**P>>α**	Statistically NOT Different
(24 / 24)	SS 340°F	MOR/MOE	DOL	0.04265	4.05174	**F<Fα**	0.83729	**P>>α**	Statistically NOT Different
(18 / 18)	SS 380°F	MOR/MOE	DOL	0.01542	4.13002	**F<Fα**	0.90192	**P>>α**	Statistically NOT Different

	Solid Sawn Edynamic from SWT - After Heated						0.88251	= average P value	
(24 / 24)	SS 300°F	MOR/MOE	DOL	0.04919	4.05174	**F<Fα**	0.82546	**P>>α**	Statistically NOT Different
(24 / 24)	SS 340°F	MOR/MOE	DOL	0.01495	4.05174	**F<Fα**	0.90321	**P>>α**	Statistically NOT Different
(18 / 18)	SS 380°F	MOR/MOE	DOL	0.01053	4.13002	**F<Fα**	0.91886	**P>>α**	Statistically NOT Different

	Laminated Veneer Lumber Edynamic from SWT								
(24 / 24)	SS 300°F	MOR/MOE	DOL	0.00037	4.05174	**F<Fα**	0.98466	**P>>α**	Statistically NOT Different
(24 / 24)	SS 340°F-1	MOR/MOE	DOL	0.00407	4.05174	**F<Fα**	0.94938	**P>>α**	Statistically NOT Different
(24 / 24)	SS 340°F-2	MOR/MOE	DOL	0.00044	4.05174	**F<Fα**	0.98331	**P>>α**	Statistically NOT Different
(19 / 19)	SS 380°F	MOR/MOE	DOL	0.01297	4.11316	**F<Fα**	0.90997	**P>>α**	Statistically NOT Different

ANOVA SUMMARY: SOLID SAWN LUMBER & LVL - STATIC DEFLECTIONS

Comparison of Temperatures

	Solid Sawn: Deflections at Peak Load							
(24 / 24)	No Temp	SS 300°F	0.24380	4.05174	**F<Fα**	0.62382	**P>>α**	Statistically NOT Different
(24 / 20)	No Temp	SS 340°F	0.10599	4.07266	**F<Fα**	0.74638	**P>>α**	Statistically NOT Different
(24 / 15)	No Temp	SS 380°F	0.30378	4.10546	**F<Fα**	0.58483	**P>>α**	Statistically NOT Different
(24 / 20)	SS 300°F	SS 340°F	0.58809	4.07266	**F<Fα**	0.44745	**P>α**	Statistically NOT Different
(24 / 15)	SS 300°F	SS 380°F	0.01431	4.10546	**F<Fα**	0.90543	**P>>α**	Statistically NOT Different
(20 / 15)	SS 340°F	SS 380°F	0.60857	4.13925	**F<Fα**	0.44089	**P>α**	Statistically NOT Different

(deflections did not include maximum deflections found when the range of LVDT was passed: NOT a comparison of "better estimate")

	Solid Sawn: Deflections at Peak Load							
(24 / 24)	No Temp	SS 300°F	0.24380	4.05174	**F<Fα**	0.62382	**P>>α**	Statistically NOT Different
(24 / 24)	No Temp	SS 340°F	0.67838	4.05174	**F<Fα**	0.41439	**P>α**	Statistically NOT Different
(24 / 18)	No Temp	SS 380°F	2.13513	4.08474	**F<Fα**	0.15177	**P>α**	Statistically NOT Different
(24 / 24)	SS 300°F	SS 340°F	0.12556	4.05174	**F<Fα**	0.72470	**P>>α**	Statistically NOT Different
(24 / 18)	SS 300°F	SS 380°F	0.97714	4.08474	**F<Fα**	0.32885	**P>α**	Statistically NOT Different
(24 / 18)	SS 340°F	SS 380°F	0.37618	4.08474	**F<Fα**	0.54313	**P>>α**	Statistically NOT Different

(deflections included maximum deflections found when the range of LVDT was passed: a comparison of "better estimate")

	Laminated Veneer Lumber: Deflections at Peak Load							
(24 / 24)	LVL 300°F	LVL 340°F	9.29144	4.05174	**F>Fα**	0.00381	**P<α**	Statistically Different
(24 / 19)	LVL 300°F	LVL 380°F	1.43849	4.07854	**F<Fα**	0.23727	**P>α**	Statistically NOT Different
(24 / 19)	LVL 340°F	LVL 380°F	3.14899	4.07854	**F<Fα**	0.08340	**P>α**	Statistically NOT Different

ANOVA SUMMARY: SOLID SAWN LUMBER - DURATION OF LOAD DEFLECTIONS

Comparison of Temperatures

	DOL: Initial Deflections							
(19 / 21)	No Temp	SS 300°F	0.34089	4.09817	**F<Fα**	0.56277	**P>>α**	Statistically NOT Different
(19 / 15)	No Temp	SS 340°F	0.06606	4.14909	**F<Fα**	0.79881	**P>>α**	Statistically NOT Different
(19 / 12)	No Temp	SS 380°F	5.75331	4.18297	**F>Fα**	0.02311	**P<α**	Statistically Different
(21 / 15)	SS 300°F	SS 340°F	0.67343	4.13002	**F<Fα**	0.41758	**P>α**	Statistically NOT Different
(21 / 12)	SS 300°F	SS 380°F	8.58567	4.15962	**F>Fα**	0.00631	**P<α**	Statistically Different
(15 / 12)	SS 340°F	SS 380°F	4.46850	4.24170	**F>Fα**	0.04467	**P<α**	Statistically Different

	DOL: Failure Deflections			43200 min				
(5 / 6)	No Temp	SS 300°F	1.80335	5.11736	**F<Fα**	0.21219	**P>α**	Statistically NOT Different
(5 / 2)	No Temp	SS 340°F	2.34304	6.60788	**F<Fα**	0.18640	**P>α**	Statistically NOT Different
(5 / 3)	No Temp	SS 380°F	0.84670	5.98737	**F<Fα**	0.39298	**P>α**	Statistically NOT Different
(6 / 2)	SS 300°F	SS 340°F	0.00631	5.98737	**F<Fα**	0.93927	**P>>α**	Statistically NOT Different
(6 / 3)	SS 300°F	SS 380°F	2.49037	5.59146	**F<Fα**	0.15855	**P>α**	Statistically NOT Different
(2 / 3)	SS 340°F	SS 380°F	1.04066	10.12796	**F<Fα**	0.38276	**P>α**	Statistically NOT Different

	DOL: Survival Deflections			43200 min				
(14 / 16)	No Temp	SS 300°F	0.05423	4.19598	**F<Fα**	0.81756	**P>>α**	Statistically NOT Different
(14 / 13)	No Temp	SS 340°F	1.24642	4.24170	**F<Fα**	0.27485	**P>α**	Statistically NOT Different
(14 / 10)	No Temp	SS 380°F	8.40905	4.30094	**F>Fα**	0.00831	**P<α**	Statistically Different
(16 / 13)	SS 300°F	SS 340°F	0.95086	4.21001	**F<Fα**	0.33816	**P>α**	Statistically NOT Different
(16 / 10)	SS 300°F	SS 380°F	8.26655	4.25968	**F>Fα**	0.00833	**P<α**	Statistically Different
(13 / 10)	SS 340°F	SS 380°F	2.75630	4.32479	**F<Fα**	0.11173	**P>α**	Statistically NOT Different

	DOL: Failure Deflections			60480 min				
(5 / 6)	No Temp	SS 300°F	1.80335	5.11736	**F<Fα**	0.21219	**P>α**	Statistically NOT Different
(5 / 3)	No Temp	SS 340°F	0.00107	5.98737	**F<Fα**	0.97497	**P>>α**	Statistically NOT Different
(5 / 4)	No Temp	SS 380°F	0.58158	5.59146	**F<Fα**	0.47061	**P>α**	Statistically NOT Different
(6 / 3)	SS 300°F	SS 340°F	0.84107	5.59146	**F<Fα**	0.38960	**P>α**	Statistically NOT Different
(6 / 4)	SS 300°F	SS 380°F	2.39456	5.31764	**F<Fα**	0.16035	**P>α**	Statistically NOT Different
(3 / 4)	SS 340°F	SS 380°F	0.30464	6.60788	**F<Fα**	0.60475	**P>>α**	Statistically NOT Different

	DOL: Survival Deflections			60480 min				
(14 / 9)	No Temp	SS 380°F	8.62479	4.32479	**F>Fα**	0.00788	**P<α**	Statistically Different

There is no deflection data for 60480 min for the 300°F or 340°F survivors

ANOVA SUMMARY: LAMINATED VENEER LUMBER - DURATION OF LOAD DEFLECTIONS

Comparison of Temperatures

	DOL: Initial Deflections							
(17 / 17)	LVL 300°F	LVL 340°F-1	0.00629	4.14909	**F<Fα**	0.93728	**P>>α**	Statistically NOT Different
(17 / 17)	LVL 300°F	LVL 340°F-2	0.14131	4.14909	**F<Fα**	0.70946	**P>>α**	Statistically NOT Different
(17 / 15)	LVL 300°F	LVL 380°F	0.11633	4.17089	**F<Fα**	0.73543	**P>>α**	Statistically NOT Different
(17 / 17)	LVL 340°F-1	LVL 340°F-2	0.16827	4.14909	**F<Fα**	0.68439	**P>>α**	Statistically NOT Different
(17 / 15)	LVL 340°F-1	LVL 380°F	0.13628	4.17089	**F>Fα**	0.71460	**P>>α**	Statistically NOT Different
(17 / 15)	LVL 340°F-2	LVL 380°F	0.02424	4.17089	**F<Fα**	0.87731	**P>>α**	Statistically NOT Different

	DOL: Failure Deflections			60480 min				
(12 / 13)	LVL 300°F	LVL 340°F-1	3.05213	4.27934	**F<Fα**	0.09397	**P>α**	Statistically NOT Different
(12 / 12)	LVL 300°F	LVL 340°F-2	0.42218	4.30094	**F<Fα**	0.52258	**P>>α**	Statistically NOT Different
(12 / 9)	LVL 300°F	LVL 380°F	1.46501	4.38075	**F<Fα**	0.24098	**P>α**	Statistically NOT Different
(13 / 12)	LVL 340°F-1	LVL 340°F-2	2.10161	4.27934	**F<Fα**	0.16064	**P>α**	Statistically NOT Different
(13 / 9)	LVL 340°F-1	LVL 380°F	6.10044	4.35125	**F>Fα**	0.02264	**P<α**	Statistically Different
(12 / 9)	LVL 340°F-2	LVL 380°F	0.04664	4.38075	**F<Fα**	0.83132	**P>>α**	Statistically NOT Different

	DOL: Survival Deflections			60480 min				
(5 / 4)	LVL 300°F	LVL 340°F-1	0.37938	5.59146	**F<Fα**	0.55742	**P>>α**	Statistically NOT Different
(5 / 5)	LVL 300°F	LVL 340°F-2	0.36310	5.31764	**F<Fα**	0.56347	**P>>α**	Statistically NOT Different
(5 / 6)	LVL 300°F	LVL 380°F	0.20199	5.11736	**F<Fα**	0.66375	**P>>α**	Statistically NOT Different
(4 / 5)	LVL 340°F-1	LVL 340°F-2	0.03245	5.59146	**F<Fα**	0.86216	**P>>α**	Statistically NOT Different
(4 / 6)	LVL 340°F-1	LVL 380°F	0.02730	5.31764	**F<Fα**	0.87287	**P>>α**	Statistically NOT Different
(5 / 6)	LVL 340°F-2	LVL 380°F	0.09530	5.11736	**F<Fα**	0.76457	**P>>α**	Statistically NOT Different

ANOVA SUMMARY: SOLID SAWN LUMBER & LVL - STATIC VS DURATION OF LOAD DEFLECTIONS

	Static	DOL	Solid Sawn: No Temp					
(24 / 19)	Δmaximum	Δinitial	22.70674	4.07854	**F>Fα**	0.00002	**P<<α**	Statistically Different
(24 / 5)	Δmaximum	Δfailure	0.28422	4.21001	**F<Fα**	0.59831	**P>>α**	Statistically NOT Different
(24 / 14)	Δmaximum	Δsurvivor (43200 min)	11.62879	4.11316	**F>Fα**	0.00162	**P<α**	Statistically Different
(24 / 14)	Δmaximum	Δsurvivor (60480 min)	10.03437	4.11316	**F>Fα**	0.00313	**P<α**	Statistically Different

	Static	DOL	Solid Sawn: 300°F					
(24 / 21)	Δmaximum	Δinitial	29.64435	4.06705	**F>Fα**	2.33E-06	**P<<α**	Statistically Different
(24 / 6)	Δmaximum	Δfailure	3.78725	4.19598	**F<Fα**	0.06174	**P>α**	Statistically NOT Different
(24 / 16)	Δmaximum	Δsurvivor (43200 min)	13.28356	4.09817	**F>Fα**	0.00080	**P<α**	Statistically Different

	Static	DOL	Solid Sawn: 340°F					
(20 / 15)	Δmaximum	Δinitial	13.35363	4.13925	**F>Fα**	0.00089	**P<α**	Statistically Different
(20 / 2)	Δmaximum	Δfailure	0.75759	4.35125	**F<Fα**	0.39441	**P>α**	Statistically NOT Different
(20 /13)	Δmaximum	Δsurvivor (43200 min)	3.67043	4.15962	**F<Fα**	0.06465	**P>α**	Statistically NOT Different

	Static	DOL	Solid Sawn: 380°F					
(15 / 12)	Δmaximum	Δinitial	5.82020	4.24170	**F>Fα**	0.02351	**P<α**	Statistically Different
(15 / 3)	Δmaximum	Δfailure (43200 min)	0.05509	4.49400	**F<Fα**	0.81742	**P>>α**	Statistically NOT Different
(15 / 10)	Δmaximum	Δsurvivor (43200 min)	0.98664	4.27934	**F<Fα**	0.33090	**P>α**	Statistically NOT Different
(15 / 4)	Δmaximum	Δfailure (60480 min)	0.00046	4.45132	**F<Fα**	0.98322	**P>>α**	Statistically NOT Different
(15 / 9)	Δmaximum	Δsurvivor (60480 min)	0.34422	4.30094	**F<Fα**	0.56337	**P>>α**	Statistically NOT Different

	Static	DOL	Laminated Veneer Lumber: 300°F					
(24 / 17)	Δmaximum	Δinitial	1.9267165	4.0912767	**F<Fα**	0.1729971	**P>α**	Statistically Different
(24 / 12)	Δmaximum	Δfailure	4.096230	4.1300154	**F<Fα**	0.0508943	**P>α**	Statistically NOT Different
(24 / 5)	Δmaximum	Δsurvivor (60480 min)	0.1514854	4.2100083	**F<Fα**	0.7001728	**P>>α**	Statistically NOT Different

	Static	DOL	Laminated Veneer Lumber: 340°F					
(24 / 17)	Δmaximum	Δinitial (1)	13.079754	4.0912767	**F>Fα**	0.0008452	**P<α**	Statistically Different
(24 / 13)	Δmaximum	Δfailure (1)	0.2553491	4.1213468	**F<Fα**	0.616501	**P>>α**	Statistically NOT Different
(24 / 4)	Δmaximum	Δsurvivor (1) (60480 min)	0.9099394	4.225200	**F<Fα**	0.3489157	**P>>α**	Statistically NOT Different
(24 /17)	Δmaximum	Δinitial (2)	13.68857	4.0912767	**F>Fα**	0.0006642	**P<α**	Statistically Different
(24 / 12)	Δmaximum	Δfailure (2)	1.8224691	4.1300154	**F<Fα**	0.1859391	**P>α**	Statistically NOT Different
(24 / 5)	Δmaximum	Δsurvivor (2) (60480 min)	0.7454062	4.2100083	**F<Fα**	0.3955394	**P>>α**	Statistically NOT Different

	Static	DOL	Laminated Veneer Lumber: 380°F					
(19 / 15)	Δmaximum	Δinitial (1)	9.7724423	4.1490864	**F>Fα**	0.0037547	**P<α**	Statistically Different
(19 / 9)	Δmaximum	Δfailure (1)	0.0026137	4.22520	**F<Fα**	0.9596169	**P>>α**	Statistically NOT Different
(19 / 6)	Δmaximum	Δsurvivor (60480 min)	0.0032377	4.2793431	**F<Fα**	0.9551156	**P>>α**	Statistically NOT Different

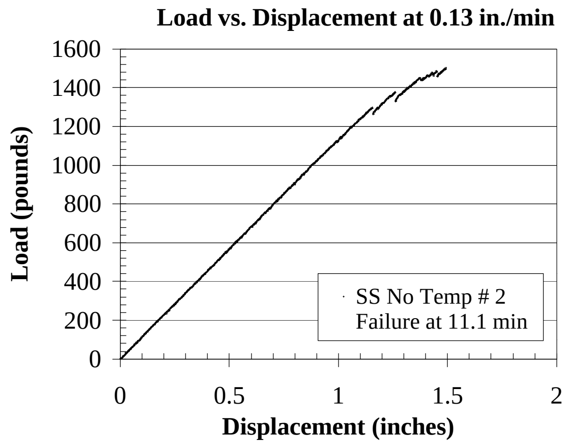
APPENDIX F

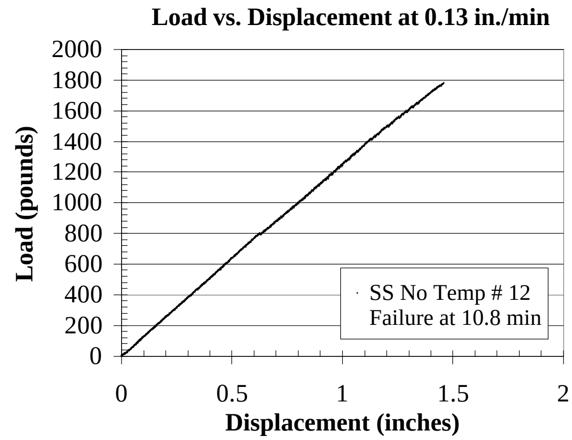
LOAD VS. DISPLACEMENT PLOTS

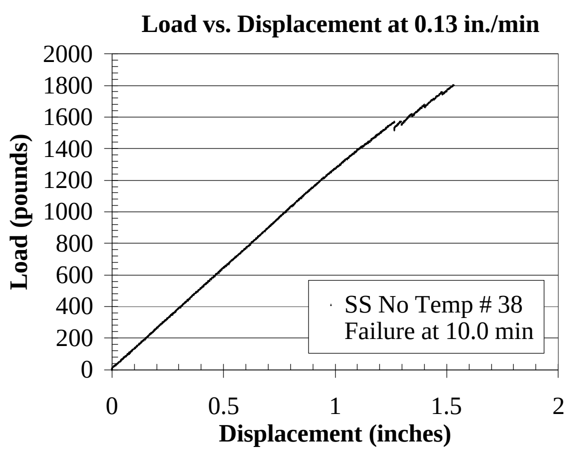
INTRODUCTION

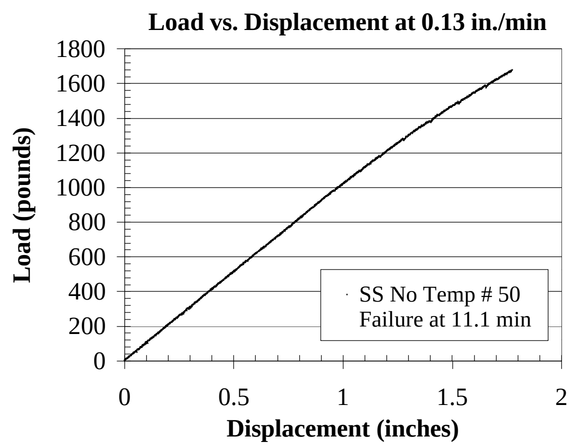
Static testing of all material provided load-displacement plots. These plots were used to determine the static modulus of elasticity of the members. They were also examined for comparison between temperature to temperature static behavior. On several of the plots, a low load jump is observed. This was not a result of material behavior, rather, it was caused by slip of the hardware.

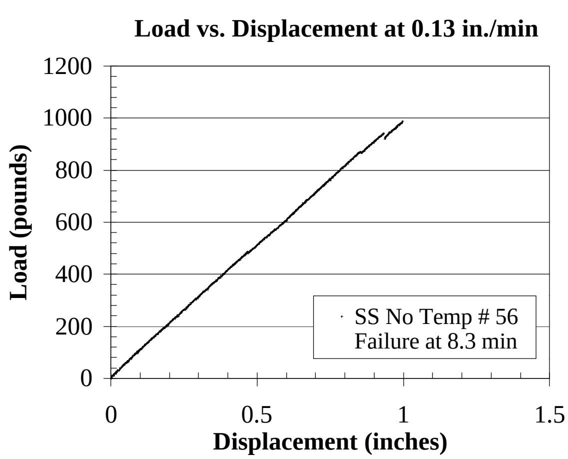
SOLID SAWN LUMBER: NO TEMPERATURE

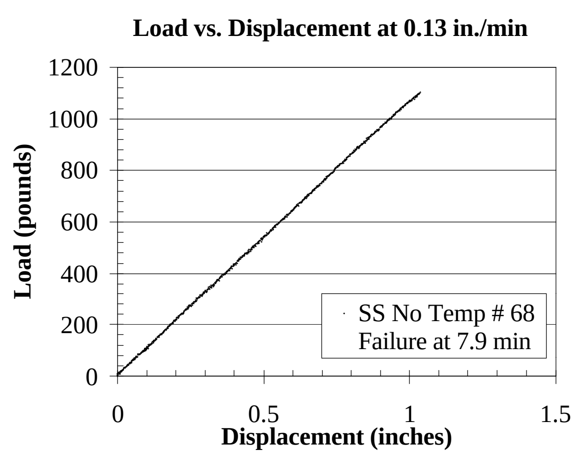


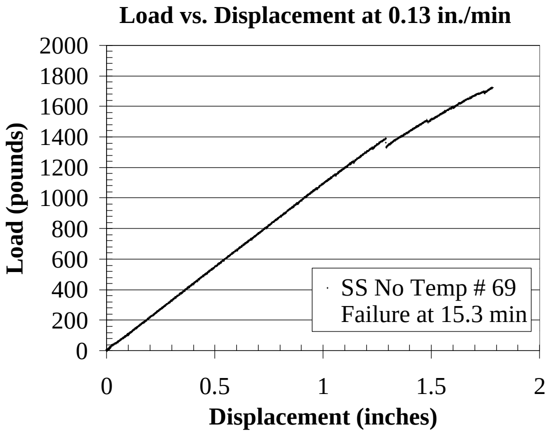




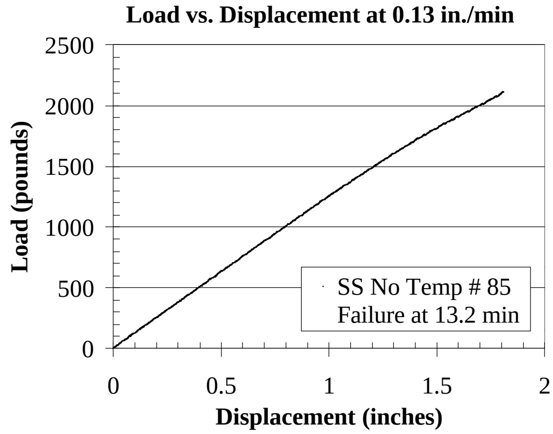




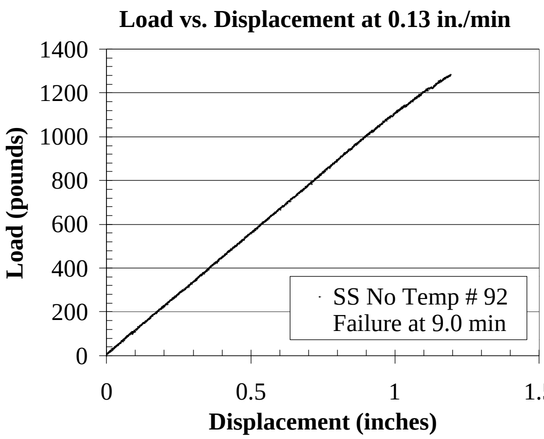




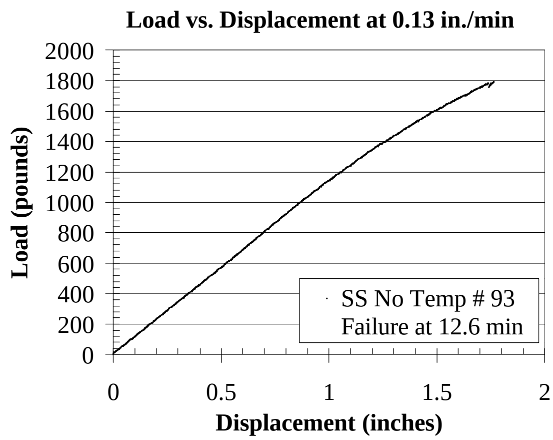
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 69
Failure at 15.3 min



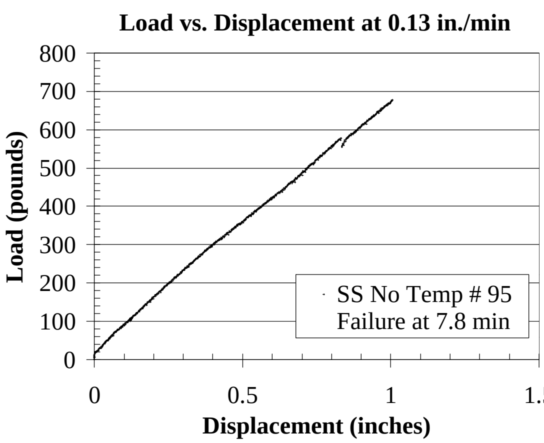
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 85
Failure at 13.2 min



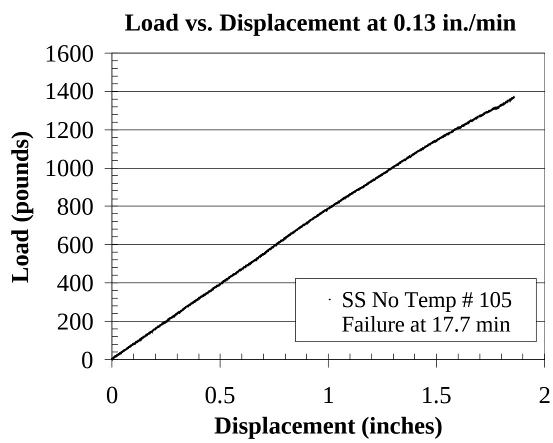
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 92
Failure at 9.0 min



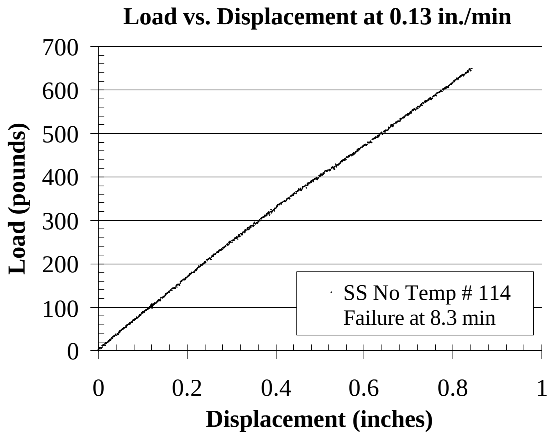
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 93
Failure at 12.6 min



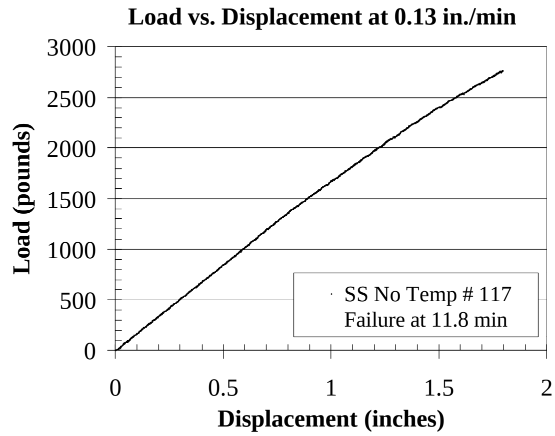
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 95
Failure at 7.8 min



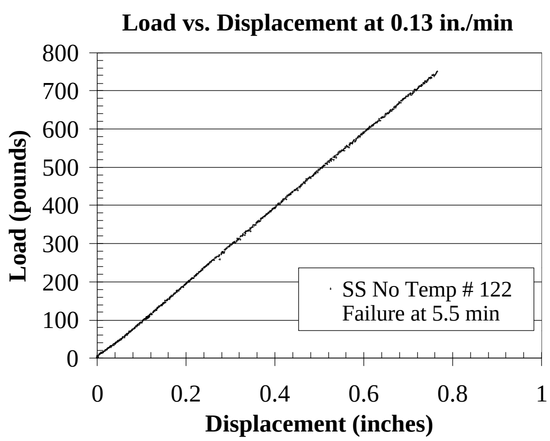
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 105
Failure at 17.7 min



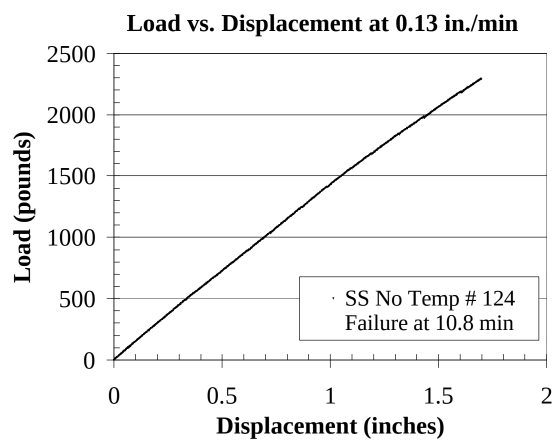
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 114
Failure at 8.3 min



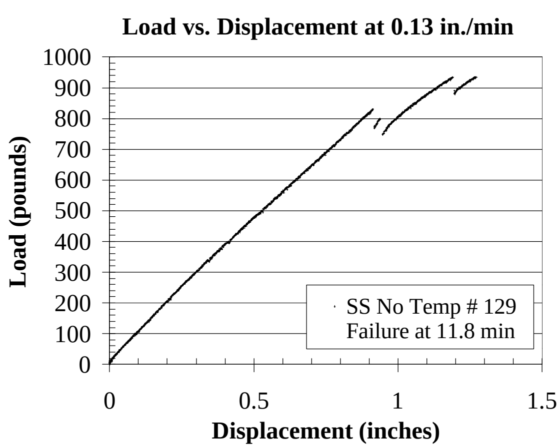
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 117
Failure at 11.8 min



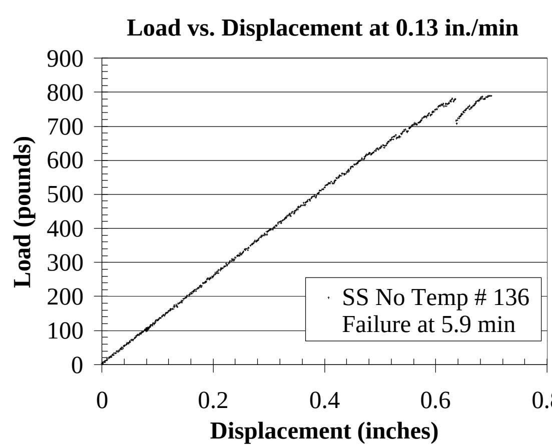
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 122
Failure at 5.5 min



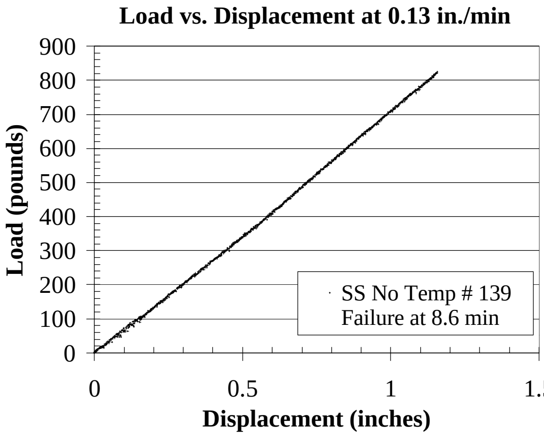
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 124
Failure at 10.8 min



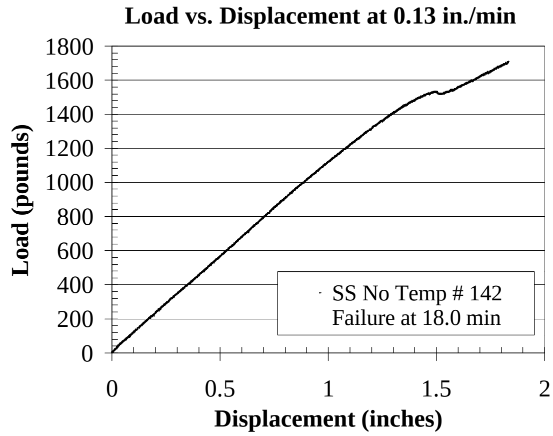
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 129
Failure at 11.8 min



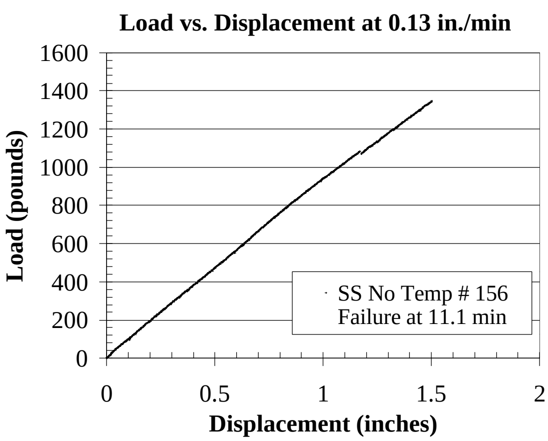
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 136
Failure at 5.9 min



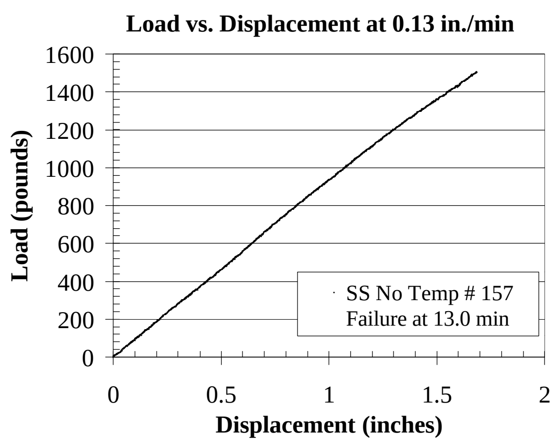
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 139
Failure at 8.6 min



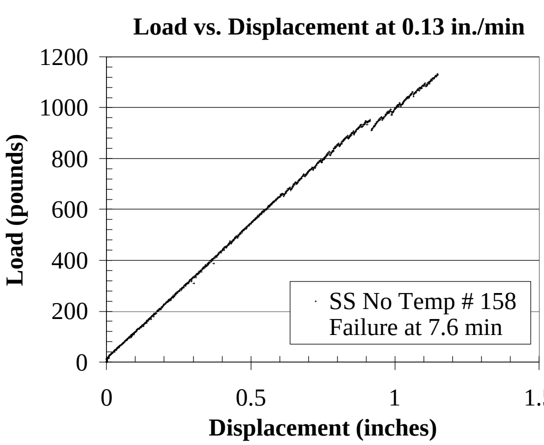
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 142
Failure at 18.0 min



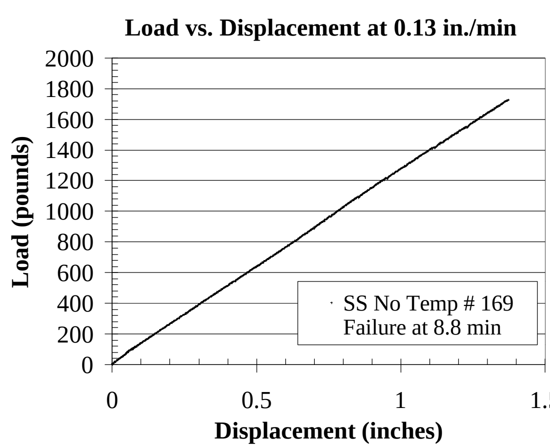
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 156
Failure at 11.1 min



Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 157
Failure at 13.0 min

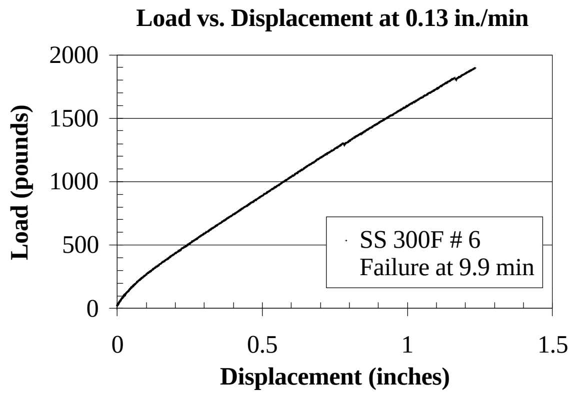


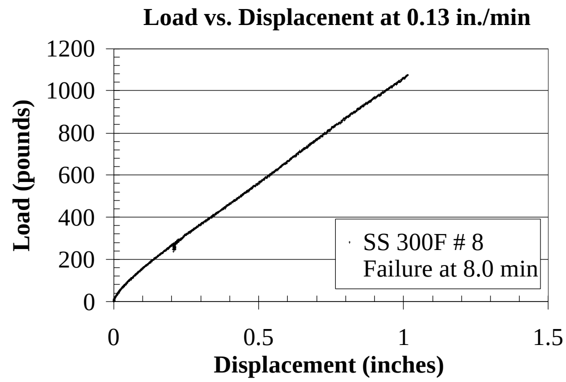
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 158
Failure at 7.6 min

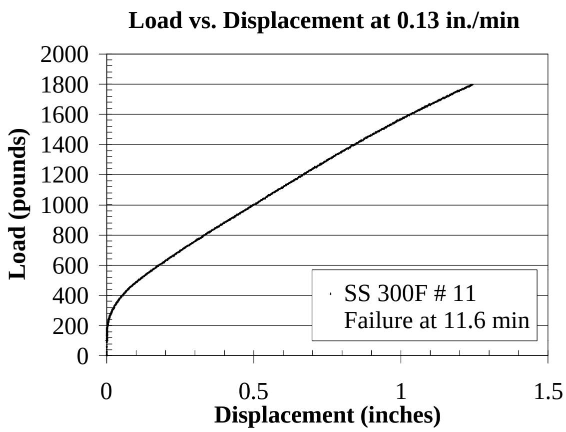


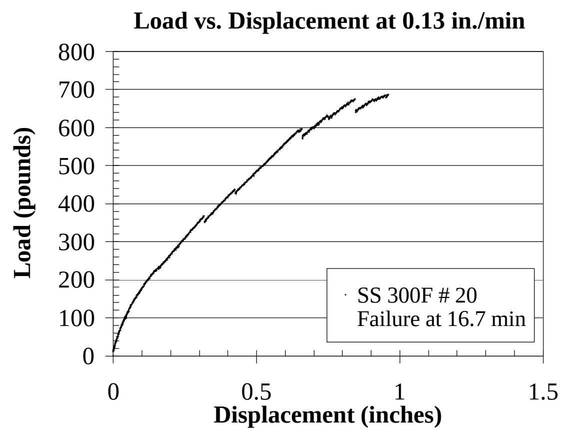
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS No Temp # 169
Failure at 8.8 min

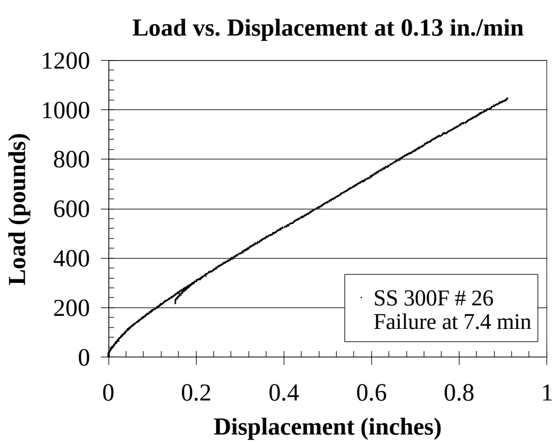
SOLID SAWN LUMBER: 300^{O}F

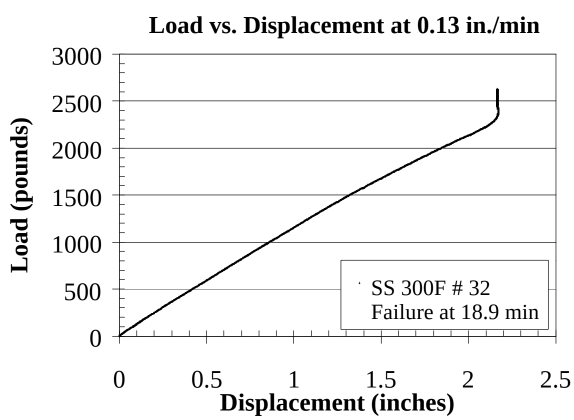


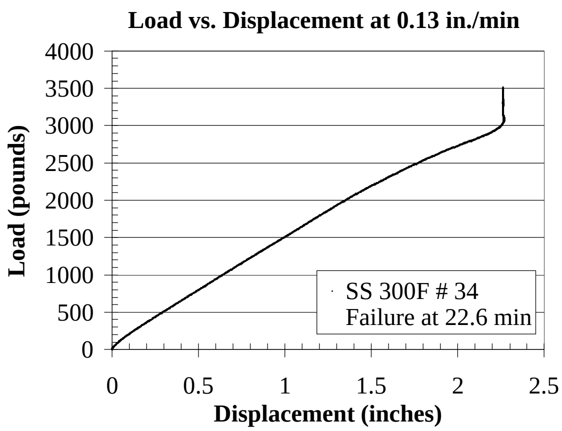


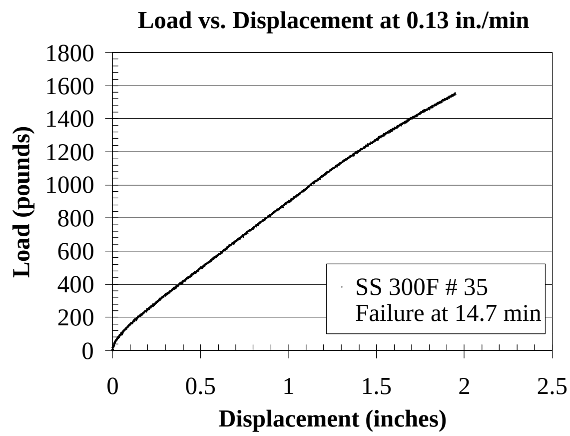


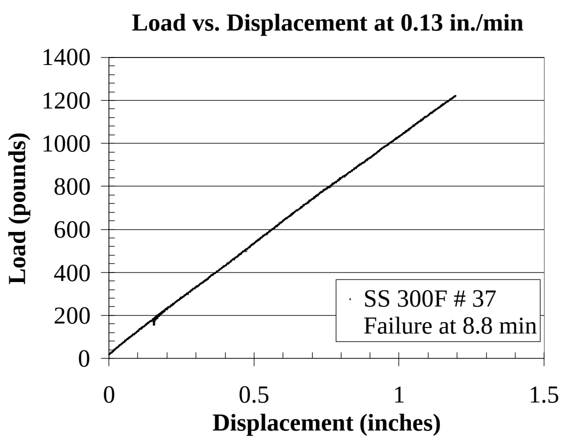


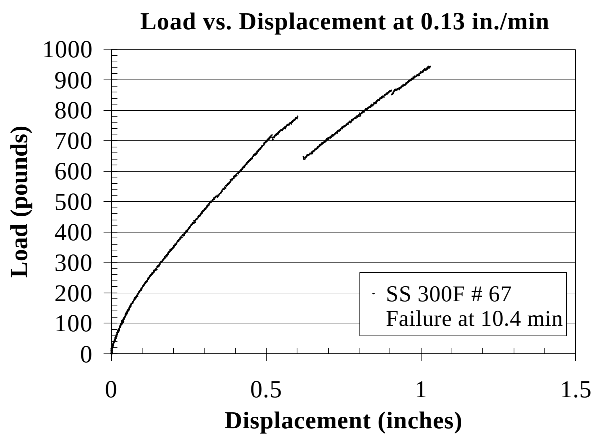


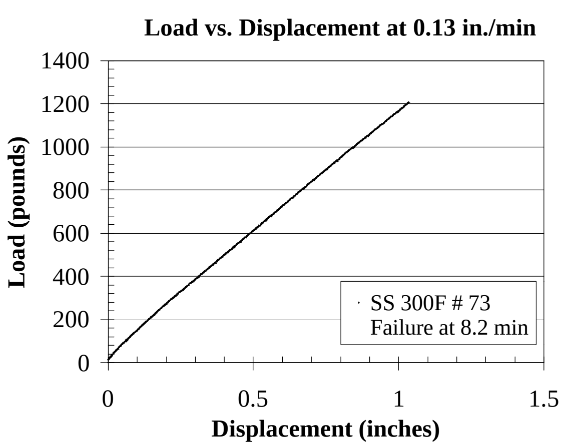


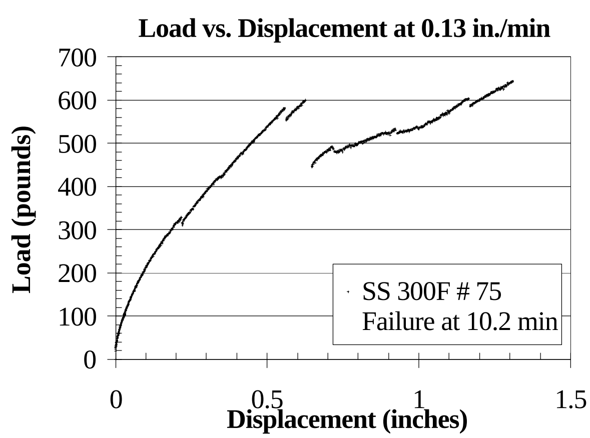

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 34
Failure at 22.6 min

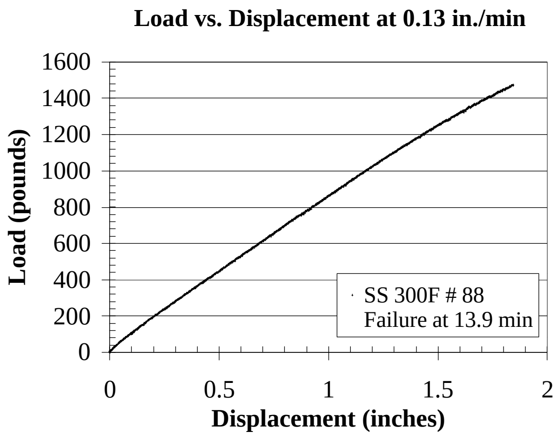

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 35
Failure at 14.7 min

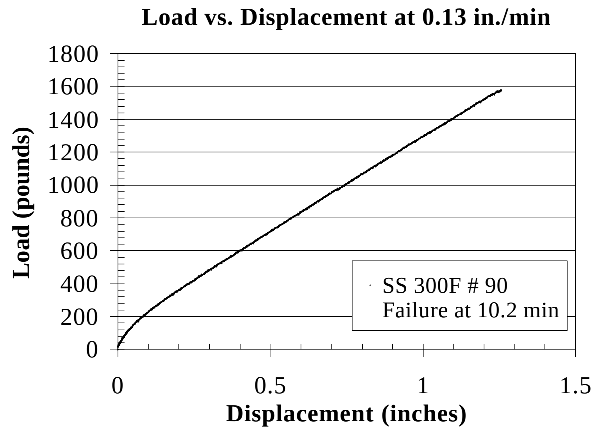

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 37
Failure at 8.8 min

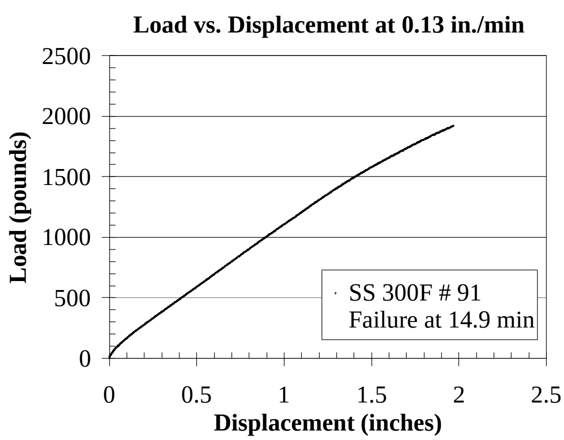

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 67
Failure at 10.4 min

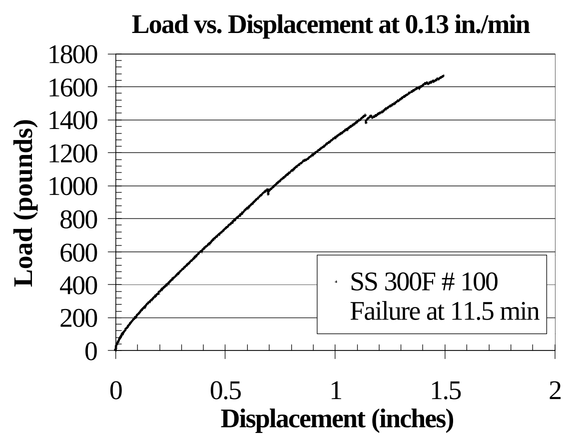

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 73
Failure at 8.2 min

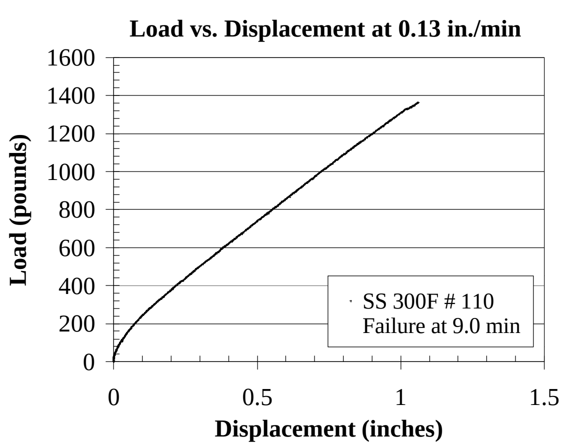

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 75
Failure at 10.2 min

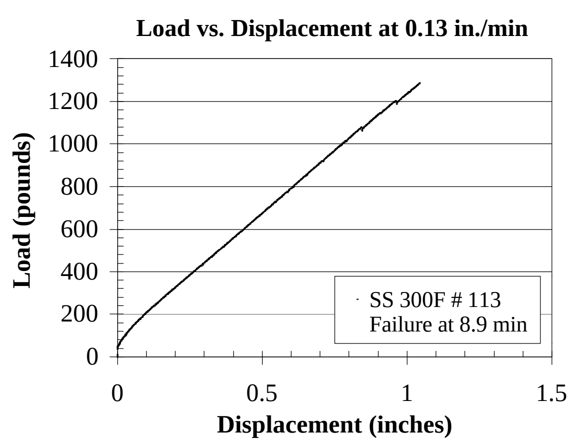

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 88
Failure at 13.9 min

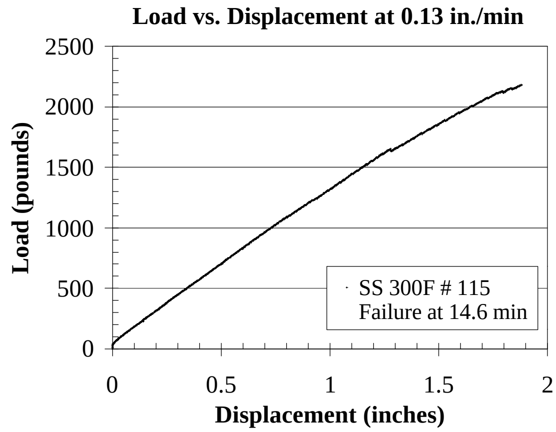

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 90
Failure at 10.2 min

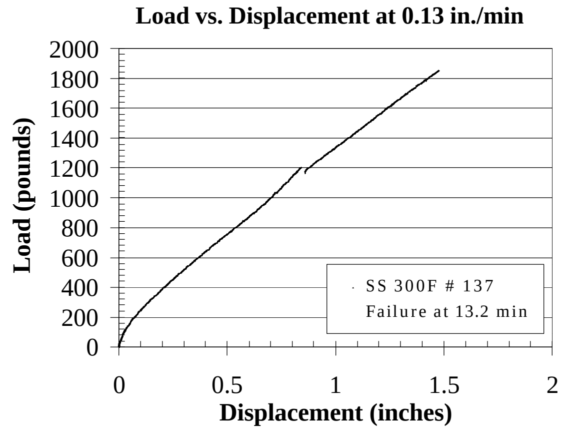

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 91
Failure at 14.9 min

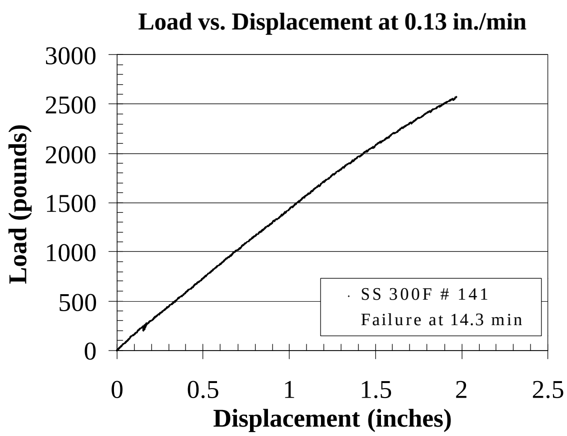

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 100
Failure at 11.5 min

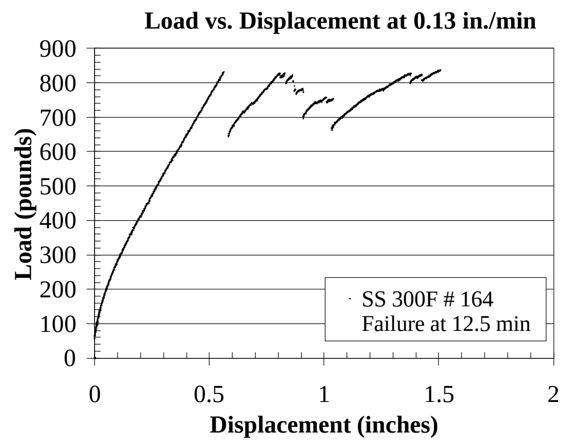

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 110
Failure at 9.0 min

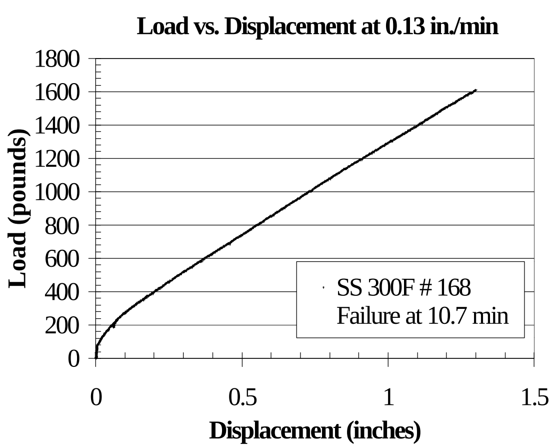

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 113
Failure at 8.9 min

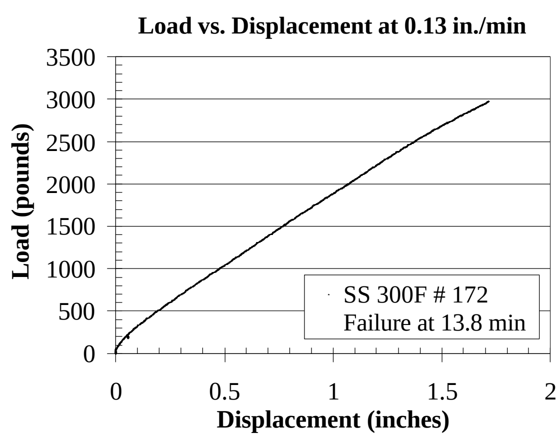

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 115
Failure at 14.6 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 137
Failure at 13.2 min

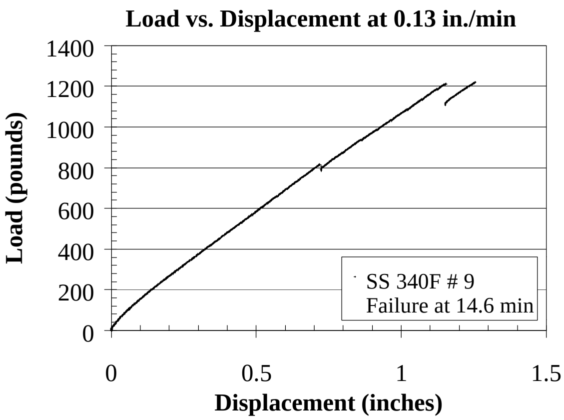

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 141
Failure at 14.3 min

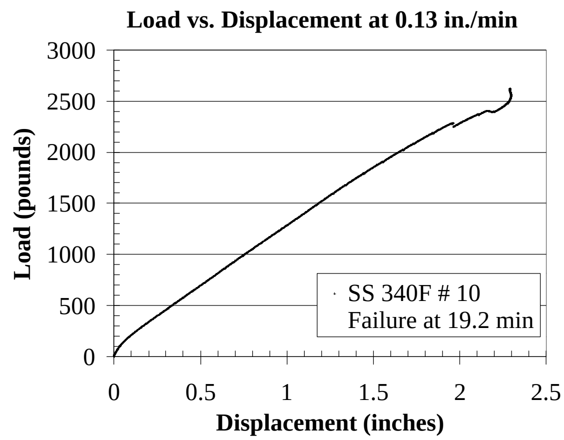

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 164
Failure at 12.5 min

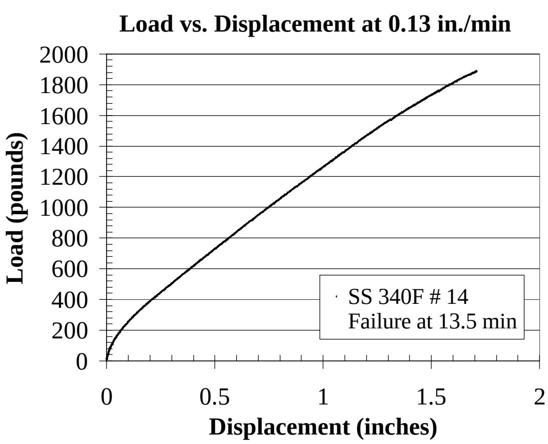

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 168
Failure at 10.7 min

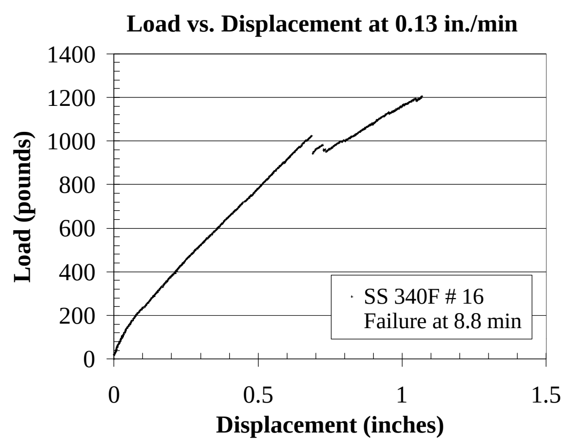

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 300F # 172
Failure at 13.8 min

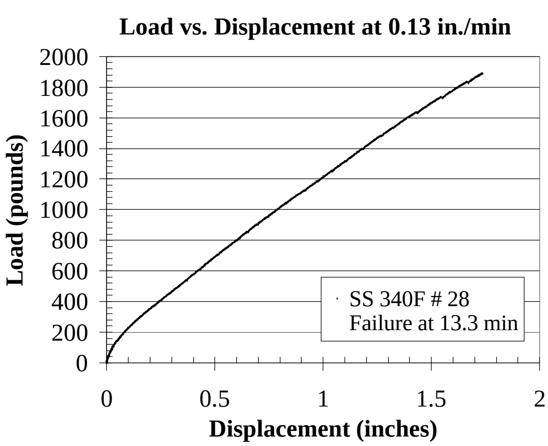
SOLID SAWN LUMBER: 340°F

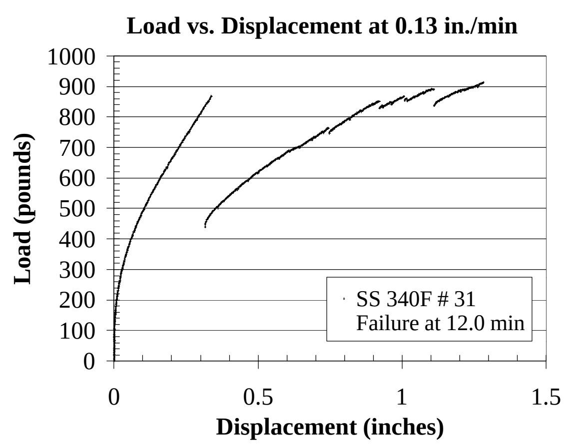


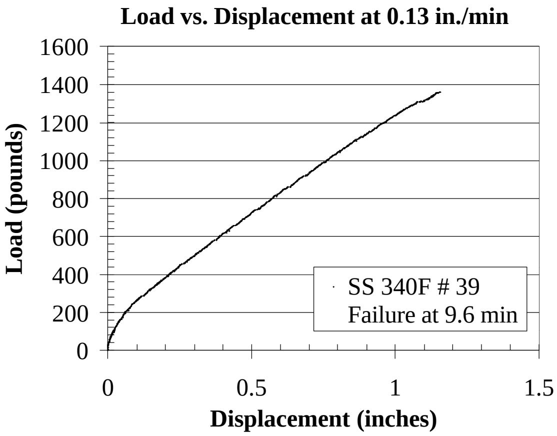


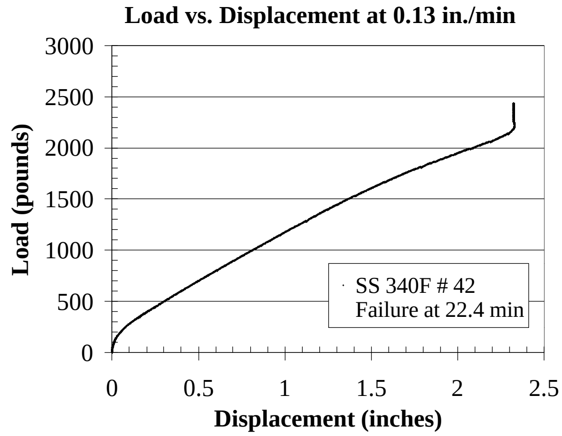


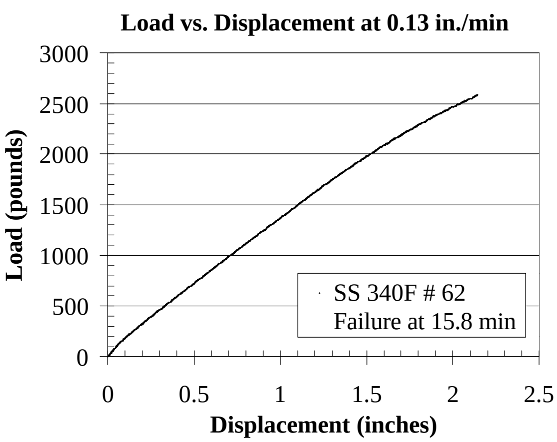


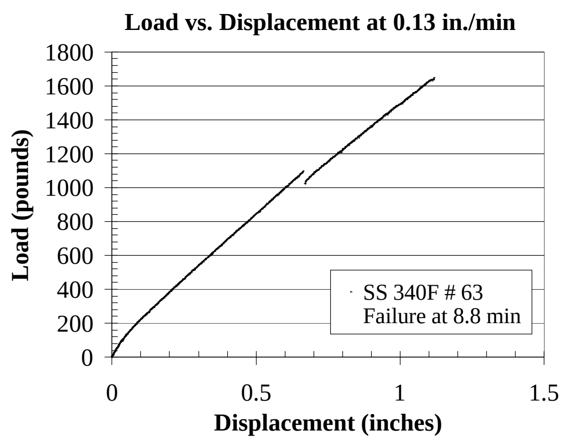


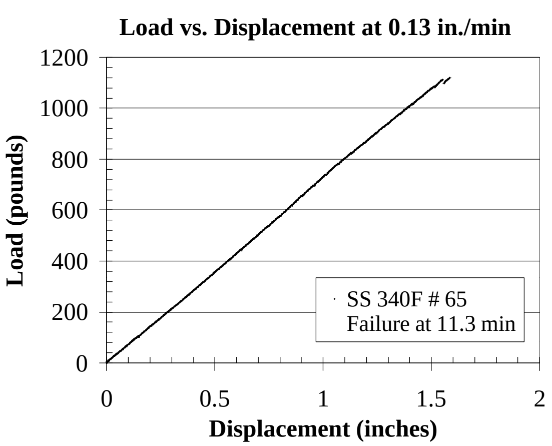


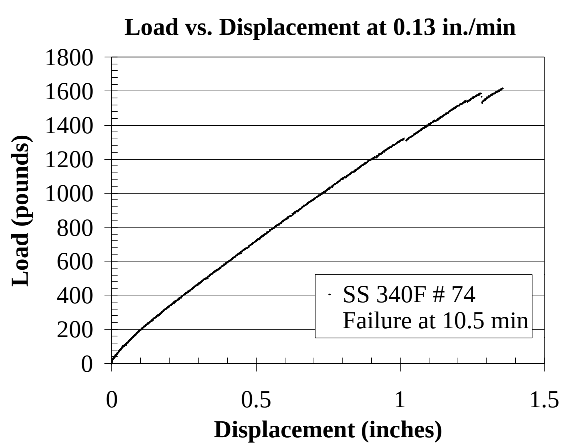

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 39
Failure at 9.6 min

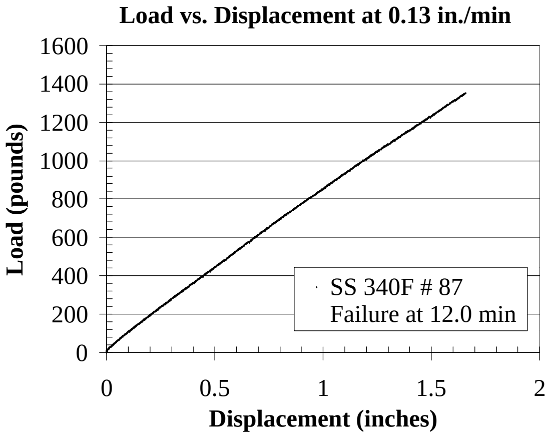

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 42
Failure at 22.4 min

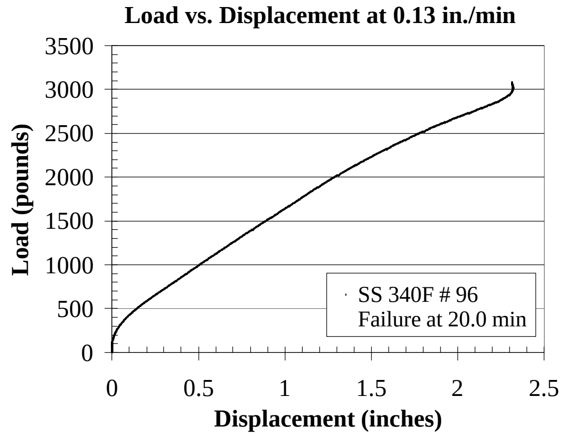

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 62
Failure at 15.8 min

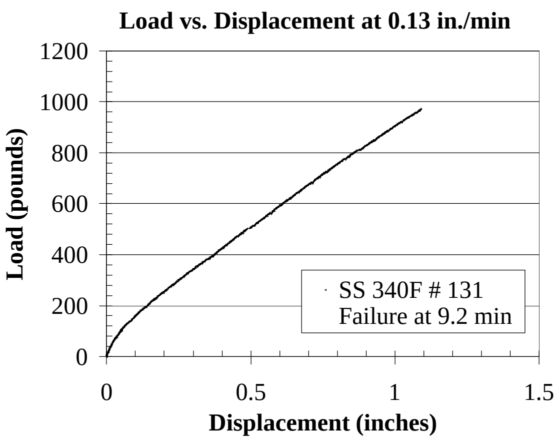

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 63
Failure at 8.8 min

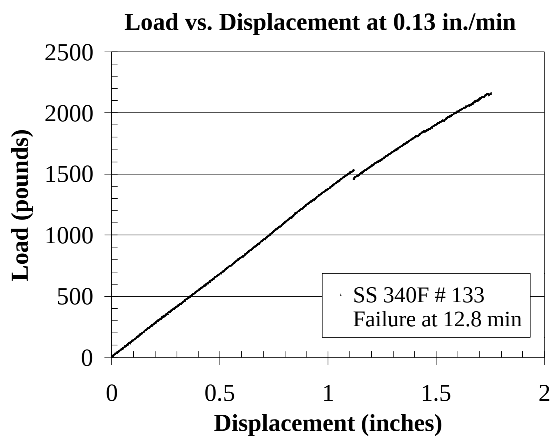

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 65
Failure at 11.3 min

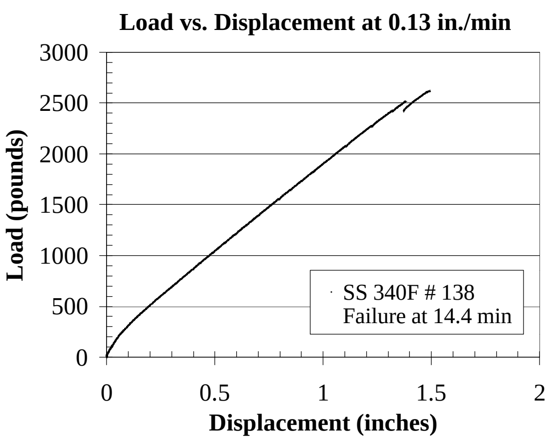

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 74
Failure at 10.5 min

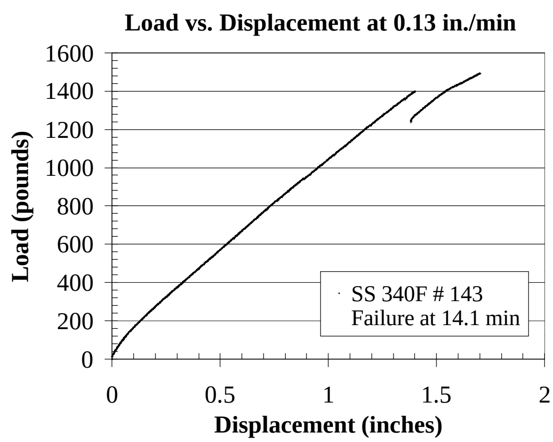

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 87
Failure at 12.0 min
0
200
400
600
800
1000
1200
1400
1600
0
0.5
1
1.5
2

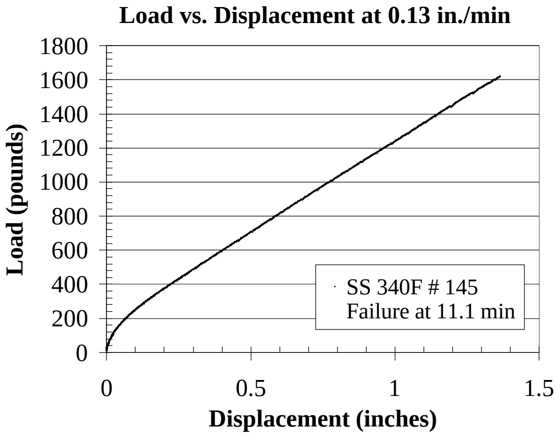

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 96
Failure at 20.0 min
0
500
1000
1500
2000
2500
3000
3500
0
0.5
1
1.5
2
2.5

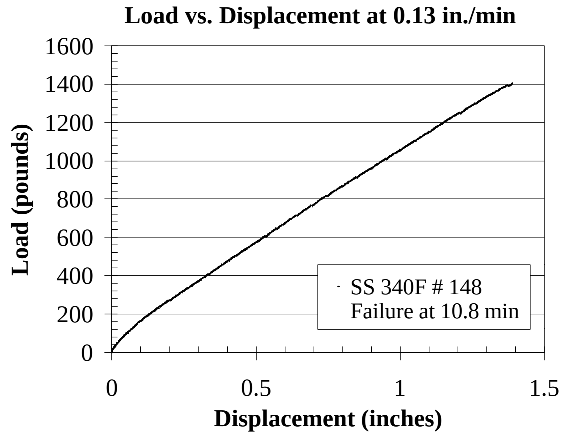

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 131
Failure at 9.2 min
0
200
400
600
800
1000
1200
0
0.5
1
1.5

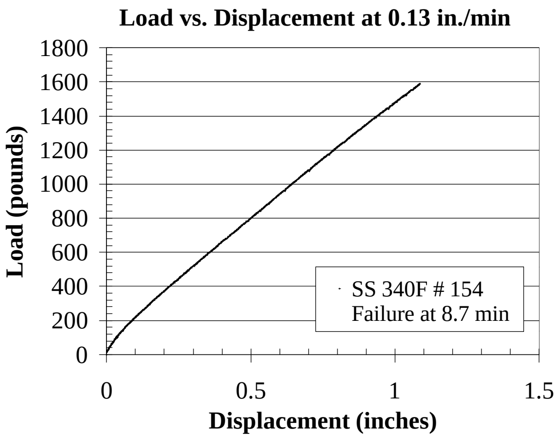

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 133
Failure at 12.8 min
0
500
1000
1500
2000
2500
0
0.5
1
1.5
2

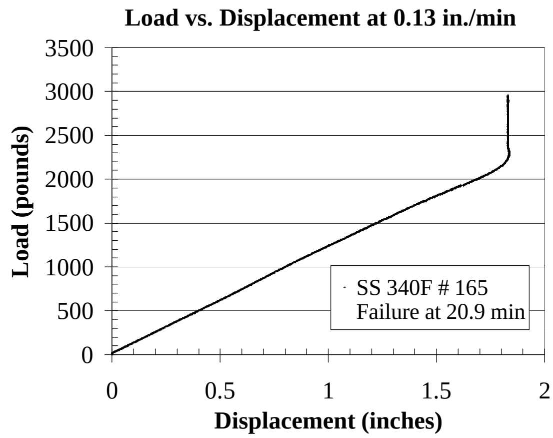

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 138
Failure at 14.4 min
0
500
1000
1500
2000
2500
3000
0
0.5
1
1.5
2

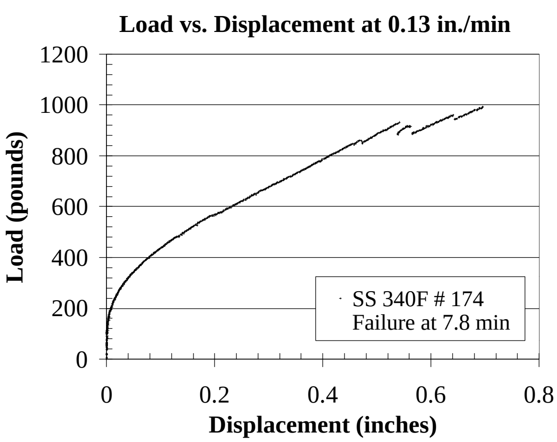

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 143
Failure at 14.1 min
0
200
400
600
800
1000
1200
1400
1600
0
0.5
1
1.5
2

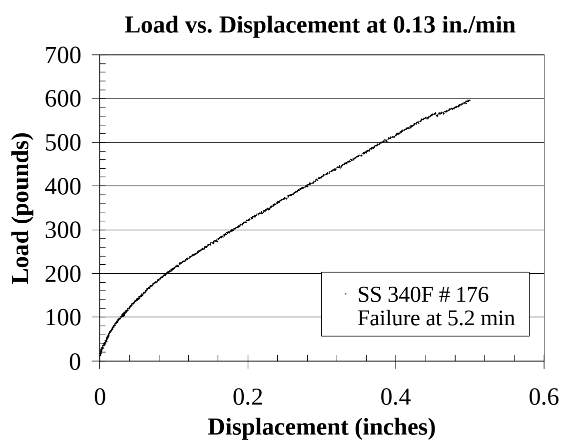

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 145
Failure at 11.1 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 148
Failure at 10.8 min

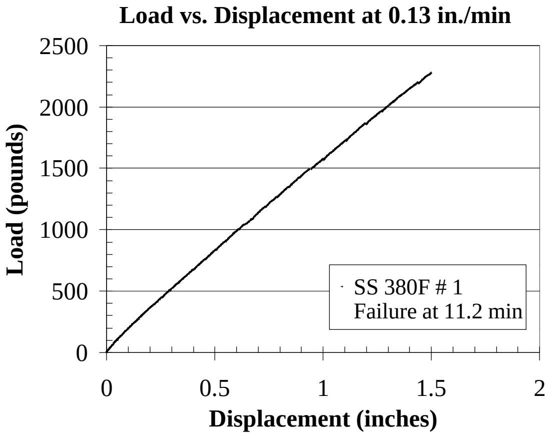

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 154
Failure at 8.7 min

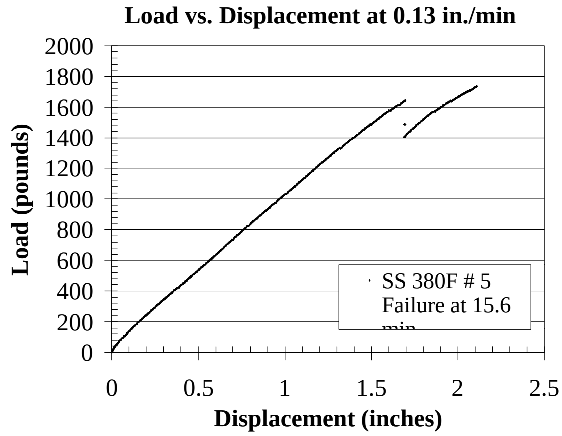

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 165
Failure at 20.9 min

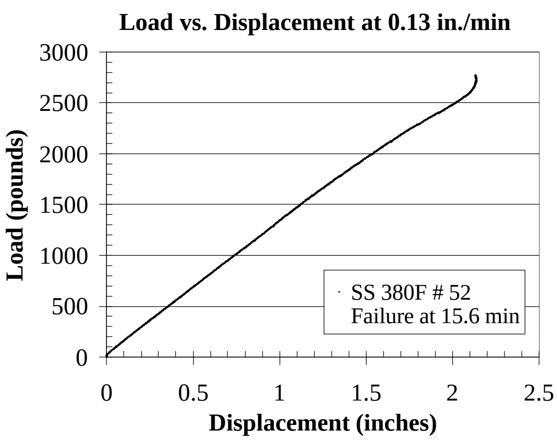

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 174
Failure at 7.8 min

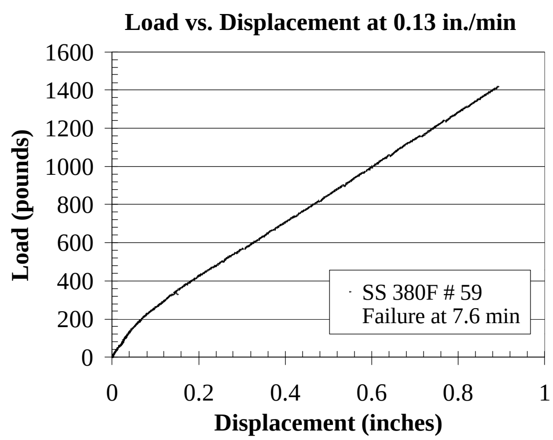

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 340F # 176
Failure at 5.2 min

