EVALUATION OF BOLTED CONNECTIONS IN WOOD PLASTIC COMPOSITES

By

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To the Faculty of Washington State University:

The members of my Committee appointed to examine the thesis of DAVID ALAN BALMA find it satisfactory and recommend that it be accepted.

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Chair

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Abstract

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The goals of this research were to verify the European Yield Model (EYM) for wood plastic composites (WPC) with 12.7 mm diameter bolts, and to observe the general behavior of WPC connections. WPCs are relatively new materials, and little is known about their connection performance. Two different formulations of WPCs were examined in this study. The first formulation was an extruded WPC with a 50/50 wood fiber to low-density polyethylene (LDPE) ratio, and the second was an extruded WPC with a 70/30 wood fiber to high-density polyethylene (HDPE). Full connection tests were designed with two different aspect ratios for each WPC. Aspect ratio is defined for this study as the ratio of main member thickness to bolt diameter. The first geometry had an aspect ratio of 3, and the second had an aspect ratio of 6. WPC dowel bearing strengths and bolt bending yield strengths were measured. Unconstrained connection tests, without nuts or washers, were conducted as well. The effect of displacement rate on dowel bearing strength was also examined.

WPC dowel bearing strength was sensitive to load rate, which has practical implications for standardization of test methods. It was found that the EYM predicted yield for the smaller aspect ratio fairly accurately with a maximum error of 4%. It was determined that for the higher aspect ratio connections the EYM tended to over-predict the 5% diameter offset yield by 15% to

20% for both WPCs. Several alternative methods of defining yield point were examined. The premature yielding of the connection was likely due to the localized deformations at the member interfaces caused by stress concentrations. More research and testing is required to better quantify the relationship of aspect on the yielding point of WPC connections.

The maximum loads for these connections were actually much higher than the yield value. For all of the tests ultimate load was at least twice as high as the predicted providing an increased measure of safety for bolted connections. One explanation is that this added strength came from the constraint of the nuts and washers on the connection.

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CHAPTER I

INTRODUCTION

Wood plastic composites are relatively new materials that are gaining market share for structural applications such as outdoor decking and shoreline facilities. A wood plastic composite, or WPC, is defined as a material that consists of wood fiber in a thermoplastic matrix, and the wood fiber must constitute greater than 50% of the mass of the composite (ASTM, 1995). WPCs are gaining in popularity for specialized applications because of several positive qualities that come from the combination of wood and plastic. These attributes include low maintenance requirements, high moisture resistance, and improved durability with respect to checking, splintering, decay, termites and marine organisms. Many of these WPCs can also be machined and installed in the field using conventional wood working tools.

The U.S. Navy is sponsoring research to develop WPCs for applications in naval wharves and piers. This material is desirable because it behaves similar to wood, but it has a greater durability in harsh environments that are commonly seen by waterfront structures. It has also been found that WPCs are resistant to the marine borers that have been a scourge to treated wood piers. WPCs are perceived as safer for the environment than pressure preservative treated lumber since toxic chemicals are not required for decay resistance. The U. S. Navy is seeking modular section designs utilizing that will allow easy replacement of individual damaged members in a fendering system. One key requirement is that WPC components have similar material properties (e.g. compliances) as the existing timber piers.

Accurate design values are needed before WPCs can be used in engineered structures. Connection design is often considered to be the most critical part of a structure (McLain, 1998). It is vital that thorough testing and analysis be conducted on this material, so that it can be applied safely and efficiently. This testing regimen should include extensive testing of connections for the best end utilization of the material.

The theoretical basis for timber connection design values in the United States is commonly referred to as the European Yield Model. Johansen (1949) originally proposed the idea that the strength calculations for connections be based on the yielding strength of the bolt and the crushing strength of the wood (Johansen, 1949). This theory was adopted into the National Design Specification for Wood Construction (NDS) in 1991 (AF&PA, 1991). It has been applied to many different types of dowel fasteners including bolts, lag screws, and nails. The three key inputs to the EYM are the dowel bearing strength of the wood, the bending yield strength of the dowel, and the overall connection geometry.

