

THE INFLUENCE OF A HORIZONTAL DENSITY DISTRIBUTION
ON MOISTURE-RELATED MECHANICAL DEGRADATION
OF ORIENTED STRAND COMPOSITES

By

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Abstract

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Non-veneer wood composites are known to degrade in conditions of elevated moisture content. Panel structure, especially the horizontal density distribution (HDD) contributes to the degradation by promoting differential swelling in a panel. This differential swelling causes internal stresses to develop due to the superposition of strains of adjacent elements. Transverse tension stresses, which develop from this mechanism, may cause fracture in the panel. The end results include loss of strength and increased thickness swell. A complete understanding of this degrading mechanism requires fundamental knowledge of the transverse physical and mechanical properties of a composite including thickness swell and the constitutive relations in tension and compression. This study characterized these properties for an oriented strand composite and related them to density, resin content and moisture content. A simple superposition model was developed to estimate the amount of damage a composite panel would experience due to moisture-related stress. Predictive equations developed in this study were used to compare the effects of density, resin content and moisture content on localized properties and whole panel swelling performance. Increased resin content improved all material properties,

while increased moisture content was detrimental to all properties. Increased density benefited mechanical properties but had a negative impact on swelling. The superposition model showed similar results: increased panel density and reduced resin levels resulted in increased damage in a panel due to differential swelling. These results indicate that efforts to improve panel durability should begin with increased resin content and reduced density. An MDI resin level of approximately 12.5% was predicted to minimize localized swelling, while the superposition model predicted that resin levels of 9-10% would minimize damage due to differential swelling.

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CHAPTER ONE

INTRODUCTION

Particulate wood composites such as oriented strandboard (OSB) and particleboard are desirable for use in many applications, both structural and non-structural. In most applications, they will be subjected to fluctuating moisture contents. Experience has shown that severe moisture exposure can cause significant degradation of these panels. After exposure to elevated moisture conditions, wood composite panels typically exhibit reduced strength values (River, 1994; Suchsland, 1973, Sleet, 1984) and permanent increases in thickness (Wu and Piao, 1999; Suchsland, 1973; River, 1994; Halligan, 1970). Visual appearance of the panels may also be adversely affected (Biblis, 1990; Suchsland, 1962). In cases of extended or repeated exposure, extreme degradation may lead to loss of panel integrity. It is believed that density variations, which cause differential swelling within a composite panel, contribute significantly to panel degradation (Suchsland, 1973; Suchsland and Xu, 1989, 1991).

Density Distributions in Wood Composites

Particulate wood composites are manufactured by pressing a loose mat of adhesive-blended particles to a desired thickness. As a result of the forming and pressing operations, the final panel is characterized by a non-homogeneous distribution of mass throughout the panel. The three-dimensional density variation of the panel can be sub-divided into a horizontal density distribution (HDD) and a vertical density profile (VDP) (Suchsland, 1962). The HDD characterizes the variability of density throughout the plane of the panel, while the VDP describes density variations through the thickness of the panel. The HDD is primarily dependent

on particle geometry and the forming process, while the VDP is created through the interaction of many variables during pressing. Key variables influencing the development of the VDP include: moisture content, temperature, and pressure (Strickler, 1959; Suchsland, 1962; Wolcott et. al., 1990; Winistorfer and Wang, 1999).

An understanding of these density variations in wood composites is necessary, because many panel properties are related to density. Density in wood composites is often considered to be a key indicator of board properties (Strickler, 1959; Plath and Schnitzler, 1974; Steiner et. al., 1978). Some of the physical and mechanical properties which are influenced by density include: bending modulus of elasticity (MOE) (Rice and Carey, 1978; Xu and Suchsland, 1998), modulus of rupture (MOR) (Rice and Carey, 1978, Hse, 1975; Wong et. al., 1998; Kwon and Geimer, 1998), tension strength perpendicular to panel surfaces (Heebink et. al., 1972; Plath and Schnitzler, 1974; Steiner et. al., 1978; Wong et. al., 1998), shear strength (Shen and Carroll, 1969, 1970), thickness swell and water absorption (Rice and Carey, 1978; Winistorfer and Wang, 1999; Winistorfer and Xu, 1996, Xu and Winistorfer, 1995a,b), and linear expansion (Suzuki and Miyamoto, 1998; Kelly, 1977). While no values for Young's moduli in tension or compression perpendicular to the panel are reported in the literature, it is reasonable to expect that they will also be dependent on density.

Panel degradation influenced by HDD

Because thickness swell is dependent on density, and the HDD is not uniform, different areas of the panel will tend to swell differently. However, continuity of the panel requires adjacent elements of the panel to swell to the same thickness. The elements with higher swelling potential are consequently restrained by areas of lower swelling tendencies. This restraint causes

the development of internal stresses (Suchsland, 1973). Low density elements, which have less swelling potential than high density areas, are subjected to tensile stresses, while the high density areas are placed in compression. Tensile stresses in the low density areas can cause fractures, allowing the high density elements to dominate the thickness swelling in the panel (Suchsland, 1973; Suchsland and Xu, 1989, 1991). Repeated moisture cycles can cause these fractures to propagate through the panel via fatigue mechanisms (River, 1994; Johnson, 1982). The end result of these fractures is permanent strength loss and increased thickness swell (Suchsland and Xu, 1989).

Objective

While it is apparent that a non-uniform HDD in a panel has negative effects, there has been no attempt to predict the fraction of a given panel that could be expected to fail when subjected to a given moisture condition. A model capable of predicting failure in the panel could be a useful tool in studying the effects of different parameters on panel performance. Computer models could be used to simulate mat formation and pressing (Dai and Steiner, 1994a,b; Lang and Wolcott, 1996a,b), and failure in the panel due to moisture exposure could be modeled in lieu of the expensive trial and error methods commonly used to develop panels. Preliminary investigations for changes in particle geometry or forming could be done via simulation, rather than experimentally.

The purpose of this study was to develop a model to predict failure in an OSB panel due to the horizontal density distribution. To this end, empirical studies were performed to characterize the transverse properties that are relative to durability of a strand composite: thickness swell and constitutive relations in tension and compression. The effects of density,

resin content, and moisture content on the panel properties were also determined. These relationships were modeled via Monte Carlo simulation and used with a simple, superposition method, to estimate the failure in of a given panel at elevated moisture contents. The model was used to compare the effects of density, resin content, and moisture content on panel swelling performance. Chapter 2 reviews the wood composite literature relating to resin content, moisture content and density. Chapter 3 characterizes the transverse physical and mechanical properties of a strand composite. Chapter 4 describes a model to predict the amount of failure in a strand composite due to differential swelling. The final chapter summarizes the results.

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CHAPTER TWO

LITERATURE REVIEW

Particulate wood composites are made from wood elements which are combined with adhesive resin and consolidated to form a panel. The physical and mechanical properties of a wood composite are influenced many variables including the amount and type of adhesive resin, moisture content, and density distribution in the panel. The effects of these parameters on panel performance will be reviewed in this paper. Other important variables such as wood species and particle geometry will not be reviewed.

Resin Level and Type

In the composite wood panel industry, four types of resins are commonly used: urea-formaldehyde (UF), phenol-formaldehyde (PF), melamine formaldehyde (MF), and polymeric methyl diisocyanate (MDI). Due to their low cost and good performance, UF resins are the predominant choice for interior panels (Moslemi, 1974; Maloney, 1993). However, UF is not suitable for use in conditions of high moisture. Because MF resin is more resistant to moisture than UF, it is sometimes mixed with UF to improve a panel's resistance to light moisture exposure. While beneficial, the addition of MF is not sufficient to make a panel suitable for exterior exposure (Moslemi, 1974). Highly water resistant PF and MDI resins are preferred for panels exposed to elevated moisture conditions (Maloney, 1993; Zucaro and Reen, 1995).

In addition to the type of adhesive, board properties are influenced by resin content. For all resin types, mechanical properties such as modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB) increase with higher resin levels (Kelly, 1977; Wilson, 1980;

Rice, 1982; Berchem et. al., 1985; Sun et. al., 1994a), presumably due to better bond development.

Physical properties such as thickness swell (TS), linear expansion (LE) and water absorption (WA) are also affected by resin content. TS and WA improve with increased resin content (Wilson, 1982; Generalla et. al., 1989; Sun et. al., 1994b), but the effect of resin on LE is not obvious. Some researchers report little or no difference in LE at different resin levels (Wu, 1999; Generalla et. al, 1989; Suzuki and Miyamoto, 1998; Berchem et. al., 1985, Sun et. al., 1994), while others report increases in LE at low resin contents (Wilson, 1982; Kelly, 1977).

Improvements in thickness swell and water absorption at increased resin levels have been attributed to reduced hygroscopicity (Kajita and Imamura, 1991), cell wall bulking (Kajita and Imamura, 1991; Schneider et. al., 1996), and possible intra-cell bonding (Krzysik and Young, 1986). Penetration of a water resistant adhesive into and through the cell walls would promote these mechanisms. Marcinko et. al (1995) reported high penetration (1.0-1.5 millimeters) and a reinforcing effect at the resin-wood inter-phase region for MDI in aspen (*Populus tremuloides*). They contrasted this with a shallow penetration (0.1-0.3 millimeters) and a smaller inter-phase region for a PF resin. Other researchers have successfully used low molecular weight phenolic resins in conjunction with regular PF adhesives to reduce swelling properties of wood composites (Kajita and Imamura, 1991). PF and MDI resins are both effective at improving physical and mechanical properties at high resin levels (Sun et. al. 1994a,b).

Moisture Content

The behavior of wood is strongly influenced by moisture content. In general, increases in moisture content below fiber saturation tend to reduce strength and stiffness of wood (Wood

Handbook, 1999; Wolcott et. al, 1990). For some species of wood the mechanical properties may reach a peak at some moisture content and then decrease at lower moisture contents (Wood Handbook, 1999). In either case, the dependence of wood properties on moisture content is well established.

The mechanical properties of a wood composite are influenced by moisture content, as well. Halligan and Schniewind (1974) showed significant decreases in MOR, MOE, and IB with increasing moisture content, above approximately five percent, in UF-bonded particleboard. Watkinson and van Gosliga (1990) obtained similar results with UF-bonded particleboard, medium density fiberboard (MDF), and tempered hardboard. A study with PF-bonded OSB's manufactured from both southern pine (*Pinus spp.*) and aspen (*Populus tremuloides*) showed linear decreases in MOR and MOE with increases in moisture content (Wu and Suchsland, 1997).

The amount of LE and TS are, obviously, related to moisture content changes. Watkinson and van Gosliga (1990) show LE and TS of particleboard, MDF, and hardboard to be directly proportional to increases in moisture content. Other researchers report non-linear relationships between swelling properties and moisture content increases (Wu, 1999; Wu and Piao, 1999; Halligan, 1970). Because TS consists of a recoverable component and a non-recoverable component (Kelly, 1977; Wu and Piao, 1999), some loss of mechanical properties due to moisture absorption is irreversible, even on subsequent re-drying. Consequently, strength reductions observed in panels at high moisture are likely to result from a combination of increased moisture content and structural changes in the panel.

Horizontal Density Distribution (HDD)

In addition to moisture and resin content, density variations in the panel contribute significantly to panel performance. Density variations in the plane of the panel are referred to as the horizontal density distribution (HDD) while density variations through the thickness of a panel are described by the vertical density profile (VDP). Each will influence panel performance, differently.

The HDD is dependent on particle geometry and forming. As particles are formed into a mat, some areas in the panel will have more particles overlapping than other areas. As the mat is pressed to a constant thickness, these areas are densified to a greater degree than the areas with fewer overlapping particles. Suchsland (1962, 1973) described the horizontal density distribution as undesirable because differential thickness swelling between areas of varying density would cause damaging stresses in a panel. . He also predicted that larger particle sizes would cause more variability in the HDD. Telegraphing of particles through thin laminates applied to the surface of a wood composite can result from the HDD (Biblis, 1990; Suchsland, 1962).

Suchsland and Xu (1989, 1991) simulated the HDD in flakeboard by crossing narrow strips of veneer in perpendicular layers to form a mat. Variations in the HDD could be controlled by the number of strips in each layer. Their results showed that large HDD variations would result in the development of damaging stresses in a panel undergoing hygroscopic swelling.

Steiner and Xu (1995) showed that the apparent HDD in wood composites is dependent on the size of the specimens used to measure the density variations. Smaller specimen sizes will have more variability in density than larger specimen sizes. They also observed that particle size

affected the variability of the HDD, but this effect was also dependent on specimen size. They indicated that board uniformity would increase with an increase in the number of layers. This indicates that thin elements will increase uniformity in the HDD. In a related study, Xu and Steiner (1995) observed that the HDD, when measured by removing finite specimens, followed a normal distribution. They cited the central limit theorem for a theoretical basis.

Other researchers have modeled the formation of the HDD using Monte-Carlo simulation. Dai and Steiner (1994a,b) noted that the formation of random flake mats was governed by a Poisson distribution of flake centers and flake coverage. Point density in the panel also will, therefore, follow the Poisson distribution. Mat formation models have been used to predict the compression behavior of particulate mats with non-uniform density (Lang and Wolcott, 1996a,b; Dai and Steiner, 1993).

Vertical Density Profile (VDP)

While the HDD is established during the forming process, the VDP is created through the interaction of variables during pressing. Moisture content, temperature, and pressure all contribute to the formation of the VDP (Strickler, 1959; Suchsland, 1962; Wolcott et. al., 1990; Winistorfer and Wang, 1999). Other factors such as particle geometry and alignment may also play a role in determining the VDP.

Effect of VDP on Board Properties

Density in wood composites is considered a key indicator of board properties (Strickler, 1959; Plath and Schnitzler, 1974; Steiner, Jozsa, et. al.; 1978). Density variations through the thickness of a panel, therefore, would be expected to impact board properties. Properties

influenced by density include: modulus of elasticity, modulus of rupture, tension strength perpendicular to the surface, shear strength, thickness swell and water absorption. The impact of VDP on these properties will be discussed.

Modulus of Elasticity (MOE)

Rice and Carey (1978) studied the effects of density on flake boards made from four, diffuse-porous, hardwood species. They observed an increase in MOE with an increase in density for all species. More recently, Xu and Suchsland (1998) developed a model to predict the MOE of composites with a uniform density profile. They predicted an increase in MOE with an increase in compaction ratio. They report good agreement between their simulation and earlier, experimental studies (Hse, 1975; Stewart and Lehmann, 1973; Suchsland and Woodson, 1974; Vital et. al., 1974).

A second model was developed to predict the MOE of composites with a non-uniform VDP using the first model and laminate theory to model the VDP (Xu, 1999). It was shown that the core stiffness of a composite board has little influence on MOE, and the layers near the surface control the MOE. Interestingly, Xu found that the MOE increased as the peak density shifted slightly away from the surface to about 1.4 millimeters from the surface causing the highest average density in the surface zone (<2 mm from surface).

Modulus of Rupture (MOR)

Because MOE and MOR of wood have been correlated, it is logical to expect that VDP might have similar effects on MOR. Research has shown that an increase in MOR can be expected with an increase in density or compaction ratio (Rice and Carey, 1978; Hse, 1975,

Wong et. al., 1998; Kwon and Geimer, 1998). In his literature review, Kelly (1977) indicated that researchers unanimously agreed that MOR increases with increase in density. Because flexure of a linearly-elastic beam causes the highest stresses to be developed at the surfaces, a VDP with high densities at the surfaces should have an increased MOR. Heebink et. al. (1972) showed a strong correlation between face layer density and MOR.

Internal Bond (IB)

Tensile strength of a wood composite, perpendicular to the plane of the panel is commonly referred to as internal bond (IB). Several researchers (Heebink et. al., 1972; Plath and Schnitzler, 1974, Steiner, Jozsa, et. al., 1978; Wong et. al., 1998) showed a positive correlation between density and IB. In his literature review, Kelly (1977) also indicated that most researchers observed an increase in IB values with increasing density. Plath and Schnitzler (1974) compared the IB measured on a layer basis with its density profile. The IB profile trends closely followed the VDP.

Because density and IB are correlated, a specimen tested in tension perpendicular to the plane of the panel would be expected to fail in the plane of lowest density. For a board with high density surfaces and low density core, failure would be expected in the core. A uniform density profile (with all other variables held constant) should provide the maximum benefit to IB, because all layers of the board would have similar strength.

Layer Shear Strength

An alternative test to IB was proposed by Shen and Carroll (1969). They suggested that a torsional-shear test could be used to determine the internal strength of particleboard. They

showed a strong correlation between IB and their torsion method. In a second study, this method was applied on a layer basis to determine a strength profile (Shen and Carroll, 1970). The trend of this strength profile followed the density profile in the particleboards they tested. They also showed a strong correlation between density and shear strength.

Thickness Swell (TS) and Water Absorption (WA)

Rice and Carey (1978) showed that increased panel density resulted in an increase in thickness swell of flake boards from four different species. Recent work has monitored TS and WA through the thickness of wood composite panels (Winistorfer and Wang, 1999; Winistorfer and Xu, 1996; Xu and Winistorfer, 1995a,b; Song and Ellis, 1997). In each study, TS and WA trends have followed the VDP. Layer TS correlations with layer density were generally better for small particle composites (MDF and particleboard) than for OSB (Xu and Winistorfer, 1995b).

Linear expansion (LE)

Suzuki and Miyamoto (1998) reported that flake board density was linearly related to the LE per unit change in moisture content. Kelly (1977) observed that a board with a non-symmetrical density gradient would be expected to undergo un-balanced dimensional changes with changes in relative humidity. Models have been developed to predict the warp caused in panels due to unbalanced dimensional changes (Xu and Suchsland, 1996; Suchsland and McNatt, 1986; Lang et. al., 1995). Because density affects LE, the VDP should be symmetrical to minimize panel warping.

Measurement of VDP

As shown by the previously mentioned studies, VDP affects virtually all board properties and must be accurately determined in the lab and mill. Both destructive and non-destructive methods have been used to measure the density profile. Non-destructive methods have an obvious advantage over destructive methods: further testing can be performed on specimens after determining the VDP.

Destructive methods

Gravimetric methods

Gravimetric methods are the oldest means for determining vertical density profiles. They typically involve removing thin layers of a specimen and monitoring the subsequent volume and mass changes of the specimen (May et. al., 1976). Surfaces may be removed by sanding, planing or slicing (May et. al., 1976; Stevens, 1978; Laufenberg, 1986). This system is time consuming and destroys the specimen in the process (May et. al., 1976; Laufenberg, 1986; Nearn and Bassett, 1967).

Drill resistance techniques

May et. al. (1976) described a drill resistance technique that utilized correlations between measured torque and the density at a given layer as a drill passed through it. They indicated several causes for error, including tool wear, oscillations of the tool, and the nature of the wood specimen. Winistorfer et. al. (1995) studied a technique that used correlations between drilling power consumption and wood density. This technique is used to detect tree rings in standing

trees. It was observed that the small sampling zone used in density profile measurements, was very sensitive to horizontal density differences between different sampling zones.

Mechanical test methods

Shen and Carroll (1970) proposed that layer torsional-shear strength could be used to indicate the vertical density profile. They indicated that this method was much faster than the gravimetric method for determining the density profile and could be used to replace the latter method in quality control settings.

Because MOR and MOE are related to VDP (Kelly, 1977), it is reasonable to assume they could also be used as an indirect measure of the VDP. These methods will provide, however, a crude estimate of VDP, at best.

Non-destructive methods

Destructive methods have the major disadvantage of destroying the specimen during measurement of the VDP. Any correlations between VDP and board properties must, therefore, be made indirectly (May et. al., 1976). Methods that can measure the VDP without destroying the specimen are desirable from both research and production standpoints. Two basic non-destructive methods are reported in the literature: visual inspection and energy attenuation. Visual inspection is only mentioned in passing because of its obvious limitations (Nearn and Basset, 1968).

Energy attenuation methods

Two major types of energy attenuation devices are discussed in the literature: gamma source devices and x-ray devices. Both measure the attenuation of energy that is passed through a specimen. Density is then related to the amount of radiation absorbed by the material by experimentally determined parameters (Winistorfer et. al., 1986; Laufenberg, 1986). Laufenberg discusses the basic theory of radiation densitometry in a little more depth.

Both laboratory and in-line machines are available commercially (Shackel, 2000). Laboratory devices typically measure the VDP of small specimens (approximately 2 x 2 inches). Modern systems determine the density profile quickly and accurately. Several specimens can be scanned in minutes and the vertical density profile can be observed on a computer screen as it is measured. A significant advantage to this type of system is that the specimen is not destroyed. Further testing can be conducted on the specimen and direct comparisons can be made between a property of interest and the VDP (Winistorfer et. al., 1993).

In-line devices are used to monitor VDP immediately after pressing and are shown to produce results comparable to laboratory radiation systems (Dueholm, 1996; Shackel, 2000). With the in-line system there is no need to remove specimens from a board and information can be used, immediately, to adjust process parameters (Dueholm, 1996).