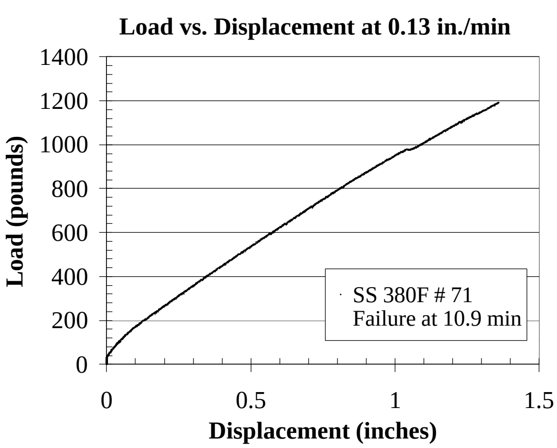
Solid Sawn Lumber: 380^{O}F

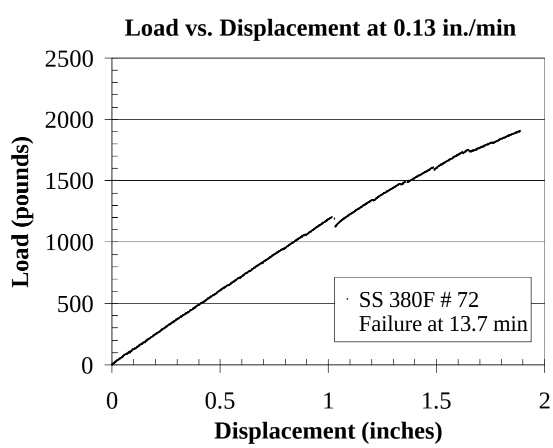


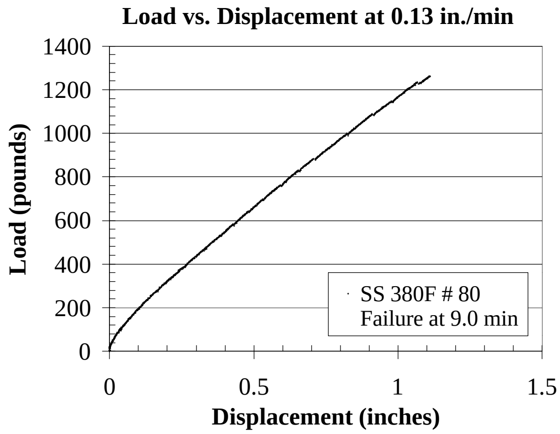


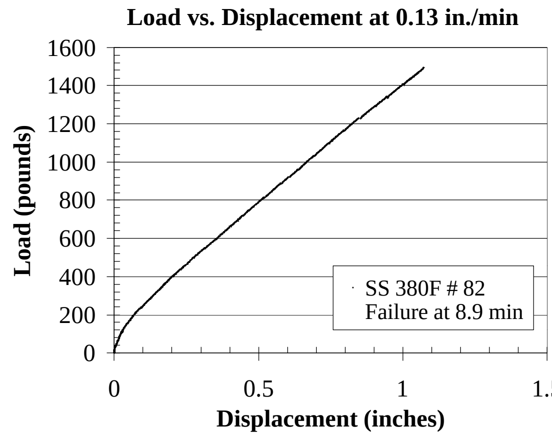


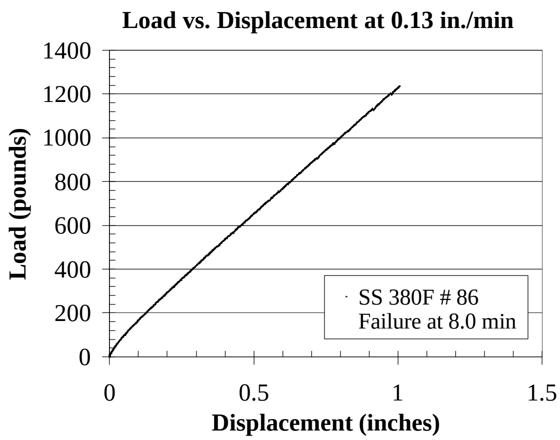


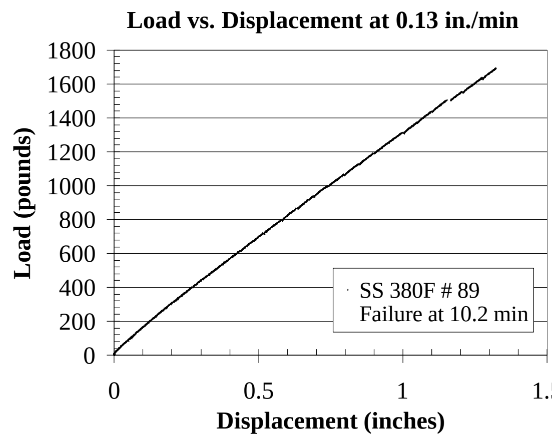


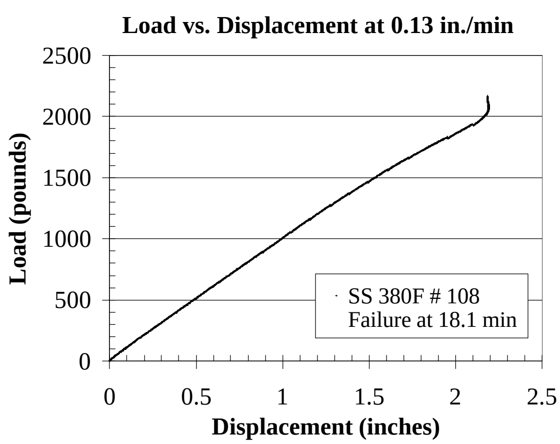


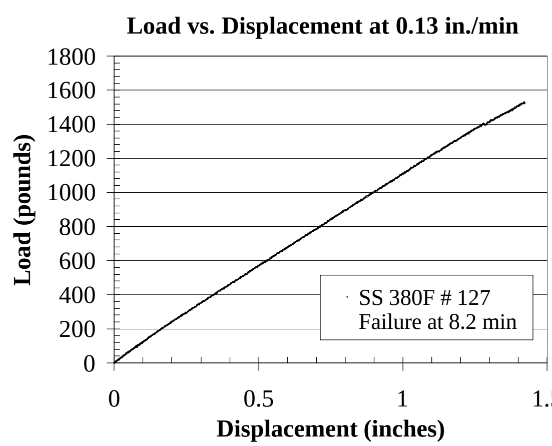

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 80
Failure at 9.0 min

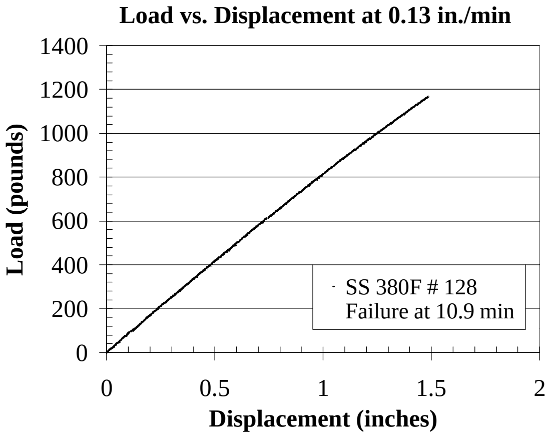

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 82
Failure at 8.9 min

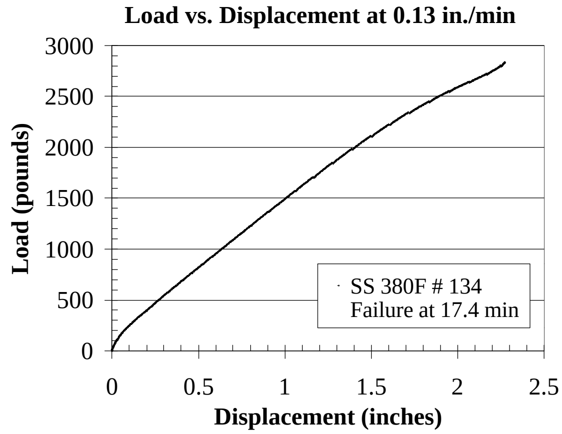

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 86
Failure at 8.0 min

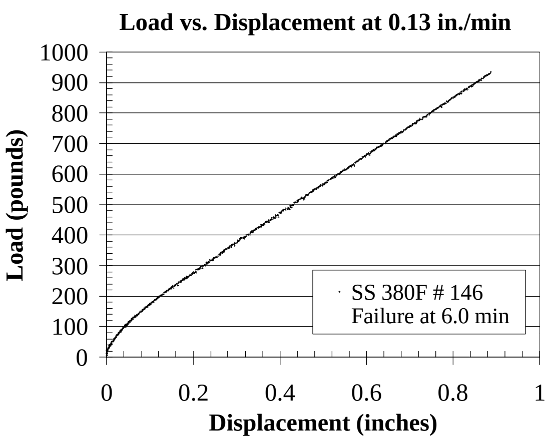

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 89
Failure at 10.2 min

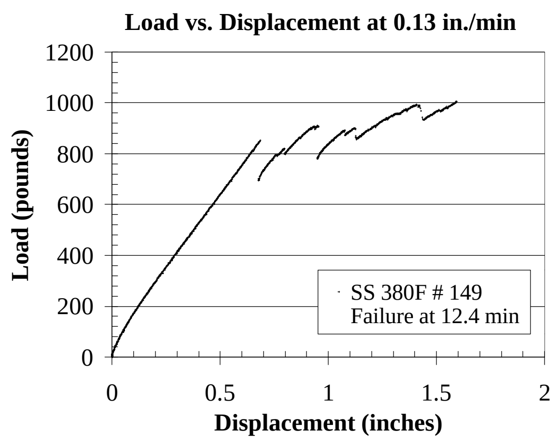

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 108
Failure at 18.1 min

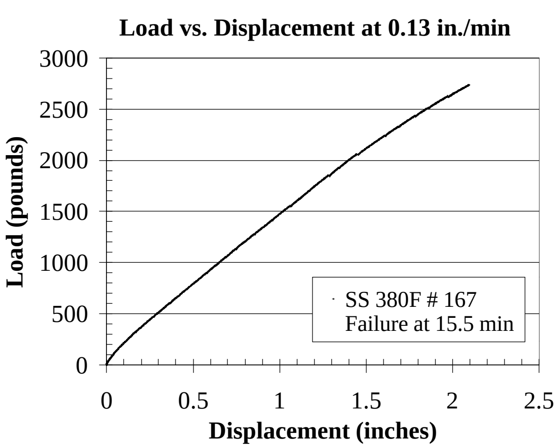

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 127
Failure at 8.2 min

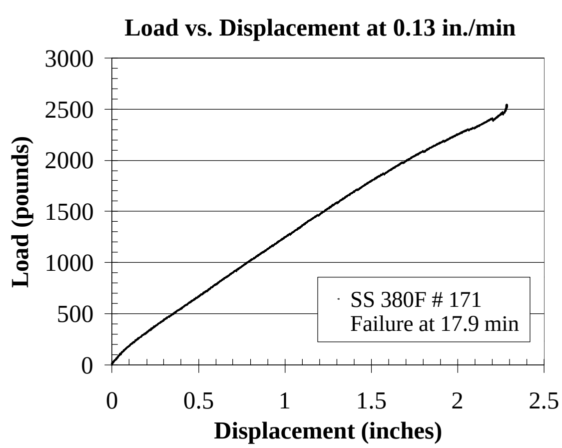

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 128
Failure at 10.9 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 134
Failure at 17.4 min

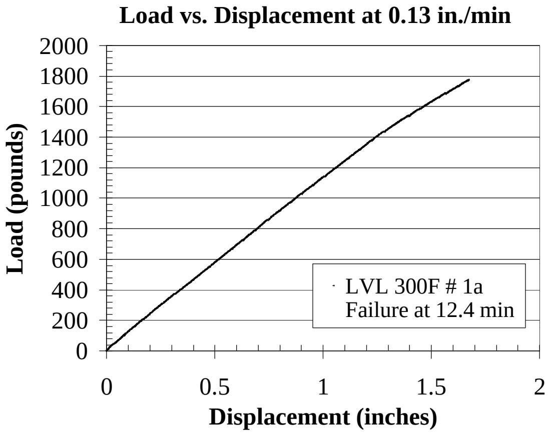

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 146
Failure at 6.0 min

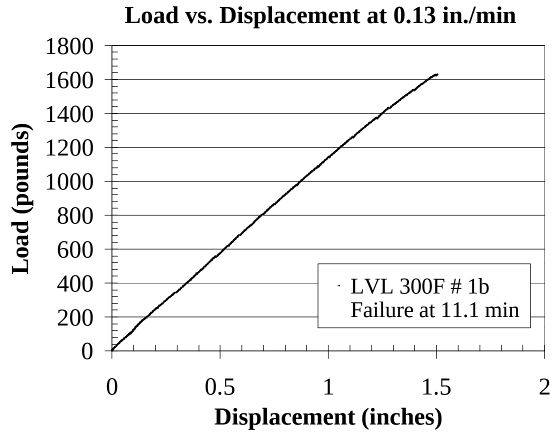

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 149
Failure at 12.4 min

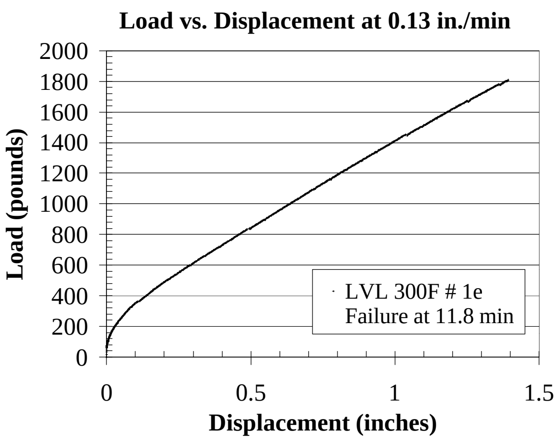

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 167
Failure at 15.5 min

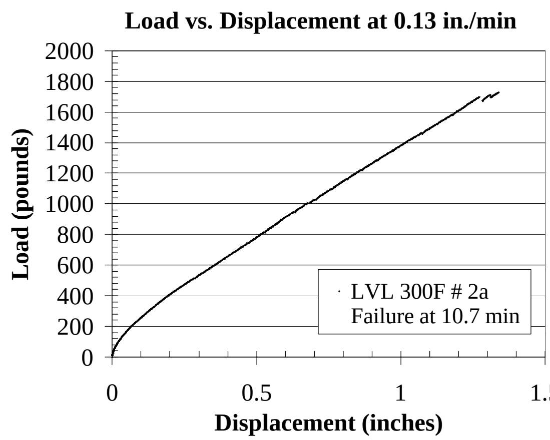

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
SS 380F # 171
Failure at 17.9 min

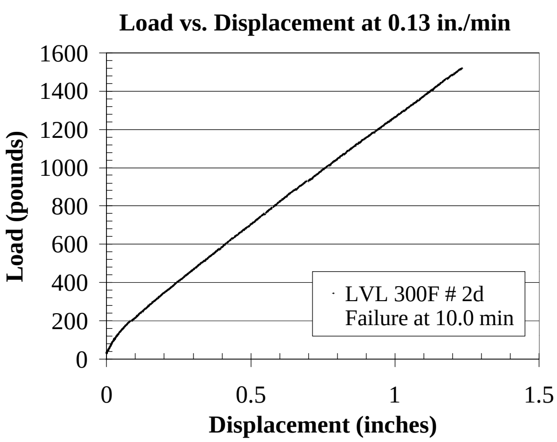
LAMINATED VENEER LUMBER: 300^{O}F

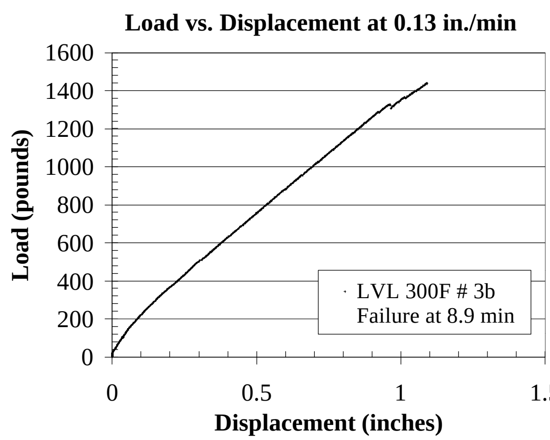


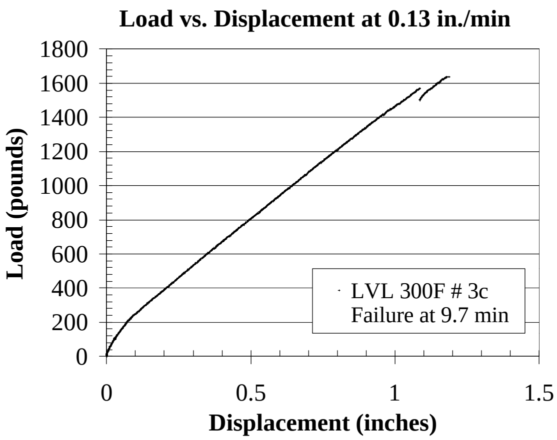


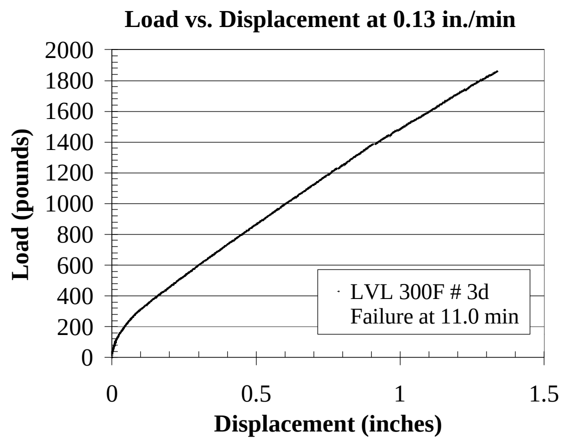


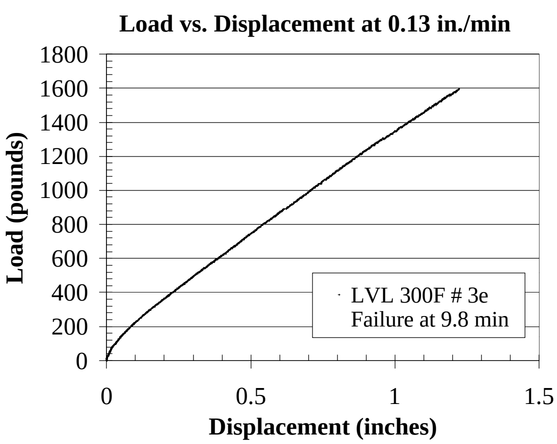


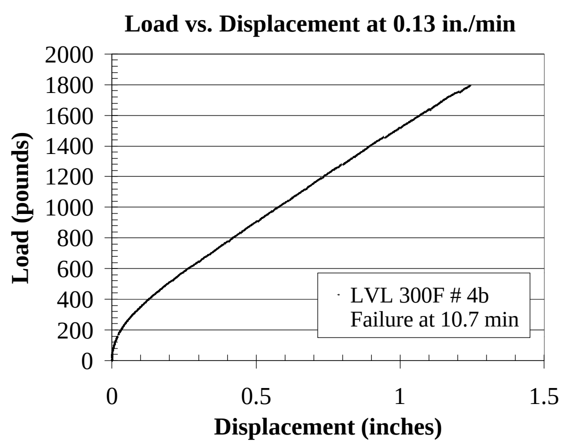


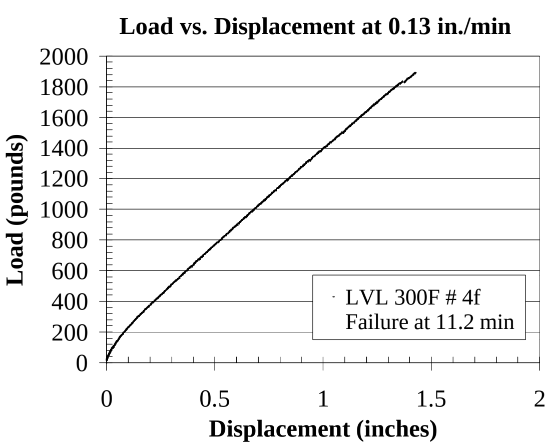


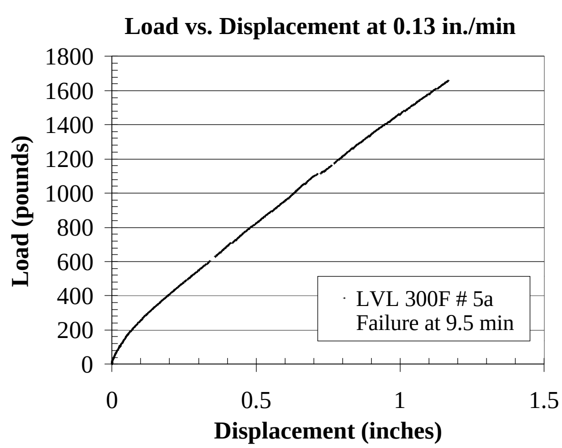

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 3c
Failure at 9.7 min

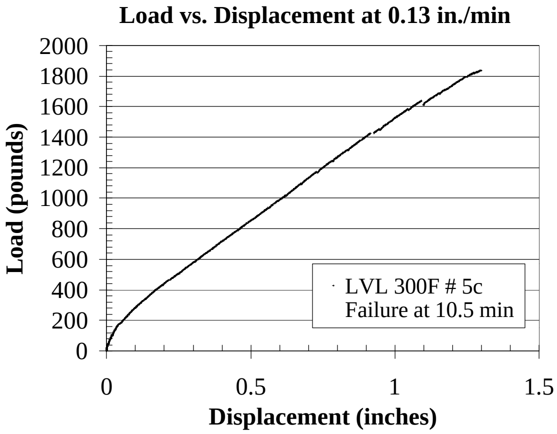

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 3d
Failure at 11.0 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 3e
Failure at 9.8 min

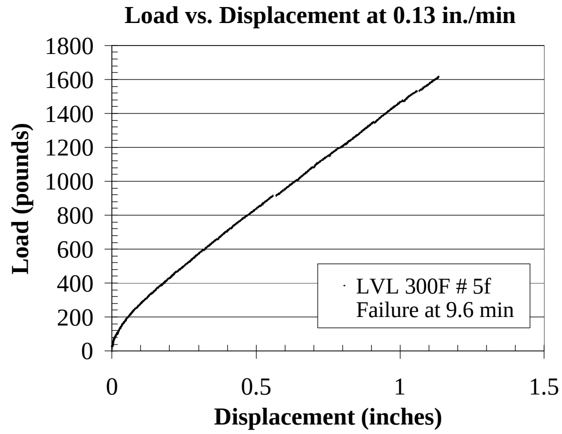

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 4b
Failure at 10.7 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 4f
Failure at 11.2 min

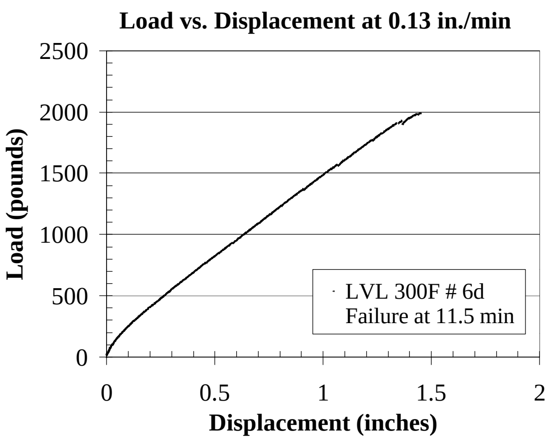

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 5a
Failure at 9.5 min



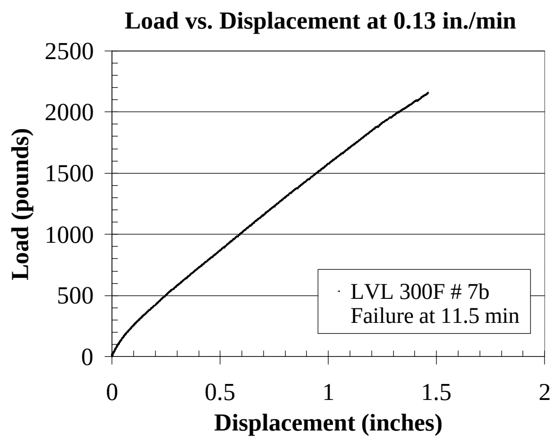
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 5c
Failure at 10.5 min



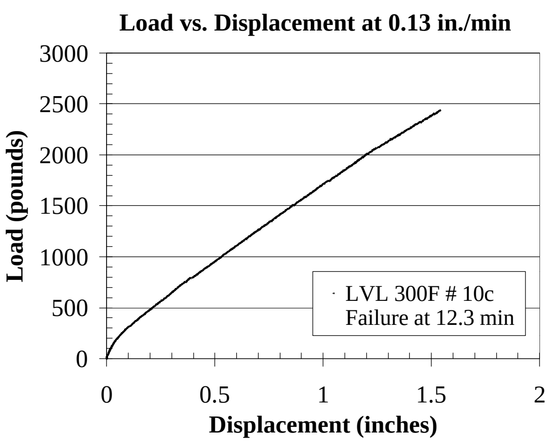
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 5f
Failure at 9.6 min



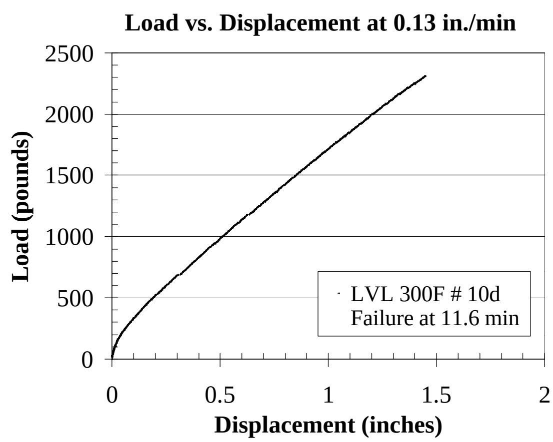
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 6d
Failure at 11.5 min



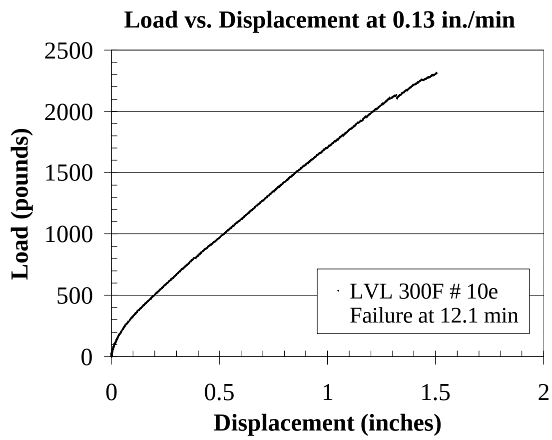
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 7b
Failure at 11.5 min

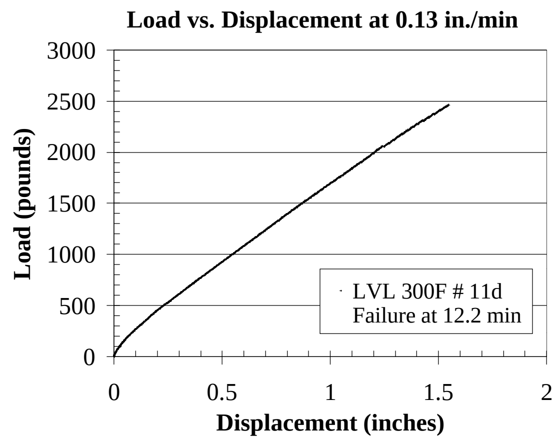


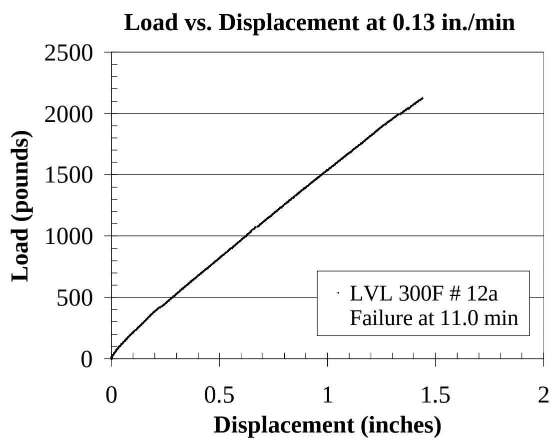
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 10c
Failure at 12.3 min

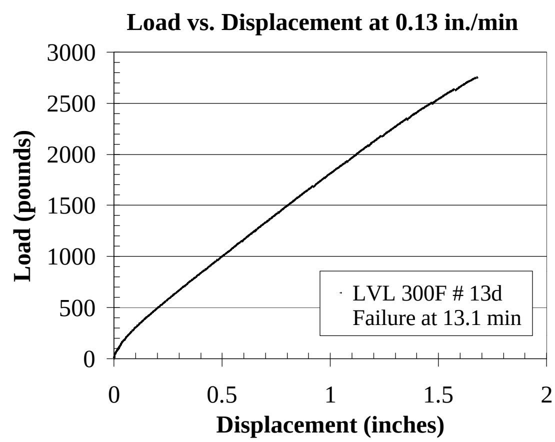


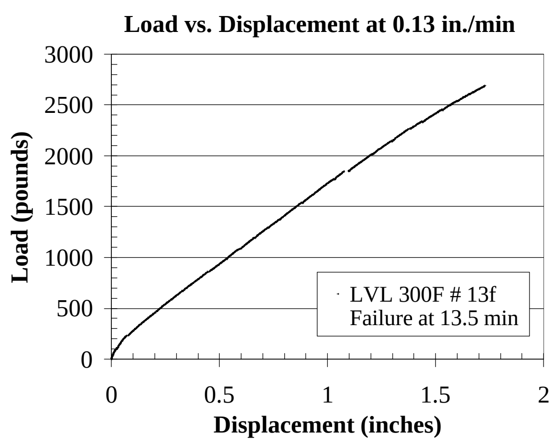
Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 10d
Failure at 11.6 min

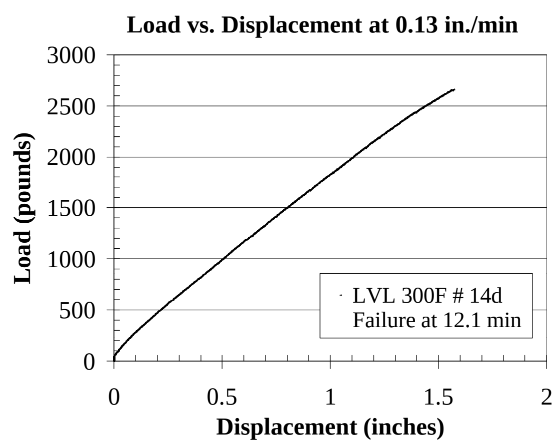

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 10e
Failure at 12.1 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 11d
Failure at 12.2 min

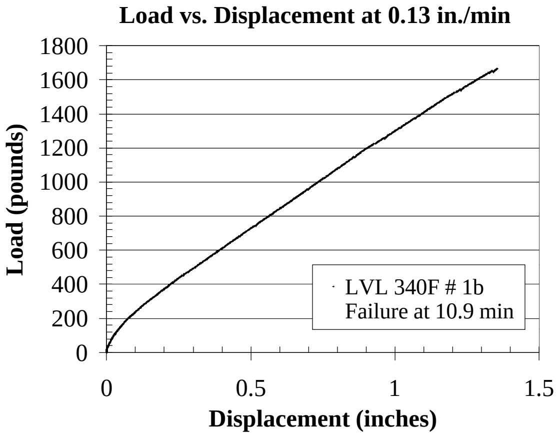

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 12a
Failure at 11.0 min

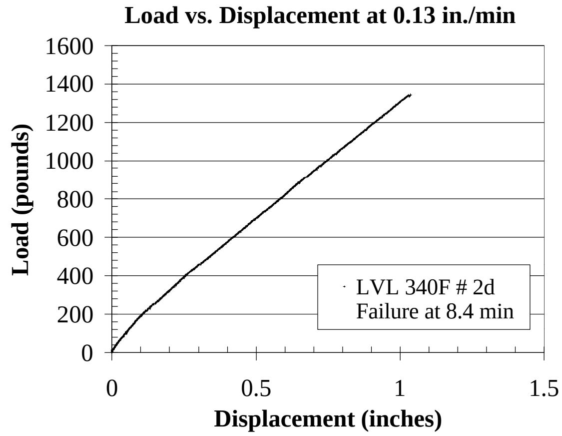

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 13d
Failure at 13.1 min

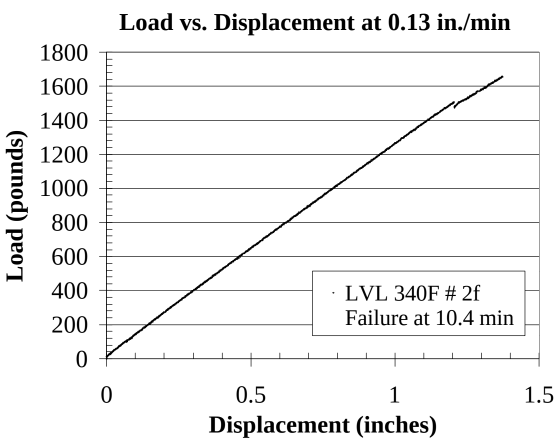

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 13f
Failure at 13.5 min

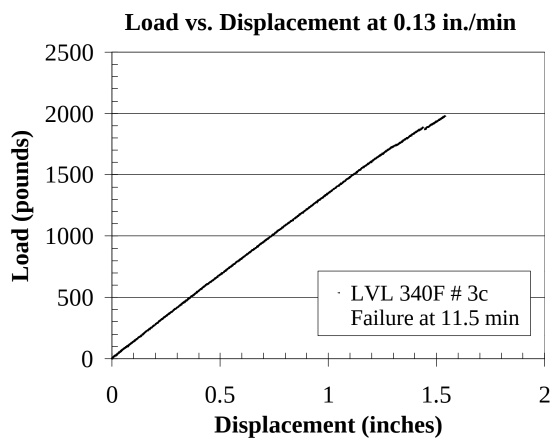

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 300F # 14d
Failure at 12.1 min

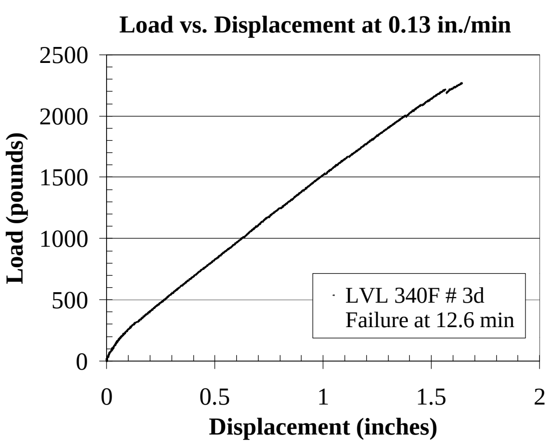
LAMINATED VENEER LUMBER: 340°F

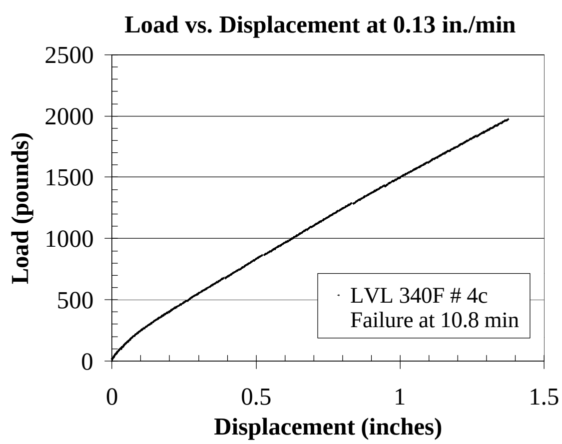


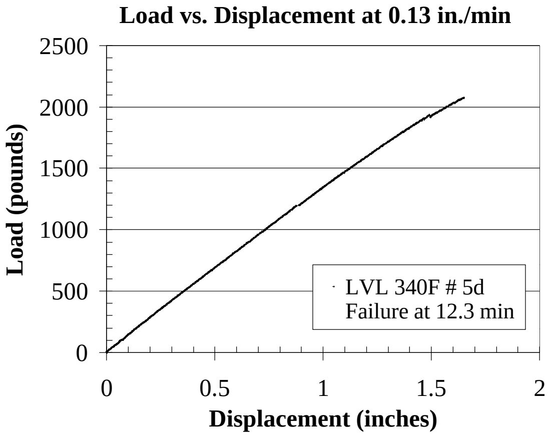


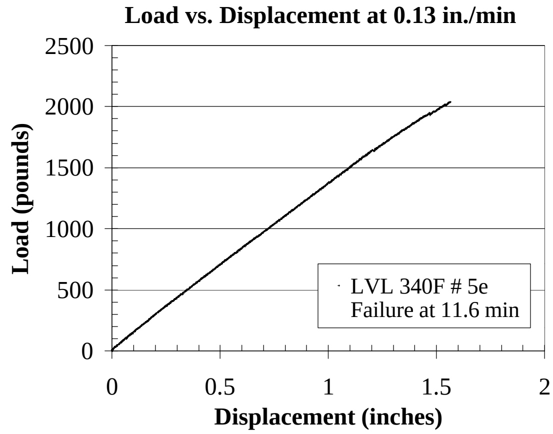


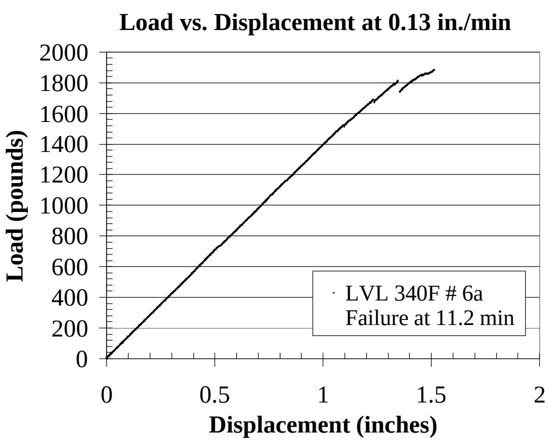


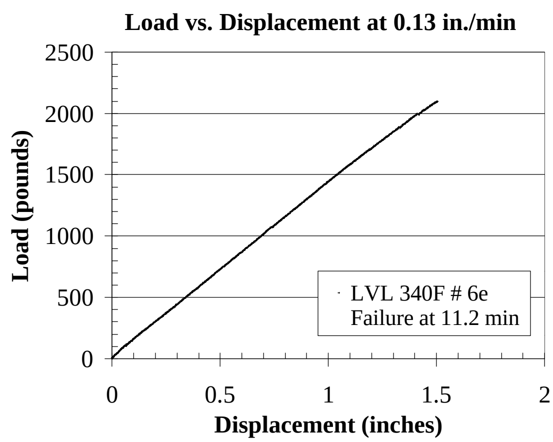


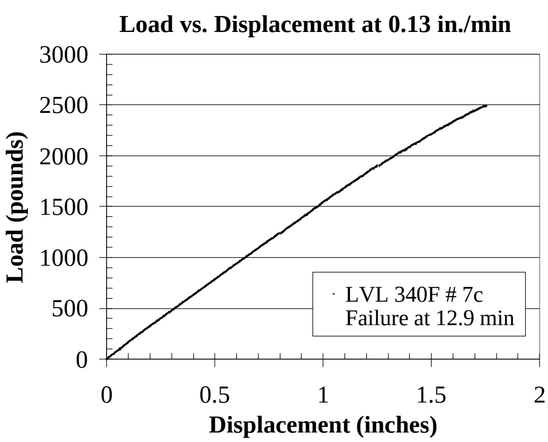


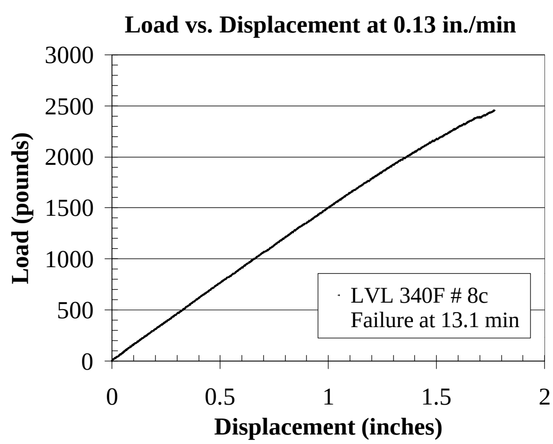

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 5d
Failure at 12.3 min

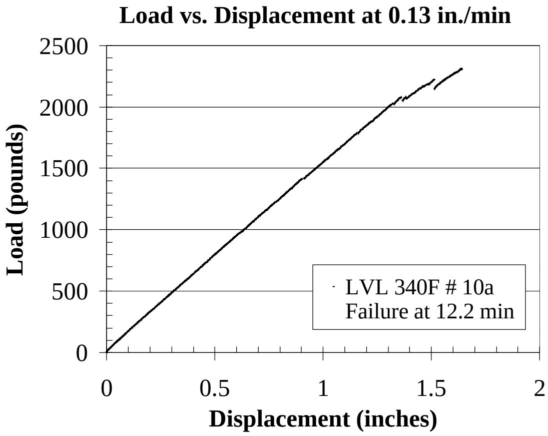

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 5e
Failure at 11.6 min

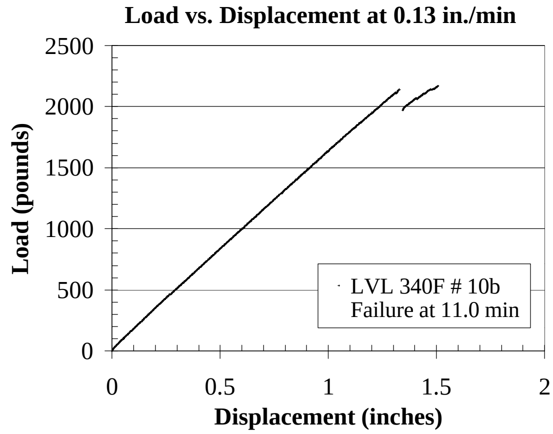

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 6a
Failure at 11.2 min

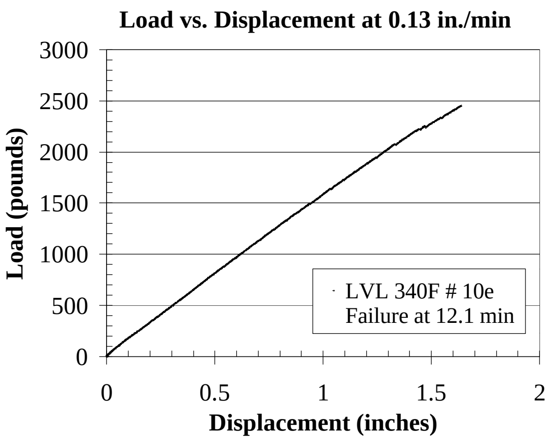

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 6e
Failure at 11.2 min

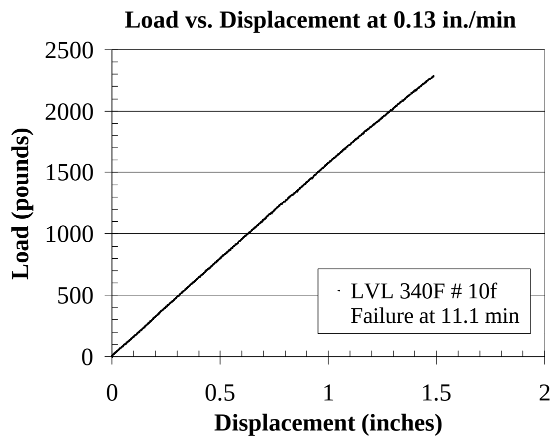

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 7c
Failure at 12.9 min

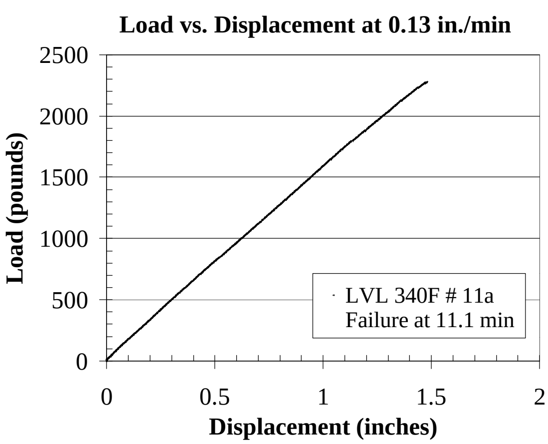

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 8c
Failure at 13.1 min

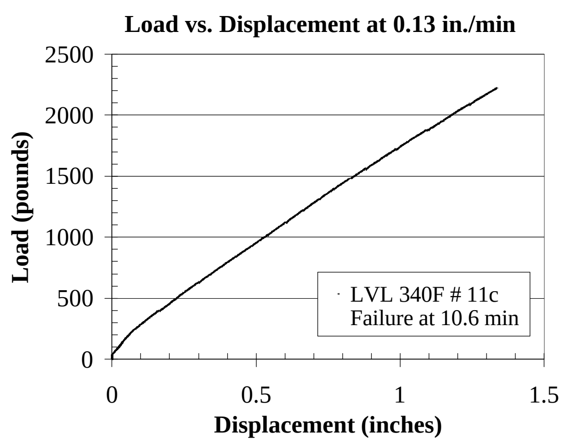

Load vs. Displacement at 0.13 in./min
Load (pounds)
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
Displacement (inches)
LVL 340F # 10a
Failure at 12.2 min

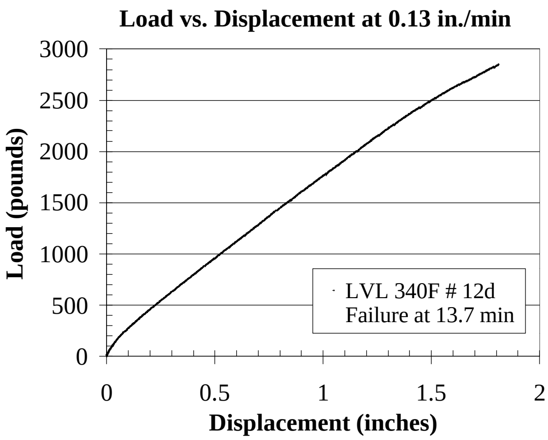

Load vs. Displacement at 0.13 in./min
Load (pounds)
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
Displacement (inches)
LVL 340F # 10b
Failure at 11.0 min

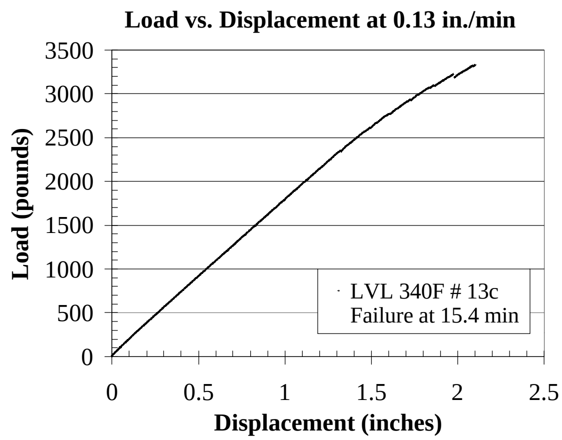

Load vs. Displacement at 0.13 in./min
Load (pounds)
3000
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
Displacement (inches)
LVL 340F # 10e
Failure at 12.1 min

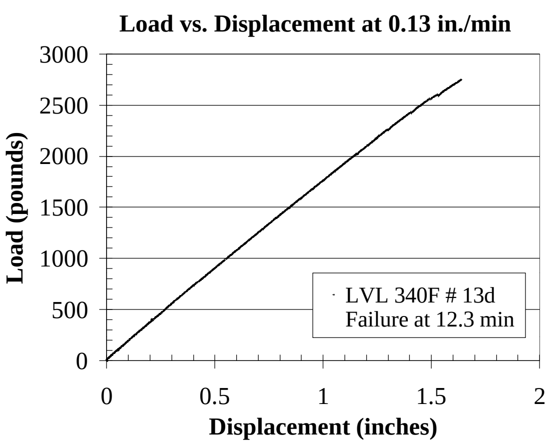

Load vs. Displacement at 0.13 in./min
Load (pounds)
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
Displacement (inches)
LVL 340F # 10f
Failure at 11.1 min

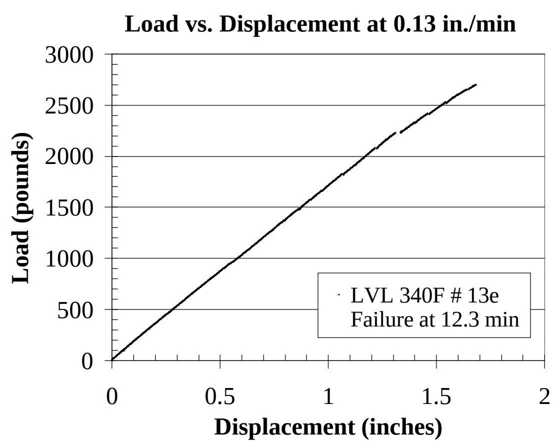

Load vs. Displacement at 0.13 in./min
Load (pounds)
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
Displacement (inches)
LVL 340F # 11a
Failure at 11.1 min

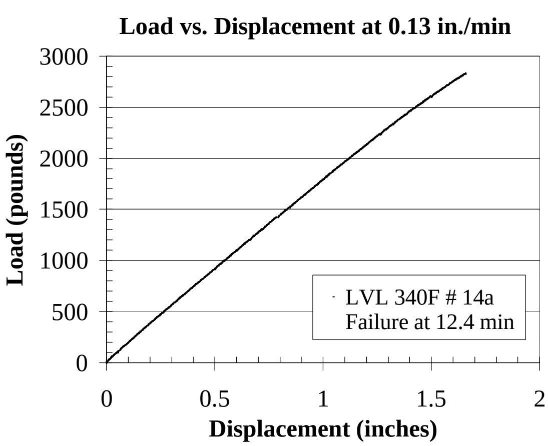

Load vs. Displacement at 0.13 in./min
Load (pounds)
2500
2000
1500
1000
500
0
0
0.5
1
1.5
Displacement (inches)
LVL 340F # 11c
Failure at 10.6 min

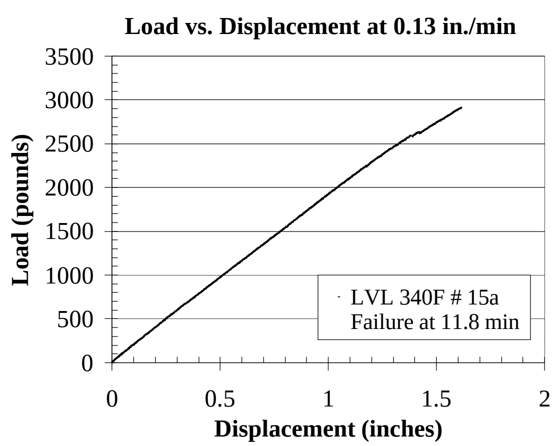

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 12d
Failure at 13.7 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 13c
Failure at 15.4 min

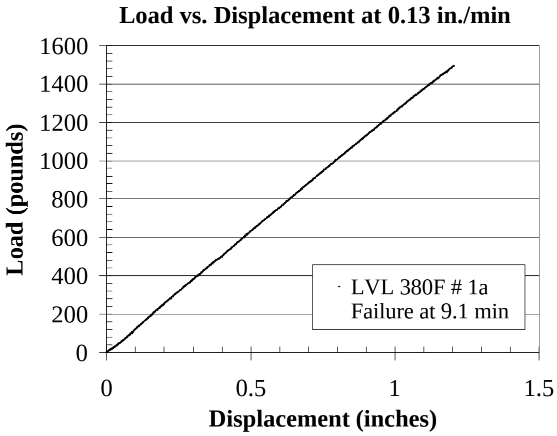

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 13d
Failure at 12.3 min

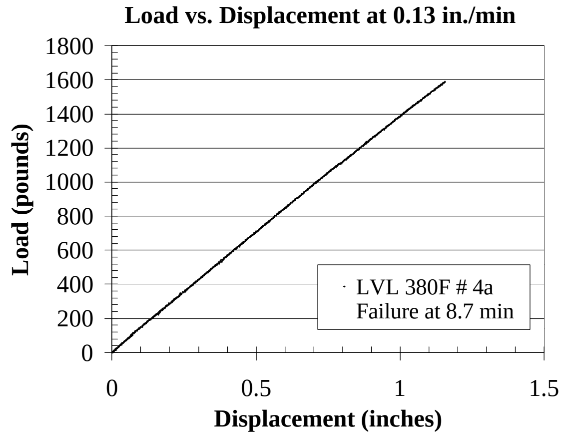

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 13e
Failure at 12.3 min

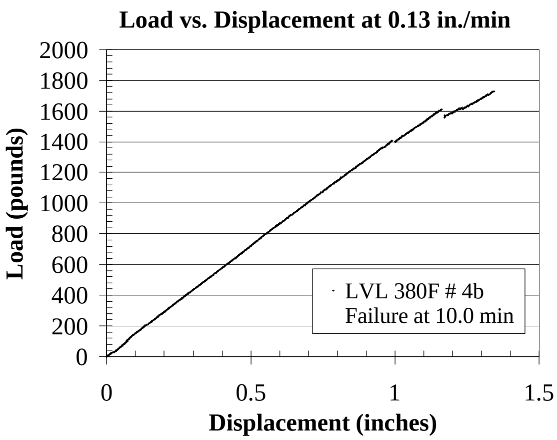

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 14a
Failure at 12.4 min

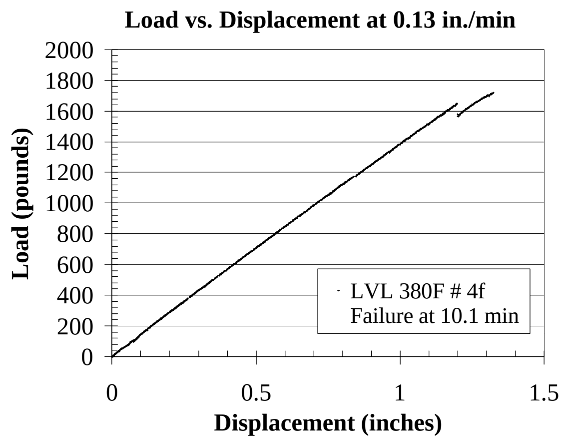

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 340F # 15a
Failure at 11.8 min

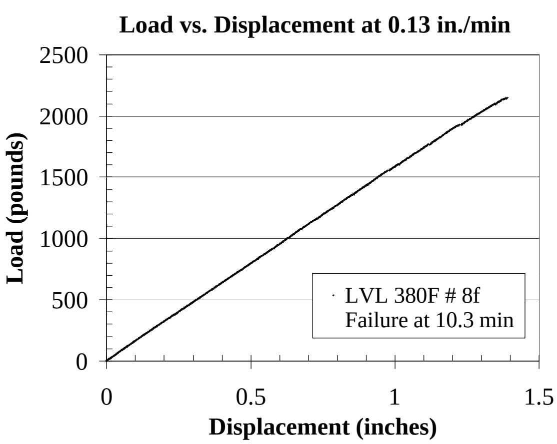
Laminated Veneer Lumber: 380°F

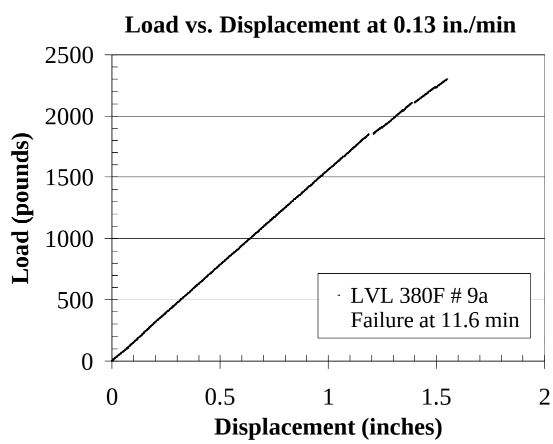


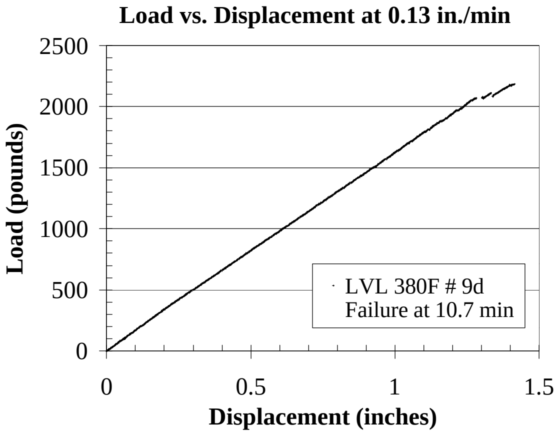


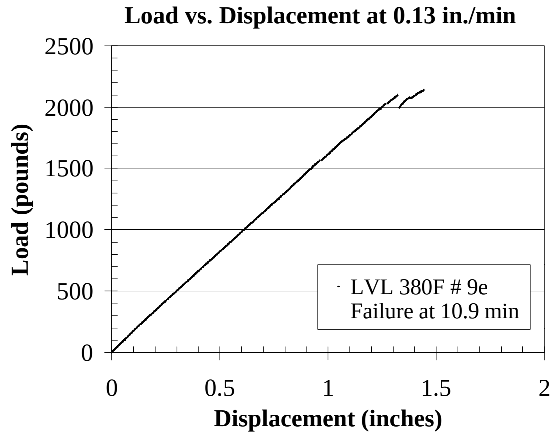


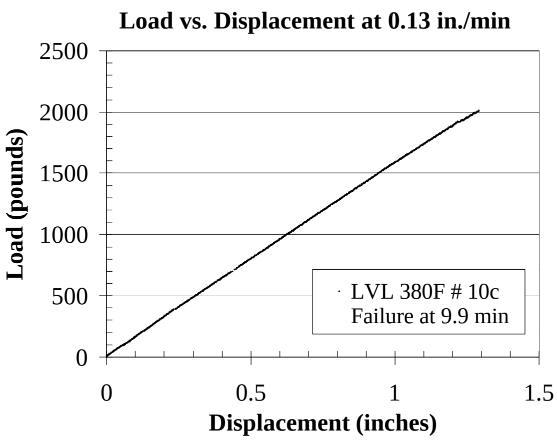


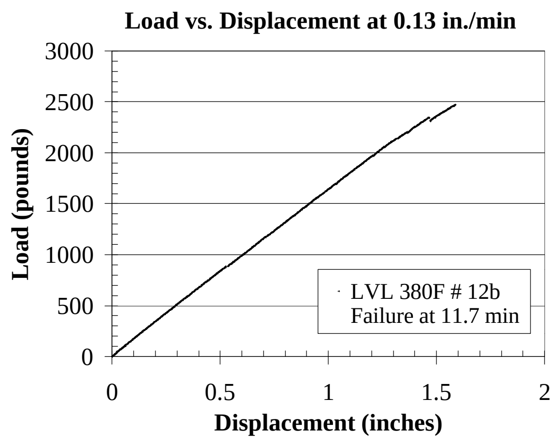


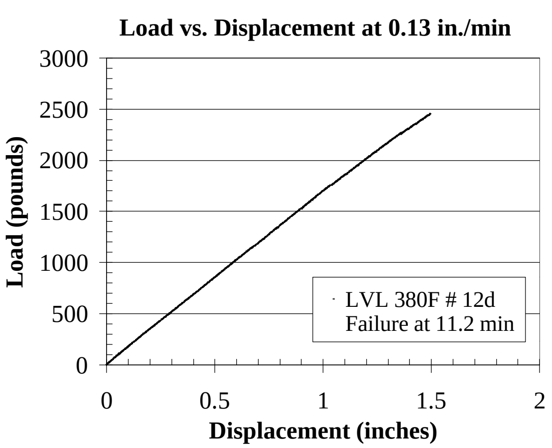


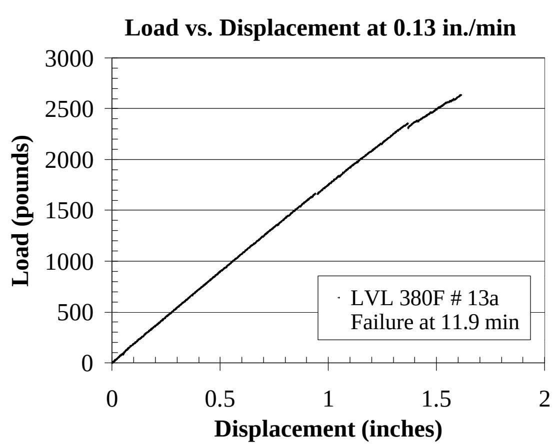

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 9d
Failure at 10.7 min

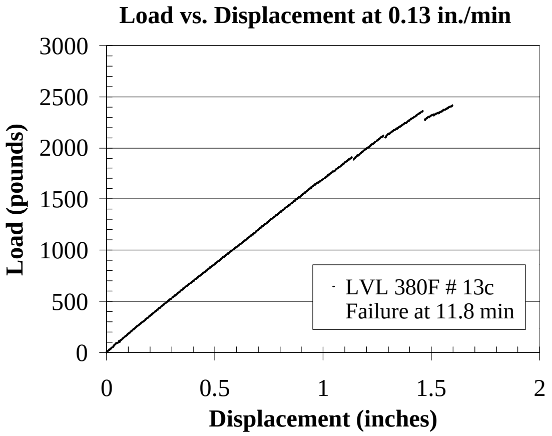

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 9e
Failure at 10.9 min

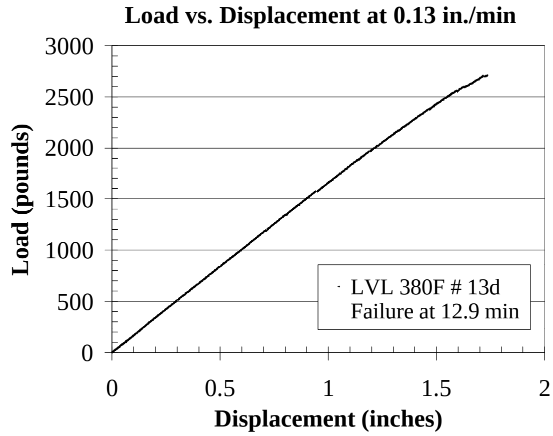

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 10c
Failure at 9.9 min

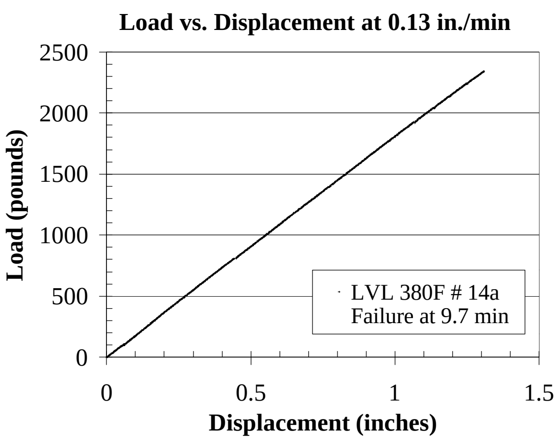

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 12b
Failure at 11.7 min

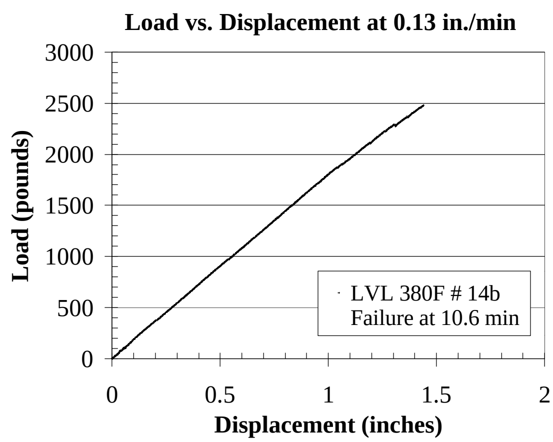

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 12d
Failure at 11.2 min

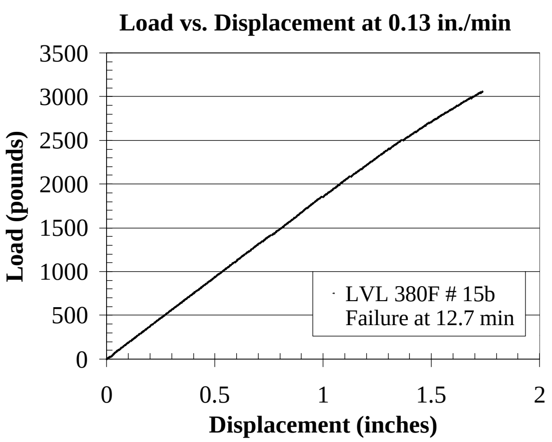

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 13a
Failure at 11.9 min

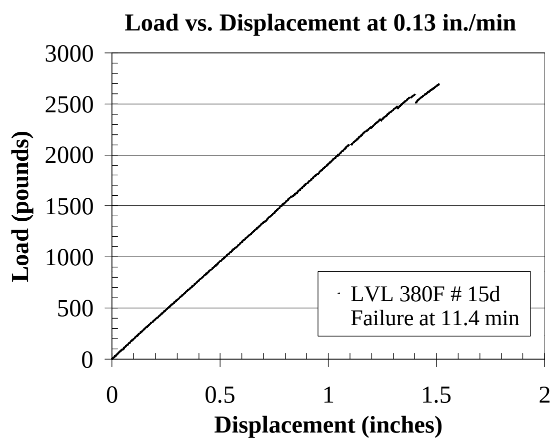

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 13c
Failure at 11.8 min

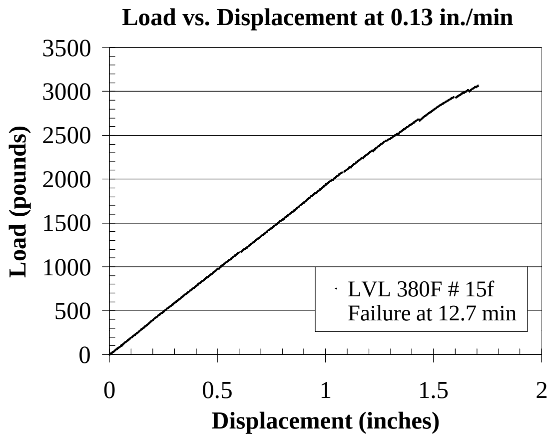

Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 13d
Failure at 12.9 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 14a
Failure at 9.7 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 14b
Failure at 10.6 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 15b
Failure at 12.7 min


Load vs. Displacement at 0.13 in./min
Load (pounds)
Displacement (inches)
LVL 380F # 15d
Failure at 11.4 min


Load vs. Displacement at 0.13 in./min
3500
3000
2500
2000
1500
1000
500
0
Load (pounds)
0
0.5
1
1.5
2
Displacement (inches)
LVL 380F # 15f
Failure at 12.7 min

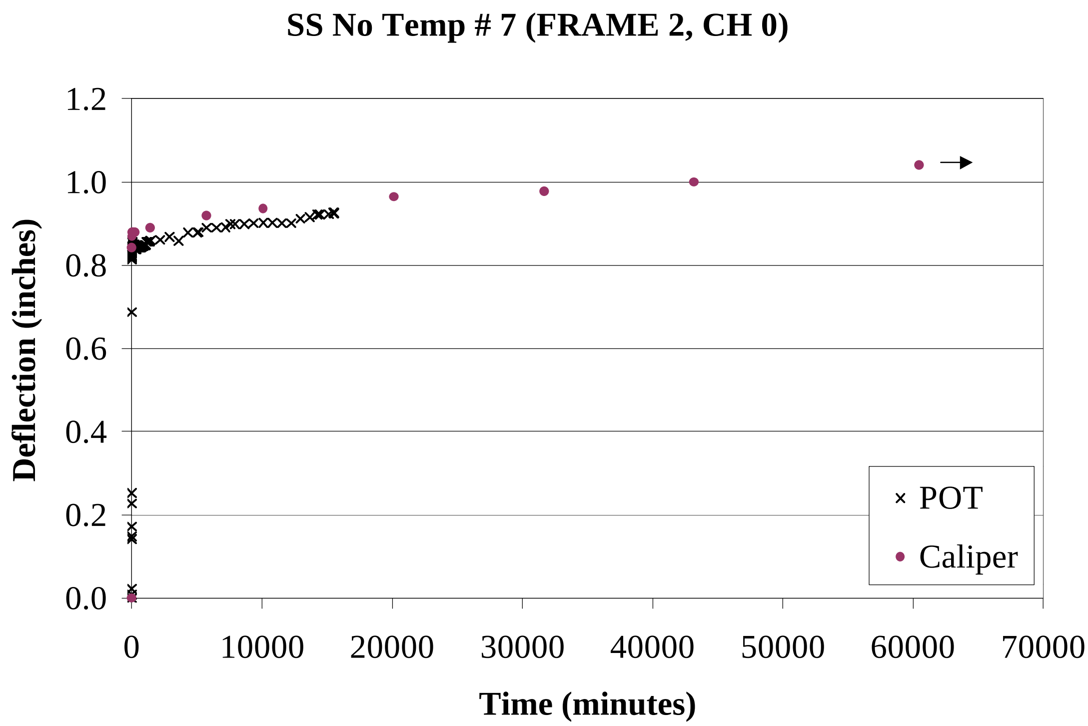
APPENDIX G

DEFLECTION VS. TIME PLOTS

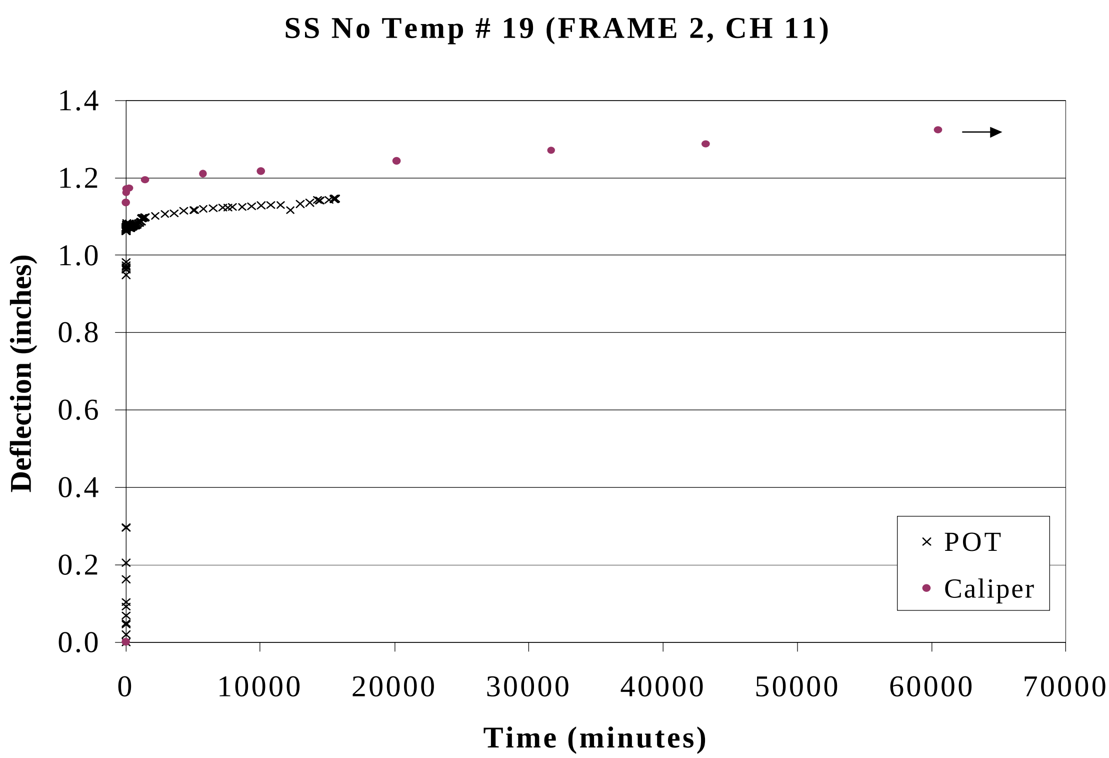
INTRODUCTION

Deflection of the members was found by using a modified caliper to obtain measurements at specific time periods with respect to the time of loading of the member. These times were as follows: one minute [initial deflection], half hour (only for the solid sawn lumber), one hour, two hours, four hours, one day, four days, seven days, fourteen days, twenty-two days, thirty days, (last collection for the solid sawn lumber 300^{o}F and 340^{o}F), and forty days. An arrow at the end of the deflection collection period means the member survived beyond the last measurement obtained.

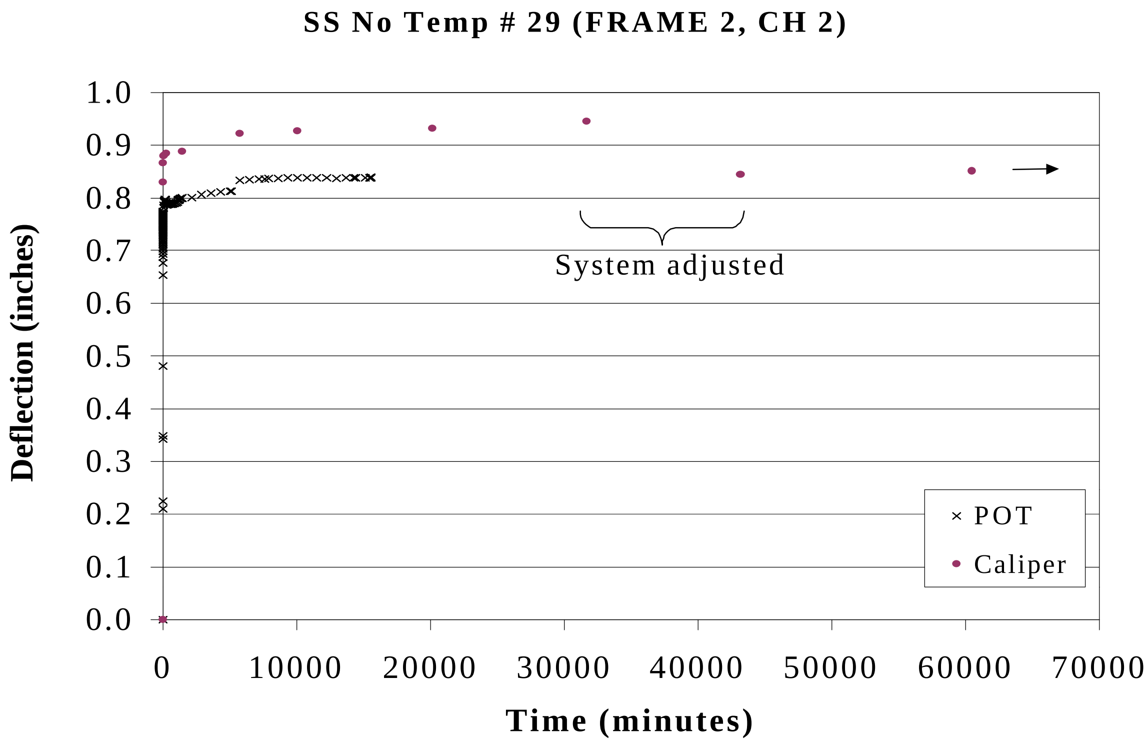
Two test groups, solid sawn no temperature and laminated veneer lumber 300^{o}F were also monitored using linear position transducers (POT). For the most part, the deflections recorded electronically and the ones found manually were comparable. Most large discrepancies were found to be the result of faulty equipment or improper calibration. Ultimately, the caliper measurements were the trusted source for duration of load deflection.

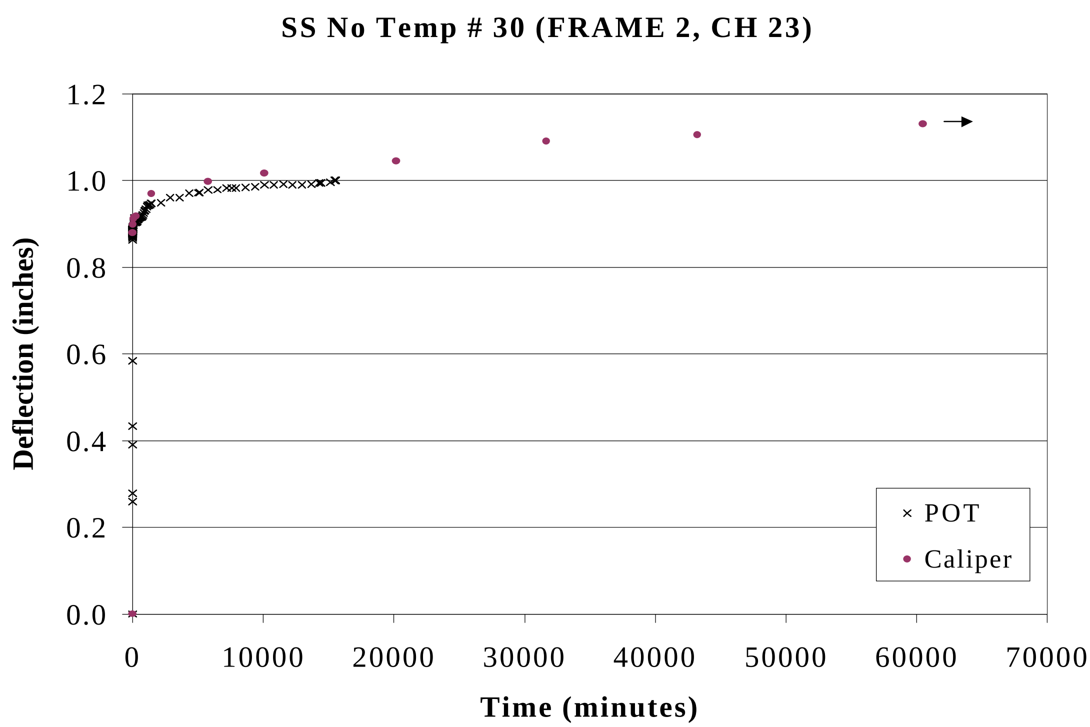


SS No Temp # 7 (FRAME 2, CH 0)
Deflection (inches)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (minutes)
POT
Caliper

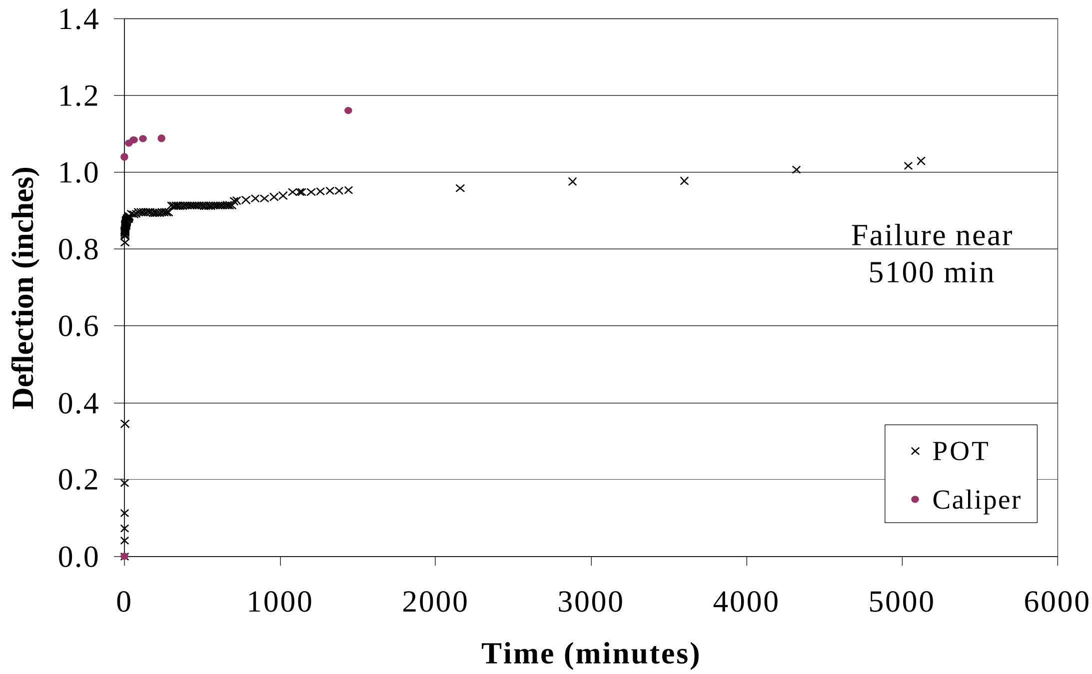


SS No Temp # 19 (FRAME 2, CH 11)
Deflection (inches)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (minutes)
POT
Caliper

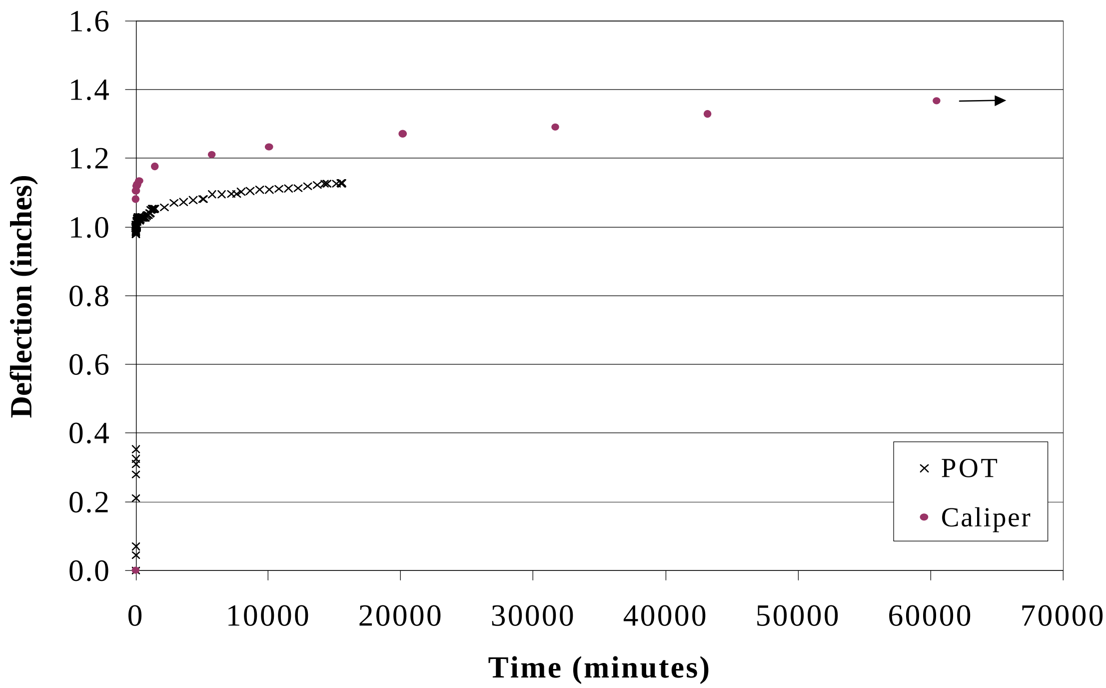

SS No Temp # 29 (FRAME 2, CH 2)
Deflection (inches)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
System adjusted
POT
Caliper
0
10000
20000
30000
40000
50000
60000
70000
Time (minutes)

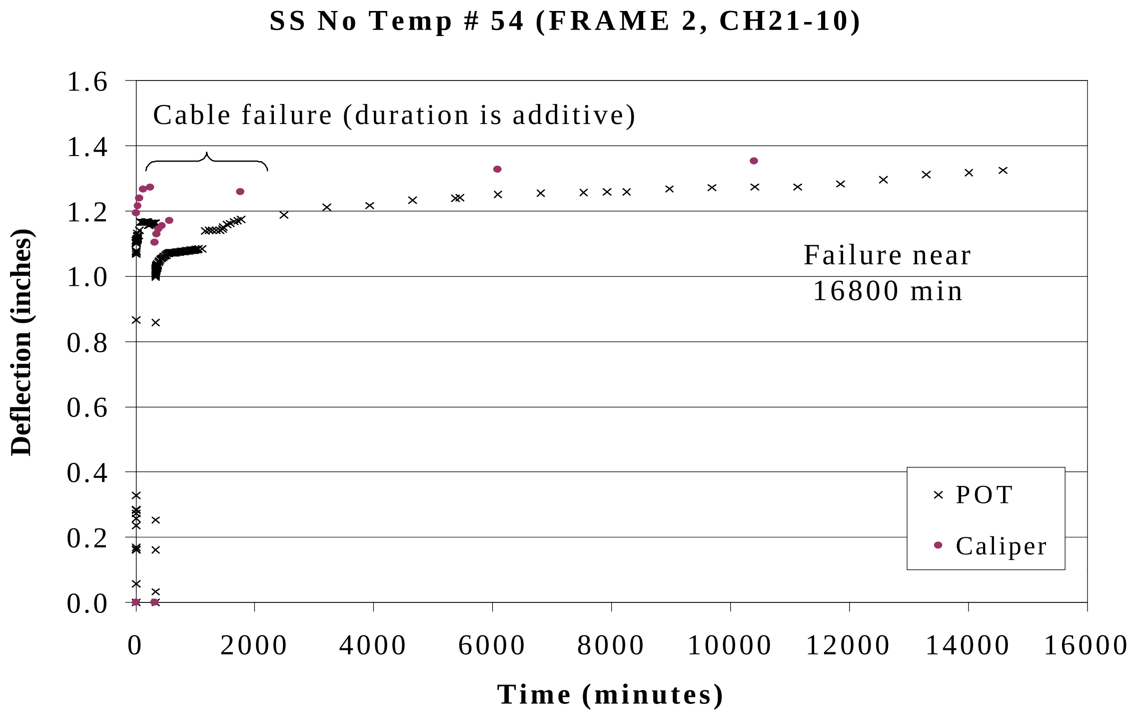

SS No Temp # 30 (FRAME 2, CH 23)
Deflection (inches)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
POT
Caliper
0
10000
20000
30000
40000
50000
60000
70000
Time (minutes)

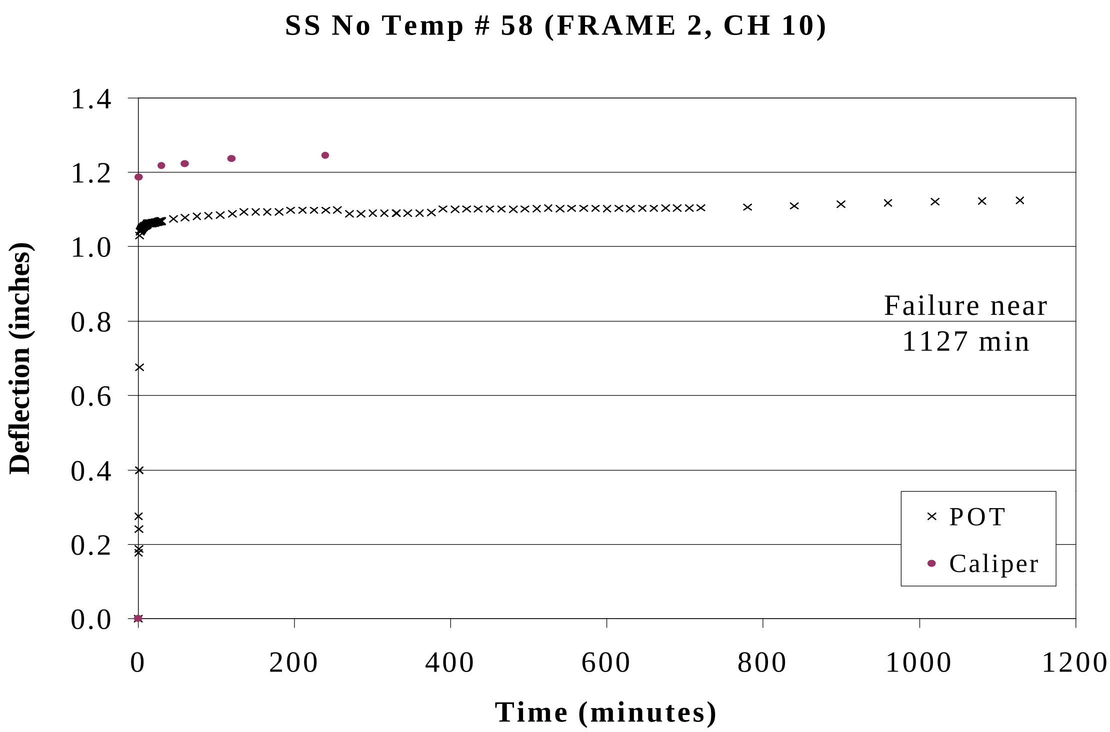
SS No Temp # 47 (FRAME 2, CH 14)