There are currently no American testing standards that address WPCs due to the recent development of this material. Numerous standards exist for wood-based materials and timber connections (e.g. ASTM), and these consensus standards are recognized by all three model building codes in the U.S. There have been a few recently adopted standards for plastic lumber, but they do not cover bolted connections. Wood standards were used in this project because of several advantages including familiarity with the current engineering community, revisions based on previous testing experience, and a standard for a bolted connection testing. A concern though is that this material may not behave exactly like timber in bolted connection, so certain aspects of the wood standard may not apply to this material. One of these concerns is displacement rate. The wood standard does not provide a displacement rate for bolted connection tests, but instead gives a time to failure criteria. The failure times that are given in the bolt standards cover a broad range, and could cause significant variability in the results depending upon what displacement rates are implemented.

Objectives

The overall goal of this research was to characterize bolted connection behavior for two different wood plastic composite formulations. The specific objectives are as follows:

1. Validation of EYM theory to provide an established and familiar design practice to be used for a wide variety of common and readily available dowel type connectors with wood plastic composites.
2. To observe the general behavior and failure mechanisms of wood plastic connections and how they differ from timber connections.
3. To investigate load rate effects on dowel bearing strengths of WPCs.

CHAPTER II

LITERATURE REVIEW

Wood Plastic Composites

There are only a few thermoplastics suitable for making wood plastic composites. These plastics are required to have a relatively low melt temperature for blending purposes, because wood starts to thermally degrade around 93°C (English and Falk, 1996). Some of the plastics that have been used in WPCs are low and high-density polyethylene, polypropylene, and polystyrene. Polyethylene is the most abundant of these three, and comes from several sources including recycled material and virgin plastic (Killough, 1996).

Many different types of filler fibers have been used in plastic composites including kenaf, wheat straw, hemp, linseed, and wood (Robson and Hague, 1996). Wood fibers that have been used have ranged in size from course particles to fine wood flours. The percentage of fiber content and fiber size have significant effects on the mechanical behavior of composites. An increase in fiber content in WPCs generally causes an increase in stiffness, but decreases ultimate strength. A higher fiber content also reduces creep in WPCs, but reduces the ductility as well (Maiti and Singh, 1985).

A concern about wood plastic composites is temperature effects. Kyanka (1993) reported that raising testing temperatures from 70 to 140 degrees Celsius caused a drop in connection performance for several unspecified WPCs. Thermal expansion is another concern for WPCs. It was found that WPCs had a significantly higher rate of thermal expansion than wood; however, increasing the wood fiber content decreased thermal expansion (English and Falk, 1996). A second concern about WPCs is creep. Research on the effects of creep in WPCs are currently being performed at Washington State University (Wolcott, 1999).

Wolcott (1999) reported that WPCs are a viable structural alternative for waterfront fendering systems. WPCs gain advantages by the combination of a hygroscopic wood and hydrophobic plastic. These composites have a much lower absorption of seawater and are much more resistant to decay than timber. The wood content of WPC also allows it to have greater creep resistance and stiffness over pure plastic lumber of the same polymer type (Wolcott and Englund, 1999).

Navy Documentation on Connections

The Naval code for Waterfront facilities is titled Military Handbook Piers and Wharves – 1025/1. This document covers most of the aspects involved in engineering requirements for naval structures. Section 4.3.2 of 1025/1 states that timber engineering shall be done in accordance with NAVFAC 2.05, Timber Structures. Section 3.2.1 in NAVFAC 2.05, asserts that mechanical connection design should follow the provisions set forth in AF&PA (American Forest and Paper Association) documents. The two current publications by the AF&PA that cover connection design are the 1997 NDS (National Design Specification for Wood Construction) using an allowable stress design methodology, and the 1996 LRFD (Load Resistance and Factor Design) using a limit state design methodology.

European Yield Model

The theoretical basis behind connection design in both the NDS and LRFD are based on what is commonly referred to as the European Yield Model. Johansen (1949) originally proposed the idea that the strength calculations for connections be based on the yielding strength of the bolt and the crushing strength of the wood. This theory was first adopted by the AF&PA

in the 1991 NDS. It has been applied to many different types of dowel fasteners including bolts, lag screws, and nails.

In application, there are four different yield modes described by the NDS. These yield modes are illustrated in Figure 2.1. The first two types of failure, modes I and II, are based solely on the crushing of the wood with little if any permanent deformation in the dowel. A mode I failure is categorized by wood crushing without rotation of the fastener out of the shear plane of the connection. A mode II failure, which only occurs in single shear connections, is identified as a combination of wood failure and rigid displacement of the bolt within the shear plane. These two modes of failure tend to have a brittle failure mechanism relative to modes III and IV. Due to this brittleness the AF&PA assigned a higher calibration (safety) factor of 4 to yield modes I and II (Wilkinson, 1993).