The literature also describes one research device where density can be monitored at three different layers in a panel during pressing (Winistorfer et. al., 1993; Winistorfer et. al., 1999). This apparatus has provided valuable insight into formation of the VDP during pressing (Winistorfer et. al. 1999, Wang and Winistorfer, 1999c).

Modeling the VDP

Winistorfer et. al. (1996) used a non-parametric regression technique to fit curves to VDP data. With a very good match between experimental data and the fitted, non-parametric curves, a statistical comparison was made to determine if there were significant differences between curves with a similar appearance. This technique could be used to compare the significance of parameter changes on the VDP.

Manipulation of VDP

Knowledge of the effects of VDP on board properties and reliable means to measure the VDP should enable wood composite manufacturers and researchers to optimize board performance through manipulation of the VDP. Parameters affecting the formation of VDP include local moisture content, temperature, and pressure in the mat during pressing (Wolcott et. al., 1990). These parameters can be manipulated through changes in pressing schedule, method of heating, particle geometry, and particle alignment.

Wood Behavior During Pressing

Wood behavior during pressing is controlled by the viscoelastic behavior of its amorphous polymers, namely the hemicelluloses and lignin (Wolcott et. al., 1990). Depending on temperature, moisture, and time, amorphous polymers can exhibit a wide range of properties. At low temperatures, low moisture, and short times they can behave as linear elastic solids. Polymers exhibiting this type of behavior are in what is termed as the glassy state (Wolcott et. al., 1990). At high temperature, high moisture, or long times, polymers are said to be in a

rubbery state. The rubbery state is characterized by large strains at failure and a modulus of approximately three orders of magnitude lower than in the glassy state (Wolcott et. al., 1990).

Temperature and moisture vary throughout the panel during pressing and change during the press cycle (Suchsland, 1962; Kamke and Casey, 1988a,b; Kamke and Wolcott, 1991). This results in the wood particles having a variable compressive modulus throughout the press cycle. Wood elements with low moduli will compress more than those with high moduli at a given pressure. This differential compression through the thickness of the panel results in the VDP (Kamke and Casey, 1988a).

While it was formerly believed that the VDP was formed during press closure (Kelly, 1977; Suo and Bowyer, 1994), recent work suggests that the VDP continues to change throughout the press cycle (Wolcott et. al, 1990; Winistorfer et. al, 1999; Wang and Winistorfer, 1999c). Understanding these changes is the first step in controlling them.

Heat and Moisture Migration Models

Several researchers have attempted to model heat and moisture conditions in a wood composite mat to better understand development of the VDP (Harless et. al, 1987; Suo and Bowyer, 1994; Kamke and Wolcott, 1991). Harless et. al (1987) and Suo and Bowyer (1994) assumed thermodynamic equilibrium at any point in the mat. They used their models to develop computer simulations to predict the VDP in a board. Comparing their simulations with real data, there were significant differences between the observed profiles and the predicted VDP.

The model presented by Kamke and Wolcott (1991) did not assume local thermodynamic equilibrium. Their model predicted that individual flakes in the mat would not be at EMC, but that a significant moisture gradient would be expected in individual flakes. Inputs to the model

include measured temperature and gas pressure from the mat. Kamke and Casey (1988a,b) described a method of obtaining this data. No attempt was made to apply this model to predict the formation of VDP.

Process Parameters Affecting VDP

Well before the development of the models discussed above, the significance of the VDP was understood and studies were conducted to determine the effect of various process parameters on the formation of the VDP (Kelly, 1977; Strickler, 1959; Suchsland and Woodson, 1974). Current research continues to further our understanding of the effects of process variables on VDP formation. Key parameters that have been studied include: furnish moisture content, particle geometry, board density, platen temperature, rate of press closure, and alternate heating methods.

Furnish Moisture Content

Because the moisture content of a wood element significantly affects its compressibility, it is obvious that manipulating furnish moisture content should change the VDP. Moisture content of the furnish may be constant or varied by layer in the mat. An increase in moisture content throughout the mat will cause a more pronounced difference between the density of the core and the density near the surface of a board (Strickler, 1959; Andrews and Winistorfer, 1999).

Strickler (1959) showed that high moisture content in the surface layers of a particleboard, relative the core moisture content, would cause a steeper density gradient from the surface to the core. Wong et. al. (1998) also showed higher peak densities for panels pressed

with high moisture surfaces compared to panels with uniform furnish moisture content.

Unfortunately, neither of these studies investigated the effect of high moisture in the core relative to the surface. Heebink et. al. (1972) showed that the density profile could be reversed with high core moisture relative to surface moisture.

Particle Geometry

VDP formation can be affected by particle geometry and alignment through two means. Packing efficiency may be altered: thereby influencing mat permeability. There is little reference in the literature to studies on how VDP may be affected. Plath and Schnitzler (1974) showed differences in the VDP of air-felted particleboard and three-layer particleboard. Based on the work of Geimer et. al. (1975) and Denisov et. al. (1975), Smith (1982) stated that particle geometry would influence the VDP by changing the rate of moisture migration.

Garcia et. al. (1999) studied the effect of flake alignment on heat and mass flow in OSB mats during pressing. They concluded flake alignment positively influenced longitudinal permeability and negatively influenced transverse thermal convection. They indicated that, as a result, poorly aligned mats should result in flatter density profiles.

Board Density

Strickler (1959) speculated that higher overall density in a board would cause higher vertical density variation. The opposite effect was observed by Suzuki and Miyamoto (1998). The latter study showed smaller vertical density variation in higher-density boards. They also noted that the peak density in boards tends to shift inward as the overall board density increases.

Platen Temperature

Heebink et. al. (1972) indicated that an increase in platen temperatures would produce a more uniform density profile. Suchsland and Woodson (1974) showed a more pronounced density gradient with higher platen temperatures. The reason for the difference in their findings is unclear.

Press Closing Rate

Many researchers have investigated the effect of press closing rate or pressure on VDP. Strickler (1959) showed that the peak density would decrease and move inward with longer press closing times. This results in a more uniform density profile. Smith (1982) and Heebink et. al. (1972) also indicated that a short press closing time would result in higher densification of the surfaces of a board. Suchsland and Woodson (1974) showed that very short press times (high pressures) can actually decrease the surface density of a board compared to a moderate press closing time. They also showed that long press closing times (low pressures) would tend to flatten out the VDP. More recent work (Wang et. al, 1999, 2000) showed that step closing of the press could be used to effectively manipulate the VDP to produce more uniform core densities and less density variation through a section.

Alternate Heating Methods

VDP formation is the result of non-uniform densification of the mat during pressing. The primary causes of this phenomenon relate to moisture and temperature gradients through the thickness of the mat, which plasticize the wood to different degrees. If conditions through the thickness of the mat were uniform during the entire press cycle, no VDP would be formed

(Suchsland, 1962). Steam injection pressing and high frequency heating can be effectively used to minimize changes in density through the thickness of the board (Jieying et. al., 1997; Kwon and Geimer, 1998; Geimer and Kwon, 1999a,b; Carll, 1979). A combination of high frequency heat and low platen temperatures can even result in a panel with low density surfaces relative to the core (Carll, 1979).

Conclusion

Composite panel properties are strongly influenced by resin, moisture content, and density. Each of these parameters affects board properties in different ways. Increased resin has been shown to improve virtually all panel properties, while elevated moisture content has a detrimental effect on all properties reported. Density effects in a composite are more complex and can be positive or negative, depending on the property.

Wood composite structure can be described by a three-dimensional density distribution. This density distribution can be sub-divided into two parts: horizontal density distribution (HDD) and vertical density profile (VDP). The HDD is dependent on particle geometry and forming while the VDP is a function of the interaction of time, temperature, moisture, and pressure differences through the thickness of the mat. The optimum shape of the VDP is dependent on the properties of interest in the board.

A non-uniform HDD is always present in wood composites and its effects on the board are negative. Differential thickness swelling between adjacent areas in the panel, due to the HDD, causes degrading stresses in the panel. These stresses can cause damage to the panel, resulting in strength loss and increased thickness swell.

The VDP of a wood composite, affects most significant physical and mechanical properties of the board. Modulus of elasticity (MOE) and modulus of rupture (MOR) are benefited by high density surfaces, while internal bond (IB) and shear strength are improved by higher core density. Thickness swell and water absorption tend to increase with increases in density, so they will be affected by the VDP.

VDP can be measured by a variety of methods. Older, gravimetric methods are being replaced by faster and more accurate radiographic methods. Torsional resistance techniques have also been used to determine VDP. Mechanical testing and visual inspection can be used for crude estimations of the VDP.

The compression behavior of wood elements during pressing is a function of the local temperature, moisture content, and pressure. Theories of viscoelastic polymers can be used to describe their behavior. By manipulating these variables with various techniques, the VDP can be altered to optimize for a given property. Methods for manipulating the VDP include changes in the following parameters: furnish moisture content, particle geometry or alignment, board density, platen temperature, press closing time, and non-conventional heating methods such as steam injection and high frequency heating.

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CHAPTER THREE
TRANSVERSE PHYSICAL AND MECHANICAL PROPERTIES
OF AN ORIENTED STRAND COMPOSITE

Abstract

Compressive damage in a particulate wood composite results in thickness swell values much greater than the swelling values of uncompressed wood of the same species. Due to increased damage, high density specimens swell more than low density specimens. Differential swelling in a panel, due to the horizontal density distribution, results in potentially damaging internal stresses. The stress imposed on an element is dependent on its swelling relative to adjacent elements and the local constitutive relations. To fully understand this degrading mechanism, an understanding of thickness swell and transverse constitutive relations is necessary. This study characterized these properties for a composite strand panel and related them to density, resin content, and moisture content. Swelling strain was shown to increase with density and moisture content changes and decrease with increasing resin content. Empirical predictive equations indicate that thickness swell may be minimized at an MDI resin level of approximately 12.5%. A two parameter, quadratic polynomial effectively described the transverse constitutive relations in tension. Additionally, the point of zero slope of the fitted polynomial corresponded to specimen failure, providing a useful failure criterion for modeling. Relatively small curvature in the compression constitutive curves suggested that a linear approximation would be appropriate for the stress levels expected in a panel due to differential swelling. In general mechanical properties decreased with increasing moisture content and increased with increasing density and resin content. Multiple linear regression was used to determine predictive equations for the mechanical properties.

Introduction

Particulate wood composites are manufactured by forming discontinuous wood elements into a mat, which is consolidated under heat and pressure to create a panel of a desired thickness. The formed mat is necessarily heterogeneous due to particle geometry and the random strand-deposition process, which governs mat formation. (Dai and Steiner, 1994a,b; Steiner and Xu, 1995; Suchsland and Xu, 1989). To provide adequate, inter-particle contact for the development of adhesive bonds, high pressures are required to compress regions of the mat with many overlapping elements and connect regions with few overlapping elements (Lang and Wolcott, 1996). These high pressures cause wood cell walls to buckle, develop plastic hinges, or fracture depending on the viscoelastic state of the polymers during compression (Wolcott et. al., 1990; Geimer et. al., 1985). When the polymers are above their glass transition temperature (ie. at high temperature or high moisture content), cell wall failure is likely to be dominated by elastic buckling, which will contribute to thickness swelling in a panel (Wolcott et. al., 1990).

Non-recoverable Thickness Swell

When water is absorbed by the product, cell walls that have buckled elastically will recover from their deformed state (Wolcott and Hua, 1997), resulting in greater thickness swell than would be expected from solid wood of the same species (Wu and Piao, 1999; Adcock and Irle, 1997; Kelly, 1977). The viscoelastic recovery of the collapsed cell walls has been described springback or non-recoverable thickness swell (Kelly, 1977; Wu and Piao, 1999).

The total thickness swell in particulate composites can exceed 40%, with non-recoverable thickness swell accounting for as much as three quarters of the total (Wu and Piao, 1999; Adcock

and Irle, 1997; Gatchell et. al., 1966; Rice and Carey, 1978; Alexopoulos, 1992). The cells that have been densified to a greater degree have greater swelling potential than those that have only been lightly compressed (Adcock and Irle, 1997). Consequently, researchers commonly observe positive correlation between density and thickness swell (Rice and Carey, 1978; Winistorfer and Wang, 1999; Xu and Winistorfer, 1995a,b; Suematsu and Okuma, 1989).

Strength Loss Due to Thickness Swell

Thickness swell is considered a key indicator of a panel's potential durability. Sleet (1984) reviewed 13 studies on durability and showed that thickness swell was included in 11 of the 13 studies reviewed, indicating that researchers agree that thickness swell is a significant degrading factor or indicator of durability. Thickness swell has also been associated with strength loss in wood composites (Suchsland, 1973; Alexopoulos, 1992; Wu and Piao, 1999; River, 1994). It is likely that this loss of strength originates from two sources: (1) a reduction in density due to non-recoverable thickness swell and (2) internal panel stresses caused by differential swelling of adjacent elements.

Because increased density is beneficial to most mechanical properties of a wood composite, it is logical to expect a reduction in panel performance to accompany permanent thickness swell. Physical and mechanical properties which are influenced by density include: bending modulus of elasticity (MOE) (Rice and Carey, 1978; Xu and Suchsland, 1998), modulus of rupture (MOR) (Rice and Carey, 1978, Hse, 1975; Wong et. al., 1998; Kwon and Geimer, 1998), internal bond strength (IB) (Heebink et. al., 1972; Plath and Schnitzler, 1974; Steiner et. al., 1978; Wong et. al., 1998), shear strength (Shen and Carroll, 1969, 1970), thickness swell and water absorption (Rice and Carey, 1978; Winistorfer and Wang, 1999; Winistorfer and Xu,

1996, Xu and Winistorfer, 1995a,b), and linear expansion (Suzuki and Miyamoto, 1998; Kelly, 1977). Thickness swell and its corresponding reduction in density would be greater for higher density regions, so reductions in properties which benefit from high density surfaces, such as MOR and MOE, would be amplified due to changes in the vertical density profile (VDP) (Xu and Winistorfer, 1995a,b; River, 1994).

While researchers have related decreases in strength to loss of density, the degrading effects of internal panel stresses have not been isolated (Wu and Piao, 1999; River, 1994; Steiner et. al., 1978). The interaction of density loss and internal stresses may be responsible for the reported strength reductions.

Internal swelling stresses arise from the heterogeneous density distribution in the plane of a composite panel, commonly referred to as the horizontal density distribution (HDD) (Suchsland, 1962, Steiner and Xu, 1995). The HDD in composite panels is considered detrimental to board performance, primarily because highly compressed areas of the panel have greater thickness swell potential than lower density areas (Suchsland and Xu, 1989). Differential thickness swell, between adjacent areas in the panel, causes potentially damaging normal stresses, as areas of low density provide restraint against the swelling of high-density regions (Suchsland, 1973; Suchsland and Xu, 1989, 1991). The stress developed in any given region of the panel will be dependent on the localized constitutive relations and the strain imposed on the area by adjacent elements. Fracture in the panel will be governed by localized tensile stress and strength. While Halligan (1970) indicated that “resistance to thickness swell is the most important property for good durability,” it is clear that a panel’s transverse mechanical properties, in addition to its thickness swell characteristics, are important factors in determining the durability of a composite panel.

Mechanical Properties

A better understanding of the transverse mechanical properties in a composite panel would be useful to further our understanding of the stress degradation that has been hypothesized. The localized constitutive relations in both tension and compression perpendicular to the panel surfaces are of particular interest.

Because most panel properties, including transverse tensile strength, have been correlated with density (Heebink et. al., 1972; Plath and Schnitzler, 1974; Steiner, et. al., 1978; Wong et. al., 1998), it is reasonable to expect that the constitutive behavior in tension and compression will be related to density, as well. Studies on the compression behavior of wood have shown constitutive relations that are highly dependent on the degree of imposed strain (Wolcott et. al. 1989; Ando and Onda, 1999; Dai and Steiner, 1993). Density in wood composites can be considered analogous to this imposed strain. No constitutive models for wood composites in tension perpendicular to the surface are evident in the literature. Tension tests perpendicular to the panel surfaces are commonly conducted in panel studies through internal bond (IB) tests, but only strength values are typically reported.

Thickness Swelling Strain

Unrestrained thickness swell in small wood specimens would be expected to change linearly with changes in moisture content based on the volume of water adsorbed (Suchsland, 1973). For solid wood, dimensional changes are commonly assumed to be linear with changes in moisture content (Hoadley, 1980; Wood Handbook, 1999; Dry Kiln Operators Manual, 1991). A linear relationship between moisture content and thickness swell in particleboard has also been

observed (Watkinson and Gosliga, 1990). Suchsland (1973) hypothesized that tensile stresses in the low density regions of a panel could cause fracture, resulting in the high density regions dominating the overall thickness swell. Accordingly, he speculated that this would be manifested in the actual swelling exceeding the swelling predicted by the linear model at high moisture contents. This may partially explain the non-linear swelling behavior observed by other researchers (Wu and Piao, 1999; Suchsland, 1973; Halligan, 1970). If horizontal density variations within a specimen are small, a linear swelling model of the following form may be appropriate:

$$\mathbf{e}_{TS} = \mathbf{b} \Delta M \quad \text{Equation 3.1}$$

Where: \mathbf{e}_{TS} = moisture induced swelling strain for the panel thickness
 β = swelling coefficient
 ΔM = change in moisture content (below fiber saturation)

Thickness swell values reported in the literature generally represent total thickness swell from some initial moisture content to fiber saturation. A swelling coefficient, β , is not typically reported. Because most thickness swell values are based on liquid water absorption, the fiber saturation point is not known, and β cannot be calculated from the given information. Those values of β reported for particleboard range from 0.75 to 1.22 (Watkinson and Gosliga, 1990; McNatt, 1974).

Objectives

To understand the damage of wood composites due to differential swelling stresses within the panel, the transverse physical and mechanical properties of the panel must be

understood. These properties include the localized swelling behavior and constitutive relations for loading in tension and compression. Knowledge of the relationships between these properties and material design parameters will allow systematic improvement of panel resistance to moisture induced degradation, through changes in process parameters. To this end, this study will characterize the:

1. Swelling behavior and constitutive properties of strand composites.
2. Dependence of transverse swelling and mechanical properties on density, resin content, and moisture content.

This knowledge will further the understanding of stress degradation in composite panels from exposure to elevated moisture contents.

Materials and Methods

Laboratory manufactured OSB panel were produced by blending commercial aspen strands with polymeric methyl diisocyanate (MDI) resin (Bayer Mondur 541) and wax (Borden Cascowax EW-58S). MDI resin was applied at a level of 2%, 4%, or 6% resin solids, while the wax was applied at a constant level of 1% solids. All application rates were based on the dry weight of the wood. Mats measuring 25.5 x 50 inches were formed with the strands mechanically aligned in one direction and pressed to a thickness of approximately 0.75 inch. Densities of 37 and 54 lb/ft³ were targeted to produce a broad range of specimen densities. After pressing, the panels were trimmed to 24 x 42 inches. Four panels from each combination of resin level and target density were manufactured, totaling 24 panels.

A combination of heated platens and radio frequency (RF) energy were used to heat the strand mats during consolidation. Press schedules were developed to minimize the confounding effects of a vertical density profile (VDP) in the panels. All panels were pressed with platen

temperatures of 230 °F using 1.75 amp/ft² of RF energy for a prescribed amount of time. Total press time for each panel was 10 minutes. Pressure and RF exposure time were used to manipulate the VDP. Each panel was subjected to a constant pressure for the first three minutes of the press cycle. After three minutes, the pressure was increased to close the press to the target panel thickness. The details of the press schedules are shown in **Table 3.1**.

Table 3.1. *Press schedule details for laboratory panels.*

Target Density (lb/ft³)	Initial Pressure (psi)	Closing Pressure (psi)	RF Application Time (seconds)	Total Press Time (seconds)
37	360	480	210	600
54	960	1200	285	600

VDP's of the finished panels were determined by x-ray attenuation (**Figure 3.1**). Each profile is the average of eight specimens from a group of similar panels. With the center 50 percent of the panel thickness designated as core and the remainder designated as surface, the ratio of average surface density divided by average core density was calculated for each profile. Ratios calculated for the profiles ranged from 0.995 to 1.015 with a mean of 1.00 and a coefficient of variation (COV) of 0.008.