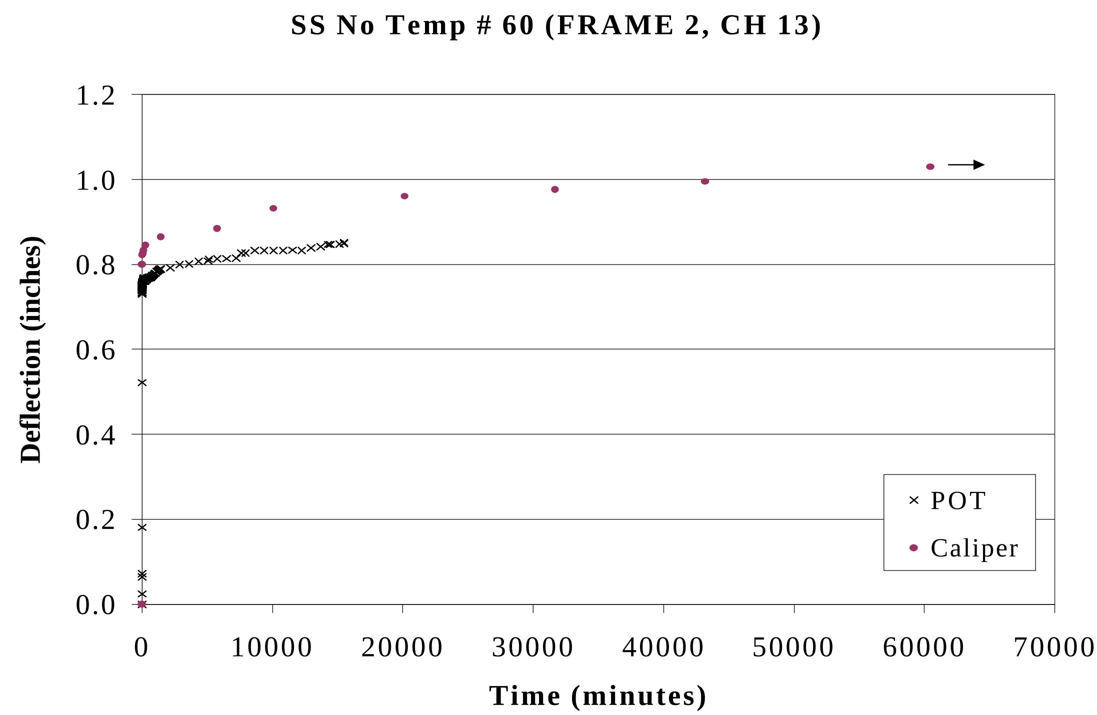


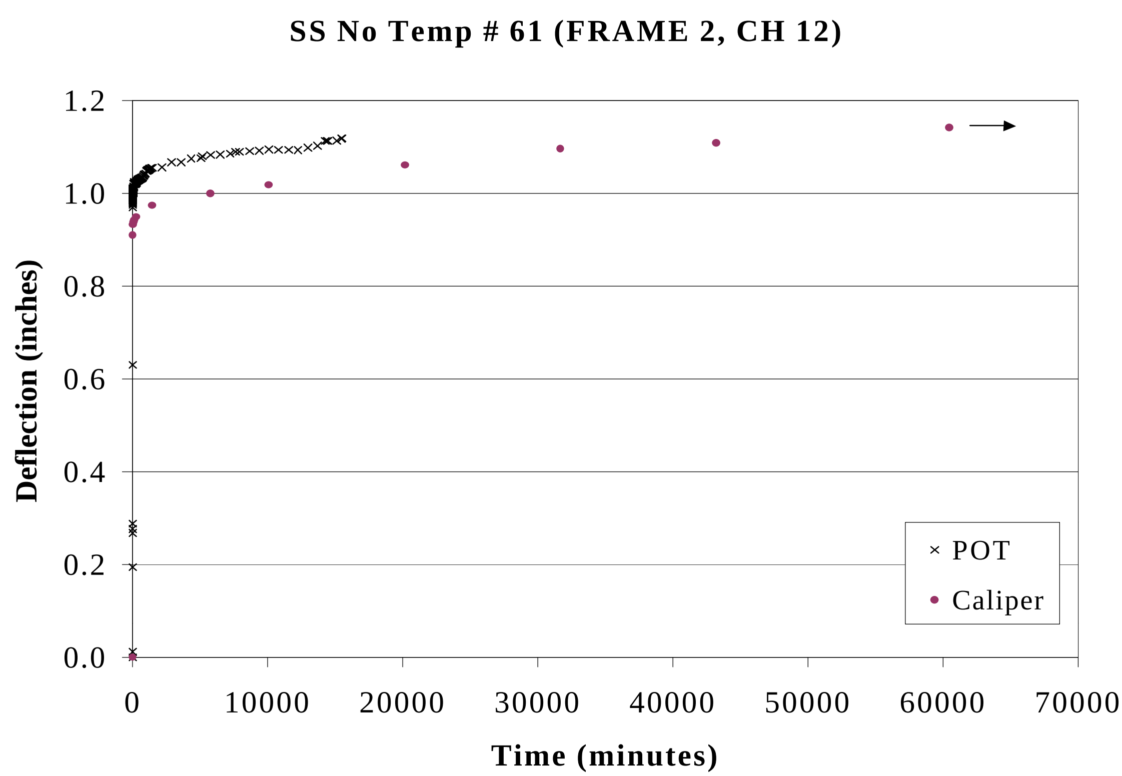
SS No Temp # 48 (FRAME 2, CH 3)

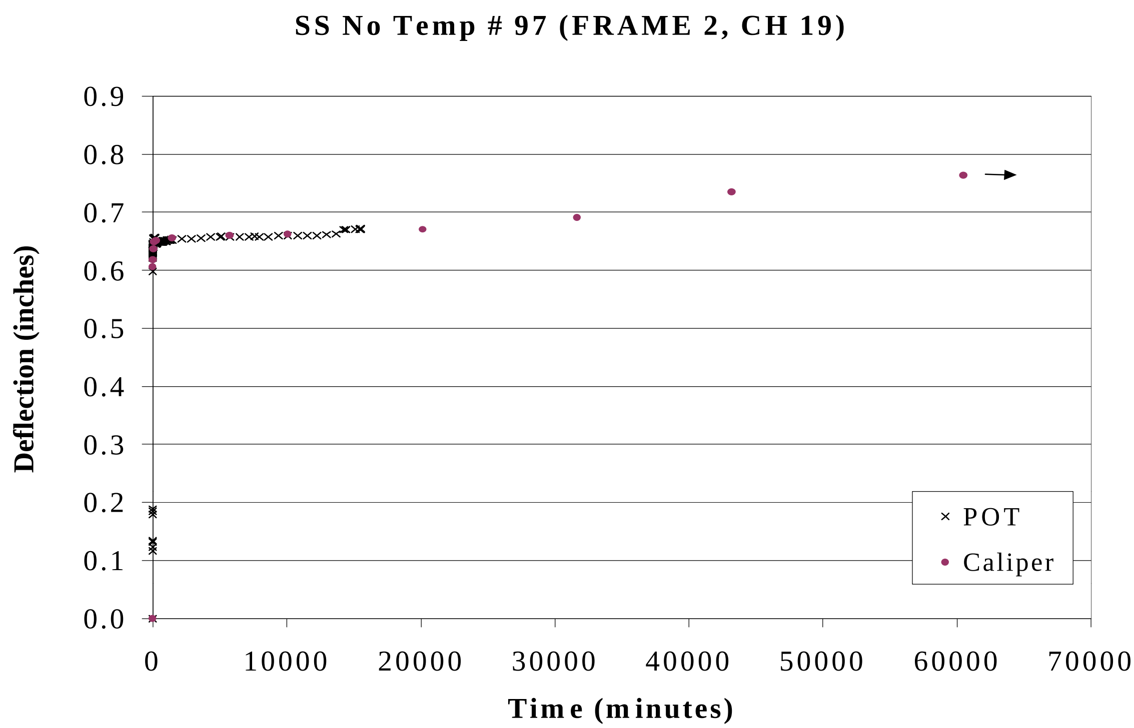


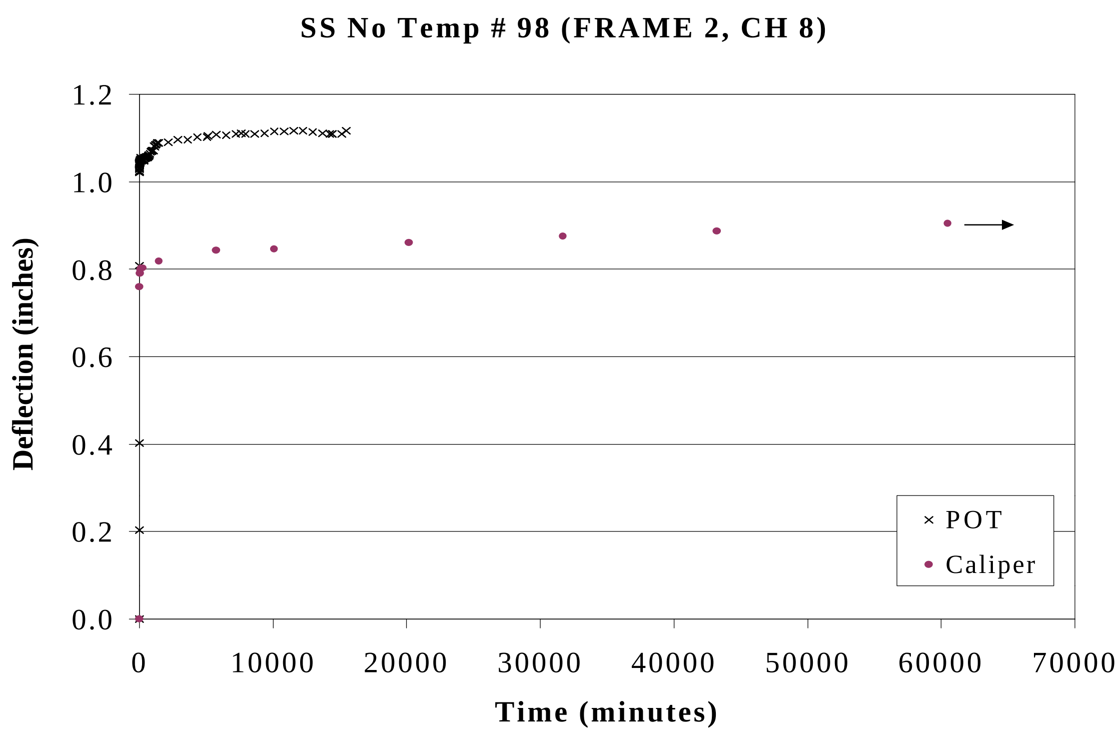

SS No Temp # 54 (FRAME 2, CH21-10)
Cable failure (duration is additive)
Failure near
16800 min
POT
Caliper
Deflection (inches)
Time (minutes)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
2000
4000
6000
8000
10000
12000
14000
16000


SS No Temp # 58 (FRAME 2, CH 10)
Failure near
1127 min
POT
Caliper
Deflection (inches)
Time (minutes)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
200
400
600
800
1000
1200

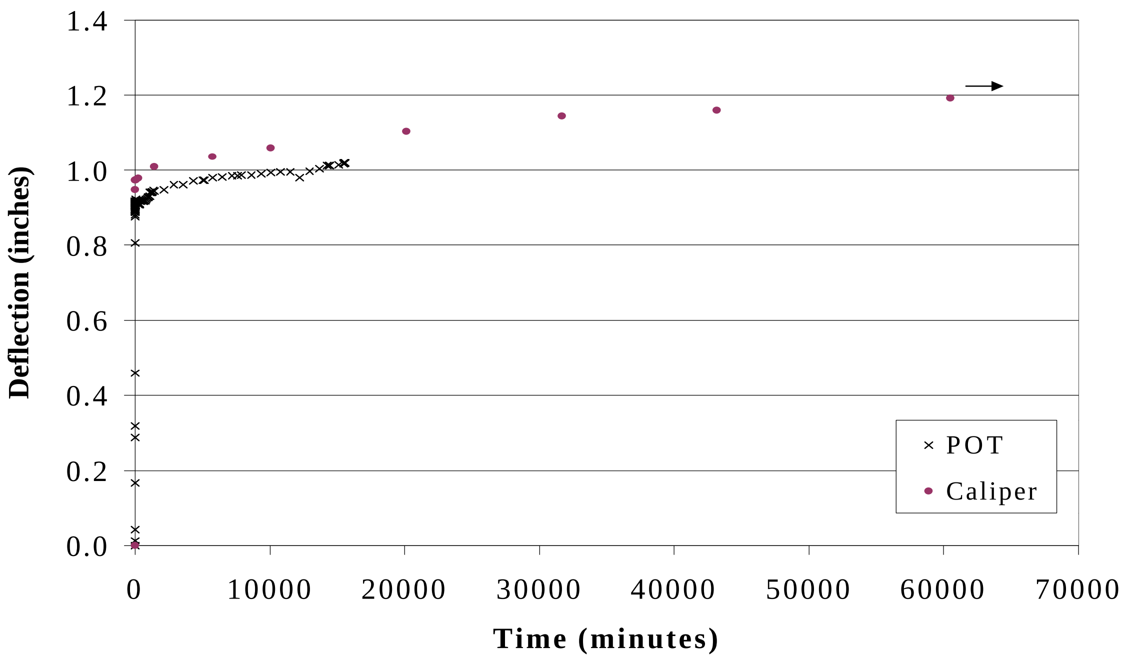

SS No Temp # 60 (FRAME 2, CH 13)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
60000
70000
Time (minutes)
POT
Caliper


SS No Temp # 61 (FRAME 2, CH 12)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
60000
70000
Time (minutes)
POT
Caliper

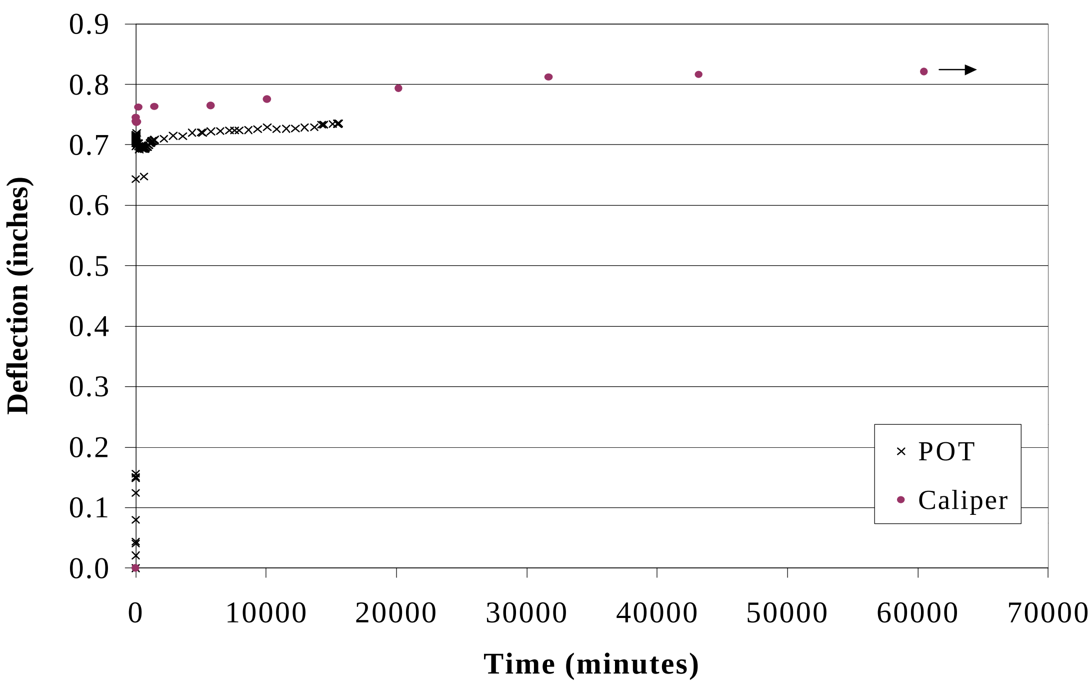

SS No Temp # 97 (FRAME 2, CH 19)
Deflection (inches)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (minutes)
POT
Caliper


SS No Temp # 98 (FRAME 2, CH 8)
Deflection (inches)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (minutes)
POT
Caliper

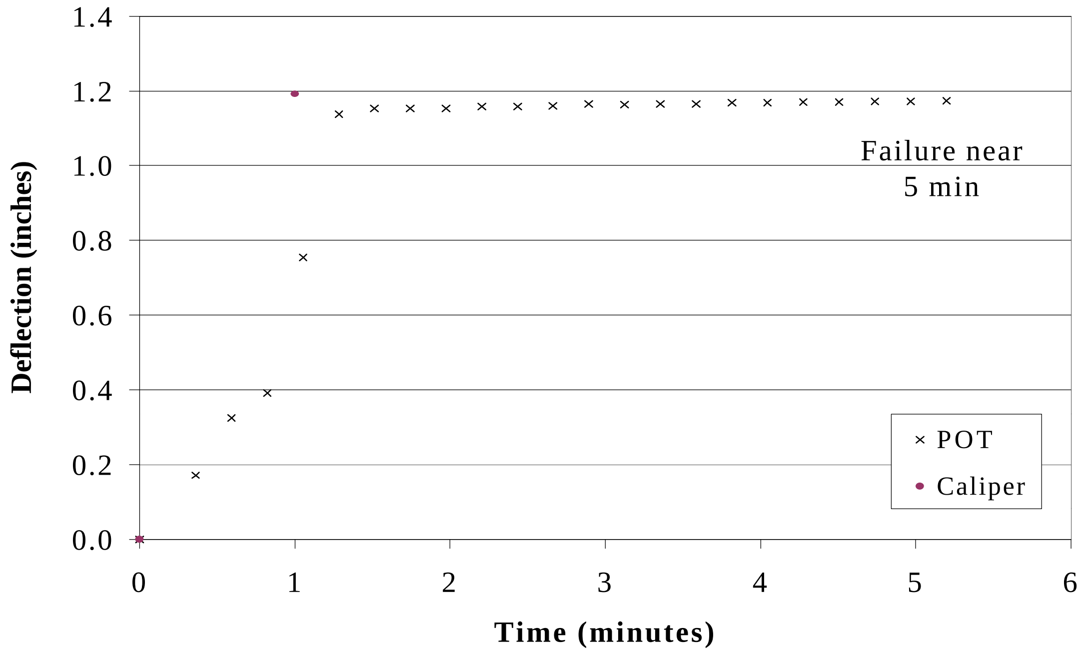
SS No Temp # 132 (FRAME 2, CH 7)



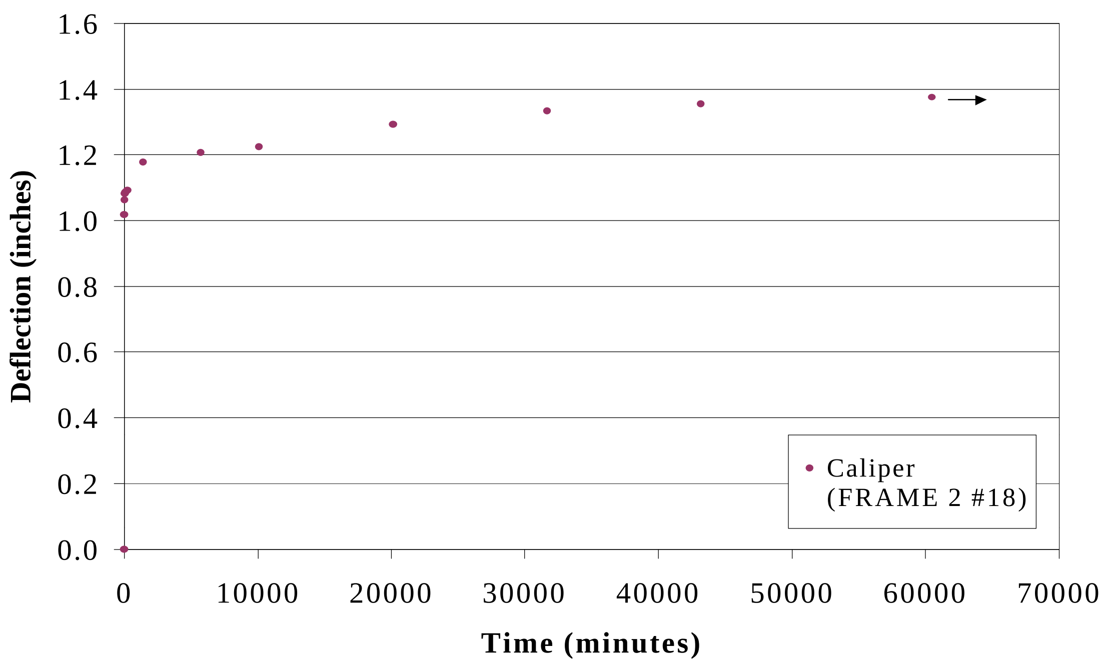
SS No Temp # 140 (FRAME 2, CH 6)



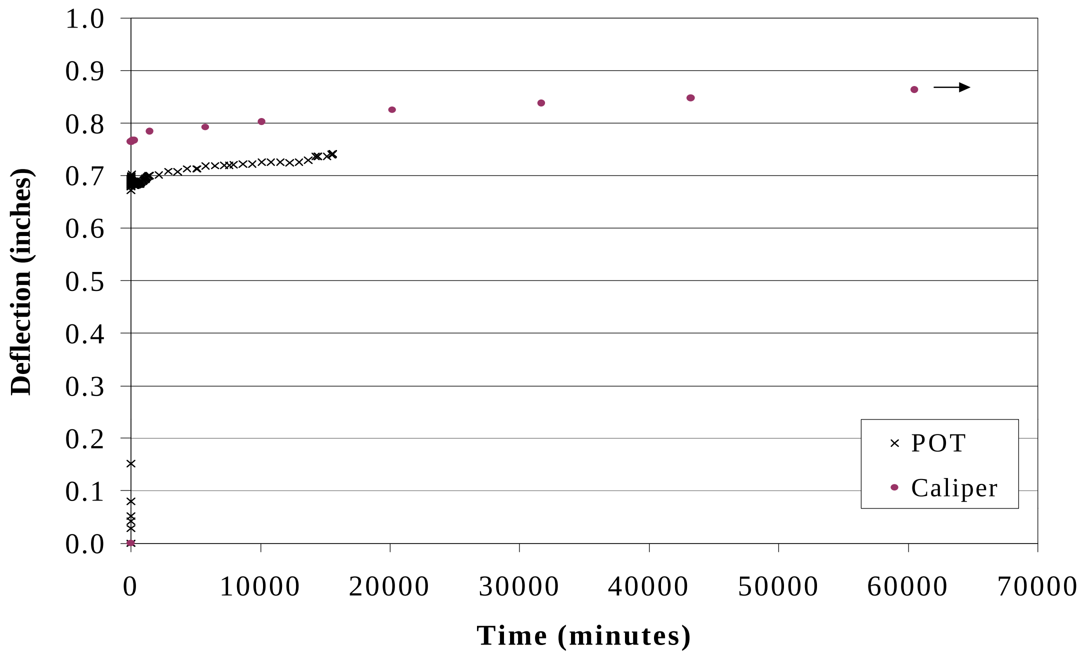
SS No Temp # 144 (FRAME 2, CH 9)



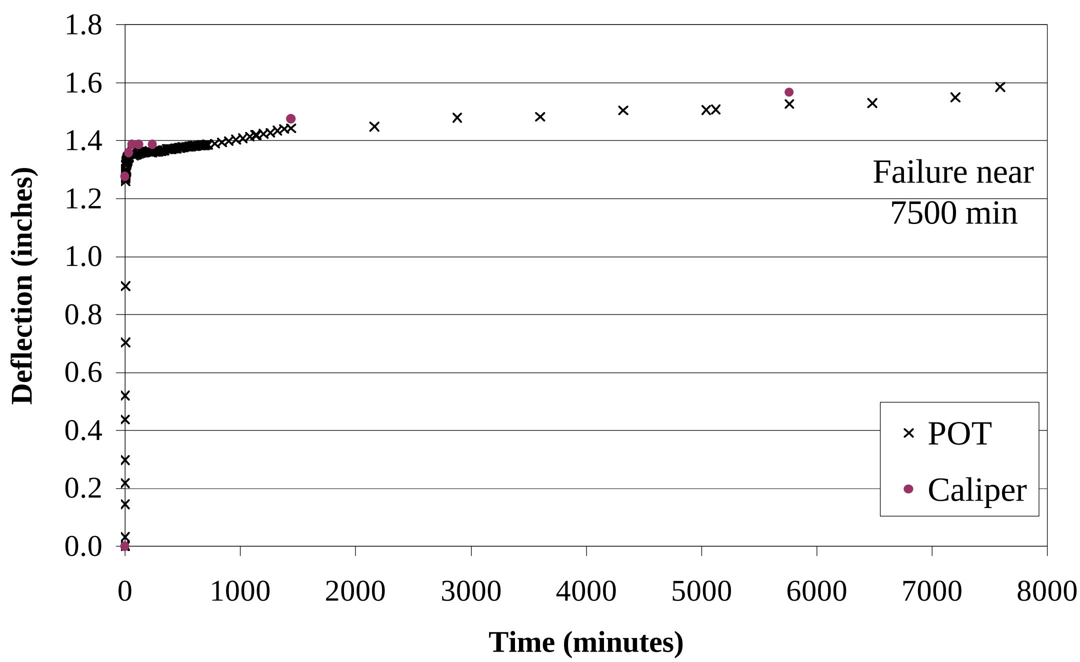
SS No Temp # 159



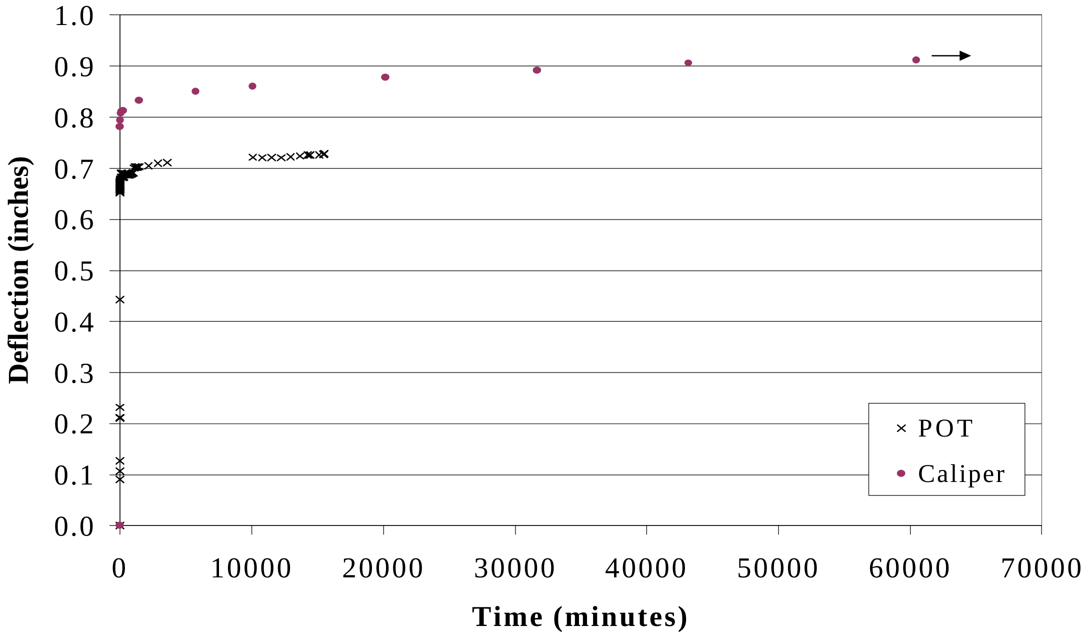
SS No Temp # 161 (FRAME 2, CH 4)



SS No Temp # 162 (FRAME 2, CH 1)

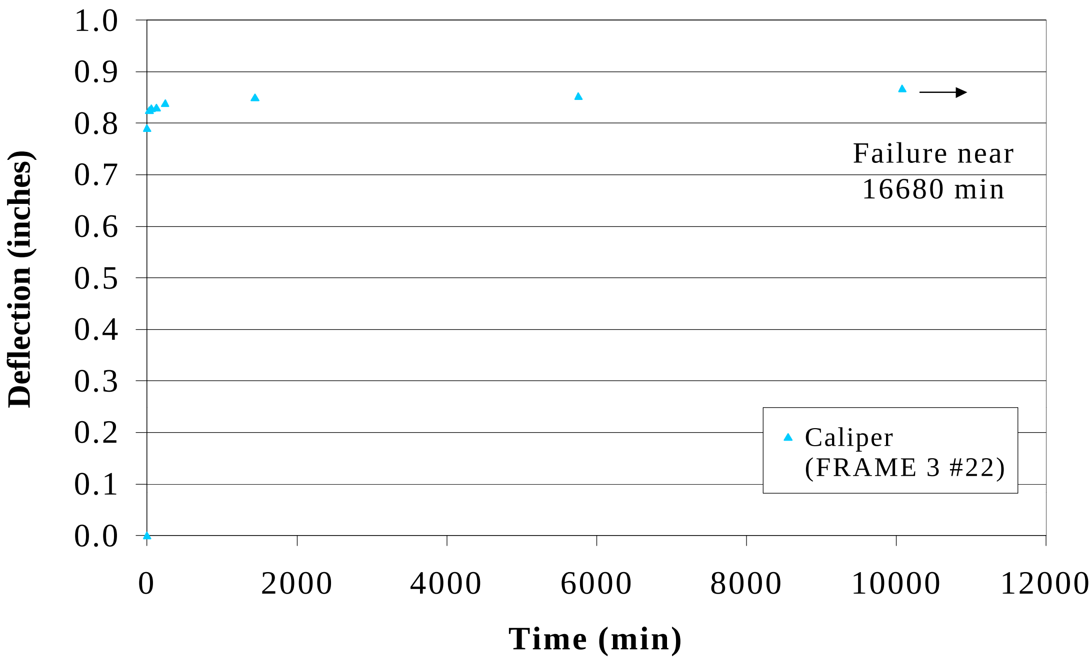


SS No Temp # 178 (FRAME 2, CH 16)

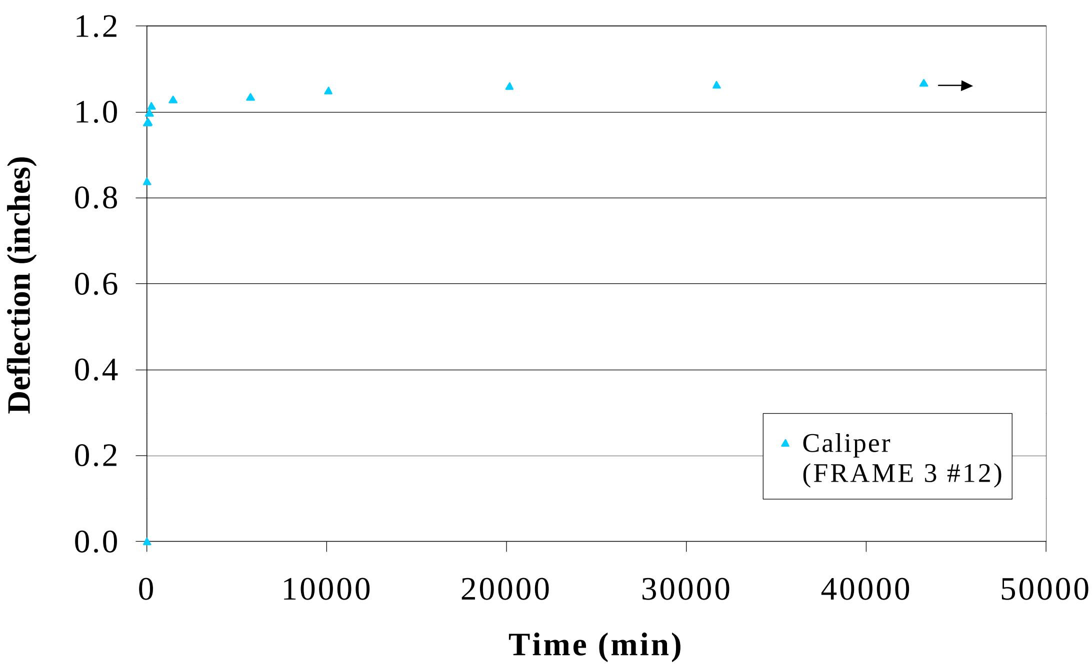


SOLID SAWN LUMBER: 300°F

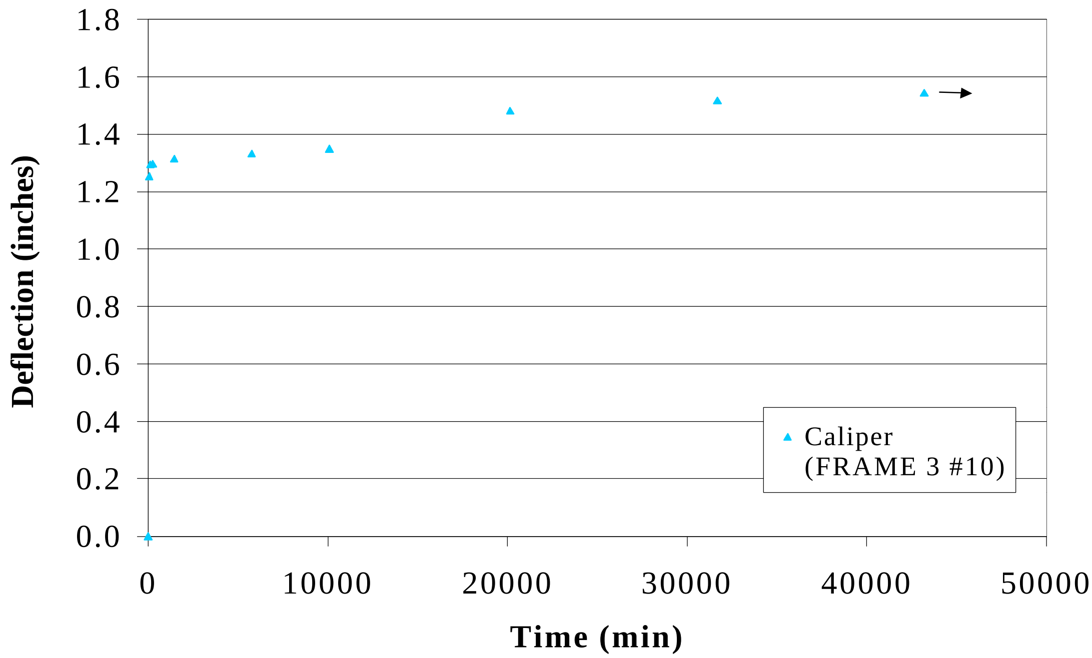
SS 300°F # 25



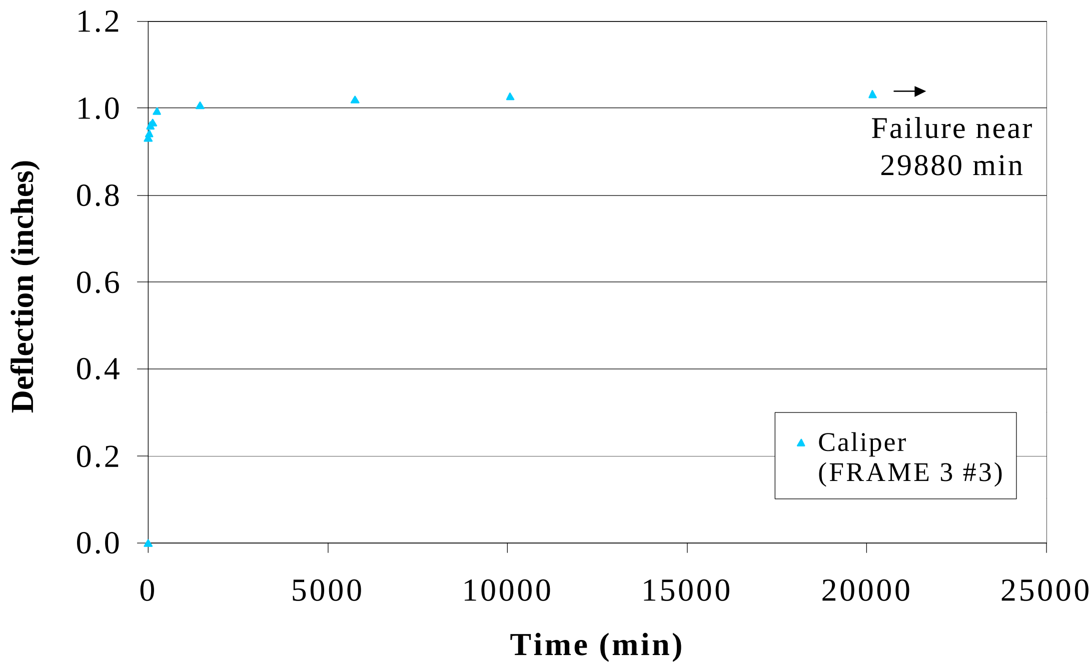
SS 300°F # 33



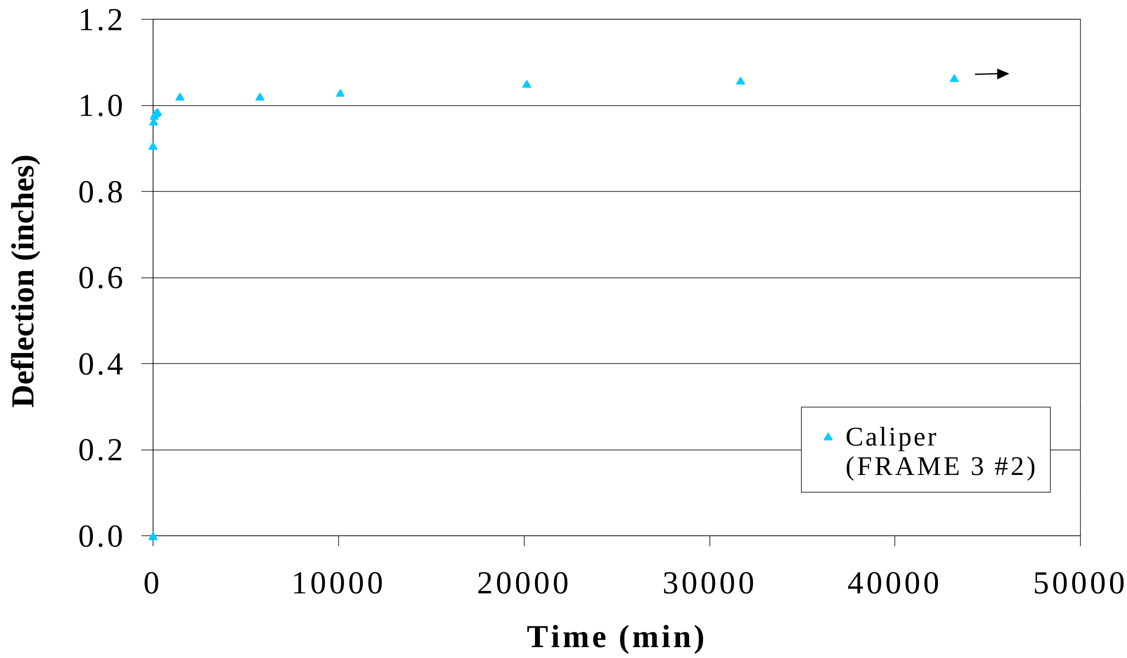
SS 300°F # 41



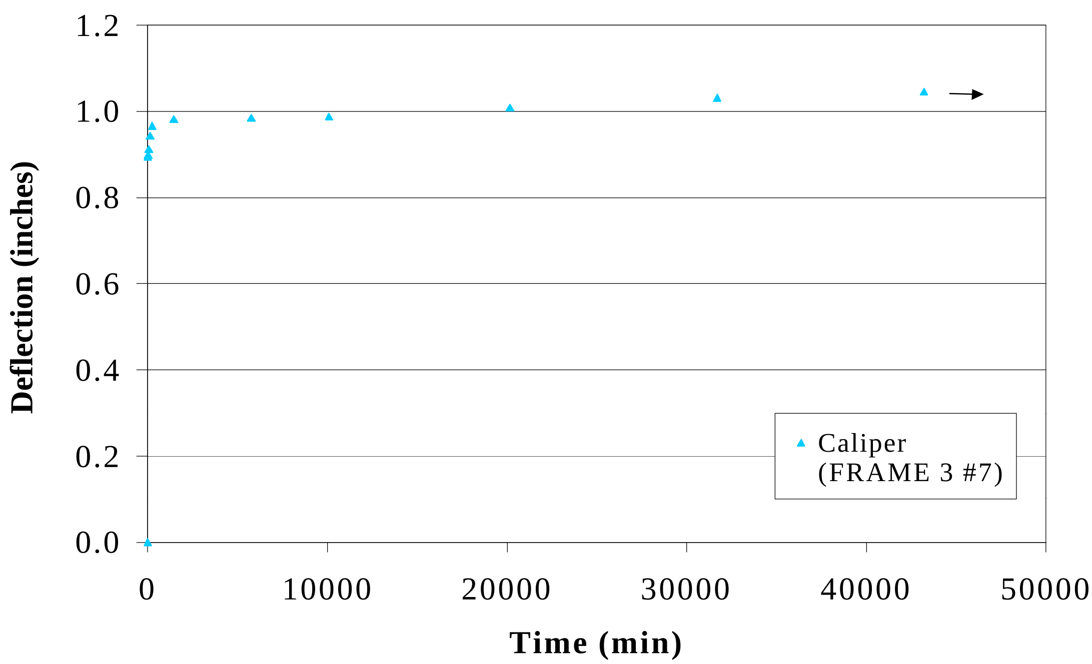
SS 300°F # 44

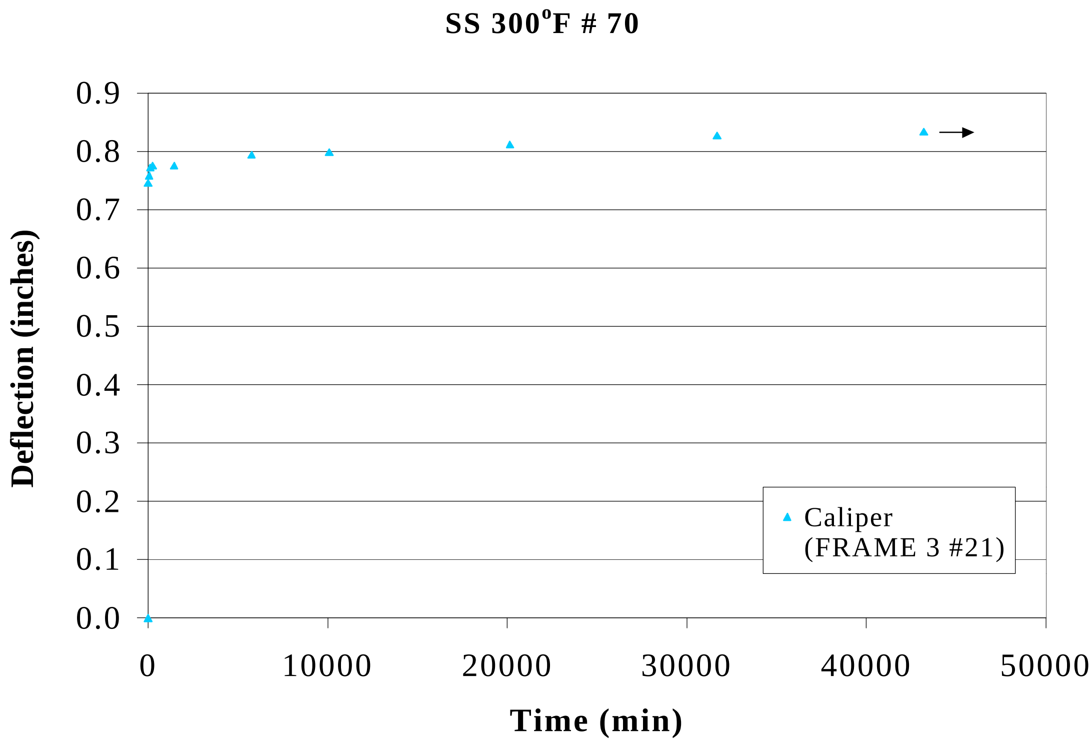


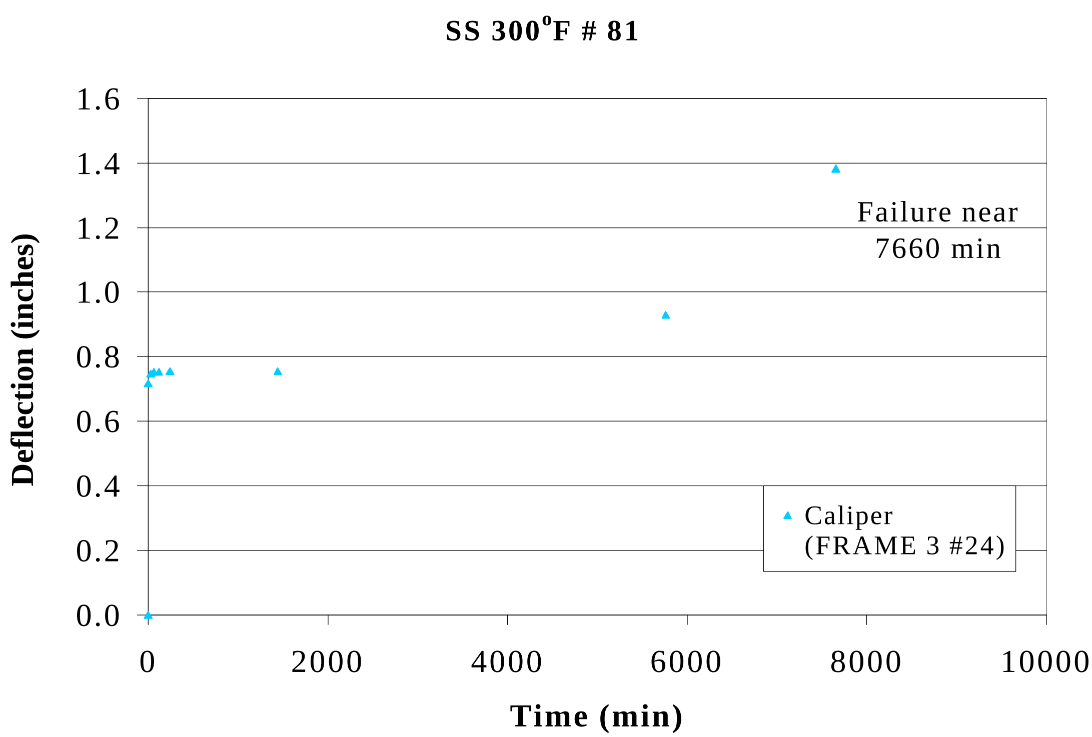
SS 300°F # 45

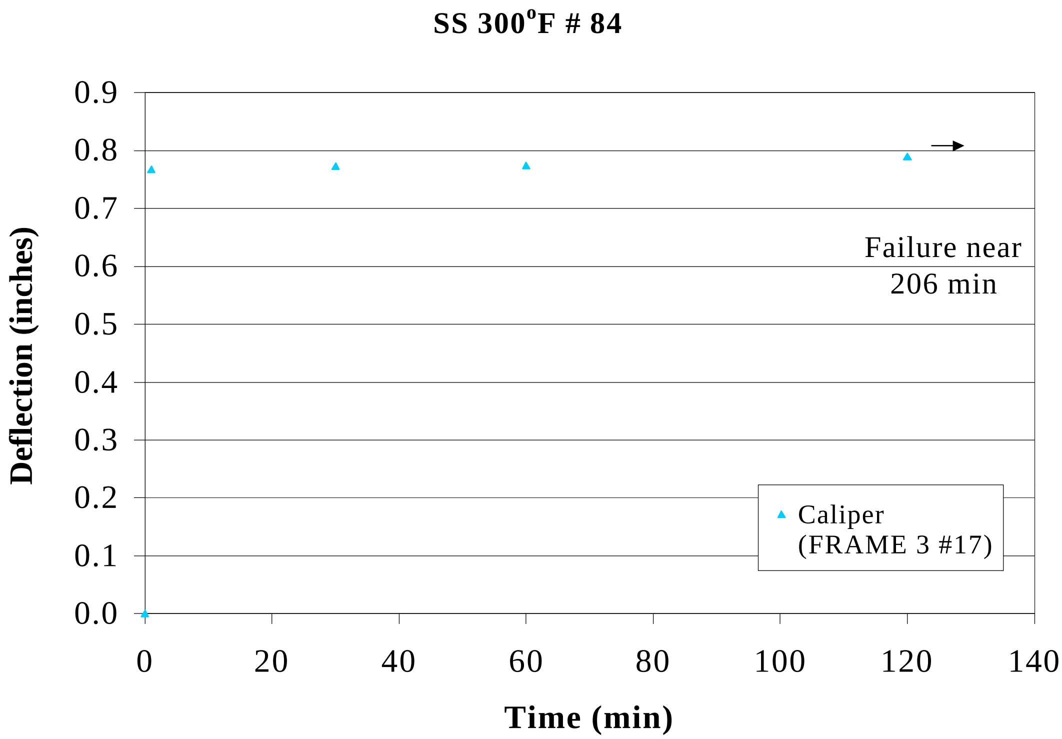


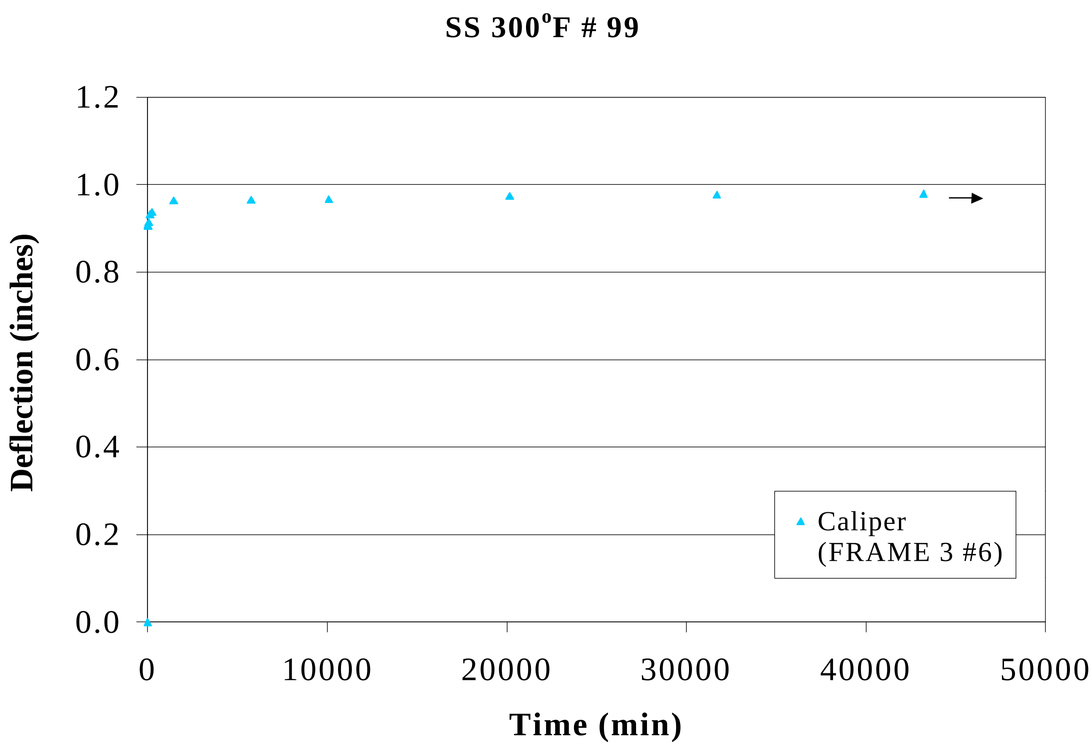
SS 300°F # 49



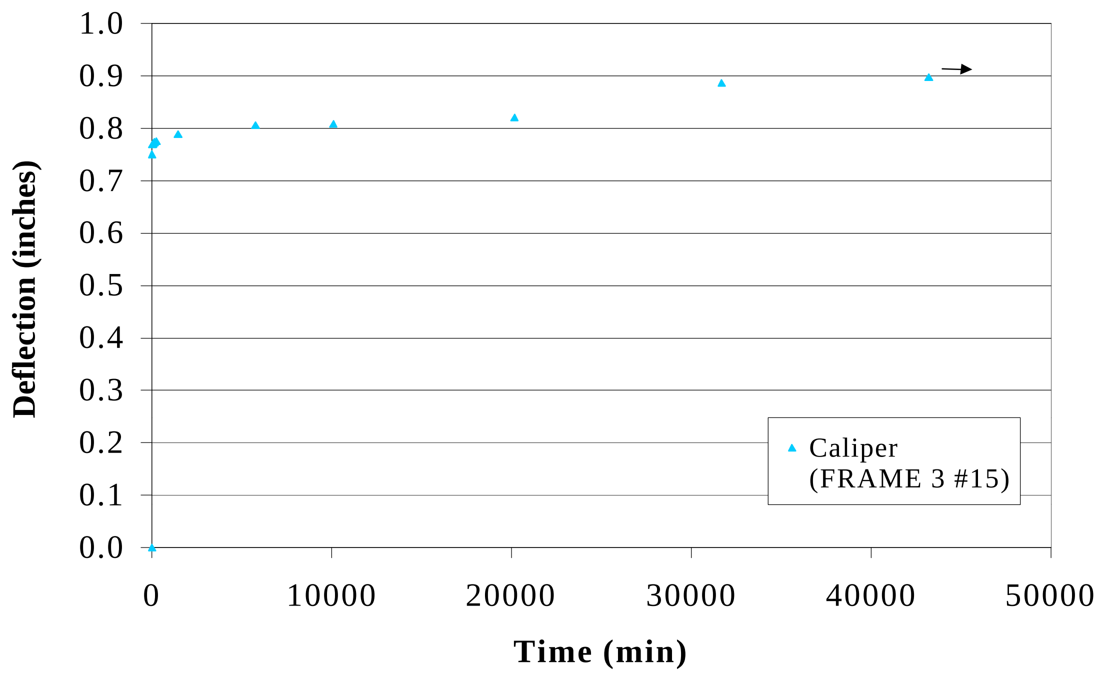

SS 300°F # 70
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 3 #21)


SS 300°F # 81
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
Failure near
7660 min
0
2000
4000
6000
8000
10000
Time (min)
Caliper
(FRAME 3 #24)

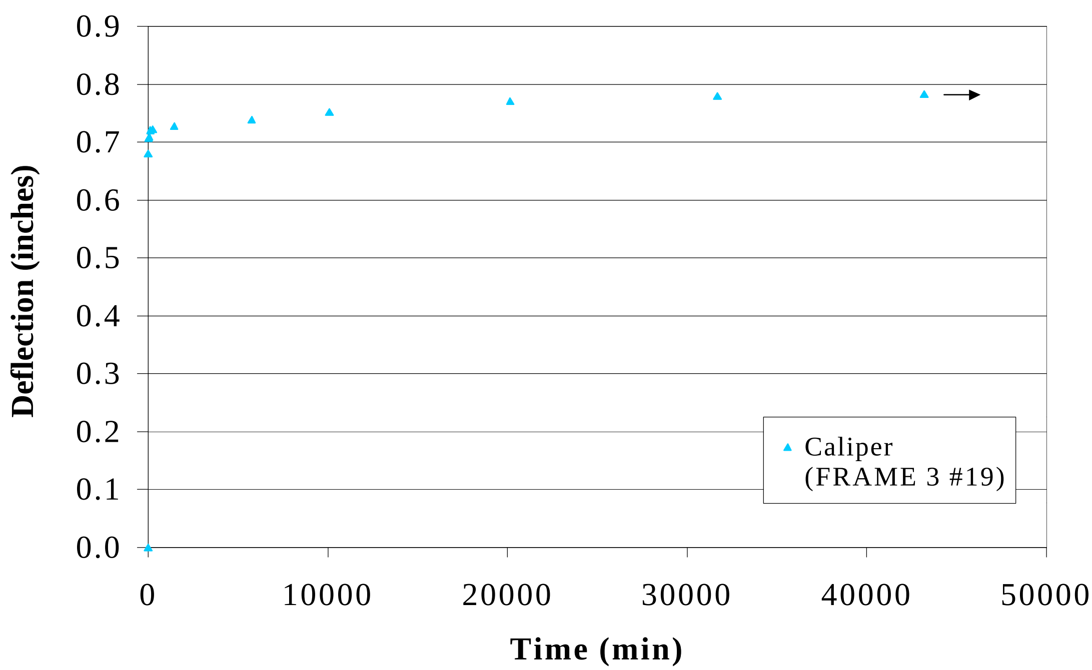

SS 300°F # 84
Deflection (inches)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
140
Time (min)
Failure near
206 min
Caliper
(FRAME 3 #17)

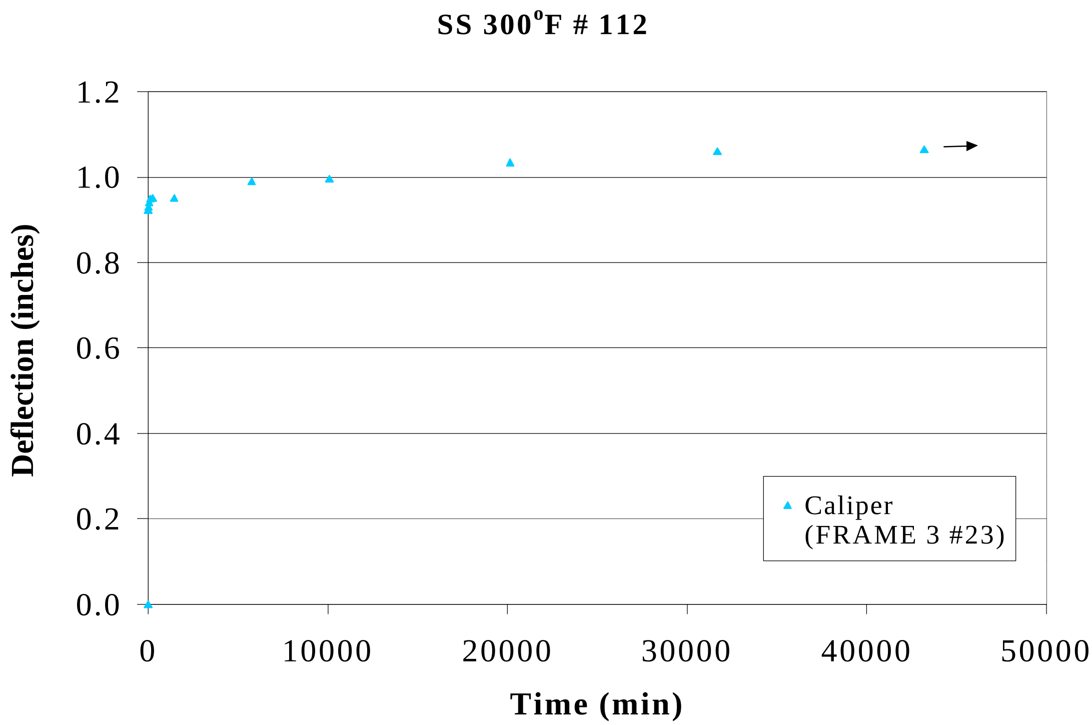

SS 300°F # 99
Deflection (inches)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 3 #6)

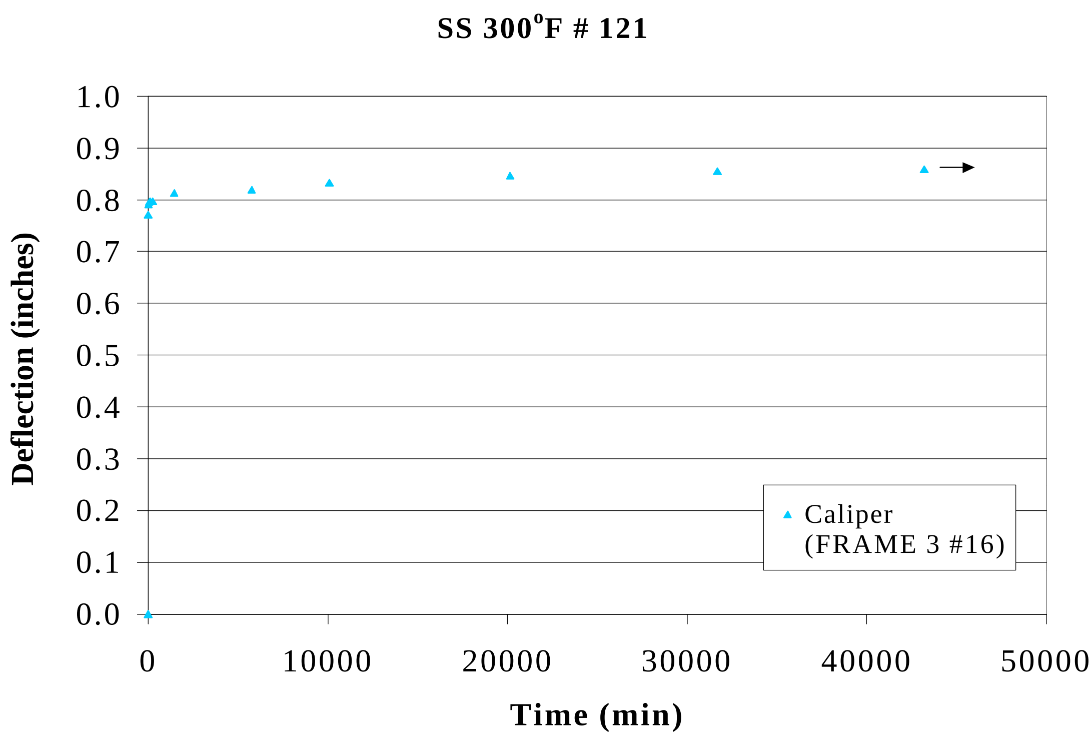
SS 300°F # 104



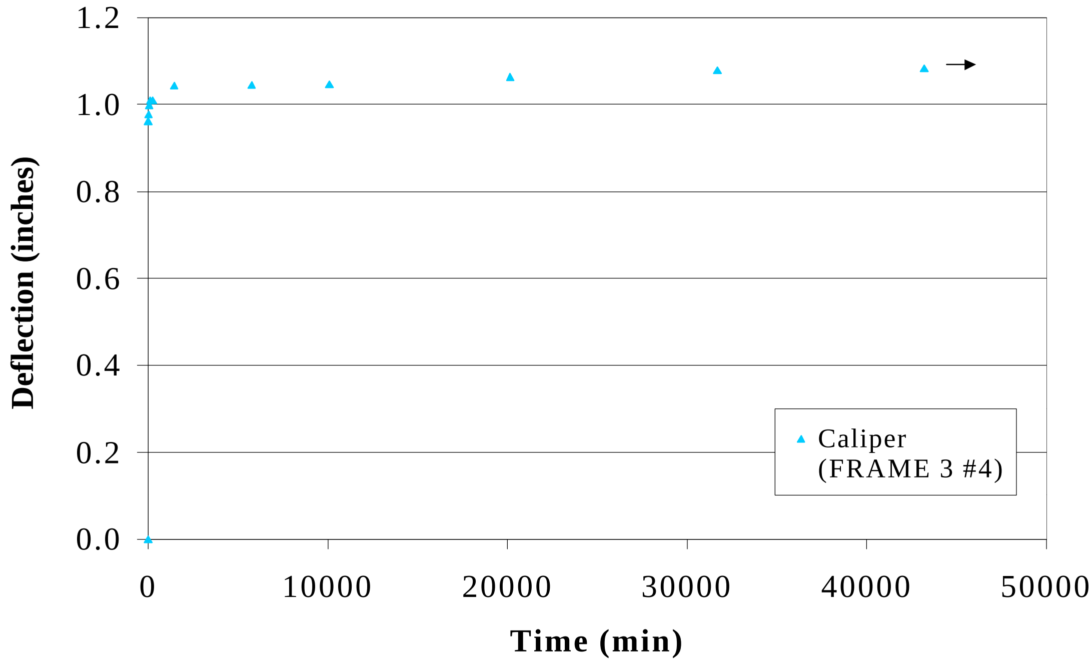
SS 300°F # 109



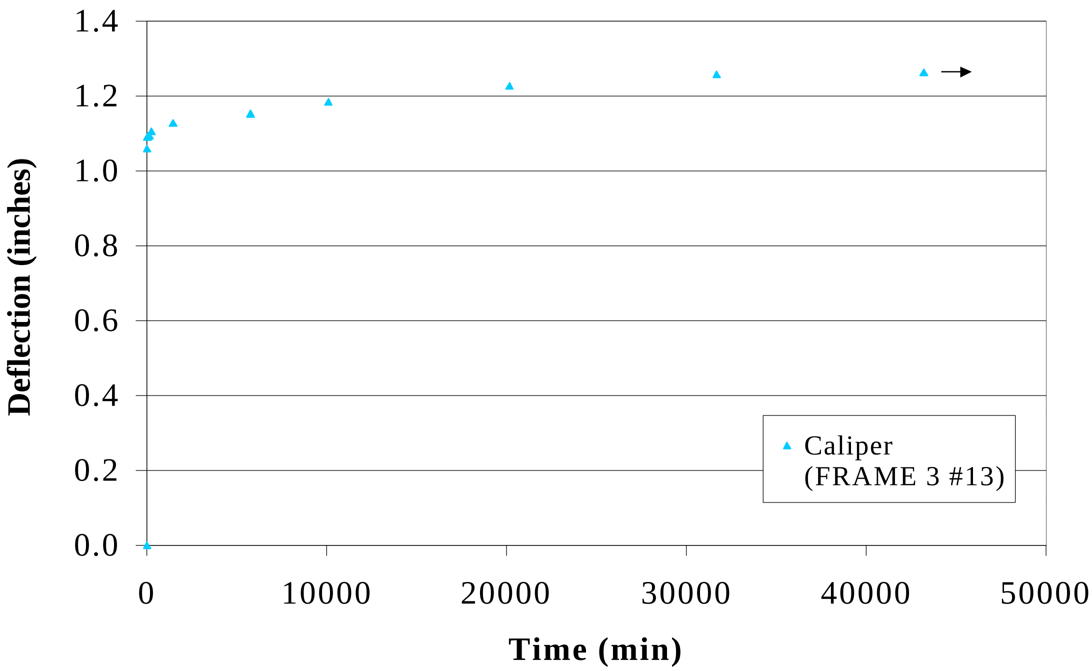

SS 300°F # 112
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 3 #23)


SS 300°F # 121
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 3 #16)

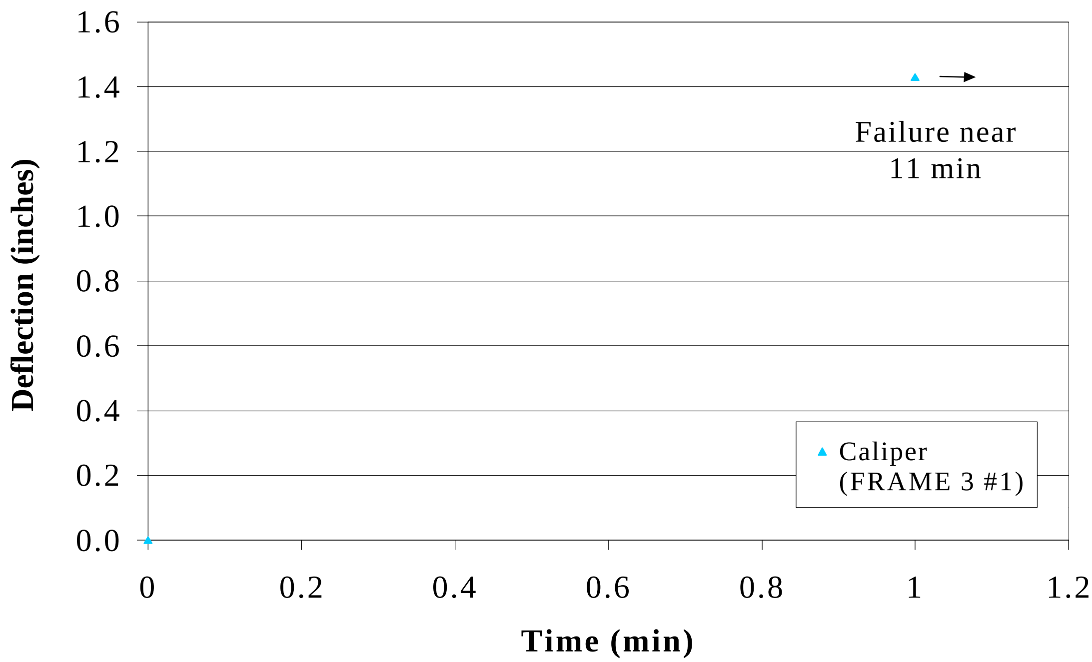
SS 300°F # 125



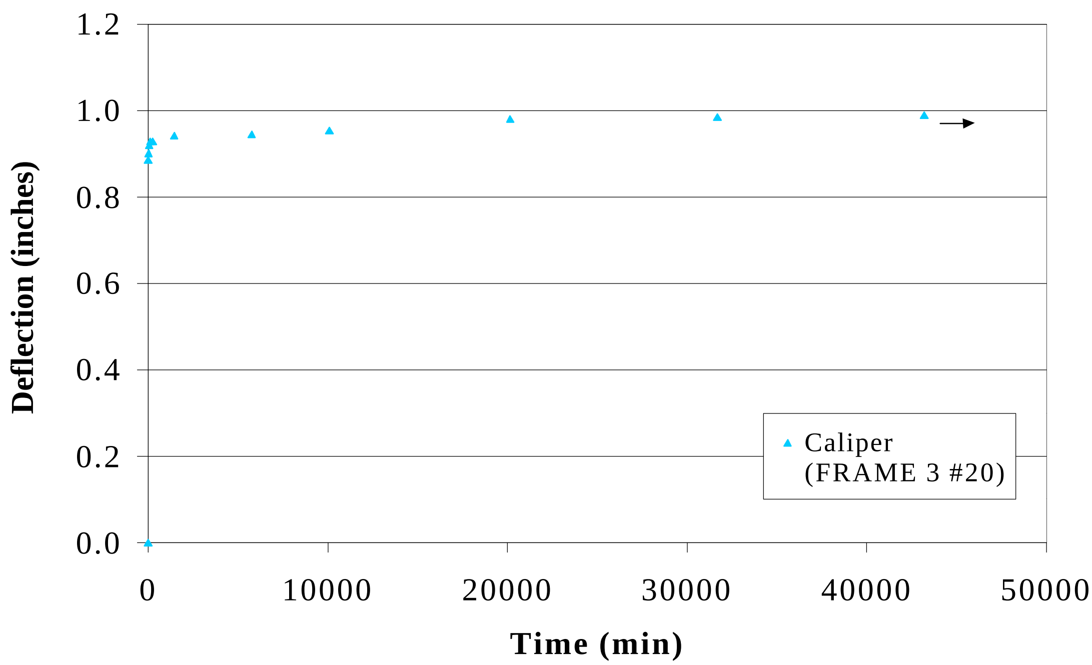
SS 300°F # 126



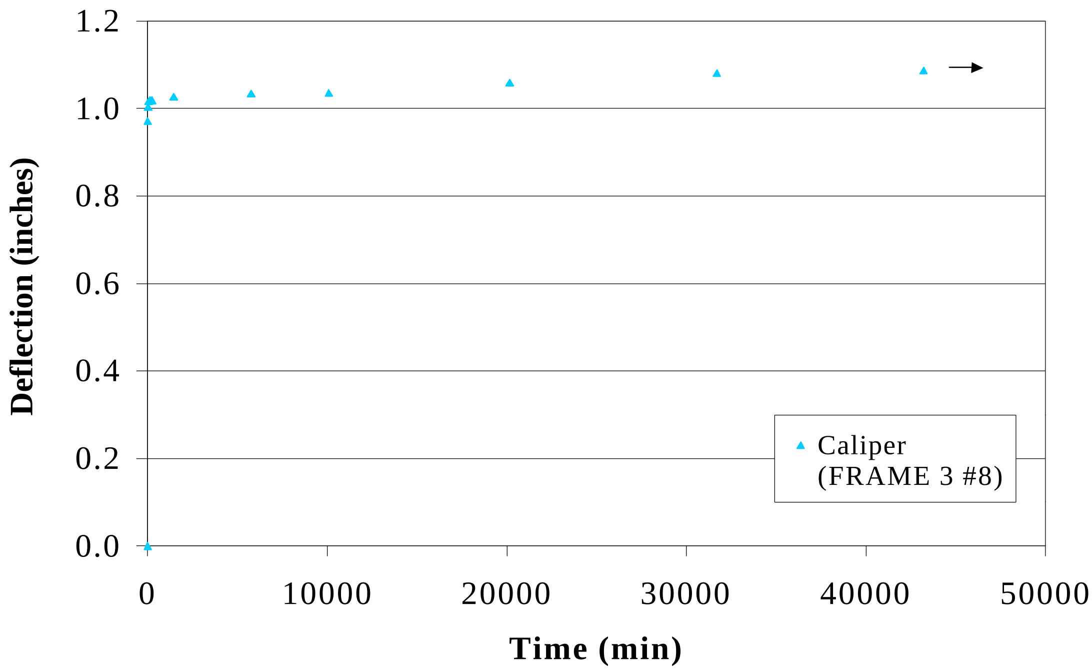
SS 300°F # 130



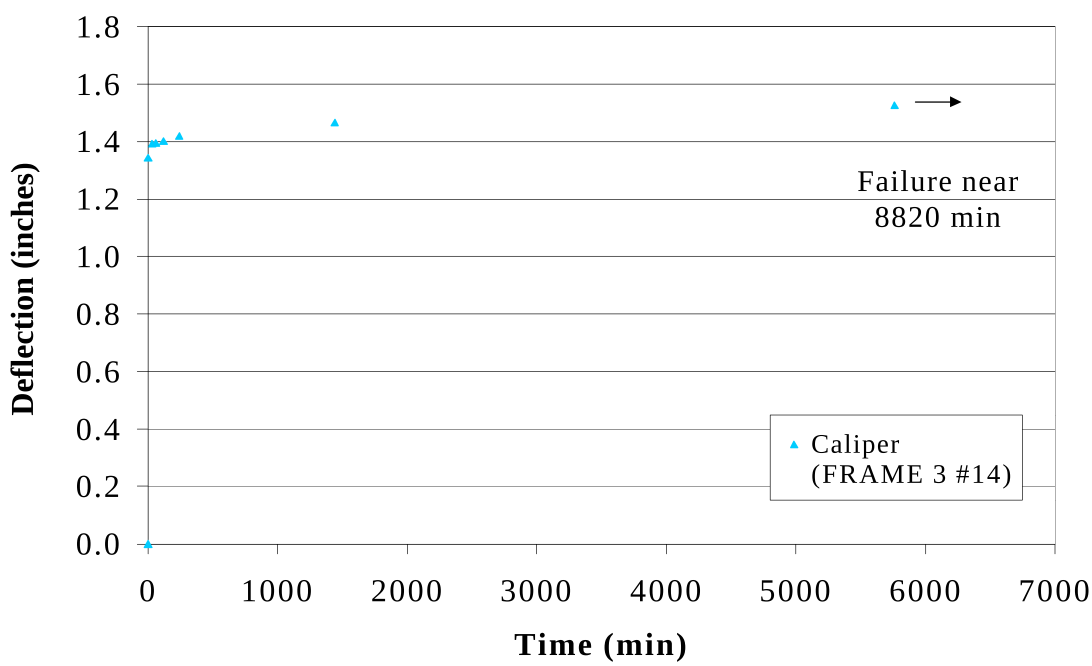
SS 300°F # 135

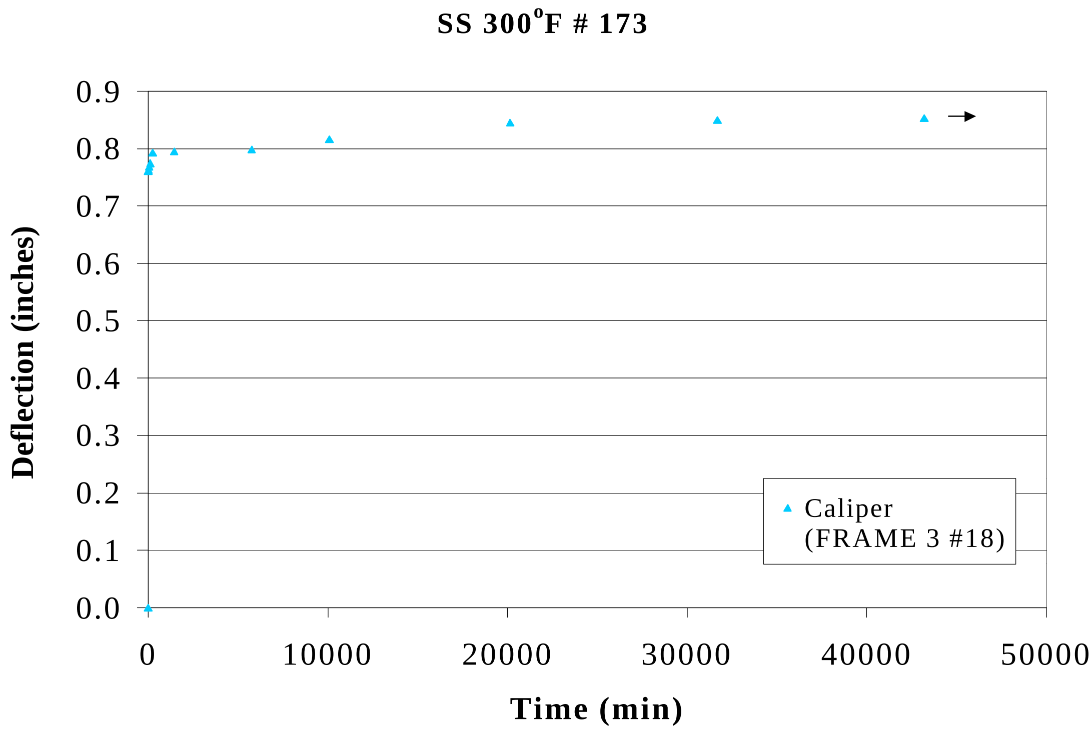


SS 300°F # 163

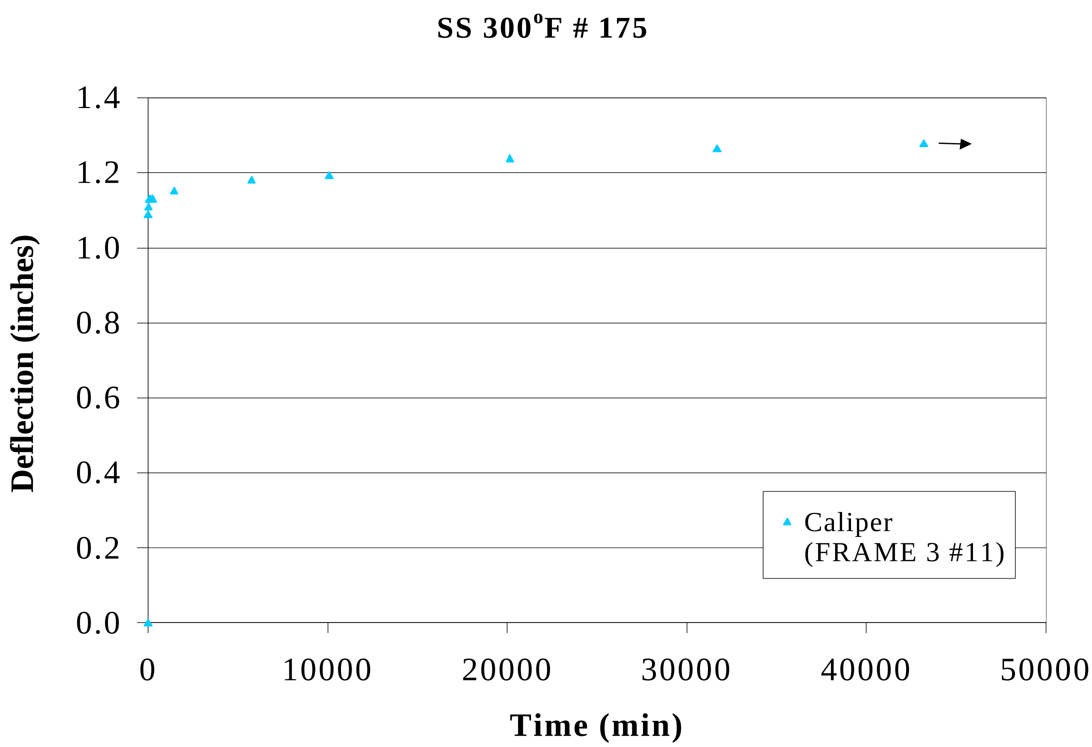


SS 300°F # 170



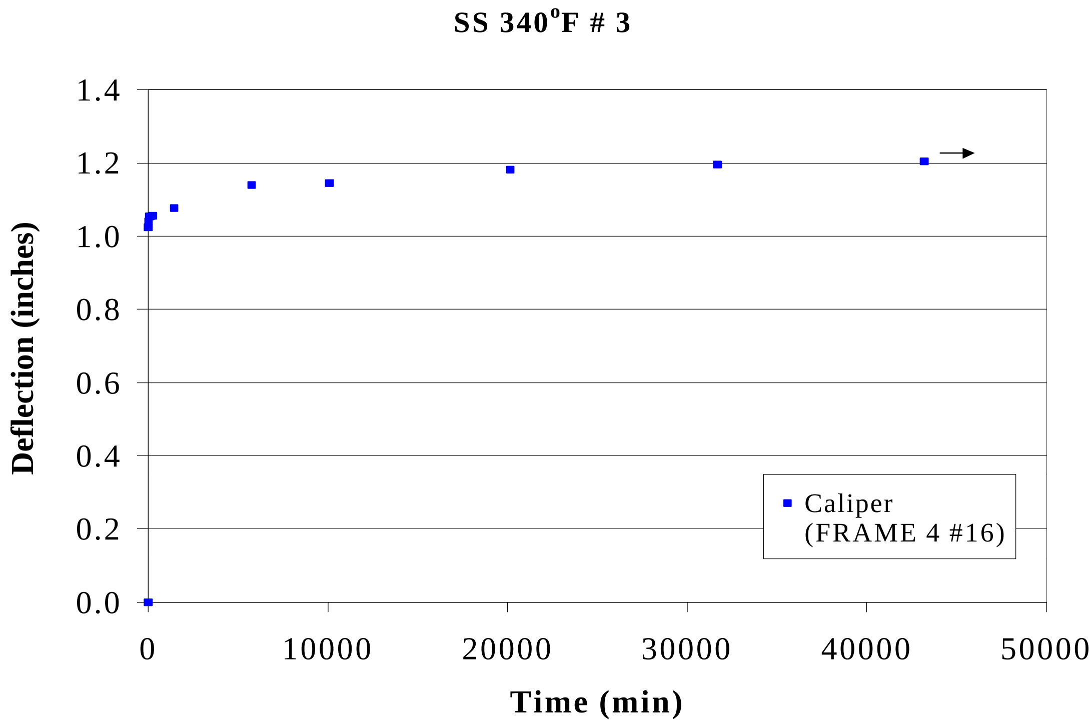


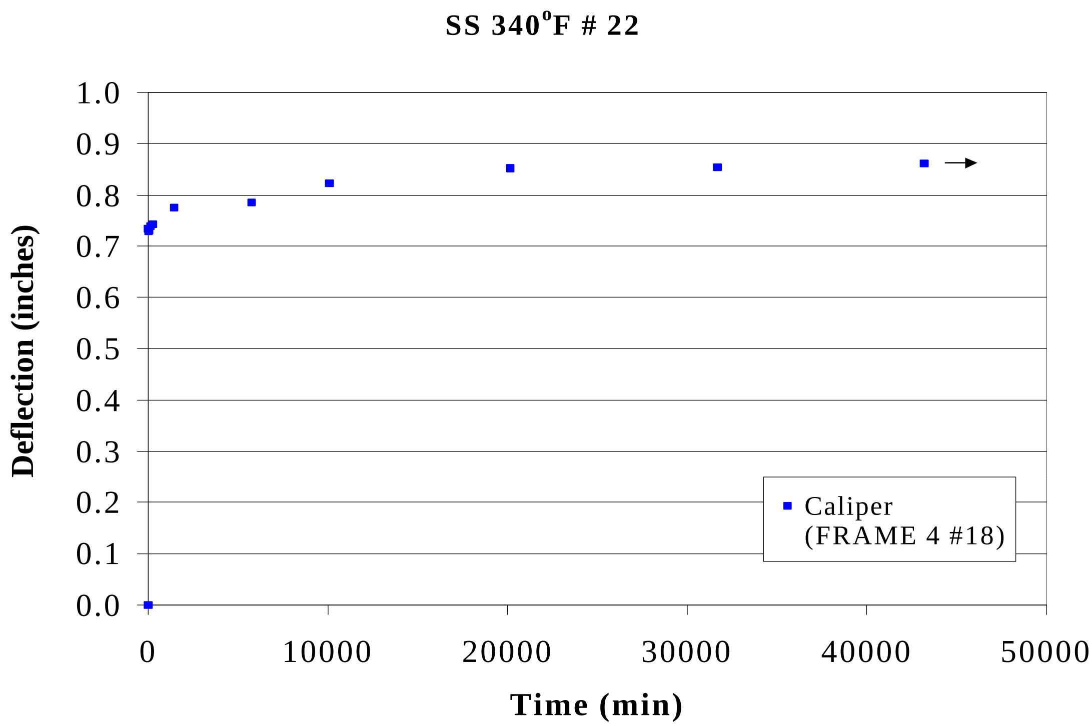
SS 300°F # 173
Deflection (inches)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 3 #18)