Yield modes III and IV are based on both the wood failure and permanent yielding of the dowel. Yield mode III has a single bolt deformation per shear plane. Yield mode 4 has two fastener deformations per shear plane. These two modes of failure are ductile compared to modes I and II since steel yielding is required for this mode. The AF&PA has assigned a lower safety factor of 3.2 to yield modes III and IV due to this ductility (Wilkinson, 1993). The equations for the allowable stress for these modes of failure can be found in the 1991 and 1997 NDS. The EYM equations for bolts in double shear are shown in Figure 2.2.

The three key parameters that are inputted into the EYM are the dowel bearing strength of the wood, the bending yield strength of the dowel, and the overall connection geometry. The dowel bearing strength has two values for parallel and perpendicular to the grain. If the connection is at an angle between 0° and 90° then the Hankinson formula can be used to interpolate the value for bearing strength (NDS, 1997). Dowel bearing strength is determined by

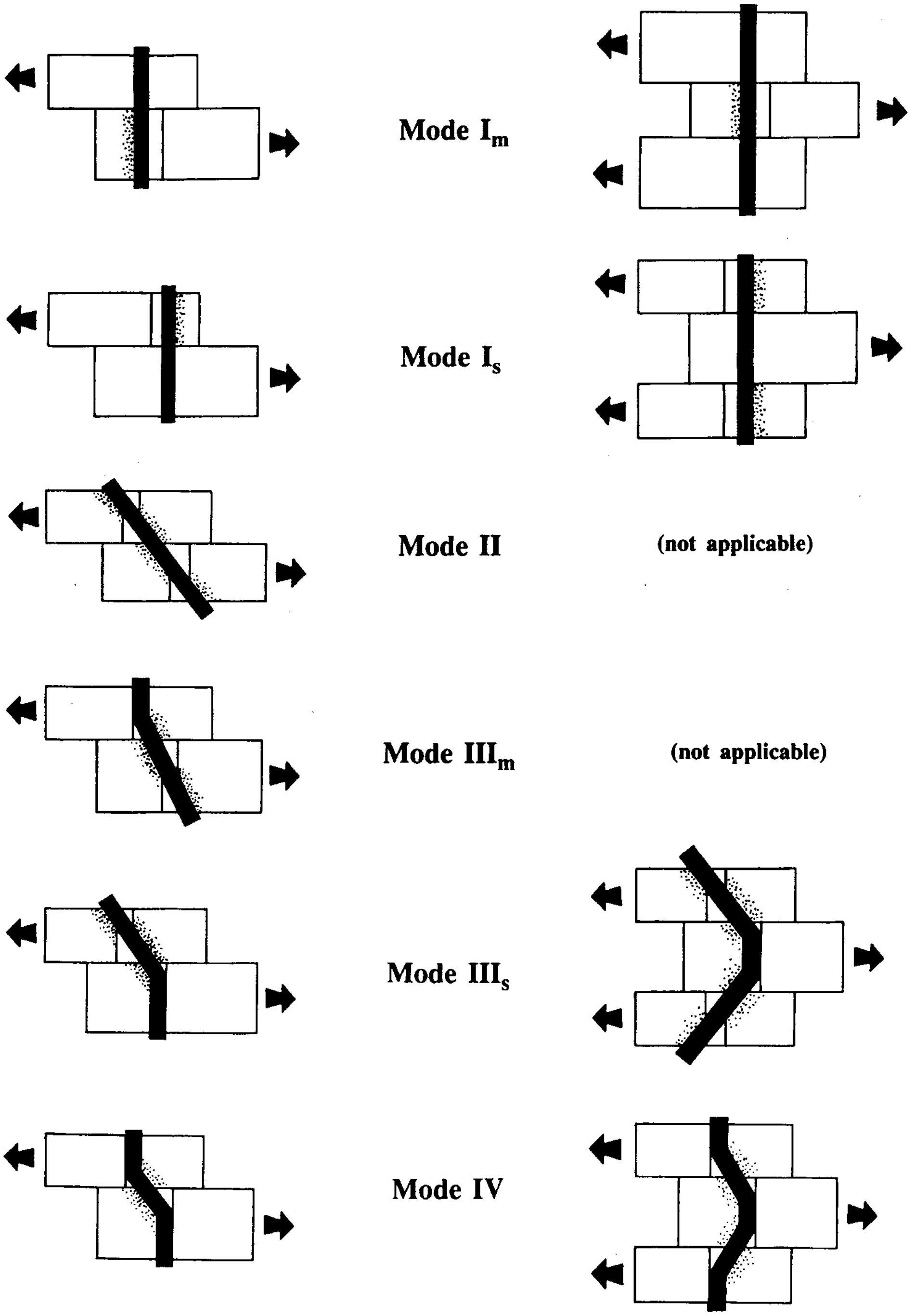

Figure 2.1 European Yield Model yield modes (AF&PA)

Mode of Failure	Equations
I_s	$Z = \dfrac{Dt_m F_{em}}{4K_\theta}$
I_m	$Z = \dfrac{Dt_s F_{es}}{2K_\theta}$
III_s	$Z = \dfrac{k_3 D t_s F_{em}}{1.6(2+R_e)K_\theta}$
IV	$Z = \dfrac{D^2}{1.6K_\theta}\sqrt{\dfrac{2F_{em}F_{yb}}{3(1+R_e)}}$

where:

$$k_3 = -1 + \sqrt{\frac{2(1+R_e)}{R_e} + \frac{2F_{yb}(2+R_e)D^2}{3F_{em}t_s^2}}$$

$$R_e = F_{em}/F_{es}$$

t_m = thickness of main member, inches
t_s = thickness of side member, inches
F_{em} = dowel bearing strength of main member, psi
F_{es} = dowel bearing strength of side member, psi
F_{yb} = bending yield strength of the bolt, psi
D = nominal bolt diameter, inches
$K_\theta = 1 + (\theta_{max}/360°)$
θ_{max} = maximum angle of load to grain ($0° \leq \theta_{max} \leq 90°$) for any member in a connection
Z = allowable connection capacity, lbs.

Figure 2.2: European Yield Model equations for bolted connections in double shear