Specimen Sampling

The HDD was determined, non-destructively, for each panel by x-ray attenuation. For this process, the panel is moved between a fixed x-ray source (60 KeV) and a detector. Because x-rays attenuate more in high density materials (Bray and Stanley, 1997), the difference between energy emitted and the energy received by the detector provides a useful, indirect measurement of density. The x-ray scanning equipment that was used has a resolution of four pixels per inch and can calculate discrete horizontal density variations based on a grid size as small as 0.5 x 0.5

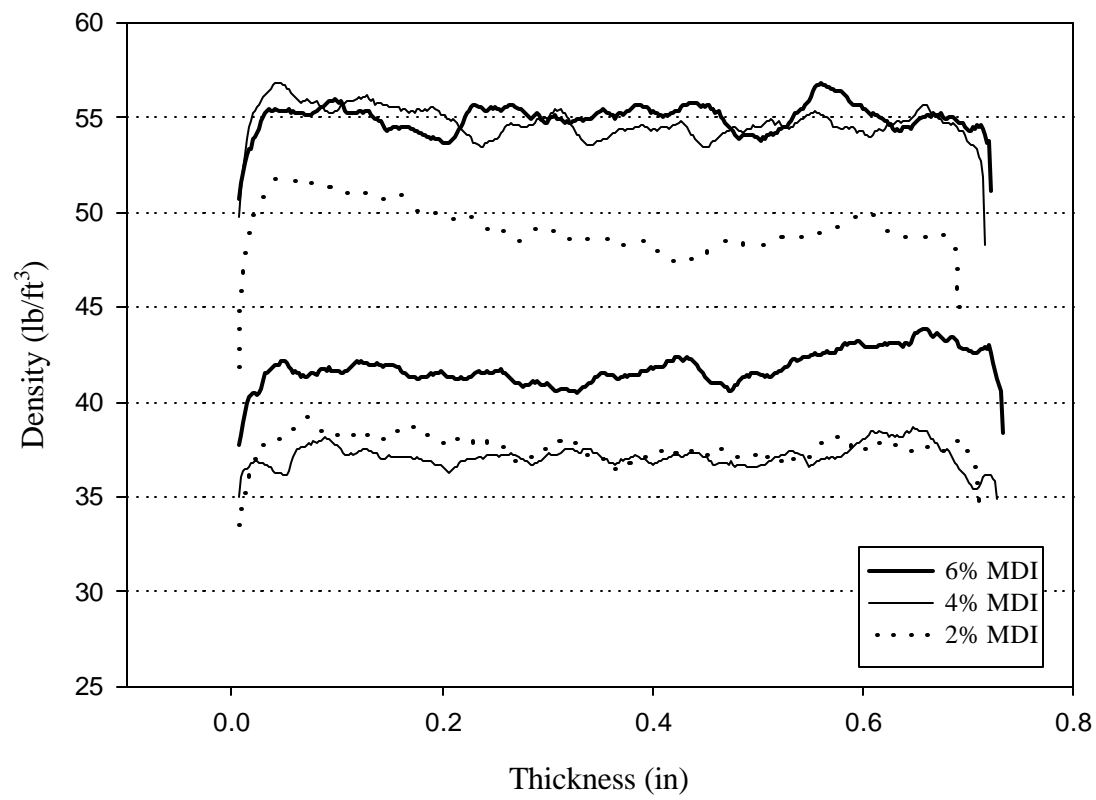


Figure 3.1. *Vertical density profiles of laboratory panels determined by x-ray attenuation.*

inches. For this study, density was calculated based on a square grid size of 0.625 inches, throughout the panel.

The density data was used to locate specimens with x-ray densities ranging from 30–65 lb/ft³. To obtain an approximately uniform density distribution, 70 cylindrical specimens of 0.625 inch diameter were removed with a carbide-tipped plug cutter from each of six, equal-density intervals in the range of interest. This was repeated for panels of each of three resin levels, resulting in 1260 specimens for this study. Sixty specimens were used in each test described below.

Tests were performed to determine swelling and mechanical properties in tension and compression at elevated moisture contents. All tests were performed in the direction perpendicular to the panel faces.

Swelling Properties

To determine the swelling properties of the strand composite panels, specimens were subjected to environmental conditions resulting in incrementally increasing equilibrium moisture contents (EMC). After equilibration by mass at each EMC, specimens were weighed and measured for thickness. Following the final equilibration step, specimens were dried and re-measured to determine the oven-dry mass and thickness. The initial thickness and mass of the specimens at atmospheric conditions in the lab were determined prior to testing, then specimens were subjected to the following conditions before being dried: 65% relative humidity (RH) at 70 °F, 88% RH at 80 °F, and 98% RH at 88 °F. The moisture content (MC) and thickness swell for the specimens were calculated at each psychrometric condition. Non-recoverable thickness swell was calculated based on the thickness after drying and the initial thickness. Density of

each specimen was determined based on the oven-dry mass of wood and the initial volume at approximately 4.5% MC.

Mechanical Properties

Specimens were placed in an environmental chamber set at each of the following conditions and allowed to equilibrate: 65% RH at 88 °F, 88% RH at 88 °F, and 96% RH at 88 °F. After mass equilibration, specimens were sanded to produce flat surfaces and a constant thickness (0.65 inch) for testing.

The moisture content of each compression specimen was determined by the oven-dry method, immediately following testing. The average moisture content of the compression specimens at a given psychrometric condition was assigned to the tension specimens at the same condition. The precise moisture content for individual tension specimens could not be determined because the specimens could not be removed from the test fixtures, intact, after testing. For the compression specimens, density was determined based on the initial volume and oven dry mass of wood, while the density of the tension specimens was determined from the initial volume and the dry mass of wood that was calculated from the estimated moisture content.

Tension

Conditioned tension specimens were bonded to specially designed test fixtures (**Figure 3.2**) using a urethane adhesive. The adhesive was allowed to cure for 12 hours in the controlled environment used to condition the test specimens. Prior to testing, specimens were sealed in plastic bags, and allowed to cool to room temperature (70 °F).

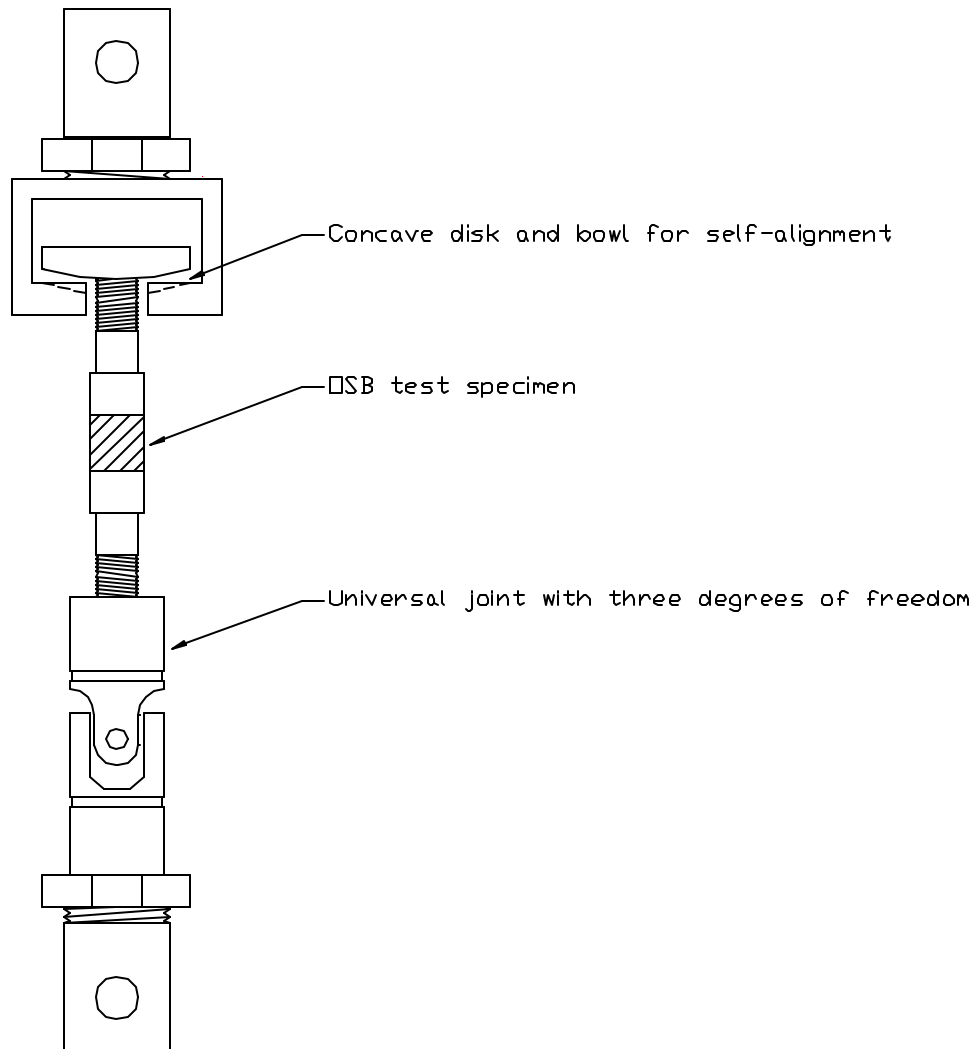


Figure 3.2. *Specially designed tension test fixture.*

Tension tests were conducted to failure with a screw-driven, universal test machine at a constant displacement rate of 0.025 inches per minute. Load and displacement were measured with a 2 kip load cell and a 0.5 inch gage length extensometer, respectively. Stress and strain were calculated based on nominal specimen gage dimensions (area = 0.3068 in², length = 0.5 in).

Compression

To determine the compressive properties of the strand composite, conditioned specimens were compressed, between two platens, with a screw-driven universal test machine. The upper platen was free to rotate with three degrees of freedom. Specimens were compressed with a displacement rate of 0.025 inches per minute. Load and displacement were measured with a 2 kip load cell and cross-head movement, respectively.

To account for compliance of the test machine and fixtures, a compression test was conducted on the platens without a specimen. A linear load-displacement relationship was observed and used to subtract machine displacements from the overall displacement during specimen tests. Stress and strain were calculated, based on a nominal cross section area (0.3068 in²) and the measured thickness of each specimen.

Results and discussion

Total and Non-Recoverable Swelling

Thickness swell increased linearly with density for each resin level tested (**Figure 3.3**). Increased resin levels in the strand composites decreased the total thickness swell. From this, it can be concluded that the localized thickness swelling of a panel will be improved by increasing resin content and decreasing density. The thickness swell behavior of the composite panels in

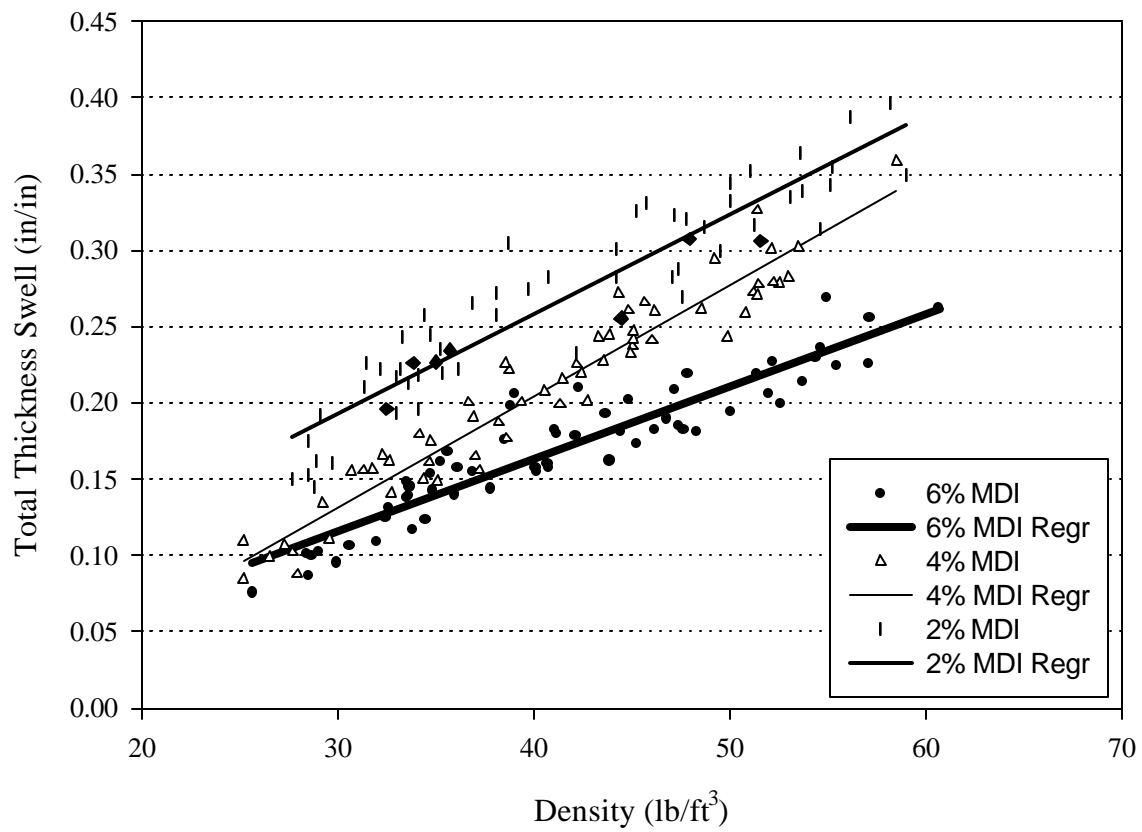


Figure 3.3. *Linear relationship between specimen density and thickness swell.*

this study agreed with the results reported in the literature. It has been shown that increasing levels of resin content tend to reduce thickness swell (Sun et. al., 1994; Rice and Carey, 1978; Maloney, 1993, 1958; Gatchell et. al., 1966; Halligan, 1970; Kelly, 1977) and that thickness swell tends to increase with density (Rice and Carey, 1978; Winistorfer and Wang, 1999; Xu and Winistorfer, 1995a,b; Kelly, 1977).

Non-recoverable thickness swell followed the same trend as total thickness swell, corroborating the findings of several researchers (Kelly, 1977). Interestingly enough, specimens with 4% and 6% resin level show very small amounts of non-recoverable thickness swell at the low density levels, while, specimens with 2% resin showed an appreciable amount of non-recoverable thickness swell at low density levels.

Inspection of the relationship between the non-recoverable fraction of total thickness swell and density showed an asymptotically increasing relationship (**Figure 3.4**). Data relating compaction ratio to thickness swell from a study by Adcock and Irle (1997) is plotted on the graph to represent the behavior of flakes without resin. Compaction ratio from that study was multiplied by the density of aspen (24 lb/ft^3) reported in the Wood Handbook (1999) for comparison. The non-recoverable fraction of thickness swell decreased with increasing resin content. A plot of the average non-recoverable fraction (**y**) vs. resin content shows that this relationship is linearly decreasing (**Figure 3.5**).

Swelling Coefficient

The linear dependence of thickness swell on density (**Figure 3.3**) is supported by others (Xu and Winistorfer, 1995a,b; Wang and Winistorfer, 1999; Suematsu and Okuma, 1989). This dependence would imply that a swelling relation might also account for material density.

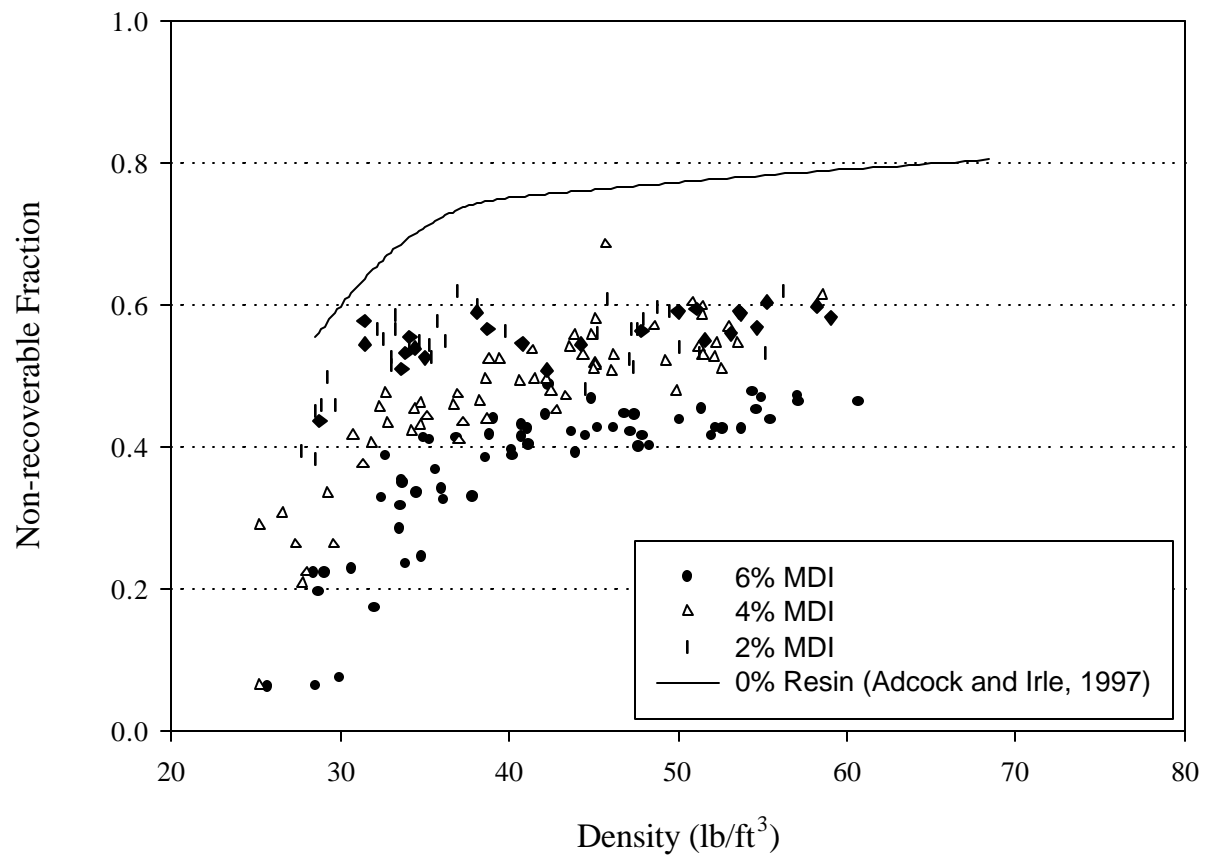


Figure 3.4. *Non-recoverable fraction of thickness swell as related to density and resin content.*

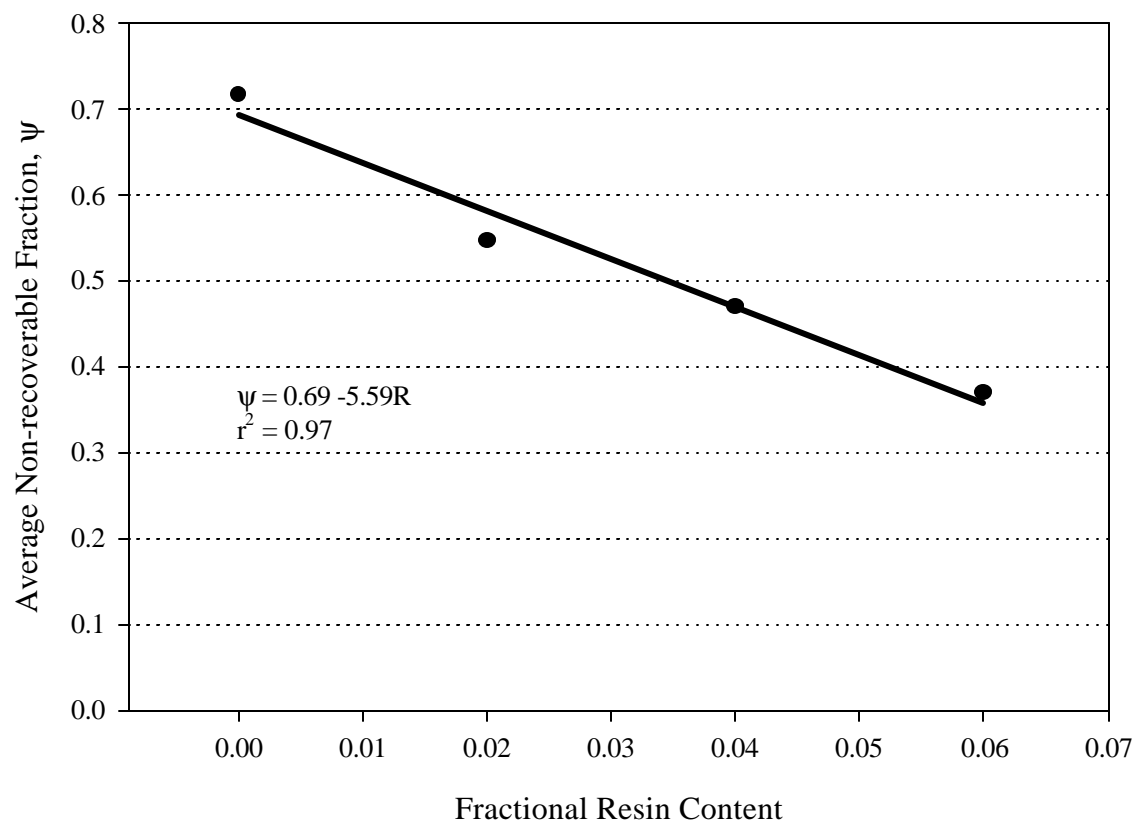


Figure 3.5. *Linear relationship between non-recoverable fraction of thickness swell and resin content.*

In determining the relationship of moisture content changes with thickness swell, the swelling strain was normalized for specimen density (ρ). The normalized swelling strain was then plotted against the moisture content change from the initial conditions of approximately 4.5% MC (**Figure 3.6**). A linear fit with zero intercept (i.e. zero swelling without moisture change) was obtained, with the slope representing the normalized swelling coefficient. The lower levels of moisture change represent the poorest fit to this linear relation, possibly resulting from measurement errors for small amounts of swelling. However, it has been hypothesized that a time-lag between mass and thickness equilibration may contribute to experimental error if mass equilibrated specimens are measured without observing for a possible time delay in swelling equilibration (Halligan, 1970; Kelly, 1970).