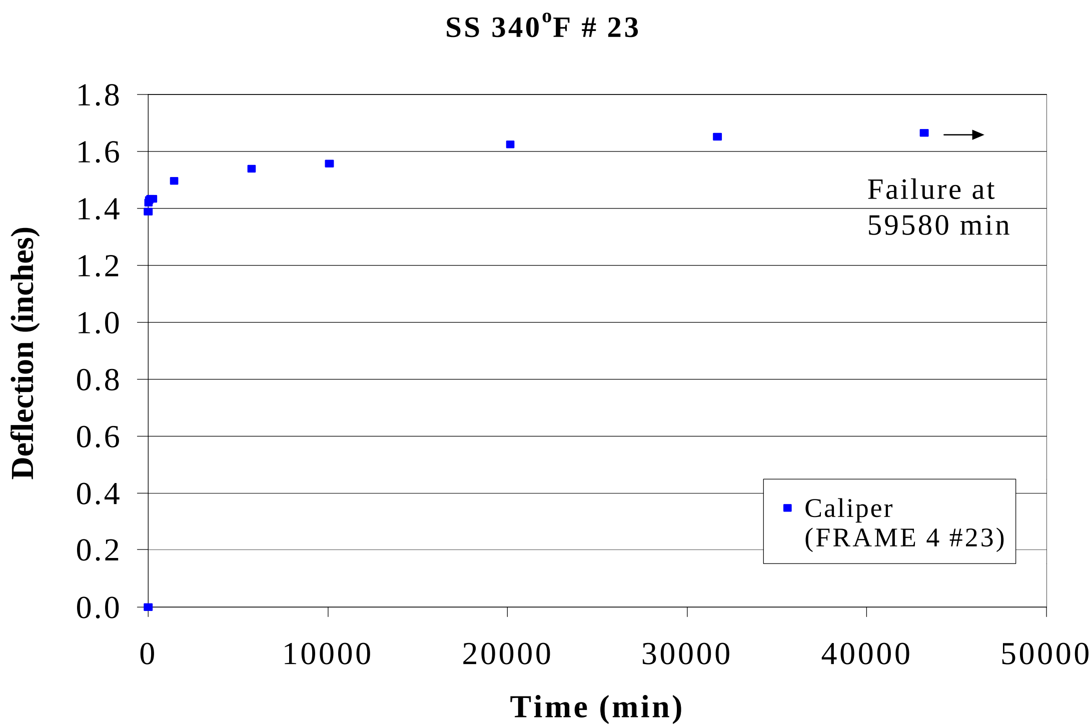


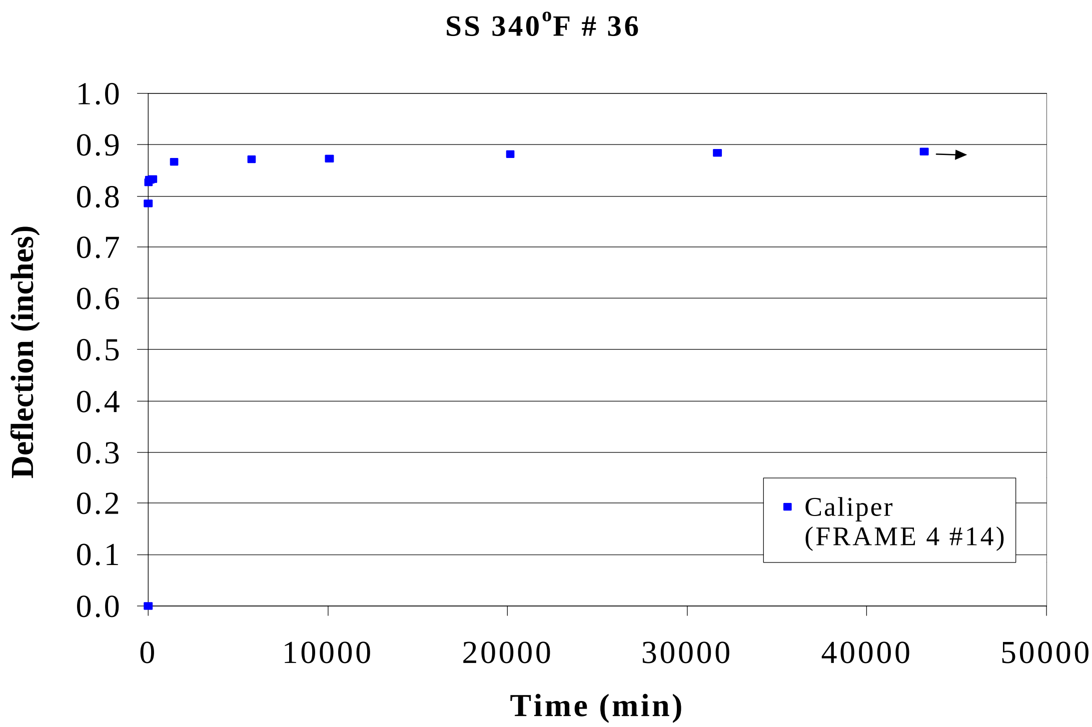
SS 300°F # 175
Deflection (inches)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 3 #11)

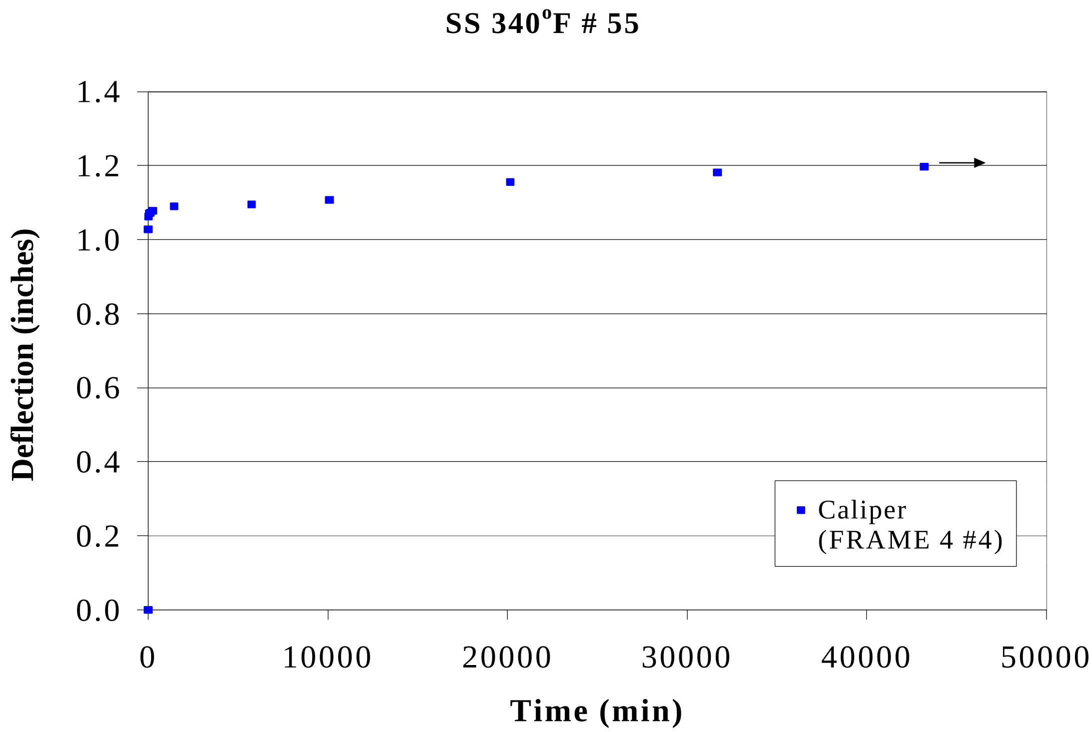
SOLID SAWN LUMBER: $340^{O}F$

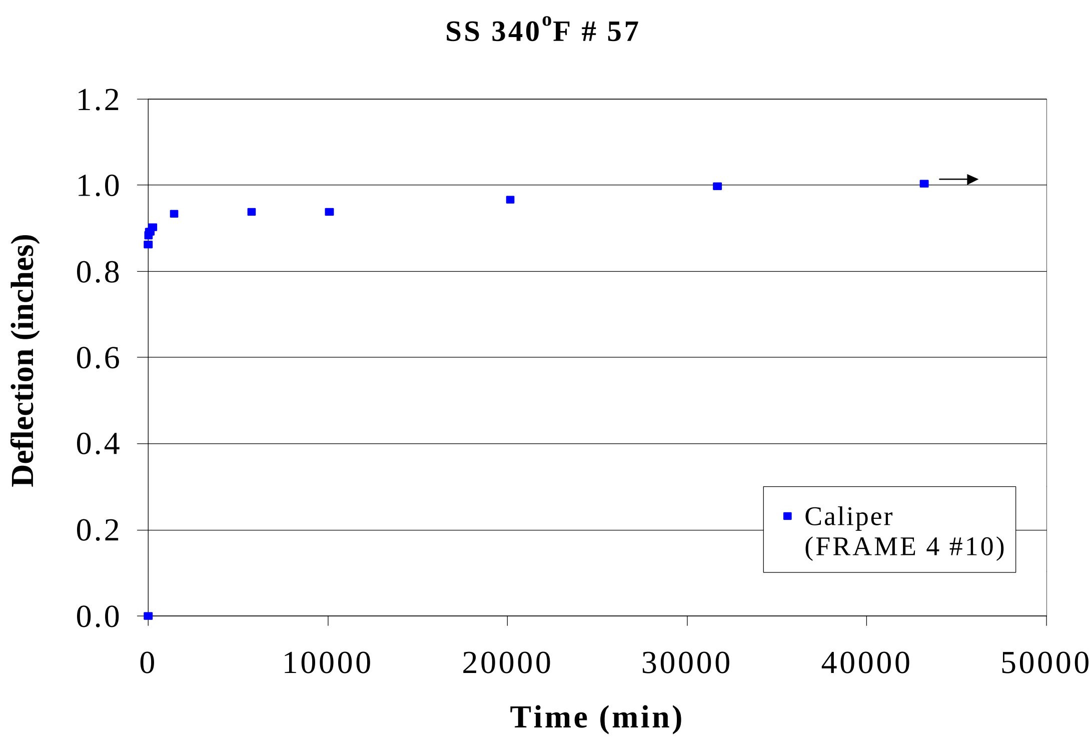




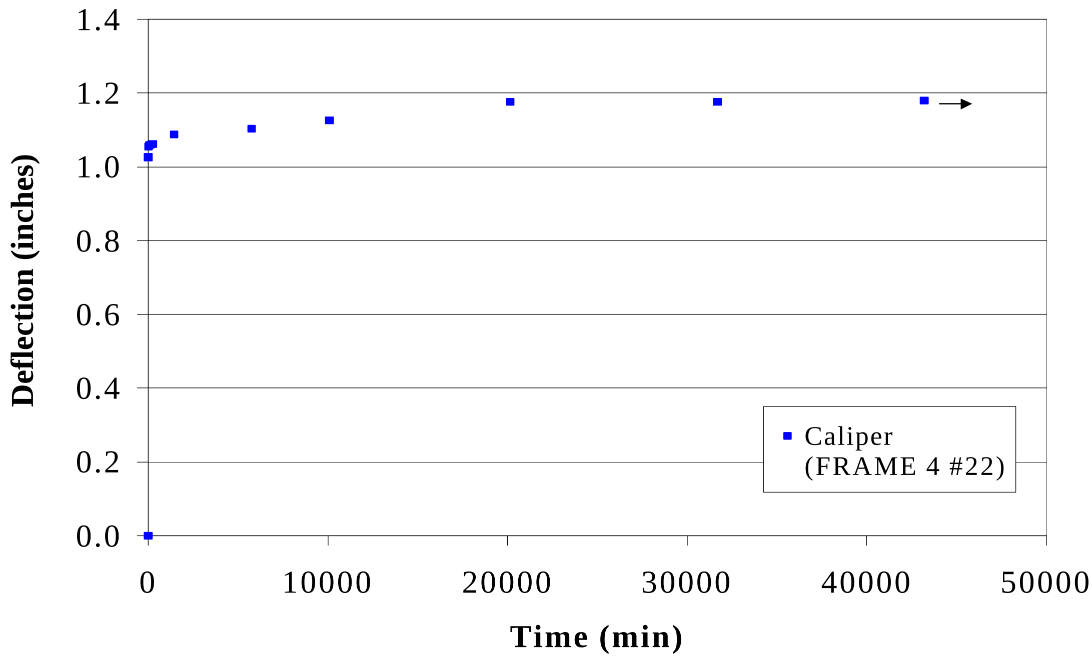

SS 340°F # 23
Deflection (inches)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
Time (min)
Failure at
59580 min
Caliper
(FRAME 4 #23)


SS 340°F # 36
Deflection (inches)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 4 #14)

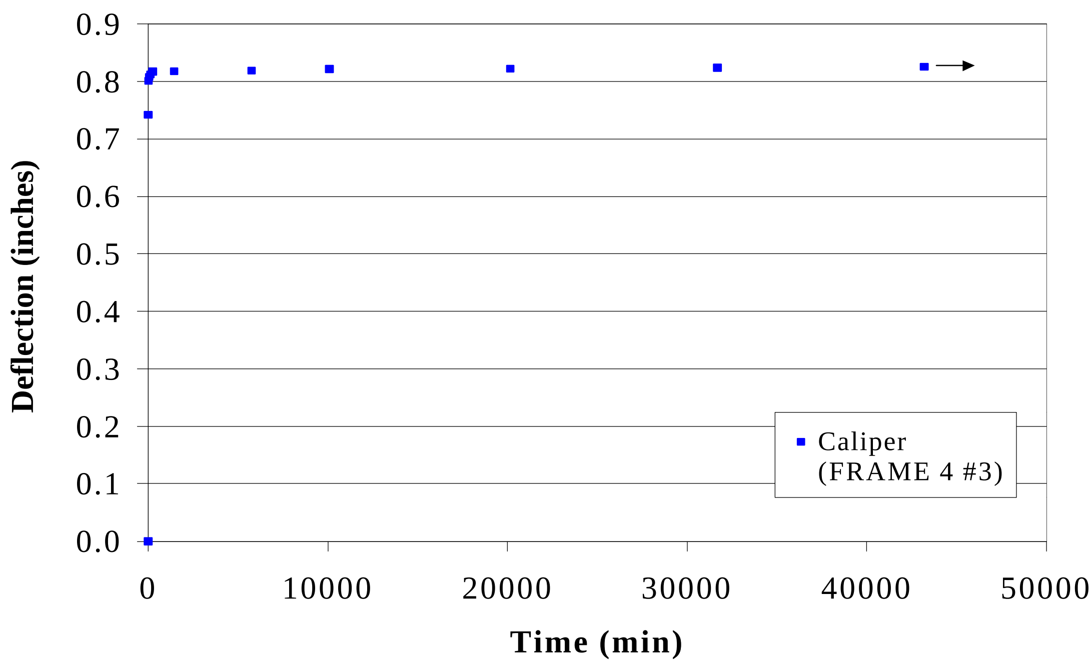

SS 340°F # 55
Deflection (inches)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 4 #4)

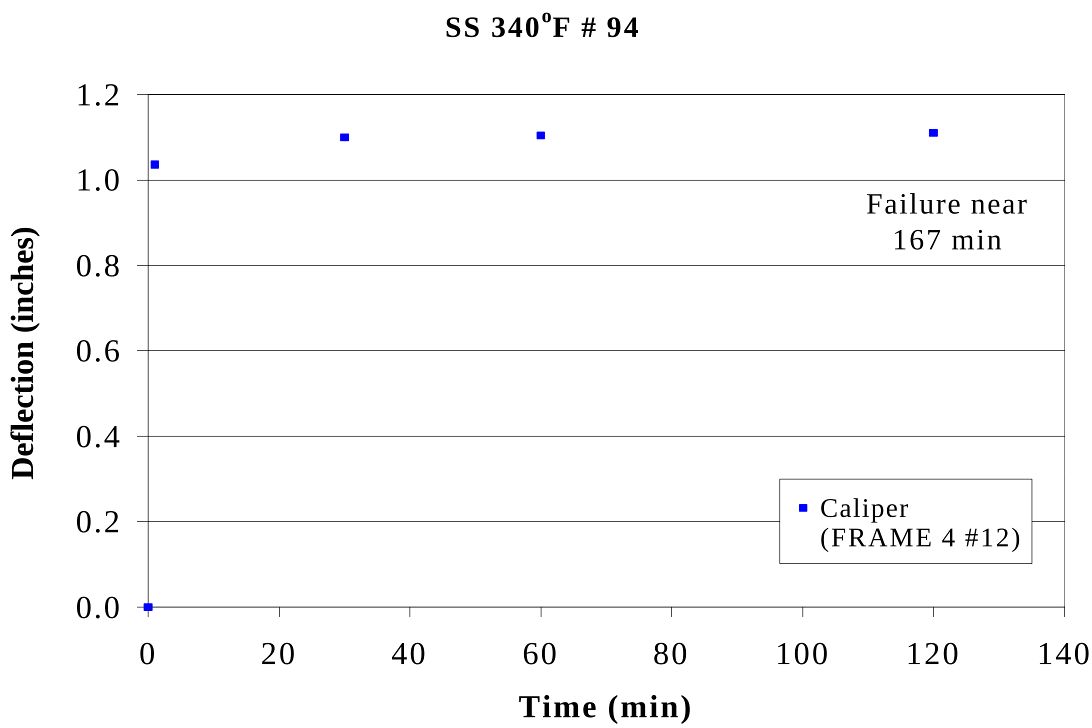

SS 340°F # 57
Deflection (inches)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 4 #10)

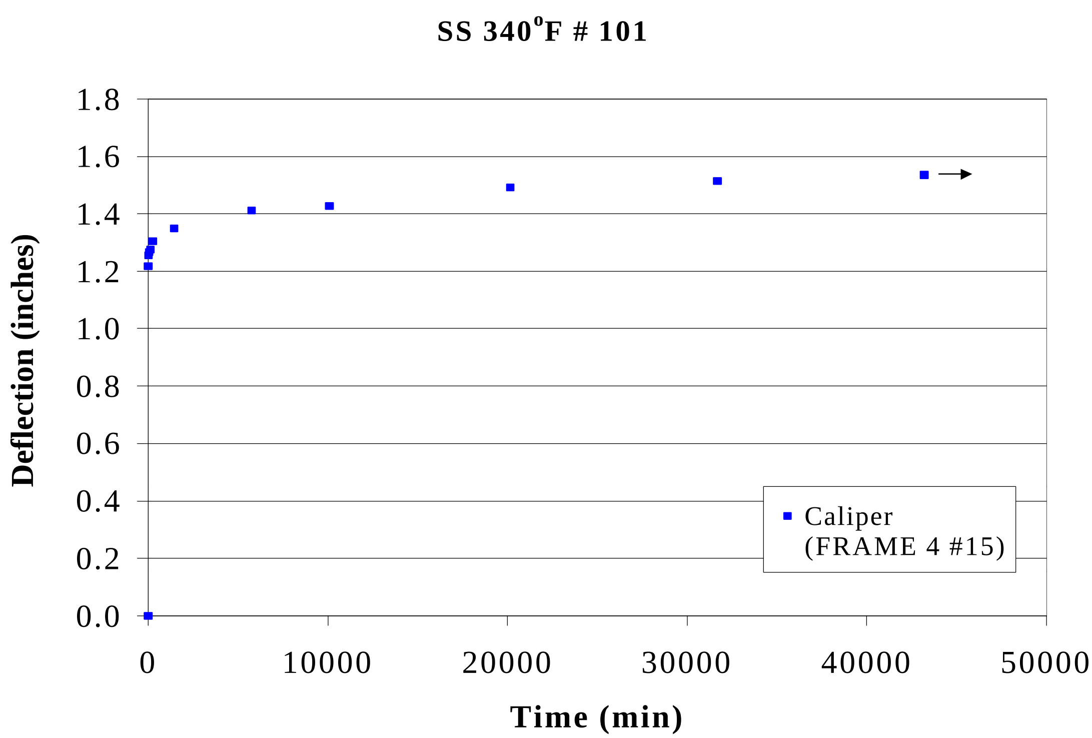
SS 340°F # 64

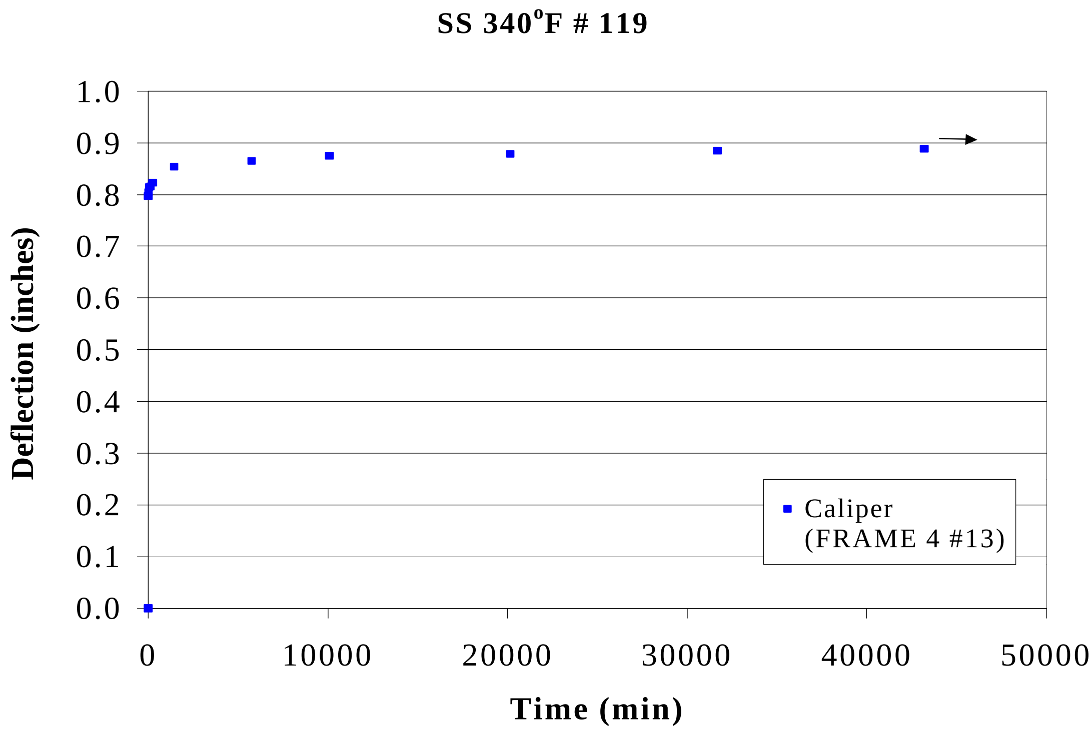


SS 340°F # 83

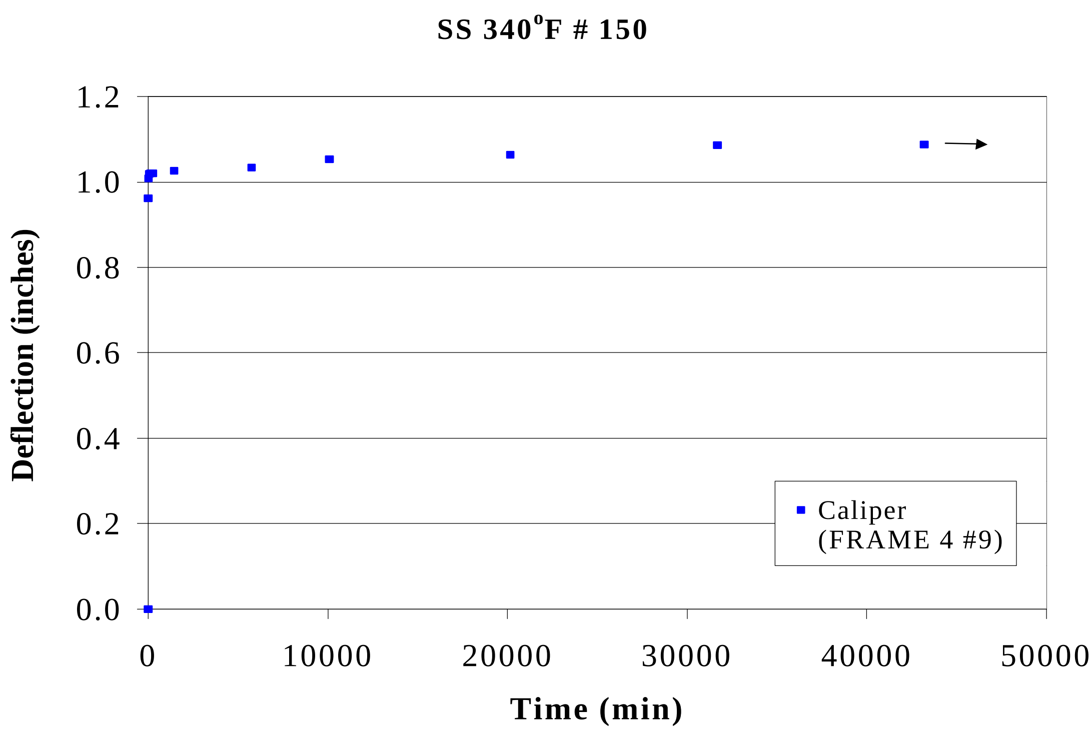



SS 340°F # 94
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
Failure near
167 min
Caliper
(FRAME 4 #12)
Deflection (inches)
Time (min)

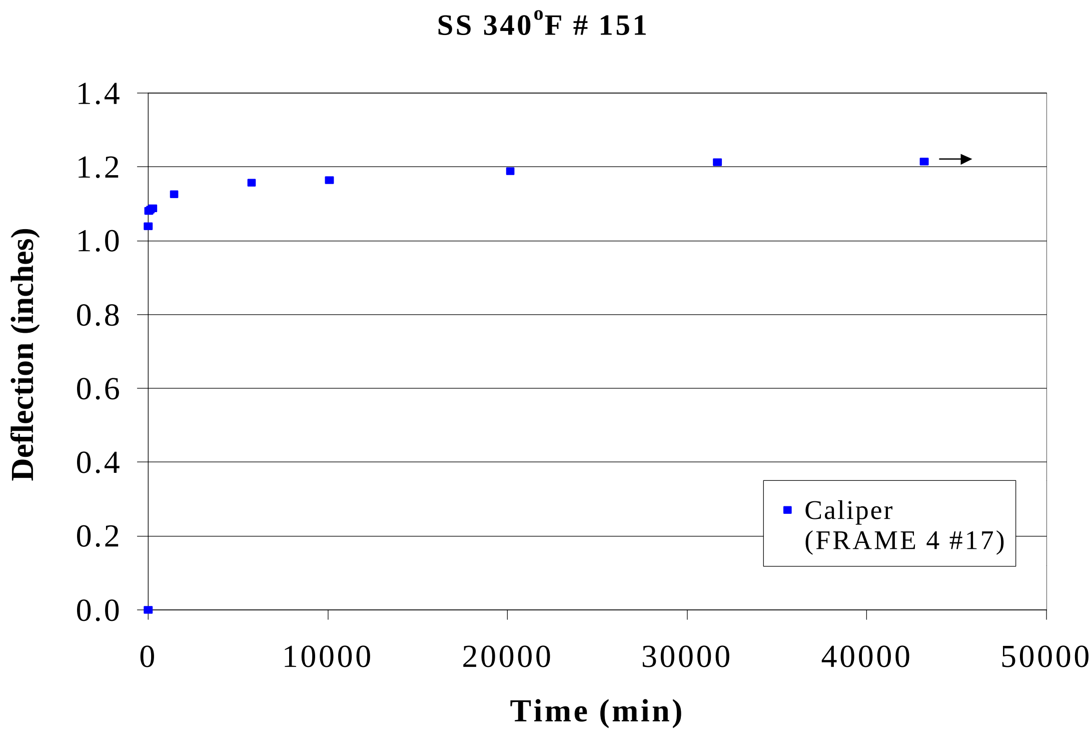

SS 340°F # 101
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
Caliper
(FRAME 4 #15)
Deflection (inches)
Time (min)

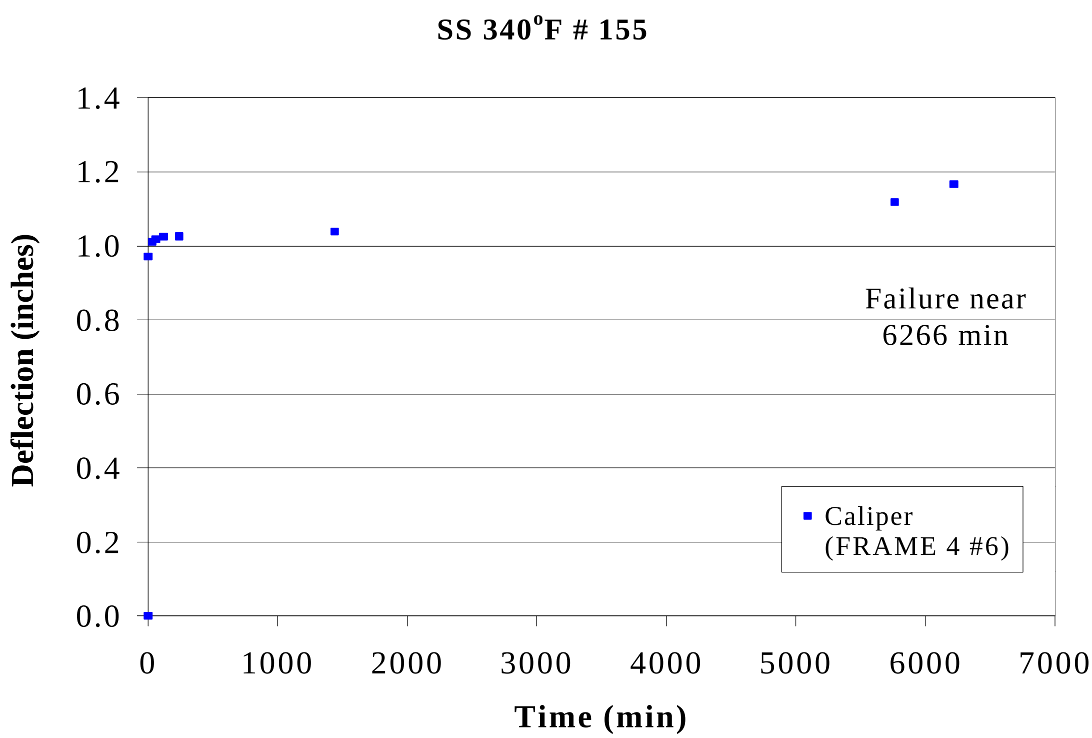


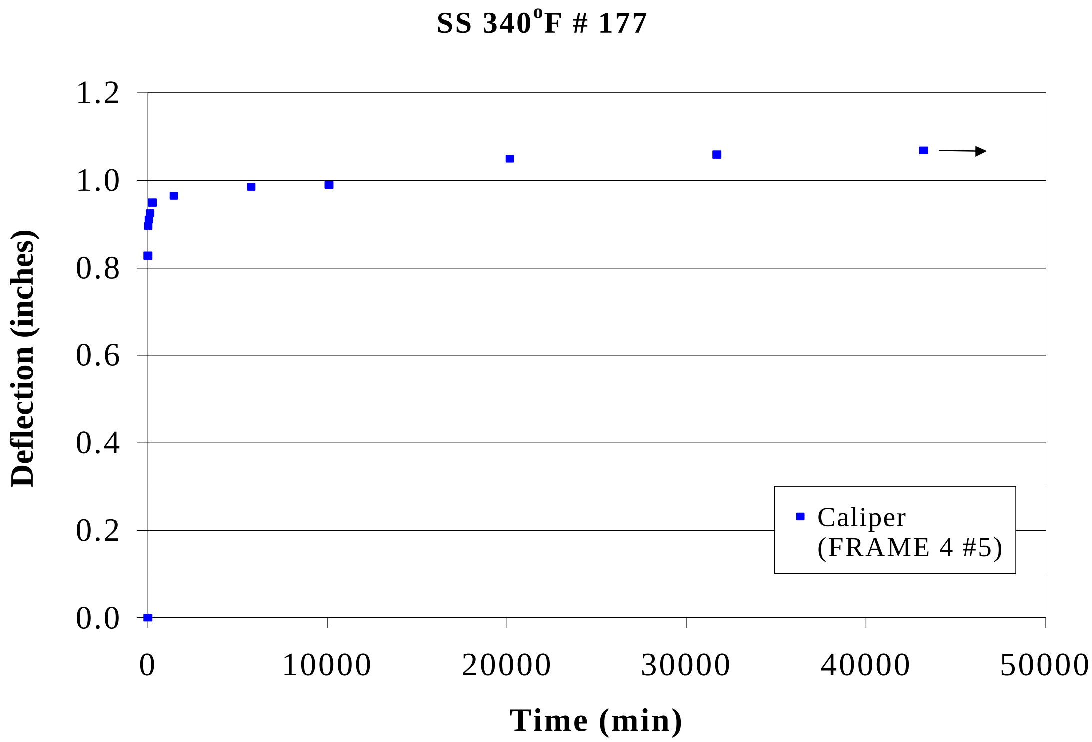
SS 340°F # 119
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 4 #13)



SS 340°F # 150
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 4 #9)


SS 340°F # 151
Deflection (inches)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 4 #17)

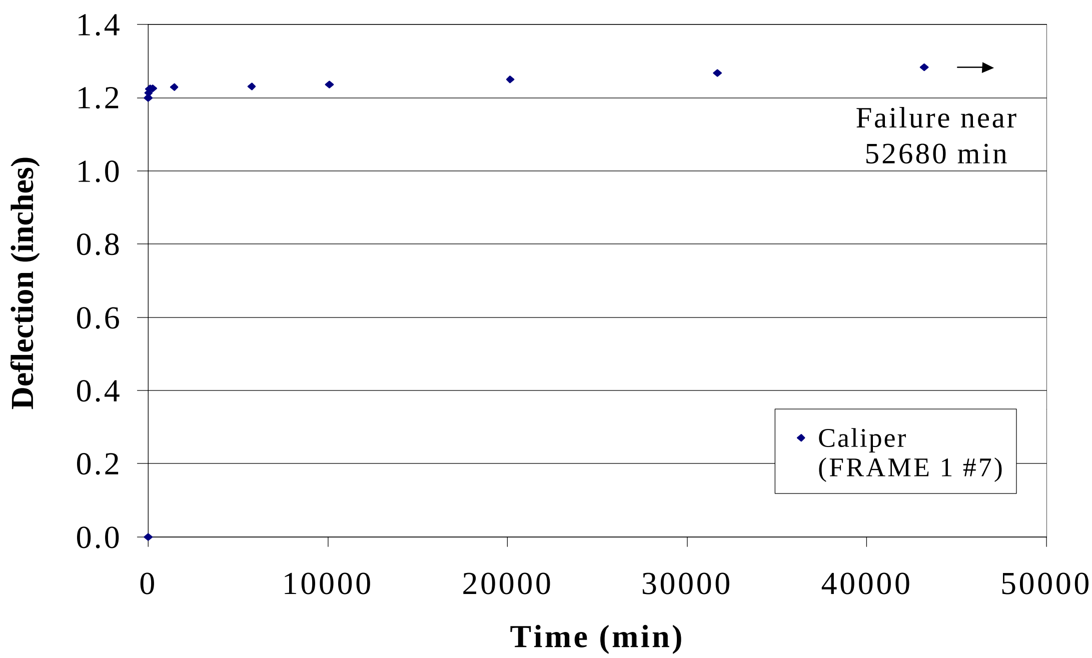

SS 340°F # 155
Deflection (inches)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
5000
6000
7000
Time (min)
Failure near
6266 min
Caliper
(FRAME 4 #6)



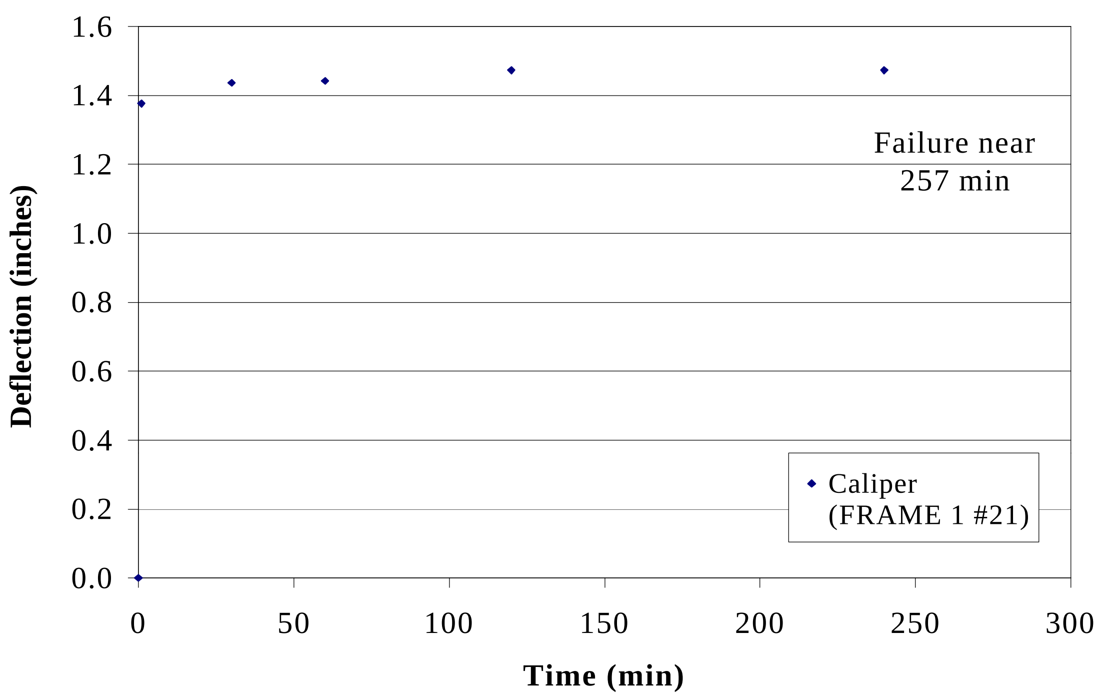
SS 340°F # 177
Deflection (inches)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
Time (min)
Caliper
(FRAME 4 #5)

SOLID SAWN LUMBER: 380°F

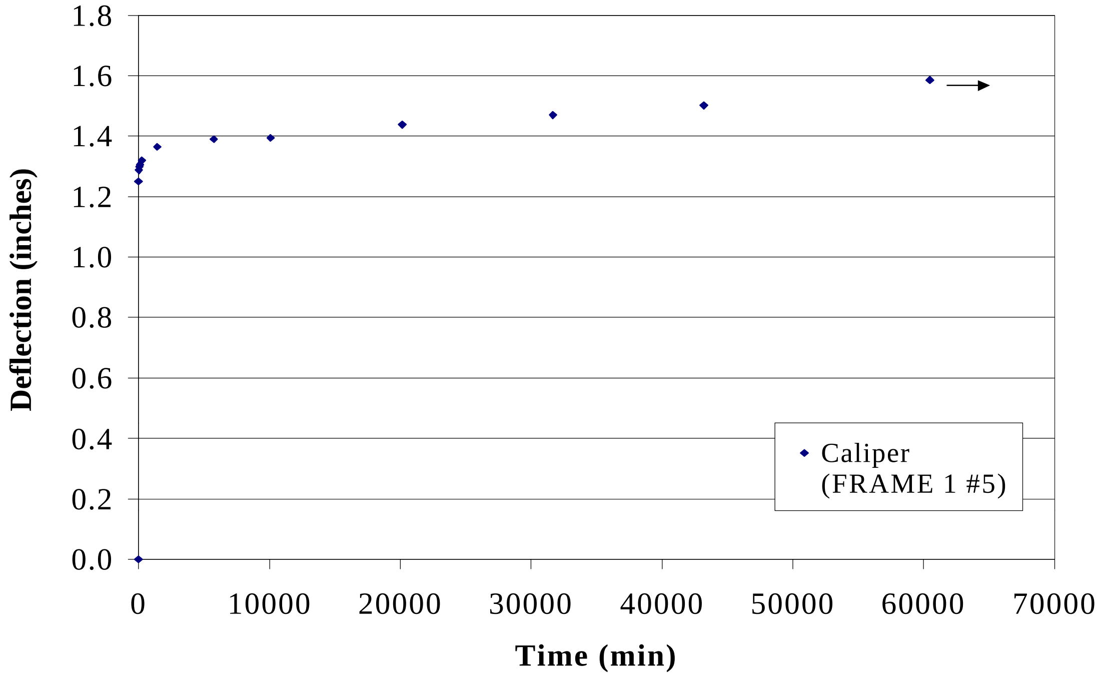
SS 380°F # 4



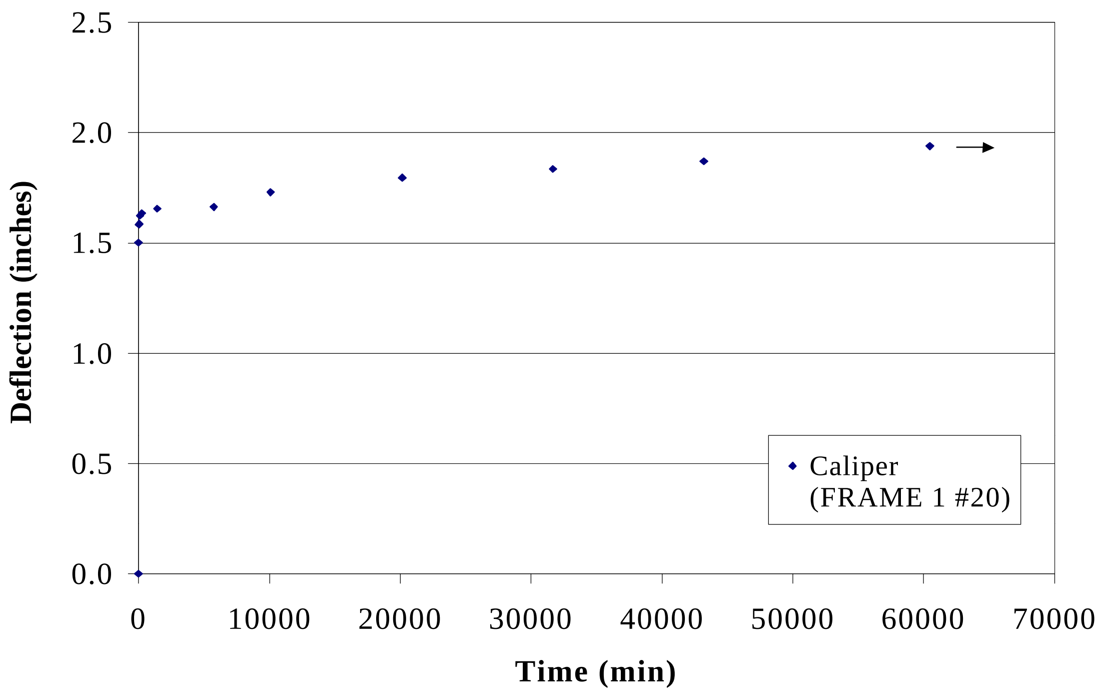
SS 380°F # 15



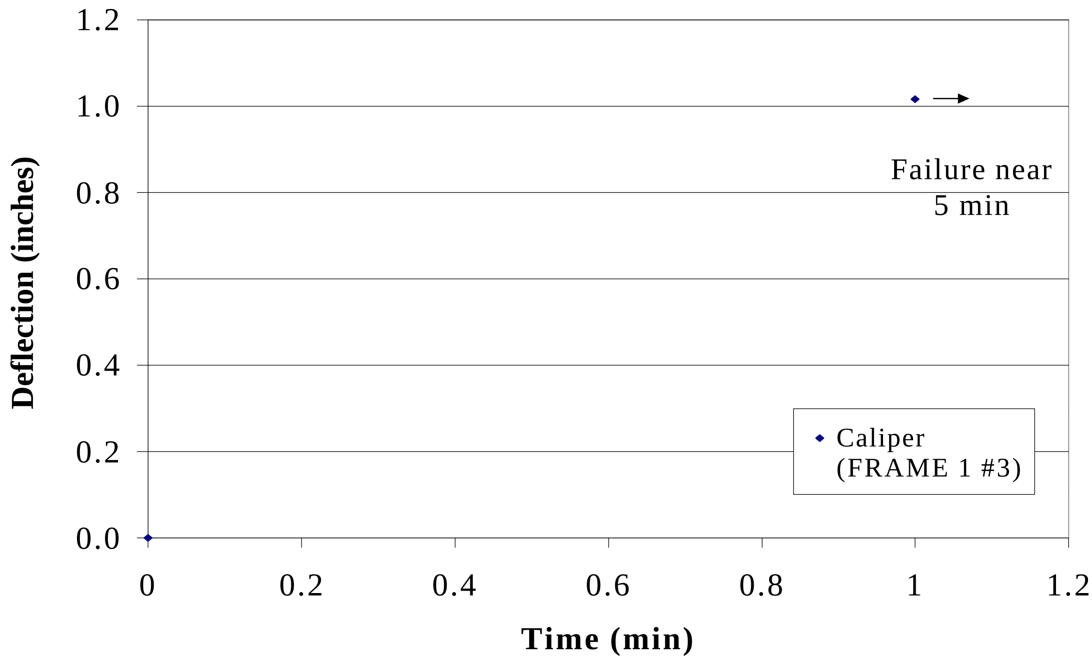
SS 380°F # 18



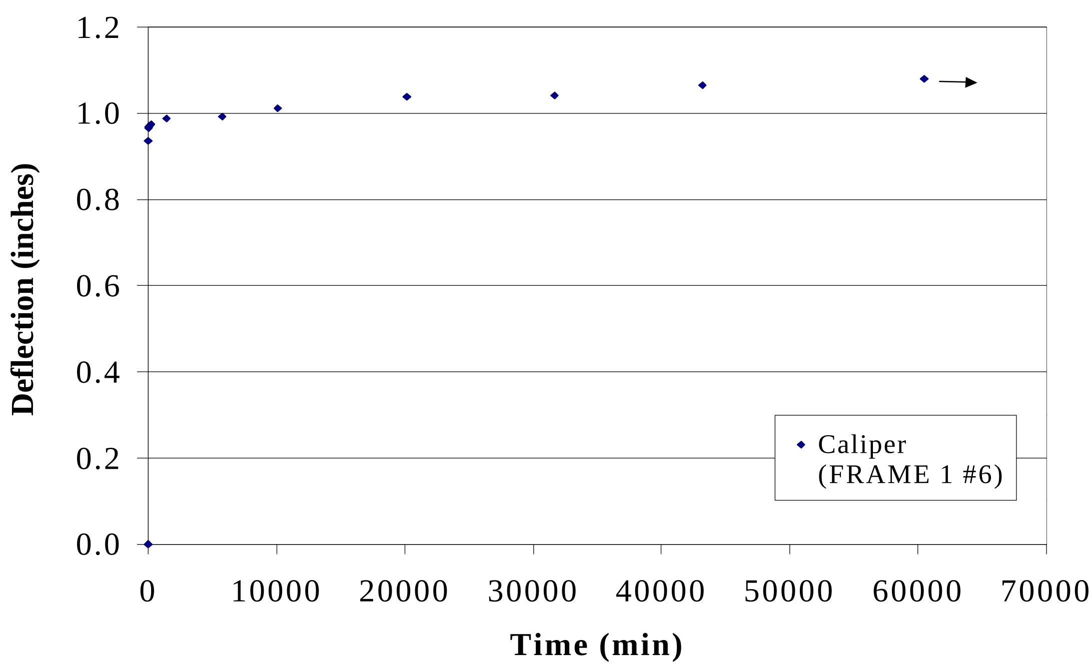
SS 380°F # 21

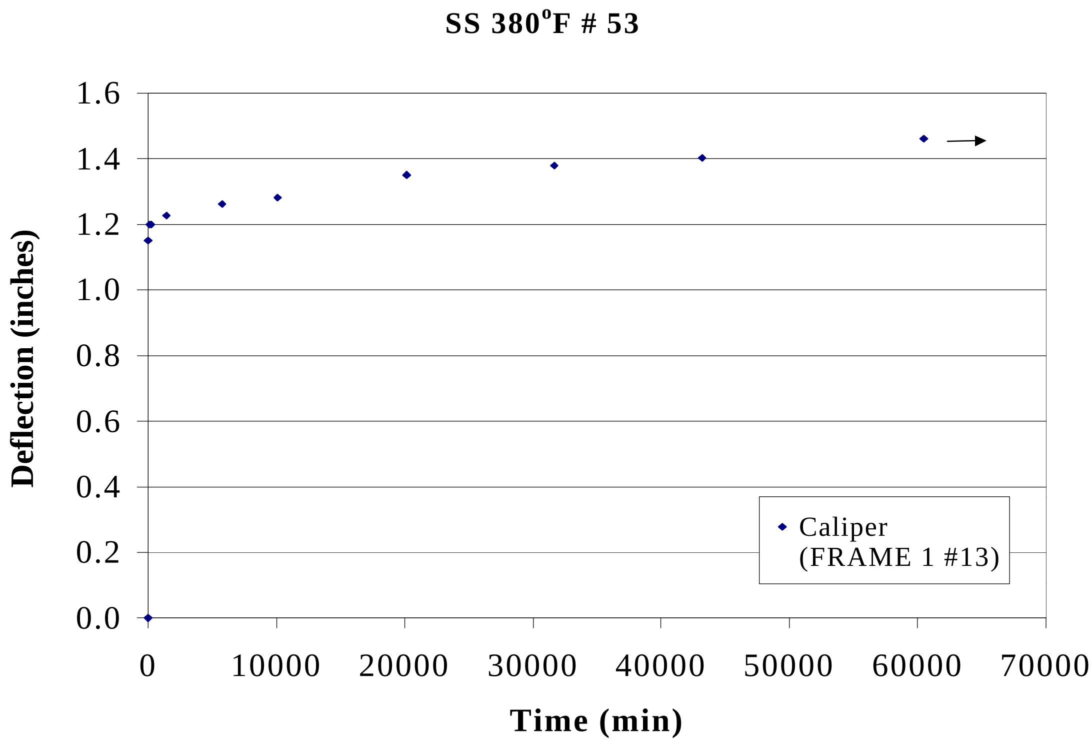


SS 380°F # 24

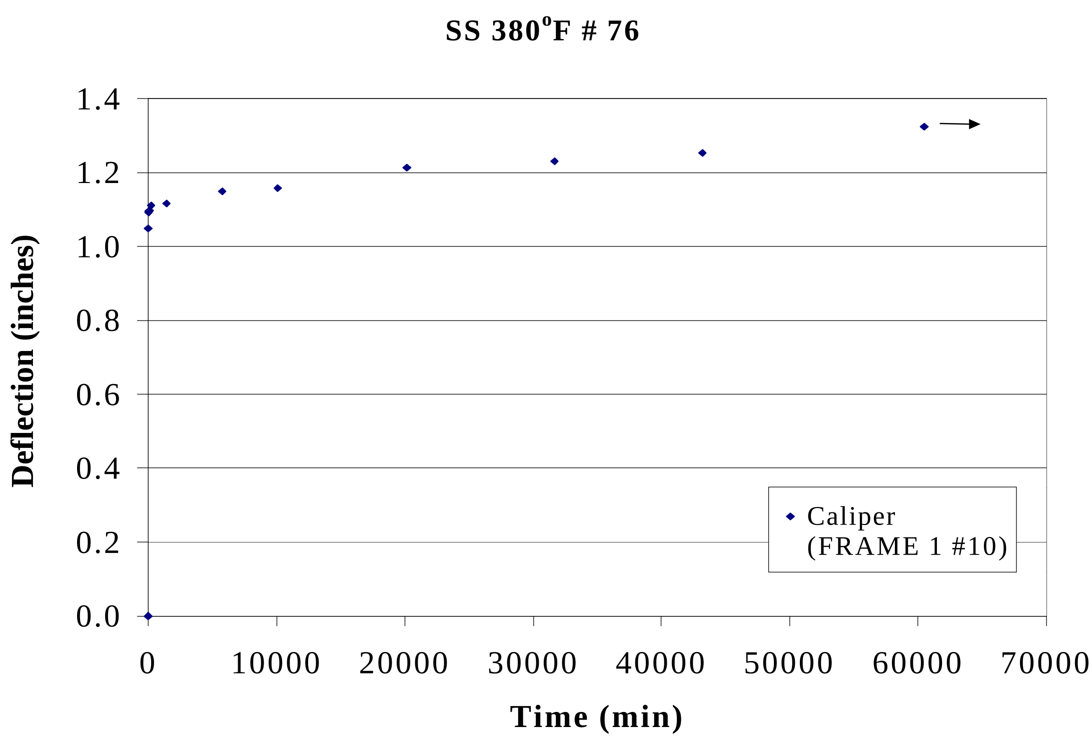


SS 380°F # 27

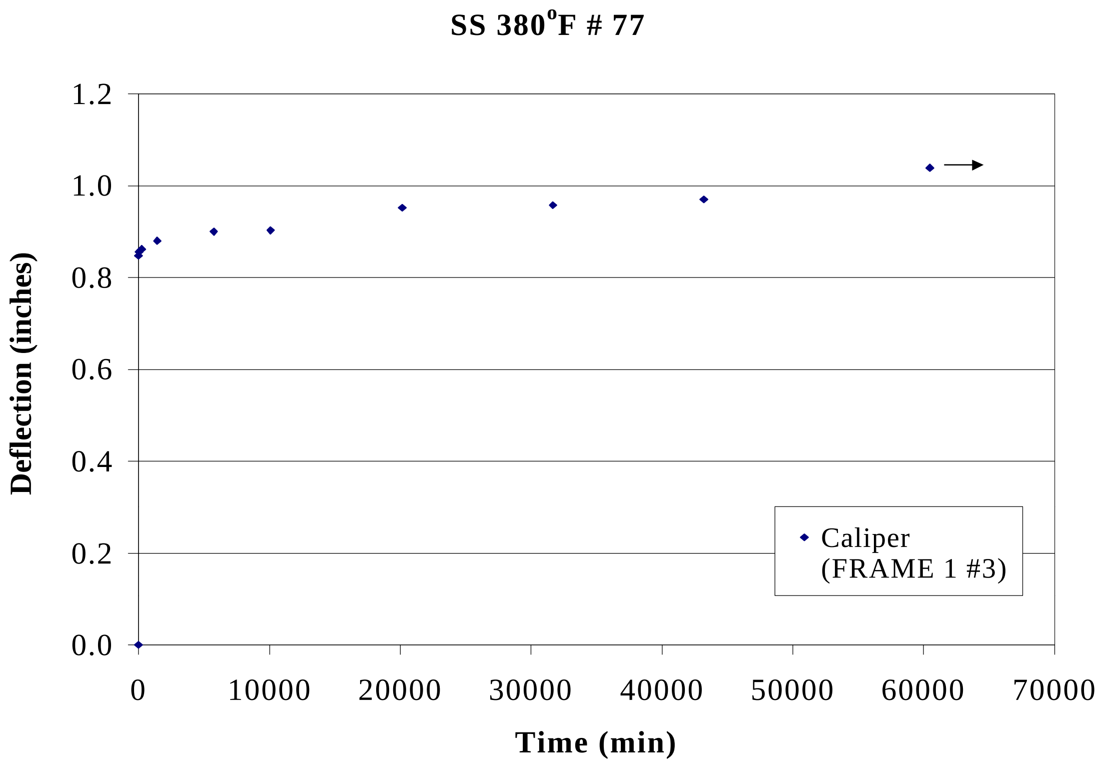


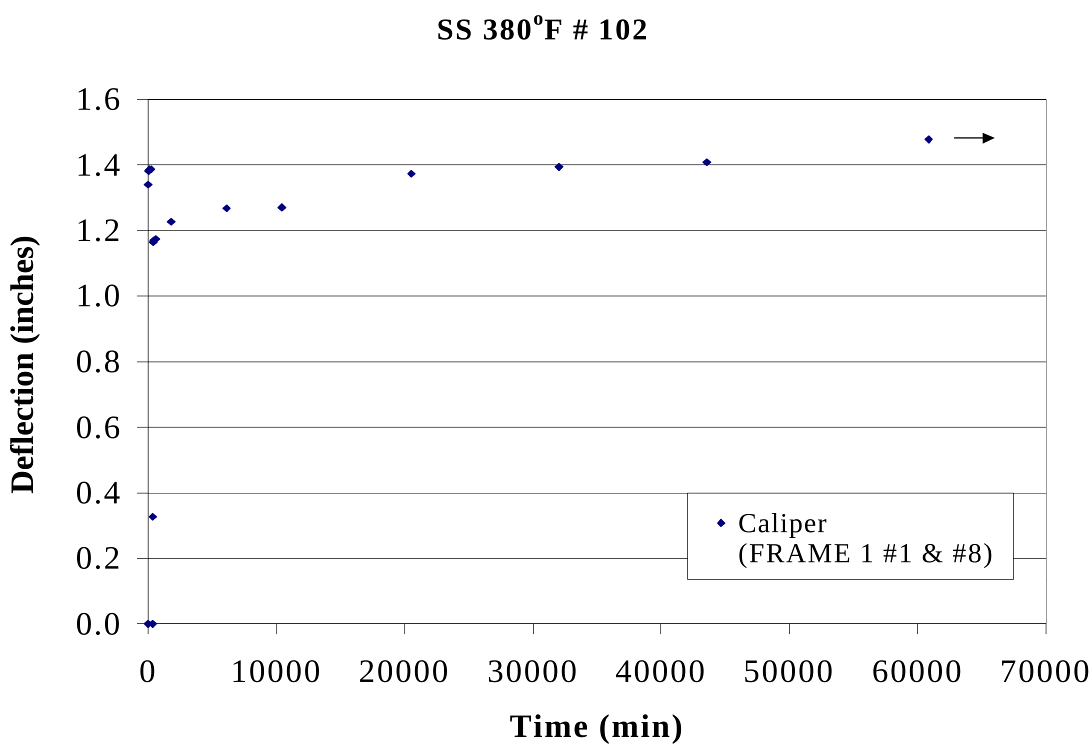


SS 380°F # 53
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 1 #13)

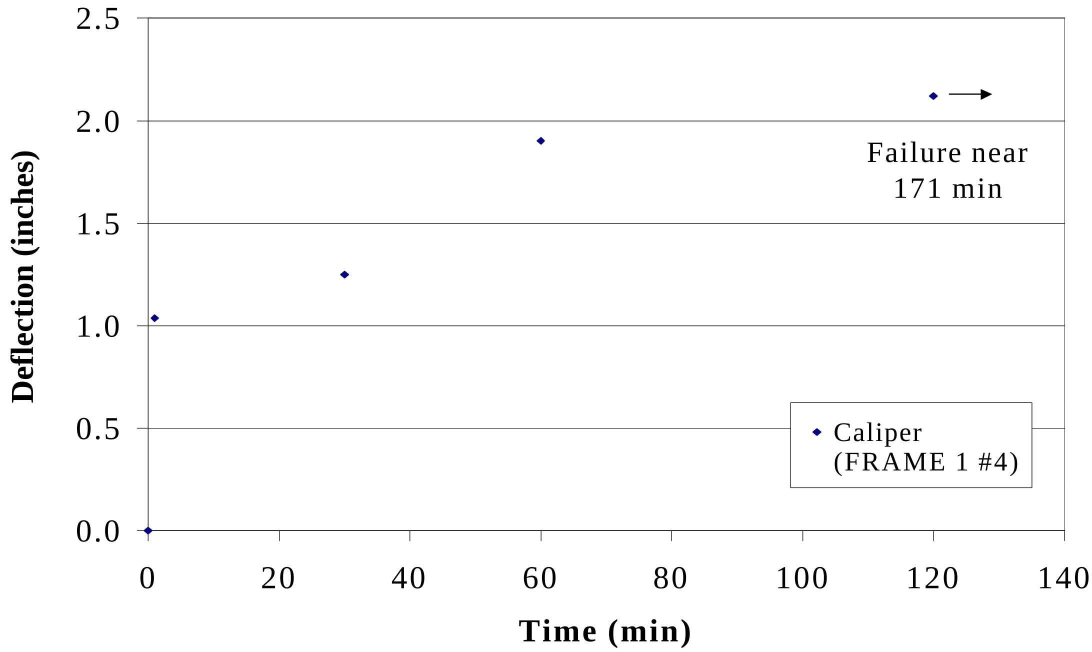


SS 380°F # 76
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 1 #10)

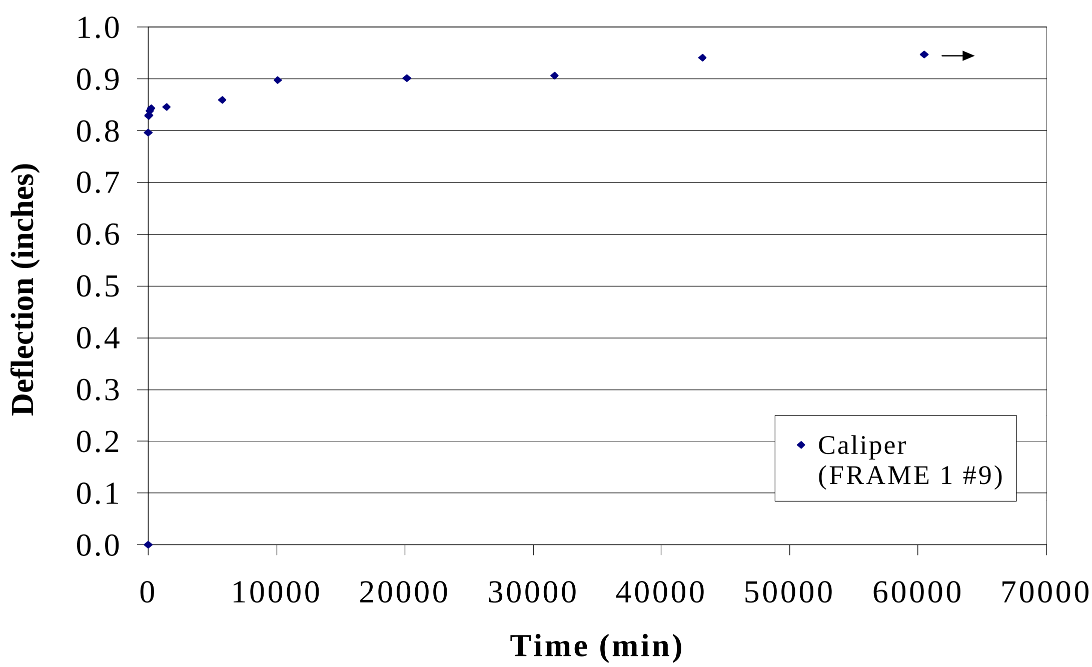

SS 380^{o}F # 77
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 1 #3)

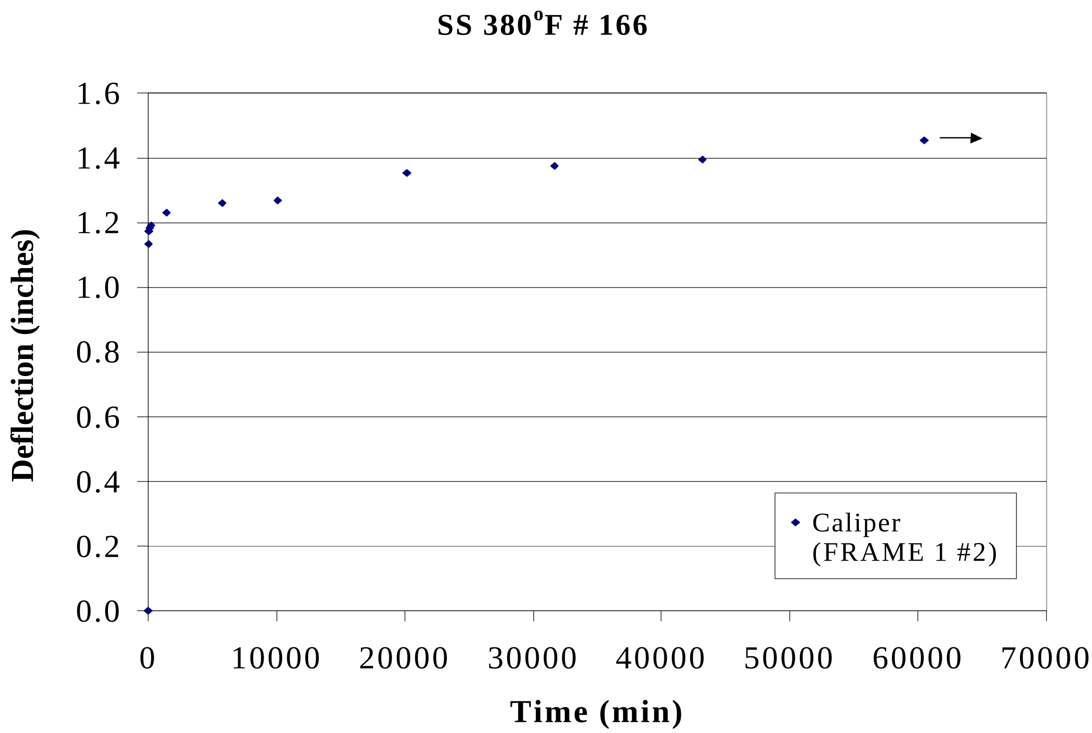

SS 380^{o}F # 102
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 1 #1 & #8)

SS 380°F # 106

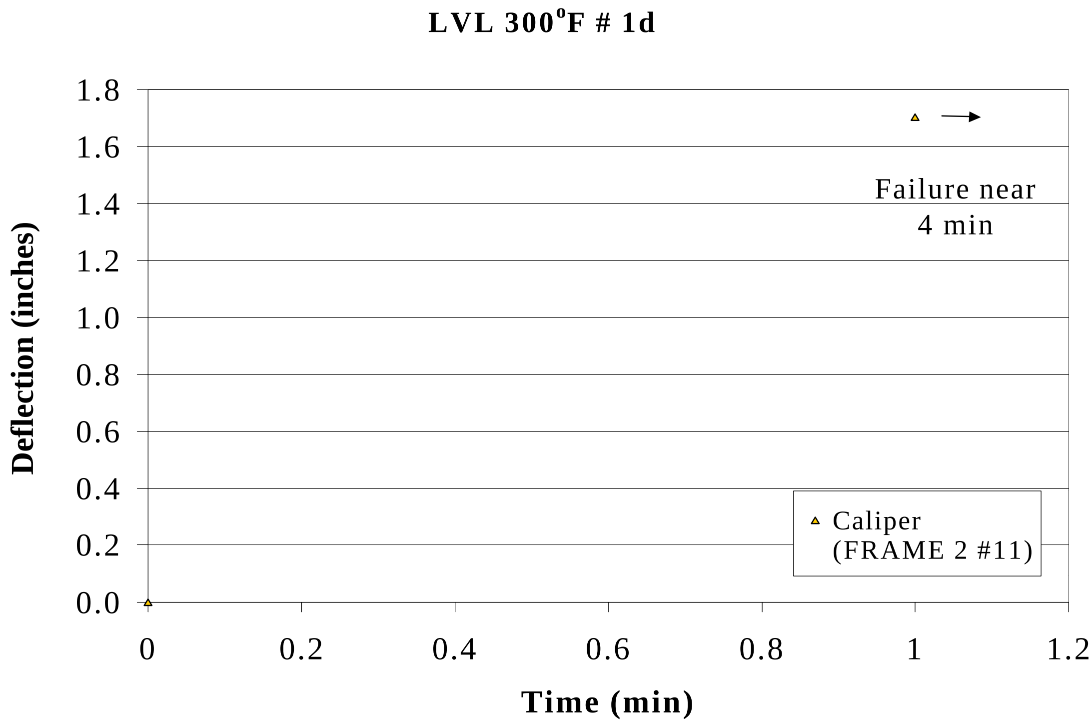


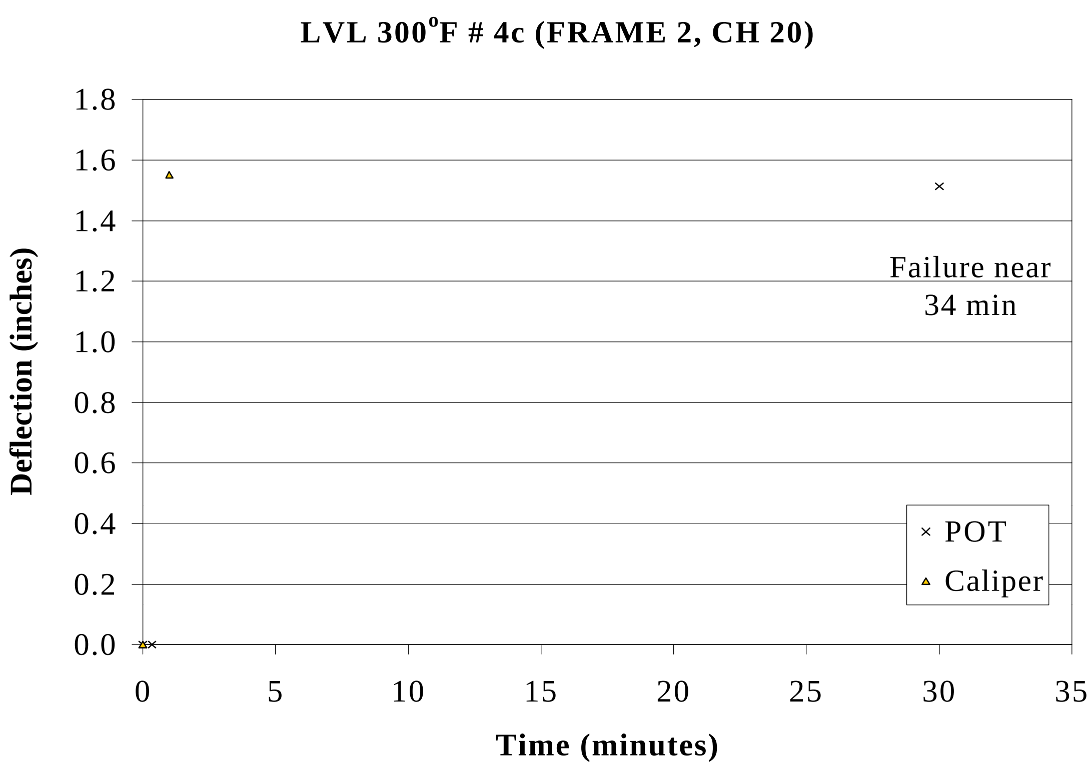
SS 380°F # 160

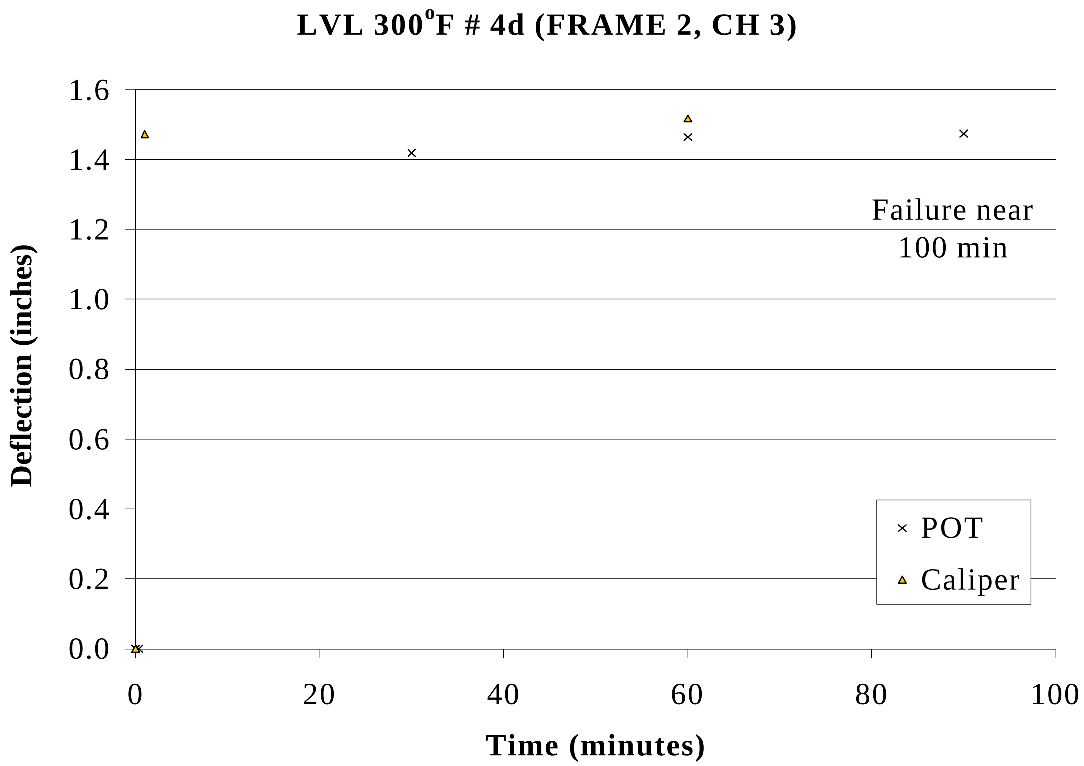



SS 380°F # 166
Deflection (inches)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 1 #2)

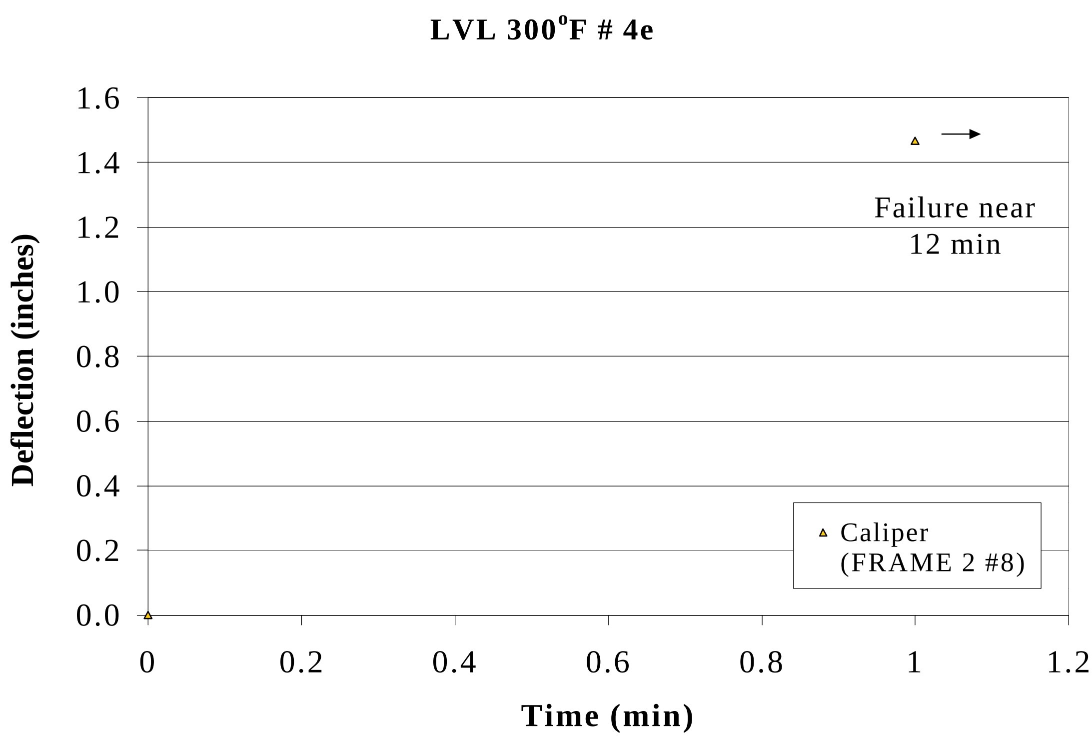
LAMINATED VENEER LUMBER: 300°F



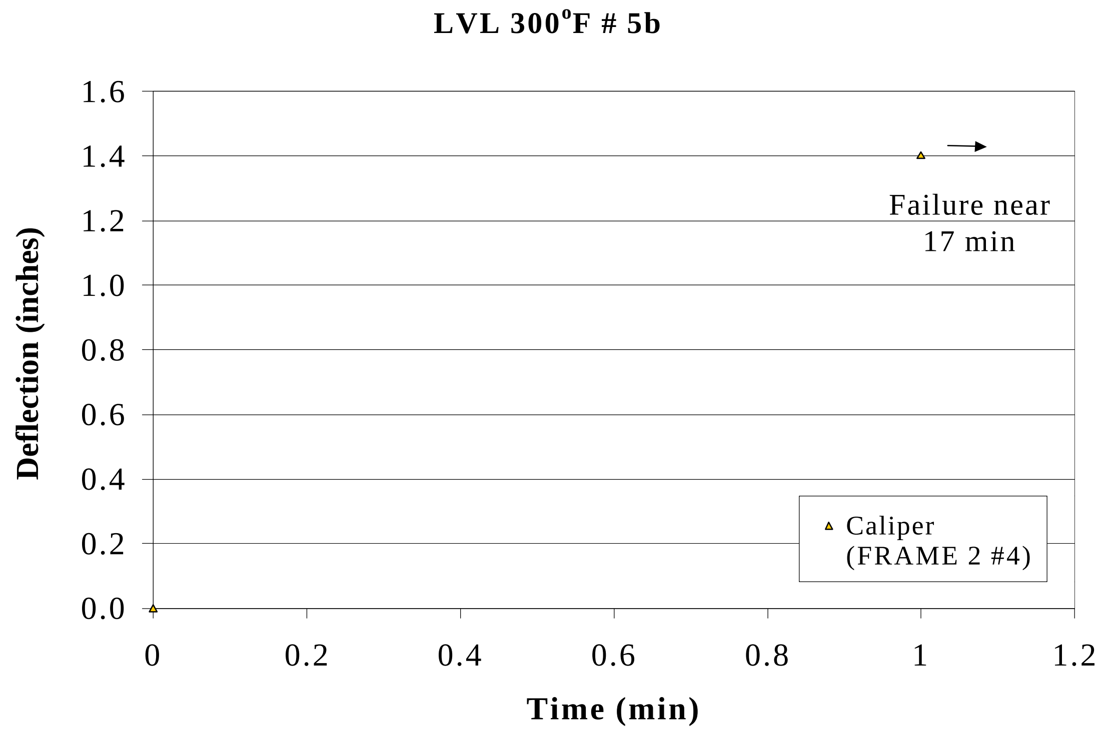


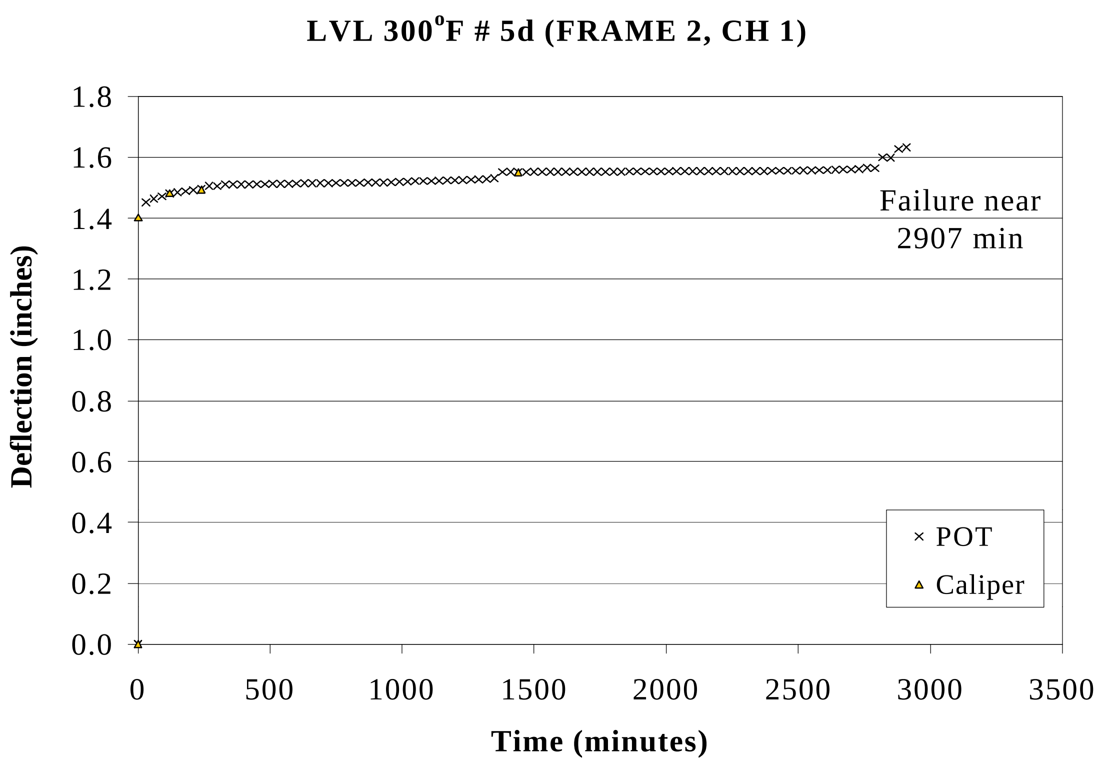


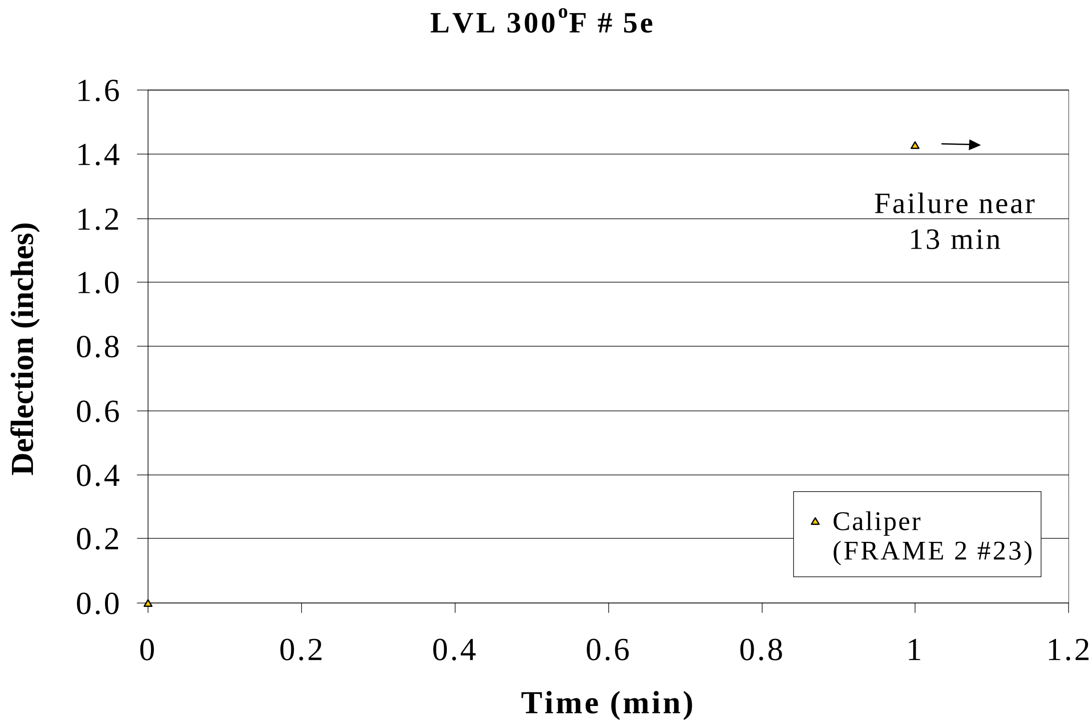
LVL 300°F # 4d (FRAME 2, CH 3)
Deflection (inches)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
Time (minutes)
Failure near
100 min
POT
Caliper

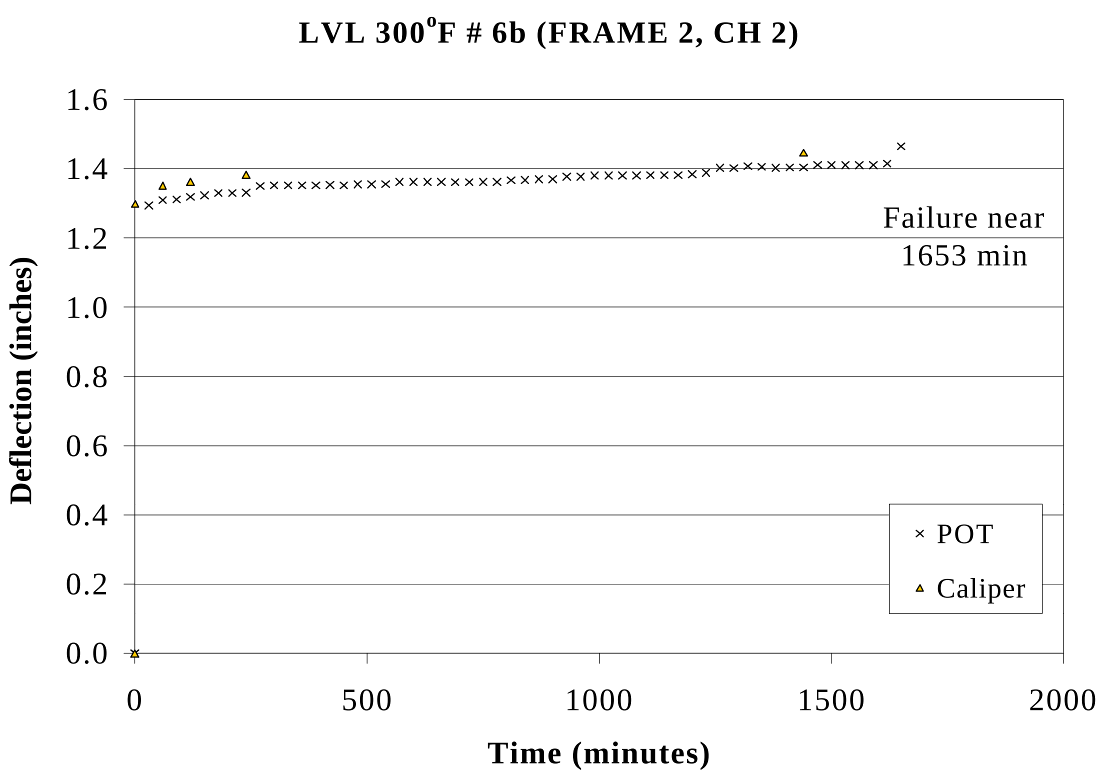


LVL 300°F # 4e
Deflection (inches)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
0.2
0.4
0.6
0.8
1
1.2
Time (min)
Failure near
12 min
Caliper
(FRAME 2 #8)