an equation relating dowel bearing strength to wood specific gravity (Wilkinson, 1991), or by testing of dowel bearing samples according to ASTM D 5764-95. A conservative estimate of the yielding strength for most dowel connectors is given in the NDS; however, the actual yield strength of a fastener varies greatly depending on the manufacturer and lot (Theilen et. al., 1998; Pollock, 1997). Testing of fastener yielding would provide the most accurate input for the EYM. Nails are the only fasteners that currently have a standard for testing of yielding strength in ASTM F 1575-95. Pollock has suggested a standard for bolt yielding that was derived from the nail standard (Pollock, 1997).

The EYM is based on several key assumptions. The first assumption is that the materials that are involved are homogenous and behave as an elastoplastic material. The wood element of the connection is modeled as orthotropic, and the steel component is considered to be isotropic. The tensile and shear stresses that develop in the dowel are ignored. It is also assumed that the ends of the dowel are free to rotate. Another assumption is that the bearing stresses in the wood are uniformly distributed under the dowel. The final assumption is that effects of friction are ignored in the connection (McLain, 1983).

The EYM is not a measure of the ultimate load, but of connection yielding. A 5% diameter offset method is used to define the yield point on a load-displacement plot. This method is applied by drawing a line parallel to the initial elastic region on a load-displacement plot of a connection test. This line is offset by 5% of the bolt diameter. The yield point is determined by the intersection of these two lines. The 5% offset was arbitrarily chosen to be the yield point for wood connections (NDS Commentary, 1991). This method is illustrated in Figure 2.3. Research has shown that this offset can be conservative for certain types of dowel connectors (Theilen et. al., 1998). The connection between the EYM and the 5% offset values