A linear relationship between the mean normalized swelling coefficients (β/ρ) and resin content is evident (**Figure 3.7**). The following regression equation describes the empirical relationship.

$$\frac{b}{r} = -0.32 R + 0.04 \quad \text{Equation 3.2}$$

where: **R** is the fractional resin content

Interestingly, extrapolation from the relationships shown in **Figure 3.5** and **Figure 3.7** shows that an MDI resin level of approximately 12.5 % should cause average swelling and the average non-recoverable fraction to be minimized. This is in agreement with a recent study on the effects of high levels of MDI on panel swelling performance (Sun et. al., 1994). That study reported that thickness swell after 24 hour soak and non-recoverable thickness swell after the six-cycle ASTM D1037 accelerated aging treatment would be effectively minimized with an MDI

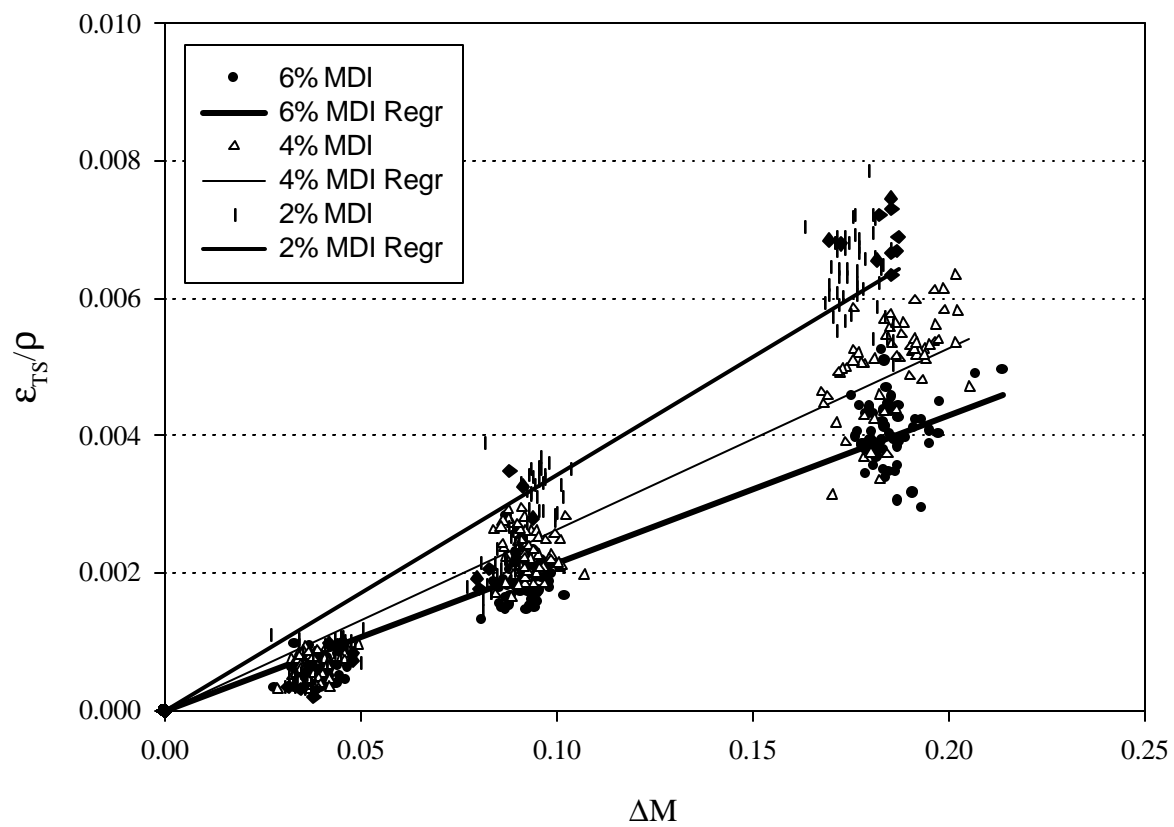


Figure 3.6. *Linear thickness swelling model is reasonable for the strand composite.*

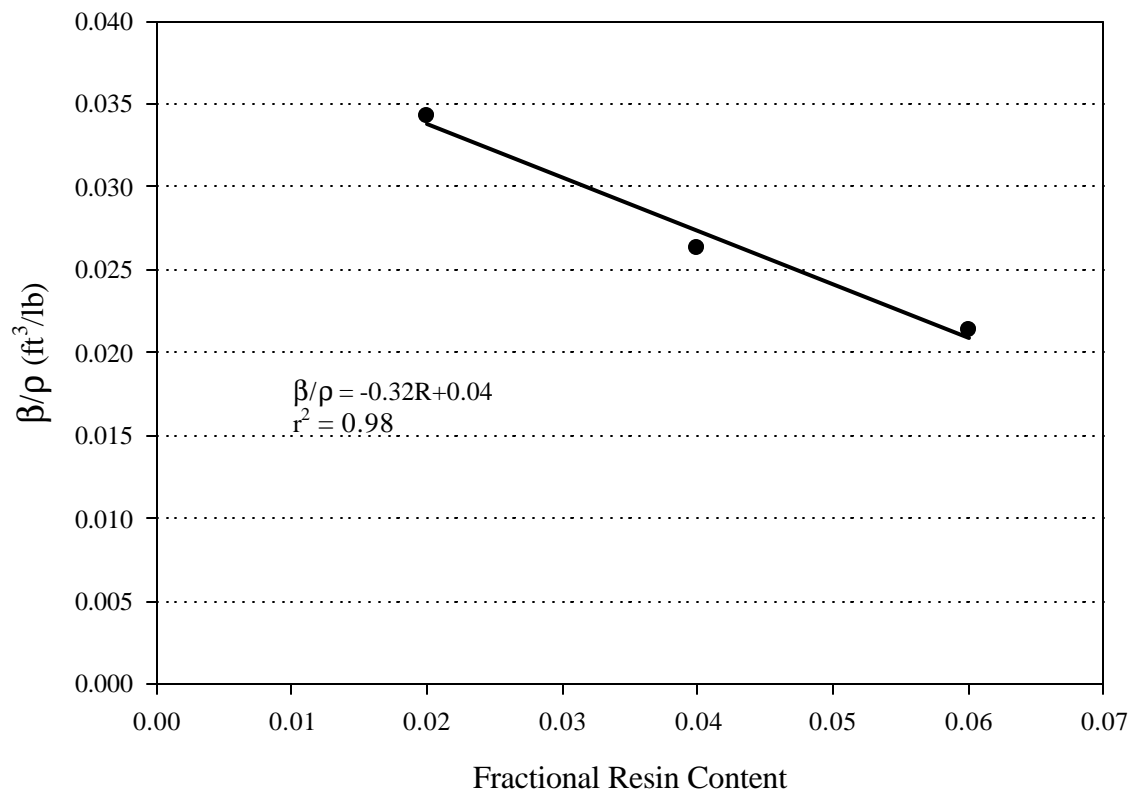


Figure 3.7. *Swelling coefficient is linearly related to resin content of composite.*

resin level near 10%. These results suggest that a stable strand composite may be produced with 12.5% MDI resin.

Tensile Properties

As expected, the tensile properties of specimens tested in this study improved with increases in resin content and density, presumably from better bond development. Tensile strength increased with density and resin content (**Figure 3.8**) and decreased with moisture content. The data in the figure represents the 13% moisture content condition. Specimens tested at other moisture contents produced similar relations. Multiple linear regression was used to determine a single predictive equation for tensile strength based on material parameters of density, resin content, and moisture content ($r^2 = 0.64$):

$$S_{ult} = -33.2 + 1.91r + 2390R - 360M \quad \text{Equation 3.3}$$

While the relationship of strength to panel properties is important, it is not sufficient to fully understand the mechanical degradation that takes place in a panel at elevated moisture contents. An understanding of the constitutive behavior of the material is equally important. Inspection of the experimental constitutive curves showed a definite, non-linear relationship

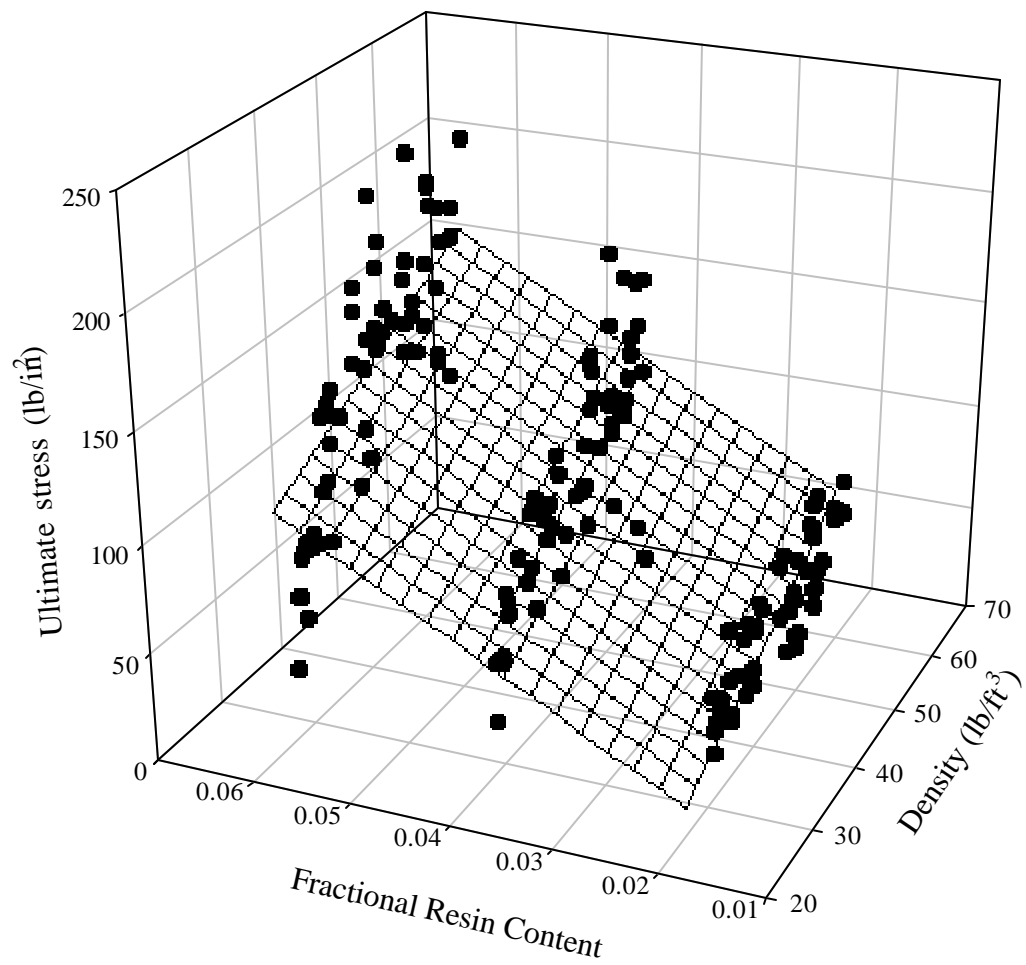


Figure 3.8. *Transverse tensile strength increases with density and resin content.*

(**Figure 3.9**). A constitutive model of the following form was fit to the empirical test data with good results:

$$\mathbf{s}_T = A_T \mathbf{e}_T + B_T \mathbf{e}_T^2 \quad \text{Equation 3.4}$$

where: \mathbf{s}_T is tensile stress

\mathbf{e}_T is tensile strain

A_T and B_T are variable coefficients

Visual comparison of the fitted curves (not shown) to the empirical data showed that the point of zero slope on the fitted curve seemed to correspond well to the point of failure on the experimental curve. The coincidence of these two points indicates that the fitted curve is also useful as a failure criterion. Strain at the point of zero slope (\mathbf{e}_{T0}) can easily be found by setting the first derivative of the constitutive function (with respect to \mathbf{e}_T) equal to zero:

$$\begin{aligned} \frac{d\mathbf{s}_T}{d\mathbf{e}_T} &= A_T + 2B_T \mathbf{e}_T = 0 \\ \mathbf{e}_{T0} &= -\frac{A_T}{2B_T} \end{aligned} \quad \text{Equation 3.5}$$

The predicted ultimate stress (\mathbf{s}_0) is found by substituting \mathbf{e}_{T0} into the constitutive equation:

$$\begin{aligned} \mathbf{s}_0 &= A_T \left(-\frac{A_T}{2B_T} \right) + B_T \left(-\frac{A_T}{2B_T} \right)^2 \\ \mathbf{s}_0 &= -\frac{A_T^2}{4B_T} \end{aligned} \quad \text{Equation 3.6}$$

The relationship between the failure stress predicted by the quadratic model (\mathbf{s}_0) and the actual failure stress (\mathbf{s}_{ult}) observed in testing is shown in **Figure 3.10**. This relationship is

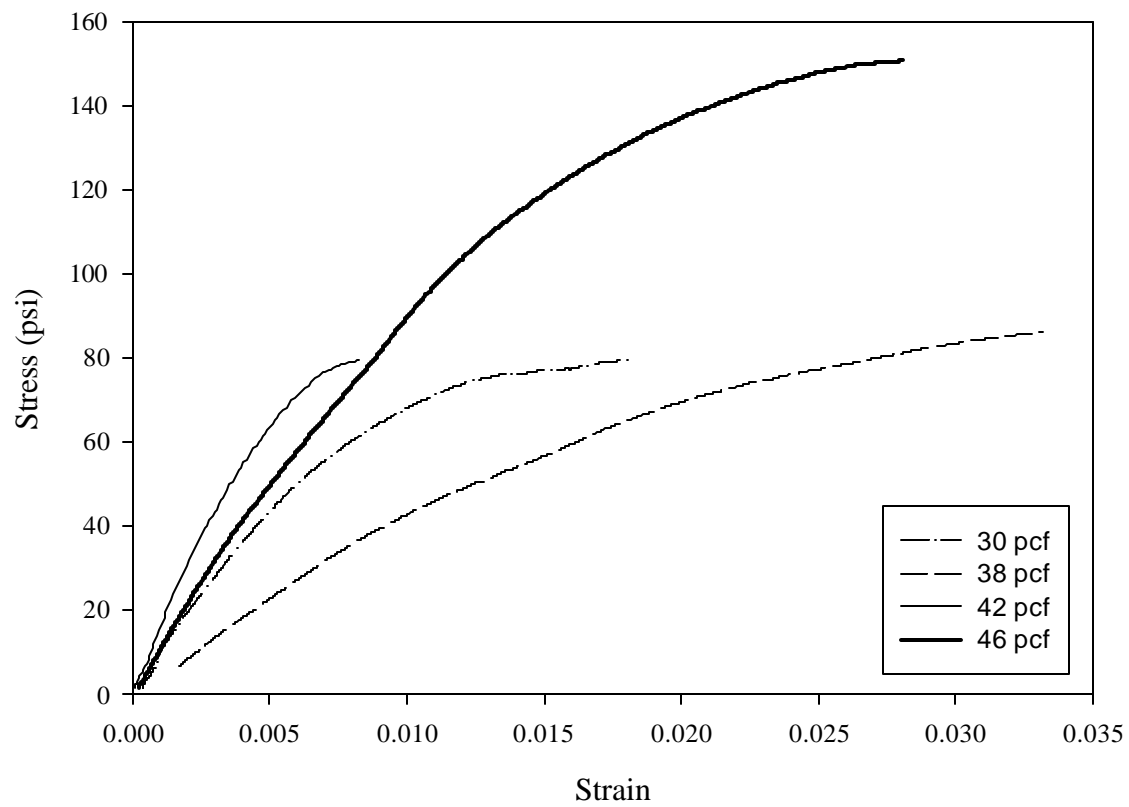


Figure 3.9. *Sample constitutive curves in tension, perpendicular to panel surface.*

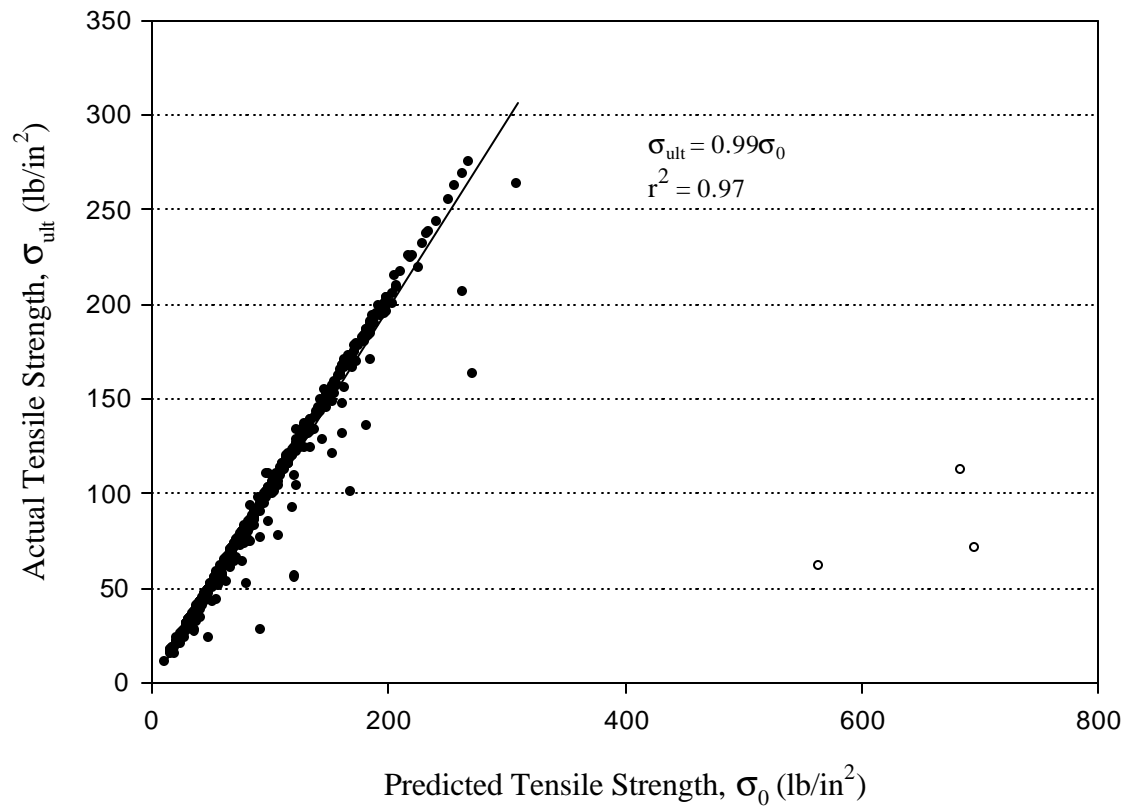


Figure 3.10. *Quadratic constitutive model adequately predicts failure stress in specimens.*

representative of panels at each resin level and moisture condition tested. Points significantly below the line correspond to specimens failed before the point of zero slope predicted by the fitted constitutive curve. Three outlying specimens with very high predicted strengths (>500 psi) were excluded from the regression. Constitutive curves for these outlying specimens showed little change in slope and brittle failure, rather than steadily decreasing slope until failure, which was observed for typical specimens.