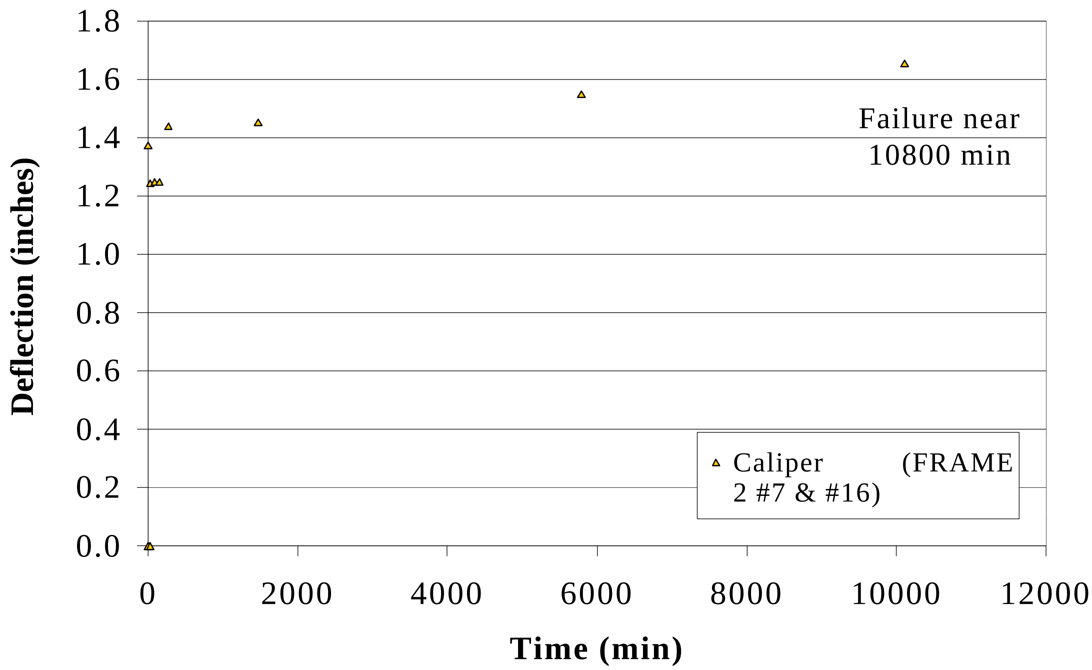

LVL 300°F # 5b
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
0.2
0.4
0.6
0.8
1
1.2
Time (min)
Failure near
17 min
Caliper
(FRAME 2 #4)


LVL 300°F # 5d (FRAME 2, CH 1)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
500
1000
1500
2000
2500
3000
3500
Time (minutes)
Failure near
2907 min
POT
Caliper

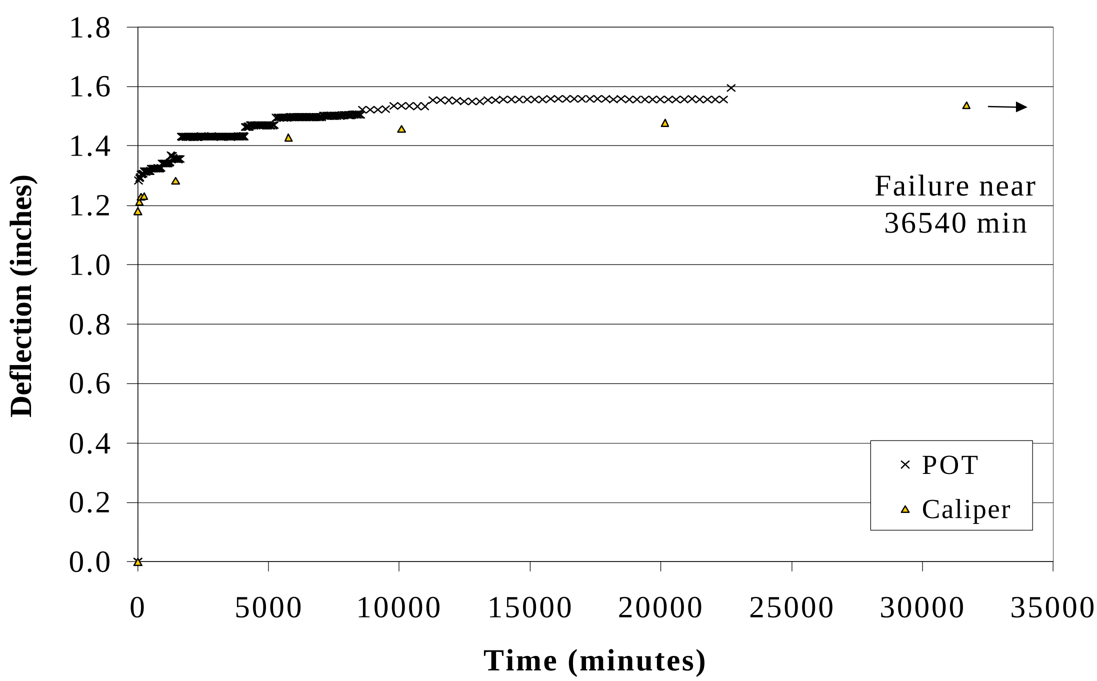

LVL 300°F # 5e
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
Failure near
13 min
Caliper
(FRAME 2 #23)
0
0.2
0.4
0.6
0.8
1
1.2
Time (min)

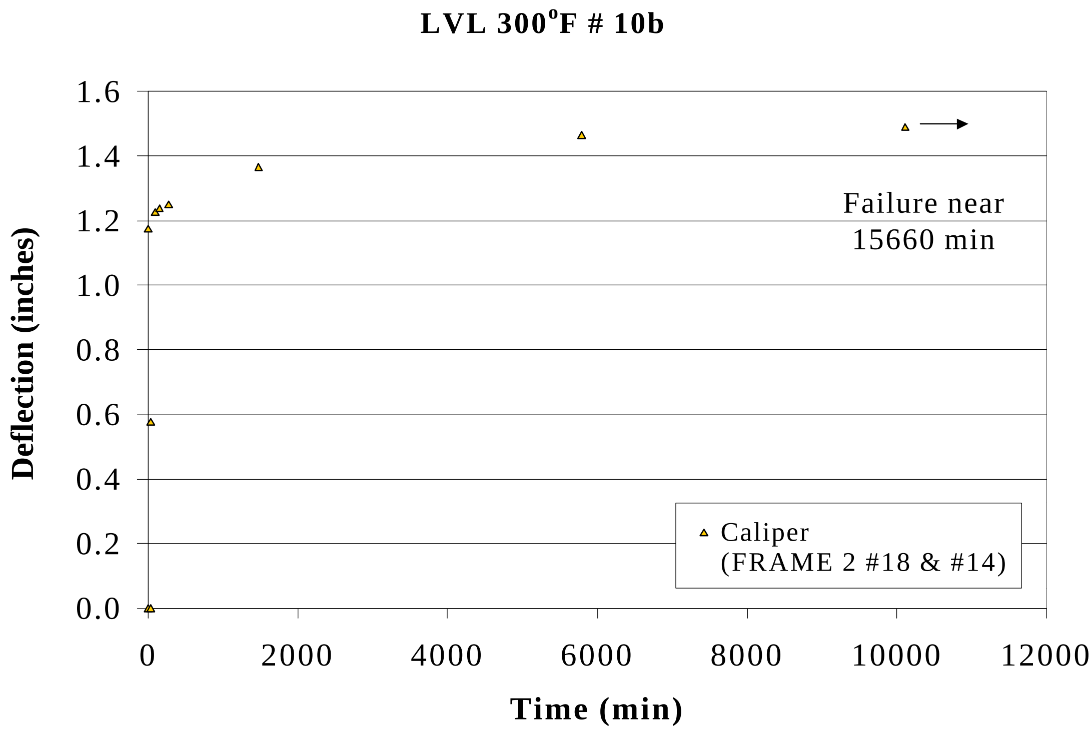

LVL 300°F # 6b (FRAME 2, CH 2)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
Failure near
1653 min
POT
Caliper
0
500
1000
1500
2000
Time (minutes)

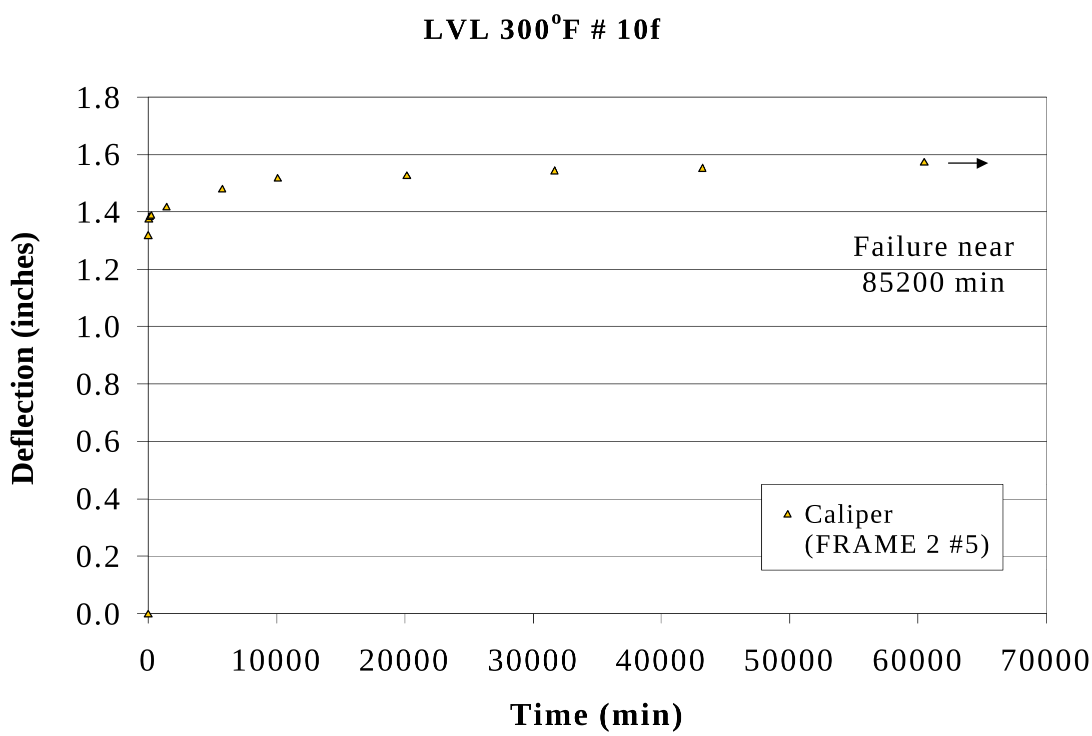
LVL 300°F # 6c



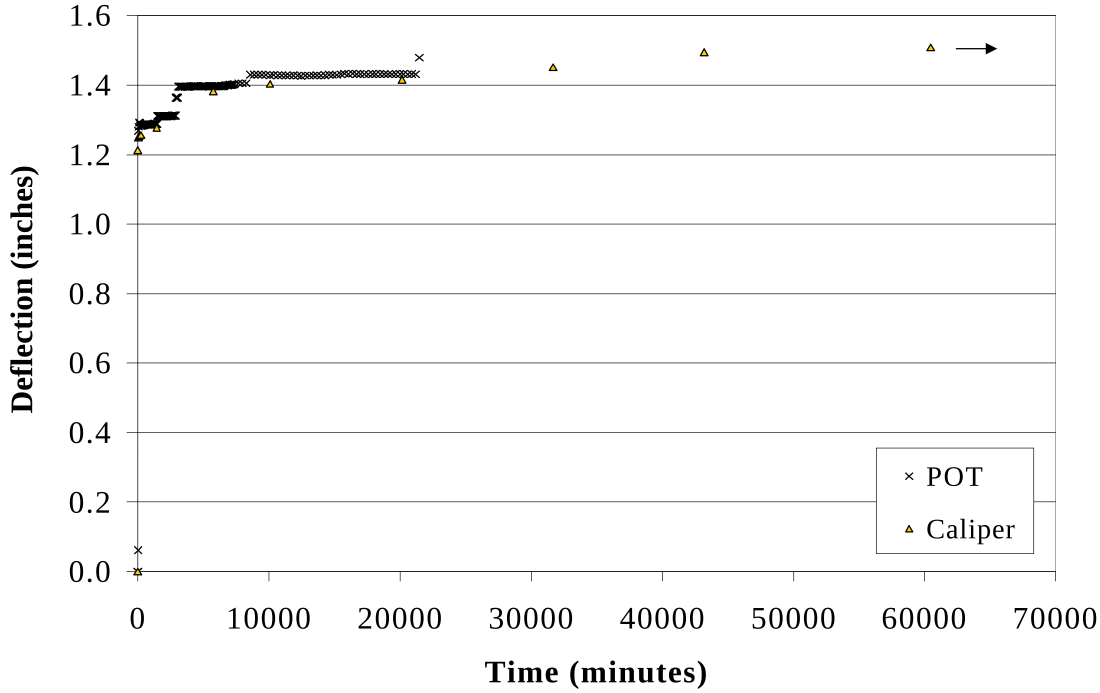
LVL 300°F # 10a (FRAME 2, CH 0)



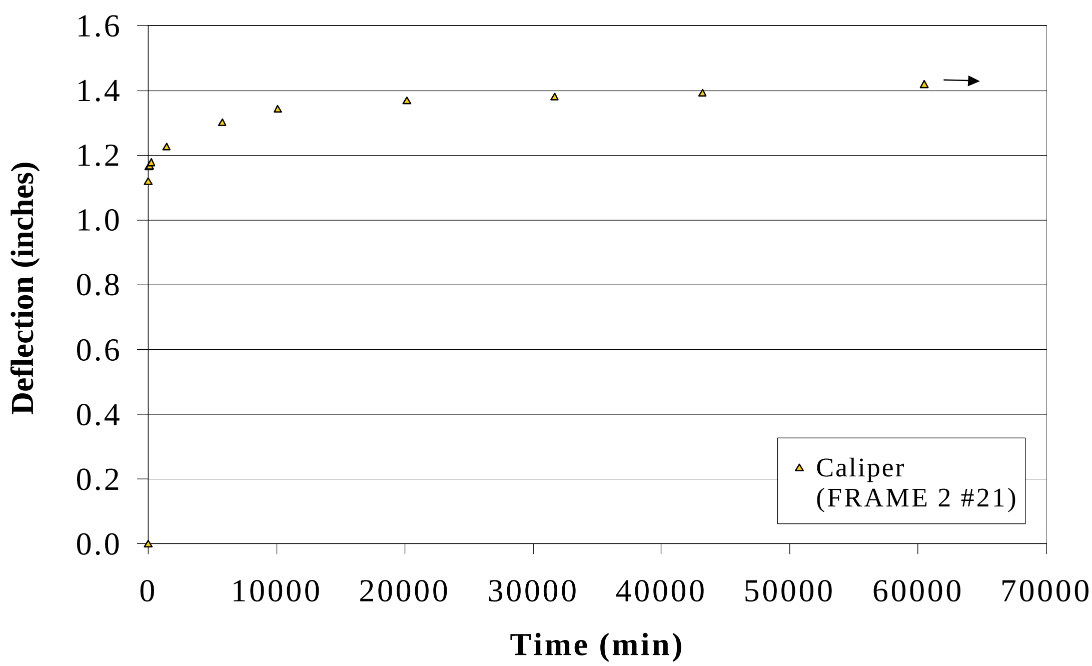

LVL 300°F # 10b
Deflection (inches)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2000
4000
6000
8000
10000
12000
Time (min)
Failure near
15660 min
Caliper
(FRAME 2 #18 & #14)


LVL 300°F # 10f
Deflection (inches)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Failure near
85200 min
Caliper
(FRAME 2 #5)

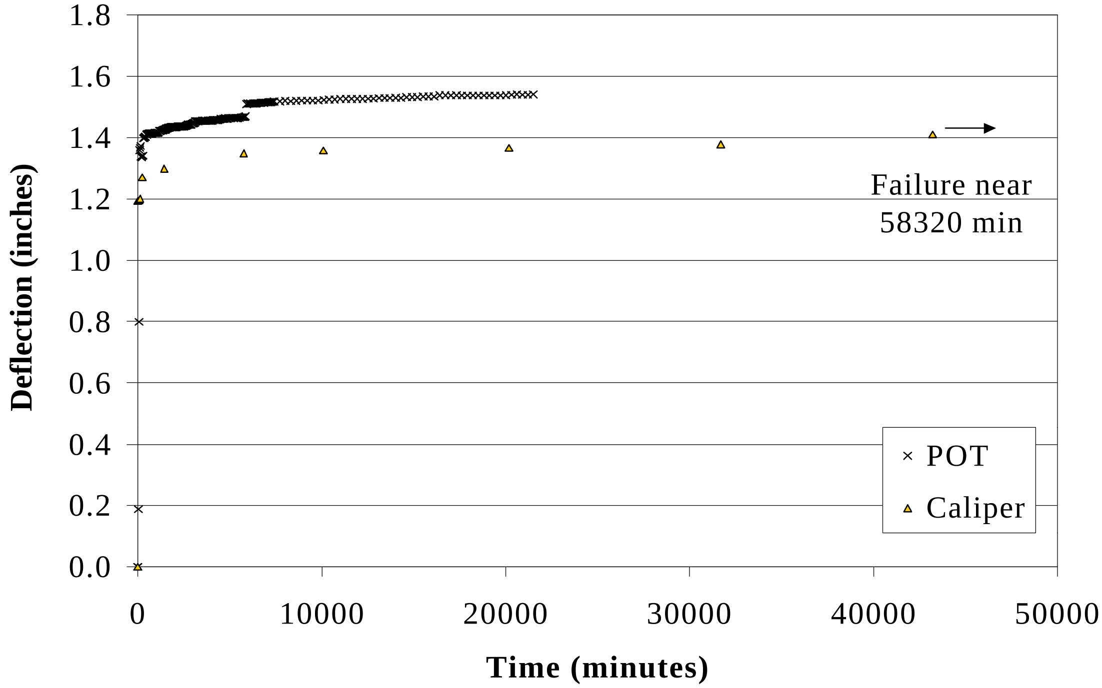
LVL 300^{o}F # 11c (FRAME 2, CH 13)



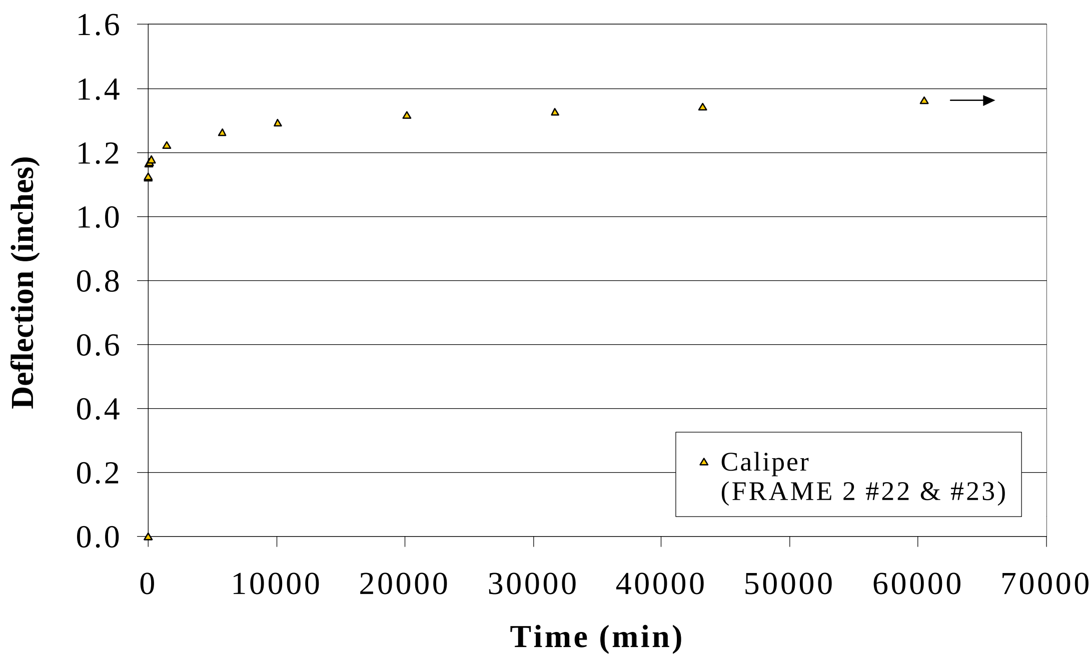
LVL 300^{o}F # 11e

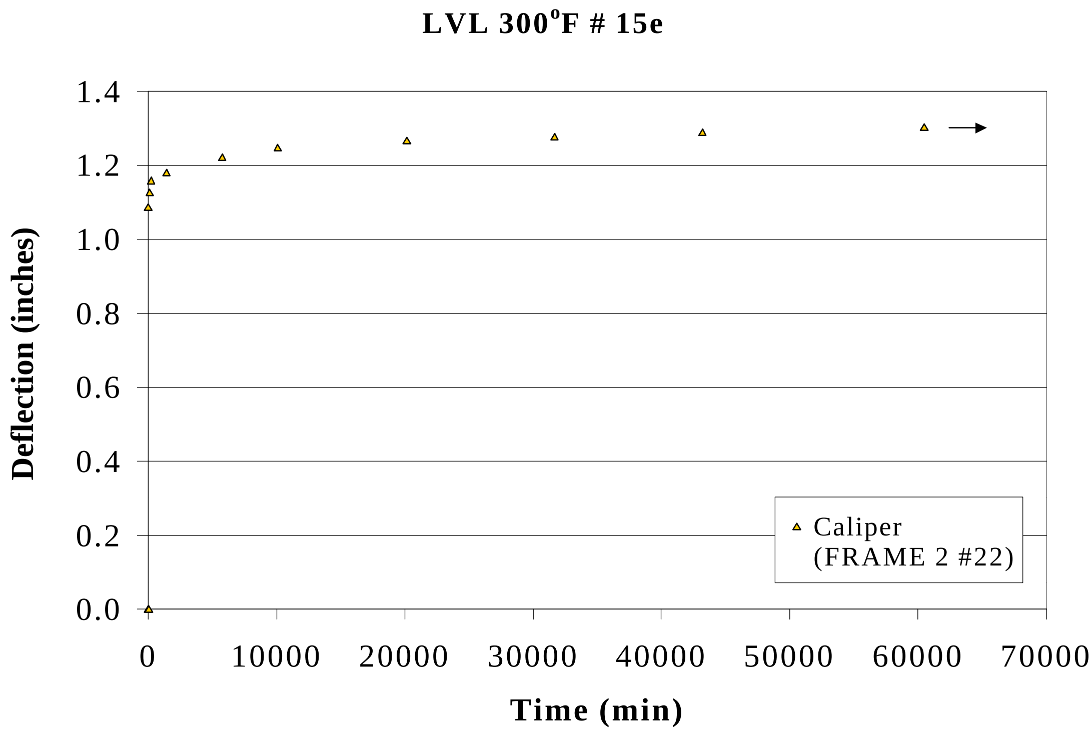


LVL 300°F # 12f (FRAME 2, CH 15)

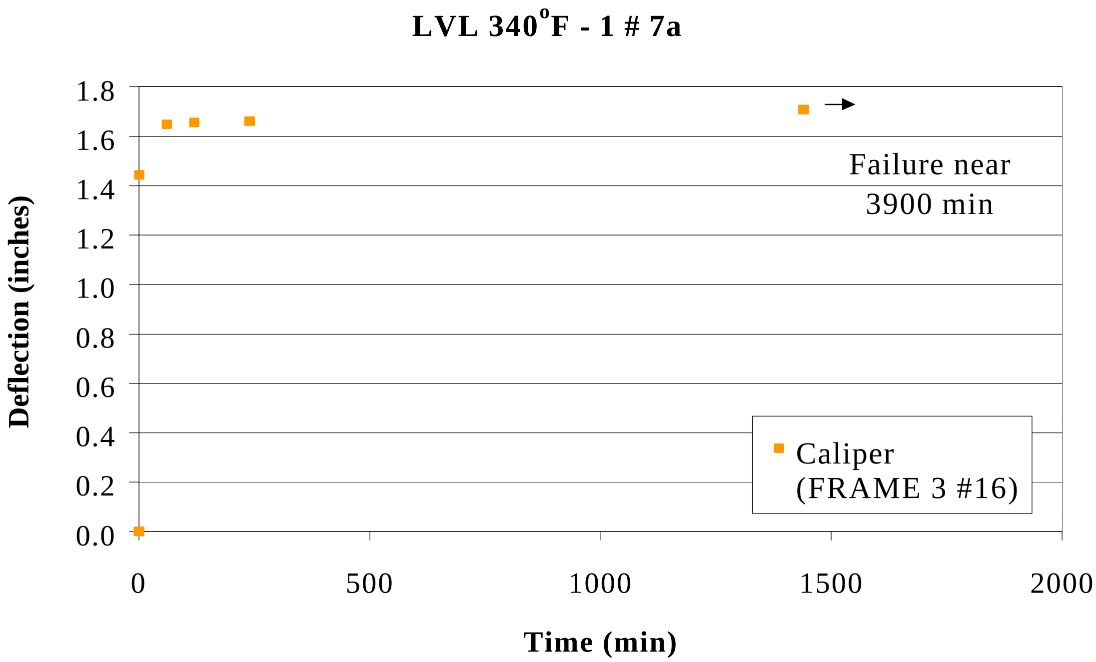


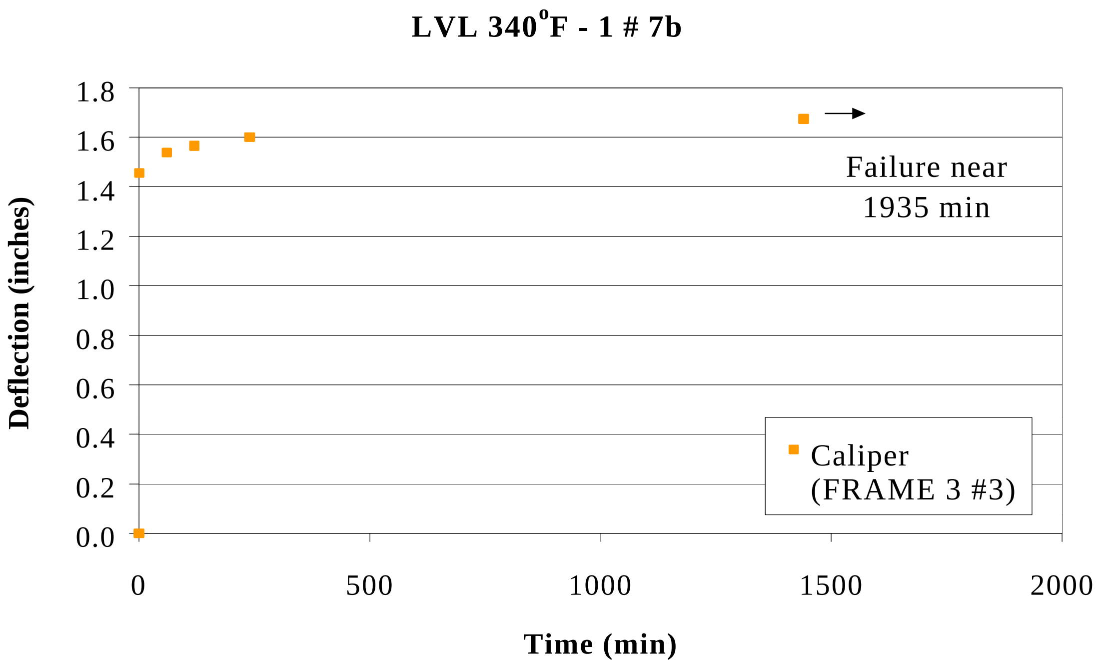
LVL 300°F # 14c



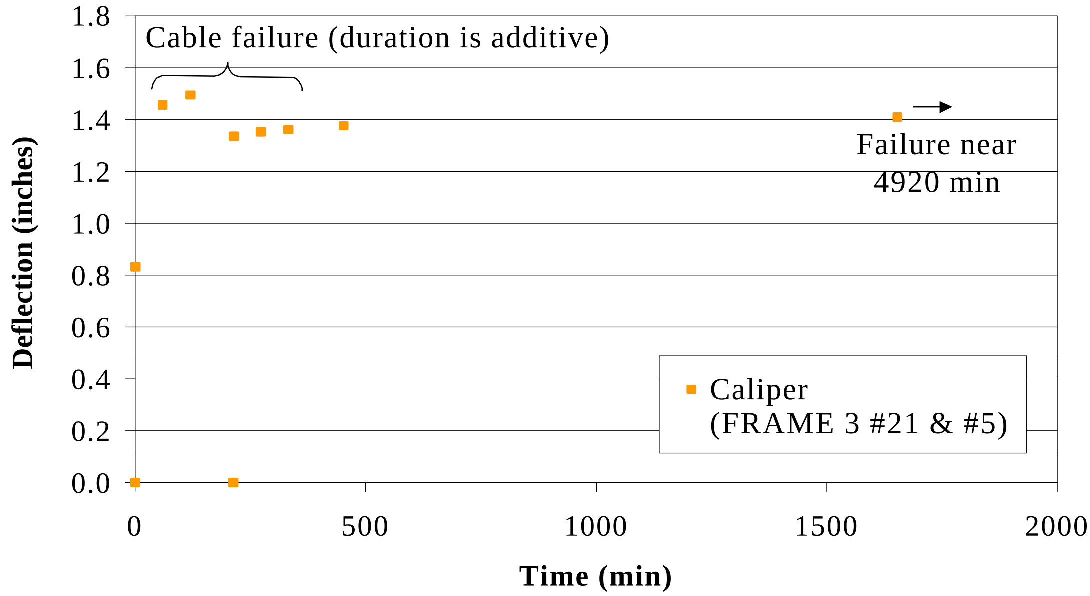

LVL 300°F # 15e
Deflection (inches)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 2 #22)

LAMINATED VENEER LUMBER: 340°F – 1

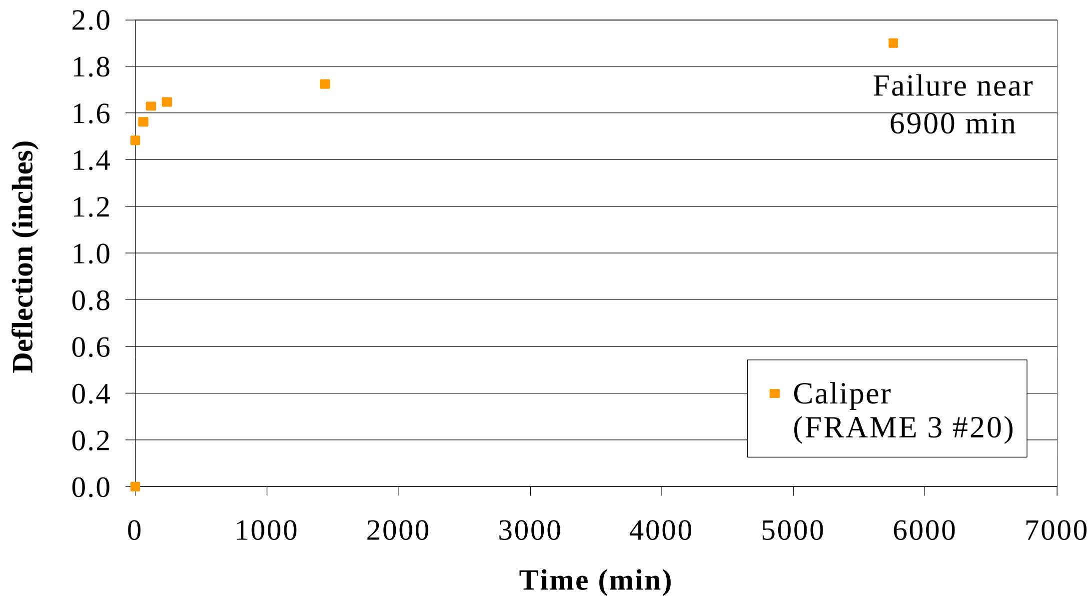




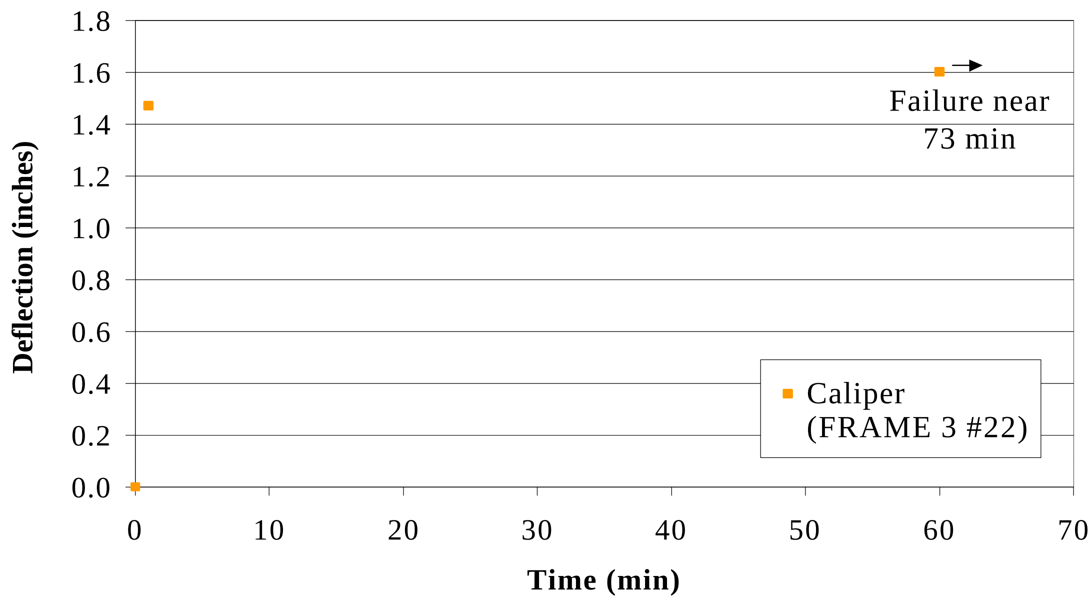
LVL 340°F - 1 # 7d



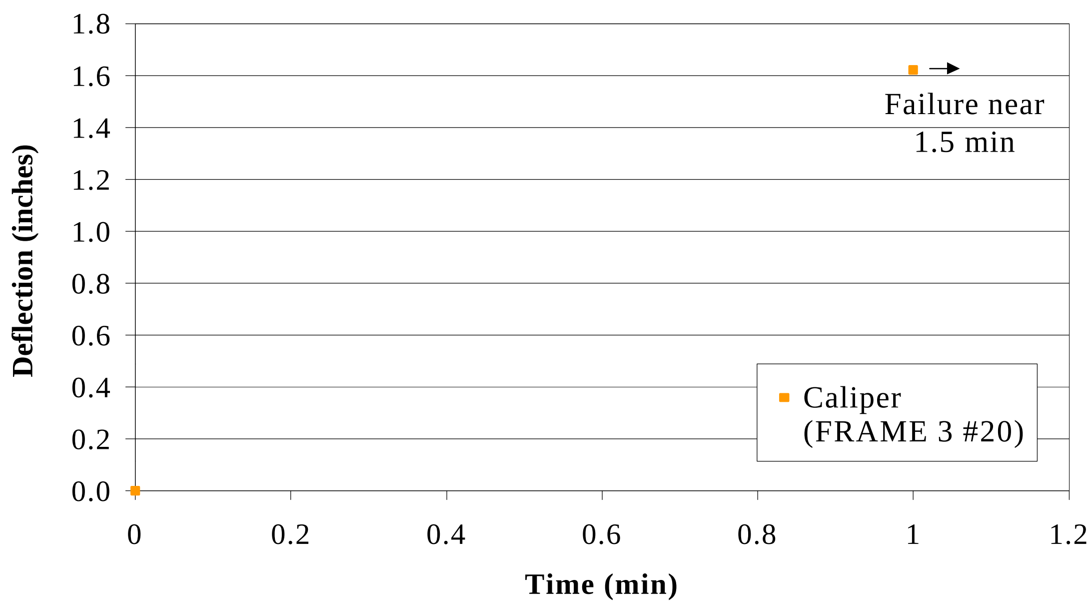
LVL 340°F - 1 # 8a



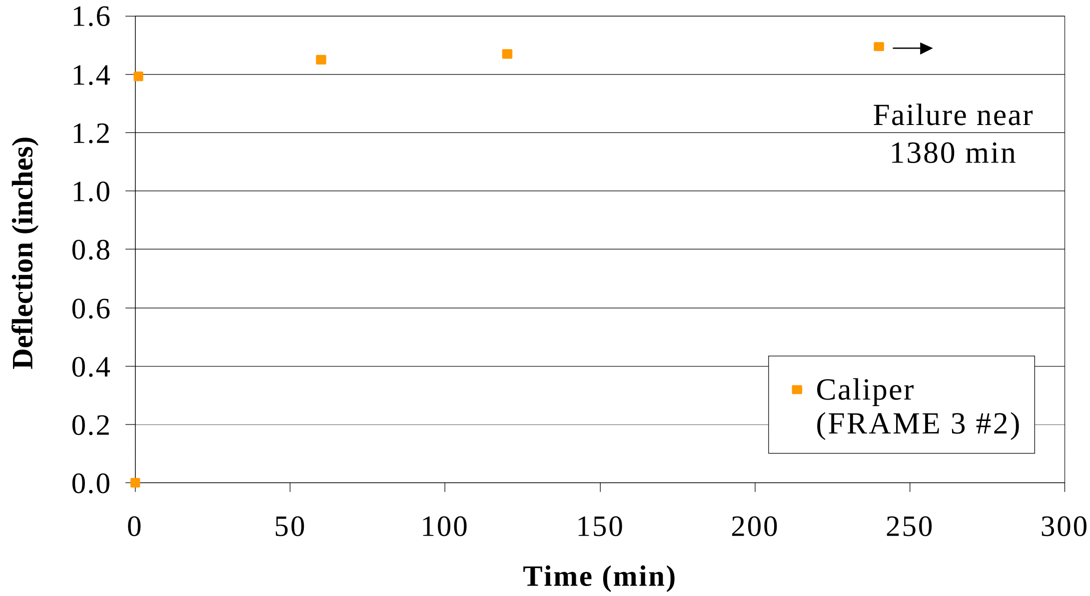
LVL 340°F - 1 # 8b



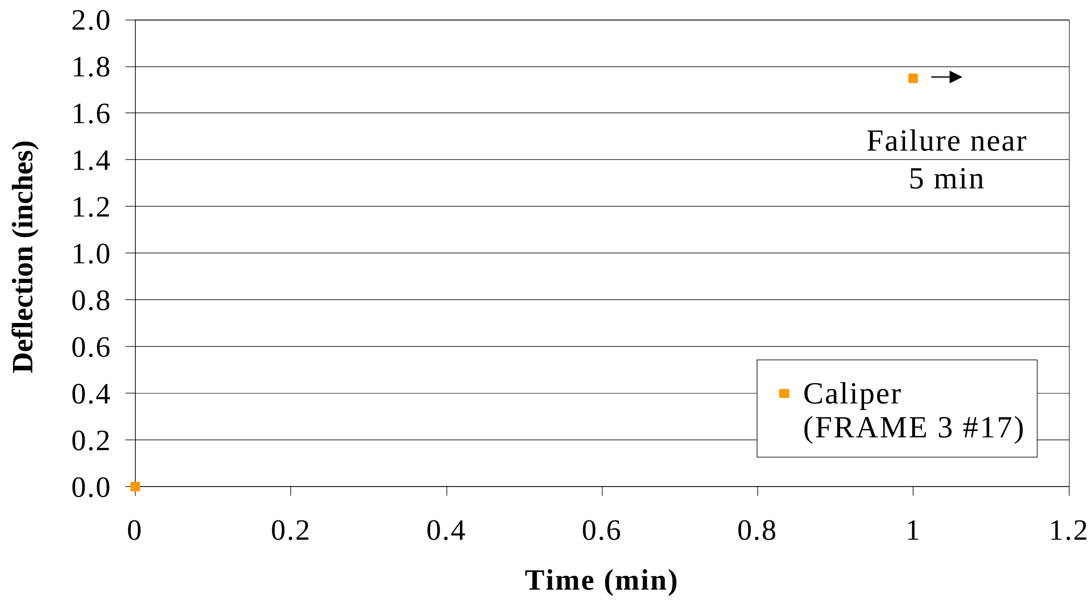
LVL 340°F - 1 # 8f



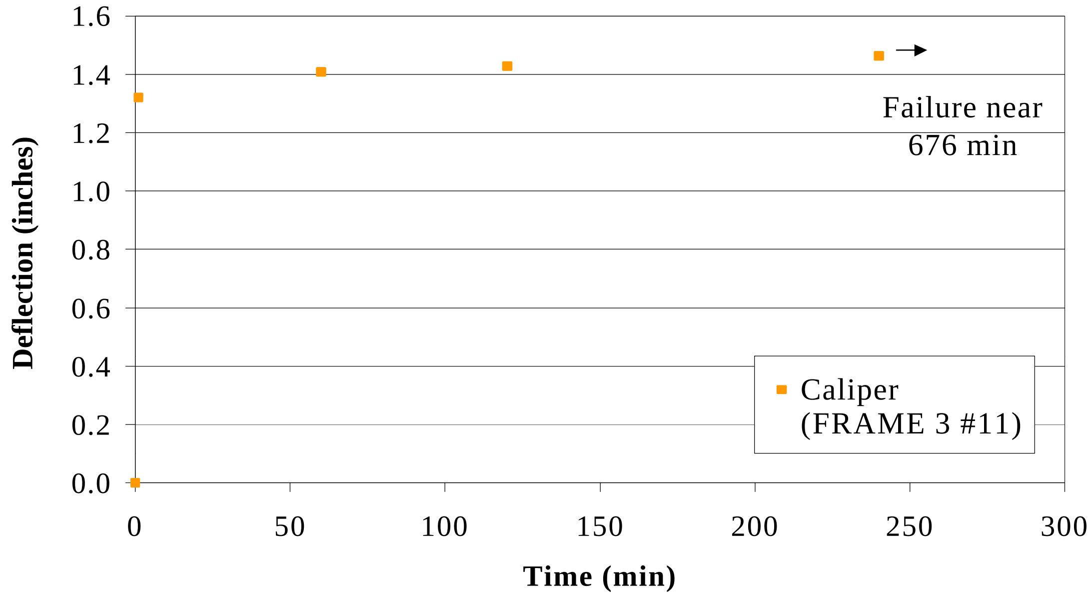
LVL 340^{o}F - 1 # 9a



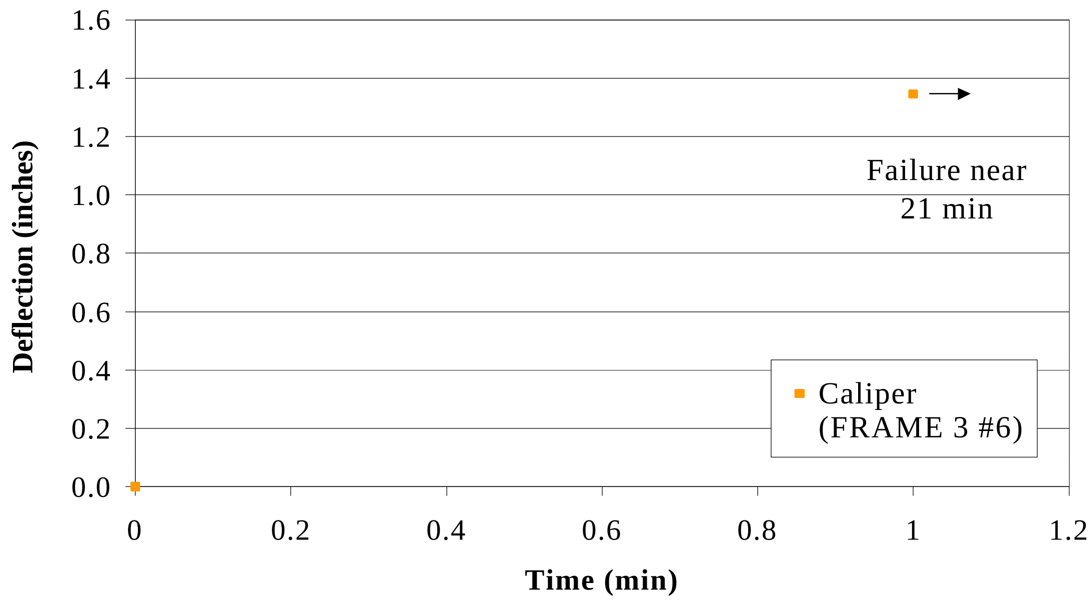
LVL 340^{o}F - 1 # 9c



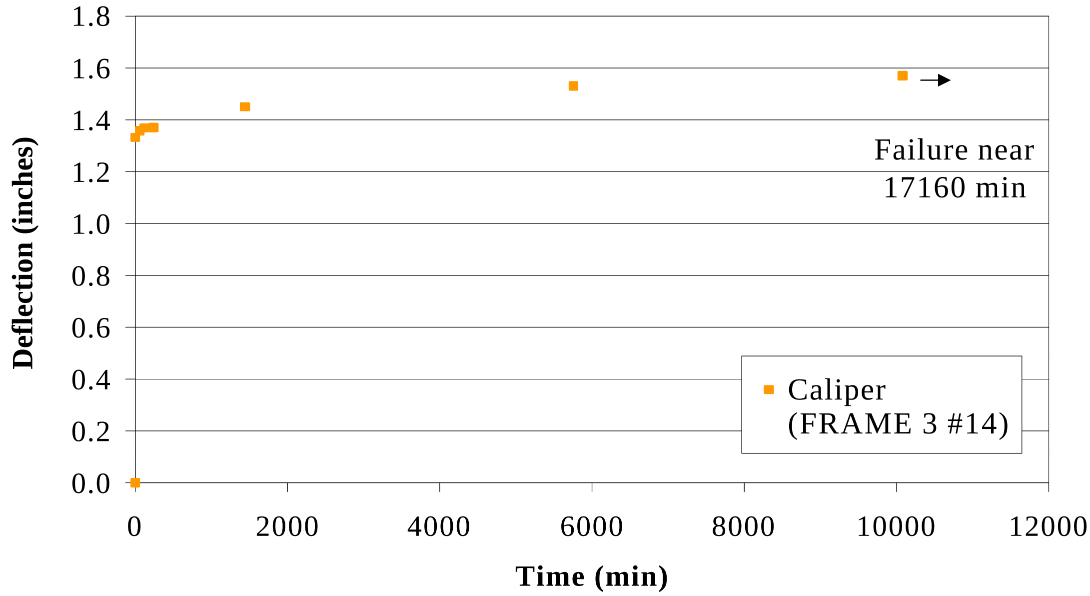
LVL 340°F - 1 # 11b



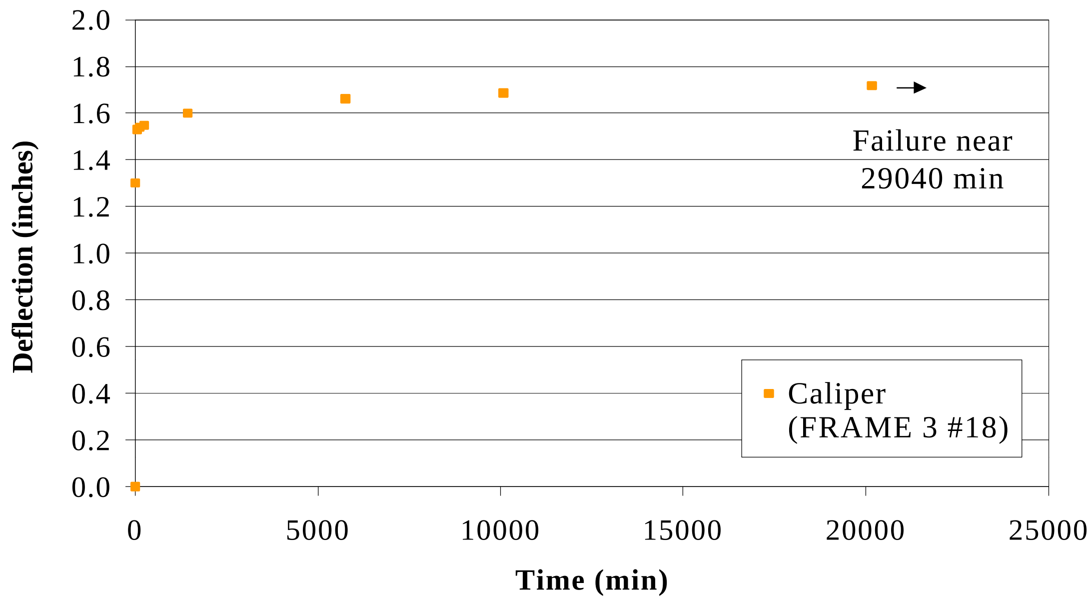
LVL 340°F - 1 # 11f



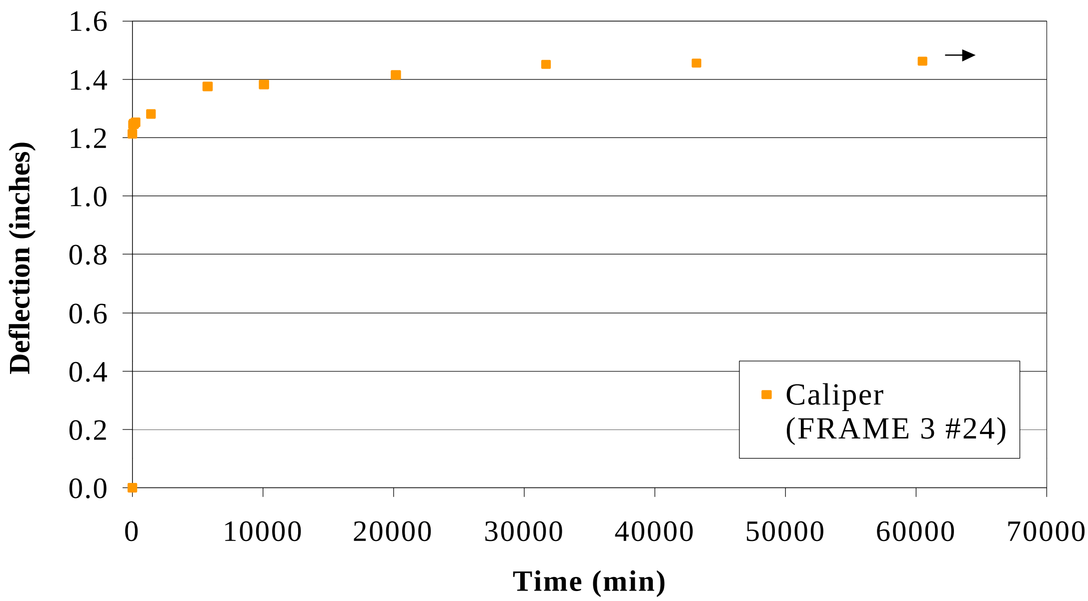
LVL 340°F - 1 # 12a



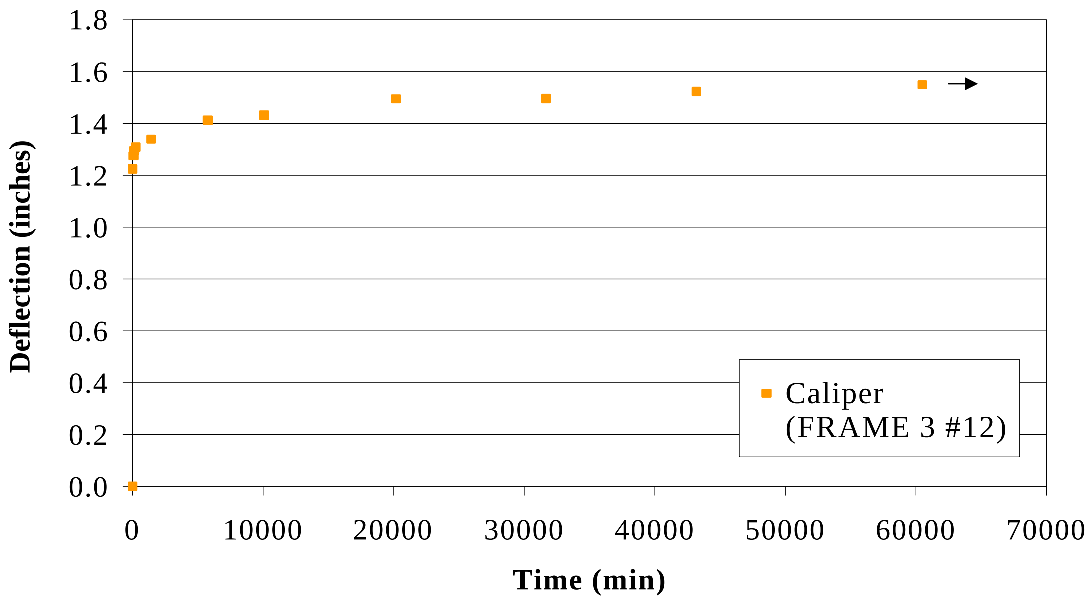
LVL 340°F - 1 # 12b

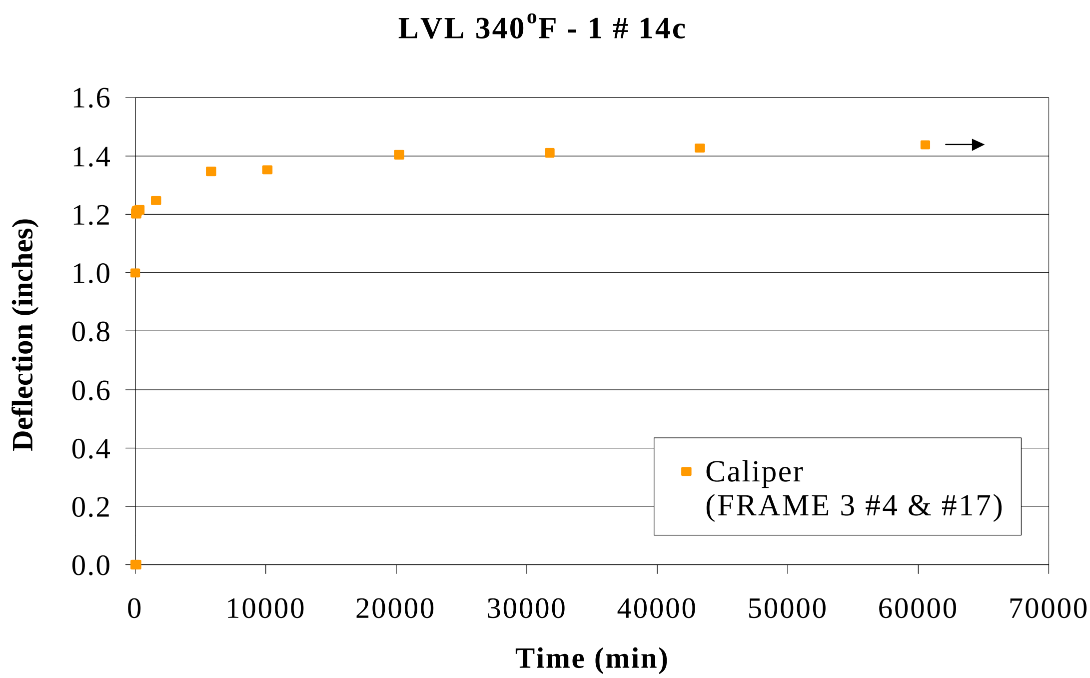


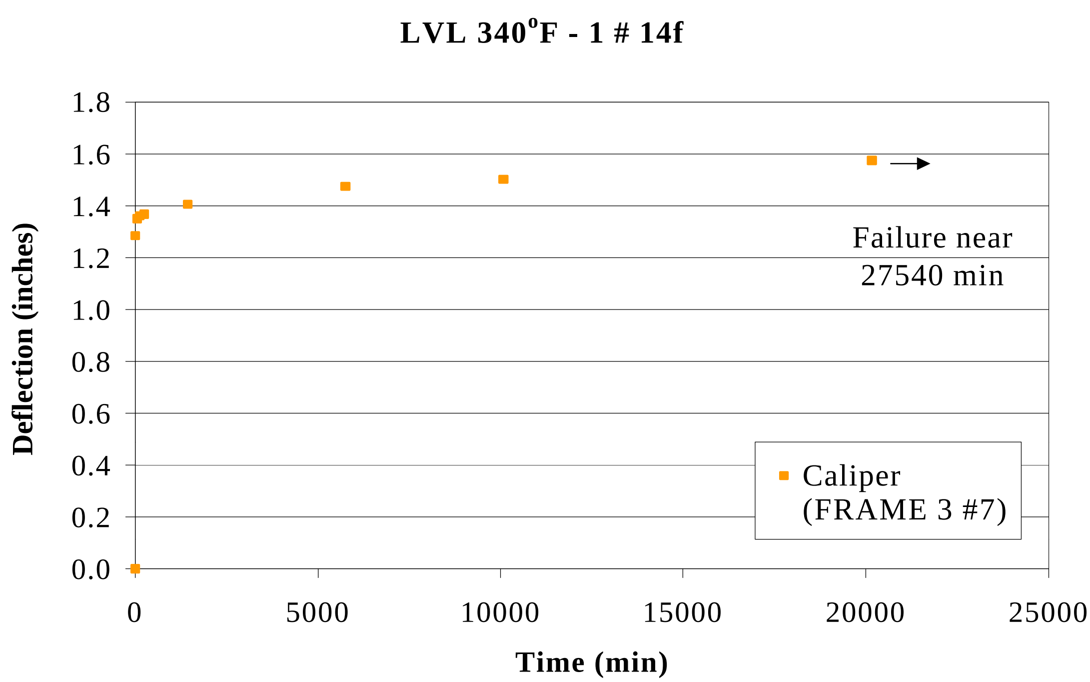
LVL 340°F - 1 # 12f

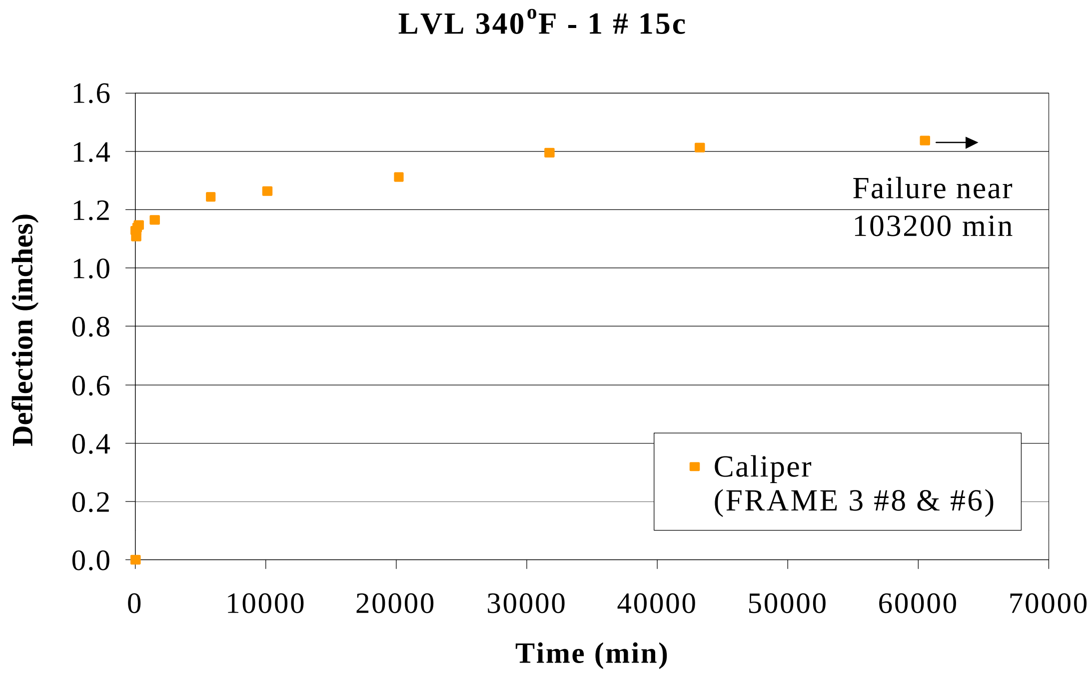


LVL 340°F - 1 # 14b




LVL 340°F - 1 # 14c
Deflection (inches)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 3 #4 & #17)

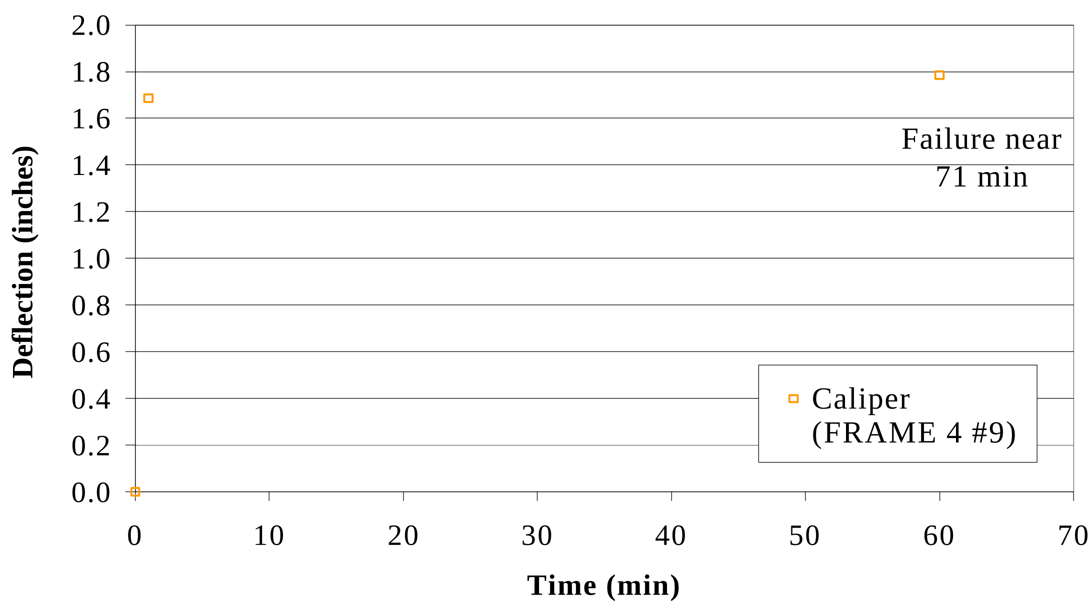

LVL 340°F - 1 # 14f
Deflection (inches)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5000
10000
15000
20000
25000
Time (min)
Failure near
27540 min
Caliper
(FRAME 3 #7)



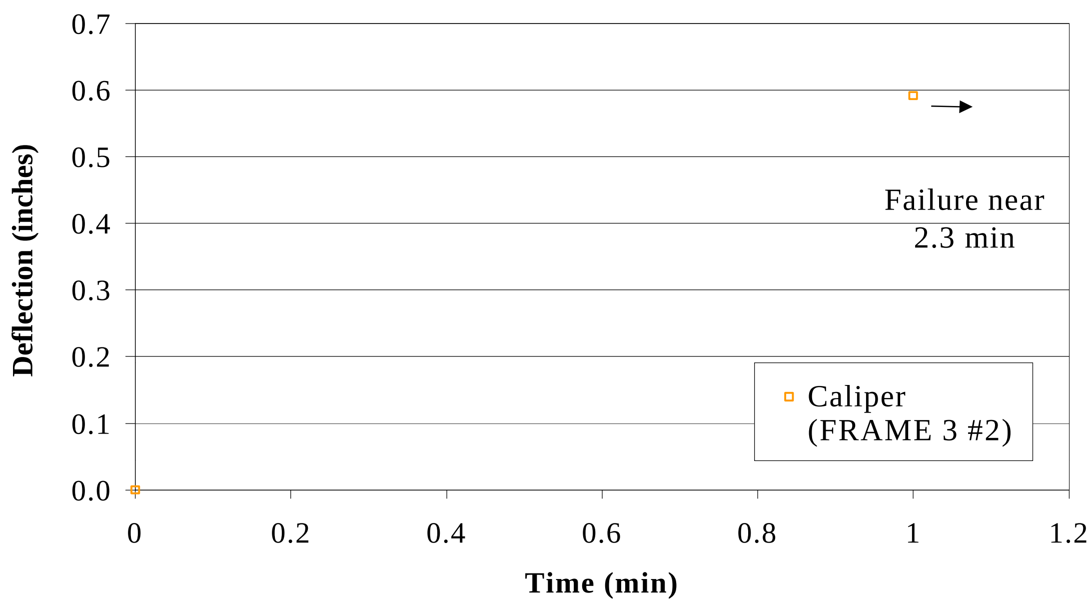
LVL 340°F - 1 # 15c
Deflection (inches)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Failure near
103200 min
Caliper
(FRAME 3 #8 & #6)

LAMINATED VENEER LUMBER: 340°F – 2

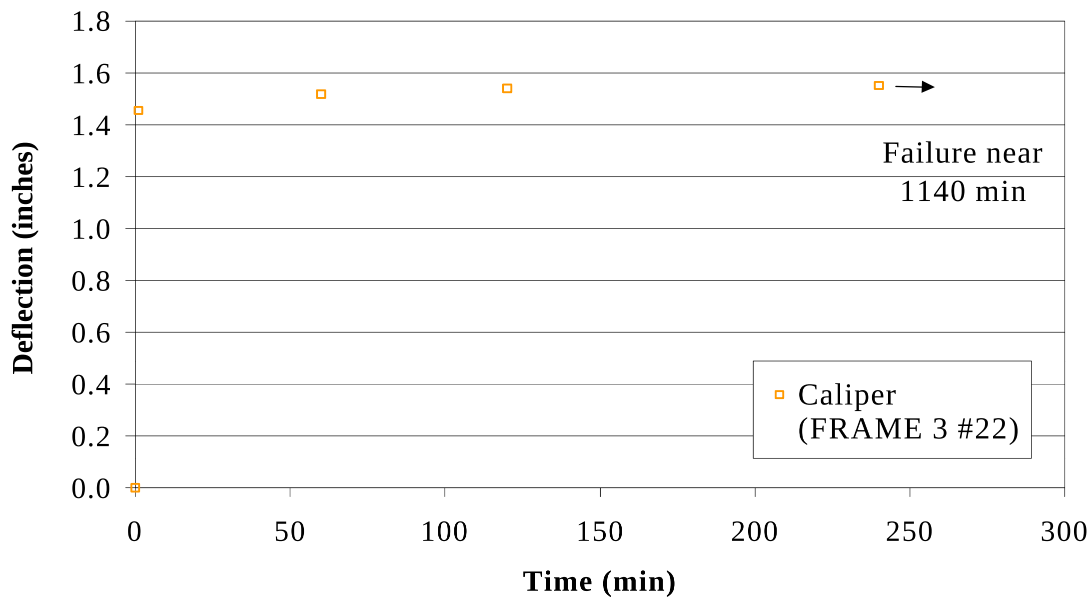
LVL 340°F - 2 # 5b



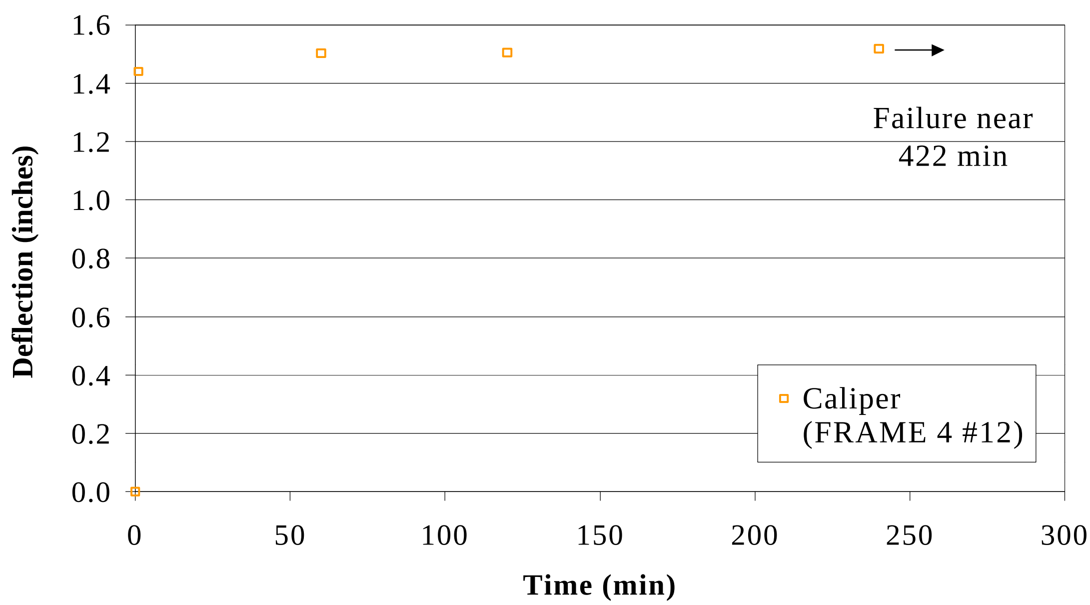
LVL 340°F - 2 # 8d

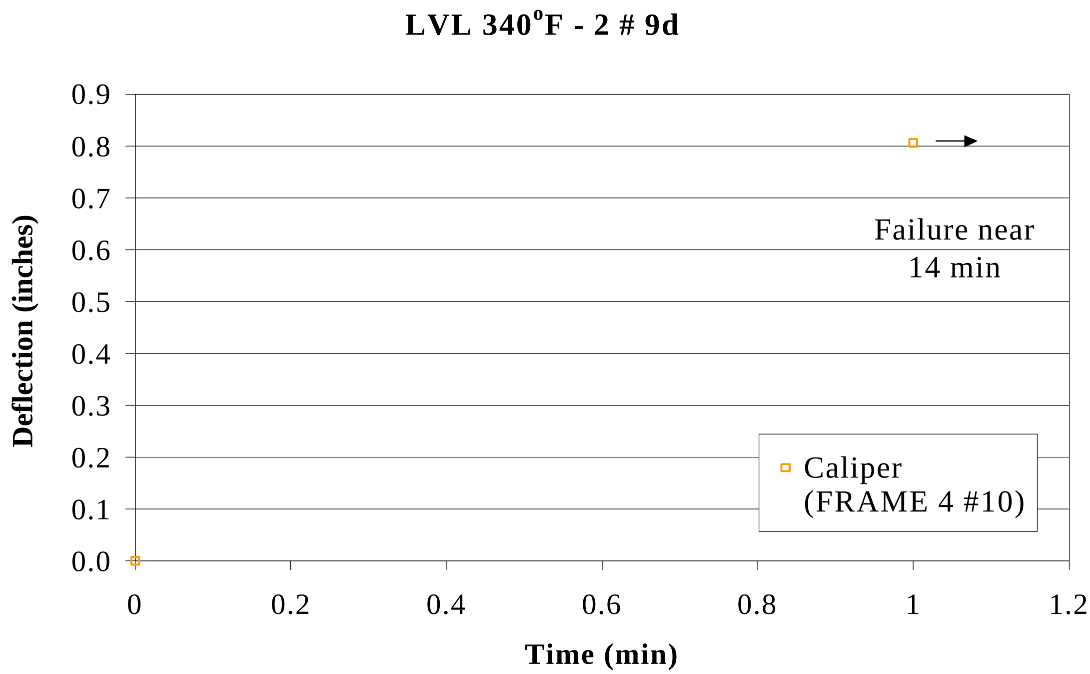


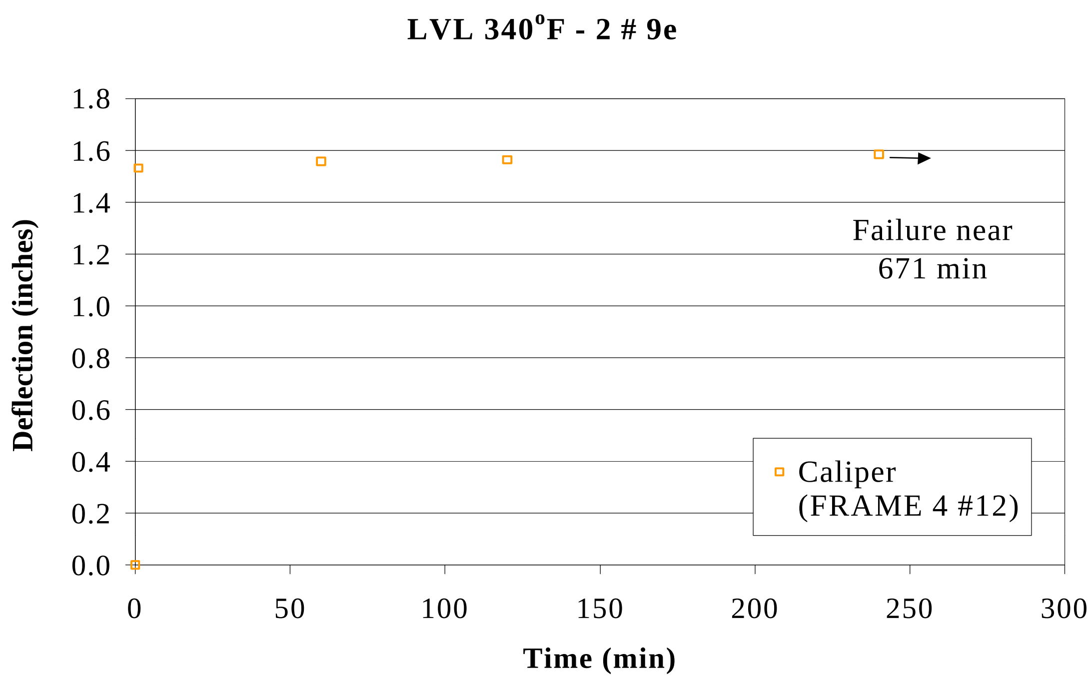
LVL 340°F - 2 # 8e

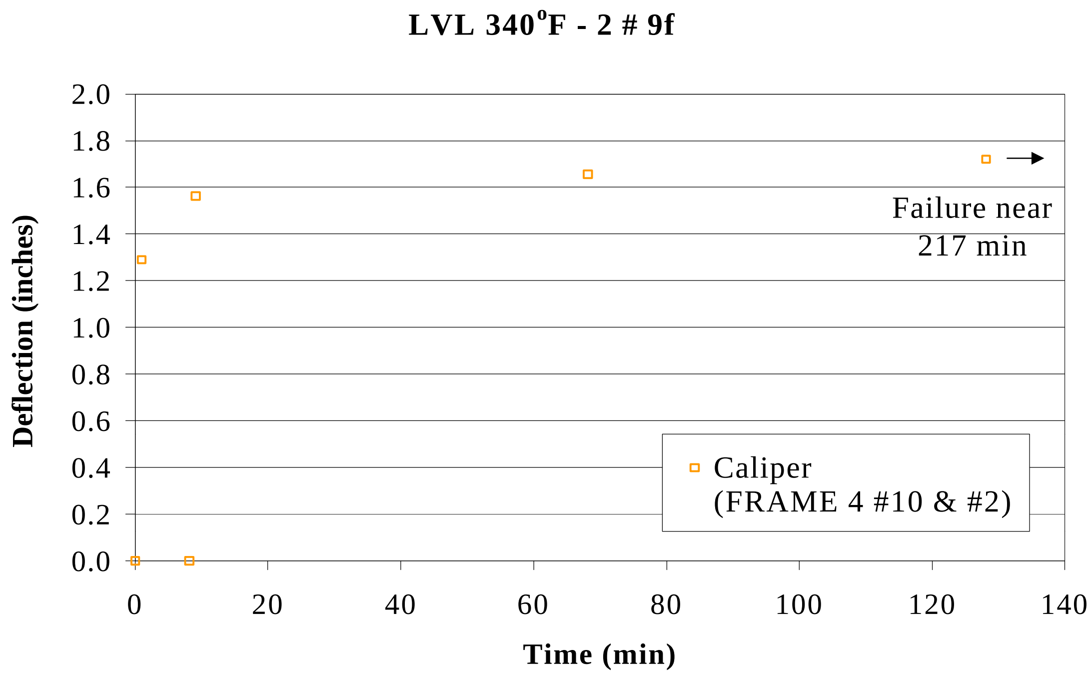


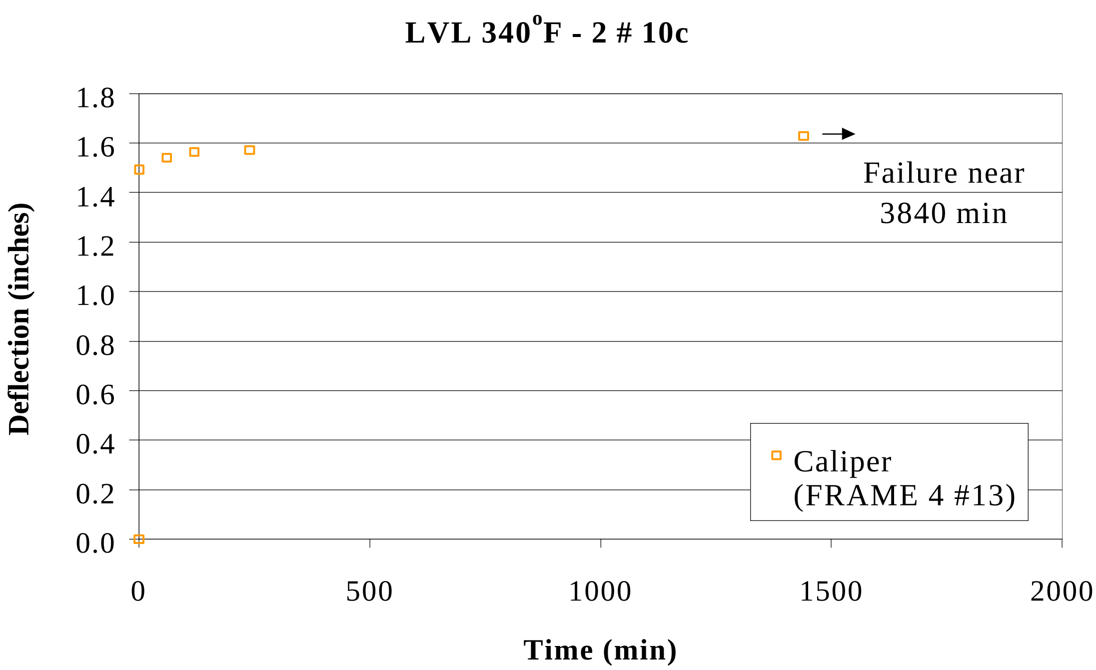
LVL 340°F - 2 # 9b

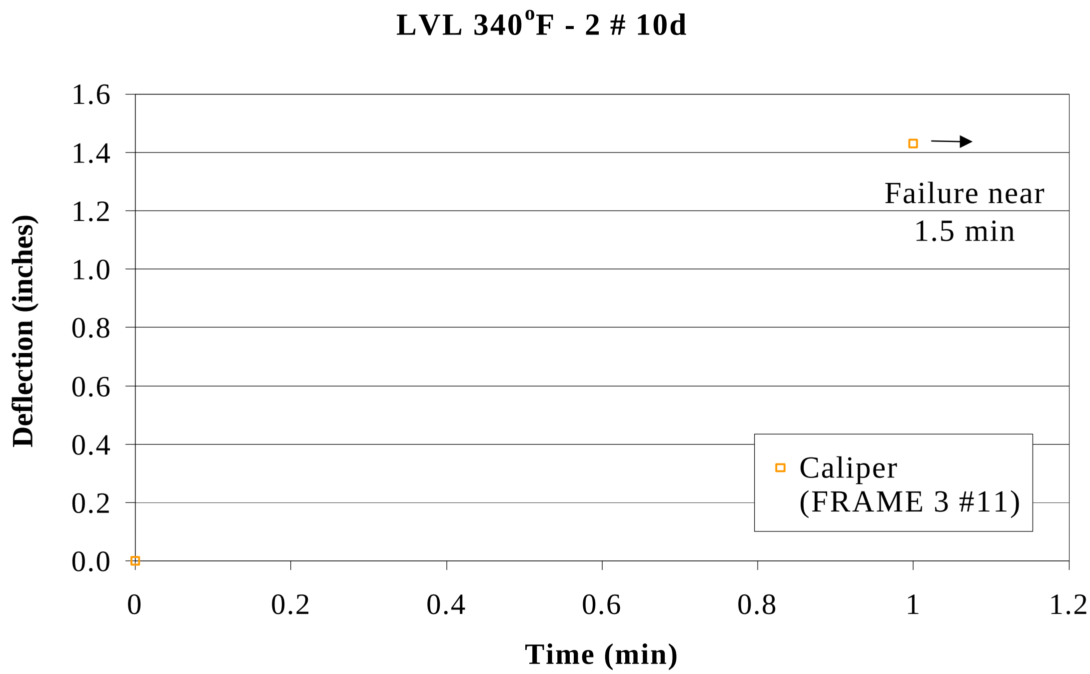


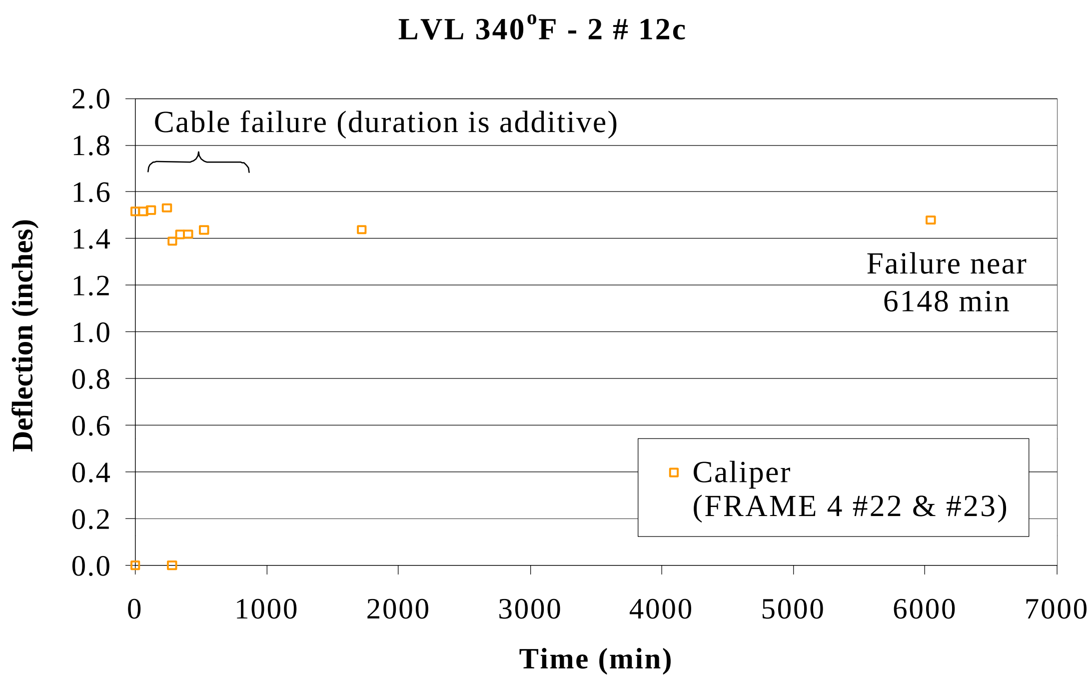

LVL 340°F - 2 # 9d
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Deflection (inches)
0
0.2
0.4
0.6
0.8
1
1.2
Time (min)
Failure near
14 min
Caliper
(FRAME 4 #10)


LVL 340°F - 2 # 9e
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
50
100
150
200
250
300
Time (min)
Failure near
671 min
Caliper
(FRAME 4 #12)

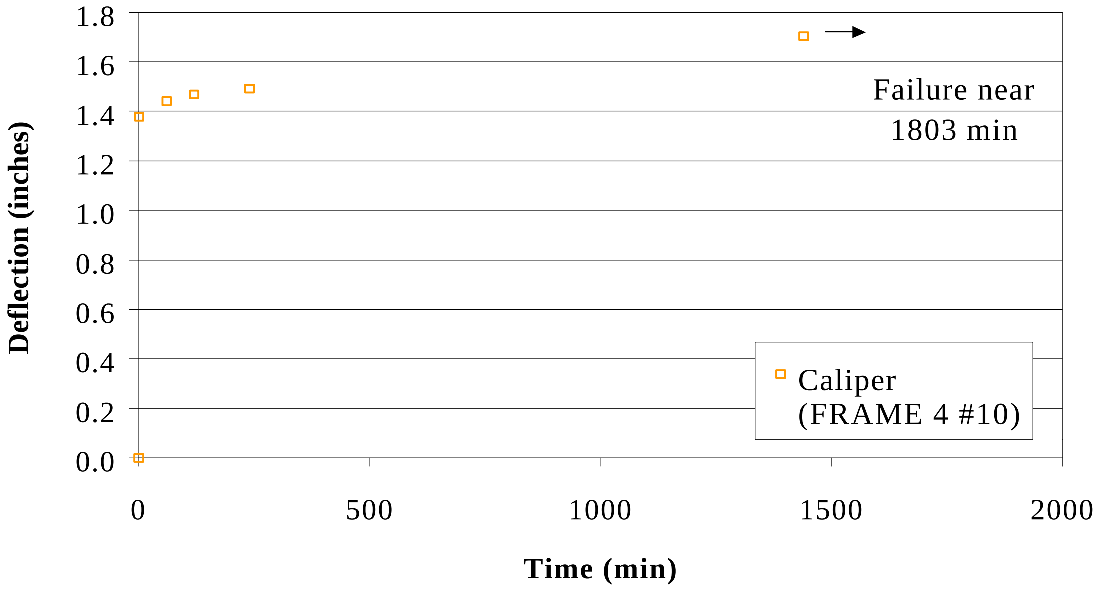

LVL 340°F - 2 # 9f
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
20
40
60
80
100
120
140
Time (min)
Failure near
217 min
Caliper
(FRAME 4 #10 & #2)