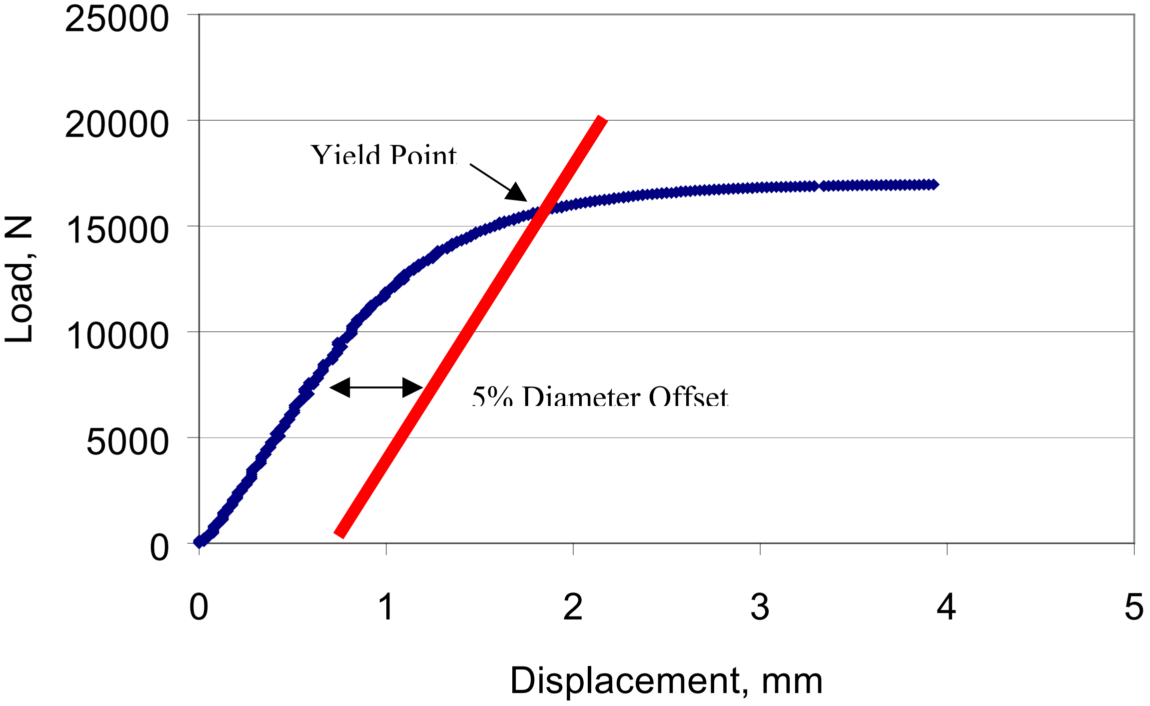

Figure 2.3: Illustration of the 5% diameter offset method

comes for the dowel bearing and bolt bending yield test. The 5% values from these two tests are the inputs to the EYM.

Previous Connection Research

The EYM has been verified for wood connections through various studies including McLain and Thangjitham (1983) and Solstis and Wilkinson (1991). Both of these papers use connection research that came from Trayer's (1932) study of bolted connections to draw their conclusions. McLain (1983) found that the EYM predicted the yielding of connections better than proportional limit theory that was used in design prior to 1991.

Bolted connection research has also been conducted on aspects of bolts that are not covered in the EYM. One important aspect is containment. The EYM does not consider the effects that the nuts and washers might have in a wood connection. Containment can increase the capacity of a connection by limiting out of plane deflection of the material, and by placing a tensile stress on the bolt. Gattesco (1998) quantified the effects of bolt containment on wood connections and found that containment increases connection resistance by approximately 10% parallel-to-grain and 40% perpendicular-to-grain. A second factor that affects wood connections is displacement rate. Girnhammar and Andersson (1986) examined the effects of displacement rate on nailed connections and found that it had an exponential effect on dowel bearing strength and nailed connection tests. These tests had an increasing load at a decreasing rate when the displacement rate was increased. Rosowsky and Reinhold (1999) also examined the effects of displacement rate on 8d nailed connections in plywood. In this connection setup they did not find an influence of displacement rate on connection strength; however, these results do not directly contradict Girnhammar and Andersson (1986). Rosowsky and Reinhold (1999) were examining load duration effects being used for roof sheathing, which led them to examine a small nail, 8d with clipped heads, in a relatively stiff material, plywood. In this particular setup the steel will undergo most of the yielding, and steel is not sensitive as sensitive to displacement rate as wood (Girnhammar and Andersson).

New models and methods for determining the behavior of bolted connections are still being developed. Several of the new models that are being examined include finite element modeling. These models are beginning to address issues that are not present in the EYM such as non-linear material behavior and friction (Patton-Mallory et. al., 1997).