To understand the stress response of a strand composite panel subject to changing moisture conditions, it would be useful to relate the tensile constitutive behavior to localized parameters in the panel, such as density and resin content. Examination of the fitted curve parameter, A_T , showed that the initial slope of the constitutive curve, A_T , tended to increase with resin level and decrease with moisture content. Multiple linear regression also showed significant increase in A_T with increased density. The combined regression equation ($r^2 = 0.53$) relating density, resin content, and moisture content is:

$$A_T = 5180 + 144\mathbf{r} + 287000R - 86600M \quad \text{Equation 3.7}$$

Instead of relating B_T to panel parameters with a regression equation, the relationship can be determined, indirectly, through the relationship between A_T and B_T . From the equation for \mathbf{s}_0 , one would expect to observe a linear relationship between $(A_T)^2$ and B_T , with a slope equal to -4 times the average ultimate stress. The linear relationship was observed in the fitted data (**Figure 3.11**), but the ultimate stress predicted by the relationship (154 psi) was somewhat higher than the actual average ultimate stress (98 psi). This is an artifact of the curve fitting process. From **Figure 3.10**, it can be seen that the fitted constitutive model is more likely to significantly over-predict the failure stress than to under-predict it, effectively raising the average. To minimize

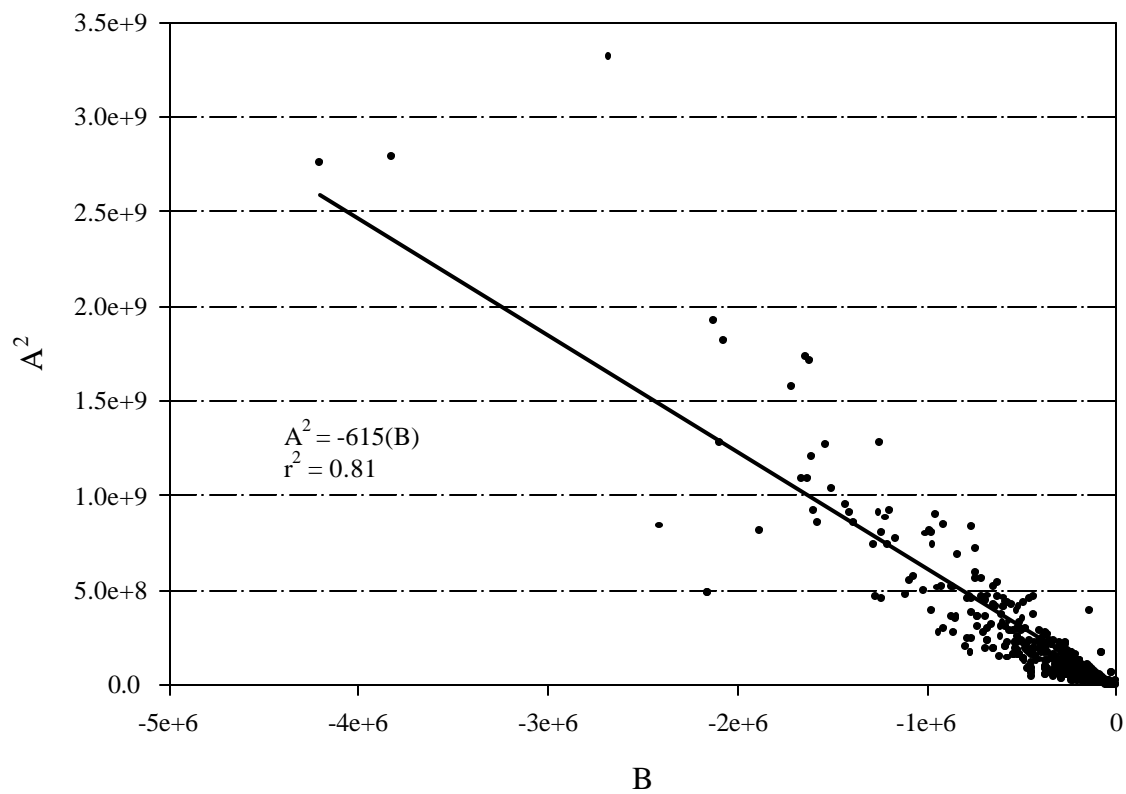


Figure 3.11. *Empirical relationship between tensile constitutive parameters.*

bias, the lower, theoretical, value should be used to infer any relationship between B_T and panel parameters.

Compressive Properties

The overall constitutive behavior in compression is non-linear and is dependent on the amount of imposed strain and initial density of the specimen. Load-displacement curves representing high and low density specimens, at the same moisture content and resin level, illustrate these relationships (**Figure 3.12**). The constitutive curve of the low density specimen shows similar behavior to wood and other cellular solids as discussed in the literature (Wolcott et. al. 1989; Ando and Onda, 1999; Dai and Steiner, 1993; Lenth and Kamke, 1996). The load-displacement curve for the high density specimen is similar to the latter part of the curve for the low density specimen. This is reflective of the amount of strain already imposed on the high density specimen during consolidation.

Because the majority of the specimens tested were compressed to less than 300 lb (975 psi), single curvature was typically observed in the load-displacement relationship. Unsurprisingly, the compression curves showed either positive or negative curvature, depending on the density (i.e. imposed strain) at the time of testing. In general, however, stiffness seemed to increase with density and resin content. To confirm this, a secant line was drawn from the origin to a set strain for each constitutive curve, so the average stiffness (E_C) of each specimen could be related to panel properties.

The strain chosen for the analysis was a near-maximum compressive strain expected to be imposed on any specimen due to differential swelling in a panel. The 95th percentile of tensile strength was determined for each panel type and moisture condition tested, then the compressive

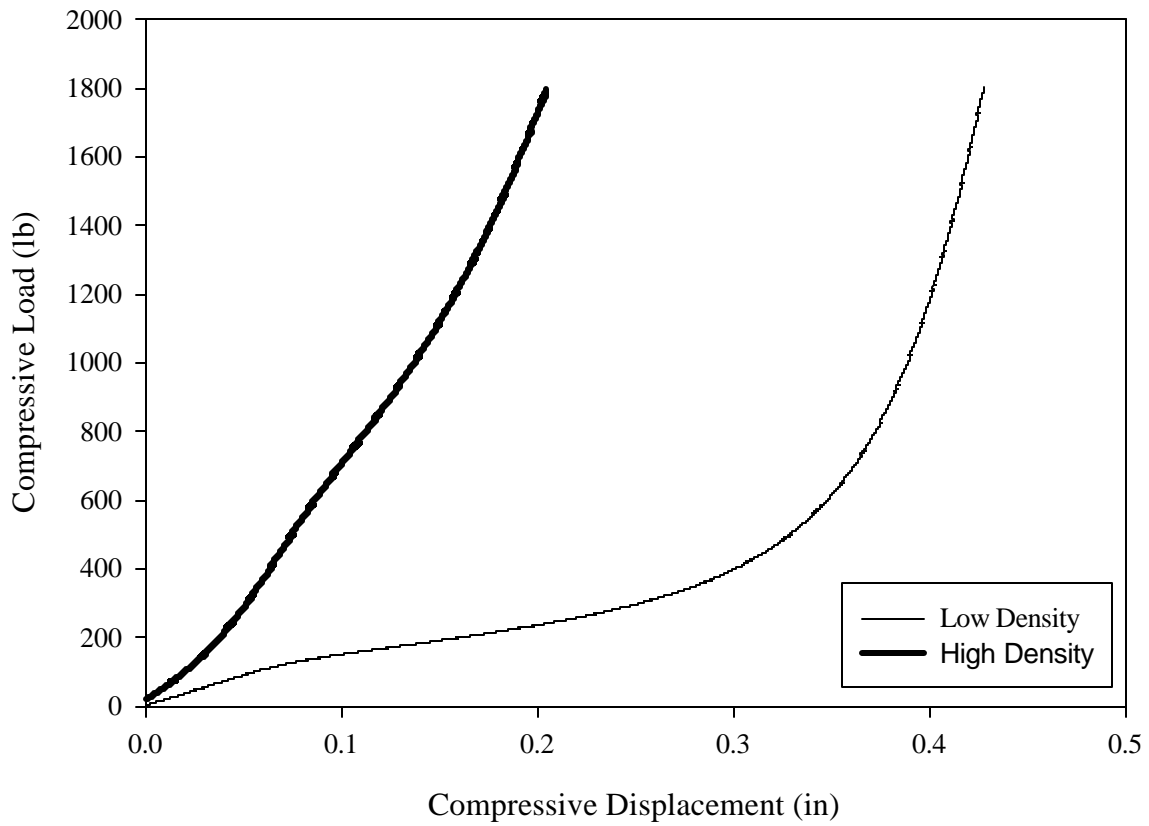


Figure 3.12. *Typical compressive load-displacement curves.*

strain corresponding to this stress was determined from each compressive constitutive curve. Of these strains, the 95th percentile for each panel type and moisture condition was used to determine the secant modulus (E_C) for each specimen. **Figure 3.13** shows the relation between

$$E_C = 6860 + 260r + 236900 * R - 114300 * M \quad \text{Equation 3.8}$$

E_C of the strand composite and panel parameters. Data shown is for tests at 13% moisture content. Other tested moisture contents showed similar results. Multiple linear regression was used to determine a single equation to relate E_C to density, resin content and moisture content ($r^2 = 0.76$):

As expected, E_C increases with density and resin content, while increased moisture content corresponds to a reduction in E_C .

Because, the constitutive curves from testing are inconvenient for analysis, a parametric model was used to represent the constitutive curves for determining E_C in the previous analysis. A two-parameter, quadratic model fit the curvilinear test data extremely well ($r^2 > 0.99$). The compressive constitutive model is similar to the tensile constitutive model discussed previously.

$$S_C = A_C e_C + B_C e_C^2 \quad \text{Equation 3.9}$$

where: S_C is compressive stress

e_C is compressive strain

A_C and B_C are variable parameters

Although the parabolic curve described above showed excellent fit with the test data, the curvature observed at stresses below 300 psi was negligible. E_C is an adequate representation of

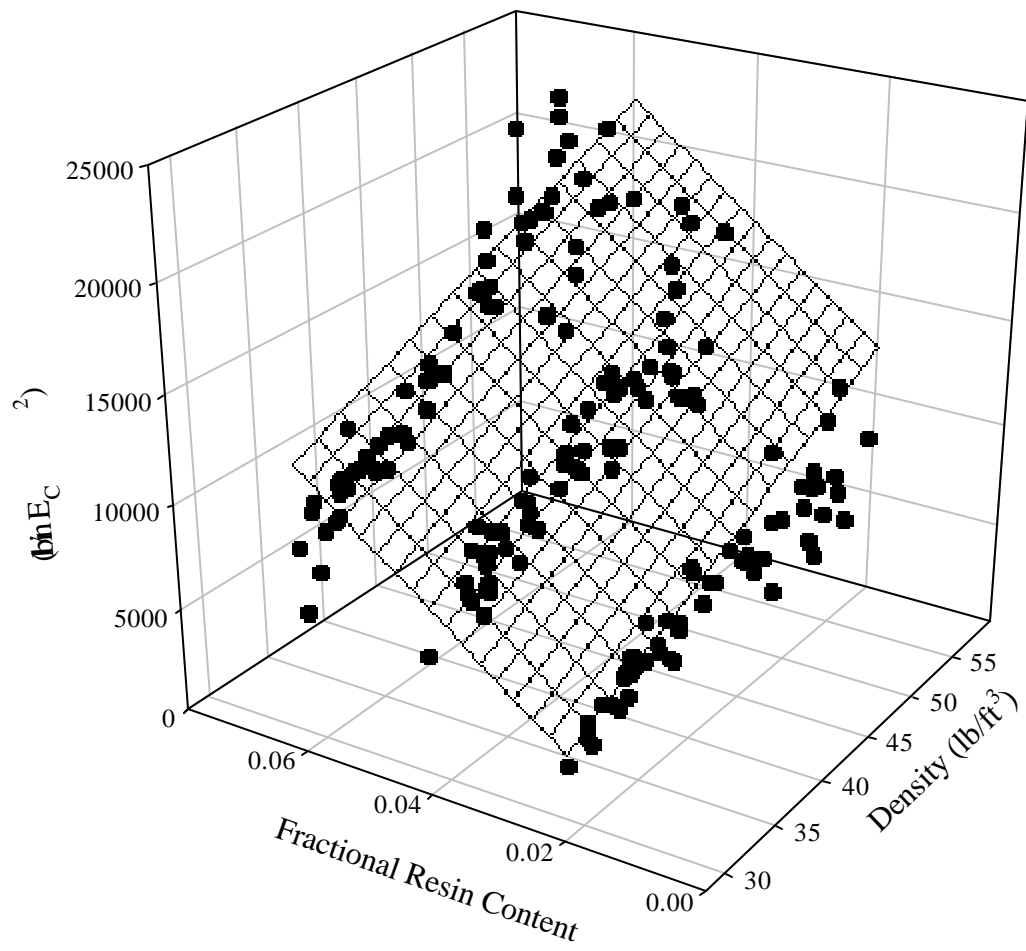


Figure 3.13. *Transverse compressive stiffness increases with density and resin level.*

the compression constitutive behavior for the level of expected stress due to differential swelling in the panel.

Summary and Conclusions

A horizontal density distribution (HDD) has been shown to be a degrading factor in particulate wood composites. Differential swelling in a panel due to the HDD causes internal stresses to develop in a composite panel, perpendicular to the panel surfaces. A complete understanding of this mechanism of degradation requires fundamental knowledge about the transverse physical and mechanical properties of the panel, including thickness swell and the constitutive behaviors of the material in tension and compression.

This study characterized these transverse properties of an oriented strand composite and related them to board processing parameters including density and resin content. Effects of moisture on the transverse properties were also discussed.

The results of this study are in general agreement with the literature. Thickness swelling strain in conditions of increasing moisture content is positively correlated to density and changes in moisture content and negatively correlated to resin content. Investigation of the transverse mechanical properties of the composite generally showed improvements with increasing density and resin content, while performance was reduced with increased moisture contents.

Linear predictive equations developed in this study indicate that optimal swelling performance in a strand composite may be achieved with 12.5% MDI resin. Further research should be done to verify this prediction. The benefits of a stable, value-added strand composite may justify the increased resin costs for some applications. Increased resin levels would also allow for density reductions to maintain a given level of mechanical performance. The savings

in wood costs due to reduced density would partially offset the increase in resin costs.

Decreased density would also provide further benefit for thickness swell.

Constitutive relations for transverse tension and compression were modeled for the strand composite. A two-parameter quadratic equation was found to be a useful constitutive model for tension perpendicular to the surface. In addition to describing the stress-strain relationship, it also provides a good prediction of tension failure. A linear compression model adequately characterizes the constitutive behavior at stress levels expected due to differential swelling in the panel. As expected the constitutive relations in both tension and compression are influenced by density, resin content, and moisture content.

Relationships from this study provide insight for improving panel resistance to thickness swell degradation. Thickness swell of high density regions should be improved, while internal bond strength of the low density areas should be improved. A combination of increased resin level and decreased panel density may be a useful starting point.

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CHAPTER 4
MOISTURE-RELATED STRESS DEGRADATION
DUE TO DIFFERENTIAL THICKNESS SWELL
IN AN ORIENTED STRAND COMPOSITE

Abstract

Horizontal density variations are a characteristic part of the structure of non-veneer wood composites. Because thickness swell in a wood composite is related to density, the presence of a horizontal density distribution (HDD) results in differential thickness swell throughout the panel. Continuity in the panel causes elements with low swelling tendency to restrain elements with higher swelling potential. Through a superposition of strain, potentially damaging normal stresses develop in the panel. These stresses may be sufficient to cause fracture in the panel exposed to elevated moisture content. A simple model was developed to predict the extent of damage a panel would experience due to this mechanism. Using non-destructively measured horizontal density distributions for laboratory-manufactured oriented strand panels, localized panel properties were assigned via Monte Carlo simulation, and the model was applied to compare the effects of material design parameters on panel performance. The results show that a panel will experience less damage due to differential swelling with increased resin content and decreased density. The influence of resin content was much greater than the effect of panel density for the ranges of variables studied. Linear predictive equations from this study indicate that fracture in a panel will be minimized with an MDI resin content of approximately 10%.

Introduction

The structure of a non-veneer wood composite is characterized by density variations throughout the panel. The distribution of density through the thickness of a panel is commonly referred to as the vertical density profile (VDP), while variations in the plane of the composite panel are described by the horizontal density distribution (HDD). The HDD is established during forming of a particulate mat and is dependent on particle geometry and the forming process (Dai and Steiner, 1994a,b; Steiner and Xu, 1995; Suchsland and Xu, 1989). The VDP develops during consolidation of the mat and is dependent on interactions between temperature, pressure, and moisture content through the thickness of the mat (Strickler, 1959; Suchsland, 1962; Wolcott et. al., 1990; Winistorfer and Wang, 1999).

Considering density distributions in a panel is important, because most physical and mechanical properties of a composite are affected by density. Mechanical properties such as modulus of elasticity (MOE), modulus of rupture (MOR), and transverse tensile strength tend to improve with density (Rice and Carey, 1978; Kelly, 1977; Hse, 1975; Plath and Schnitzler, 1974; Steiner et. al., 1978). In contrast, physical properties such as thickness swell (TS), linear expansion, and water absorption are adversely affected by increased density (Rice and Carey, 1978; Winistorfer and Wang, 1999; Winistorfer and Xu, 1996; Xu and Winistorfer, 1995a,b; Suzuki and Miyamoto, 1998).

A HDD is always present in a non-veneer composite and its effects are always negative (Suchsland, 1962; Suchsland and Xu, 1989). Because fastener performance in wood is related to density (AF&PA, 1997), large density variations may result in undesirable variability in fastener performance. Density differences can also have confounding effects when comparing panel properties or performing quality control tests (Shi and Gardner, 1999; Xu and Steiner, 1995).

However, the most significant effect of the HDD is related to thickness swell (TS) (Suchsland and Xu, 1999).

Because TS increases with density (Linville, 2000; Xu and Winistorfer 1995a,b; Rice and Carey, 1978), areas of high density will tend to swell more than low density areas. Due to continuity of the panel, areas of low density provide mechanical restraint against the swelling of high density areas (Suchsland, 1973, Suchsland and Xu, 1989). This restraint causes transverse tensile stresses to develop in areas of low density and transverse compression in high density areas. The out-of-plane tensile stresses may be sufficient to cause damage via fractures or micro-delamination in the panel, contributing to permanent thickness swell and strength loss (Suchland and Xu, 1989; Suchsland, 1973).

The stresses developed in a panel are dependent on the localized constitutive relations, in addition to the swelling properties. Transverse constitutive relations and swelling properties of an oriented strand composite were developed by Linville (2000). Multiple linear regression was used to relate the material properties to density, resin content and moisture content. It was shown that increased density benefits the transverse mechanical properties, but results in increased swelling. Each property tested improved with increased resin content and worsened with increased moisture content.

Objectives

Although the degrading influence of differential swelling has been understood, qualitatively, for years, no attempt has been made to predict the extent of damage expected in a panel due to the HDD at elevated moisture contents. To further our understanding of this degrading mechanism, a study was conducted with the following objectives:

1. Develop a simple model to estimate the strain superimposed on an area of a panel by differential swelling of adjacent elements.
2. Using superposition with empirically determined material properties, predict the amount of damage (fracture) a panel will experience when subjected to elevated moisture content.
3. Compare effects of density and resin content on damage resulting from differential thickness swell.

An adequate model, capable of quantifying the degrading effects of differential swelling due to the HDD, would enable improvement in the design of a panel through simulation, rather than costly trial and error. Such a model would be a natural extension of models that have been previously developed to simulate formation of the HDD (Dai and Steiner, 1994a,b).

Experimental Methods and Materials

Oriented strand panels were manufactured in the laboratory from commercially obtained aspen (*Populus tremuloides*) strands. Polymeric methyl diisocyanate (MDI) resin (Bayer Mondur 541) was applied at levels of 2, 4, and 6% resin solids. Emulsified wax (Borden Cascowax EW-58S) was applied at a constant rate of 1% solids. All application rates were based on the weight of the dry wood.

Single layer, mechanically aligned mats measuring 25.5 x 50 inches were pressed using a combination of radio frequency (RF) energy and heated platens to heat the mat during consolidation. Press schedules were developed to minimize confounding effects of a non-uniform VDP. Details of the press cycle were presented earlier (Linville, 2000). Panels were manufactured at a thickness of approximately 0.75 inches with target density levels of 37 and 54

lb/ft³ then trimmed to finished dimensions of 24 x 42 inches. Five panels from each resin level and target density were manufactured, totaling 30 panels.

To model swelling stresses due to the HDD, relationships between density and the transverse physical and mechanical properties were needed. These relationships were determined, empirically, for different levels of resin content and moisture content. Cylindrical specimens (0.625 inch diameter) with gravimetric densities ranging from approximately 30-65 lb/ft³ (based on dry wood mass and volume at approximately 4.5% moisture content) were tested to determine thickness swelling coefficients and constitutive relations at elevated moisture contents in both tension and compression. A detailed description of sampling and test methods are presented elsewhere (Linville, 2000).

The HDD for each panel was determined, non-destructively, by x-ray attenuation. Because x-ray attenuation increases with density (Bray and Stanley, 1997), this is a convenient way to obtain a non-destructive density measurement. The x-ray scanning equipment used for this study uses a fixed source that generates x-rays in the 60 KeV range and has a resolution of 4 pixels per inch and can calculate discrete horizontal density variations based on a grid size as small as 0.5 inch. For this study, density was calculated based on a grid size of 0.625 inch. .

Model Development

Superposition Model

Differential swelling in a panel causes strain to be imposed on an area by adjacent areas with different swelling potential. An area of localized low swelling will be subjected to an imposed tensile strain while a localized area of high swelling will have a compressive strain imposed on it. This superposition of strain can be modeled by two columns of equal area, which

are constrained to swell together (**Figure 4.1**). The equilibrium stress and strain of each column is governed by strain compatibility between the columns, force equilibrium, and the constitutive relations for each column.