LVL 340°F - 2 # 10c
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
0
500
1000
1500
2000
Time (min)
Failure near
3840 min
Caliper
(FRAME 4 #13)

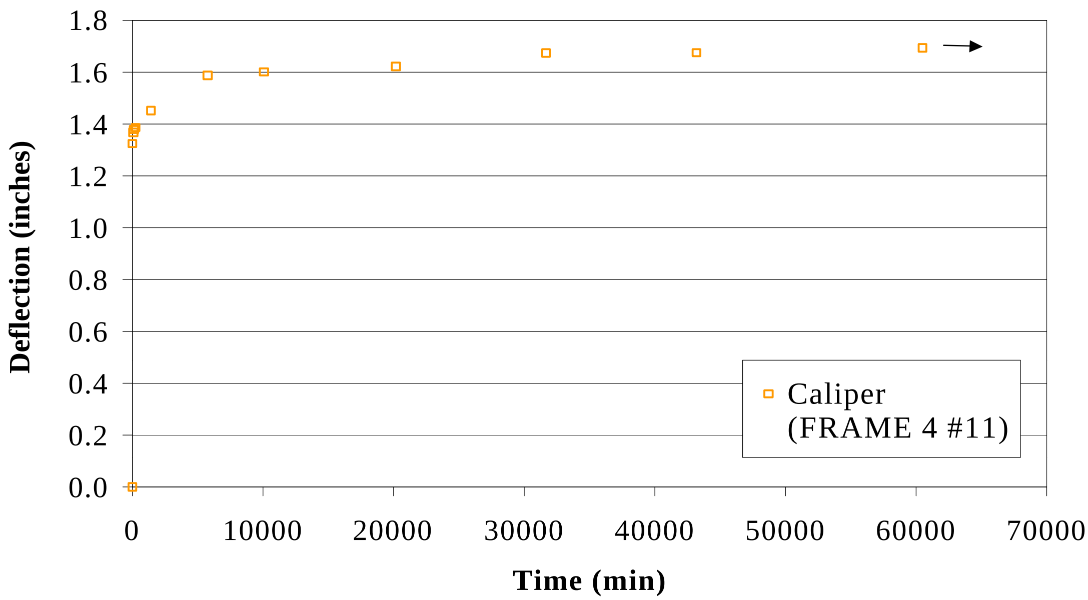

LVL 340°F - 2 # 10d
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
Failure near
1.5 min
Caliper
(FRAME 3 #11)
0
0.2
0.4
0.6
0.8
1
1.2
Time (min)


LVL 340°F - 2 # 12c
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
Cable failure (duration is additive)
Failure near
6148 min
Caliper
(FRAME 4 #22 & #23)
0
1000
2000
3000
4000
5000
6000
7000
Time (min)

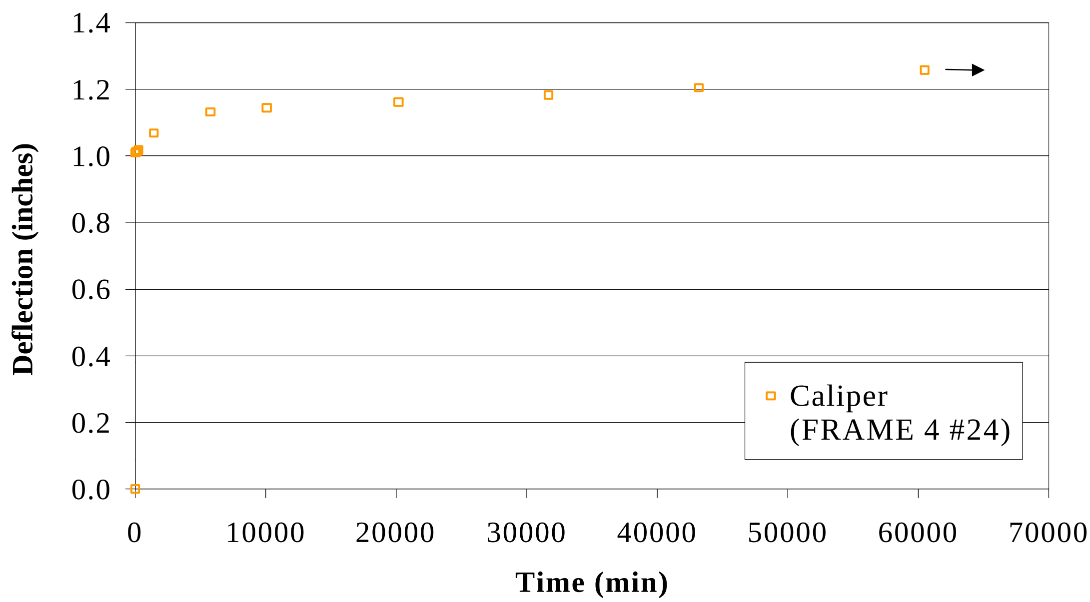
LVL 340°F - 2 # 12e



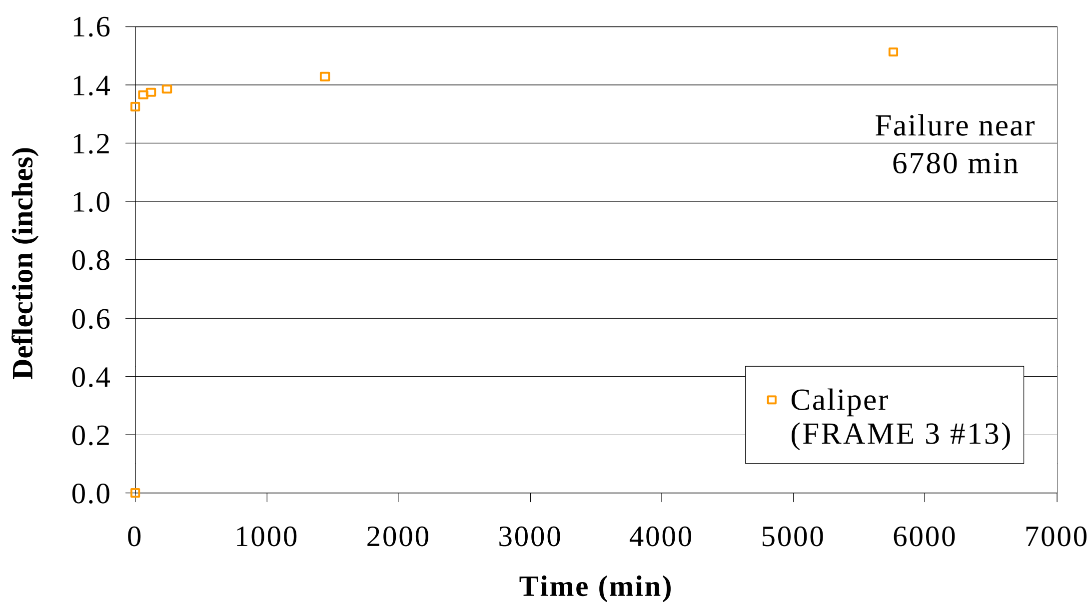
LVL 340°F - 2 # 13a

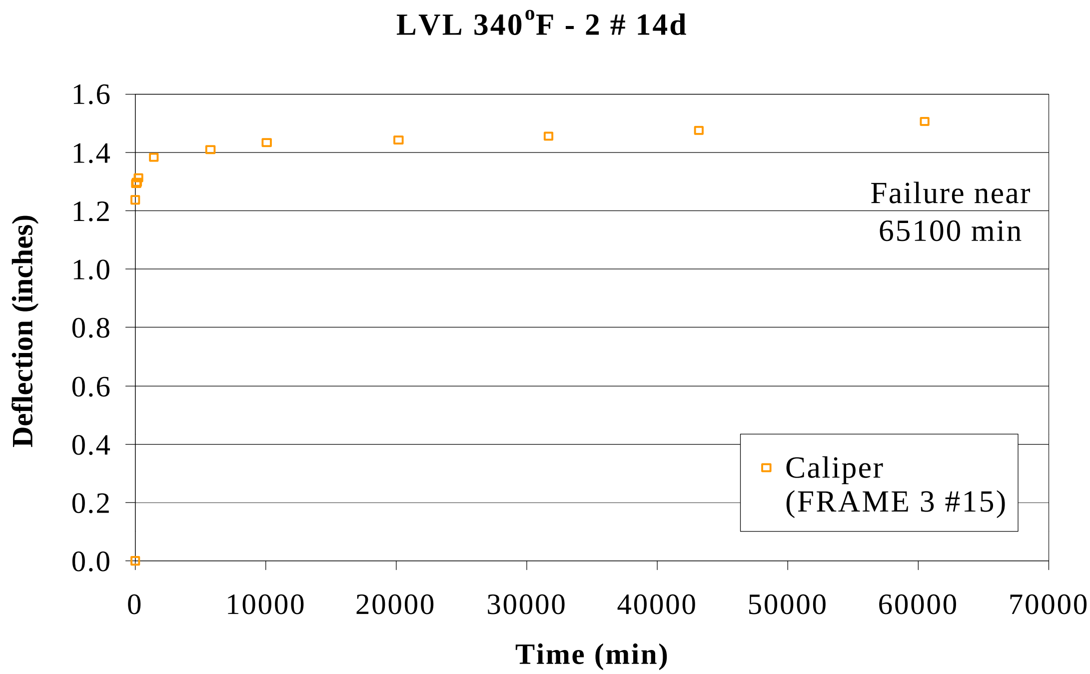


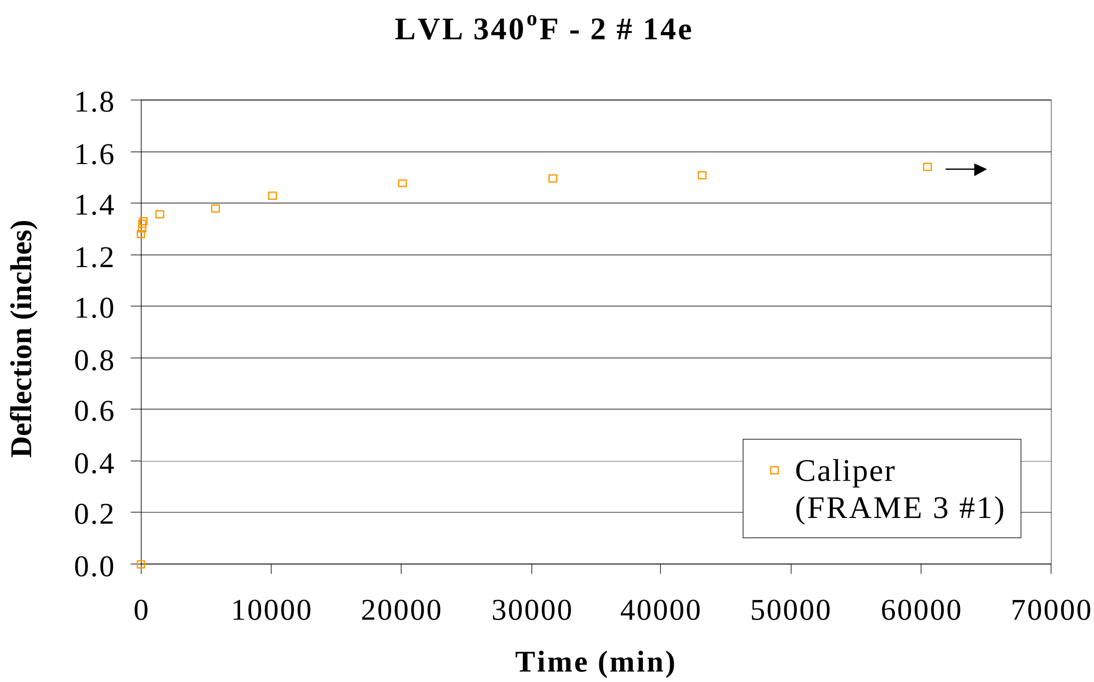
LVL 340°F - 2 # 13b



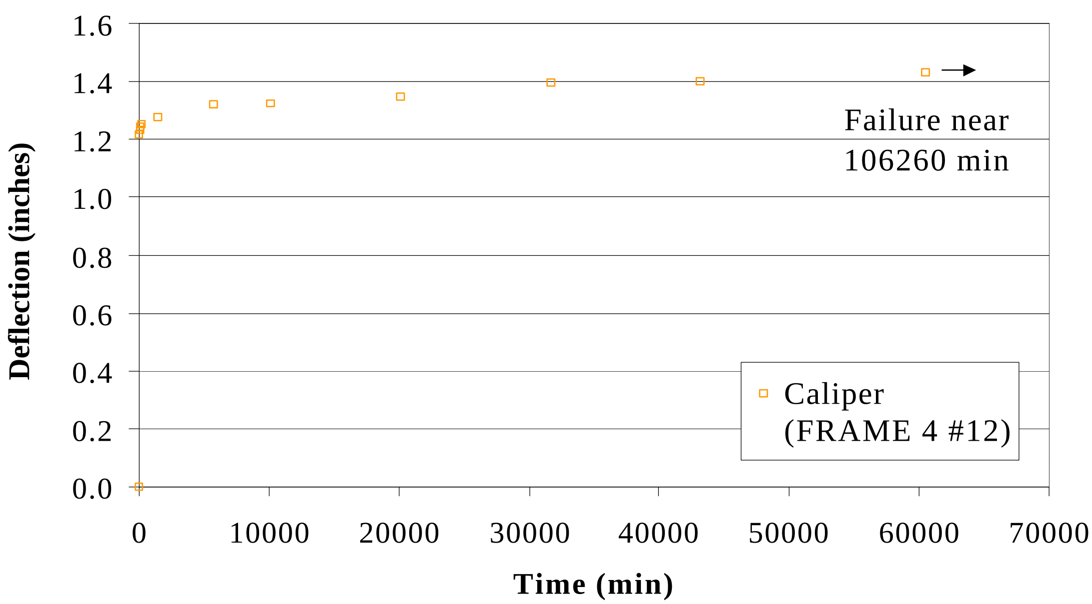
LVL 340°F - 2 # 13f



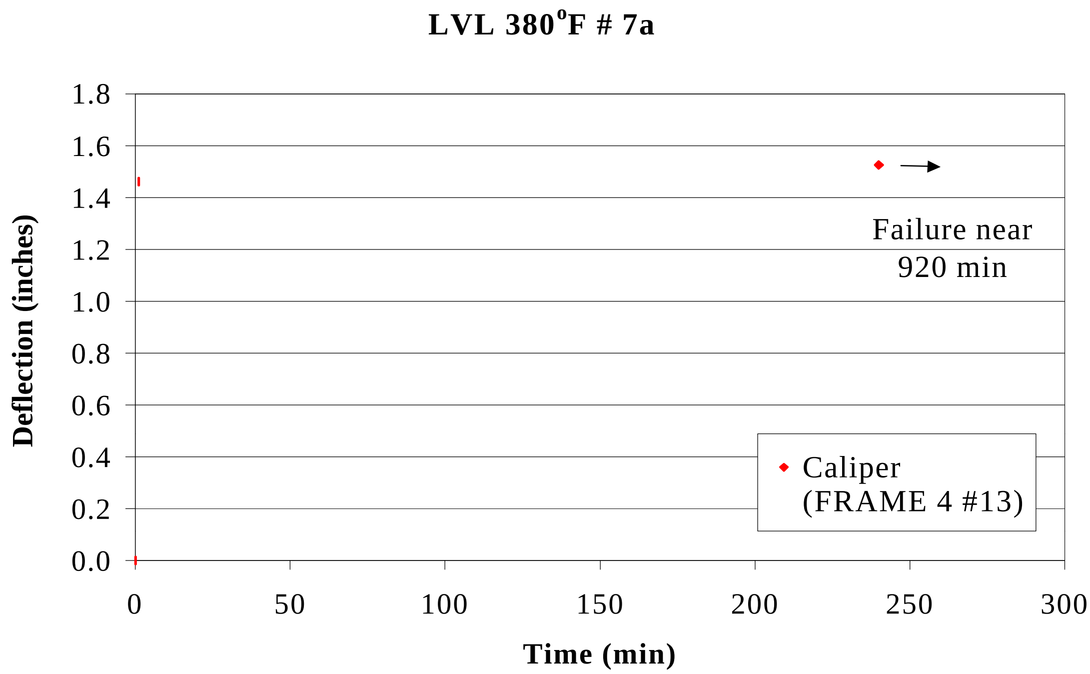

LVL 340°F - 2 # 14d
Deflection (inches)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Failure near
65100 min
Caliper
(FRAME 3 #15)

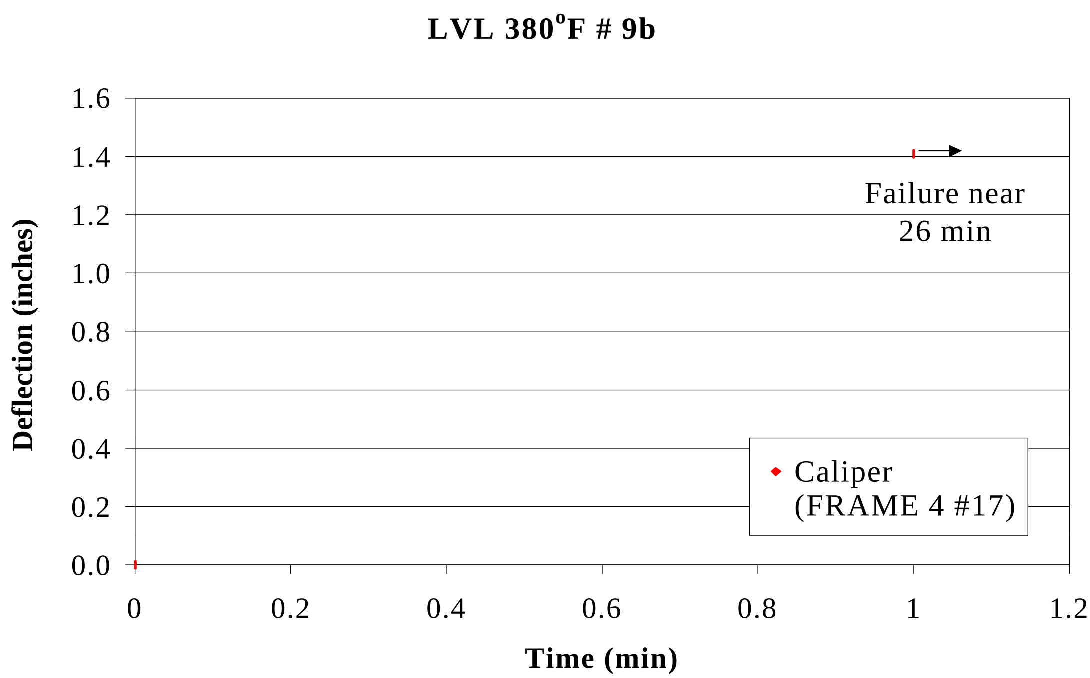

LVL 340°F - 2 # 14e
Deflection (inches)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 3 #1)

LVL 340°F - 2 # 15b

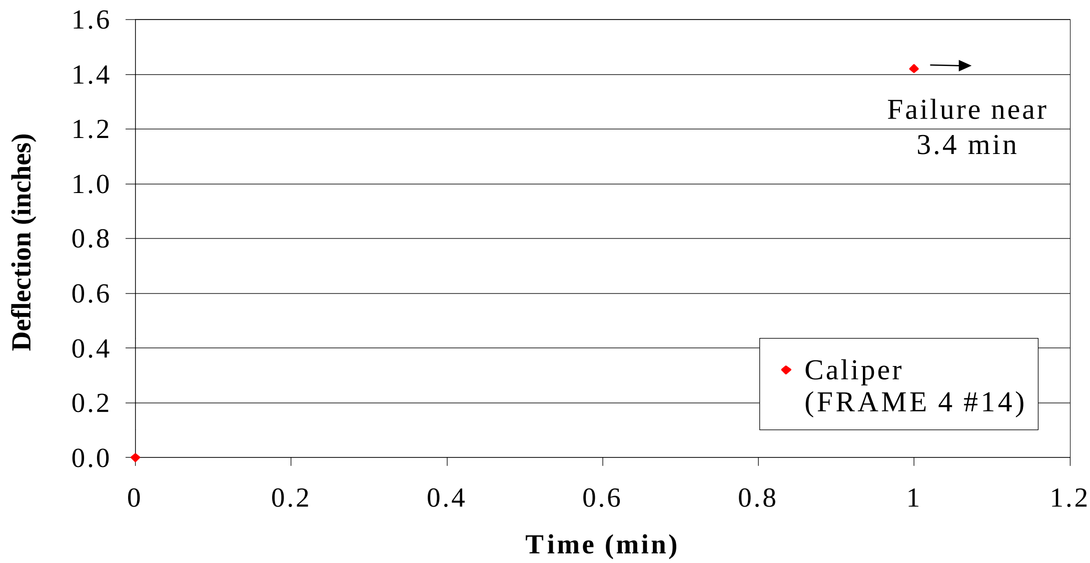


LAMINATED VENEER LUMBER: 380^{O}F

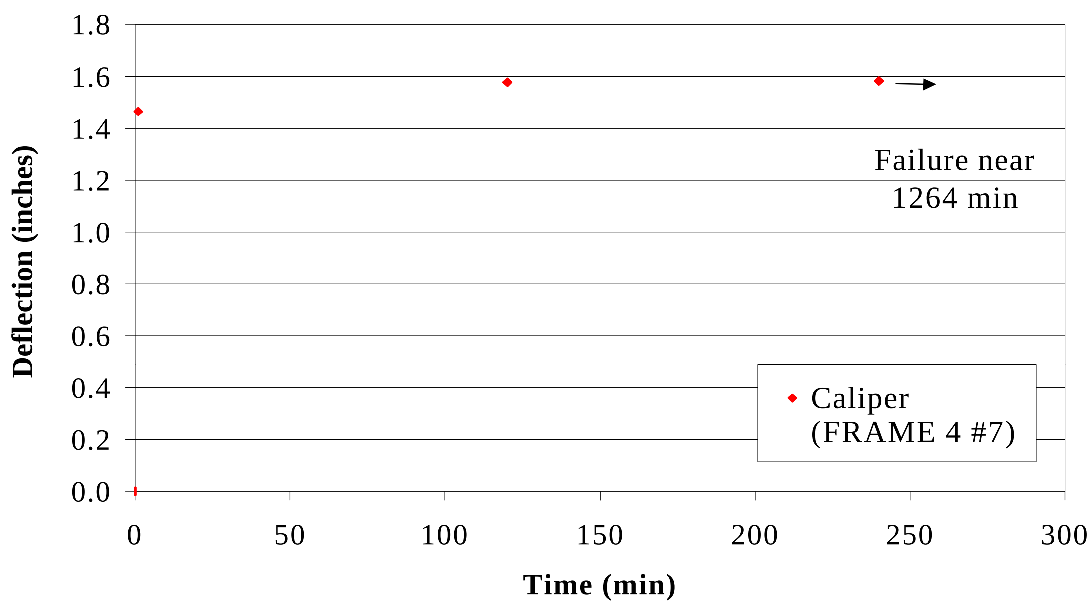


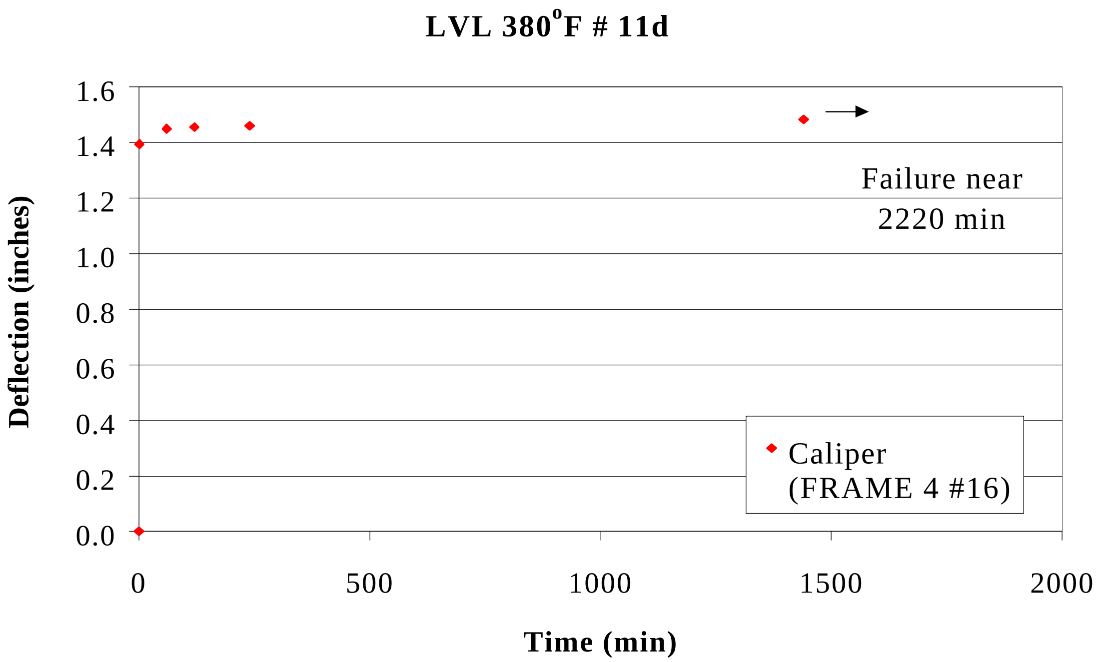


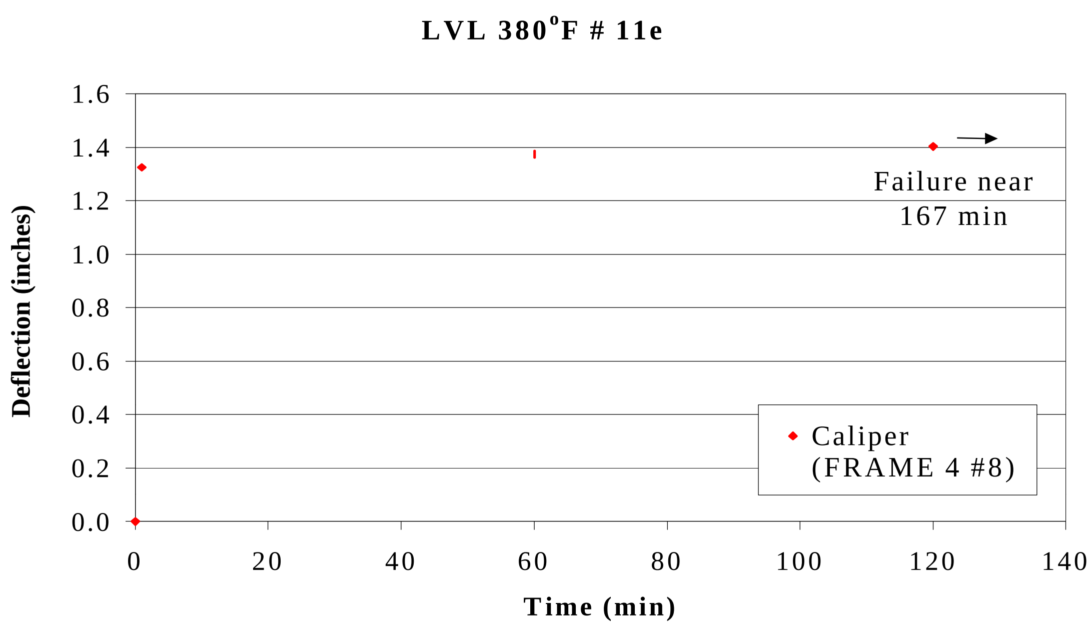
LVL 380°F # 9c

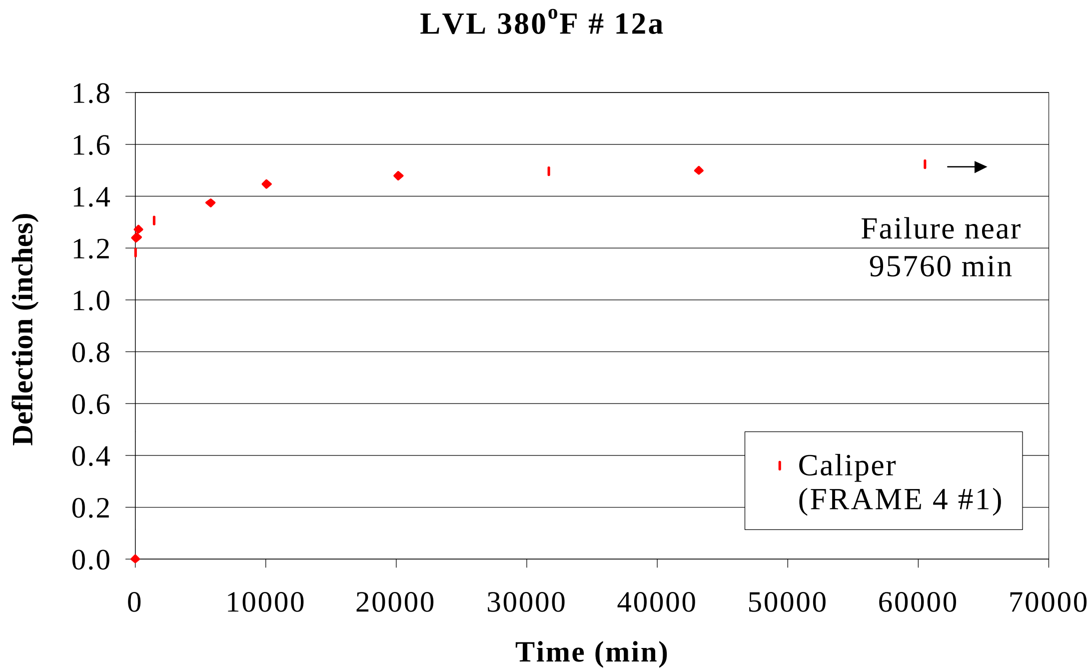


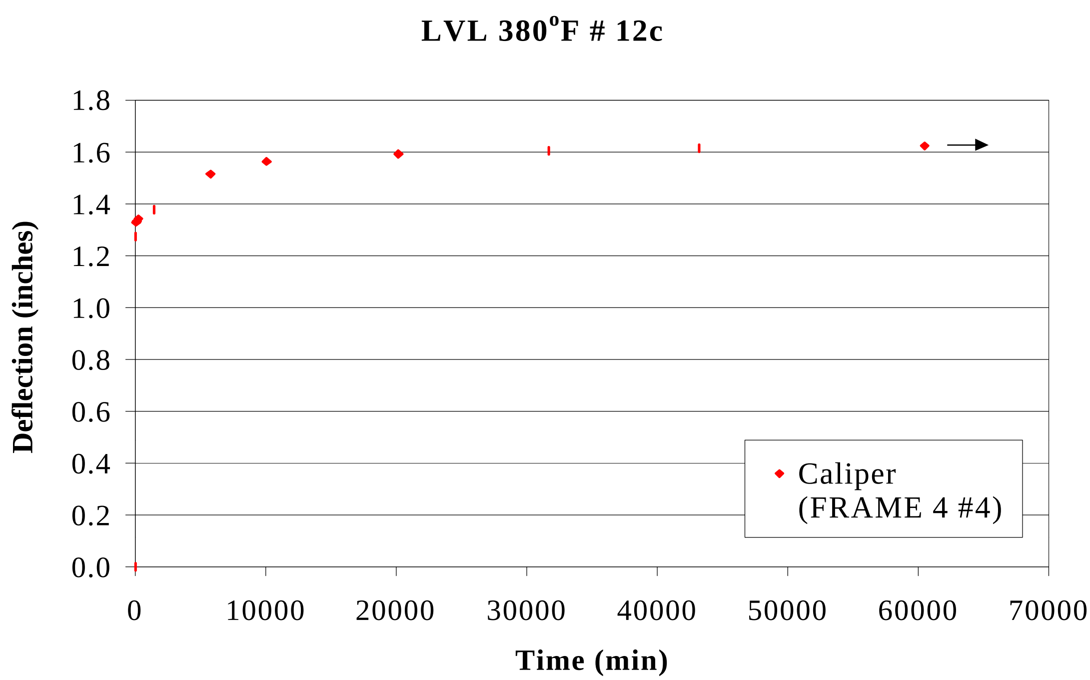
LVL 380°F # 10a



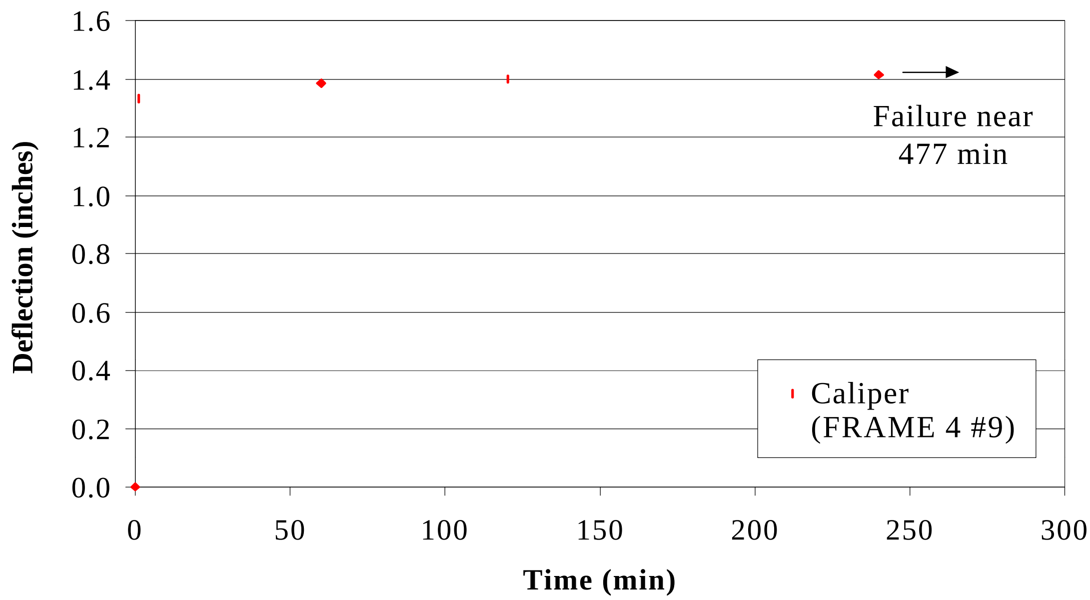

LVL 380°F # 11d
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
Failure near
2220 min
Caliper
(FRAME 4 #16)
0
500
1000
1500
2000
Time (min)


LVL 380°F # 11e
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Deflection (inches)
Failure near
167 min
Caliper
(FRAME 4 #8)
0
20
40
60
80
100
120
140
Time (min)

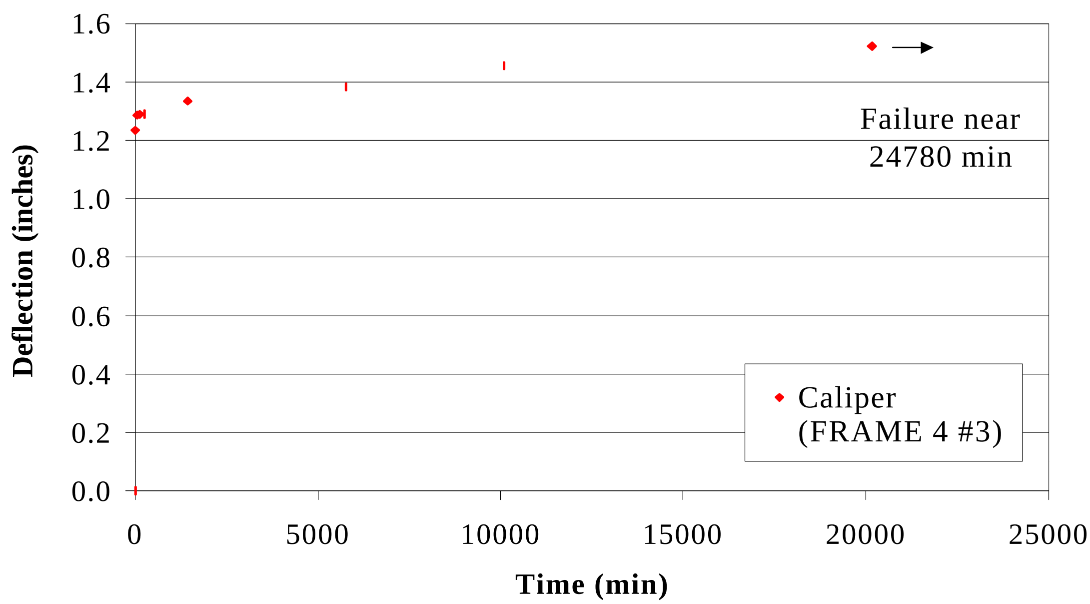

LVL 380°F # 12a
Deflection (inches)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Failure near
95760 min
Caliper
(FRAME 4 #1)

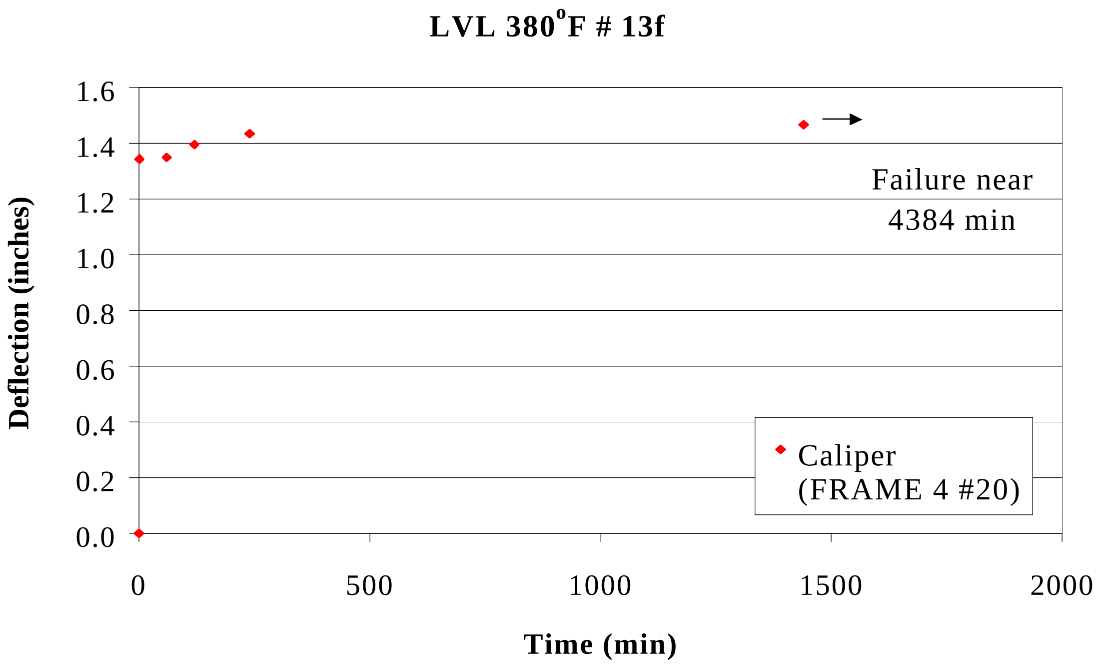

LVL 380°F # 12c
Deflection (inches)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 4 #4)

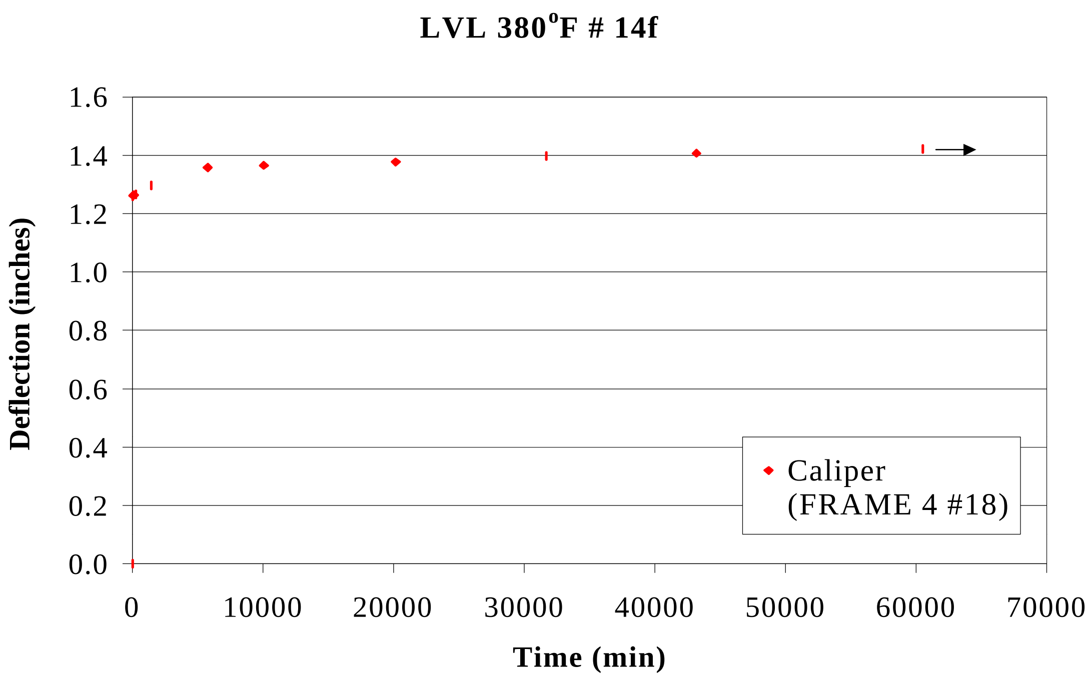
LVL 380°F # 13b



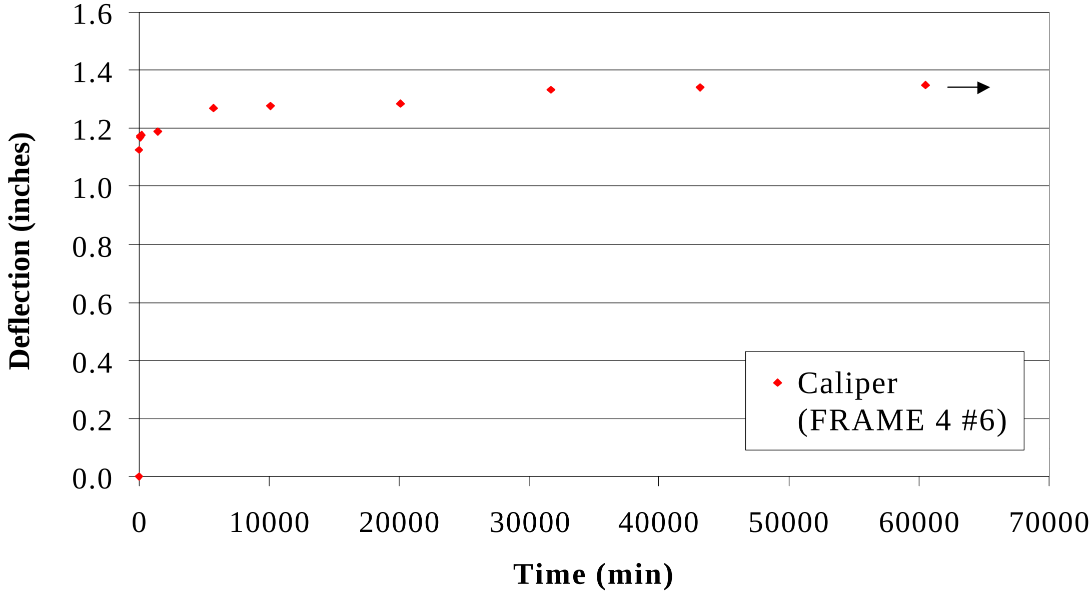
LVL 380°F # 13e



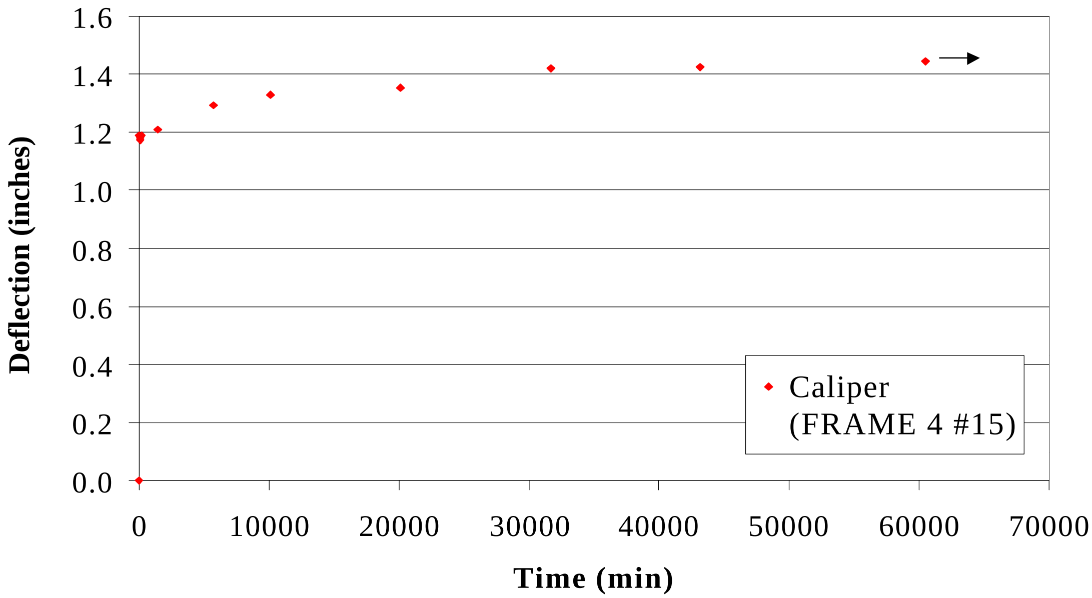

LVL 380°F # 13f
Failure near
4384 min
Caliper
(FRAME 4 #20)
Deflection (inches)
Time (min)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000

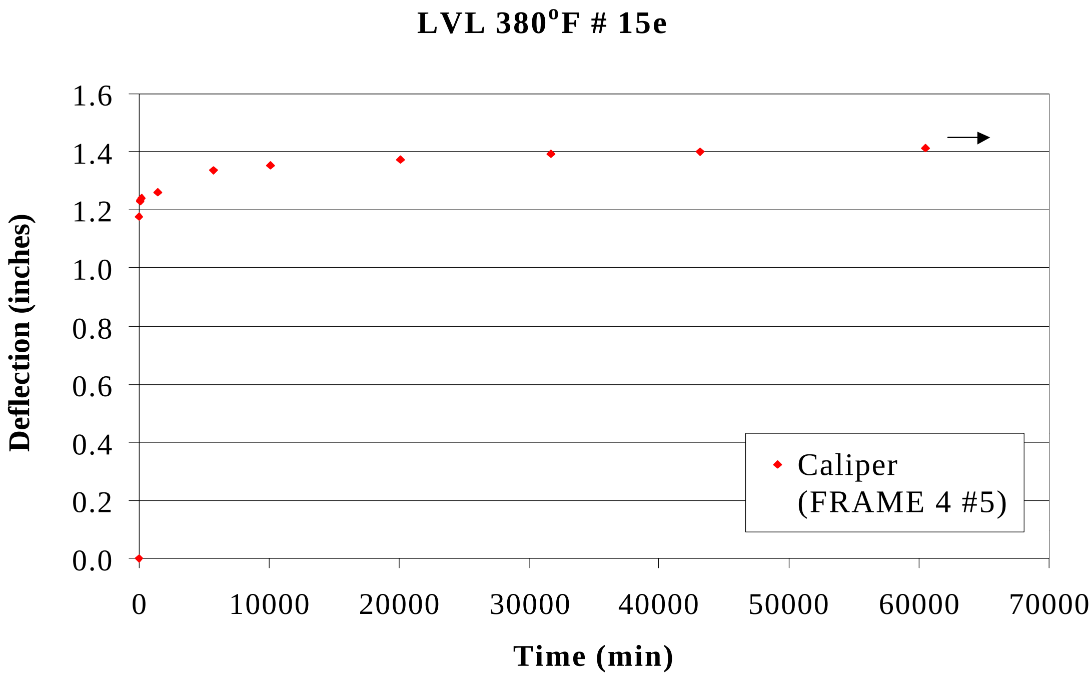

LVL 380°F # 14f
Caliper
(FRAME 4 #18)
Deflection (inches)
Time (min)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000

LVL 380°F # 15a



LVL 380°F # 15c




LVL 380°F # 15e
Deflection (inches)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
60000
70000
Time (min)
Caliper
(FRAME 4 #5)

APPENDIX H

DAMAGE ACCUMULATION MODEL DERIVATIONS

INTRODUCTION

The idea that, for a given member, a certain stress will cause unrecoverable damage is the basis of the linear theory of damage accumulation. The total damage present can be found by summing the damage accumulated for multiple load histories. This unrecoverable damage will continue to accumulate until a sufficient level of damage has occurred at which time, the member will fail. Further explanation of the two methods used in this research, Wood (1951) and Gerhards (1979), is provided in this appendix.

Since the linear best fit models were the available means of comparison, statistical analysis of the equations of the lines was performed. This was done through the hypothesis of regression line equality. First, the slopes of the lines were compared. If it was determined that the slopes were different, the analysis stopped there. However, if it was determined that the slopes were statistically equal, then the elevations of the lines were compared. This analysis was done to compare the temperature categories and to compare a given temperature between laminated veneer lumber and solid sawn lumber.

DAMAGE ACCUMULATION MODELS

In general, the summation of damage is expressed as:

$$\alpha = \sum_{i=1}^{n} \frac{t_i}{(t_f)_i}$$

α = state variable representing damage: range zero (no damage) to one (failure)

t_i = duration of load (time) at a specific stress level, σ_i

t_f = duration of load (time) required at σ_i to cause failure

In integral form:

$$\alpha = \int_0^t \left(\frac{1}{t_f}\right) dt$$

Rewritten where time is a function of applied stress:

$$\frac{d\alpha}{dt} = f(\sigma)$$

MADISON CURVE (WOOD'S MODEL)

The Madison Curve (Wood, 1951) can be expressed in damage accumulation form:

$$\frac{d\alpha}{dt} = A(\sigma - \sigma_o)^B$$

α = parameter of damage accumulation (see above)

$d\alpha/dt$ = time rate of damage accumulation

A, B = model constants determined through experimental data

σ = ratio of applied stress to ultimate stress (static test strength)

σ_o = stress threshold

Manipulation of the above model (to obtain a time-to-failure equation) yeilds:

$$\int d\alpha = \int A(\sigma - \sigma_o)^B dt$$

$$\alpha = t \cdot A(\sigma - \sigma_o)^B$$

Failure must occure so $\alpha = 1$ and $t = t_f$:

$$1 = t_f \cdot A(\sigma - \sigma_o)^B$$

Solve for t_f to obtain the general form:

$$t_f = \frac{1}{A(\sigma - \sigma_o)^B}$$

Applying the calibration by Wood (1951):

$$\sigma = \frac{1.084}{t_f^{0.04635}} + 0.183$$

where time to failure, t_f, is in seconds

The design curve is then defined as:

$$t_f = \frac{0.0949}{(\sigma - 0.183)^{21.575}}$$

where time to failure, t_f, is in minutes

*G*ERHARDS' *E*XPONENTIAL *D*AMAGE *R*ATE *M*ODEL *(EDRM)*

The EDRM (Gerhards, 1979) can be expressed in damage accumulation form:

$$\frac{d\alpha}{dt} = \exp(-A + B\sigma)$$

α = parameter of damage accumulation (see above)

$d\alpha/dt$ = time rate of damage accumulation

A, B = model constants determined through experimental data

σ = ratio of applied stress to ultimate stress (static test strength)

Manipulation of the above model (to obtain a time-to-failure equation) yeilds:

$$\int d\alpha = \int \exp(-A + B\sigma)\, dt$$

$$\alpha = t \cdot \exp(-A + B\sigma)$$

Failure must occure so $\alpha = 1$ and $t = t_f$:

$$1 = t_f \cdot \exp(-A + B\sigma)$$

Solve for t_f to obtain the general form:

$$t_f = \frac{1}{\exp(-A + B\sigma)} \qquad \text{or} \qquad t_f = \exp(A - B\sigma)$$

Linear regression is used to determine the model constatnts A and B:

$$LN(t_f) = A - B\sigma$$

The linear equation, $y = mx + b$ is defined as:

$y = LN(t_f)$ $\qquad$ $m = B$ $\qquad$ $b = A$

Hypothesis of Regression Line Equality

To compare the time to failure regression line between temperatures, testing for difference between two population regression coefficients (slope similarity) and elevations was done. (95% confidence)

Solid Sawn Lumber: Regression analysis provided slope (B) and y-intercept (A)

No Temp	300 ºF	340 ºF	380 ºF
$n_{NT} := 5$	$n_{300} := 6$	$n_{340} := 3$	$n_{380} := 4$
$X_{NT} := 0.83539131$	$X_{300} := 0.94987776$	$X_{340} := 0.72394169$	$X_{380} := 0.793770315$
$Y_{NT} := 7.167822246$	$Y_{300} := 7.635215162$	$Y_{340} := 8.286223662$	$Y_{380} := 5.775816746$
$Sx2_{NT} := 3.50399228$	$Sx2_{300} := 5.4752171$	$Sx2_{340} := 1.57417125$	$Sx2_{380} := 2.528659465$
$Sxy_{NT} := 29.2284703$	$Sxy_{300} := 41.880889$	$Sxy_{340} := 17.81494866$	$Sxy_{380} := 17.76054$
$Sy2_{NT} := 299.1710022$	$Sy2_{300} := 397.5154945$	$Sy2_{340} := 223.5523052$	$Sy2_{380} := 177.8044807$
$B_{NT} := -48.716313$	$B_{300} := -26.525292$	$B_{340} := -95.585684$	$B_{380} := -69.039324$
$A_{NT} := 47.8650072$	$A_{300} := 32.8310001$	$A_{340} := 77.4846858$	$A_{380} := 60.5771826$

Residual Degrees of Freedom (2 sets will always be compared):

$resDF_{NT} := n_{NT} - 2$	$resDF_{300} := n_{300} - 2$	$resDF_{340} := n_{340} - 2$	$resDF_{380} := n_{380} - 2$
$resDF_{NT} = 3$	$resDF_{300} = 4$	$resDF_{340} = 1$	$resDF_{380} = 2$

Residual Sum of Squares:

$$resSS_{NT} := Sy2_{NT} - \left[\frac{(Sxy_{NT})^2}{Sx2_{NT}}\right] \qquad resSS_{NT} = 55.362$$

$$resSS_{300} := Sy2_{300} - \left[\frac{(Sxy_{300})^2}{Sx2_{300}}\right] \qquad resSS_{300} = 77.161$$

$$resSS_{340} := Sy2_{340} - \left[\frac{(Sxy_{340})^2}{Sx2_{340}}\right] \qquad resSS_{340} = 21.94$$

$$resSS_{380} := Sy2_{380} - \left[\frac{(Sxy_{380})^2}{Sx2_{380}}\right] \qquad resSS_{380} = 53.06$$

Populations: No Temperature & 300°F

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2{}_{Y\cdot X})p =$ $p := \dfrac{resSS_{NT} + resSS_{300}}{resDF_{NT} + resDF_{300}}$ $p = 18.932$

$\nu := resDF_{NT} + resDF_{300}$ $\nu = 7$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{NT}} + \dfrac{p}{Sx2_{300}}}$ $bd = 2.977$

$t := \dfrac{B_{NT} - B_{300}}{bd}$ $\boxed{t = -7.455}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.365$

H_o is rejected: the regression lines of No Temperature and 300°F have different slopes. No need to check elevation.

Populations: No Temperature & 340°F

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2{}_{Y\cdot X})p =$ $p := \dfrac{resSS_{NT} + resSS_{340}}{resDF_{NT} + resDF_{340}}$ $p = 19.326$

$\nu := resDF_{NT} + resDF_{340}$ $\nu = 4$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{NT}} + \dfrac{p}{Sx2_{340}}}$ $bd = 4.218$

$t := \dfrac{B_{NT} - B_{340}}{bd}$ $\boxed{t = 11.112}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.776$

H_o is rejected: the regression lines of No Temperature and 340°F have different slopes. No need to check elevation.

Populations: No Temperature & 380°F

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2{}_{Y \cdot X})p =$ $p := \dfrac{resSS_{NT} + resSS_{380}}{resDF_{NT} + resDF_{380}}$ $p = 21.684$

$\nu := resDF_{NT} + resDF_{380}$ $\nu = 5$

call this variable bd: $s_{b1-b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{NT}} + \dfrac{p}{Sx2_{380}}}$ $bd = 3.842$

$t := \dfrac{B_{NT} - B_{380}}{bd}$ $\boxed{t = 5.289}$

Reject H_o if: $|t| \geq t_{\alpha 2 \nu}$

From Table: $t_{\alpha 2 \nu} := 2.571$

H_0 is rejected: the regression lines of No Temperature and 380°F have different slopes. No need to check elevation.

Populations: 300°F & 340°F

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2{}_{Y \cdot X})p =$ $p := \dfrac{resSS_{300} + resSS_{340}}{resDF_{300} + resDF_{340}}$ $p = 19.82$

$\nu := resDF_{300} + resDF_{340}$ $\nu = 5$

call this variable bd: $s_{b1-b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{300}} + \dfrac{p}{Sx2_{340}}}$ $bd = 4.026$

$t := \dfrac{B_{300} - B_{340}}{bd}$ $\boxed{t = 17.152}$

Reject H_o if: $|t| \geq t_{\alpha 2 \nu}$

From Table: $t_{\alpha 2 \nu} := 2.571$

H_0 is rejected: the regression lines of 300°F and 340°F have different slopes. No need to check elevation.

Populations: 300°F & 380°F

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y\cdot X})p =$ $p := \dfrac{resSS_{300} + resSS_{380}}{resDF_{300} + resDF_{380}}$ $p = 21.704$

$\nu := resDF_{300} + resDF_{380}$ $\nu = 6$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{300}} + \dfrac{p}{Sx2_{380}}}$ $bd = 3.542$

$t := \dfrac{B_{300} - B_{380}}{bd}$ $\boxed{t = 12.002}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.447$

H_o is rejected: the regression lines of 300°F and 380°F have different slopes. No need to check elevation.

Populations: 340°F & 380°F

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y\cdot X})p =$ $p := \dfrac{resSS_{340} + resSS_{380}}{resDF_{340} + resDF_{380}}$ $p = 25$

$\nu := resDF_{340} + resDF_{380}$ $\nu = 3$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{340}} + \dfrac{p}{Sx2_{380}}}$ $bd = 5.076$

$t := \dfrac{B_{340} - B_{380}}{bd}$ $\boxed{t = -5.23}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 3.182$

H_o is rejected: the regression lines of 340°F and 380°F have different slopes. No need to check elevation.

LAMINATED VENEER LUMBER: Regression analysis provided slope (B) and y-intercept (A)

300 ºF	340 ºF - 1	340 ºF - 2	380 ºF
$n_{L300} := 13$	$n_{L3401} := 14$	$n_{L3402} := 14$	$n_{L380} := 10$
$X_{L300} := 0.80943866$	$X_{L340} := 0.7932401$	$X_{L340} = 0.7932401$	$X_{L380} := 0.84213006$
$Y_{L300} := 6.49379631$	$Y_{L3401} := 7.01406498$	$Y_{L3402} := 6.35974262$	$Y_{L380} := 6.74008759$
$Sx2_{L300} := 8.56971787$	$Sx2_{L340} := 8.88015362$	$Sx2_{L340} = 8.88015362$	$Sx2_{L380} := 7.13633119$
$Sxy_{L300} := 65.45868159$	$Sxy_{L3401} := 74.73491632$	$Sxy_{L3402} := 67.40314361$	$Sxy_{L380} := 54.87194439$
$Sy2_{L300} := 713.5774258$	$Sy2_{L3401} := 839.8166348$	$Sy2_{L3402} := 718.2368259$	$Sy2_{L380} := 537.4468519$
$B_{L300} := -55.01235$	$B_{L3401} := -44.530709$	$B_{L3402} := -45.451072$	$B_{L380} := -42.434281$
$A_{L300} := 51.01235$	$A_{L3401} := 42.3376095$	$A_{L3402} := 42.4133555$	$A_{L380} := 42.4752716$

Residual Degrees of Freedom (2 sets will always be compared):

$resDF_{L300} := n_{L300} - 2$	$resDF_{L3401} := n_{L3401} - 2$	$resDF_{L3402} := n_{L3402} - 2$	$resDF_{L380} := n_{L380} - 2$
$resDF_{L300} = 11$	$resDF_{L3401} = 12$	$resDF_{L3402} = 12$	$resDF_{L380} = 8$

Residual Sum of Squares:

$$resSS_{L300} := Sy2_{L300} - \left[\frac{(Sxy_{L300})^2}{Sx2_{L300}}\right] \qquad resSS_{L300} = 213.58$$

$$resSS_{L3401} := Sy2_{L3401} - \left[\frac{(Sxy_{L3401})^2}{Sx2_{L340}}\right] \qquad resSS_{L3401} = 210.851$$

$$resSS_{L3402} := Sy2_{L3402} - \left[\frac{(Sxy_{L3402})^2}{Sx2_{L340}}\right] \qquad resSS_{L3402} = 206.626$$

$$resSS_{L380} := Sy2_{L380} - \left[\frac{(Sxy_{L380})^2}{Sx2_{L380}}\right] \qquad resSS_{L380} = 115.531$$

Populations: 300ºF & 340ºF - 1

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y \cdot X})p =$ $p := \dfrac{resSS_{L300} + resSS_{L3401}}{resDF_{L300} + resDF_{L3401}}$ $p = 18.454$

$\nu := resDF_{L300} + resDF_{L3401}$ $\nu = 23$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{L300}} + \dfrac{p}{Sx2_{L340}}}$ $bd = 2.057$

$t := \dfrac{B_{L300} - B_{L3401}}{bd}$ $\boxed{t = -5.096}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.069$

H_o is rejected: the regression lines of 300ºF and 340ºF - 1 have different slopes. No need to check elevation.

Populations: 300ºF & 340ºF - 2

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y \cdot X})p =$ $p := \dfrac{resSS_{L300} + resSS_{L3402}}{resDF_{L300} + resDF_{L3402}}$ $p = 18.27$

$\nu := resDF_{L300} + resDF_{L3402}$ $\nu = 23$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{L300}} + \dfrac{p}{Sx2_{L340}}}$ $bd = 2.047$

$t := \dfrac{B_{L300} - B_{L3402}}{bd}$ $\boxed{t = -4.671}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.069$

H_o is rejected: the regression lines of 300ºF and 340ºF - 2 have different slopes. No need to check elevation.

Populations: 300°F & 380°F

H$_o$: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H$_A$: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y \cdot X})p =$ $p := \frac{resSS_{L300} + resSS_{L380}}{resDF_{L300} + resDF_{L380}}$ $p = 17.322$

$\nu := resDF_{L300} + resDF_{L380}$ $\nu = 19$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\frac{p}{Sx2_{L300}} + \frac{p}{Sx2_{L380}}}$ $bd = 2.109$

$t := \frac{B_{L300} - B_{L380}}{bd}$ $\boxed{t = -5.964}$

Reject H$_o$ if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.093$

H$_o$ is rejected: the regression lines of 300°F and 380°F have different slopes. No need to check elevation.

Populations: 340°F - 1 & 340°F - 2

H$_o$: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H$_A$: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y \cdot X})p =$ $p := \frac{resSS_{L3401} + resSS_{L3402}}{resDF_{L3401} + resDF_{L3402}}$ $p = 17.395$

$\nu := resDF_{L3401} + resDF_{L3402}$ $\nu = 24$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\frac{p}{Sx2_{L340}} + \frac{p}{Sx2_{L340}}}$ $bd = 1.979$

$t := \frac{B_{L3401} - B_{L3402}}{bd}$ $\boxed{t = 0.465}$

Reject H$_o$ if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.064$

H$_o$ is accepted: the regression lines of 340°F - 1 and 340°F - 2 do **not** have different slopes. Check elevation.

H_o: The two population regression lines have the same elevation.
H_A: The two population regression lines do not have the same elevation.

$A_c := Sx2_{L340} + Sx2_{L340}$ $\qquad$ $A_c = 17.76$

$B_c := Sxy_{L3401} + Sxy_{L3402}$ $\qquad$ $B_c = 142.138$

$C_c := Sy2_{L3401} + Sy2_{L3402}$ $\qquad$ $C_c = 1.558 \times 10^3$

$$b_c := \frac{Sx2_{L340} \cdot B_{L3401} + Sx2_{L340} \cdot B_{L3402}}{Sx2_{L340} + Sx2_{L340}} \qquad b_c = -44.991$$

$$SS_c := C_c - \frac{B_c{}^2}{A_c} \qquad SS_c = 420.504$$

$DF_c := n_{L3401} + n_{L3402} - 3$ $\qquad$ $DF_c = 25$

$$(s^2{}_{Y \cdot X})c = \quad c := \frac{SS_c}{DF_c} \qquad c = 16.82$$

$$t := \frac{(Y_{L3401} - Y_{L3402}) - b_c \cdot (X_{L340} - X_{L340})}{\sqrt{c \cdot \left[\frac{1}{n_{L3401}} + \frac{1}{n_{L3402}} + \frac{(X_{L340} - X_{L340})^2}{A_c}\right]}} \qquad t = 0.422$$

Reject H_o if: $|t| \geq t_{\alpha 2c}$

From Table: $t_{\alpha 2DFc} := 2.060$

H_o is accepted: the regression lines of 340^{o}F - 1 and 340^{o}F - 2 have the same elevations.

Since the "two population regressions have neither different slopes nor different elevations, then both sample regressions estimate the same population regression." (Zar, 1996)

This is expected because the two populations, 340^{o}F - 1 and 340^{o}F - 2, were in fact taken from the same population, LVL 340^{o}F.

The two regression equations can be written as one:

$$X_p := \frac{n_{L3401} \cdot X_{L340} + n_{L3402} \cdot X_{L340}}{n_{L3401} + n_{L3402}} \qquad Y_p := \frac{n_{L3401} \cdot Y_{L3401} + n_{L3402} \cdot Y_{L3402}}{n_{L3401} + n_{L3402}}$$

$a_c := Y_p - b_c \cdot X_p$ $\qquad$ $a_c = 42.375$ $\qquad$ $Y_i = 42.375 - 44.991X_i$ is the common equation

Populations: 340°F - 1 & 380°F

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y \cdot X})p =$ $p := \dfrac{resSS_{L3401} + resSS_{L380}}{resDF_{L3401} + resDF_{L380}}$ $p = 16.319$

$\nu := resDF_{L3401} + resDF_{L380}$ $\nu = 20$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{L340}} + \dfrac{p}{Sx2_{L380}}}$ $bd = 2.031$

$t := \dfrac{B_{L3401} - B_{L380}}{bd}$ $\boxed{t = -1.032}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.086$

H_o is accepted: the regression lines of 340°F - 1 and 380°F do **not** have different slopes. Check elevation.

H_o: The two population regression lines have the same elevation.
H_A: The two population regression lines do not have the same elevation.

$A_c := Sx2_{L340} + Sx2_{L380}$ $A_c = 16.016$

$B_c := Sxy_{L3401} + Sxy_{L380}$ $B_c = 129.607$

$C_c := Sy2_{L3401} + Sy2_{L380}$ $C_c = 1.377 \times 10^3$

$b_c := \dfrac{Sx2_{L340} \cdot B_{L3401} + Sx2_{L380} \cdot B_{L380}}{Sx2_{L340} + Sx2_{L380}}$ $b_c = -43.597$

$SS_c := C_c - \dfrac{B_c^{\,2}}{A_c}$ $SS_c = 328.473$

$DF_c := n_{L3401} + n_{L380} - 3$ $DF_c = 21$

$(s^2_{Y \cdot X})c =$ $c := \dfrac{SS_c}{DF_c}$ $c = 15.642$

$$t := \frac{(Y_{L3401} - Y_{L380}) - b_c \cdot (X_{L340} - X_{L380})}{\sqrt{c \cdot \left[\frac{1}{n_{L3401}} + \frac{1}{n_{L380}} + \frac{(X_{L340} - X_{L380})^2}{A_c}\right]}} \qquad t = -1.134$$

Reject H_o if: $|t| \geq t_{\alpha 2c}$

From Table: $t_{\alpha 2DFc} := 2.080$

H_o is accepted: the regression lines of 340°F - 1 and 380°F have the same elevations.

Since the "two population regressions have neither different slopes nor different elevations, then both sample regressions estimate the same population regression." (Zar, 1996)

The two regression equations can be written as one:

$$X_p := \frac{n_{L3401} \cdot X_{L340} + n_{L380} \cdot X_{L380}}{n_{L3401} + n_{L380}} \qquad Y_p := \frac{n_{L3401} \cdot Y_{L3401} + n_{L380} \cdot Y_{L380}}{n_{L3401} + n_{L380}}$$

$a_c := Y_p - b_c \cdot X_p \qquad a_c = 42.371$

$Y_i = 42.371 - 43.597X_i$ is the common equation

(slightly different from the common 340°F Eqn.)

<u>Populations: 340°F - 2 & 380°F</u>

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y \cdot X})p = \quad p := \frac{resSS_{L3402} + resSS_{L380}}{resDF_{L3402} + resDF_{L380}} \qquad p = 16.108$

$$\nu := resDF_{L3402} + resDF_{L380} \qquad \nu = 20$$

call this variable bd: $s_{b1\text{-}b2} = \quad bd := \sqrt{\frac{p}{Sx2_{L340}} + \frac{p}{Sx2_{L380}}} \qquad bd = 2.018$

$$t := \frac{B_{L3402} - B_{L380}}{bd} \qquad \boxed{t = -1.495}$$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.086$

H_o is accepted: the regression lines of 340°F - 2 and 380°F do **not** have different slopes. Check elevation.

H_o: The two population regression lines have the same elevation.
H_A: The two population regression lines do not have the same elevation.

$A_c := Sx2_{L340} + Sx2_{L380}$ $\qquad A_c = 16.016$

$B_c := Sxy_{L3402} + Sxy_{L380}$ $\qquad B_c = 122.275$

$C_c := Sy2_{L3402} + Sy2_{L380}$ $\qquad C_c = 1.256 \times 10^3$

$$b_c := \frac{Sx2_{L340} \cdot B_{L3402} + Sx2_{L380} \cdot B_{L380}}{Sx2_{L340} + Sx2_{L380}} \qquad b_c = -44.107$$

$$SS_c := C_c - \frac{{B_c}^2}{A_c} \qquad SS_c = 322.196$$

$DF_c := n_{L3402} + n_{L380} - 3$ $\qquad DF_c = 21$

$$(s^2_{Y \cdot X})c = \quad c := \frac{SS_c}{DF_c} \qquad c = 15.343$$

$$t := \frac{(Y_{L3402} - Y_{L380}) - b_c \cdot (X_{L340} - X_{L380})}{\sqrt{c \cdot \left[\frac{1}{n_{L3402}} + \frac{1}{n_{L380}} + \frac{(X_{L340} - X_{L380})^2}{A_c} \right]}} \qquad t = -1.563$$

Reject H_o if: $|t| \geq t_{\alpha 2c}$

From Table: $t_{\alpha 2DFc} := 2.080$

H_0 is accepted: the regression lines of 340°F - 2 and 380°F have the same elevations.

Since the "two population regressions have neither different slopes nor different elevations, then both sample regressions estimate the same population regression." (Zar, 1996)

The two regression equations can be written as one:

$$X_p := \frac{n_{L3402} \cdot X_{L340} + n_{L380} \cdot X_{L380}}{n_{L3402} + n_{L380}} \qquad Y_p := \frac{n_{L3402} \cdot Y_{L3402} + n_{L380} \cdot Y_{L380}}{n_{L3402} + n_{L380}}$$

$a_c := Y_p - b_c \cdot X_p$ $\qquad a_c = 42.404$

$Y_i = 42.404 - 44.107X_i$ is the common equation

(slightly different from the other common Eqns.)

MULTIREGRESSION LINE COMPARISON FOR LAMINATED VENEER LUMBER:

Since it was found that three of the temperatures had the same slope and elevation when compared one-on-one, a multiregression was done to see if all three coincide.
(95% confidence)

Populations: 340°F - 1, 340°F - 2, and 380°F

Pooled Regression: $k := 3$

$$SS_p = \sum_{i=1}^{k} resSS_i \qquad DFp = \sum_{i=1}^{k} resDF_i$$

$SS_p := resSS_{L3401} + resSS_{L3402} + resSS_{L380}$ $\qquad$ $DF_p := resDF_{L3401} + resDF_{L3402} + resDF_{L380}$

$SS_p = 533.008$ $\qquad$ $DF_p = 32$

Common Regression:

$$A_c = \sum_{i=1}^{k} Sx2_i \qquad B_c = \sum_{i=1}^{k} Sxy_i \qquad C_c = \sum_{i=1}^{k} Sy2_i$$

$A_c := 2 \cdot Sx2_{L340} + Sx2_{L380}$ $\qquad$ $B_c := Sxy_{L3401} + Sxy_{L3402} + Sxy_{L380}$ $\qquad$ $C_c := Sy2_{L3401} + Sy2_{L3402} + Sy2_{L380}$

$A_c = 24.897$ $\qquad$ $B_c = 197.01$ $\qquad$ $C_c = 2.096 \times 10^3$

$$SS_c := C_c - \frac{B_c^{\,2}}{A_c} \qquad DF_c = \left(\sum_{i=1}^{k} n_i\right) - k - 1$$

$SS_c = 536.537$ $\qquad$ $DF_c := (n_{L3401} + n_{L3402} + n_{L380}) - k - 1$

$DF_c = 34$

To obtain the "total" SS, all three data sets were combined: $n_{all} := 38$

$X_{all} := 0.806105882$ $\quad$ $Sx2_{all} := 24.8966384$ $\quad$ $Sy2_{all} := 2095.500313$

$Y_{all} := 6.70089954$ $\quad$ $Sxy_{all} := 197.0100043$

$$SS_{all} := Sy2_{all} - \left[\frac{(Sxy_{all})^2}{Sx2_{all}}\right] \qquad SS_{all} = 536.537$$

Test for differences among slopes:

H_o: $\beta_1 = \beta_2 = \beta_3$

H_A: All three β's are not equal

$$F := \frac{\frac{SS_c - SS_p}{k-1}}{\frac{SS_p}{DF_p}} \qquad F = 0.106$$

Reject H_o if: $F > F_{a(1),k-1,DFp}$

From Table: $F_{0.05(1),2,30} = 3.32 > F_{0.05(1),2,32} > F_{0.05(1),2,35} = 3.27$

H_o is accepted: the regression lines of 340°F - 1, 340°F - 2, and 380°F do **not** have different slopes. Check elevation.

$$b_c := \frac{Sx2_{L340} \cdot B_{L3401} + Sx2_{L340} \cdot B_{L3402} + Sx2_{L380} \cdot B_{L380}}{Sx2_{L340} + Sx2_{L340} + Sx2_{L380}} \qquad b_c = -44.2581$$

Test for differences among elevations:

H_o: The three population regression lines have the same elevation.
H_A: The three population regression lines do not have the same elevation.

$$F := \frac{\frac{SS_{all} - SS_c}{k-1}}{\frac{SS_c}{DF_c}} \qquad F = -3.682 \times 10^{-8}$$

Note the great similarity of the "total" regression and the "common" regression:

$SS_c = 536.537165374569$ $\qquad$ $SS_{all} = 536.537164212571$

Reject H_o if: $F > F_{a(1),k-1,DFc}$

From Table: $F_{0.05(1),2,30} = 3.32 > F_{0.05(1),2,34} > F_{0.05(1),2,35} = 3.27$

H_o is accepted: the regression lines of 340°F - 1, 340°F - 2, and 380°F do **not** have different elevations.

Since the three population regressions have neither different slopes nor different elevations, then both sample regressions estimate the same population regression. (Zar, 1996)

The three regression equations can be written as one:

$$X_p := \frac{n_{L3401} \cdot X_{L340} + n_{L3402} \cdot X_{L340} + n_{L380} \cdot X_{L380}}{n_{L3401} + n_{L3402} + n_{L380}} \qquad X_p = 0.806$$

$$Y_p := \frac{n_{L3401} \cdot Y_{L3401} + n_{L3402} \cdot Y_{L3402} + n_{L380} \cdot Y_{L380}}{n_{L3401} + n_{L3402} + n_{L380}} \qquad Y_p = 6.701$$

$$a_c := Y_p - b_c \cdot X_p \qquad a_c = 42.3776$$

$Y_i = 42.378 - 44.258X_i$ is the common equation for all three temperatures: 340ºF - 1, 340ºF - 2, 380ºF

The other common equations that were found are well represented by the total common equation.

$Y_i = 42.375 - 44.991X_i$ is the common equation for 340ºF - 1 and 340ºF - 2

$Y_i = 42.371 - 43.597X_i$ is the common equation for 340ºF -1 and 380ºF

$Y_i = 42.404 - 44.107X_i$ is the common equation for 340ºF - 2 and 380ºF

COMPARISON BETWEEN SOLID SAWN LUMBER AND LAMINATED VENEER LUMBER:

Populations: 300°F Solid Sawn Lumber & 300°F Laminated Veneer Lumber

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y \cdot X})p =$ $p := \dfrac{resSS_{300} + resSS_{L300}}{resDF_{300} + resDF_{L300}}$ $p = 19.383$

$\nu := resDF_{300} + resDF_{L300}$ $\nu = 15$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{300}} + \dfrac{p}{Sx2_{L300}}}$ $bd = 2.409$

$t := \dfrac{B_{300} - B_{L300}}{bd}$ $\boxed{t = 11.827}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.131$

H_o is rejected: the regression lines of Solid Sawn Lumber 300°F and Laminated Veneer Lumber 300°F have different slopes. No need to check elevation.

Populations: Solid Sawn Lumber 340°F & Laminated Veneer Lumber 340°F - 1

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y \cdot X})p =$ $p := \dfrac{resSS_{340} + resSS_{L3401}}{resDF_{340} + resDF_{L3401}}$ $p = 17.907$

$\nu := resDF_{340} + resDF_{L3401}$ $\nu = 13$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{340}} + \dfrac{p}{Sx2_{L340}}}$ $bd = 3.66$

$t := \dfrac{B_{340} - B_{L3401}}{bd}$ $\boxed{t = -13.951}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.160$

H_o is rejected: the regression lines of Solid Sawn Lumber 340°F and Laminated Veneer Lumber 340°F - 1 have different slopes. No need to check elevation.

Populations: 340°F Solid Sawn Lumber & 340°F - 2 Laminated Veneer Lumber

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y\cdot X})p =$ $p := \dfrac{resSS_{340} + resSS_{L3402}}{resDF_{340} + resDF_{L3402}}$ $p = 17.582$

$\nu := resDF_{340} + resDF_{L3402}$ $\nu = 13$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{340}} + \dfrac{p}{Sx2_{L340}}}$ $bd = 3.626$

$t := \dfrac{B_{340} - B_{L3402}}{bd}$ $\boxed{t = -13.826}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.160$

H_o is rejected: the regression lines of Solid Sawn Lumber 340°F and Laminated Veneer Lumber 340°F - 2 have different slopes. No need to check elevation.

Populations: Solid Sawn Lumber 380°F & Laminated Veneer Lumber 380°F

H_o: $\beta_1 = \beta_2$ (if rejected, two different populations) OR (if not rejected, lines are parallel)

H_A: $\beta_1 \neq \beta_2$

call this variable p: $(s^2_{Y\cdot X})p =$ $p := \dfrac{resSS_{380} + resSS_{L380}}{resDF_{380} + resDF_{L380}}$ $p = 16.859$

$\nu := resDF_{380} + resDF_{L380}$ $\nu = 10$

call this variable bd: $s_{b1\text{-}b2} =$ $bd := \sqrt{\dfrac{p}{Sx2_{380}} + \dfrac{p}{Sx2_{L380}}}$ $bd = 3.005$

$t := \dfrac{B_{380} - B_{L380}}{bd}$ $\boxed{t = -8.854}$

Reject H_o if: $|t| \geq t_{\alpha 2\nu}$

From Table: $t_{\alpha 2\nu} := 2.228$

H_o is rejected: the regression lines of Solid Sawn Lumber 380°F and Laminated Veneer Lumber 380°F have different slopes. No need to check elevation.

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APPENDIX I

DATA

INTRODUCTION

This appendix provides all pertinent numerical data for nondestructive testing, static testing and duration of load testing. Data is specimen specific in that individual dimensions and calculations are provided. For laminated veneer lumber, information for the members that were both used and not used for the research testing are provided in the nondestructive testing tables.