CHAPTER III

EXPERIMENTAL METHODS

Two different formulations of wood plastic composites were tested with 12.7 mm bolts. The testing regimen included dowel bearing strength tests, bolt bending yield strength tests, and double shear connection tests. The sample size used for most tests was ten. The sample size was low because the COVs for WPCs are low when compared to timber. The sample size required by ASTM D 2915-94, ”Standard practice for evaluating allowable properties of structural lumber”, for a 95% confidence of the mean is six for the COV seen in this material. ASTM Standard D 5456-96, ”Standard specification for evaluation of structural composite lumber products”, recommends a minimum sample size of 10 for establishing design values for wood base composites.

Bolt Specimens

The dowels that were tested were all 12.7 mm diameter ASTM 307 hex bolts. The bolts were full body diameter, which means the shaft was the same diameter as the threads. Three different lengths of bolts were used in this project consisting of 14, 19.1, and 26.8 cm long bolts. The bolts all came from a single domestic manufacturer, and were drawn from the same batch to reduce the variability of the test population. This group of bolts was used in all testing.

Wood Plastic Specimens

An extruded wood plastic composite composed of a 50/50 mixture of low-density polyethylene and wood particles obtained at a local retailer was the first material tested. The material had the dimensions of 38 mm by 139.7 mm with lengths of 3.66 m and 4.9 m. The material was then cut and glued to appropriate dimensions for testing. A picture of the composite is shown in Figure 3.1.

A second type of wood plastic composite composed of a 70/30 mixture of high-density polyethylene and wood flour was tested as well. This composite was manufactured at the Wood Materials and Engineering Laboratory at Washington State University using a twin-screw extruder. The material was continuously extruded as a hollow box section. A picture of the extruded shape is shown in Figure 3.2. The top and bottom flanges of the box section were then removed. These flanges had dimensions of 17.9 cm by 102 cm by 0.765 cm. Both sides of the flanges were then planed to minimize residual stresses caused by the extrusion process. The panels were then glued together with a PVA adhesive to form the thickness required for testing, and then clamped for two hours in a hydraulic press.

Conditioning for plastic lumber specimens is set forth in ASTM D618-96, " Standard Practice for Conditioning Plastics for Testing". This standard specifies a conditioning regimen of 23°C ± 2°C, and a relative humidity of 50% ± 5%. These conditions apply for the testing environment as well. Conditioning for wood connection tests is in ASTM D1761-95,"Standard Test Methods for Mechanical Fasteners in Wood". The wood standard recommends conditioning samples at 20°C ± 3°C, and a relative humidity of 65% ± 3%. WPC samples were stored and tested in ambient lab conditions. Temperatures ranged from 20° to 25° C, and the relative humidity was 30% ± 5%. The lower relative humidity in the testing environment was judged to have minimal effect on the test specimen due to the encapsulation of the wood fiber by the plastic. Water absorption rates in wood plastics is typically less than 2% after several days of complete immersion illustrating the resistance of this material to moisture (English and Falk, 1996).

Figure 3.1: LDPE composite

Figure 3.2: Cross section of HDPE composite

Bolt Bending Yield Strength Tests

Bolt bending yield strength tests were conducted on thirty of the 12.7 mm diameter bolts. The bolts were selected at random from the population that originated from the same lot. The purpose of this test was to determine the average bolt bending yield strength (F_{yb}) for the population to predict the yield point using the EYM. This test used was modified from the nail standard by Pollock (1997), since there is no current standard in the United States to determine the F_{yb} of bolts. The current nail standard is ASTM F1575-96, ”Standard test method for determining bending yield strength for nails”. A three-point bending test with center point load was implemented with a span of 102 mm that is consistent with the span to fastener diameter ratio in the nail standard. A picture of the test setup is shown in Figure 3.3. The bearing points and loading head were fabricated of 19.1 mm diameter SAE Grade 8 bolts to minimize the effects of fixture deformation on the results. The tests were run at a constant displacement rate of 0.11 mm/s. Bolt resistance was recorded from a 245 kN load cell, and displacements were acquired from the internal LVDT at a rate of 2 Hz.