The change in height (Δh) of column **i** has a component due to its own thickness swell (Δh_{TSi}) and a component imposed from differential thickness swell of the adjacent column (Δh_{Ii}).

$$\Delta h = \Delta h_{TSi} + \Delta h_{Ii} \quad \text{Equation 4.1}$$

Converting to a strain basis with swelling strain based on the original height and the imposed strain based on the free swelling height, yields:

$$\begin{aligned} \frac{\Delta h}{h_0 + \Delta h_{TSi}} &= \frac{\Delta h_{TSi}}{h_0 + \Delta h_{TSi}} + \frac{\Delta h_{Ii}}{h_0 + \Delta h_{TSi}} \\ \frac{\Delta h}{h_0(1 + e_{TSi})} &= \frac{\Delta h_{TSi}}{h_0(1 + e_{TSi})} + e_{Ii} \\ \frac{e_A}{1 + e_{TSi}} &= \frac{e_{TSi}}{1 + e_{TSi}} + e_{Ii} \\ e_A &= e_{TSi} + e_{Ii}(1 + e_{TSi}) \end{aligned} \quad \text{Equation 4.2}$$

where: h_0 = original height of column

e_{TSi} = free swelling strain of column **i** based on original height

e_{Ii} = strain imposed on column **i** by adjacent column based on free swelling height

e_A = actual strain based on original height

Compatibility of strains requires the actual strain of the two columns to be equal, resulting in the following relationship:

$$e_{TS1} + e_{I1}(1 + e_{TS1}) = e_{TS2} + e_{I2}(1 + e_{TS2}) \quad \text{Equation 4.3}$$

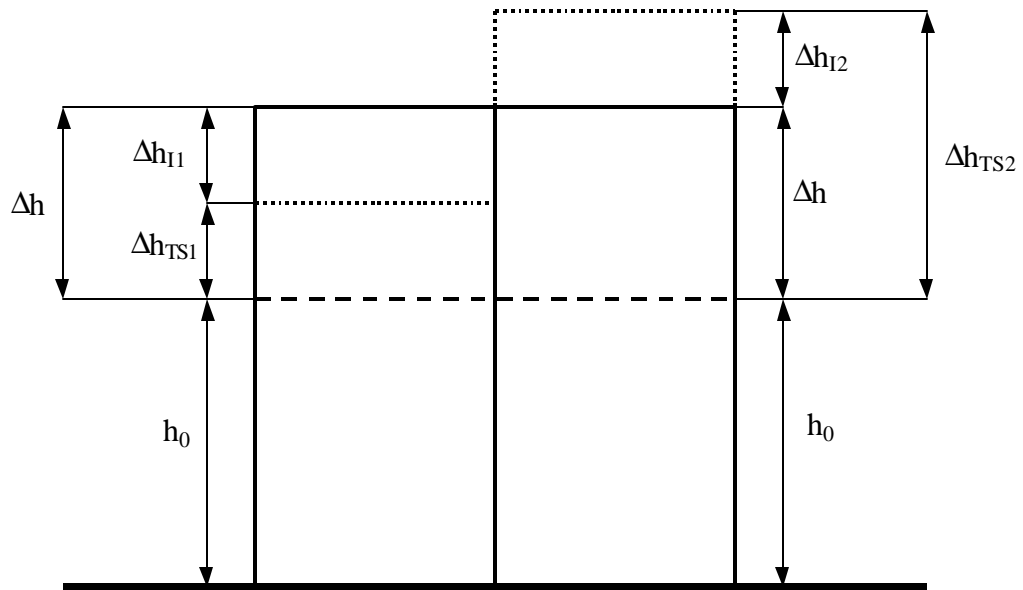


Figure 4.1. *Superposition of strain can be modeled by two columns constrained to swell together.*

Force equilibrium and the column constitutive relations produce the following relationship:

$$\begin{aligned}
 P_1 &= -P_2 \\
 A_1 E_1 \{\mathbf{e}_{11}\} \mathbf{e}_{11} &= -A_2 E_2 \{\mathbf{e}_{12}\} \mathbf{e}_{12} \\
 A_1 &= A_2 \\
 E_1 \{\mathbf{e}_{11}\} \mathbf{e}_{11} &= -E_2 \{\mathbf{e}_{12}\} \mathbf{e}_{12}
 \end{aligned}
 \tag{Equation 4.4}$$

where : $E_i \{\mathbf{e}_{1i}\} = \frac{d\mathbf{S}_i}{d\mathbf{e}_{1i}}$

A_i = Area of column i

P_i = Force on column i

To apply this model to a panel with given moisture content and resin content, localized properties were simulated and assigned throughout the panel, based on a HDD determined for a 0.625 inch grid size and empirical relationships with density (**Figure 4.2**). Each square of the grid was subdivided into four triangular columns with identical properties. Because the properties of the four columns from each square are the same, the columns within a square impose no strain on each other (i.e. no differential swelling); all imposed strain comes from columns in adjacent squares. Therefore, each column was constrained to swell with the adjacent column from a neighboring square and was allowed to swell independently of other columns from the same square (**Figure 4.3**). Because the simple model assumes constant strain for a column (i.e. no bending), it was necessary to allow each two-column system in the model to swell independently. Otherwise, the model would predict the same strain throughout the panel: a condition that is not observed in real panels.

For simplicity in applying the model, the swelling and imposed strains for each column were applied in separate steps: it was assumed that each column could swell freely to its predicted height at a given moisture content, then equal and opposite loads were applied to the

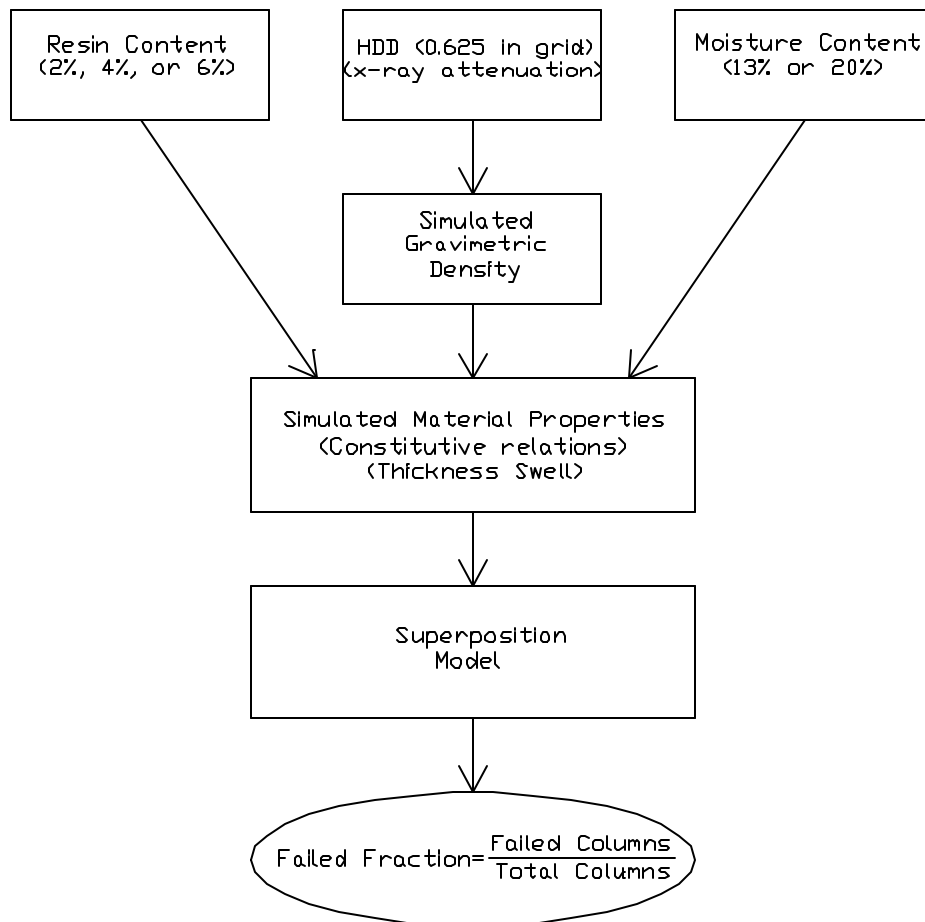


Figure 4.2. *Flowchart for modeling process.*

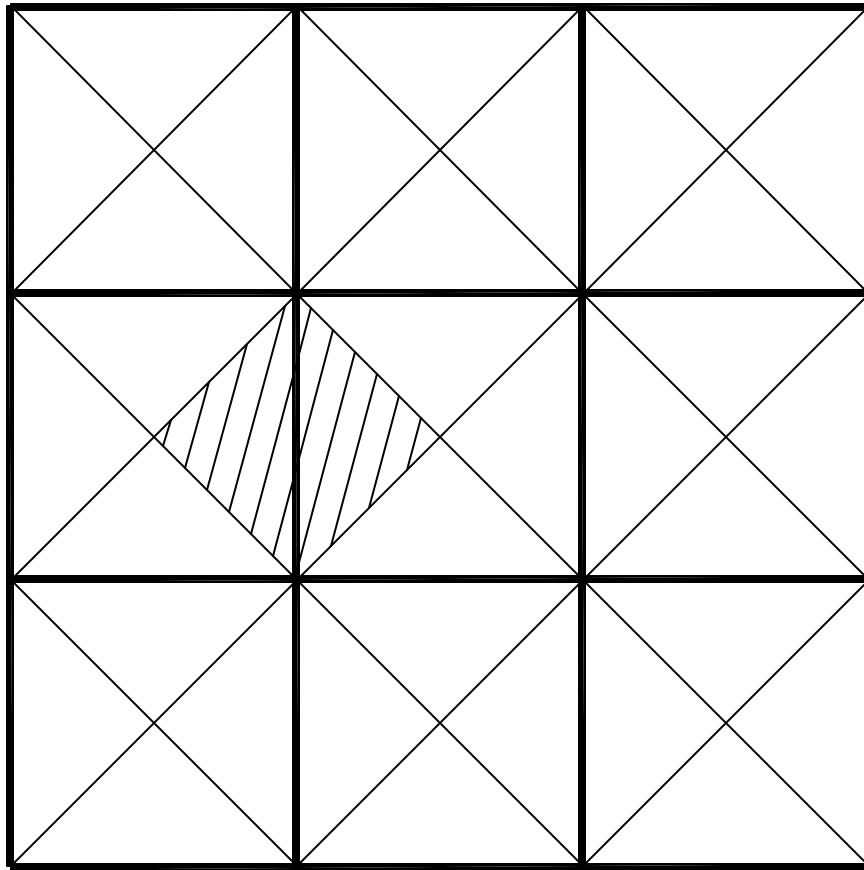


Figure 4.3. *Connecting columns (hatched) from adjacent squares are constrained to swell together, independent of all other columns.*

columns to constrain them to the same height. The constitutive relations assigned were based on the final moisture content.

Equation 4.3 and **Equation 4.4** were solved by iteration for each two-column system. Stress was increased incrementally, using the appropriate constitutive relation for each column to calculate the imposed strain. Stress was increased until the strain compatibility condition was satisfied or the applied stress was greater than the tensile strength of the tension column. If the applied stress exceeded the tensile strength, the column was considered failed. The failed fraction of the panel was then calculated by dividing the number of failed columns by the total number of columns. A FORTRAN program was written to facilitate the calculations.

Model Input Data

Linear regression was used to determine empirical relationships between transverse panel properties and gravimetric density for each resin content and moisture content tested. Simple or weighted regression was used where appropriate. Dependent variable transformations were also applied, as necessary, to reduce heteroscedasticity in the regressions.

Material properties were determined at discrete resin contents and moisture contents. No attempt was made to develop continuous moisture or resin content relationships for the simulation. Therefore, application of the model is limited to the discrete moisture contents (13 and 20%) and the discrete resin contents (2, 4, and 6%) at which empirical data were obtained.

Properties were assigned to areas of the panel via Monte Carlo simulation, based on the regression relationships. The simulated properties were used with the previously described superposition model to estimate the impact of HDD on panel swelling performance (**Figure 4.2**).

Horizontal Density Distributions

Based on the central limit theorem, the HDD of a composite panel will be normally distributed when measured with finite specimen sizes (Xu and Steiner, 1995). While useful for comparing the severity of different HDD's, the probability density function of the HDD provides no information about the spatial correlations of density in the panel. An in-depth study of spatial correlations was beyond the scope of this project, so the necessary HDD information was obtained directly from the scanned panels, rather than through statistical modeling. A three-dimensional contour map of a panel illustrates the spatial variations in the HDD (**Figure 4.4**). The panel shown has a mean x-ray density ($\bar{\mu}$) of 40.3 lb/ft³ and a standard deviation (S_{μ}) of 5.5 lb/ft³, based on a grid size of 0.625 inches.

For the panels manufactured at the target density of 37 lb/ft³, mean x-ray density ranged from 38-41 lb/ft³ with standard deviations of 4.8-5.5 lb/ft³. The 54 lb/ft³ target density panels had mean x-ray densities ranging from 57-60 lb/ft³ and standard deviations in the 5.8-7.5 lb/ft³ range.

The relationship between the x-ray density and the gravimetric density determined for this study is shown in **Figure 4.5**. The regression equation shown was used to simulate and assign gravimetric density values from x-ray densities assuming normally distributed residual errors with a constant standard deviation of 2.66 lb/ft³. It was necessary to convert from x-ray density to gravimetric density, because the following empirical relationships used to simulate material properties were based on gravimetric density.

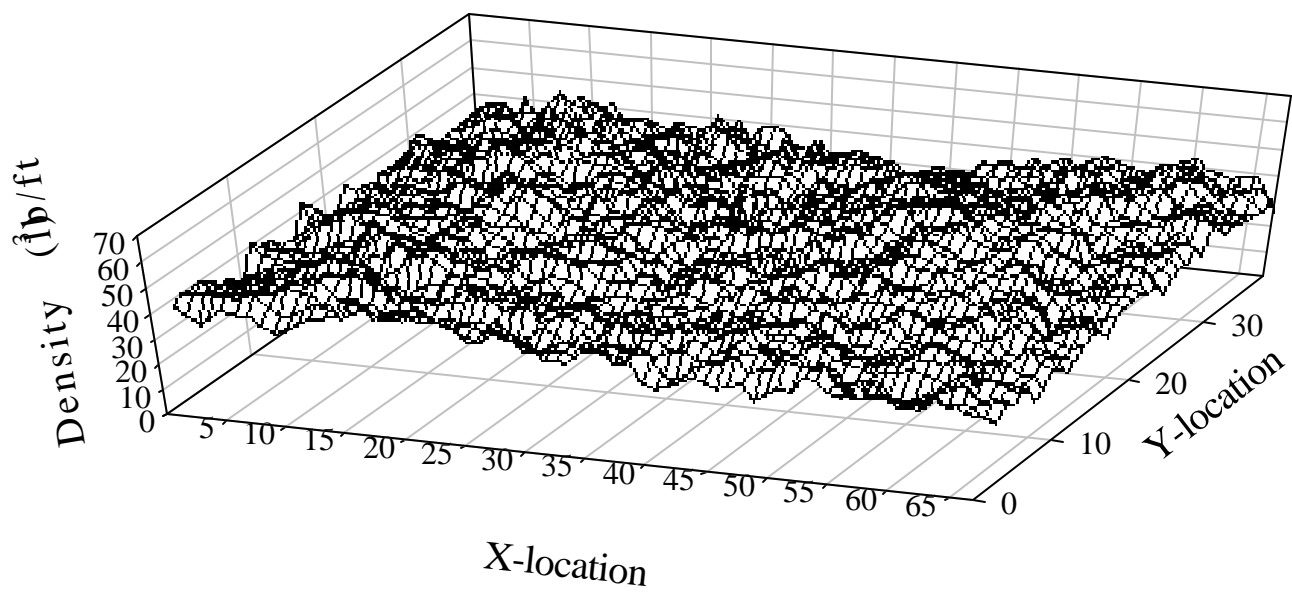


Figure 4.4. *Illustration of HDD in oriented strand panel.*

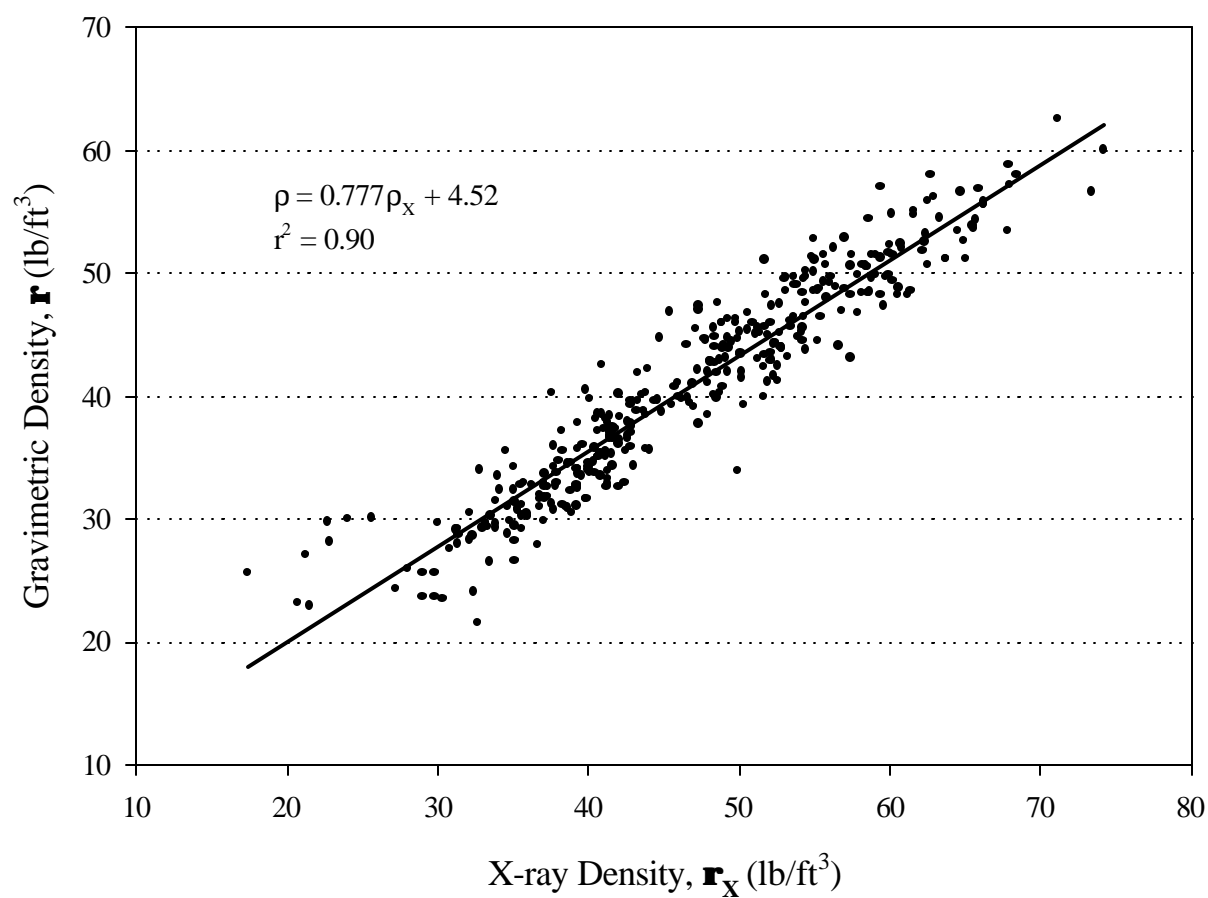


Figure 4.5. Relationship between x-ray density and gravimetric density.

Simulation of Swelling Strain

A previous study (Linville, 2000) showed swelling strain to be linearly related to density and changes in moisture content. An empirical model of the following form describes the swelling strain for a given resin level:

$$\frac{e_{TS}}{r} = \left(\frac{b}{r} \right) \Delta M + error_{TS} \quad \text{Equation 4.5}$$

where: ϵ_{TS} = unrestrained swelling strain

ρ = gravimetric density (lb/ft³)

β = swelling coefficient

ΔM = change in moisture content (below fiber saturation)

$error_{TS}$ = residual error

For the purpose of simulating the data, the residual error was assumed to be normally distributed about the regression line. This assumption is obviously violated at low moisture content changes where the observations consistently fall below the regression line (**Figure 4.6**). It is believed that this resulted from experimental error, possibly due to a time lag between mass equilibrium and thickness swell equilibrium (Linville, 2000; Halligan, 1970; Kelly, 1970). To avoid simulation of this experimental error and to maintain simplicity of the model, the assumption of normally distributed errors was followed in simulating the data.

Inspection of **Figure 4.5** shows that residual error in the model increases with changes in moisture content. A relationship between the standard error and the change in moisture content was estimated by calculating the standard deviation of the tightly grouped data for each equilibrated condition. A fitted quadratic function was used to estimate the relationship between moisture content changes and the standard deviation of the errors. **Table 4.1** shows the regression equations and the estimated standard deviation of error (standard error) as a function of moisture content change.