NONDESTRUCTIVE TESTING DATA (FOR STATIC TESTING)

SS No Temp Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s^2/in^4)	$E_{dynamic}$ (psi)
2	96.1875	3.479	1.472	492.00	194105.69	4022	0.0179952	0.0000466	1754667.88
12	96.25	3.451	1.481	486.67	196232.88	4346	0.0194752	0.0000504	1940830.92
38	96.25	3.439	1.482	474.67	201193.82	4234	0.0190346	0.0000493	1994049.53
50	96.25	3.478	1.484	517.33	184600.52	3905	0.0173297	0.0000448	1528339.30
56	96.1875	3.461	1.482	481.33	198407.20	4013	0.0179346	0.0000464	1827126.41
68	96.25	3.469	1.505	493.33	193581.08	3884	0.0170417	0.0000441	1652731.79
69	96.1875	3.454	1.495	532.00	179511.28	4589	0.0203736	0.0000527	1699078.16
85	96.1875	3.415	1.478	486.67	196232.88	4082	0.0185363	0.0000480	1847267.99
92	96.1875	3.460	1.487	528.00	180871.21	4317	0.0192271	0.0000498	1627852.46
93	96.1875	3.446	1.484	461.33	207008.67	4205	0.0188490	0.0000488	2090393.07
95	96.1875	3.435	1.479	533.33	179062.50	3708	0.0167308	0.0000433	1388316.07
105	96.25	3.491	1.487	540.00	176851.85	3320	0.0146524	0.0000379	1186015.21
114	96.25	3.470	1.487	494.67	193059.30	4009	0.0177980	0.0000461	1716782.15
117	96.1875	3.401	1.479	428.00	223130.84	4323	0.0196962	0.0000510	2537847.82
122	96.1875	3.483	1.488	501.33	190492.02	3605	0.0159464	0.0000413	1497539.36
124	96.25	3.469	1.473	489.33	195163.49	4792	0.0214756	0.0000556	2116922.89
129	96.25	3.453	1.485	458.67	208212.21	4281	0.0191205	0.0000495	2145237.78
136	96.1875	3.438	1.476	453.33	210661.76	4504	0.0203453	0.0000527	2336674.41
139	96.1875	3.458	1.488	501.33	190492.02	3808	0.0169661	0.0000439	1593303.11
142	96.1875	3.452	1.483	489.33	195163.49	4293	0.0192186	0.0000497	1894447.88
156	96.25	3.447	1.476	477.33	200069.83	4065	0.0183048	0.0000474	1896228.28
157	96.1875	3.489	1.469	488.00	195696.72	3647	0.0163143	0.0000422	1616957.68
158	96.1875	3.483	1.419	524.00	182251.91	4215	0.0195469	0.0000506	1680290.54
169	96.1875	3.461	1.490	477.33	200069.83	3912	0.0173893	0.0000450	1801391.22

NONDESTRUCTIVE TESTING DATA (FOR DOL TESTING)

SS No Temp Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s^2/in^4)	$E_{dynamic}$ (psi)
7	96.25	3.468	1.481	505.33	188984.17	4395	0.0196064	0.0000507	1812222.38
19	96.25	3.455	1.481	473.33	201760.56	3295	0.0147465	0.0000382	1553543.93
29	96.25	3.473	1.480	460.00	207608.70	4443	0.0197990	0.0000512	2208499.46
30	96.25	3.482	1.483	532.00	179511.28	4414	0.0195748	0.0000507	1632468.04
46	96.1875	3.430	1.476	484.00	197314.05	4508	0.0204069	0.0000528	2056154.53
47	96.25	3.467	1.473	558.67	170942.72	4717	0.0211517	0.0000547	1599589.88
48	96.1875	3.318	1.472	470.67	202903.68	3376	0.0158449	0.0000410	1688228.93
51	96.1875	3.487	1.478	552.00	173007.25	3782	0.0168156	0.0000435	1302579.68
54	96.25	3.488	1.489	537.33	177729.53	4207	0.0185557	0.0000480	1516905.15
58	96.1875	3.463	1.478	513.33	186038.96	4151	0.0185860	0.0000481	1664776.72
60	96.25	3.486	1.494	454.67	210043.99	3922	0.0172528	0.0000447	1969896.61
61	96.25	3.436	1.427	498.67	191510.70	3758	0.0175596	0.0000454	1666723.56
97	96.25	3.458	1.479	472.00	202330.51	5641	0.0252718	0.0000654	2677452.92
98	96.25	3.477	1.487	490.67	194633.15	4323	0.0191454	0.0000495	1876984.29
123	96.125	3.449	1.487	528.00	180871.21	3528	0.0157734	0.0000408	1335447.31
132	96.25	3.482	1.484	522.67	182716.84	4608	0.0204234	0.0000529	1764604.49
140	96.25	3.450	1.481	460.00	207608.70	4364	0.0195634	0.0000506	2182217.69
144	96.1875	3.449	1.480	500.00	191000.00	4098	0.0184048	0.0000476	1737641.21
152	96.25	3.443	1.492	494.67	193059.30	4717	0.0210279	0.0000544	2028340.53
159	96.1875	3.451	1.477	509.33	187500.00	4618	0.0207589	0.0000537	1888728.68
161	96.1875	3.442	1.475	464.00	205818.97	4253	0.0191960	0.0000497	2104474.41
162	96.1875	3.486	1.469	506.67	188486.84	3535	0.0158218	0.0000409	1454724.73
178	96.1875	3.472	1.489	484.00	197314.05	4279	0.0189731	0.0000491	1911692.06
180	96.1875	3.489	1.483	477.33	200069.83	3805	0.0168604	0.0000436	1746599.71

NONDESTRUCTIVE TESTING DATA (UNHEATED FOR STATIC TESTING)

SS UH 300°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s²/in⁴)	$E_{dynamic}$ (psi)
6	96.1875	3.466000	1.479667	473.33	201760.56	4022	0.0215412	0.0000557	2269371.82
8	96.1875	3.405667	1.475000	488.00	195696.72	4346	0.0163299	0.0000423	1618501.64
11	96.25	3.462333	1.485667	524.00	182251.91	4234	0.0204655	0.0000530	1759261.25
20	96.25	3.489333	1.487333	524.00	182251.91	3905	0.0185367	0.0000480	1593452.39
26	96.25	3.478667	1.489667	465.33	205229.23	4013	0.0161996	0.0000419	1765821.84
32	96.25	3.470667	1.479000	478.67	199512.53	3884	0.0188440	0.0000488	1941229.04
34	96.25	3.471000	1.483333	481.33	198407.20	4589	0.0188984	0.0000489	1925317.72
35	96.1875	3.461000	1.490000	564.00	169326.24	4082	0.0163071	0.0000422	1210004.22
37	96.1875	3.478000	1.480000	534.67	178615.96	4317	0.0193426	0.0000501	1597046.47
67	96.25	3.482333	1.484000	496.00	192540.32	4205	0.0176051	0.0000456	1689058.89
73	96.25	3.470000	1.484667	506.67	188486.84	3708	0.0196649	0.0000509	1808077.27
75	96.25	3.480667	1.495667	521.33	183184.14	3320	0.0172693	0.0000447	1499735.15
88	96.1875	3.484333	1.487333	501.33	190492.02	4009	0.0148028	0.0000383	1390144.00
90	96.1875	3.488000	1.488000	486.67	196232.88	4323	0.0164234	0.0000425	1636699.00
91	96.25	3.467667	1.484333	498.67	191510.70	3605	0.0161403	0.0000418	1532008.73
100	96.1875	3.468000	1.484333	464.00	205818.97	4792	0.0192126	0.0000497	2106296.75
110	96.25	3.490333	1.491333	481.33	198407.20	4281	0.0179360	0.0000464	1827274.59
113	96.25	3.479667	1.489667	478.67	199512.53	4504	0.0207994	0.0000538	2142664.78
115	96.1875	3.470000	1.495667	445.33	214446.11	3808	0.0158940	0.0000411	1891613.47
137	96.25	3.474667	1.476000	489.33	195163.49	4293	0.0202674	0.0000525	1997830.00
141	96.25	3.471333	1.485333	492.00	194105.69	4065	0.0212300	0.0000549	2070092.37
164	96.25	3.473667	1.485333	478.67	199512.53	3647	0.0163591	0.0000423	1685241.71
168	96.1875	3.459667	1.483667	512.00	186523.44	4215	0.0191246	0.0000495	1721958.99
172	96.1875	3.454333	1.473333	434.67	219708.59	3912	0.0204144	0.0000528	2550310.36

NONDESTRUCTIVE TESTING DATA (UNHEATED FOR DOL TESTING)

SS UH 300°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s²/in⁴)	$E_{dynamic}$ (psi)
25	96.1875	3.475000	1.485333	464.00	205818.97	3906	0.0173448	0.0000449	1901528.28
33	96.25	3.458000	1.482333	477.33	200069.83	4535	0.0202647	0.0000524	2099259.12
41	96.25	3.488667	1.481000	534.67	178615.96	3978	0.0176353	0.0000456	1456086.49
44	96.25	3.449333	1.479333	521.33	183184.14	4743	0.0212905	0.0000551	1848945.35
45	96.25	3.435333	1.476000	480.00	198958.33	4261	0.0192482	0.0000498	1971864.03
49	96.1875	3.452333	1.467333	521.33	183184.14	4632	0.0209577	0.0000542	1820041.56
70	96.1875	3.431000	1.461000	489.33	195163.49	4849	0.0221716	0.0000574	2185530.62
81	96.25	3.474000	1.489333	470.67	202903.68	5073	0.0224583	0.0000581	2392871.63
84	96.1875	3.487667	1.494000	486.67	196232.88	4287	0.0188575	0.0000488	1879273.38
99	96.25	3.474333	1.486000	509.33	187500.00	4228	0.0187576	0.0000485	1706646.73
104	96.25	3.484667	1.475667	476.00	200630.25	4372	0.0194744	0.0000504	2028709.61
109	96.25	3.474000	1.485333	477.33	200069.83	4677	0.0207609	0.0000537	2150667.38
112	96.1875	3.460667	1.485333	512.00	186523.44	3985	0.0177689	0.0000460	1599889.38
120	96.1875	3.461667	1.485000	468.00	204059.83	3620	0.0161403	0.0000418	1739363.74
121	96.25	3.467000	1.473667	482.67	197859.12	3975	0.0178204	0.0000461	1805479.51
125	96.25	3.484000	1.484000	505.33	188984.17	3795	0.0168125	0.0000435	1553985.59
126	96.1875	3.484333	1.497333	536.00	178171.64	4213	0.0185084	0.0000479	1520578.83
130	96.1875	3.477333	1.489667	560.00	170535.71	4041	0.0178801	0.0000463	1345744.52
135	96.1875	3.474667	1.497667	486.67	196232.88	3990	0.0175736	0.0000455	1751324.52
153	96.125	3.433333	1.460667	502.67	189986.74	3915	0.0179045	0.0000463	1672522.76
163	96.1875	3.462000	1.483333	510.67	187010.44	4097	0.0182859	0.0000473	1655047.15
170	96.25	3.494667	1.484333	541.33	176416.26	3666	0.0161878	0.0000419	1303853.72
173	96.125	3.433333	1.476333	488.00	195696.72	4726	0.0213841	0.0000553	2119440.41
175	96.1875	3.441333	1.488333	521.33	183184.14	4191	0.0187545	0.0000485	1628714.53

NONDESTRUCTIVE TESTING DATA (HEATED FOR STATIC TESTING)

SS H 300°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
6	96.25	3.466000	1.478667	473.33	201760.56	4784	0.0213809	0.0000553	2252481.83
8	96.1875	3.394667	1.487333	481.33	198407.20	3519	0.0159746	0.0000413	1627448.26
11	96.1875	3.459667	1.491333	520.00	183653.85	4554	0.0202302	0.0000524	1765885.76
20	96.1875	3.484333	1.486667	524.00	182251.91	4159	0.0184023	0.0000476	1581897.34
26	96.25	3.473333	1.489333	464.00	205818.97	3625	0.0160510	0.0000415	1759692.66
32	96.25	3.461333	1.486000	473.33	201760.56	4144	0.0184540	0.0000478	1944135.27
34	96.25	3.468667	1.480667	476.00	200630.25	4180	0.0186419	0.0000482	1941984.04
35	96.1875	3.460667	1.479333	557.33	171351.67	3630	0.0162516	0.0000421	1234912.03
37	96.1875	3.468000	1.485000	533.33	179062.50	4259	0.0189547	0.0000491	1572859.35
67	96.25	3.479333	1.490333	488.00	195696.72	3933	0.0173731	0.0000450	1721900.28
73	96.1875	3.468333	1.486667	506.67	188486.84	4355	0.0193584	0.0000501	1779894.69
75	96.25	3.457333	1.481333	525.33	181789.34	3856	0.0172455	0.0000446	1474946.29
88	96.1875	3.476333	1.488667	500.00	191000.00	3286	0.0145534	0.0000377	1374022.74
90	96.25	3.480667	1.488333	486.67	196232.88	3671	0.0162314	0.0000420	1617564.80
91	96.25	3.461333	1.476667	492.00	194105.69	3577	0.0160297	0.0000415	1563025.22
100	96.25	3.461667	1.486000	458.67	208212.21	4250	0.0189242	0.0000490	2123213.48
110	96.25	3.476667	1.469667	482.67	197859.12	4025	0.0180434	0.0000467	1828068.73
113	96.25	3.465000	1.484000	473.33	201760.56	4660	0.0207578	0.0000537	2186843.70
115	96.25	3.467333	1.483000	444.00	215090.09	3569	0.0158980	0.0000411	1903474.26
137	96.25	3.461000	1.476667	484.00	197314.05	4465	0.0200111	0.0000518	2016275.23
141	96.25	3.455333	1.473333	492.00	194105.69	4694	0.0211196	0.0000547	2059325.81
164	96.25	3.468000	1.474000	477.33	200069.83	3619	0.0162161	0.0000420	1679854.36
168	96.1875	3.443667	1.483333	510.67	187010.44	4220	0.0189351	0.0000490	1713810.56
172	96.1875	3.443667	1.474333	436.00	219036.70	4470	0.0201793	0.0000522	2505549.58

NONDESTRUCTIVE TESTING DATA (HEATED FOR DOL TESTING)

SS H 300°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
25	96.25	3.471667	1.478667	452.00	211283.19	3870	0.0172678	0.0000447	1994935.87
33	96.25	3.454000	1.481667	468.00	204059.83	4439	0.0198676	0.0000514	2141034.88
41	96.1875	3.492000	1.485667	534.67	178615.96	3930	0.0173625	0.0000449	1433560.30
44	96.25	3.448333	1.473000	521.33	183184.14	4646	0.0209508	0.0000542	1819446.87
45	96.1875	3.437333	1.479333	478.67	199512.53	4215	0.0189988	0.0000492	1957170.96
49	96.1875	3.443333	1.477000	521.33	183184.14	4553	0.0205189	0.0000531	1781937.01
70	96.25	3.427333	1.477000	494.67	193059.30	4790	0.0216737	0.0000561	2090626.87
81	96.25	3.462667	1.481667	476.00	200630.25	4988	0.0222689	0.0000576	2319821.07
84	96.25	3.475667	1.482667	486.67	196232.88	4228	0.0187926	0.0000486	1872808.11
99	96.25	3.475000	1.480333	504.00	189484.13	4187	0.0186433	0.0000482	1732330.32
104	96.25	3.478667	1.480000	474.67	201193.82	4302	0.0191394	0.0000495	2005033.13
109	96.25	3.480333	1.489667	474.67	201193.82	4603	0.0203360	0.0000526	2130378.21
112	96.25	3.447667	1.483667	510.67	187010.44	3908	0.0174995	0.0000453	1583875.61
120	96.1875	3.454000	1.488000	462.67	206412.10	3576	0.0159473	0.0000413	1758413.75
121	96.25	3.463333	1.479667	477.33	200069.83	3938	0.0176016	0.0000456	1823379.84
125	96.25	3.473667	1.488667	498.67	191510.70	3736	0.0165484	0.0000428	1570737.93
126	96.25	3.474000	1.492667	541.33	176416.26	4159	0.0183709	0.0000475	1479687.07
130	96.1875	3.467333	1.490000	561.33	170130.64	3967	0.0175993	0.0000455	1318329.35
135	96.25	3.460333	1.493000	485.33	196771.98	3938	0.0174595	0.0000452	1749527.91
153	96.125	3.421333	1.456000	494.67	193059.30	3848	0.0177164	0.0000458	1708915.31
163	96.25	3.457667	1.482000	508.00	187992.13	4028	0.0180049	0.0000466	1646773.45
170	96.25	3.490333	1.485000	541.33	176416.26	3604	0.0159267	0.0000412	1282817.96
173	96.1875	3.427333	1.483333	501.33	190492.02	4660	0.0210091	0.0000544	1972980.99
175	96.1875	3.421333	1.491000	517.33	184600.52	4100	0.0184216	0.0000477	1624632.54

NONDESTRUCTIVE TESTING DATA (UNHEATED FOR STATIC TESTING)

SS UH 340°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s^2/in^4)	$E_{dynamic}$ (psi)
9	96.25	3.464000	1.477000	508.00	187992.13	4386	0.0196356	0.0000508	1795915.80
10	96.25	3.422000	1.472667	509.33	187500.00	4025	0.0182943	0.0000473	1664486.86
14	96.25	3.450667	1.479333	518.67	184125.96	4398	0.0197342	0.0000511	1731460.72
16	96.25	3.467000	1.474000	493.33	193581.08	4562	0.0204474	0.0000529	1983015.83
28	96.25	3.484333	1.488667	514.67	185556.99	4422	0.0195270	0.0000505	1740013.60
31	96.1875	3.436667	1.468333	477.33	200069.83	4915	0.0223243	0.0000578	2312614.13
39	96.25	3.480000	1.490000	502.67	189986.74	4101	0.0181158	0.0000469	1692260.55
42	96.375	3.442333	1.470000	553.33	172590.36	4264	0.0192760	0.0000499	1485979.32
62	96.25	3.398667	1.469667	497.33	192024.13	4614	0.0211584	0.0000548	2019101.65
63	96.25	3.487667	1.487333	472.00	202330.51	4494	0.0198437	0.0000514	2102368.96
65	96.1875	3.448000	1.482333	530.67	179962.31	3710	0.0166371	0.0000431	1394448.27
74	96.25	3.488333	1.465000	497.33	192024.13	4222	0.0189233	0.0000490	1805804.11
87	96.1875	3.442667	1.478000	488.00	195696.72	3752	0.0169009	0.0000437	1675093.39
96	96.25	3.460333	1.489000	480.00	198958.33	4159	0.0184888	0.0000478	1894074.07
131	96.125	3.484667	1.471667	537.33	177729.53	3626	0.0162164	0.0000420	1325675.02
133	96.25	3.486667	1.482667	468.00	204059.83	4522	0.0200360	0.0000519	2159176.00
138	96.25	3.474000	1.481333	420.00	227380.95	4388	0.0195307	0.0000505	2613295.83
143	96.1875	3.438667	1.475000	512.00	186523.44	3925	0.0177367	0.0000459	1596992.54
145	96.25	3.444667	1.487333	510.67	187010.44	4031	0.0180215	0.0000466	1631118.11
148	96.1875	3.484667	1.496000	490.67	194633.15	3484	0.0153180	0.0000396	1501749.34
154	96.25	3.477667	1.478667	489.33	195163.49	4630	0.0206232	0.0000534	2032901.33
165	96.25	3.446667	1.484667	514.67	185556.99	4606	0.0206172	0.0000534	1837159.05
174	96.1875	3.474667	1.484333	458.67	208212.21	3883	0.0172559	0.0000447	1936037.17
176	96.1875	3.474667	1.481333	524.00	182251.91	4004	0.0178297	0.0000461	1532677.56

NONDESTRUCTIVE TESTING DATA (UNHEATED FOR DOL TESTING)

SS UH 340°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
3	96.1875	3.453667	1.463333	514.67	185556.99	3862	0.0175148	0.0000453	1560708.34
13	96.1875	3.471667	1.498000	500.00	191000.00	3910	0.0172323	0.0000446	1626942.35
17	96.25	3.471333	1.490667	496.00	192540.32	4286	0.0189718	0.0000491	1820183.20
22	96.25	3.448333	1.475000	468.00	204059.83	5046	0.0227237	0.0000588	2448823.17
23	96.25	3.495333	1.497333	585.33	163154.90	4066	0.0177948	0.0000461	1225905.28
36	96.25	3.472667	1.483667	456.00	209429.82	4176	0.0185650	0.0000480	2107339.53
40	96.25	3.479000	1.482000	490.67	194633.15	4268	0.0189607	0.0000491	1858881.97
55	96.25	3.479667	1.497333	448.00	213169.64	3760	0.0165297	0.0000428	1943921.97
57	96.25	3.446667	1.474333	454.67	210043.99	4272	0.0192562	0.0000498	2198635.27
64	96.1875	3.451000	1.496000	510.67	187010.44	3989	0.0177094	0.0000458	1602867.82
78	96.125	3.451000	1.460667	521.33	183184.14	4168	0.0189640	0.0000491	1646903.59
79	96.25	3.479000	1.489000	530.67	179962.31	4549	0.0201141	0.0000521	1685878.76
83	96.25	3.477667	1.485333	484.00	197314.05	4496	0.0199365	0.0000516	2008754.42
94	96.1875	3.468667	1.495667	492.00	194105.69	3970	0.0175392	0.0000454	1710204.98
101	96.1875	3.483000	1.484667	582.67	163901.60	4447	0.0197106	0.0000510	1370343.98
103	96.1875	3.495333	1.487000	525.33	181789.34	4037	0.0178022	0.0000461	1522560.34
111	96.1875	3.469667	1.467667	497.33	192024.13	4433	0.0199525	0.0000516	1904025.05
116	96.1875	3.471333	1.473333	533.33	179062.50	3941	0.0176614	0.0000457	1465537.36
118	96.1875	3.447333	1.478000	500.00	191000.00	4439	0.0199684	0.0000517	1885266.16
119	96.1875	3.456000	1.469333	477.33	200069.83	4573	0.0206406	0.0000534	2138202.62
150	96.25	3.470667	1.485000	500.00	191000.00	4203	0.0186790	0.0000483	1763531.29
151	96.1875	3.426333	1.469667	488.00	195696.72	3831	0.0174373	0.0000451	1728260.88
155	96.25	3.495000	1.492333	468.00	204059.83	3701	0.0162532	0.0000421	1751529.70
177	96.1875	3.453333	1.487667	461.33	207008.67	4186	0.0186754	0.0000483	2071145.78

NONDESTRUCTIVE TESTING DATA (HEATED FOR STATIC TESTING)

SS H 340°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
9	96.1875	3.448000	1.460000	508.00	187992.13	4268	0.0194321	0.0000503	1777305.65
10	96.25	3.417667	1.477000	509.33	187500.00	3937	0.0178644	0.0000462	1625377.20
14	96.1875	3.436000	1.482667	518.67	184125.96	4306	0.0193728	0.0000501	1699753.40
16	96.25	3.453000	1.486000	494.67	193059.30	4496	0.0200699	0.0000519	1935926.07
28	96.25	3.468333	1.486333	510.67	187010.44	4319	0.0191902	0.0000497	1736897.87
31	96.25	3.416333	1.472000	477.33	200069.83	4799	0.0218583	0.0000566	2264343.56
39	96.25	3.458667	1.491000	501.33	190492.02	3982	0.0176868	0.0000458	1660981.85
42	96.3125	3.441333	1.486667	550.67	173426.15	4175	0.0186796	0.0000483	1453984.53
62	96.25	3.375667	1.471667	493.33	193581.08	4497	0.0207342	0.0000537	2010833.47
63	96.25	3.489000	1.477333	469.33	203480.11	4398	0.0195438	0.0000506	2094190.11
65	96.125	3.433000	1.474000	522.67	182716.84	3607	0.0163483	0.0000423	1412514.06
74	96.25	3.473333	1.494333	493.33	193581.08	4129	0.0182215	0.0000472	1767148.96
87	96.1875	3.419000	1.487333	485.33	196771.98	3657	0.0164829	0.0000427	1651667.24
96	96.25	3.438667	1.486667	477.33	200069.83	4039	0.0180969	0.0000468	1874691.42
131	96.125	3.461667	1.471667	532.00	179511.28	3536	0.0159190	0.0000412	1327583.43
133	96.25	3.469333	1.493333	474.67	201193.82	4431	0.0195899	0.0000507	2052223.42
138	96.25	3.448333	1.478333	421.33	226661.39	4292	0.0192846	0.0000499	2564068.43
143	96.1875	3.417000	1.464333	508.00	187992.13	3819	0.0174936	0.0000453	1600009.47
145	96.25	3.433000	1.487333	510.67	187010.44	3929	0.0176252	0.0000456	1595247.38
148	96.1875	3.454667	1.496333	486.67	196232.88	3380	0.0149864	0.0000388	1493496.63
154	96.25	3.453000	1.469000	486.67	196232.88	4508	0.0203563	0.0000527	2028642.30
165	96.25	3.417333	1.482333	505.33	188984.17	4444	0.0200944	0.0000520	1857325.78
174	96.1875	3.449000	1.482333	456.00	209429.82	3774	0.0169191	0.0000438	1920518.03
176	96.1875	3.452000	1.491333	524.00	182251.91	3900	0.0173634	0.0000449	1492594.27

Nondestructive Testing Data (Heated For DOL Testing)

SS H 340°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
3	96.1875	3.459333	1.469333	512.00	186523.44	3790	0.0170900	0.0000442	1538763.21
13	96.1875	3.460667	1.490667	497.33	192024.13	3849	0.0171011	0.0000443	1631915.67
17	96.25	3.463333	1.487667	496.00	192540.32	4207	0.0187028	0.0000484	1794371.57
22	96.25	3.427333	1.483000	458.67	208212.21	4920	0.0221718	0.0000574	2487576.21
23	96.1875	3.480333	1.490333	572.00	166958.04	3945	0.0174324	0.0000451	1257580.93
36	96.25	3.454333	1.491667	449.33	212537.09	4067	0.0180789	0.0000468	2113508.58
40	96.25	3.476667	1.482000	489.33	195163.49	4135	0.0183822	0.0000476	1811998.37
55	96.1875	3.468667	1.483333	452.00	211283.19	3661	0.0163085	0.0000422	1884112.30
57	96.25	3.414000	1.478333	449.33	212537.09	4138	0.0187797	0.0000486	2195434.44
64	96.25	3.429667	1.489000	509.33	187500.00	3877	0.0173893	0.0000450	1582151.76
78	96.1875	3.451333	1.455667	520.00	183653.85	4083	0.0186271	0.0000482	1625957.15
79	96.25	3.465667	1.485667	528.00	180871.21	4415	0.0196407	0.0000508	1662868.25
83	96.25	3.469667	1.472000	486.67	196232.88	4369	0.0195939	0.0000507	1952659.08
94	96.25	3.459000	1.467000	493.33	193581.08	3911	0.0176539	0.0000457	1712100.94
101	96.125	3.473667	1.484000	578.67	165034.56	4356	0.0193804	0.0000502	1366080.93
103	96.1875	3.479000	1.486333	524.00	182251.91	3943	0.0174772	0.0000452	1502376.58
111	96.1875	3.445333	1.482000	496.00	192540.32	4336	0.0194637	0.0000504	1867375.77
116	96.1875	3.464667	1.449667	536.00	178171.64	3885	0.0177287	0.0000459	1456522.11
118	96.1875	3.427000	1.481667	496.00	192540.32	4335	0.0195677	0.0000506	1877354.90
119	96.25	3.438000	1.474333	472.00	202330.51	4476	0.0202266	0.0000523	2142928.45
150	96.25	3.455667	1.480667	502.67	189986.74	4092	0.0183181	0.0000474	1711155.41
151	96.1875	3.397333	1.469333	482.67	197859.12	3723	0.0170943	0.0000442	1731909.44
155	96.25	3.485333	1.497000	468.00	204059.83	3599	0.0157997	0.0000409	1702657.00
177	96.1875	3.417333	1.488667	461.33	207008.67	4093	0.0184405	0.0000477	2045090.42

NONDESTRUCTIVE TESTING DATA (UNHEATED FOR STATIC TESTING)

SS UH 380^{o}F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s^{2}/in^{4})	$E_{dynamic}$ (psi)
1	96.1875	3.417333	1.456667	476.00	200630.25	4842	0.0222943	0.0000577	2322461.92
5	96.1875	3.441667	1.478000	496.00	192540.32	3508	0.0158064	0.0000409	1516485.42
52	96.25	3.428333	1.471333	494.67	193059.30	4771	0.0216645	0.0000561	2089744.33
59	96.25	3.467333	1.469000	458.67	208212.21	4170	0.0187522	0.0000485	2103911.43
71	96.1875	3.481333	1.490000	496.00	192540.32	3376	0.0149172	0.0000386	1431174.06
72	96.125	3.426333	1.480333	469.33	203480.11	3932	0.0177796	0.0000460	1905149.72
80	97.4375	3.488667	1.488000	497.33	192024.13	4123	0.0179705	0.0000465	1714879.24
82	96.1875	3.485333	1.495667	442.67	215737.95	3447	0.0151558	0.0000392	1825550.10
86	96.1875	3.483333	1.482333	500.00	191000.00	4024	0.0178621	0.0000462	1686406.63
89	96.1875	3.449667	1.482333	504.00	189484.13	5197	0.0232941	0.0000603	2164481.53
108	96.1875	3.409333	1.479667	528.00	180871.21	4167	0.0189324	0.0000490	1602904.13
127	96.1875	3.462667	1.477333	501.33	190492.02	4276	0.0191586	0.0000496	1799204.79
128	96.1875	3.488667	1.492667	612.00	156045.75	4608	0.0202818	0.0000525	1278122.75
134	96.25	3.422000	1.476333	478.67	199512.53	4254	0.0192871	0.0000499	1986871.73
146	96.25	3.460667	1.497000	512.00	186523.44	3855	0.0170442	0.0000441	1534638.32
149	96.25	3.494333	1.489333	500.00	191000.00	3976	0.0174994	0.0000453	1652164.45
167	96.1875	3.470333	1.488000	502.67	189986.74	4509	0.0200134	0.0000518	1869524.61
171	96.1875	3.460667	1.481667	506.67	188486.84	4269	0.0190823	0.0000494	1754512.46

NONDESTRUCTIVE TESTING DATA (UNHEATED FOR DOL TESTING)

SS UH 380°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s^2/in^4)	$E_{dynamic}$ (psi)
4	96.25	3.453000	1.469000	516.00	185077.52	4065	0.0183559	0.0000475	1627218.67
15	96.1875	3.477000	1.473000	557.33	171351.67	4479	0.0200442	0.0000519	1523101.47
18	96.1875	3.484667	1.481333	498.67	191510.70	3872	0.0171924	0.0000445	1631871.22
21	96.1875	3.491000	1.490667	586.67	162784.09	4417	0.0194542	0.0000503	1334133.94
24	96.25	3.462667	1.485667	484.00	197314.05	4385	0.0195241	0.0000505	1967206.52
27	96.25	3.473000	1.476000	458.67	208212.21	4388	0.0196069	0.0000507	2199805.41
43	96.1875	3.466000	1.483333	537.33	177729.53	4840	0.0215771	0.0000558	1763907.18
53	96.125	3.447667	1.470667	538.67	177289.60	5015	0.0226845	0.0000587	1845265.01
66	96.1875	3.459000	1.484333	502.67	189986.74	4017	0.0179323	0.0000464	1675116.06
76	96.25	3.395333	1.464333	494.67	193059.30	4249	0.0195748	0.0000507	1888174.90
77	96.1875	3.466333	1.470667	470.67	202903.68	4403	0.0197961	0.0000512	2109222.89
102	96.25	3.441000	1.484667	525.33	181789.34	4429	0.0198575	0.0000514	1698342.51
106	96.1875	3.472000	1.485667	496.00	192540.32	4794	0.0213016	0.0000551	2043707.92
107	96.1875	3.471667	1.475000	474.67	201193.82	4136	0.0185125	0.0000479	1939359.26
147	96.1875	3.486000	1.483667	521.33	183184.14	3590	0.0159091	0.0000412	1381608.47
160	96.25	3.420667	1.463667	434.67	219708.59	4347	0.0198870	0.0000515	2484432.35
166	96.1875	3.472333	1.467333	522.67	182716.84	4491	0.0202027	0.0000523	1745534.76
179	96.25	3.470667	1.483000	518.67	184125.96	4074	0.0181301	0.0000469	1590718.89

NONDESTRUCTIVE TESTING DATA (HEATED FOR STATIC TESTING)

SS H 380°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
1	96.25	3.412333	1.472667	476.00	200630.25	4727	0.0215458	0.0000558	2244496.53
5	96.125	3.415667	1.480333	492.00	194105.69	3401	0.0154266	0.0000399	1504211.69
52	96.1875	3.397667	1.466333	489.33	195163.49	4616	0.0212358	0.0000550	2093283.11
59	96.25	3.397000	1.469000	454.67	210043.99	4049	0.0185851	0.0000481	2122009.63
71	96.1875	3.469667	1.481667	496.00	192540.32	3260	0.0145343	0.0000376	1394444.49
72	96.1875	3.413333	1.473333	465.33	205229.23	3841	0.0175057	0.0000453	1908189.54
80	97.375	3.460000	1.472000	488.00	195696.72	3969	0.0176435	0.0000457	1748694.57
82	96.25	3.466000	1.488333	440.00	217045.45	3346	0.0148570	0.0000384	1811319.09
86	96.1875	3.469667	1.476000	496.00	192540.32	3889	0.0174052	0.0000450	1669881.78
89	96.25	3.435000	1.486667	500.00	191000.00	5022	0.0225253	0.0000583	2126667.04
108	96.1875	3.378667	1.471333	524.00	182251.91	4044	0.0186453	0.0000483	1602792.86
127	96.25	3.447333	1.481667	498.67	191510.70	4137	0.0185518	0.0000480	1760898.00
128	96.1875	3.466333	1.481333	598.67	159521.16	4467	0.0199392	0.0000516	1313130.61
134	96.25	3.385333	1.466000	474.67	201193.82	4122	0.0190242	0.0000492	1992958.51
146	96.1875	3.430000	1.499000	506.67	188486.84	3697	0.0164805	0.0000427	1515284.84
149	96.25	3.474000	1.487667	497.33	192024.13	3851	0.0170676	0.0000442	1628718.70
167	96.1875	3.449667	1.488000	494.67	193059.30	4368	0.0195038	0.0000505	1881319.35
171	96.25	3.442667	1.474000	505.33	188984.17	4120	0.0185968	0.0000481	1718905.54

NONDESTRUCTIVE TESTING DATA (HEATED FOR DOL TESTING)

SS H 380°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
4	96.25	3.455667	1.465000	514.67	185556.99	3963	0.0179303	0.0000464	1597738.38
15	96.1875	3.469333	1.479000	556.00	171762.59	4396	0.0196363	0.0000508	1499267.56
18	96.1875	3.468333	1.477333	493.33	193581.08	3758	0.0168102	0.0000435	1630278.40
21	96	3.437333	1.485333	586.67	162784.09	4258	0.0191524	0.0000496	1313438.99
24	96.1875	3.446000	1.480333	485.33	196771.98	4257	0.0191269	0.0000495	1916610.51
27	96.25	3.464667	1.482667	458.67	208212.21	4290	0.0191287	0.0000495	2146155.07
43	96.125	3.453333	1.475333	548.00	174270.07	4644	0.0209055	0.0000541	1643122.61
53	96.0625	3.415000	1.468000	540.00	176851.85	4833	0.0221249	0.0000573	1790863.61
66	96.125	3.434333	1.484667	500.00	191000.00	3865	0.0173851	0.0000450	1641366.70
76	96.1875	3.370000	1.467333	492.00	194105.69	4096	0.0189853	0.0000491	1851212.63
77	96.1875	3.463667	1.468000	469.33	203480.11	4258	0.0191937	0.0000497	2056676.37
102	96.25	3.422333	1.476333	513.33	186038.96	4293	0.0194620	0.0000504	1743244.77
106	96.25	3.446000	1.481333	488.00	195696.72	4640	0.0208201	0.0000539	2063542.48
107	96.1875	3.452000	1.470667	478.67	199512.53	4034	0.0182124	0.0000471	1876159.41
147	96.1875	3.464333	1.483000	518.67	184125.96	3453	0.0154046	0.0000399	1351588.00
160	96.25	3.393667	1.468667	433.33	220384.62	4241	0.0194899	0.0000504	2449823.54
166	96.1875	3.432333	1.467000	517.33	184600.52	4312	0.0196279	0.0000508	1731025.65
179	96.25	3.440000	1.481667	517.33	184600.52	3948	0.0177420	0.0000459	1564697.59

STATIC TESTING DATA

SS No Temp Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Failure Time (min)	Peak Load (lb)	Deflection @ P.L. (in)	Elastic Region Slope (lb/in)	E_{static} (psi)	MOR (psi)
2	96.1875	3.479	1.472	11.11	1501.5	1.4932	1136.69	1456960.27	6065.40
12	96.25	3.451	1.481	10.77	1780.3	1.4577	1281.31	1672786.25	7266.02
38	96.25	3.439	1.482	10.03	1801.6	1.5315	1281.41	1690707.02	7403.89
50	96.25	3.478	1.484	11.08	1678.0	1.7734	1019.16	1297545.85	6730.25
56	96.1875	3.461	1.482	8.30	988.4	0.9974	1031.10	1333898.66	4008.92
68	96.25	3.469	1.505	7.94	1103.4	1.0357	1114.02	1409841.08	4387.37
69	96.1875	3.454	1.495	15.31	1723.7	1.7822	1104.49	1425445.94	6959.93
85	96.1875	3.415	1.478	13.24	2112.7	1.8093	1254.64	1694236.78	8825.00
92	96.1875	3.460	1.487	9.00	1283.1	1.1938	1097.80	1416409.47	5188.39
93	96.1875	3.446	1.484	12.63	1791.8	1.7643	1129.84	1478799.77	7321.01
95	96.1875	3.435	1.479	7.77	678.0	1.0055	684.61	907754.71	2797.40
105	96.25	3.491	1.487	17.69	1371.7	1.8574	783.04	984058.02	5451.03
114	96.25	3.470	1.487	8.34	650.1	0.842	830.18	1062432.46	2614.73
117	96.1875	3.401	1.479	11.84	2762.5	1.7963	1702.04	2324632.73	11624.34
122	96.1875	3.483	1.488	5.45	750.6	0.765	1009.37	1276393.97	2994.53
124	96.25	3.469	1.473	10.81	2296.6	1.6985	1468.66	1898049.49	9326.28
129	96.25	3.453	1.485	11.80	934.2	1.2717	977.40	1270825.40	3798.74
136	96.1875	3.438	1.476	5.92	789.1	0.6995	1322.35	1752948.38	3257.25
139	96.1875	3.458	1.488	8.56	824.4	1.1565	707.66	914413.33	3336.68
142	96.1875	3.452	1.483	18.01	1708.3	1.8325	1112.37	1449016.72	6958.73
156	96.25	3.447	1.476	11.13	1347.3	1.5018	939.02	1234990.32	5532.56
157	96.1875	3.489	1.469	12.99	1507.1	1.685	920.07	1172793.57	6070.61
158	96.1875	3.483	1.419	7.55	1130.4	1.1487	1060.92	1406498.98	4727.98
169	96.1875	3.461	1.490	8.80	1728.3	1.3728	1257.24	1617706.50	6972.29

STATIC TESTING DATA

SS H 300°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Failure Time (min)	Peak Load (lb)	Deflection @ P.L. (in)	Elastic Region Slope (lb/in)	E_{static} (psi)	MOR (psi)
6	96.250000	3.466000	1.478667	9.90	1897.6	1.2333	1600.79	2066715.29	7691.48
8	96.187500	3.394667	1.487333	8.03	1075.2	1.0144	1018.89	1391970.27	4516.68
11	96.187500	3.459667	1.491333	11.62	1796.4	1.2429	1231.24	1584777.41	7245.90
20	96.187500	3.484333	1.486667	16.69	686.5	0.9594	859.39	1086217.26	2738.55
26	96.250000	3.473333	1.489333	7.43	1046.4	0.9101	1108.30	1411650.06	4193.20
32	96.250000	3.461333	1.486000	18.87	2627.5	2.1656	1150.32	1483780.84	10625.99
34	96.250000	3.468667	1.480667	22.59	3511.5	2.2614	1455.67	1872494.74	14191.97
35	96.187500	3.460667	1.479333	14.70	1555.0	1.9481	819.98	1063064.29	6319.42
37	96.187500	3.468000	1.485000	8.81	1221.5	1.1949	1013.44	1300579.68	4924.26
67	96.250000	3.479333	1.490333	10.42	944.0	1.0288	1197.01	1515750.34	3767.29
73	96.187500	3.468333	1.486667	8.16	1206.3	1.0356	1144.75	1467023.14	4856.60
75	96.250000	3.457333	1.481333	10.16	643.8	1.3098	758.56	984950.96	2617.87
88	96.187500	3.476333	1.488667	13.95	1476.1	1.8444	859.69	1092647.88	5907.56
90	96.250000	3.480667	1.488333	10.15	1576.4	1.2561	1236.73	1566355.08	6294.68
91	96.250000	3.461333	1.476667	14.87	1920.9	1.9686	1033.39	1341387.76	7817.50
100	96.250000	3.461667	1.486000	11.50	1668.6	1.4931	1289.20	1662445.25	6746.76
110	96.250000	3.476667	1.469667	9.04	1363.2	1.0616	1204.88	1550728.26	5525.19
113	96.250000	3.465000	1.484000	8.88	1287.4	1.0446	1166.94	1624428.48	5202.42
115	96.250000	3.467333	1.483000	14.63	2182.3	1.8794	1309.22	1683390.89	8812.81
137	96.250000	3.461000	1.476667	13.24	1850.3	1.4755	1261.66	1638162.37	7531.63
141	96.250000	3.455333	1.473333	14.26	2574.0	1.971	1405.66	1838270.63	10535.62
164	96.250000	3.468000	1.474000	12.46	837.1	1.5071	1245.34	1610113.28	3399.81
168	96.187500	3.443667	1.483333	10.68	1610.8	1.3007	1191.95	1564074.45	6593.15
172	96.187500	3.443667	1.474333	13.79	2972.5	1.7171	1826.56	2411440.52	12240.99

STATIC TESTING DATA

SS H 340°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Failure Time (min)	Peak Load (lb)	Deflection @ P.L. (in)	Elastic Region Slope (lb/in)	E_{static} (psi)	MOR (psi)
9	96.1875	3.448000	1.460000	14.63	1221.2	1.2557	1081.47	1436356.83	5065.61
10	96.25	3.417667	1.477000	19.21	2625.9	2.2966 (NA)	1234.48	1664243.63	10959.00
14	96.1875	3.436000	1.482667	13.46	1888.7	1.7094	1137.66	1503526.17	7768.65
16	96.25	3.453000	1.486000	8.76	1205.2	1.0686	1464.84	1903193.12	4897.56
28	96.25	3.468333	1.486333	13.31	1892.1	1.7364	1136.08	1456237.71	7619.36
31	96.25	3.416333	1.472000	11.95	913.9	1.2826	1526.02	2066677.59	3830.04
39	96.25	3.458667	1.491000	9.55	1360.8	1.1567	1132.90	1459781.59	5493.28
42	96.3125	3.441333	1.486667	22.41	2437.6	2.3295 (NA)	998.61	1310099.44	9968.45
62	96.25	3.375667	1.471667	15.85	2586.0	2.1416	1353.24	1900150.31	11102.80
63	96.25	3.489000	1.477333	8.78	1646.1	1.1187	1603.53	2031403.00	6590.35
65	96.125	3.433000	1.474000	11.31	1119.5	1.5864	719.52	959018.92	4639.93
74	96.25	3.473333	1.494333	10.46	1614.8	1.3563	1283.77	1629673.35	6449.27
87	96.1875	3.419000	1.487333	12.01	1353.5	1.6577	840.08	1123359.39	5605.11
96	96.25	3.438667	1.486667	20.01	3083.5	2.3209 (NA)	1341.20	1974804.09	12629.40
131	96.125	3.461667	1.471667	9.18	971.4	1.091	859.92	1271725.91	3965.98
133	96.25	3.469333	1.493333	12.81	2161.2	1.7538	1369.18	1745286.64	8657.22
138	96.25	3.448333	1.478333	14.40	2618.0	1.4947	1855.85	2433576.52	10722.88
143	96.1875	3.417000	1.464333	14.07	1492.6	1.7025	989.61	1346457.90	6285.59
145	96.25	3.433000	1.487333	11.13	1620.7	1.3647	1120.13	1479583.05	6657.01
148	96.1875	3.454667	1.496333	10.83	1403.8	1.3884	1025.89	1321763.47	5659.75
154	96.25	3.453000	1.469000	8.71	1589.1	1.0862	1463.92	1924008.81	6532.34
165	96.25	3.417333	1.482333	20.91	2955.4	1.8367 (NA)	1223.26	1643663.87	12292.16
174	96.1875	3.449000	1.482333	7.81	992.1	0.6956	1106.11	1445684.25	4050.94
176	96.1875	3.452000	1.491333	5.19	596.6	0.4996	1009.36	1307851.46	2417.13

STATIC TESTING DATA

SS H 380°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Failure Time (min)	Peak Load (lb)	Deflection @ P.L. (in)	Elastic Region Slope (lb/in)	E_{static} (psi)	MOR (psi)
1	96.25	3.412333	1.472667	11.17	2277.6	1.4997	1631.64	2216496.54	9563.19
5	96.125	3.415667	1.480333	15.65	1737.4	2.1112	983.43	1325130.13	7243.06
52	96.1875	3.397667	1.466333	15.63	2772.3	2.1368 (NA)	1311.02	1811910.60	11791.76
59	96.25	3.397000	1.469000	7.59	1417.7	0.8928	1396.75	1928020.27	6021.49
71	96.1875	3.469667	1.481667	10.95	1192.4	1.3587	907.97	1166165.67	4813.14
72	96.1875	3.413333	1.473333	13.69	1906.4	1.8869	1196.55	1623281.26	7996.28
80	97.375	3.460000	1.472000	8.99	1262.6	1.1119	1146.58	1494760.61	5158.68
82	96.25	3.466000	1.488333	8.92	1494.9	1.0725	1405.56	1802866.60	6019.87
86	96.1875	3.469667	1.476000	7.99	1236.4	1.0061	1239.62	1598230.33	5009.91
89	96.25	3.435000	1.486667	10.17	1693.0	1.3228	1331.90	1757026.79	6949.00
108	96.1875	3.378667	1.471333	18.13	2166.1	2.1916 (NA)	995.76	1394792.94	9285.58
127	96.25	3.447333	1.481667	8.23	1529.5	1.4221	1099.54	1439832.79	6254.10
128	96.1875	3.466333	1.481333	10.87	1166.9	1.4859	819.92	1056351.46	4720.33
134	96.25	3.385333	1.466000	17.39	2834.2	2.2724	1440.84	2013627.78	12145.80
146	96.1875	3.430000	1.499000	6.03	934.4	0.887	1008.60	1325362.66	3814.83
149	96.25	3.474000	1.487667	12.42	1004.6	1.5927	1157.14	1474664.25	4028.66
167	96.1875	3.449667	1.488000	15.49	2739.0	2.096	1443.96	1878978.08	11136.98
171	96.25	3.442667	1.474000	17.91	2543.3	2.2841 (NA)	1168.50	1544359.88	10481.96

DOL TESTING DATA

SS No Temp	Average	Average	Average	Moment of	$E_{dynamic}$	app = 3715.39 (psi)	Stress Ratio	Time To Failure	
Number	Length (in)	Width (in)	Thickness (in)	Inertia (in^4)	(psi)	MOR = ult (psi)	(app/ult)	(h:m:s)	LN(t_f) (mins)
51	96.1875	3.487	1.478	5.223	1302579.68	2661.88	1.3958	6/18 (7:56-8:07pm)	0
123	96.125	3.449	1.487	5.085	1335447.31	3060.33	1.2140	6/18 (8:11-8:23pm)	0
152	96.25	3.443	1.492	5.076	2028340.53	3358.15	1.1064	6/18 (8:41-8:47pm)	0
46	96.1875	3.430	1.476	4.965	2056154.53	3611.97	1.0286	6/18 (9:21-9:33pm)	0
180	96.1875	3.489	1.483	5.246	1746599.71	3841.80	0.9671	6/18 (post 10:00pm)	0
144	96.1875	3.449	1.480	5.059	1737641.21	4057.46	0.9157	0:05:04	1.6227
58	96.1875	3.463	1.478	5.115	1664776.72	4264.76	0.8712	18:47:22	7.0276
47	96.25	3.467	1.473	5.117	1599589.88	4467.64	0.8316	85:00:00	8.5370
162	96.1875	3.486	1.469	5.186	1454724.73	4669.02	0.7958	125:00:00	8.9227
54	96.25	3.488	1.489	5.264	1516905.15	4871.36	0.7627	280:00:00	9.7291

DOL TESTING DATA

SS 300°F	Average	Average	Average	Moment of	$E_{dynamic}$	app = 4062.77 (psi)	Stress Ratio	Time To Failure	
Number	Length (in)	Width (in)	Thickness (in)	Inertia (in^4)	(psi)	MOR = ult (psi)	(app/ult)	(h:m:s)	LN(t_f) (mins)
120	96.1875	3.454	1.488	5.110	1758413.75	2825.47	1.4379	6/14 (11:04-11:31am)	0
153	96.125	3.421	1.456	4.859	1708915.31	3289.02	1.2353	6/14 (11:39-11:52am)	0
130	96.1875	3.467	1.490	5.176	1318329.35	3639.05	1.1164	0:11:20	2.4277
84	96.25	3.476	1.483	5.188	1872808.11	3939.58	1.0313	3:26:02	5.3280
81	96.25	3.463	1.482	5.126	2319821.07	4213.33	0.9643	127:40:23	8.9438
170	96.25	3.490	1.485	5.262	1282817.96	4471.54	0.9086	147:00:00	9.0848
25	96.25	3.472	1.479	5.156	1994935.87	4720.90	0.8606	278:00:00	9.7220
44	96.25	3.448	1.473	5.033	1819446.87	4965.98	0.8181	498:00:00	10.3049

DOL TESTING DATA

SS 340°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Moment of Inertia (in^4)	$E_{dynamic}$ (psi)	app = 4432.74 (psi) MOR = ult (psi)	Stress Ratio (app/ult)	Time To Failure (h:m:s)	LN(t_f) (mins)
118	96.1875	3.427	1.482	4.969	1877354.90	3136.41	1.4133	6/15 (12:44-12:56pm)	0
111	96.1875	3.445	1.482	5.051	1867375.77	3624.76	1.2229	6/15 (12:44-12:56pm)	0
116	96.1875	3.465	1.450	5.024	1456522.11	3991.33	1.1106	6/15 (2:21-2:40pm)	0
103	96.1875	3.479	1.486	5.216	1502376.58	4304.72	1.0297	6/15 (2:21-2:40pm)	0
78	96.1875	3.451	1.456	4.987	1625957.15	4589.20	0.9659	6/15 (8:00-8:24pm)	0
13	96.1875	3.461	1.491	5.148	1631915.67	4856.72	0.9127	6/15 (8:32-9:11pm)	0
40	96.25	3.477	1.482	5.190	1811998.37	5114.39	0.8667	6/15 (8:32-9:11pm)	0
79	96.25	3.466	1.486	5.153	1662868.25	5366.99	0.8259	6/15 (8:32-9:11pm)	0
17	96.25	3.463	1.488	5.150	1794371.57	5618.17	0.7890	6/14 (less 1 min)	0
94	96.25	3.459	1.467	5.059	1712100.94	5870.95	0.7550	2:47:26	5.1206
155	96.25	3.485	1.497	5.282	1702657	6128.09	0.7233	104:26:44	8.7430
23	96.1875	3.480	1.490	5.236	1257580.93	6392.30	0.6934	993:00:00	10.9951

DOL Testing Data

SS 380°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Moment of Inertia (in^4)	$E_{dynamic}$ (psi)	app = 4934.74 (psi) MOR = ult (psi)	Stress Ratio (app/ult)	Time To Failure (h:m:s)	LN(t_f) (mins)
179	96.25	3.440	1.482	5.026	1564697.59	3758.83	1.3128	6/18 (3:03-3:20pm)	0
43	96.125	3.453	1.475	5.063	1643122.61	4313.07	1.1441	6/18 (3:56-4:10pm)	0
147	96.1875	3.464	1.483	5.138	1351588.00	4734.01	1.0424	6/18 (4:18-5:02pm)	0
107	96.1875	3.452	1.471	5.041	1876159.41	5098.96	0.9678	6/18 (6:41-7:19pm)	0
66	96.125	3.434	1.485	5.012	1641366.70	5435.65	0.9078	6/18 (less 1 min)	0
24	96.1875	3.446	1.480	5.048	1313438.99	5758.23	0.8570	0:04:40	1.5404
106	96.25	3.446	1.481	5.051	2063542.48	6075.66	0.8122	2:50:43	5.1400
15	96.1875	3.469	1.479	5.147	1499267.56	6394.71	0.7717	4:17:27	5.5508
4	96.25	3.456	1.465	5.038	1597738.38	6721.34	0.7342	878:00:00	10.8720

NONDESTRUCTIVE TESTING DATA

Veneer #	Average Length (in)	Average Width (in)	Average Thick. (in)	Average SWT (μs)	C ([100.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
1	101.5000	24.0000	0.1495	497.33	202077.75	2298	0.0139112	0.0000360	1470163.64
2	101.3125	25.1250	0.1478	518.67	193766.07	2873	0.0168412	0.0000436	1636408.11
3	101.5313	23.9375	0.1434	493.33	203716.22	2732	0.0172787	0.0000447	1855776.44
4	101.5313	23.9167	0.1520	492.00	204268.29	2767	0.0165272	0.0000428	1784695.99
5	101.5000	25.7083	0.1433	525.33	191307.11	2613	0.0154113	0.0000399	1459701.86
6	101.5000	25.1250	0.1463	537.33	187034.74	2577	0.0152328	0.0000394	1379075.78
7	101.5938	23.9375	0.1430	492.00	204268.29	3002	0.0190311	0.0000493	2055076.19
8	101.6250	23.9167	0.1490	485.33	207074.18	2979	0.0181350	0.0000469	2012482.21
9	101.5000	25.6250	0.1513	500.00	201000.00	2768	0.0155123	0.0000401	1621922.29
10	101.5000	25.1458	0.1423	506.67	198355.26	2630	0.0159700	0.0000413	1626132.75
11	101.5625	23.8958	0.1470	490.67	204823.37	3040	0.0187860	0.0000486	2039655.59
12	101.5625	23.8333	0.1425	496.00	202620.97	2939	0.0187846	0.0000486	1995870.98
13	101.5000	25.4583	0.1520	504.00	199404.76	2699	0.0151495	0.0000392	1558947.46
14	101.5000	25.5833	0.1430	514.67	195272.02	2649	0.0157274	0.0000407	1552029.36
15	101.5313	25.6458	0.1418	521.33	192774.94	2886	0.0172382	0.0000446	1657887.24
16	101.5313	24.8542	0.1510	514.67	195272.02	2840	0.0164315	0.0000425	1621510.02
17	101.5313	25.5625	0.1468	529.33	189861.46	3132	0.0181290	0.0000469	1691263.84
18	101.5625	24.9375	0.1610	514.67	195272.02	3110	0.0168144	0.0000435	1659301.86
19	101.5000	25.5000	0.1433	505.33	198878.63	3016	0.0179335	0.0000464	1835709.08
20	101.5625	23.9583	0.1470	489.33	205381.47	2874	0.0177139	0.0000458	1933744.57
21	101.5625	23.8333	0.1445	484.00	207644.63	2973	0.0187389	0.0000485	2090968.23
22	101.5625	23.9167	0.1418	490.67	204823.37	2978	0.0190679	0.0000493	2070254.55
23	101.6250	23.9167	0.1455	482.67	208218.23	3023	0.0188455	0.0000488	2114504.41
24	101.6250	23.8958	0.1473	465.33	215974.21	3038	0.0187303	0.0000485	2261052.60
25	101.5313	25.2708	0.1473	518.67	193766.07	2526	0.0147398	0.0000381	1432225.28
26	101.4688	25.5000	0.1443	550.67	182506.05	2541	0.0150090	0.0000388	1293802.66
27	101.5625	23.9375	0.1445	493.33	203716.22	2907	0.0182431	0.0000472	1959356.02
28	101.5625	23.9375	0.1425	489.33	205381.47	2896	0.0184292	0.0000477	2011829.55
29	101.5313	23.9375	0.1440	497.33	202077.75	2362	0.0148790	0.0000385	1572436.10
30	101.5313	25.5625	0.1423	530.67	189384.42	2470	0.0147495	0.0000382	1369075.09
31	101.6250	23.8958	0.1440	477.33	210544.69	2717	0.0171293	0.0000443	1965124.84
32	101.6250	23.9583	0.1450	480.00	209375.00	2723	0.0170042	0.0000440	1929164.53
33	101.5625	23.8750	0.1465	494.67	203167.12	2922	0.0181343	0.0000469	1937179.20
34	101.5000	24.9167	0.1510	506.67	198355.26	3019	0.0174287	0.0000451	1774658.44
35	101.5313	25.5833	0.1433	502.67	199933.69	3092	0.0183199	0.0000474	1895208.89
36	101.5313	23.8750	0.1423	492.00	204268.29	2902	0.0185539	0.0000480	2003554.13
37	101.5313	25.6042	0.1445	514.67	195272.02	2589	0.0151946	0.0000393	1499446.61
38	101.4688	25.1542	0.1435	512.00	196289.06	2498	0.0150360	0.0000389	1499296.86
39	101.5313	24.9167	0.1448	510.67	196801.57	2498	0.0150390	0.0000389	1507434.43
40	101.5000	25.6250	0.1440	505.33	198878.63	2549	0.0150042	0.0000388	1535857.06
41	101.5000	24.7708	0.1445	501.33	200465.43	3085	0.0187204	0.0000484	1946958.81
42	101.4688	23.9375	0.1413	492.00	204268.29	2575	0.0165467	0.0000428	1786803.26
43	101.5000	23.9375	0.1478	493.33	203716.22	3006	0.0184608	0.0000478	1982736.48
44	101.5000	23.9792	0.1470	488.00	205942.62	3054	0.0188185	0.0000487	2065576.06
45	101.3438	23.8542	0.1470	488.00	205942.62	2573	0.0159623	0.0000413	1752067.58
46	101.5313	23.7917	0.1535	486.67	206506.85	2951	0.0175457	0.0000454	1936432.19
47	101.4375	23.9167	0.1413	484.00	207644.63	2588	0.0166499	0.0000431	1857869.35

48	101.2813	23.8333	0.1488	496.00	202620.97	2628	0.0161357	0.0000418	1714432.77
49	101.5938	23.9792	0.1453	472.00	212923.73	2703	0.0168408	0.0000436	1975941.56
50	101.6250	23.9375	0.1440	482.67	208218.23	2705	0.0170239	0.0000441	1910117.48
51	101.6250	23.9167	0.1378	474.67	211727.53	2735	0.0180094	0.0000466	2089374.60
52	101.6250	23.9167	0.1435	485.33	207074.18	2710	0.0171297	0.0000443	1900925.98
53	101.4375	25.6042	0.1340	538.67	186571.78	2955	0.0187188	0.0000484	1686291.17
54	101.4375	24.9167	0.1465	542.67	185196.56	2842	0.0169212	0.0000438	1501968.91
55	101.5000	23.9375	0.1450	497.33	202077.75	2431	0.0152127	0.0000394	1607704.59
56	101.5313	23.8333	0.1520	477.33	210544.69	2776	0.0166389	0.0000431	1908873.25
57	101.5000	23.7083	0.1473	474.67	211727.53	2790	0.0173587	0.0000449	2013880.19
58	101.5000	23.7500	0.1478	497.33	202077.75	3045	0.0188480	0.0000488	1991885.08
59	101.5000	23.9167	0.1463	492.00	204268.29	3084	0.0191508	0.0000496	2068001.56
60	101.5313	23.9167	0.1508	489.33	205381.47	2649	0.0159536	0.0000413	1741581.96
61	101.4688	25.0833	0.1500	510.67	196801.57	2636	0.0152220	0.0000394	1525776.18
62	101.5625	25.6042	0.1575	509.33	197316.75	3257	0.0175318	0.0000454	1766518.70
63	101.5625	24.7917	0.1445	534.67	187967.58	3212	0.0194627	0.0000504	1779637.83
64	101.6250	23.9375	0.1445	474.67	211727.53	2635	0.0165260	0.0000428	1917278.57
65	101.5000	23.9167	0.1420	482.67	208218.23	2509	0.0160465	0.0000415	1800446.72
66	101.4688	23.8125	0.1435	484.00	207644.63	2575	0.0163728	0.0000424	1826949.62
67	101.5000	25.6250	0.1528	500.00	201000.00	2661	0.0147662	0.0000382	1543913.61
68	101.3750	23.8542	0.1413	494.67	203167.12	2695	0.0173944	0.0000450	1858143.15
69	101.4375	25.2292	0.1398	516.00	194767.44	2868	0.0176791	0.0000458	1735624.41
70	101.5000	25.5833	0.1530	522.67	192283.16	3338	0.0185228	0.0000479	1772357.75
71	101.5000	24.7083	0.1493	518.67	193766.07	3229	0.0190186	0.0000492	1847978.02
73	101.4688	25.5833	0.1393	514.67	195272.02	2812	0.0171500	0.0000444	1692418.86
74	101.5000	24.8750	0.1458	516.00	194767.44	2833	0.0169724	0.0000439	1666244.55
75	101.5000	25.5833	0.1435	533.33	188437.50	2928	0.0173233	0.0000448	1591944.08
76	101.5000	24.4375	0.1420	536.00	187500.00	2796	0.0175009	0.0000453	1592302.92
77	101.4688	25.5833	0.1450	521.33	192774.94	2903	0.0170029	0.0000440	1635263.98
78	101.4375	25.2917	0.1415	506.67	198355.26	2738	0.0166278	0.0000430	1693111.72
79	101.4375	25.5417	0.1458	502.67	199933.69	2716	0.0158565	0.0000410	1640372.67
80	101.5000	24.6667	0.1453	512.00	196289.06	3302	0.0200179	0.0000518	1996060.79
81	101.5000	25.5625	0.1333	512.00	196289.06	3319	0.0211643	0.0000548	2110376.83
82	101.5938	23.7708	0.1500	486.67	206506.85	2678	0.0162983	0.0000422	1798763.14
83	101.5625	23.8125	0.1508	496.00	202620.97	2662	0.0160971	0.0000417	1710323.52
84	101.5000	25.5417	0.1455	556.00	180755.40	3107	0.0181592	0.0000470	1535474.71
85	101.5000	25.0417	0.1448	578.67	173675.12	3026	0.0181324	0.0000469	1415446.35
86	101.5000	25.5625	0.1433	500.00	201000.00	2703	0.0160331	0.0000415	1676375.50
87	101.5313	23.8958	0.1465	482.67	208218.23	2483	0.0154011	0.0000399	1728032.21
88	101.5000	23.8542	0.1465	493.33	203716.22	2440	0.0151655	0.0000392	1628809.35
89	101.5313	23.8750	0.1450	490.67	204823.37	2444	0.0153294	0.0000397	1664356.06
90	101.5625	23.8125	0.1478	485.33	207074.18	2539	0.0156650	0.0000405	1738384.58
91	101.5313	23.8125	0.1413	473.33	212323.94	2625	0.0169461	0.0000439	1977111.72
92	101.5000	25.5625	0.1520	521.33	192774.94	2897	0.0161946	0.0000419	1557520.66
93	101.5000	25.0417	0.1455	506.67	198355.26	2853	0.0170076	0.0000440	1731785.52
94	101.5000	25.6667	0.1435	509.33	197316.75	2824	0.0166537	0.0000431	1678040.14
95	101.5000	24.6667	0.1510	524.00	191793.89	2740	0.0159783	0.0000414	1521121.13
96	101.4688	25.5417	0.1525	540.00	186111.11	2725	0.0152002	0.0000393	1362563.86
97	101.4688	24.9583	0.1515	549.33	182949.03	2705	0.0155432	0.0000402	1346369.01
98	101.5000	25.5625	0.1453	508.00	197834.65	2837	0.0165962	0.0000430	1681030.79
99	101.5000	24.8958	0.1490	502.67	199933.69	2828	0.0165590	0.0000429	1713047.94

100	101.5313	23.7917	0.1460	481.33	208795.01	2678	0.0167405	0.0000433	1888732.73
101	101.5313	23.8958	0.1450	472.00	212923.73	2644	0.0165694	0.0000429	1944091.95
102	101.5938	23.8333	0.1445	490.67	204823.37	2657	0.0167420	0.0000433	1817724.60
103	101.5938	23.9583	0.1440	476.00	211134.45	2672	0.0168068	0.0000435	1938946.06
104	101.5000	23.8125	0.1460	488.00	205942.62	2661	0.0166248	0.0000430	1824780.39
105	101.5000	24.7917	0.1450	514.67	195272.02	2880	0.0174015	0.0000450	1717235.67
106	101.5000	23.9167	0.1598	477.33	210544.69	3193	0.0181520	0.0000470	2082462.06
107	101.6250	23.6250	0.1420	492.00	204268.29	2622	0.0169553	0.0000439	1830926.99
108	101.5625	23.8958	0.1403	489.33	205381.47	2579	0.0167043	0.0000432	1823528.57
110	101.5000	25.1667	0.1490	533.33	188437.50	2816	0.0163113	0.0000422	1498947.60
111	101.5625	25.2500	0.1583	510.67	196801.57	3245	0.0176283	0.0000456	1766975.23
112	101.5625	24.7917	0.1603	508.00	197834.65	3128	0.0170909	0.0000442	1731137.01
113	101.5000	23.8125	0.1453	482.67	208218.23	3128	0.0196433	0.0000508	2204013.34
114	101.4375	25.2292	0.1485	518.67	193766.07	2886	0.0167418	0.0000433	1626750.76
116	101.5000	24.6458	0.1410	508.00	197834.65	2880	0.0180011	0.0000466	1823331.63
117	101.5000	25.5833	0.1433	513.33	195779.22	2837	0.0168142	0.0000435	1667907.13
118	101.4375	25.5208	0.1463	508.00	197834.65	3025	0.0176145	0.0000456	1784177.08
119	101.5000	25.1458	0.1463	506.67	198355.26	3057	0.0180552	0.0000467	1838451.12
120	101.5625	23.9583	0.1540	482.67	208218.23	3195	0.0187973	0.0000486	2109088.52
123	101.5625	23.9167	0.1470	485.33	207074.18	3333	0.0205787	0.0000533	2283668.02
124	101.3438	23.6875	0.1433	486.67	206506.85	2348	0.0150529	0.0000390	1661320.13
125	101.1875	23.8958	0.1443	490.67	204823.37	2433	0.0153784	0.0000398	1669680.58
126	101.3125	23.7083	0.1423	485.33	207074.18	2387	0.0154018	0.0000399	1709169.41
127	101.2188	23.9792	0.1455	477.33	210544.69	2464	0.0153821	0.0000398	1764689.87
128	101.5625	23.8958	0.1483	481.33	208795.01	2710	0.0166056	0.0000430	1873511.72
129	101.5625	23.9792	0.1460	472.00	212923.73	2734	0.0169517	0.0000439	1988948.11
130	101.3125	23.9167	0.1413	477.33	210544.69	2523	0.0162517	0.0000421	1864450.47
131	101.5625	23.8958	0.1465	489.33	205381.47	2877	0.0178394	0.0000462	1947450.10
132	101.5625	23.8333	0.1488	473.33	212323.94	2942	0.0180137	0.0000466	2101660.73
133	101.4688	23.8333	0.1485	485.33	207074.18	2540	0.0155928	0.0000404	1730370.85
134	101.5313	23.9167	0.1425	496.00	202620.97	2576	0.0164121	0.0000425	1743799.40
137	101.5000	25.0000	0.1323	528.00	190340.91	2416	0.0158719	0.0000411	1488183.96
138	101.2813	23.8125	0.1443	470.67	213526.91	2487	0.0157601	0.0000408	1859637.52
139	101.5938	23.8750	0.1508	477.33	210544.69	3403	0.0205177	0.0000531	2353856.57
140	101.5625	23.9583	0.1545	478.67	209958.22	3415	0.0200266	0.0000518	2284731.31
141	101.5625	25.5625	0.1320	513.33	195779.22	2744	0.0176526	0.0000457	1751071.18
142	101.5938	23.9792	0.1530	492.00	204268.29	3449	0.0204002	0.0000528	2202925.17
143	101.5938	23.9167	0.1505	498.67	201537.43	3431	0.0206848	0.0000535	2174328.53
144	101.6250	23.8958	0.1505	461.33	217846.82	3374	0.0203526	0.0000527	2499685.86
145	101.5625	23.8958	0.1518	480.00	209375.00	3388	0.0202812	0.0000525	2300943.37
146	101.4688	25.2083	0.1418	533.33	188437.50	3181	0.0193419	0.0000501	1777444.17
147	101.5938	23.9167	0.1465	482.67	208218.23	3464	0.0214539	0.0000555	2407172.80
148	101.6250	25.5625	0.1363	510.67	196801.57	2872	0.0178887	0.0000463	1793074.30
149	101.6250	24.3125	0.1303	514.67	195272.02	2664	0.0182499	0.0000472	1800957.62
150	101.5625	25.5000	0.1453	530.67	189384.42	3199	0.0187482	0.0000485	1740244.16
153	101.5625	25.3958	0.1510	508.00	197834.65	2812	0.0159176	0.0000412	1612294.45
154	101.5000	24.7083	0.1493	544.00	184742.65	2777	0.0163563	0.0000423	1444719.42
155	101.5000	24.5208	0.1460	506.67	198355.26	2733	0.0165813	0.0000429	1688379.64
156	101.5313	26.0417	0.1355	522.67	192283.16	2605	0.0160300	0.0000415	1533838.31
157	101.5625	24.6250	0.1423	522.67	192283.16	2473	0.0153249	0.0000397	1466364.30
159	101.5000	24.6250	0.1430	513.33	195779.22	2803	0.0172894	0.0000447	1715043.39

160	101.5625	23.9375	0.1478	493.33	203716.22	3506	0.0215182	0.0000557	2311109.87
162	101.5000	26.0417	0.1473	521.33	192774.94	2947	0.0166926	0.0000432	1605418.61
163	101.5000	24.0000	0.1443	488.00	205942.62	2706	0.0169773	0.0000439	1863478.16
164	101.5625	26.0000	0.1448	504.00	199404.76	2954	0.0170380	0.0000441	1753288.48
166	101.5625	26.0208	0.1425	512.00	196289.06	2937	0.0171937	0.0000445	1714446.12
167	101.5000	23.9583	0.1415	485.33	207074.18	2541	0.0162802	0.0000421	1806652.41
168	101.5625	23.9167	0.1470	473.33	212323.94	3279	0.0202453	0.0000524	2362028.51
170	101.5000	23.8750	0.1448	489.33	205381.47	2692	0.0169193	0.0000438	1846999.27
171	101.5000	26.0000	0.1443	518.67	193766.07	2965	0.0171713	0.0000444	1668484.11
172	101.5625	24.1458	0.1498	506.67	198355.26	2861	0.0171755	0.0000445	1748880.13
173	101.5000	23.8958	0.1483	490.67	204823.37	2525	0.0154815	0.0000401	1680871.88
174	101.5000	25.7500	0.1510	514.67	195272.02	2585	0.0144402	0.0000374	1425008.67
175	101.5313	23.9792	0.1418	492.00	204268.29	2914	0.0186152	0.0000482	2010165.06
176	101.5625	23.9583	0.1415	470.67	213526.91	2838	0.0181719	0.0000470	2144215.08
177	101.5313	24.3125	0.1425	504.00	199404.76	2399	0.0150356	0.0000389	1547227.67
178	101.5000	25.7083	0.1413	512.00	196289.06	2586	0.0154680	0.0000400	1542373.10
179	101.6250	24.0000	0.1385	493.33	203716.22	2662	0.0173732	0.0000450	1865927.74
180	101.6250	25.7500	0.1408	500.00	201000.00	2944	0.0176216	0.0000456	1842471.87
181	101.4688	23.7917	0.1515	485.33	207074.18	2300	0.0138641	0.0000359	1538533.83
182	101.5000	25.6875	0.1423	500.00	201000.00	2437	0.0144860	0.0000375	1514623.29
183	101.5313	23.9375	0.1520	492.00	204268.29	2878	0.0171752	0.0000444	1854674.65
185	101.5313	23.6875	0.1438	489.33	205381.47	2806	0.0178935	0.0000463	1953352.02
186	101.3750	25.7292	0.1423	560.00	179464.29	2854	0.0169582	0.0000439	1413508.15
187	101.4688	24.8750	0.1410	553.33	181626.51	2747	0.0170168	0.0000440	1452779.64
188	101.5625	23.9583	0.1470	484.00	207644.63	2869	0.0176831	0.0000458	1973157.58
189	101.5625	24.5417	0.1438	526.67	190822.78	2600	0.0159979	0.0000414	1507598.37
190	101.4688	25.7083	0.1498	521.33	192774.94	2717	0.0153338	0.0000397	1474737.94
191	101.5625	23.9792	0.1458	498.67	201537.43	2671	0.0165895	0.0000429	1743839.23
192	101.5000	25.6875	0.1468	500.00	201000.00	2833	0.0163236	0.0000422	1706749.72
193	101.5000	25.6667	0.1525	529.33	189861.46	2750	0.0152602	0.0000395	1423633.23
194	101.4688	24.7292	0.1435	518.67	193766.07	2579	0.0157904	0.0000409	1534299.84
195	101.5313	23.9167	0.1473	490.67	204823.37	2789	0.0171960	0.0000445	1867020.05
196	101.5000	23.9167	0.1465	490.67	204823.37	2782	0.0172459	0.0000446	1872444.54
197	101.5000	25.7292	0.1440	514.67	195272.02	2610	0.0153010	0.0000396	1509953.02
198	101.4688	24.9167	0.1440	525.33	191307.11	2536	0.0153567	0.0000397	1454533.92
199	101.5625	25.7500	0.1458	502.67	199933.69	2961	0.0171259	0.0000443	1771692.39
201	101.5625	23.6250	0.1435	498.67	201537.43	2629	0.0168332	0.0000436	1769465.39
202	101.5313	23.8542	0.1415	496.00	202620.97	2675	0.0172083	0.0000445	1828391.85
203	101.6250	23.9167	0.1480	476.00	211134.45	2688	0.0164741	0.0000426	1900560.50
204	101.5313	23.9167	0.1430	497.33	202079.10	2671	0.0169579	0.0000439	1792162.63
205	101.5625	23.9583	0.1495	492.00	204268.29	2767	0.0167692	0.0000434	1810827.33
206	101.5625	23.9583	0.1478	498.67	201537.43	2818	0.0172806	0.0000447	1816486.19
208	101.5000	25.6458	0.1470	508.00	197834.65	2612	0.0150490	0.0000389	1524315.34
209	101.5625	23.9583	0.1463	498.67	201537.43	2744	0.0169994	0.0000440	1786927.10
210	101.5625	23.9167	0.1443	486.67	206506.85	2726	0.0171518	0.0000444	1892962.71
211	101.4688	23.8958	0.1520	484.00	207644.63	2640	0.0157921	0.0000409	1762156.15
212	101.4688	23.8750	0.1565	493.33	203716.22	2600	0.0151188	0.0000391	1623796.72
213	101.6250	23.8542	0.1465	496.00	202620.97	2147	0.0133280	0.0000345	1416105.22
214	101.6250	23.9167	0.1485	497.33	202077.75	2145	0.0131019	0.0000339	1384630.08
215	101.4063	24.0000	0.1458	477.33	210544.69	2726	0.0169424	0.0000438	1943690.28
216	101.5313	23.8958	0.1470	478.67	209958.22	2684	0.0165912	0.0000429	1892806.24

217	101.5313	24.2500	0.1415	509.33	197316.75	2713	0.0171679	0.0000444	1729844.02
218	101.5625	25.6667	0.1463	513.33	195779.22	2995	0.0173194	0.0000448	1718020.86
219	101.6250	24.8958	0.1430	510.67	196801.57	3054	0.0186097	0.0000482	1865348.63
220	101.5000	25.7292	0.1400	505.33	198878.63	2884	0.0173904	0.0000450	1780118.16
221	101.6250	25.0208	0.1375	501.33	200465.43	3022	0.0190556	0.0000493	1981826.06
222	101.5000	23.8750	0.1530	486.67	206506.85	2633	0.0156561	0.0000405	1727889.91
223	101.5000	23.9583	0.1443	473.33	212323.94	2651	0.0166612	0.0000431	1943866.10
224	101.6250	25.6250	0.1475	500.00	201000.00	3101	0.0177983	0.0000461	1860949.42
225	101.4688	25.0417	0.1485	502.67	199933.69	2673	0.0156175	0.0000404	1615645.43
226	101.4688	25.6667	0.1395	506.67	198355.26	2723	0.0165236	0.0000428	1682504.57
227	101.6698	23.8958	0.1438	485.33	207074.18	2199	0.0138815	0.0000359	1540467.23
228	101.6250	23.8333	0.1405	481.33	208795.01	2166	0.0140324	0.0000363	1583194.13
229	101.5000	24.5208	0.1538	529.33	189861.46	2385	0.0137406	0.0000356	1281866.42
230	101.4688	25.6875	0.1495	510.67	196801.57	2711	0.0153380	0.0000397	1537405.46
231	101.4375	25.5625	0.1433	502.67	199933.69	2647	0.0157106	0.0000407	1625273.82
233	101.4688	23.9167	0.1495	486.67	206506.85	2540	0.0154345	0.0000399	1703435.23
234	101.3750	23.8750	0.1470	478.67	209958.22	2680	0.0166065	0.0000430	1894550.15
235	101.4688	23.7917	0.1475	472.00	212923.73	2653	0.0164256	0.0000425	1927228.99
236	101.5313	24.8750	0.1448	532.00	188909.77	2841	0.0171326	0.0000443	1582325.55
237	101.5625	25.7292	0.1473	532.00	188909.77	2881	0.0165068	0.0000427	1524526.06
238	101.5000	23.9583	0.1430	442.67	227033.13	2413	0.0152979	0.0000396	2040676.97
239	101.5313	24.0000	0.1390	438.67	229103.34	2501	0.0162788	0.0000421	2211301.26
240	101.5625	25.8125	0.1108	528.00	190340.91	1989	0.0151030	0.0000391	1416084.00
241	101.5938	24.1667	0.1153	529.33	189861.46	2024	0.0157696	0.0000408	1471148.83
242	101.5313	23.9792	0.1475	476.00	211134.45	2546	0.0156303	0.0000405	1803216.69
244	101.5313	24.7917	0.1453	549.33	182949.03	2737	0.0165039	0.0000427	1429586.90
245	101.5313	23.9375	0.1523	460.00	218478.26	2902	0.0172900	0.0000447	2135871.81
246	101.2500	25.6458	0.1428	534.67	187967.58	2895	0.0172185	0.0000446	1574431.07
247	101.5000	24.9792	0.1430	534.67	187967.58	2818	0.0171354	0.0000443	1566837.69
249	101.5000	23.9792	0.1455	438.67	229103.34	2536	0.0157878	0.0000409	2144599.12
250	101.5000	23.9167	0.1525	444.00	226351.35	2524	0.0150310	0.0000389	1993040.57
251	101.5625	24.0000	0.1508	453.33	221691.18	2996	0.0179752	0.0000465	2286303.19
252	101.5938	23.8125	0.1495	457.33	219752.19	2903	0.0176957	0.0000458	2211553.30
253	101.5625	23.9375	0.1453	493.33	203716.22	2666	0.0166443	0.0000431	1787640.45
254	101.5000	25.6458	0.1460	514.67	195272.02	2957	0.0171534	0.0000444	1692749.89
255	101.5000	25.2083	0.1430	540.00	186111.11	2980	0.0179558	0.0000465	1609577.15
256	101.5313	25.6875	0.1480	513.33	195779.22	2874	0.0164149	0.0000425	1628297.70
257	101.5313	23.9583	0.1515	458.67	219113.37	3021	0.0180724	0.0000468	2245518.63
258	101.5313	23.9583	0.1458	482.67	208218.23	2801	0.0174174	0.0000451	1954262.33
259	101.5313	23.9375	0.1523	478.67	209958.22	2816	0.0167776	0.0000434	1914078.39
260	101.5625	23.9167	0.1488	469.33	214133.52	2686	0.0163889	0.0000424	1944829.20
261	101.5625	23.9583	0.1480	474.67	211727.53	2821	0.0172697	0.0000447	2003563.82
262	101.5625	23.9375	0.1493	458.67	219113.37	3029	0.0184038	0.0000476	2286691.97
263	101.5000	24.9375	0.1480	534.67	187967.58	2761	0.0162488	0.0000421	1485760.41
264	101.5313	23.8958	0.1483	484.00	207644.63	2742	0.0168068	0.0000435	1875380.42
265	101.5313	23.8333	0.1425	482.67	208218.23	2836	0.0181318	0.0000469	2034424.11
266	101.5625	23.9583	0.1405	461.33	217846.82	3009	0.0194039	0.0000502	2383172.46
267	101.5313	23.9583	0.1473	468.00	214743.59	3001	0.0184709	0.0000478	2204407.68
268	101.4063	25.3333	0.1635	513.33	195779.22	2765	0.0145129	0.0000376	1439629.21
269	101.5000	23.7917	0.1415	437.33	229801.83	2647	0.0170782	0.0000442	2334052.91
270	101.0000	25.7083	0.1493	517.33	194265.46	2859	0.0162644	0.0000421	1588520.63

271	101.3750	24.8750	0.1455	513.33	195779.22	2828	0.0169925	0.0000440	1685593.27
272	101.5625	23.8125	0.1443	449.33	223664.69	2587	0.0163484	0.0000423	2116577.73
273	101.5313	23.8958	0.1460	466.67	215357.14	2937	0.0182795	0.0000473	2194041.72
275	101.5625	23.8958	0.1445	449.33	223664.69	2973	0.0186898	0.0000484	2419710.95
276	101.5625	23.9375	0.1513	466.67	215357.14	2979	0.0178606	0.0000462	2143772.27
277	101.5938	23.8542	0.1460	486.67	206506.85	3105	0.0193469	0.0000501	2135224.63
278	101.6250	23.9583	0.1453	482.67	208218.23	3127	0.0194935	0.0000504	2187203.69
280	101.5313	24.0417	0.1480	440.00	228409.09	2770	0.0169039	0.0000437	2282325.91
281	101.5625	23.8125	0.1468	460.00	218478.26	2938	0.0182503	0.0000472	2254493.09
282	101.5938	23.9583	0.1465	454.67	221041.06	2889	0.0178616	0.0000462	2258548.17
283	101.2188	23.9375	0.1430	490.67	204823.37	2622	0.0166837	0.0000432	1811394.50
284	101.1875	25.0625	0.1410	500.00	201000.00	2850	0.0175715	0.0000455	1837230.93
285	101.5313	23.9167	0.1430	428.00	234813.08	2772	0.0175991	0.0000455	2511299.63
286	101.5625	23.9375	0.1390	428.00	234813.08	2709	0.0176732	0.0000457	2521876.17
287	101.5313	23.9583	0.1473	473.33	212323.94	2933	0.0180524	0.0000467	2106180.12
288	101.5313	23.9375	0.1448	472.00	212923.73	2878	0.0180355	0.0000467	2116113.51
289	101.2500	23.8958	0.1495	486.67	206506.85	2718	0.0165663	0.0000429	1828340.63
290	101.4688	23.9167	0.1430	492.00	204268.29	2738	0.0173940	0.0000450	1878293.71
291	101.5938	23.9375	0.1350	424.00	237028.30	2680	0.0179966	0.0000466	2616693.14
292	101.6875	23.8750	0.1425	478.67	209958.22	3130	0.0199459	0.0000516	2275523.99
293	101.6563	23.7917	0.1460	478.67	209958.22	3145	0.0196356	0.0000508	2240122.34
294	101.5625	23.8958	0.1465	484.00	207644.63	2828	0.0175356	0.0000454	1956702.32
295	101.5625	23.9583	0.1458	465.33	215974.21	2951	0.0183445	0.0000475	2214479.16
296	101.3750	23.8125	0.1473	490.67	204823.37	3060	0.0189786	0.0000491	2060565.47
297	101.5625	23.9375	0.1430	458.67	219113.37	2873	0.0182189	0.0000472	2263717.99
298	101.5625	23.9375	0.1460	469.33	214133.52	2880	0.0178880	0.0000463	2122725.92
299	101.5625	23.8750	0.1418	470.67	213526.91	2900	0.0186008	0.0000481	2194828.29
301	101.4375	23.8542	0.1478	489.33	205381.47	3082	0.0190054	0.0000492	2074732.08
302	101.4063	25.6250	0.1490	574.67	174883.99	2891	0.0164614	0.0000426	1302958.18
304	101.6250	25.6458	0.1538	510.67	196801.57	3448	0.0189701	0.0000491	1901467.92
305	101.5625	23.9375	0.1435	465.33	215974.21	2929	0.0185093	0.0000479	2234375.88
306	101.5625	23.8542	0.1360	485.33	207074.18	2715	0.0181663	0.0000470	2015961.89
307	101.3750	23.8750	0.1438	481.33	208795.01	3105	0.0196750	0.0000509	2219815.56
308	101.5625	25.6042	0.1468	508.00	197834.65	3411	0.0197058	0.0000510	1996004.07
309	101.5625	25.0417	0.1558	502.67	199933.69	3338	0.0185779	0.0000481	1921899.86
310	101.6250	23.9167	0.1433	493.33	203716.22	3083	0.0195214	0.0000505	2096650.44
311	101.6250	23.8958	0.1428	486.67	206506.85	3052	0.0194097	0.0000502	2142159.17
312	101.4063	23.9167	0.1498	478.67	209958.22	3106	0.0188540	0.0000488	2150959.05
313	101.4063	23.8542	0.1428	478.67	209958.22	3138	0.0200347	0.0000518	2285655.35
314	101.5625	25.5833	0.1488	500.00	201000.00	3382	0.0192913	0.0000499	2017044.01
315	101.5625	24.9792	0.1490	505.33	198878.63	3299	0.0192406	0.0000498	1969509.55
316	101.5000	25.6042	0.1385	513.33	195779.22	2729	0.0167152	0.0000433	1658087.36
317	101.5625	24.7292	0.1423	502.67	199933.69	2613	0.0161242	0.0000417	1668066.51
318	101.3750	23.8542	0.1465	485.33	207074.18	3094	0.0192540	0.0000498	2136665.77
319	101.5313	23.8750	0.1433	494.67	203167.12	2600	0.0165071	0.0000427	1763354.28
320	101.3750	23.9375	0.1405	493.33	203716.22	3152	0.0203814	0.0000527	2189014.16
321	101.3750	23.9375	0.1398	477.33	210544.69	3156	0.0205168	0.0000531	2353755.01
322	101.5000	25.6250	0.1455	510.67	196801.57	2795	0.0162826	0.0000421	1632086.40
323	101.5000	24.6667	0.1453	508.00	197834.65	2589	0.0156954	0.0000406	1589795.42
324	101.5000	25.6250	0.1348	505.33	198878.63	2785	0.0175187	0.0000453	1793246.04
325	101.5625	25.6875	0.1405	502.67	199933.69	2795	0.0168107	0.0000435	1739079.19