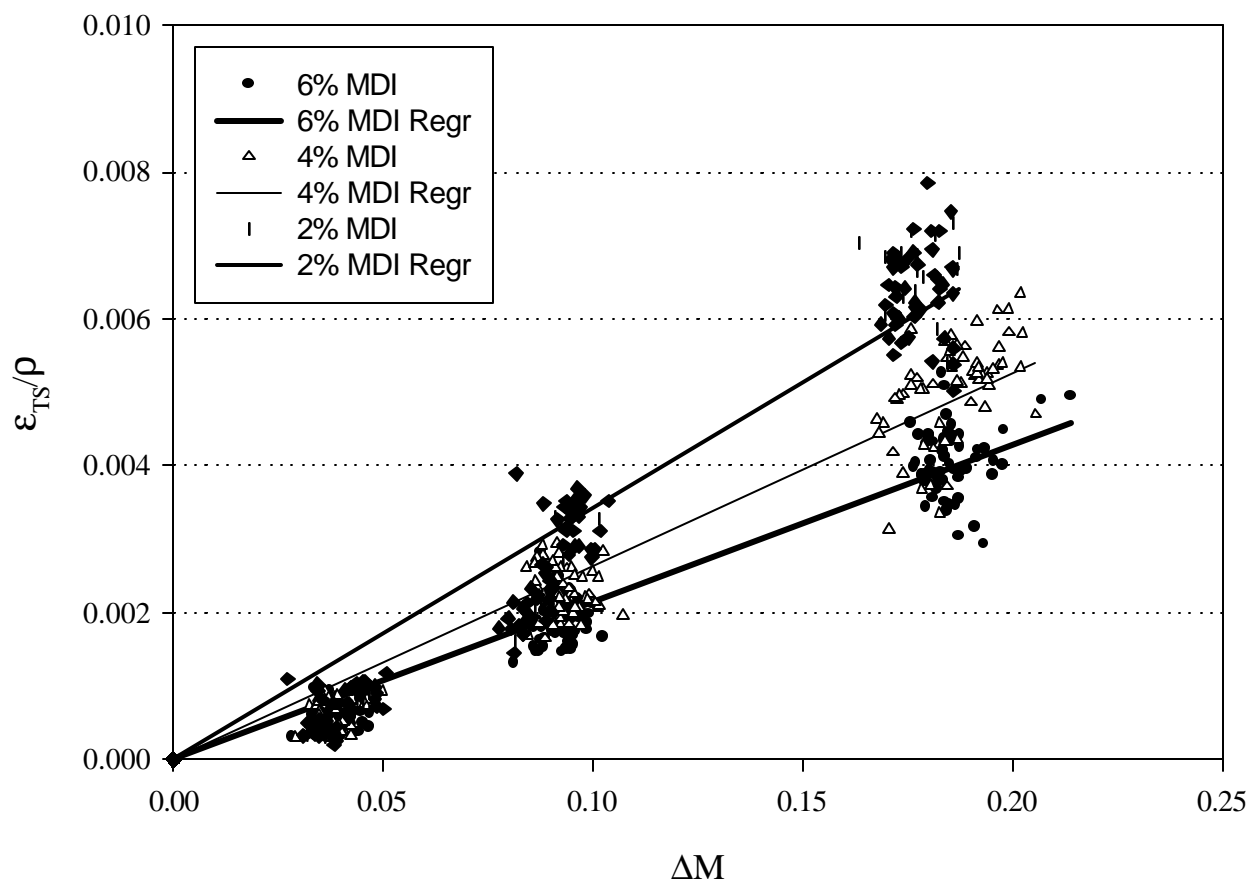


Figure 4.6. Relationship between swelling strain and change in moisture content.

Table 4.1. Summary table for regression of swelling strain on moisture content change.

Resin Level	Regression Equation	Correlation Coefficient (r^2)	Standard Error
0.02	$\varepsilon_{TS}/\rho = 0.0343\Delta M$	0.94	$-0.0212(\Delta M)^2 + 0.0073(\Delta M)$
0.04	$\varepsilon_{TS}/\rho = 0.0263\Delta M$	0.96	$-0.0005(\Delta M)^2 + 0.0042(\Delta M)$
0.06	$\varepsilon_{TS}/\rho = 0.0214\Delta M$	0.96	$-0.0107(\Delta M)^2 + 0.0045(\Delta M)$

Monte Carlo simulation was used to generate errors, for use with the regression equations, to simulate swelling strain data dependent on moisture content, resin content, and density. Visual comparison of the simulated and observed data showed acceptable agreement (Figure 4.7).

Simulation of Tension Properties

A previous study (Linville 2000) reported that a quadratic equation described the constitutive relation in tension perpendicular to the panel:

$$\mathbf{s}_T = A_T \mathbf{e}_T + B_T \mathbf{e}_T^2 \quad \text{Equation 4.6}$$

where: \mathbf{s}_T is tensile stress

\mathbf{e}_T is tensile strain

A_T and B_T are variable coefficients

It was also shown that the point of zero slope ($\mathbf{e}_0, \mathbf{s}_0$) on the fitted polynomial generally corresponded to the point of maximum stress on the test curve ($\mathbf{s}_{ult} \sim \mathbf{s}_0$). Strain at the point of zero slope (\mathbf{e}_0) can easily be found by setting the first derivative of the constitutive function (with respect to \mathbf{e}_T) equal to zero. The predicted ultimate stress (\mathbf{s}_0) is then found by substituting \mathbf{e}_0 into the constitutive equation.

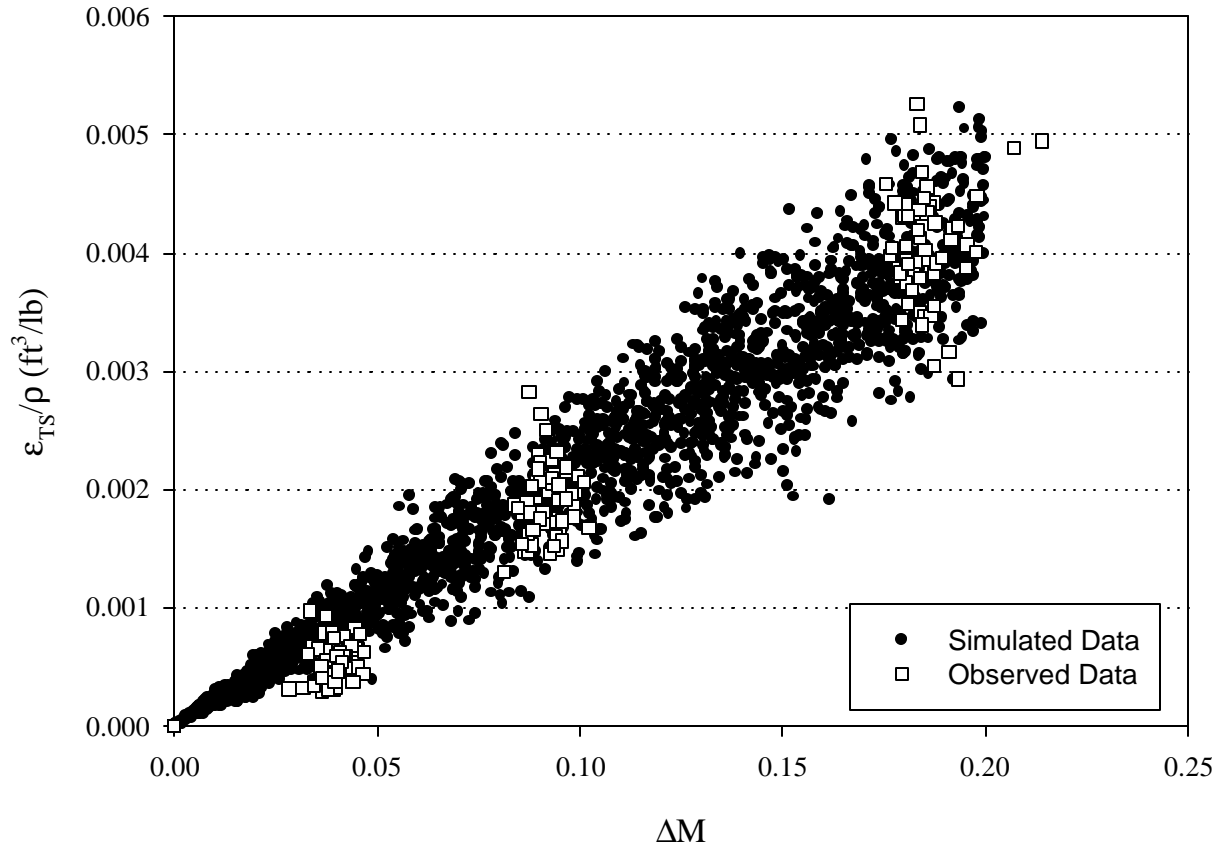


Figure 4.7. Comparison of simulated and actual data. Relationship shown (4% MDI) is typical.

$$\mathbf{e}_{T0} = -\frac{A_T}{2B_T} \quad \text{Equation 4.7}$$

$$\mathbf{s}_0 = -\frac{A_T^2}{4B_T} \cong \mathbf{s}_{ult} \quad \text{Equation 4.8}$$

For the purpose of simulating tension properties, linear regression was used to determine relationships between properties. As shown in a previous paper (Linville, 2000), ultimate tensile strength was correlated to density, but the existence of heteroscedasticity in the data suggested that a transformation of the dependent variable might be appropriate. The transformed data passed tests for homoscedasticity and normality of errors.

Ultimate tensile strength was simulated with the following relationship for each resin level and moisture content tested:

$$\sqrt{\mathbf{s}_{ult}} = K\mathbf{r} + L + error_s \quad \text{Equation 4.9}$$

where: K = slope of regression line
L = intercept of regression line
error_σ = normally distributed residual error

Visual inspection and Kolmogorov-Smirnov (K-S) goodness-of-fit tests showed agreement between the observed and simulated data. The procedure used for the comparisons was described by Woeste et. al. (1979). Regression information is shown in **Table 4.2**.

Table 4.2. Summary table for regression of ultimate strength on density.

Resin Content	Moisture Content	K	L	Correlation Coefficient (r^2)	Standard Error
0.02	0.12	0.0546	4.72	0.16	1.11
0.02	0.20	0.0637	3.03	0.25	1.71
0.04	0.13	0.114	4.98	0.29	1.61
0.04	0.19	0.153	1.77	0.63	1.08
0.06	0.13	0.163	4.73	0.52	1.41
0.06	0.21	0.181	2.71	0.60	1.33

Analysis of the constitutive data showed that the initial slope (A_T) of the tension curve was correlated to the ultimate strength (s_{ult}). Some correlation was also observed between density and A_T . The former relationship was determined to be more important, so A_T was simulated from its relationship to s_{ult} . A logarithmic transformation of the dependent variable was used to eliminate heteroscedasticity.

The following relationship was used to simulated A_T for each resin level and moisture content in this study:

$$\ln(A_T) = N s_{ult} + U + error_A \quad \text{Equation 4.10}$$

where: N = slope of regression line
 U = intercept of regression line
 $error_A$ = normally distributed residual error

The regression information for each resin level and moisture content is shown in **Table 4.3**. Visual inspection and K-S goodness of fit tests showed agreement between the simulated and observed data.

Table 4.3. *Summary table for regression of A_T on \mathbf{s}_{ult} .*

Resin Content	Moisture Content	N	U	Regression Coefficient (r^2)	Standard Error
0.02	0.12	0.0158	7.73	0.43	0.317
0.02	0.20	0.0168	7.53	0.37	0.346
0.04	0.13	0.0062	8.63	0.32	0.339
0.04	0.19	0.014	7.60	0.53	0.381
0.06	0.13	0.0062	8.71	0.38	0.357
0.06	0.21	0.0112	7.63	0.57	0.391

With simulated data for \mathbf{s}_{ult} and \mathbf{A}_T , the third tension constitutive parameter (\mathbf{B}_T) can be calculated as follows:

$$B_T = -\frac{A_T^2}{4(\mathbf{s}_{ult})} \quad \text{Equation 4.11}$$

Simulation of Compression Properties

A previous paper showed that the constitutive behavior in transverse compression was approximately linear for the range of stress that could be expected in a panel due to differential swelling (Linville, 2000). A secant modulus (\mathbf{E}_C), which was correlated to density, was used to model the constitutive relation.

The secant modulus was simulated from its relationship to density. A logarithmic transformation of \mathbf{E}_C improved the correlation, but did not entirely eliminate heteroscedasticity in the relationship. Therefore, weighted least squares regression was used to model the data for simulation. A linear weighting function for variance was used to fit the regression line with parameters estimated by standard statistical methods (Draper et. al., 1966). The following model was used to simulate the compressive secant modulus for a given density:

$$\ln(E_C) = P\mathbf{r} + Q + error_C\{\mathbf{r}\} \quad \text{Equation 4.12}$$

where: P = slope of regression line

Q = intercept of regression line

$\text{error}_C\{\rho\}$ = normally distributed random error dependent on density

Visual inspection and K-S goodness of fit tests showed agreement between simulated and observed data. **Table 4.4** shows the regression parameters for each resin content and moisture content tested.

Table 4.4. *Summary table for regression of E_C on density.*

Resin Content	Moisture Content	P	Q	Correlation Coefficient (r^2)	Standard Error
0.02	0.12	0.0177	7.97	0.29	$(0.00133\rho)^{0.5}$
0.02	0.20	0.0220	7.08	0.35	$(0.00101\rho)^{0.5}$
0.04	0.13	0.0205	8.43	0.55	$(0.000943\rho)^{0.5}$
0.04	0.19	0.0265	7.46	0.64	$(0.000461\rho)^{0.5}$
0.06	0.13	0.0262	8.45	0.63	$(0.000768\rho)^{0.5}$
0.06	0.21	0.0350	7.28	0.82	$(0.000392\rho)^{0.5}$

Model Validation

Validating the superposition model presented is a complex problem. Essentially, knowledge of the physical and mechanical properties throughout a panel is needed. This knowledge could be gained through destructive testing the panel, but then there would be no panel left for subsequent destructive tests. Another difficulty with the validation is due to the failure criterion used for the model. For simplicity, the model assumes that a column with an imposed strain exceeding the strain corresponding to its ultimate stress has no residual strength (ie. complete fracture). In reality, however, while load decreased with increased strain after the ultimate stress was reached, tension specimens showed some residual strength after reaching their ultimate stress. With these difficulties in mind, two experiments were performed to provide experimental evidence for the model on a panel with 6% MDI resin and a 4% MDI panel. Each panel had a target density of 37 lb/ft³.

Experiment 1

A panel, initially at 4.5% moisture content, was conditioned to approximately 20% moisture content. After conditioning, one hundred plug specimens were removed from randomly selected locations with a 0.625 inch, carbide-tipped, plug cutter. The fraction of specimens that failed during removal (number failed/number removed) was compared to the failed fraction of panel area predicted by the model.

This test would be expected to show a smaller failed fraction than that predicted by the model for two reasons: (1) the model neglects any strength remaining in a specimen beyond its ultimate strength, as discussed previously, and (2) each removed specimen was larger than the size of an individual column from the model. The 0.625 inch diameter specimens removed from the panel were more than three times larger than the area of a single column from the model. Conceivably, a specimen could contain a failed column with enough undamaged material to prevent failure of the plug specimen upon removal.

A comparison of the fraction of specimens that failed upon removal after conditioning to the fraction of panel area predicted to fail in the model did indeed show a lower failed fraction than predicted (**Table 4.5**). Five percent of the specimens failed upon removal from the 4% MDI panel, while the model predicted a failed fraction of 17%. Similarly, three of one hundred specimens failed upon removal from the panel with 6% MDI, while the model predicted a failure rate of 6%.

Table 4.5. *Comparison of predicted failure to observed failure.*

Panel Resin Content	Predicted Failed Fraction	Observed Failed Fraction
0.04	0.17	0.05
0.06	0.06	0.03

Experiment 2

The second test compared the residual strength of specimens subjected to constrained swelling in a panel to the strength of specimens that were allowed to swell freely. Fifty plug specimens were randomly selected and removed from opposite ends of the same panel. One group of specimens was removed from the panel at approximately 4.5% moisture content, and the other group was removed after conditioning to approximately 20% moisture content. Tensile strength was determined for each specimen by testing. Specimens that failed upon removal were assigned zero strength.

Because the model predicts the occurrence of tensile stresses in the low density specimens, the results of this test were expected to show a reduction in strength for the low density specimens removed after panel was conditioned. High density specimens, which would be subjected to imposed compressive strains, were expected to show minimal strength loss compared to free swelling specimens. Inspection of scatterplots of tensile strength vs. density for each group confirms the expected trends (**Figure 4.8, Figure 4.9**). Furthermore, improvements in the slope-sensitive coefficient of determination and increased slope of the regression line for the constrained specimens also support these trends.

Model Parameter Sensitivity Analyses

The superposition model and the simulated data were used to compare the effects of average panel density (determined by x-ray attenuation), resin content, and moisture content on panel performance. The influence of the standard deviation of density in the HDD was also investigated.

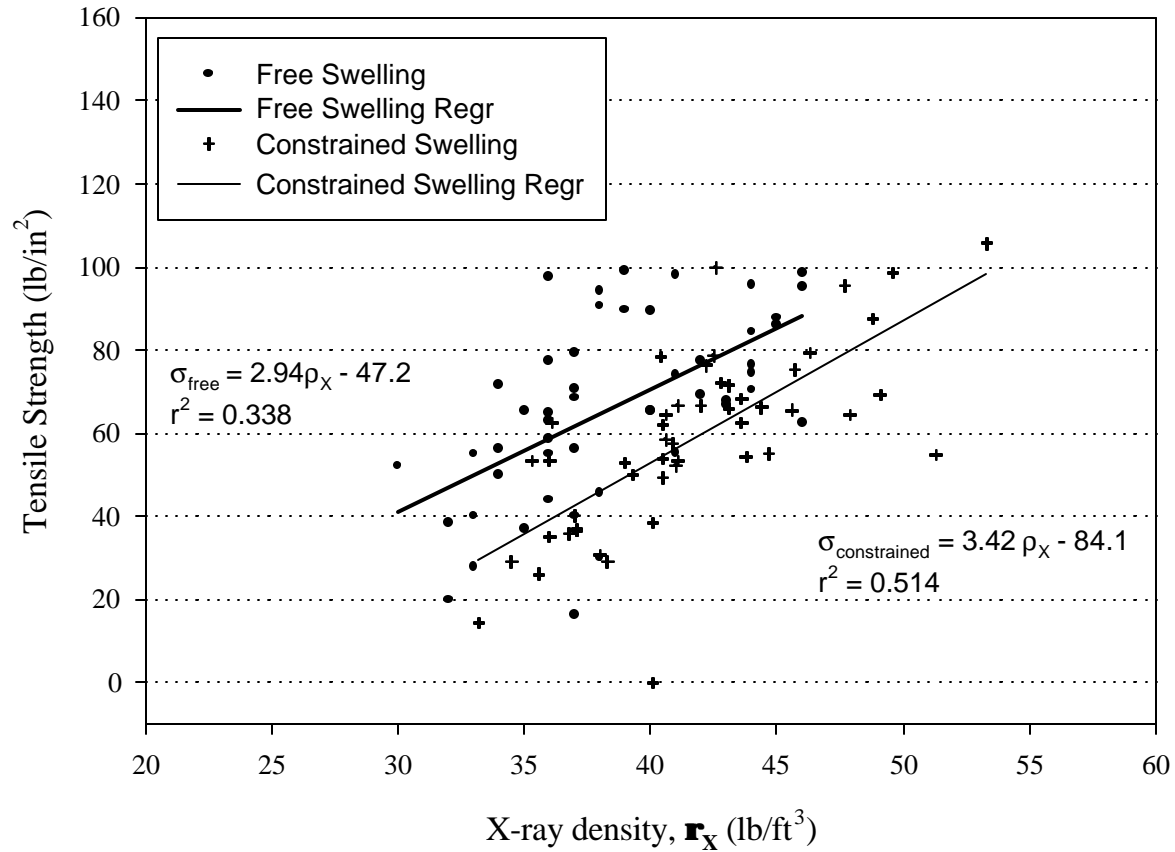


Figure 4.8. Scatterplots of the tensile strength of two groups of specimens removed from a panel with 4% MDI resin. One group was removed prior to conditioning and allowed to swell freely, while the other was removed from panels after conditioning.

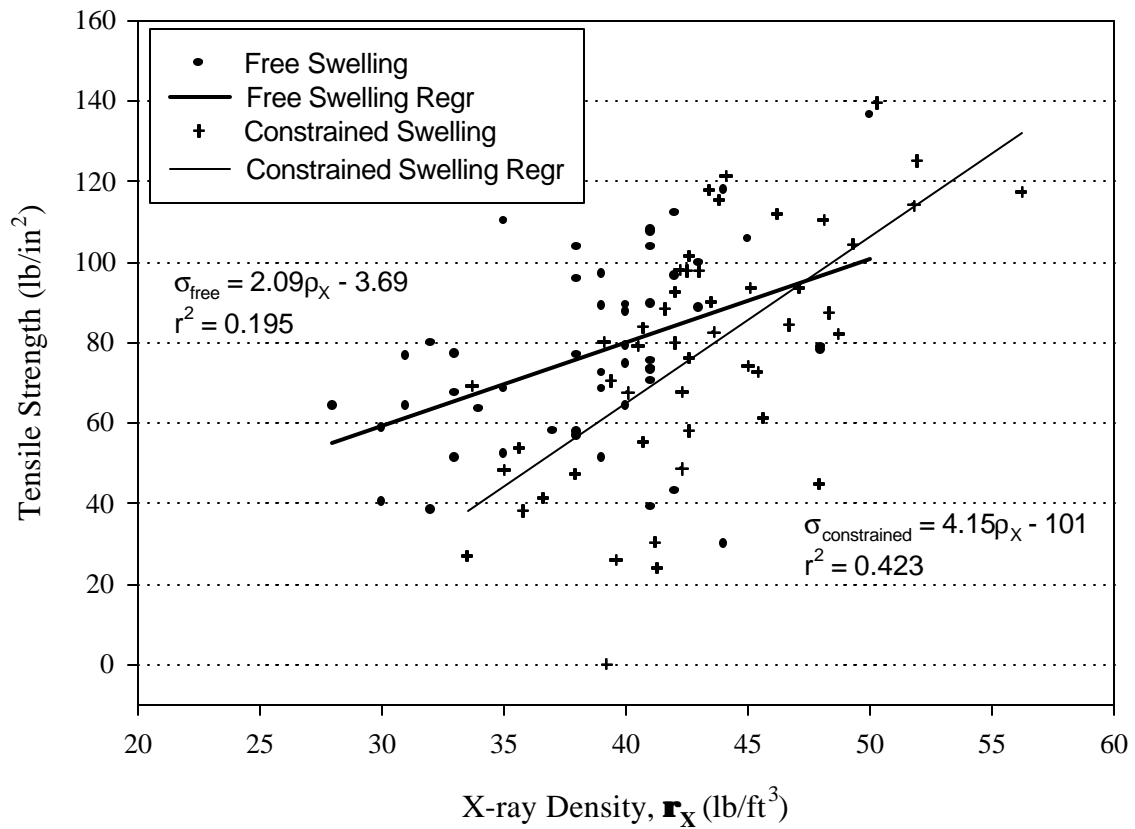


Figure 4.9. Scatterplots of the tensile strength of two groups of specimens removed from a panel with 6% MDI resin. One group was removed prior to conditioning and allowed to swell freely, while the other was removed from panels after conditioning.

Case Study 1: Influence of Moisture Content and Resin Content

The effects of moisture content and resin content were isolated by using identical HDD's. As expected, the model predicted that the failed fraction of the panel would increase with increasing moisture content and would decrease with resin content increases. **Figure 4.10** shows the model predictions of panel failure for a single HDD with varied resin content and moisture content. At the 13% moisture level, a linear decrease in the failed fraction is evident as resin content increases. At the higher moisture content, panel performance also improves with increasing resin content. It should be noted, however, that the improved performance of the 6% resin panel at 20% moisture content (compared to the 6% resin content at 13% moisture) is due to the empirical nature of this study and the model assumption that imposed strains were applied after each column reached moisture equilibrium. Obviously, a panel cannot experience decreased failure with increased moisture content.

Case Study 2: Influence of Average Panel Density

To determine the influence of average panel density on performance, it was desirable to eliminate confounding variation in the standard deviation of density. This was accomplished by using a single HDD (ie. from a single panel) that was shifted by adding or subtracting a constant density throughout the panel to create HDD's with different mean densities. In addition to maintaining a constant standard deviation (5.5 lb/ft^3), this ensured that spatial correlations were not altered. The model showed that increases in panel density result in increased damage in the panel due to superposition of strain. Linear relationships between panel density and the failed fraction of the panel are shown for 13% moisture content at each resin level used in this study (**Figure 4.11**). Similar relationships were predicted at 20% moisture content.

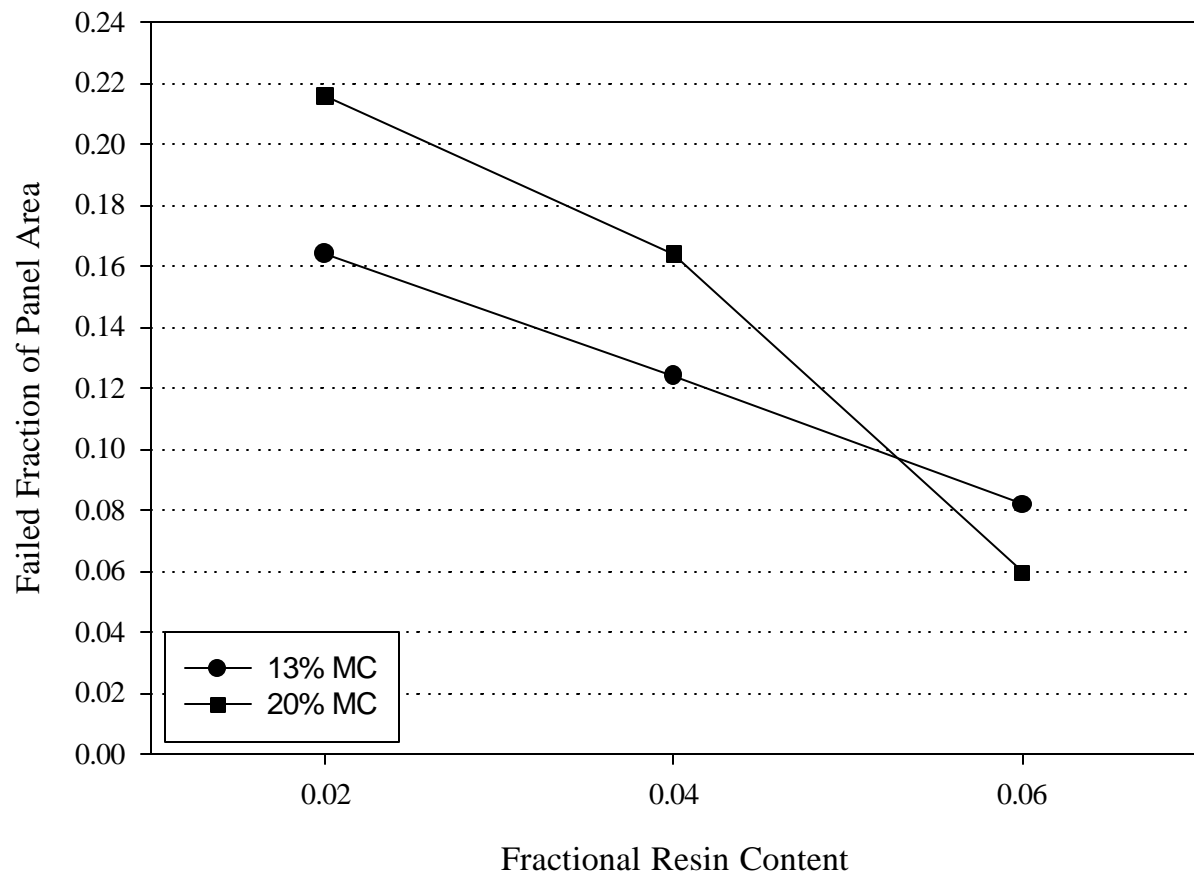


Figure 4.10. *Relationship between resin content and failed fraction of panel at two, elevated moisture contents.*

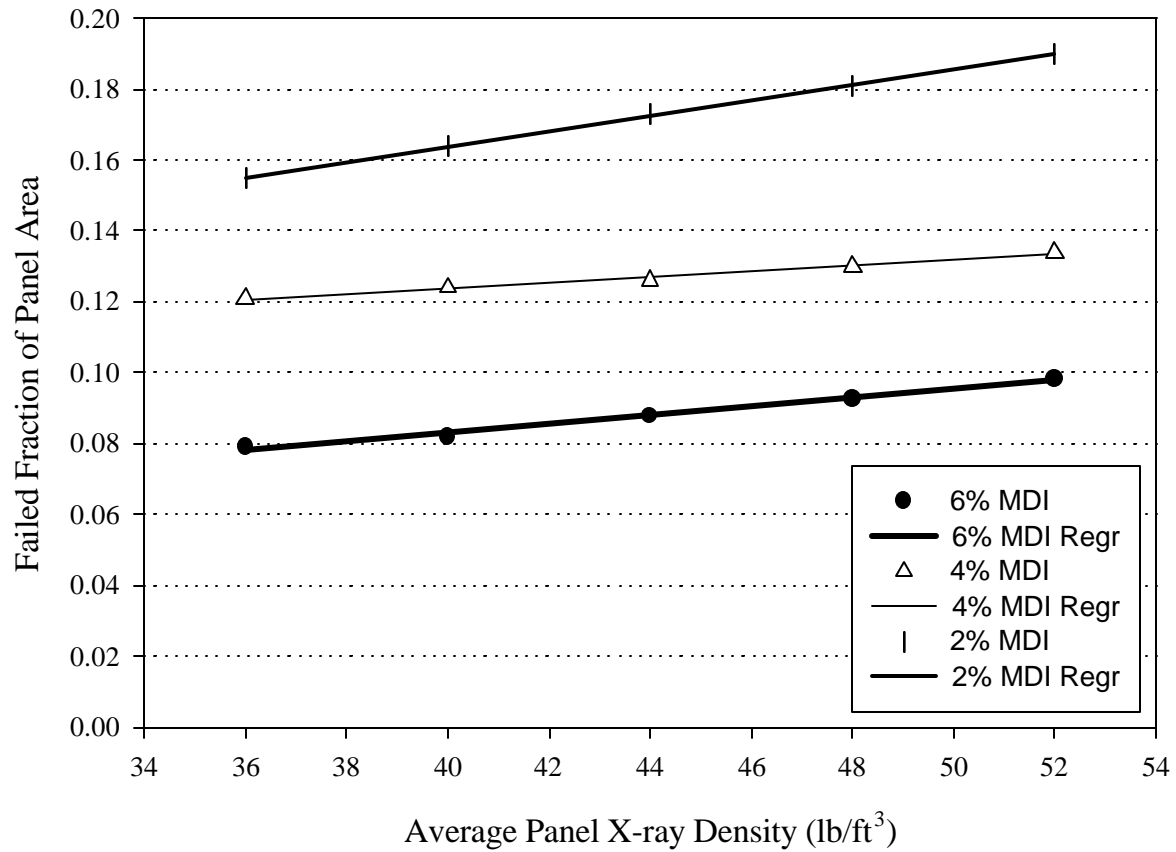


Figure 4.11. Relationship between failed fraction of panel and average density for three resin contents at 13% moisture content. Similar trends were observed at 20% moisture content.

Because the standard deviation of density was held constant while mean density was varied, the coefficient of variation (CoV) decreased with increasing density. It would be expected that a decrease in CoV would result in decreased panel failures. The decreasing CoV with increasing density may have biased the apparent impact of density on panel performance. Unfortunately, it was not possible vary both the mean and standard deviation of density to maintain a constant CoV without information about the spatial correlations of density in the panel.

Case Study 3: Influence of Standard Deviation of Density

The effect of the standard deviation of density on panel performance was determined by normalizing multiple HDD's with different standard deviations to a constant density (40 lb/ft³) by shifting the mean, while the standard deviation remained unaltered. For this case study CoV increased with standard deviation. Using the HDD's of 12 panels from the study, a range of standard deviations from approximately 4.5 to 7.0 lb/ft³ was tested. As expected, the model predicts increased failure in a panel resulting from increased standard deviation of density (**Figure 4.12**). Interestingly, however, the model seems somewhat insensitive to changes in standard deviation for the HDD's tested. One possible explanation for the lack of sensitivity is that positive correlations exist between the densities of adjacent columns. The forming process may have caused large areas of high or low density, which would result in increased standard deviations, but would not necessarily cause more severe density differentials in the panel.

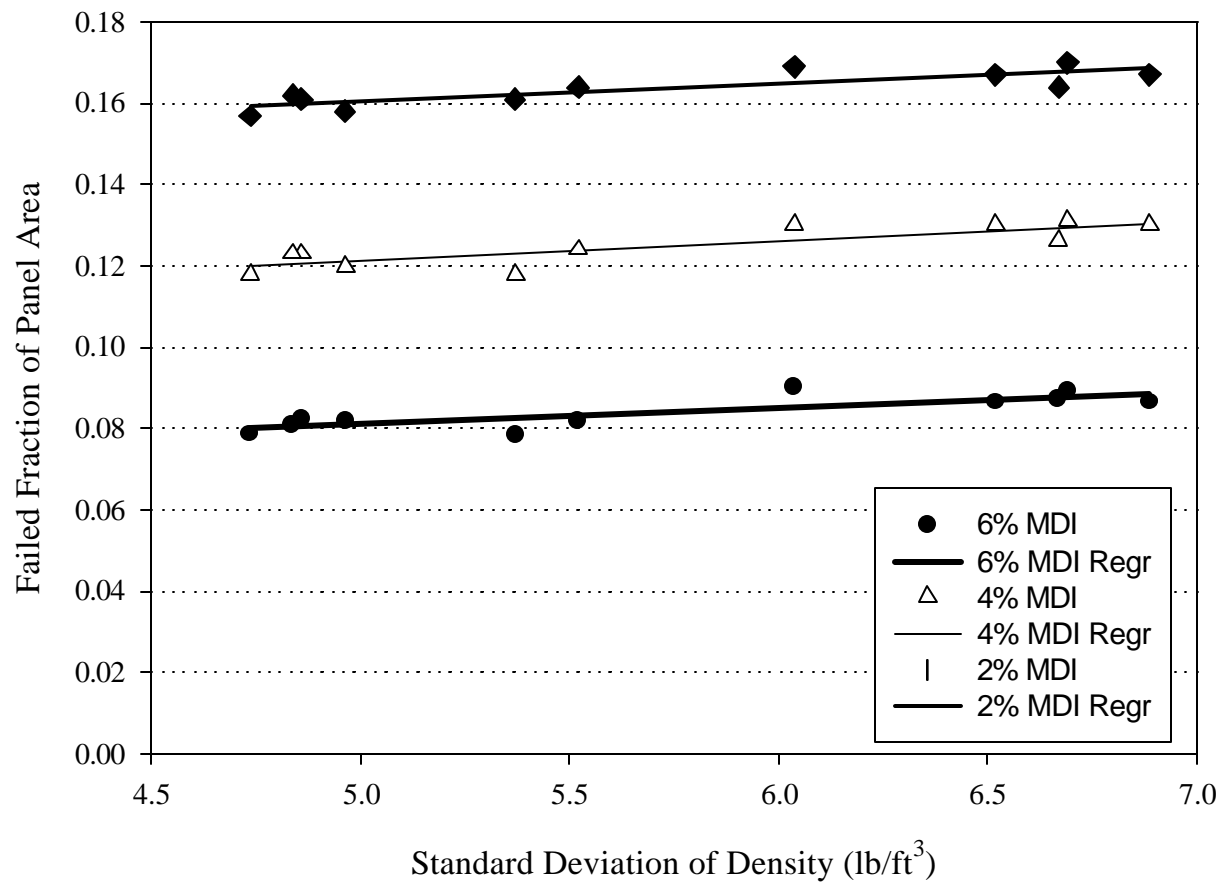


Figure 4.12. Relationship between the failed fraction and the standard deviation of density for three resin levels at 13% moisture content. Similar trends were observed at 20% moisture content.

Combined Parameter Effects

To determine the combined effects of panel parameters on the failed fraction, the model was applied with twelve HDD's for each combination of moisture content and resin content used in this study, resulting in 72 tests. Multiple linear regression was used to relate the failed fraction of area to panel design parameters. Although both panel density and the standard deviation of density influenced performance, the two variables were not independent of each other in the laboratory panels for this study. Consequently, the regression was not improved by including both variables. Inclusion of either variable gives a satisfactory predictive equation:

$$F = 0.126 + 0.302M - 2.896R + 0.0150S_r \quad \text{Equation 4.13}$$

$$r^2 = 0.90$$

or

$$F = 0.131 + 0.302M - 2.896R + 0.00169\mu_r \quad \text{Equation 4.14}$$

$$r^2 = 0.91$$

where: F = failed fraction of panel area

M = equilibrated panel moisture content (below fiber saturation)

R = resin content

S_p = standard deviation of x-ray density (lb/ft³)

μ_p = average panel x-ray density (lb/ft³)

For the HDD's observed in panels from this study, these equations predict that resin levels of 9-10% should be adequate to prevent fracture in the panel after a single exposure to high moisture. This is in agreement with other studies, which have reported or predicted good swelling performance with MDI resin levels near 10% (Linville, 2000; Sun et. al., 1994). The practical significance of this result may apply to high value products that are exposed to moisture cycling and must meet stringent performance criteria.

Improvements in panel performance with decreasing density indicate that increases in transverse tensile properties, which accompany high density, are not sufficient to counteract the

increased swelling due to density increases. This suggests that efforts to improve panel resistance to moisture-related stress degradation should focus on reducing thickness swell, rather than on improving transverse tensile strength. Both properties can, however, be improved simultaneously by increasing resin levels.

Summary and Conclusions

The horizontal density distribution in a panel causes differential thickness swelling throughout a panel, resulting in internal stresses. These stresses contribute to the degradation of a panel exposed to elevated moisture levels. It has been hypothesized that a single exposure to high moisture content can cause fracture in a panel, resulting in strength loss and contributing to permanent thickness swell. Swelling stresses are governed by the localized properties in the panel: transverse constitutive relations and swelling properties.

An empirical study related these properties to density, resin content, and moisture content for an oriented strand composite. Monte Carlo simulation was used to reproduce the empirical relationships, which were used with a simple superposition model to predict the amount of failure in the panel. The model predicts that increased resin levels and decreased density will result in improvements in panel performance at elevated moisture contents. An MDI resin level near 10% should be adequate to prevent fracture of the panel after a single moisture cycle. Increased failure at high density levels suggests that improvements in mechanical properties at increased density levels are not sufficient to counteract the accompanying increase in thickness swell. Efforts to improve the durability of composite panels should, therefore, be focused on the swelling properties rather than mechanical properties. An effective way to improve both physical and mechanical properties is with increased resin levels.

Areas of future research needs related to this topic would include fatigue behavior of a composite and spatial modeling of the HDD. The results of this study indicate that a single moisture exposure may cause mechanical damage in a panel. It would be useful to extend this concept to fatigue loading due to multiple moisture exposures. Research should also be done to determine the spatial correlations of density within a panel. This would provide a relatively simple means of simulating HDD's for modeling.

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CHAPTER 5

CONCLUSION

Oriented strand composites are known to degrade in conditions of elevated moisture content. Panel structure, especially the horizontal density distribution (HDD) contributes to the degradation by promoting differential swelling in a panel. This differential swelling causes internal stresses to develop due to the superposition of strains of adjacent elements. Transverse tension stresses, which develop from this mechanism, may cause fracture in the panel. The end results include loss of strength and increased thickness swell. A complete understanding of this degrading mechanism requires fundamental knowledge of the transverse physical and mechanical properties of a composite including thickness swell and the constitutive relations in tension and compression.

A review of the literature showed that the physical and mechanical properties of a composite are strongly influenced by resin, moisture content, and density. Each of these parameters affects board properties differently. Increased resin has been shown to improve virtually all panel properties, while elevated moisture content has a detrimental effect on all properties reported. Density effects in a composite are more complex and can be positive or negative, depending on the property. In general, mechanical properties benefit from increased density, while physical properties (ie. swelling) benefit from decreased density.

This study characterized the transverse properties of an oriented strand composite and related them to panel processing parameters including density and resin content. The effects of moisture content were also studied. A simple superposition method was used with simulated panel properties to model the swelling performance of laboratory panels. This model was used

to predict the amount of fracture expected in a panel. Predictive equations developed in this study were used to compare the effects of density, resin content, and moisture content on the localized panel properties and whole panel swelling performance.

Linear equations developed in this study suggest that thickness swell of small specimens may be minimized with the use of 12.5% MDI resin. Minimum fracture in a panel was predicted at MDI resin levels from 9-10%. These results are in close agreement with the literature (Sun et. al., 1994). The practical significance of these findings may apply to high value products that are exposed to moisture cycling and must meet stringent performance criteria.

The benefits (ie. higher price) of a stable, value-added strand composite may justify the increased resin costs for some applications. Increased resin levels would also allow for density reductions to maintain a given level of mechanical performance. The savings in wood costs due to reduced density would partially offset the increase in resin costs. Further savings would be realized with decreased drying and processing costs as well as reduced shipping costs.

Decreased density would also provide further benefit for thickness swell. Because thickness swell is positively correlated to density, higher target density levels will result in higher overall thickness swell. Additionally, the superposition model developed in this study shows that fracture in the panel will increase with increased density levels. This indicates that increases in mechanical properties due to increased density are not sufficient to offset the accompanying increase in thickness swell.

Increased resin content benefits both the physical and the mechanical properties of a composite, while density increases benefit mechanical properties at the expense of swelling properties. This study showed that benefits to mechanical properties with increased density are

not sufficient to offset the negative impact of density on thickness swell. Accordingly, improvements in panel durability should begin with decreased density levels and increased resin content.