326	101.4375	24.5208	0.1453	506.67	198355.26	2644	0.0161341	0.0000418	1642843.32
327	101.5938	23.9375	0.1455	496.00	202620.97	3124	0.0194642	0.0000504	2068083.94
328	101.5000	23.8750	0.1453	496.00	202620.97	2613	0.0163662	0.0000424	1738920.62
329	101.5000	25.6458	0.1428	500.00	201000.00	2766	0.0164107	0.0000425	1715862.40
330	101.5938	23.9375	0.1453	498.67	201537.43	3142	0.0196100	0.0000508	2061355.26
331	101.5313	23.8958	0.1455	504.00	199404.76	2586	0.0161502	0.0000418	1661926.47
332	101.5000	23.8958	0.1413	501.33	200465.43	2590	0.0166670	0.0000431	1733401.58
333	101.5625	23.8750	0.1490	493.33	203716.22	3124	0.0190626	0.0000493	2047370.01
334	101.5000	23.9583	0.1460	488.00	205942.62	2666	0.0165546	0.0000428	1817080.91
335	101.4063	23.8958	0.1453	504.00	199404.76	2729	0.0170936	0.0000442	1759011.52
336	101.5938	23.8333	0.1485	501.33	200465.43	3110	0.0190685	0.0000493	1983162.31
337	101.5000	23.8542	0.1455	512.00	196289.06	2562	0.0160332	0.0000415	1598730.22
338	101.4375	23.8333	0.1478	512.00	196289.06	2599	0.0160409	0.0000415	1599502.08
339	101.5625	23.9375	0.1468	497.33	202077.75	3071	0.0189768	0.0000491	2005504.59
340	101.5000	23.7917	0.1453	517.33	194265.46	2556	0.0160653	0.0000416	1569069.36
341	101.5625	23.9375	0.1473	498.67	201537.43	3127	0.0192573	0.0000498	2024272.58
342	101.5000	23.8958	0.1450	489.33	205381.47	2598	0.0162861	0.0000421	1777880.58
343	101.5938	23.8750	0.1441	500.00	201000.00	2627	0.0165757	0.0000429	1733108.27
344	101.5625	23.9167	0.1433	481.33	208795.01	2600	0.0164732	0.0000426	1858583.48
345	101.6250	23.8333	0.1408	482.67	208218.23	2590	0.0167494	0.0000433	1879319.70
346	101.5000	23.4583	0.1428	489.33	205381.47	2654	0.0172146	0.0000446	1879235.77
347	101.5000	23.8750	0.1443	522.67	192283.16	2661	0.0167824	0.0000434	1605828.97
348	101.4375	23.7292	0.1470	474.67	211727.53	2659	0.0165674	0.0000429	1922081.39
349	101.6250	23.9167	0.1358	472.00	212923.73	2595	0.0173393	0.0000449	2034424.52
350	101.5625	23.9792	0.1360	472.00	212923.73	2574	0.0171331	0.0000443	2010237.79
351	101.4375	23.9167	0.1428	501.33	200465.43	2606	0.0165895	0.0000429	1725342.06
352	101.6250	23.7292	0.1383	500.00	201000.00	2577	0.0170412	0.0000441	1781785.79
353	101.4375	23.9583	0.1460	481.33	208795.01	2699	0.0167698	0.0000434	1892048.55
354	101.5000	23.9167	0.1508	576.00	174479.17	2513	0.0151392	0.0000392	1192759.20
355	101.5000	23.7083	0.1450	556.00	180755.40	2468	0.0155935	0.0000404	1318529.25
356	101.5000	23.8542	0.1458	542.67	185196.56	2529	0.0157995	0.0000409	1402403.37
357	100.6875	23.7708	0.1443	486.67	206506.85	2774	0.0177135	0.0000458	1954954.86
358	100.6875	23.9583	0.1458	488.00	205942.62	2797	0.0175382	0.0000454	1925047.12
359	101.4375	23.8750	0.1480	480.00	209375.00	2737	0.0168347	0.0000436	1909932.22
360	100.6875	23.8333	0.1428	489.33	205381.47	2797	0.0180007	0.0000466	1965059.33
361	100.7500	23.8542	0.1460	489.33	205381.47	2836	0.0178188	0.0000461	1945197.62
362	101.5313	23.8542	0.1550	470.67	213526.91	2708	0.0159033	0.0000412	1876529.35
363	101.5313	23.8750	0.1430	480.00	209375.00	2639	0.0167840	0.0000434	1904175.75
364	101.5000	23.8333	0.1450	549.33	182949.03	2501	0.0157192	0.0000407	1361608.39
365	101.4688	23.9167	0.1453	474.67	211727.53	2694	0.0168493	0.0000436	1954790.80
366	101.5625	23.9792	0.1475	485.33	207074.18	2727	0.0167363	0.0000433	1857268.42
367	101.5313	23.8750	0.1440	518.67	193766.07	2922	0.0184548	0.0000478	1793193.66
368	101.5000	23.9375	0.1433	517.33	194265.46	2968	0.0188000	0.0000487	1836169.52
369	101.6250	23.8333	0.1413	508.00	197834.65	2644	0.0170381	0.0000441	1725796.12
370	101.5625	23.8958	0.1420	506.67	198355.26	2651	0.0169590	0.0000439	1726833.32
371	101.2500	23.9375	0.1445	466.67	215357.14	2599	0.0163606	0.0000423	1963723.39
372	101.2813	23.8542	0.1443	485.33	207074.18	2565	0.0162260	0.0000420	1800641.56
373	101.5313	23.8958	0.1413	488.00	205942.62	2645	0.0170157	0.0000440	1867690.58
374	101.5313	23.8958	0.1443	482.67	208218.23	2645	0.0166618	0.0000431	1869487.61
375	101.5000	23.8958	0.1498	536.00	187500.00	2602	0.0157938	0.0000409	1436983.97
376	101.5000	23.8750	0.1433	570.67	176109.81	2534	0.0160930	0.0000416	1291715.32

377	101.4688	23.8542	0.1448	557.33	180322.97	2596	0.0163352	0.0000423	1374639.39
378	101.2813	23.9583	0.1455	481.33	208795.01	2637	0.0164663	0.0000426	1857799.62
379	101.2813	23.7917	0.1453	486.67	206506.85	2715	0.0171015	0.0000443	1887408.20
380	101.5938	23.9375	0.1380	486.67	206506.85	2481	0.0162981	0.0000422	1798738.20
381	101.5000	23.8542	0.1440	500.00	201000.00	2704	0.0170981	0.0000442	1787735.07
382	101.5000	23.8958	0.1438	508.00	197834.65	2767	0.0174963	0.0000453	1772208.94
383	101.5000	23.8333	0.1450	566.67	177352.94	2598	0.0163288	0.0000423	1329211.98
384	101.5313	23.9375	0.1458	490.67	204823.37	2782	0.0173143	0.0000448	1879862.97
385	101.5625	23.6458	0.1418	485.33	207074.18	2756	0.0178485	0.0000462	1980692.99
386	101.5000	23.8542	0.1413	562.67	178613.74	2579	0.0166252	0.0000430	1372648.96
387	101.5000	23.8750	0.1438	565.33	177771.23	2584	0.0163535	0.0000423	1337504.69
388	101.6250	23.9375	0.1403	472.00	212923.73	2540	0.0164129	0.0000425	1925736.07
389	101.5313	23.7500	0.1428	468.00	214743.59	2860	0.0183173	0.0000474	2186070.32
390	101.5000	23.8333	0.1425	562.67	178613.74	2609	0.0166856	0.0000432	1377638.51
391	101.4375	23.7917	0.1425	560.00	179464.29	2628	0.0168470	0.0000436	1404236.65
392	101.3125	23.9583	0.1423	481.33	208795.01	2755	0.0175907	0.0000455	1984664.41
393	101.4063	23.8542	0.1428	472.00	212923.73	2639	0.0168488	0.0000436	1976876.64
394	101.3125	23.2500	0.1383	473.33	212323.94	2617	0.0177169	0.0000459	2067034.28
395	101.5000	23.9375	0.1438	466.67	215357.14	2884	0.0182044	0.0000471	2185034.37
396	101.3125	23.8750	0.1438	473.33	212323.94	2733	0.0173284	0.0000448	2021717.41
397	101.4688	23.8750	0.1440	554.67	181189.90	2646	0.0167219	0.0000433	1420747.13
398	101.5000	23.8958	0.1408	534.67	187967.58	2644	0.0170749	0.0000442	1561305.43
399	101.2500	23.9167	0.1423	478.67	209958.22	2737	0.0175171	0.0000453	1998433.65
400	101.3125	23.9583	0.1465	478.67	209958.22	2687	0.0166588	0.0000431	1900523.75
401	101.5313	23.6250	0.1413	484.00	207644.63	2679	0.0174320	0.0000451	1945141.72
402	101.5625	23.9375	0.1418	486.67	206506.85	2675	0.0171129	0.0000443	1888663.59
403	101.5313	23.7708	0.1458	482.67	208218.23	2700	0.0169218	0.0000438	1898653.49
404	101.3750	23.9167	0.1455	478.67	209958.22	2771	0.0173171	0.0000448	1975626.80
405	101.4375	16.8333	0.1473	556.00	180755.40	2668	0.0233935	0.0000605	1978069.49
406	101.4688	23.8542	0.1418	553.33	181626.51	2652	0.0170407	0.0000441	1454820.76
407	101.2813	23.9375	0.1498	484.00	207644.63	2723	0.0165351	0.0000428	1845064.31
408	101.3438	23.8333	0.1465	474.67	211727.53	2764	0.0172208	0.0000446	1997884.85
409	101.5938	23.9167	0.1478	462.67	217219.02	2547	0.0156411	0.0000405	1909970.48
410	101.5938	23.8750	0.1448	466.67	215357.14	2514	0.0157859	0.0000409	1894750.51
411	101.5000	23.9167	0.1430	460.00	218478.26	2590	0.0164487	0.0000426	2031938.86
412	101.5000	23.8333	0.1473	557.33	180322.97	2415	0.0149467	0.0000387	1257796.06
413	101.5313	23.8333	0.1435	549.33	182949.03	2473	0.0157008	0.0000406	1360019.25
414	101.2813	23.8125	0.1440	500.00	201000.00	2706	0.0171777	0.0000445	1796058.64
415	101.5000	23.8250	0.1480	529.33	189861.46	2496	0.0153751	0.0000398	1434348.53
416	101.5000	23.7708	0.1493	526.67	190822.78	2507	0.0153484	0.0000397	1446395.78
417	101.5625	23.7500	0.1443	498.67	201537.43	2636	0.0167019	0.0000432	1755663.07
418	101.5313	23.3750	0.1408	492.00	204268.29	2638	0.0174104	0.0000451	1880070.33
419	101.5625	23.8958	0.1440	477.33	210544.69	2549	0.0160800	0.0000416	1844750.00
420	101.5000	23.8333	0.1435	526.67	190822.78	2442	0.0155088	0.0000401	1461505.76
421	101.5000	23.8750	0.1458	521.33	192774.94	2507	0.0156484	0.0000405	1504993.50
422	101.5000	23.9583	0.1413	494.67	203167.12	2713	0.0174130	0.0000451	1860127.29
423	101.5313	23.9167	0.1435	490.67	204823.37	2734	0.0172974	0.0000448	1878029.37
424	101.5000	23.8750	0.1515	478.67	209958.22	2495	0.0149824	0.0000388	1709272.83
425	101.5000	23.9583	0.1430	477.33	210544.69	2507	0.0158939	0.0000411	1823397.65
426	101.5625	23.9375	0.1430	505.33	198878.63	2721	0.0172550	0.0000447	1766256.21
427	101.5625	23.9167	0.1455	492.00	204268.29	2707	0.0168859	0.0000437	1823435.01

428	101.5938	23.9375	0.1435	484.00	207644.63	2538	0.0160335	0.0000415	1789091.19
429	101.5313	23.9583	0.1503	488.00	205942.62	2533	0.0152791	0.0000395	1677080.83
430	101.5313	23.9375	0.1450	484.00	207644.63	2741	0.0171473	0.0000444	1913379.21
431	101.5000	23.8958	0.1415	492.00	204268.29	2708	0.0173956	0.0000450	1878464.78
432	101.5313	23.9375	0.1448	485.33	207074.18	2552	0.0159926	0.0000414	1774731.26
433	101.5000	23.8958	0.1455	517.33	194265.46	2556	0.0159678	0.0000413	1559545.23
434	101.5000	23.8750	0.1528	517.33	194265.46	2606	0.0155209	0.0000402	1515905.44
435	101.5000	23.9167	0.1478	510.67	196801.57	2644	0.0162518	0.0000421	1629001.61
436	101.5000	23.9583	0.1460	501.33	200465.43	2646	0.0164304	0.0000425	1708796.87
437	101.5625	23.7292	0.1438	498.67	201537.43	2627	0.0167175	0.0000433	1757296.07
438	101.5000	23.9167	0.1430	512.00	196289.06	2666	0.0169314	0.0000438	1688288.87
439	101.5000	23.9583	0.1445	512.00	196289.06	2724	0.0170903	0.0000442	1704142.68
440	101.5625	23.9583	0.1473	536.00	187500.00	2509	0.0154380	0.0000400	1404607.74
441	101.5625	23.9167	0.1413	526.67	190822.78	2534	0.0162824	0.0000421	1534411.06
442	101.5000	23.9167	0.1440	501.33	200465.43	2802	0.0176715	0.0000457	1837871.10
443	101.5000	24.0000	0.1428	520.00	193269.23	2541	0.0161096	0.0000417	1557305.59
444	101.5625	23.8125	0.1433	512.00	196289.06	2879	0.0183207	0.0000474	1826829.44
445	101.5000	23.8750	0.1468	514.67	195272.02	2912	0.0180525	0.0000467	1781480.29
446	101.5000	23.9375	0.1510	528.00	190340.91	2549	0.0153173	0.0000396	1436181.99
447	101.4688	23.9583	0.1425	506.67	198355.26	2794	0.0177810	0.0000460	1810536.24
448	101.5000	24.0000	0.1365	505.33	198878.63	2536	0.0168141	0.0000435	1721126.08
449	101.5000	23.9375	0.1450	500.00	201000.00	2795	0.0174905	0.0000453	1828766.40
450	101.5000	23.9167	0.1438	497.33	202077.75	2808	0.0177401	0.0000459	1874807.51
451	101.1875	23.8750	0.1460	488.00	205942.62	2896	0.0181013	0.0000468	1986849.98
452	101.5000	23.8750	0.1353	509.33	197316.75	2597	0.0174687	0.0000452	1760152.59
453	101.5000	23.9167	0.1455	518.67	193766.07	2569	0.0160350	0.0000415	1558070.15
454	101.5000	23.9375	0.1423	513.33	195779.22	2823	0.0180073	0.0000466	1786257.65
455	101.5313	23.9583	0.1320	500.00	201000.00	2658	0.0182498	0.0000472	1908156.39
456	101.5313	23.9167	0.1380	501.33	200465.43	2574	0.0169341	0.0000438	1761185.80
457	101.5313	23.8958	0.1403	492.00	204268.29	2511	0.0162688	0.0000421	1756794.60
458	101.5313	23.9583	0.1415	514.67	195272.02	2583	0.0165442	0.0000428	1632633.91
459	101.5000	23.9375	0.1415	536.00	187500.00	2528	0.0162110	0.0000420	1474943.83
460	101.5000	23.9167	0.1453	526.67	190822.78	2591	0.0162001	0.0000419	1526659.48
461	101.5000	23.9167	0.1423	489.33	205381.47	2893	0.0184699	0.0000478	2016272.05
462	101.5000	23.9583	0.1430	488.00	205942.62	2884	0.0182840	0.0000473	2006902.13
463	101.5000	23.9583	0.1465	490.67	204823.37	2796	0.0173026	0.0000448	1878594.52
464	101.5000	23.9583	0.1443	493.33	203716.22	2804	0.0176228	0.0000456	1892726.60
465	101.5000	23.9375	0.1433	490.67	204823.37	2834	0.0179512	0.0000465	1949021.08
466	101.5625	23.9167	0.1448	488.00	205942.62	2841	0.0178136	0.0000461	1955276.81
467	101.4375	23.9167	0.1475	550.67	182506.05	2561	0.0157780	0.0000408	1360097.55
468	101.5000	23.8542	0.1488	497.33	202077.75	2613	0.0159951	0.0000414	1690387.50
469	101.5000	23.9375	0.1405	514.67	195272.02	2545	0.0164362	0.0000425	1621973.71
470	101.5313	23.9583	0.1418	481.33	208795.01	2490	0.0159204	0.0000412	1796210.92
471	101.5625	23.9792	0.1410	472.00	212923.73	2513	0.0161339	0.0000418	1893002.45
473	101.5313	23.9375	0.1443	469.33	214133.52	2483	0.0156141	0.0000404	1852886.59
474	101.5000	23.9375	0.1473	508.00	197834.65	2543	0.0156704	0.0000406	1587259.97
475	101.5000	23.9792	0.1413	504.00	199404.76	2546	0.0163269	0.0000423	1680111.12
476	101.5000	23.9167	0.1445	477.33	210544.69	2824	0.0177486	0.0000459	2036178.70
477	101.5313	23.9375	0.1440	481.33	208795.01	2781	0.0175184	0.0000453	1976502.47
478	101.5000	23.9792	0.1438	493.33	203716.22	2522	0.0158917	0.0000411	1706811.04
479	101.3750	23.8958	0.1478	517.33	194265.46	2620	0.0161382	0.0000418	1576191.91

480	101.4063	23.9375	0.1473	500.00	201000.00	2744	0.0169246	0.0000438	1769597.70
481	101.4375	23.9167	0.1448	541.33	185652.71	2142	0.0134473	0.0000348	1199503.26
482	101.5000	23.9375	0.1385	536.00	187500.00	2156	0.0141250	0.0000366	1285150.04
484	101.4688	23.6458	0.1435	545.33	184290.95	2410	0.0154317	0.0000399	1356386.26
485	101.5938	23.9167	0.1530	460.00	218478.26	3197	0.0189591	0.0000491	2342055.41
486	101.5625	23.8958	0.1508	460.00	218478.26	3230	0.0194636	0.0000504	2404380.74
487	101.5000	23.9583	0.1475	517.33	194265.46	2297	0.0141182	0.0000365	1378906.03
488	101.5000	24.0000	0.1463	518.67	193766.07	2304	0.0142575	0.0000369	1385357.64
489	101.5313	23.6667	0.1450	498.67	201537.43	3145	0.0198999	0.0000515	2091820.47
490	101.3438	23.8750	0.1485	520.00	193269.23	2215	0.0135907	0.0000352	1313800.75
491	101.5000	23.8542	0.1445	518.67	193766.07	2207	0.0139072	0.0000360	1351315.58
492	101.2813	23.9375	0.1413	510.67	196801.57	2267	0.0145945	0.0000378	1462882.56
493	101.4688	23.9167	0.1485	493.33	203716.22	2347	0.0143578	0.0000372	1542062.65
494	101.4688	24.0417	0.1455	493.33	203716.22	2355	0.0146273	0.0000379	1571011.56
495	101.5313	23.9583	0.1380	484.00	207644.63	3255	0.0213772	0.0000553	2385360.99
496	101.5313	23.9167	0.1470	490.67	204823.37	2372	0.0146498	0.0000379	1590571.22
497	101.5000	23.9583	0.1488	496.00	202620.97	2424	0.0147736	0.0000382	1569708.13
498	101.5000	23.8958	0.1453	502.67	199933.69	2301	0.0143995	0.0000373	1489640.07
499	101.5000	23.9375	0.1483	517.33	194265.46	2305	0.0141080	0.0000365	1377906.46
500	101.3125	23.8958	0.1440	526.67	190822.78	2212	0.0139885	0.0000362	1318241.62
502	101.4375	23.6667	0.1448	513.33	195779.22	2266	0.0143761	0.0000372	1426054.21
503	101.5313	23.8333	0.1443	512.00	196289.06	3122	0.0197182	0.0000510	1966173.78
504	101.6250	23.8125	0.1435	488.00	205942.62	2734	0.0173570	0.0000449	1905156.60
505	101.5000	23.7708	0.1483	502.67	199933.69	2445	0.0150698	0.0000390	1558988.11
506	101.4688	23.9375	0.1468	509.33	197316.75	2423	0.0149864	0.0000388	1510042.84
507	101.5625	23.7708	0.1415	501.33	200465.43	3174	0.0204836	0.0000530	2130339.38
508	101.5938	23.8958	0.1415	504.00	199404.76	2713	0.0174116	0.0000451	1791729.21
509	101.6250	24.0000	0.1453	498.67	201537.43	2792	0.0173749	0.0000450	1826400.68
510	101.5313	23.8125	0.1413	514.67	195272.02	3155	0.0203676	0.0000527	2009941.25
511	101.5313	23.9167	0.1445	514.67	195272.02	3064	0.0192511	0.0000498	1899755.51
512	101.5938	23.9583	0.1415	521.33	192774.94	3061	0.0195937	0.0000507	1884436.78
513	101.5625	23.9167	0.1430	514.67	195272.02	3140	0.0199294	0.0000516	1966693.85
514	101.6250	23.8542	0.1405	482.67	208218.23	2825	0.0182857	0.0000473	2051691.08
515	101.4063	23.9167	0.1468	505.33	198878.63	2330	0.0144327	0.0000374	1477358.21
516	101.6563	23.9792	0.1438	478.67	209958.22	2967	0.0186671	0.0000483	2129631.28
517	101.4063	23.9583	0.1470	501.33	200465.43	2327	0.0143645	0.0000372	1493942.30
518	101.4375	23.9167	0.1455	513.33	195779.22	2352	0.0146896	0.0000380	1457154.06
519	101.5625	23.9167	0.1515	494.67	203167.12	2813	0.0168522	0.0000436	1800226.04
521	101.5625	24.1042	0.1428	533.33	188437.50	2398	0.0151280	0.0000392	1390206.67
522	101.5000	23.8542	0.1430	533.33	188437.50	2322	0.0147853	0.0000383	1358712.89
527	101.5000	23.8958	0.1443	518.67	193766.07	2529	0.0159360	0.0000412	1548450.67
528	101.5000	23.8333	0.1438	512.00	196289.06	2512	0.0159256	0.0000412	1587999.26
529	101.5938	23.9375	0.1505	490.67	204823.37	2912	0.0175406	0.0000454	1904431.00
530	101.5313	23.6250	0.1463	481.33	208795.01	2988	0.0187779	0.0000486	2118607.75
531	101.5625	23.8542	0.1425	484.00	207644.63	3115	0.0198921	0.0000515	2219647.94
532	101.5938	23.9375	0.1395	488.00	205942.62	3084	0.0200414	0.0000519	2199804.07
533	101.4375	23.8750	0.1463	504.00	199404.76	2407	0.0149821	0.0000388	1541723.49
534	101.4688	23.9375	0.1470	504.00	199404.76	2398	0.0148066	0.0000383	1523663.05
535	101.5000	23.9792	0.1428	525.33	191307.11	2285	0.0144992	0.0000375	1373312.29
537	101.5625	23.9583	0.1410	520.00	193269.23	2771	0.0178058	0.0000461	1721276.38
538	101.4063	23.9583	0.1463	501.33	200465.43	2442	0.0151517	0.0000392	1575812.57

539	101.4375	23.9375	0.1445	492.00	204268.29	2462	0.0154695	0.0000400	1670482.51
540	101.5000	23.9375	0.1458	532.00	188909.77	2329	0.0144994	0.0000375	1339128.00
541	101.5938	23.9167	0.1395	472.00	212923.73	2811	0.0182832	0.0000473	2145182.59
542	101.5625	23.8750	0.1403	480.00	209375.00	2860	0.0185405	0.0000480	2103454.83
544	101.5000	23.9375	0.1473	504.00	199404.76	2559	0.0157690	0.0000408	1622700.39
545	101.5000	23.8750	0.1465	502.67	199933.69	2442	0.0151647	0.0000392	1568800.45
546	101.5000	23.9375	0.1400	497.33	202077.75	2451	0.0158856	0.0000411	1678821.69
547	101.5000	23.8958	0.1413	492.00	204268.29	2476	0.0159334	0.0000412	1720572.67
548	101.5000	23.8750	0.1428	466.67	215357.14	2993	0.0190746	0.0000494	2289480.14
549	101.5625	23.9375	0.1425	481.33	208795.01	2918	0.0185692	0.0000481	2095056.01
550	101.5000	24.0417	0.1450	542.67	185196.56	2383	0.0148477	0.0000384	1317918.03
551	101.5625	23.9583	0.1413	501.33	200465.43	2374	0.0152278	0.0000394	1583719.90
552				524.00	191793.89				
553	101.5938	23.9583	0.1468	510.67	196801.57	2361	0.0145723	0.0000377	1460657.95
554	101.5625	23.9375	0.1463	513.33	195779.22	2986	0.0185147	0.0000479	1836589.46
555	101.6250	23.9583	0.1430	505.33	198878.63	3015	0.0190910	0.0000494	1954193.16
556	101.5000	23.9375	0.1448	534.67	187967.58	2390	0.0149820	0.0000388	1369927.37
557	101.5625	23.9583	0.1463	498.67	201537.43	2677	0.0165843	0.0000429	1743295.86
558	101.5000	23.9167	0.1470	585.33	171697.04	2375	0.0146728	0.0000380	1119443.91
559	101.5000	23.9167	0.1430	569.33	176522.25	2344	0.0148864	0.0000385	1200468.92
561	101.5000	23.9167	0.1433	580.00	173275.86	2356	0.0149365	0.0000387	1160612.49
562	101.5000	23.9792	0.1413	497.33	202077.75	2456	0.0157498	0.0000408	1664462.08
563	101.6250	23.9375	0.1383	478.67	209958.22	2683	0.0175878	0.0000455	2006499.60
564	101.5625	23.8958	0.1405	494.67	203167.12	2678	0.0173146	0.0000448	1849620.62
565	101.5313	23.9167	0.1428	496.00	202620.97	2818	0.0179225	0.0000464	1904278.22
566	101.5625	23.9375	0.1505	480.00	209375.00	2818	0.0169796	0.0000439	1926367.33
567	101.5625	23.8558	0.1410	477.33	210544.69	2810	0.0181340	0.0000469	2080391.02
568	101.5625	23.9167	0.1463	520.00	193269.23	2430	0.0150803	0.0000390	1457803.35
569	101.5625	23.9583	0.1458	529.33	189861.46	2411	0.0149876	0.0000388	1398200.46
570	101.5000	23.8333	0.1430	520.00	193269.23	2443	0.0155694	0.0000403	1505078.59
571	101.5625	23.7708	0.1403	484.00	207644.63	2757	0.0179511	0.0000465	2003063.18
572	101.5313	23.9375	0.1398	486.67	206506.85	2782	0.0180576	0.0000467	1992933.69
573	101.5313	23.9167	0.1375	478.67	209958.22	2862	0.0188973	0.0000489	2155904.12
574	101.5313	23.9167	0.1398	474.67	211727.53	2669	0.0173393	0.0000449	2011630.30
575	101.5625	23.8958	0.1478	510.67	196801.57	2976	0.0182972	0.0000474	1834020.21
576	101.6250	23.9583	0.1458	509.33	197316.75	2996	0.0186127	0.0000482	1875431.26
577	101.5625	23.9375	0.1420	474.67	211727.53	2880	0.0183919	0.0000476	2133751.14
578	101.5625	23.8750	0.1395	469.33	214133.52	2875	0.0187379	0.0000485	2223582.99
579	101.5000	23.9375	0.1410	516.00	194767.44	2456	0.0158052	0.0000409	1551651.83
580	101.5313	23.8125	0.1510	454.67	221041.06	2793	0.0168664	0.0000437	2132712.41
581	101.5938	23.9792	0.1448	474.67	211727.53	2762	0.0172679	0.0000447	2003345.34
582	101.5000	23.8750	0.1430	518.67	193766.07	2449	0.0155804	0.0000403	1513895.56
583	101.4375	23.7917	0.1455	518.67	193766.07	2456	0.0154197	0.0000399	1498285.42
584	101.5625	23.8958	0.1423	469.33	214133.52	2914	0.0186087	0.0000482	2208249.67
585	101.5625	23.9167	0.1418	472.00	212923.73	2896	0.0185428	0.0000480	2175638.45
586	101.5000	23.9375	0.1465	525.33	191307.11	2488	0.0154100	0.0000399	1459577.86
587	101.4688	23.8750	0.1430	520.00	193269.23	2486	0.0158206	0.0000409	1529367.91
588	101.4688	23.9583	0.1445	516.00	194767.44	2469	0.0154953	0.0000401	1521227.58
590	101.4375	23.8750	0.1458	541.33	185652.71	2702	0.0168760	0.0000437	1505339.95
591	101.3438	24.0208	0.1430	554.67	181189.90	2650	0.0167826	0.0000434	1425902.82

Veneer Lay-Up for LVL

#	300°F	340°F	380°F	#	300°F	340°F	380°F	#	300°F	340°F	380°F
	85	446	553		370	328	437		215	357	404
	440	25	586		351	69	45		33	555	315
	356	502	518		448	343	172		20	465	503
	521	174	187		218	112	134		235	41	360
	214	397	154		329	217	60		388	260	27
	6	213	268		159	87	150		358	101	294
	488	193	416		105	133	557		566	361	371
	569	591	406		547	93	191		32	131	31
	391	244	568		537	332	141		46	185	513
	186	415	5		369	90	417		103	258	188
1	240	375	420	6	222	325	335	11	223	466	49
	517	582	194		480	4	470		451	581	8
	263	197	460		111	445	324		336	399	574
	459	39	237		426	63	148		221	80	175
	241	570	534		319	146	381		405	12	462
	157	38	95		456	70	209		393	572	339
	492	110	434		452	382	42		477	58	261
	1	421	588		211	34	253		91	250	563
	190	590	208		127	342	508		385	308	510
	515	189	61		62	220	367		43	408	350
	498	506	156		201	352	414		392	571	28
2	583	182	441	7	199	454	82	12	129	36	57
	177	340	528		206	289	419		11	22	287
	178	247	551		205	444	119		349	59	132
	533	433	236		167	104	284		411	44	549
	181	13	538		149	427	368		396	296	21
	40	443	29		65	116	575		461	514	106
	84	14	494		519	102	449		306	333	567
	230	92	246		372	425	19		314	7	51
	227	505	479		242	108	554		341	330	489
	493	398	228		447	509	442		265	394	310
	67	545	474		283	66	180		476	327	542
3	527	497	270	8	334	202	407	13	238	301	120
	255	88	124		68	196	345		277	585	584
	347	10	316		378	195	463		580	573	113
	338	212	326		3	219	290		516	541	532
	76	469	2		473	163	362		530	176	273
	496	16	458		71	422	264		288	311	278
	323	225	322		170	138	450		81	318	389
	75	9	77		564	224	576		272	276	320
	337	544	79		183	130	423		298	249	299
	162	231	15		366	179	431		507	312	142
	55	256	18		47	373	346		577	143	267
4	153	435	331	9	344	128	384	14	245	395	239
	546	73	48		471	565	309		24	269	286
	86	468	83		216	304	259		281	548	144
	125	438	126		353	203	50		293	251	486
	317	271	192		402	511	359		578	140	266
	562	98	233		512	35	455		295	280	139
	89	173	78		418	410	504		252	292	321
	74	226	439		379	403	56		307	123	168
	171	53	436		100	400	409		305	313	495
	539	155	424		464	52	430		257	262	275
	94	17	99		210	363	64		282	160	285
5	475	254	166	10	234	529	348	15	297	485	291

NONDESTRUCTIVE TESTING DATA (FOR STATIC TESTING)

LVL 300°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s²/in⁴)	$E_{dynamic}$ (psi)
1a	96	3.501000	1.522667	512.00	186523.44	4067	0.0175202	0.0000453	1577502.12
1b	96	3.516000	1.525667	521.33	183184.14	4074	0.0174412	0.0000451	1514656.54
1e	96.0625	3.501333	1.526000	510.67	187010.44	4094	0.0175849	0.0000455	1591603.28
2a	96.0625	3.376333	1.518000	492.00	194105.69	3958	0.0177231	0.0000459	1728138.30
2d	96.125	3.458667	1.509667	486.67	196232.88	3896	0.0171130	0.0000443	1705428.45
3b	96.125	3.514667	1.527667	492.00	194105.69	4171	0.0178166	0.0000461	1737259.80
3c	96.125	3.530000	1.524667	484.00	197314.05	4153	0.0176974	0.0000458	1783155.14
3d	96.125	3.533667	1.523667	486.67	196232.88	4146	0.0176609	0.0000457	1760021.94
3e	96.125	3.520333	1.517333	488.00	195696.72	4077	0.0175055	0.0000453	1735017.31
4b	96.1875	3.434000	1.522000	497.33	192024.13	4363	0.0191331	0.0000495	1825830.18
4f	96.125	3.456333	1.523000	501.33	190492.02	4364	0.0190137	0.0000492	1785597.58
5a	96.25	3.478333	1.510000	482.67	197859.12	4240	0.0184906	0.0000479	1873381.57
5c	96.1875	3.441333	1.519000	481.33	198407.20	4296	0.0188363	0.0000487	1918991.84
5f	96.25	3.477000	1.522000	484.00	197314.05	4255	0.0184168	0.0000477	1855635.38
6d	96.125	3.436667	1.520000	488.00	195696.72	4483	0.0196827	0.0000509	1950812.94
7b	96.1875	3.479333	1.516667	476.00	200630.25	4564	0.0198233	0.0000513	2065051.08
10c	96.0625	3.468333	1.518000	466.67	204642.86	4557	0.0198640	0.0000514	2152895.08
10d	96	3.479333	1.525667	478.67	199512.53	4632	0.0200390	0.0000519	2064330.06
10e	96.0625	3.484000	1.523667	476.00	200630.25	4579	0.0197962	0.0000512	2062237.24
11d	96	3.483667	1.507000	470.67	202903.68	4683	0.0204851	0.0000530	2182629.80
12a	96.0625	3.477333	1.511000	488.00	195696.72	4659	0.0203499	0.0000527	2016936.75
13d	96	3.482000	1.524667	465.33	205229.23	4751	0.0205515	0.0000532	2240194.27
13f	96.0625	3.479667	1.524667	472.00	202330.51	4685	0.0202664	0.0000524	2147153.28
14d	96.1875	3.484667	1.509667	466.67	204642.86	4851	0.0211351	0.0000547	2290660.11

NONDESTRUCTIVE TESTING DATA (FOR DOL TESTING)

LVL 300°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
1c	96.125	3.513000	1.516333	520.00	183653.85	3982	0.0171446	0.0000444	1496543.24
1d	96.0625	3.473000	1.526000	513.33	186038.96	4046	0.0175205	0.0000453	1569342.11
2b	96.125	3.476667	1.505333	497.33	192024.13	3962	0.0173627	0.0000449	1656880.30
2c	96.125	3.447333	1.511667	493.33	193581.08	3900	0.0171642	0.0000444	1664607.71
2f	96.125	3.470667	1.514667	484.00	197314.05	3959	0.0172724	0.0000447	1740332.93
3a	96.125	3.481333	1.528000	484.00	197314.05	4060	0.0175047	0.0000453	1763737.22
3f	96.125	3.520667	1.526000	486.67	196232.88	4083	0.0174300	0.0000451	1737017.80
4a	96.1875	3.461333	1.512333	506.67	188486.84	4267	0.0186830	0.0000484	1717798.72
4c	96.125	3.363667	1.524667	501.33	190492.02	4309	0.0192702	0.0000499	1809685.08
4d	96.125	3.454333	1.514333	505.33	188984.17	4310	0.0188969	0.0000489	1746639.12
4e	96.125	3.440667	1.523667	489.33	195163.49	4337	0.0189738	0.0000491	1870315.12
5b	96.1875	3.482333	1.520667	484.00	197314.05	4277	0.0185119	0.0000479	1865217.19
5d	96.1875	3.473000	1.516667	485.33	196771.98	4240	0.0184496	0.0000477	1848740.43
5e	96.25	3.475000	1.517333	478.67	199512.53	4213	0.0183016	0.0000474	1885351.92
6b	96.125	3.461667	1.515333	476.00	200630.25	4400	0.0192379	0.0000498	2004069.97
6c	96.125	3.462333	1.517667	481.33	198407.20	4427	0.0193224	0.0000500	1968520.33
10a	96.125	3.437000	1.509667	474.67	201193.82	4459	0.0197095	0.0000510	2064747.44
10b	96.0625	3.484333	1.524000	480.00	198958.33	4611	0.0199283	0.0000516	2041540.43
10f	96.125	3.417000	1.519000	470.67	202903.68	4562	0.0201581	0.0000522	2147796.73
11c	96	3.474667	1.507333	476.00	200630.25	4609	0.0202091	0.0000523	2105246.74
11e	96	3.480333	1.516667	472.00	202330.51	4687	0.0203914	0.0000528	2160392.32
12f	96.0625	3.471333	1.513333	477.33	200069.83	4771	0.0208429	0.0000539	2159160.73
14c	96.0625	3.482000	1.522333	472.00	202330.51	4927	0.0213316	0.0000552	2260008.34
15e	96.125	3.485000	1.522000	466.67	204642.86	4931	0.0213214	0.0000552	2310848.84

NONDESTRUCTIVE TESTING DATA (MEMBERS NOT USED)

LVL 300°F Number	Member Condition	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
1f	cutting loss	----------	----------	----------	----------	----------	----------	----------	----------	----------
2e		96.125	3.464000	1.512000	486.67	196232.88	3976	0.0174106	0.0000451	1735086.10
6a	1 long min.	96.1875	3.463000	1.514333	494.67	193059.30	4503	0.0196808	0.0000509	1898400.89
6e	2 maj. delam	96.1875	3.478667	1.520000	484.00	197314.05	4523	0.0196059	0.0000507	1975443.94
6f	1 min.	96.1875	3.452000	1.514333	485.33	196771.98	4432	0.0194323	0.0000503	1947208.65
7a	2 maj. delam	96.1875	3.454333	1.530333	477.33	200069.83	4646	0.0201439	0.0000521	2086751.07
7c	2 maj. delam	96.1875	3.483333	1.518000	480.00	198958.33	4580	0.0198525	0.0000514	2033768.16
7d	2 maj. delam	96.25	3.488000	1.524000	477.33	200069.83	4663	0.0200927	0.0000520	2081438.54
7e	2 maj. delam	96.25	3.475667	1.520333	473.33	201760.56	4597	0.0199265	0.0000516	2099261.47
7f	2 maj. delam	96.25	3.477667	1.522000	480.00	198958.33	4488	0.0194215	0.0000503	1989623.56
8a	2 maj. delam	96.125	3.409667	1.530000	468.00	204059.83	4426	0.0194583	0.0000504	2096929.75
8b	2 maj. delam	96.125	3.479333	1.520333	481.33	198407.20	4499	0.0195065	0.0000505	1987269.62
8c	2 maj. delam	96.1875	3.465333	1.531333	474.67	201193.82	4440	0.0191771	0.0000496	2008981.77
8d	1 maj. delam	96.1875	3.438333	1.524667	474.67	201193.82	4539	0.0198451	0.0000514	2078954.95
8e	1 maj. delam	96.1875	3.483000	1.519333	469.33	203480.11	4557	0.0197373	0.0000511	2114924.83
8f	1 maj. delam	96.1875	3.472667	1.529667	477.33	200069.83	4392	0.0189504	0.0000490	1963107.81
9a	1 min.	96	3.486333	1.509000	468.00	204059.83	4538	0.0198093	0.0000513	2134751.31
9b	2 maj. delam	96.0625	3.491000	1.538333	474.67	201193.82	4586	0.0195981	0.0000507	2053081.94
9c	2 maj. delam	96.0625	3.488333	1.536667	470.67	202903.68	4592	0.0196600	0.0000509	2094726.60
9d	1 maj. delam	96.0625	3.470000	1.534000	466.67	204642.86	4581	0.0197509	0.0000511	2140631.42
9e	2 maj. delam	96.0625	3.494000	1.513667	476.00	200630.25	4519	0.0196096	0.0000507	2042797.36
9f	2 maj. delam	96.0625	3.473333	1.521000	489.33	195163.49	4548	0.0197572	0.0000511	1947534.57
11a	2 maj. delam	96	3.484667	1.516333	482.67	197859.12	4707	0.0204574	0.0000529	2072651.63
11b	2 maj. delam	96.0625	3.482667	1.523000	478.67	199512.53	4627	0.0200202	0.0000518	2062392.48
11f	2 maj. delam	96.0625	3.458000	1.519000	469.33	203480.11	4614	0.0201593	0.0000522	2160140.64
12b	1 maj. delam	96.0625	3.478000	1.514333	482.67	197859.12	4688	0.0204276	0.0000529	2069626.27
12c	2 maj. delam	96.0625	3.476667	1.516333	485.33	196771.98	4745	0.0206566	0.0000535	2069894.64
12d	2 maj. delam	96.0625	3.475000	1.525333	481.33	198407.20	4770	0.0206528	0.0000534	2104054.24
12e	1 min.	96.0625	3.471000	1.523667	478.67	199512.53	4814	0.0208902	0.0000541	2152014.21

NONDESTRUCTIVE TESTING DATA (MEMBERS NOT USED): ***continued***

LVL 300°F Number	Member Condition	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
13a	2 maj. delam	96.0625	3.476333	1.523333	469.33	203480.11	4726	0.0204813	0.0000530	2194646.41
13b	2 maj. delam	96	3.480333	1.538667	457.33	208819.24	4769	0.0204515	0.0000529	2307963.17
13c	2 maj. delam	96	3.478667	1.530000	461.33	207008.67	4715	0.0203442	0.0000527	2256214.74
13e	1 maj. delam	96	3.473667	1.528333	461.33	207008.67	4683	0.0202573	0.0000524	2246574.95
14a	2 maj. delam	96.1875	3.487000	1.522000	478.67	199512.53	4943	0.0213471	0.0000552	2199089.41
14b	2 maj. delam	96.1875	3.473667	1.523667	460.00	207608.70	5022	0.0217477	0.0000563	2425873.69
14e	2 maj. delam	96.1875	3.473333	1.522333	473.33	201760.56	5034	0.0218209	0.0000565	2298836.36
14f	1 min.	96.125	3.477333	1.522667	468.00	204059.83	4941	0.0214024	0.0000554	2306425.95
15a	2 maj. delam	96.1875	3.474000	1.525667	460.00	207608.70	4995	0.0216004	0.0000559	2409437.17
15b	1 min.	96.1875	3.474667	1.511667	453.33	210661.76	4935	0.0215344	0.0000557	2473249.40
15c	1 min.	96.1875	3.487000	1.528000	461.33	207008.67	5044	0.0216978	0.0000562	2406330.93
15d	2 maj. delam	96.1875	3.474667	1.525000	453.33	210661.76	4971	0.0215019	0.0000556	2469509.56
15f	2 min.	96.1875	3.485667	1.527667	460.00	207608.70	5030	0.0216506	0.0000560	2415033.25

NONDESTRUCTIVE TESTING DATA (FOR STATIC TESTING)

LVL 340°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
1b	96.0625	3.506667	1.533333	509.33	187500.00	4270	0.0182254	0.0000472	1658221.78
2d	96.125	3.505333	1.528333	498.67	191510.70	4176	0.0178777	0.0000463	1696914.41
2f	96.0625	3.498000	1.540333	501.33	190492.02	4229	0.0180129	0.0000466	1691609.06
3c	96.125	3.506333	1.522333	493.33	193581.08	4276	0.0183727	0.0000475	1781809.83
3d	96.125	3.493000	1.529667	486.67	196232.88	4332	0.0185948	0.0000481	1853093.74
4c (1 min.)	96.1875	3.497667	1.526000	481.33	198407.20	4458	0.0191436	0.0000495	1950295.79
5d	96.25	3.490000	1.518667	502.67	189986.74	4515	0.0195121	0.0000505	1822690.12
5e	96.25	3.489333	1.535000	490.67	194633.15	4557	0.0194878	0.0000504	1910549.20
6a	96.0625	3.472333	1.513000	476.00	200630.25	4391	0.0191815	0.0000496	1998201.10
6e	96.125	3.450000	1.526000	473.33	201760.56	4411	0.0192159	0.0000497	2024402.11
7c	96.25	3.488333	1.526000	480.00	198958.33	4715	0.0202882	0.0000525	2078403.46
8c	96.125	3.484000	1.517333	470.67	202903.68	4445	0.0192846	0.0000499	2054722.93
10a	96.1875	3.503000	1.513333	480.00	198958.33	4680	0.0202342	0.0000524	2072878.71
10b	96.1875	3.475667	1.522667	464.00	205818.97	4722	0.0204503	0.0000529	2241982.97
10e	96.1875	3.475000	1.529000	468.00	204059.83	4700	0.0202745	0.0000525	2184887.63
10f	96.1875	3.486000	1.521667	472.00	202330.51	4629	0.0200012	0.0000518	2119051.55
11a	96.125	3.484000	1.523000	470.67	202903.68	4687	0.0202589	0.0000524	2158527.33
11c	96.125	3.469333	1.528667	466.67	204642.86	4700	0.0203253	0.0000526	2202890.97
12d	96.0625	3.492000	1.536000	458.67	208212.21	4889	0.0209187	0.0000541	2346984.54
13c	96.1875	3.500667	1.539000	464.00	205818.97	5016	0.0213395	0.0000552	2339469.76
13d	96.1875	3.500667	1.543333	465.33	205229.23	5019	0.0212923	0.0000551	2320938.44
13e	96.1875	3.491000	1.530333	468.00	204059.83	4990	0.0214082	0.0000554	2307056.34
14a	96.0625	3.481000	1.523667	454.67	210043.99	4905	0.0212239	0.0000549	2423308.97
15a	96.1875	3.487333	1.538000	449.33	212537.09	5318	0.0227255	0.0000588	2656724.43

NONDESTRUCTIVE TESTING DATA (FOR DOL TESTING)

LVL 340°F-1 Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
1a	96.0625	3.496667	1.528333	512.00	186523.44	4216	0.0181054	0.0000469	1630190.51
1f	96.0625	3.477667	1.527000	504.00	189484.13	4143	0.0179048	0.0000463	1663707.10
2b	96	3.490333	1.526333	496.00	192540.32	4184	0.0180359	0.0000467	1730392.73
3a	96.125	3.516333	1.517000	500.00	191000.00	4327	0.0186041	0.0000481	1756462.17
3e	96.125	3.496667	1.527000	494.67	193059.30	4340	0.0186421	0.0000482	1798202.92
4d	96.125	3.490000	1.517333	488.00	195696.72	4402	0.0190652	0.0000493	1889607.05
5c	96.1875	3.475000	1.507000	497.33	192024.13	4516	0.0197652	0.0000512	1886148.94
7a	96.1875	3.489333	1.536667	496.00	192540.32	4737	0.0202487	0.0000524	1942688.41
7b	96.1875	3.497667	1.528333	489.33	195163.49	4737	0.0203106	0.0000526	2002085.07
7d	96.25	3.496667	1.523000	474.67	201193.82	4734	0.0203614	0.0000527	2133043.90
8a	96.1875	3.490000	1.507000	474.67	201193.82	4537	0.0197718	0.0000512	2071275.55
8b	96.125	3.482667	1.512667	472.00	202330.51	4460	0.0194168	0.0000503	2057137.15
8f	96	3.468000	1.512000	477.33	200069.83	4449	0.0194847	0.0000504	2018462.34
9a	96.125	3.480667	1.523333	468.00	204059.83	4603	0.0199105	0.0000515	2145652.67
9c	96.125	3.475000	1.527000	470.67	202903.68	4568	0.0197438	0.0000511	2103647.16
11b	96.125	3.479000	1.525667	470.67	202903.68	4745	0.0205031	0.0000531	2184553.97
11f	96.1875	3.480000	1.520000	469.33	203480.11	4731	0.0204996	0.0000531	2196608.01
12a	96.0625	3.481000	1.535000	466.67	204642.86	4798	0.0206076	0.0000533	2233491.37
12b	96.125	3.491667	1.529000	460.00	207608.70	4842	0.0208009	0.0000538	2320258.60
12f	96.0625	3.503667	1.521667	457.33	208819.24	4755	0.0204686	0.0000530	2309896.39
14b	96.0625	3.493667	1.525333	458.67	208212.21	5026	0.0216450	0.0000560	2428465.28
14c	96.0625	3.499333	1.527000	461.33	207008.67	4986	0.0214145	0.0000554	2374916.00
14f	96.0625	3.493000	1.524667	460.00	207608.70	4830	0.0208139	0.0000539	2321710.02
15c	96.1875	3.502667	1.533667	445.33	214446.11	5090	0.0217172	0.0000562	2584656.51

NONDESTRUCTIVE TESTING DATA (FOR DOL TESTING)

LVL 340°F-2 Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s^2/in^4)	$E_{dynamic}$ (psi)
1c	96.0625	3.504667	1.528333	508.00	187992.13	4238	0.0181584	0.0000470	1660805.31
2c	96	3.496667	1.510667	501.33	190492.02	4152	0.0180508	0.0000467	1695172.72
2e	96.125	3.506000	1.540000	501.33	190492.02	4204	0.0178578	0.0000462	1677043.95
3b	96.125	3.509000	1.526000	497.33	192024.13	4290	0.0183746	0.0000476	1753443.54
3f	96.125	3.491333	1.520667	490.67	194633.15	4311	0.0186230	0.0000482	1825774.36
5a	96.1875	3.480000	1.522333	489.33	195163.49	4494	0.0194428	0.0000503	1916548.06
5b	96.1875	3.476000	1.524000	493.33	193581.08	4542	0.0196516	0.0000509	1905841.25
5f	96.1875	3.484000	1.521667	497.33	192024.13	4536	0.0196106	0.0000508	1871395.08
8d	96.125	3.473333	1.516000	473.33	201760.56	4524	0.0197049	0.0000510	2075918.42
8e	96.0625	3.466000	1.511667	477.33	200069.83	4507	0.0197416	0.0000511	2045075.93
9b	96.125	3.474000	1.525667	469.33	203480.11	4603	0.0199182	0.0000515	2134303.79
9d	96.125	3.474333	1.523333	481.33	198407.20	4514	0.0195611	0.0000506	1992832.43
9e	96.125	3.456667	1.525667	473.33	201760.56	4441	0.0193135	0.0000500	2034683.98
9f	96.125	3.459667	1.509000	466.67	204642.86	4445	0.0195275	0.0000505	2116421.86
10c	96.1875	3.500000	1.516000	476.00	200630.25	4677	0.0202030	0.0000523	2104609.21
10d	96.1875	3.479333	1.520000	469.33	203480.11	4705	0.0203909	0.0000528	2184954.76
12c	96.125	3.502333	1.532667	461.33	207008.67	4827	0.0206239	0.0000534	2287230.69
12e	96.0625	3.503667	1.529000	469.33	203480.11	4830	0.0206918	0.0000536	2217195.88
13a	96.1875	3.495667	1.522667	464.00	205818.97	5006	0.0215562	0.0000558	2363226.12
13b	96.1875	3.502333	1.531333	470.67	202903.68	5111	0.0218421	0.0000565	2327217.81
13f	96.1875	3.498000	1.523000	469.33	203480.11	4985	0.0214467	0.0000555	2298094.60
14d	96.0625	3.501667	1.529000	450.67	211908.28	4942	0.0211837	0.0000548	2461838.62
14e	96.0625	3.497000	1.528333	460.00	207608.70	4832	0.0207488	0.0000537	2314448.62
15b	96.1875	3.498000	1.530667	450.67	211908.28	5215	0.0223239	0.0000578	2594348.16

Nondestructive Testing Data (Members Not Used)

LVL 340°F Number	Member Condition	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s^2/in^4)	$E_{dynamic}$ (psi)
1d	3 maj. wdf-delam	96.0625	3.487667	1.527000	498.67	191510.70	4237	0.0182585	0.0000473	1733060.72
1e	1 min.	96.0625	3.491333	1.527333	497.33	192024.13	4191	0.0180374	0.0000467	1721263.58
2a	3 maj. delam	96.0625	3.491000	1.539667	501.33	190492.02	4204	0.0179501	0.0000465	1685710.48
4a	3 maj. wdf-delam	96.1875	3.500000	1.521667	480.00	198958.33	4340	0.0186775	0.0000483	1913396.31
4b	3 maj. delam	96.1875	3.509000	1.524000	492.00	194105.69	4438	0.0190211	0.0000492	1854701.42
4e	1maj/1min delam	96.125	3.492667	1.526667	485.33	196771.98	4355	0.0187320	0.0000485	1877042.42
4f	3 maj. delam	96.125	3.488000	1.523000	492.00	194105.69	4311	0.0186123	0.0000482	1814842.62
6b	2maj/surf wdf-delam	96.0625	3.480000	1.524667	481.33	198407.20	4421	0.0191226	0.0000495	1948159.40
6c	2 maj. wdf-delam	96.0625	3.475000	1.522333	480.00	198958.33	4385	0.0190233	0.0000492	1948823.72
6d	4 maj. wdf-delam	96.125	3.465667	1.523667	482.67	197859.12	4410	0.0191540	0.0000496	1940594.30
6f	3maj/surf wdf-delam	96.125	3.471333	1.522333	482.67	197859.12	4348	0.0188704	0.0000488	1911861.28
7e	1 maj. wdf-delam	96.25	3.492333	1.511333	480.00	198958.33	4813	0.0208869	0.0000541	2139737.92
7f	2 maj. wdf-delam	96.25	3.492667	1.519333	482.67	197859.12	4807	0.0207490	0.0000537	2102192.34
11d	2 maj. wdf-delam	96.1875	3.510333	1.520333	464.00	205818.97	4741	0.0203610	0.0000527	2232194.67
11e	1 maj. wood fail	96.1875	3.500000	1.525667	470.67	202903.68	4781	0.0205214	0.0000531	2186499.62
15d	1 maj. delam	96.25	3.479667	1.530333	436.00	219036.70	4985	0.0214425	0.0000555	2662389.86
15e	3 maj. delam	96.1875	3.492667	1.558000	454.67	210043.99	5138	0.0216414	0.0000560	2470975.98
15f	3 maj. delam	96.25	3.499667	1.537333	456.00	209429.82	5282	0.0224873	0.0000582	2552566.90

NONDESTRUCTIVE TESTING DATA (FOR STATIC TESTING)

LVL 380°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
1a	96	3.482000	1.509333	494.67	193059.30	4169	0.0182172	0.0000471	1757216.71
4a (1min wdf surf)	96	3.506333	1.520333	473.33	201760.56	4256	0.0183347	0.0000474	1931559.43
4b (1 min. wdf)	96	3.502333	1.540000	473.33	201760.56	4352	0.0185299	0.0000480	1952131.91
4f (1 maj. wdf)	96.125	3.499333	1.523667	481.33	198407.20	4285	0.0184320	0.0000477	1877808.07
8f	96.0625	3.491667	1.528333	464.00	205818.97	4641	0.0199591	0.0000517	2188138.19
9a	96.1875	3.479333	1.522000	462.67	206412.10	4474	0.0193643	0.0000501	2135178.14
9d	96.125	3.505000	1.527000	456.00	209429.82	4517	0.0193562	0.0000501	2197155.92
9e	96.125	3.502667	1.526667	461.33	207008.67	4563	0.0195707	0.0000506	2170427.57
10c	96.1875	3.488000	1.518333	458.67	208212.21	4535	0.0196268	0.0000508	2202036.83
12b	96.125	3.476667	1.503000	465.33	205229.23	4644	0.0203830	0.0000528	2221822.61
12d	96.125	3.476333	1.511667	458.67	208212.21	4621	0.0201677	0.0000522	2262724.57
13a	96.125	3.489333	1.533333	461.33	207008.67	4875	0.0208975	0.0000541	2317573.12
13c	96.125	3.466333	1.519000	464.00	205818.97	4894	0.0213174	0.0000552	2337046.96
13d	96.125	3.465667	1.526333	461.33	207008.67	4804	0.0208288	0.0000539	2309961.18
14a	96.0625	3.457000	1.533000	453.33	210661.76	4936	0.0213754	0.0000553	2454981.98
14b	96.0625	3.455333	1.531667	453.33	210661.76	4841	0.0209924	0.0000543	2410990.86
15b	96.25	3.478667	1.546667	448.00	213169.64	5102	0.0217202	0.0000562	2554336.04
15d	96.1875	3.466667	1.527000	444.00	215090.09	5034	0.0217960	0.0000564	2609644.79
15f	96.1875	3.461000	1.525000	436.00	219036.70	4957	0.0215260	0.0000557	2672758.66

NONDESTRUCTIVE TESTING DATA (FOR DOL TESTING)

LVL 380°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (µs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ (lb*s^2/in^4)	$E_{dynamic}$ (psi)
1f	96	3.480667	1.515333	494.67	193059.30	4174	0.0181738	0.0000470	1753029.37
4d	96.0625	3.507333	1.538000	474.67	201193.82	4301	0.0182985	0.0000474	1916940.33
5a	96.125	3.484000	1.537667	473.33	201760.56	4175	0.0178737	0.0000463	1882996.39
7a	96.1875	3.502667	1.504000	464.00	205818.97	4371	0.0190173	0.0000492	2084891.45
9b (1 min. wdf)	96.125	3.510000	1.528333	469.33	203480.11	4519	0.0193204	0.0000500	2070245.61
9c	96.125	3.503667	1.506333	462.67	206412.10	4570	0.0198596	0.0000514	2189794.91
10a	96.125	3.466667	1.521000	456.00	209429.82	4499	0.0195692	0.0000506	2221327.23
10d	96.1875	3.483000	1.515000	465.33	205229.23	4539	0.0197156	0.0000510	2149072.15
11d	96.1875	3.471333	1.512667	468.00	204059.83	4665	0.0203623	0.0000527	2194348.66
11e	96.1875	3.468333	1.508333	468.00	204059.83	4677	0.0204911	0.0000530	2208222.10
12a	96.125	3.488667	1.515667	458.67	208212.21	4756	0.0206289	0.0000534	2314471.54
12c	96.125	3.478000	1.511667	456.00	209429.82	4664	0.0203456	0.0000527	2309461.75
13b	96.125	3.467333	1.526000	460.00	207608.70	4849	0.0210184	0.0000544	2344519.91
13e	96.1875	3.459333	1.533667	461.33	207008.67	4874	0.0210561	0.0000545	2335165.75
13f	96.1875	3.469667	1.519000	458.67	208212.21	4793	0.0208438	0.0000539	2338583.01
14f (1 ext.min. wdf)	96.0625	3.441667	1.525000	452.00	211283.19	4912	0.0214783	0.0000556	2481377.50
15a	96.1875	3.448333	1.540667	440.00	217045.45	5078	0.0219074	0.0000567	2670881.77
15c	96.25	3.471000	1.556333	440.00	217045.45	5027	0.0213150	0.0000552	2598659.91
15e	96.25	3.481000	1.517000	437.33	218368.90	4995	0.0216660	0.0000561	2673768.94

Nondestructive Testing Data (Members Not Used)

LVL 380°F Number	Member Condition	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
1b	1maj/1min wood fail	96	3.492333	1.508333	493.33	193581.08	4099	0.0178701	0.0000462	1733072.10
1c	1 maj. wood fail	96	3.479667	1.500667	497.33	192024.13	4087	0.0179740	0.0000465	1715221.75
1d	surface wood fail	96	3.470000	1.512333	497.33	192024.13	4046	0.0177057	0.0000458	1689609.70
1e	1maj/1min wood fail	96	3.480000	1.515667	500.00	191000.00	4079	0.0177596	0.0000460	1676731.04
2a	3 maj. wood fail	96.125	3.492333	1.523333	490.67	194633.15	4126	0.0177876	0.0000460	1743865.60
2b	2 maj. wood fail	96.1875	3.493667	1.524333	489.33	195163.49	4165	0.0179254	0.0000464	1766970.26
2c	1 maj. wood fail	96.1875	3.488667	1.501667	489.33	195163.49	4115	0.0180033	0.0000466	1774649.00
2d	3 maj. wood fail	96.125	3.488333	1.523000	477.33	200069.83	4149	0.0179111	0.0000464	1855451.30
2e	2 maj. wood fail	96.125	3.504333	1.512667	498.67	191510.70	4174	0.0180593	0.0000467	1714157.22
2f	1maj/1min wood fail	96.1875	3.487667	1.513000	494.67	193059.30	4094	0.0177824	0.0000460	1715275.54
3a	2 maj. wood fail	96.0625	3.492000	1.509333	480.00	198958.33	4015	0.0174826	0.0000452	1790992.13
3b	3 maj. wood fail	96.125	3.503000	1.503000	484.00	197314.05	4145	0.0180561	0.0000467	1819291.23
3c	2 maj. wood fail	96.125	3.512333	1.531333	489.33	195163.49	4178	0.0178156	0.0000461	1756147.16
3d	2 maj. wood fail	96.125	3.500000	1.519333	468.00	204059.83	4095	0.0176616	0.0000457	1903306.02
3e	2 maj. wood fail	96.1875	3.490667	1.513333	476.00	200630.25	4104	0.0178066	0.0000461	1854964.99
3f	2 maj. wood fail	96.0625	3.478000	1.518000	476.00	200630.25	4089	0.0177744	0.0000460	1851619.97
4c	1maj/1min wood fail	96.0625	3.501000	1.529333	480.00	198958.33	4378	0.0187656	0.0000486	1922423.28
4e	1maj/1min wood fail	96.0625	3.497333	1.520333	482.67	197859.12	4233	0.0182706	0.0000473	1851091.17
5b	2 maj. wood fail	96.0625	3.502333	1.527667	462.67	206412.10	4260	0.0182727	0.0000473	2014823.91
5c	1 maj. wood fail	96	3.496667	1.506667	464.00	205818.97	4200	0.0183080	0.0000474	2007125.68
5d	2 maj. wood fail	96.0625	3.525667	1.520667	469.33	203480.11	4260	0.0182354	0.0000472	1953986.34
5e	2 maj. wood fail	96.0625	3.517000	1.528333	461.33	207008.67	4283	0.0182868	0.0000473	2028046.69
5f	2 maj. wood fail	96.0625	3.519000	1.522667	466.67	204642.86	4296	0.0184001	0.0000476	1994236.24
6a	1 maj. wood fail	96.125	3.490000	1.499667	480.00	198958.33	4384	0.0192109	0.0000497	1968046.87
6b	2maj/surf wood fail	96.125	3.510333	1.514333	468.00	204059.83	4469	0.0192814	0.0000499	2077860.28
6c	2 maj. wood fail	96.0625	3.493667	1.514333	468.00	204059.83	4330	0.0187830	0.0000486	2024152.56
6d	1 maj. wood fail	96.125	3.493333	1.498667	468.00	204059.83	4394	0.0192492	0.0000498	2074391.88
6e	2 maj. wood fail	96.0625	3.504667	1.516000	472.00	202330.51	4392	0.0189713	0.0000491	2009936.86
6f	2 maj. wood fail	96.0625	3.506000	1.517333	474.67	201193.82	4420	0.0190682	0.0000493	1997569.46

*Nondestructive Testing Data (Members Not Used): **continued***

LVL 380°F Number	Member Condition	Average Length (in)	Average Width (in)	Average Thickness (in)	Average SWT (μs)	C ([95.5]in/s)	mass (g)	ρ (lb/in3)	ρ ($lb*s^2/in^4$)	$E_{dynamic}$ (psi)
7b	2 maj. wood fail	96.1875	3.505333	1.522333	464.00	205818.97	4367	0.0187568	0.0000485	2056332.78
7c	2 maj. wood fail	96.125	3.509333	1.517333	466.67	204642.86	4407	0.0189817	0.0000491	2057270.51
7d	1maj/1min wood fail	96.125	3.506667	1.503000	470.67	202903.68	4352	0.0189380	0.0000490	2017790.48
7e	2 maj. wood fail	96.125	3.498000	1.524333	464.00	205818.97	4422	0.0190203	0.0000492	2085213.64
7f	2maj/surf wood fail	96.1875	3.508000	1.515000	469.33	203480.11	4384	0.0189066	0.0000489	2025912.93
8a	1 ext.min. wood fail	96.125	3.504667	1.512000	461.33	207008.67	4584	0.0198401	0.0000513	2200310.45
8b	2maj/surf wood fail	96.0625	3.493333	1.528333	466.67	204642.86	4615	0.0198378	0.0000513	2150057.28
8c	2 maj. wood fail	96.0625	3.500000	1.517000	472.00	202330.51	4665	0.0201641	0.0000522	2136308.78
8d	2 maj. wood fail	96.125	3.499000	1.524667	469.33	203480.11	4615	0.0198404	0.0000513	2125972.24
8e	1 maj. wood fail	96.0625	3.502333	1.521667	466.67	204642.86	4719	0.0203214	0.0000526	2202467.00
9f	3 maj. wood fail	96.125	3.506667	1.536667	456.00	209429.82	4517	0.0192253	0.0000498	2182296.63
10b	2 maj. wood fail	96.125	3.480667	1.525333	462.67	206412.10	4433	0.0191500	0.0000496	2111551.34
10e	1 maj. wood fail	96.125	3.491667	1.522333	466.67	204642.86	4415	0.0190496	0.0000493	2064629.58
10f	1 maj. wood fail	96.125	3.482	1.528	454.67	210043.99	4490	0.0193573	0.0000501	2210185.37
11a	2 maj. wood fail	96.1875	3.454	1.535	462.67	206412.10	4631	0.0200222	0.0000518	2207726.66
11b	1maj/1min wood fail	96.1875	3.470	1.525	462.67	206412.10	4657	0.0201664	0.0000522	2223621.31
11c	1 maj. wood fail	96.1875	3.478	1.522	466.67	204642.86	4658	0.0201709	0.0000522	2186152.45
11f	surface marked	96.1875	3.471	1.516	465.33	205229.23	4608	0.0200737	0.0000520	2188111.12
12e	2 maj. wood fail	96.125	3.488	1.517	461.33	207008.67	4657	0.0201856	0.0000522	2238628.57
12f	1 maj. wood fail	96.125	3.485	1.523	457.33	208819.24	4564	0.0197197	0.0000510	2225375.14
14c	1 maj. wood fail	96.0625	3.449	1.536	457.33	208819.24	4905	0.0212468	0.0000550	2397711.45
14d	1maj/1min wood fail	96.0625	3.453	1.529	462.67	206412.10	4865	0.0211501	0.0000547	2332089.03
14e	1 maj. wood fail	96.0625	3.439	1.538	449.33	212537.09	4906	0.0212826	0.0000551	2488041.63

STATIC TESTING DATA

LVL 300°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Failure Time (min)	Peak Load (lb)	Deflection @ P.L. (in)	Elastic Region Slope (lb/in)	E_{static} (psi)	MOR (psi)
1a	96	3.501000	1.522667	12.41	1775.2	1.6736	1613.1	1962373.58	6848.43
1b	96	3.516000	1.525667	11.15	1629.5	1.5052	1195.9	1433475.18	6220.56
1e	96.0625	3.501333	1.526000	11.79	1809.1	1.3937	1993.6	2419271.93	6962.63
2a	96.0625	3.376333	1.518000	10.73	1727.9	1.3388	2155.3	2932253.94	7189.33
2d	96.125	3.458667	1.509667	10.02	1520.1	1.2329	1666.5	2120799.91	6060.47
3b	96.125	3.514667	1.527667	8.91	1439.4	1.092	2196.1	2631919.80	5491.83
3c	96.125	3.530000	1.524667	9.68	1637.7	1.1893	2216.3	2626824.72	6206.44
3d	96.125	3.533667	1.523667	10.97	1861.1	1.3374	2149.6	2541514.06	7043.05
3e	96.125	3.520333	1.517333	9.82	1596.2	1.2218	2138.7	2568142.26	6111.83
4b	96.1875	3.434000	1.522000	10.67	1793.7	1.2428	1669.0	2152496.14	7195.60
4f	96.125	3.456333	1.523000	11.19	1891.0	1.4286	1989.8	2515151.99	7483.30
5a	96.25	3.478333	1.510000	9.51	1658.2	1.1673	1826.9	2285208.35	6535.07
5c	96.1875	3.441333	1.519000	10.52	1836.3	1.2992	1970.0	2529471.55	7349.62
5f	96.25	3.477000	1.522000	9.60	1615.9	1.1342	1603.2	1991867.98	6323.00
6d	96.125	3.436667	1.520000	11.47	1990.2	1.4504	1733.8	2233802.38	7981.98
7b	96.1875	3.479333	1.516667	11.45	2157.0	1.461	1725.4	2146906.39	8458.64
10c	96.0625	3.468333	1.518000	12.27	2437.1	1.5415	1723.4	2162984.45	9609.31
10d	96	3.479333	1.525667	11.58	2312.0	1.4483	2289.7	2832255.20	9012.98
10e	96.0625	3.484000	1.523667	12.07	2315.2	1.5066	2256.6	2783759.73	9013.11
11d	96	3.483667	1.507000	12.15	2463.4	1.5478	2064.3	2575439.49	9697.97
12a	96.0625	3.477333	1.511000	11.02	2126.8	1.4407	1995.1	2496104.73	8381.12
13d	96	3.482000	1.524667	13.06	2751.8	1.6791	2253.6	2783025.58	10718.08
13f	96.0625	3.479667	1.524667	13.46	2688.2	1.7285	1897.7	2348233.57	10484.41
14d	96.1875	3.484667	1.509667	12.15	2660.4	1.5727	2195.8	2732307.42	10449.03

STATIC TESTING DATA

LVL 340°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Failure Time (min)	Peak Load (lb)	Deflection @ P.L. (in)	Elastic Region Slope (lb/in)	E_{static} (psi)	MOR (psi)
1b	96.0625	3.506667	1.533333	10.85	1665.9	1.3555	1639.3	1970788.31	6361.45
2d	96.125	3.505333	1.528333	8.44	1344.2	1.0366	1348.3	1628103.65	5153.71
2f	96.0625	3.498000	1.540333	10.42	1656.7	1.3741	1239.9	1494906.74	6328.81
3c	96.125	3.506333	1.522333	11.48	1979.0	1.5406	1329.2	1609987.65	7613.11
3d	96.125	3.493000	1.529667	12.62	2268.8	1.6413	1761.0	2147179.57	8752.55
4c (1 min.)	96.1875	3.497667	1.526000	10.81	1975.1	1.3754	2008.1	2444539.83	7617.46
5d	96.25	3.490000	1.518667	12.26	2075.4	1.6515	1442.6	1776269.08	8078.32
5e	96.25	3.489333	1.535000	11.57	2039.8	1.5636	1444.1	1760204.31	7858.27
6a	96.0625	3.472333	1.513000	11.17	1884.7	1.5125	1399.2	1755812.80	7438.63
6e	96.125	3.450000	1.526000	11.16	2098.1	1.5045	1465.0	1858349.42	8316.99
7c	96.25	3.488333	1.526000	12.88	2492.9	1.7541	1686.4	2069444.08	9666.00
8c	96.125	3.484000	1.517333	13.13	2456.5	1.7681	1586.0	1964668.65	9603.11
10a	96.1875	3.503000	1.513333	12.16	2313.0	1.642	1633.1	1995534.95	8967.95
10b	96.1875	3.475667	1.522667	11.03	2167.7	1.5074	1694.6	2106927.42	8484.98
10e	96.1875	3.475000	1.529000	12.07	2450.8	1.6376	1662.5	2059639.97	9557.04
10f	96.1875	3.486000	1.521667	11.06	2284.2	1.4864	1545.0	1905146.50	8893.90
11a	96.125	3.484000	1.523000	11.11	2278.9	1.4801	1660.3	2049055.85	8875.68
11c	96.125	3.469333	1.528667	10.61	2222.0	1.3362	2467.4	3072488.37	8695.04
12d	96.0625	3.492000	1.536000	13.75	2849.5	1.8107	2234.5	2715613.81	10953.72
13c	96.1875	3.500667	1.539000	15.45	3330.9	2.1011	1908.4	2297629.93	12716.10
13d	96.1875	3.500667	1.543333	12.28	2749.4	1.6372	1813.0	2176643.78	10466.69
13e	96.1875	3.491000	1.530333	12.27	2700.4	1.6818	1821.3	2223552.93	10424.97
14a	96.0625	3.481000	1.523667	12.44	2832.6	1.6586	1846.7	2283998.86	11046.37
15a	96.1875	3.487333	1.538000	11.80	2913.3	1.6155	1983.3	2416869.85	11214.36

STATIC TESTING DATA

LVL 380°F Number	Average Length (in)	Average Width (in)	Average Thickness (in)	Failure Time (min)	Peak Load (lb)	Deflection @ P.L. (in)	Elastic Region Slope (lb/in)	E_{static} (psi)	MOR (psi)
1a	96	3.482000	1.509333	9.11	1496.0	1.2047	1390.9	1735106.01	5886.02
4a (1min wdf/s.mkd)	96	3.506333	1.520333	8.68	1588.2	1.1561	1487.0	1803491.58	6117.76
4b (1 min. wdf)	96	3.502333	1.540000	9.96	1729.2	1.3436	1364.5	1639388.77	6590.86
4f (1 maj. wdf)	96.125	3.499333	1.523667	10.10	1719.2	1.3244	1468.6	1787965.71	6634.35
8f	96.0625	3.491667	1.528333	10.27	2148.0	1.3899	1629.9	1991343.19	8300.10
9a	96.1875	3.479333	1.522000	11.59	2300.9	1.5497	1640.1	2033616.85	8991.32
9d	96.125	3.505000	1.527000	10.67	2182.8	1.4144	1724.4	2084665.98	8377.83
9e	96.125	3.502667	1.526667	10.92	2140.8	1.4444	1731.8	2098256.87	8229.37
10c	96.1875	3.488000	1.518333	9.86	2011.9	1.2911	1583.9	1954036.96	7841.86
12b	96.125	3.476667	1.503000	11.67	2471.7	1.5882	1722.4	2167641.44	9795.87
12d	96.125	3.476333	1.511667	11.17	2457.3	1.4952	1744.9	2183995.99	9684.83
13a	96.125	3.489333	1.533333	11.90	2632.1	1.6138	1824.0	2225678.60	10151.11
13c	96.125	3.466333	1.519000	11.79	2415.5	1.5978	1813.2	2278130.17	9528.86
13d	96.125	3.465667	1.526333	12.86	2708.3	1.7352	1669.5	2088710.44	10636.69
14a	96.0625	3.457000	1.533000	9.69	2341.2	1.3096	1757.8	2206128.15	9200.90
14b	96.0625	3.455333	1.531667	10.64	2481.6	1.4411	1983.8	2495544.65	9770.57
15b	96.25	3.478667	1.546667	12.71	3059.3	1.7373	1883.1	2299004.28	11768.80
15d	96.1875	3.466667	1.527000	11.36	2694.9	1.5121	1966.9	2457585.07	10573.33
15f	96.1875	3.461000	1.525000	12.75	3066.2	1.7066	1984.2	2494665.80	12085.37

DOL TESTING DATA

LVL 300°F	Average	Average	Average	Moment of	$E_{dynamic}$	app = 6366.63 (psi)	Stress Ratio	Time To Failure	
Number	Length (in)	Width (in)	Thickness (in)	Inertia (in^4)	(psi)	MOR = ult (psi)	(app/ult)	(h:m:s)	LN(t_f) (mins)
1c	96.125	3.513	1.516	5.478	1496543.24	5411.16	1.1766	immediate	0
2b	96.125	3.477	1.505	5.272	1656880.30	5792.33	1.0991	immediate	0
2c	96.125	3.447	1.512	5.161	1664607.71	6060.87	1.0504	immediate	0
4a	96.1875	3.461	1.512	5.226	1717798.72	6280.26	1.0138	immediate	0
3f	96.125	3.521	1.526	5.549	1737017.80	6472.19	0.9837	immediate	0
2f	96.125	3.471	1.515	5.277	1740332.93	6647.01	0.9578	immediate	0
3a	96.125	3.481	1.528	5.373	1763737.22	6810.63	0.9348	immediate	0
1d	96.0625	3.473	1.526	5.327	1569342.11	6966.85	0.9138	0:03:39	1.2947
4e	96.125	3.441	1.524	5.172	1870315.12	7118.38	0.8944	0:11:39	2.4553
5e	96.25	3.475	1.517	5.306	1885351.92	7267.29	0.8761	0:12:37	2.5350
5b	96.1875	3.482	1.521	5.351	1865217.19	7415.32	0.8586	0:17:12	2.8449
4c	96.125	3.364	1.525	4.835	1809685.08	7564.03	0.8417	0:33:41	3.5170
4d	96.125	3.454	1.514	5.202	1746639.12	7714.96	0.8252	1:40:19	4.6083
6b	96.125	3.462	1.515	5.238	2004069.97	7869.69	0.8090	27:33:17	7.4105
5d	96.1875	3.473	1.517	5.294	1848740.43	8029.99	0.7929	48:26:38	7.9748
6c	96.125	3.462	1.518	5.249	1968520.33	8197.97	0.7766	180:00:00	9.2873
10b	96.0625	3.484	1.524	5.372	2041540.43	8376.27	0.7601	261:00:00	9.6589
10a	96.125	3.437	1.510	5.108	2064747.44	8568.40	0.7430	609:00:00	10.5062
12f	96.0625	3.471	1.513	5.275	2159160.73	8779.31	0.7252	972:00:00	10.9737
10f	96.125	3.417	1.519	5.050	2147796.73	9016.45	0.7061	1420:00:00	11.3528
11c	96	3.475	1.507	5.269	2105246.74	9292.00	0.6852	survivor	
11e	96	3.480	1.517	5.328	2160392.32	9628.35	0.6612	survivor	
14c	96.0625	3.482	1.522	5.356	2260008.34	10074.73	0.6319	survivor	
15e	96.125	3.485	1.522	5.368	2310848.84	10784.43	0.5904	survivor	

DOL TESTING DATA

LVL 340°F-1	Average	Average	Average	Moment of	$E_{dynamic}$	app = 7201.57 (psi)	Stress Ratio	Time To Failure	
Number	Length (in)	Width (in)	Thickness (in)	Inertia (in^4)	(psi)	MOR = ult (psi)	(app/ult)	(h:m:s)	LN(t_f) (mins)
1a	96.0625	3.497	1.528	5.445	1630190.51	6079.03	1.1847	immediate	0
1f	96.0625	3.478	1.527	5.352	1663707.10	6525.92	1.1035	immediate	0
2b	96	3.490	1.526	5.408	1730392.73	6841.50	1.0526	immediate	0
3a	96.125	3.516	1.517	5.496	1756462.17	7099.76	1.0143	immediate	0
5c	96.1875	3.475	1.507	5.270	1886148.94	7326.00	0.9830	immediate	0
4d	96.125	3.490	1.517	5.375	1889607.05	7532.32	0.9561	immediate	0
3e	96.125	3.497	1.527	5.440	1798202.92	7725.63	0.9322	0:00:15	0
8f	96	3.468	1.512	5.255	2018462.34	7910.39	0.9104	0:01:40	0.5108
9c	96.125	3.475	1.527	5.340	2103647.16	8089.75	0.8902	0:05:12	1.6487
11f	96.1875	3.480	1.520	5.338	2196608.01	8266.17	0.8712	0:20:36	3.0253
8b	96.125	3.483	1.513	5.325	2057137.15	8441.71	0.8531	1:13:19	4.2948
11b	96.125	3.479	1.526	5.354	2184553.97	8618.20	0.8356	11:15:44	6.5158
9a	96.125	3.481	1.523	5.353	2145652.67	8797.47	0.8186	23:00:00	7.2298
7b	96.1875	3.498	1.528	5.450	2002085.07	8981.41	0.8018	32:15:22	7.5681
7a	96.1875	3.489	1.537	5.440	1942688.41	9172.13	0.7852	65:00:00	8.2687
7d	96.25	3.497	1.523	5.426	2133043.90	9372.16	0.7684	82:00:00	8.5011
8a	96.1875	3.490	1.507	5.338	2071275.55	9584.67	0.7514	115:00:00	8.8393
12a	96.0625	3.481	1.535	5.396	2233491.37	9813.88	0.7338	286:00:00	9.7503
14f	96.0625	3.493	1.525	5.415	2321710.02	10065.74	0.7155	459:00:00	10.2234
12b	96.125	3.492	1.529	5.424	2320258.60	10349.23	0.6959	484:00:00	10.2764
15c	96.1875	3.503	1.534	5.492	2584656.51	10679.02	0.6744	1720:00:00	11.5444
12f	96.0625	3.504	1.522	5.454	2309896.39	11082.14	0.6498	survivor (NOV 11)	
14c	96.0625	3.499	1.527	5.453	2374916.00	11618.04	0.6199	survivor	
14b	96.0625	3.494	1.525	5.420	2428465.28	12472.11	0.5774	survivor	

DOL TESTING DATA

LVL 340^{o}F-2	Average	Average	Average	Moment of	$E_{dynamic}$	app = 7201.57 (psi)	Stress Ratio	Time To Failure	
Number	Length (in)	Width (in)	Thickness (in)	Inertia (in^4)	(psi)	MOR = ult (psi)	(app/ult)	(h:m:s)	LN(t_f) (mins)
1c	96.0625	3.505	1.528	5.482	1660805.31	6079.03	1.1847	immediate	0
2e	96.125	3.506	1.540	5.531	1677043.95	6525.92	1.1035	immediate	0
2c	96	3.497	1.511	5.382	1695172.72	6841.50	1.0526	immediate	0
3b	96.125	3.509	1.526	5.494	1753443.54	7099.76	1.0143	immediate	0
5a	96.1875	3.480	1.522	5.346	1916548.06	7326.00	0.9830	immediate	0
5f	96.1875	3.484	1.522	5.363	1871395.08	7532.32	0.9561	0:00:18	0
3f	96.125	3.491	1.521	5.393	1825774.36	7725.63	0.9322	0:00:22	0
10d	96.1875	3.479	1.520	5.335	2184954.76	7910.39	0.9104	0:01:31	0.4165
8d	96.125	3.473	1.516	5.294	2075918.42	8089.75	0.8902	0:02:17	0.8256
9d	96.125	3.474	1.523	5.324	1992832.43	8266.17	0.8712	0:13:38	2.6125
5b	96.1875	3.476	1.524	5.334	1905841.25	8441.71	0.8531	1:10:33	4.2563
9f	96.125	3.460	1.509	5.207	2116421.86	8618.20	0.8356	3:36:44	5.3787
9b	96.125	3.474	1.526	5.330	2134303.79	8797.47	0.8186	7:02:25	6.0460
9e	96.125	3.457	1.526	5.251	2034683.98	8981.41	0.8018	11:11:02	6.5088
8e	96.0625	3.466	1.512	5.245	2045075.93	9172.13	0.7852	19:00:00	7.0388
12e	96.0625	3.504	1.529	5.480	2217195.88	9372.16	0.7684	30:02:29	7.4969
10c	96.1875	3.500	1.516	5.417	2104609.21	9584.67	0.7514	64:00:00	8.2532
12c	96.125	3.502	1.533	5.487	2287230.69	9813.88	0.7338	102:28:21	8.7239
13f	96.1875	3.498	1.523	5.432	2298094.60	10065.74	0.7155	113:00:00	8.8217
14d	96.0625	3.502	1.529	5.471	2461838.62	10349.23	0.6959	1085:00:00	11.0837
15b	96.1875	3.498	1.531	5.460	2594348.16	10679.02	0.6744	1771:00:00	11.5736
14e	96.0625	3.497	1.528	5.447	2314448.62	11082.14	0.6498	survivor (NOV 11)	
13b	96.1875	3.502	1.531	5.482	2327217.81	11618.04	0.6199	survivor	
13a	96.1875	3.496	1.523	5.420	2363226.12	12472.11	0.5774	survivor	

DOL TESTING DATA

LVL 380°F	Average	Average	Average	Moment of	$E_{dynamic}$	app = 7264.33 (psi)	Stress Ratio	Time To Failure	
Number	Length (in)	Width (in)	Thickness (in)	Inertia (in^4)	(psi)	MOR = ult (psi)	(app/ult)	(h:m:s)	LN(t_f) (mins)
1f	96	3.481	1.515	5.325	1753029.37	6209.89	1.1698	immediate	0
4d	96.0625	3.507	1.538	5.530	1916940.33	6703.03	1.0837	immediate	0
5a	96.125	3.484	1.538	5.419	1882996.39	7057.68	1.0293	0:00:30	0
10d	96.1875	3.483	1.515	5.334	2149072.15	7352.88	0.9880	0:00:47	0
9c	96.125	3.504	1.506	5.399	2189794.91	7615.96	0.9538	0:03:25	1.2287
9b	96.125	3.510	1.528	5.508	2070245.61	7860.23	0.9242	0:25:35	3.2419
11e	96.1875	3.468	1.508	5.244	2208222.10	8093.57	0.8975	2:46:57	5.1177
13b	96.125	3.467	1.526	5.301	2344519.91	8321.38	0.8730	7:56:48	6.1671
7a	96.1875	3.503	1.504	5.386	2084891.45	8547.90	0.8498	15:20:22	6.8248
10a	96.125	3.467	1.521	5.281	2221327.23	8776.84	0.8277	21:04:24	7.1424
11d	96.1875	3.471	1.513	5.273	2194348.66	9011.92	0.8061	37:00:00	7.7053
13f	96.1875	3.470	1.519	5.287	2338583.01	9257.23	0.7847	73:03:55	8.3857
13e	96.1875	3.459	1.534	5.291	2335165.75	9517.80	0.7632	413:00:00	10.1178
12a	96.125	3.489	1.516	5.363	2314471.54	9800.35	0.7412	1596:00:00	11.4696
12c	96.125	3.478	1.512	5.300	2309461.75	10114.67	0.7182	survivor (NOV 11)	
14f	96.0625	3.442	1.525	5.181	2481377.50	10476.57	0.6934	survivor	
15c	96.25	3.471	1.556	5.424	2598659.91	10914.77	0.6655	survivor	
15a	96.1875	3.448	1.541	5.264	2670881.77	11492.27	0.6321	survivor	
15e	96.25	3.481	1.517	5.332	2673768.94	12404.88	0.5856	survivor	