The yield load was then determined from the data using the 5% diameter offset method. Bolt bending yield strength (F_{yb}) was calculated from yield load by the following equation:

$$F_{yb} = \frac{M}{S_p} = \frac{3P_y s_{bp}}{2D^3}$$

Where:

M = bending moment in bolt

S_p = plastic section modulus for bolt

P_y = bolt yield load

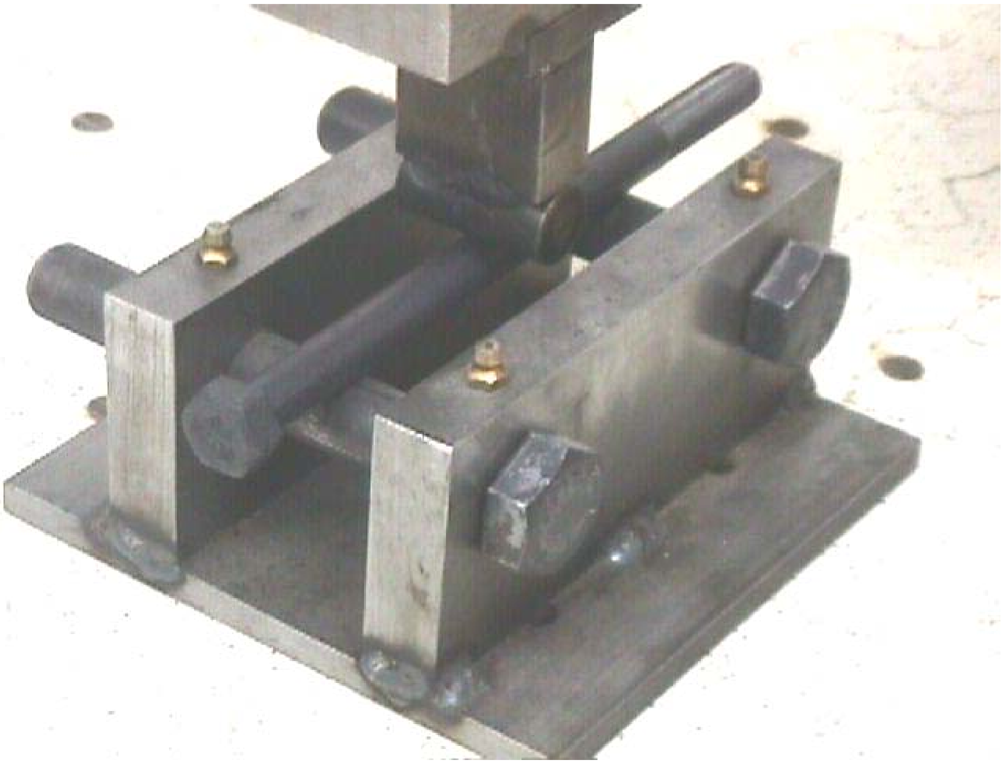

Figure 3.3: Bolt bending yield strength test assembly

s_{bp} = spacing of bearing points

D = bolt diameter

Dowel Bearing Strength

Dowel bearing strength tests were performed on WPC specimens according to ASTM D5764-95, ”Standard test method for evaluating dowel-bearing strength of wood and wood based composites”. Four specimens were taken from each board of the LDPE composite to determine the dowel bearing strength of each specimen to be tested. Ten samples of the HDPE composite were tested. All tests were loaded parallel to the extruded directions.

A 127.5 mm by 63.8 mm by 38.3 mm segment was taken from both composite types. The samples were then drilled in the middle with a 14.3 mm diameter bit, and then cut in half through the bolt hole for a final specimen dimension of 63.8 mm by 63.8 mm by 38.3 mm. Both halves of the original parcel were used in testing. The dowel bearing specimen is illustrated in Figure 3.4.

The testing assembly consisted of a circular base plate that held the sample secure with adjustable clamps, and a top bearing member that pressed the bolt into the specimen. A picture of the dowel bearing test setup is shown in Figure 3.5. The tests were run on a MTS hydraulic testing machine with a 97.8 kN load cell. A constant displacement rate of 0.02 mm/s was used, and the tests were run to a maximum displacement of 6.4 mm. The resistance load was recorded from the load cell, and displacements were acquired from the internal LVDT at a rate of 2 Hz.

The yield load for the dowel bearing samples was determined with the 5 % diameter offset method. Dowel bearing strength (F_e) was then determined by the following equation:

$$F_e = \frac{P}{D \cdot t}$$

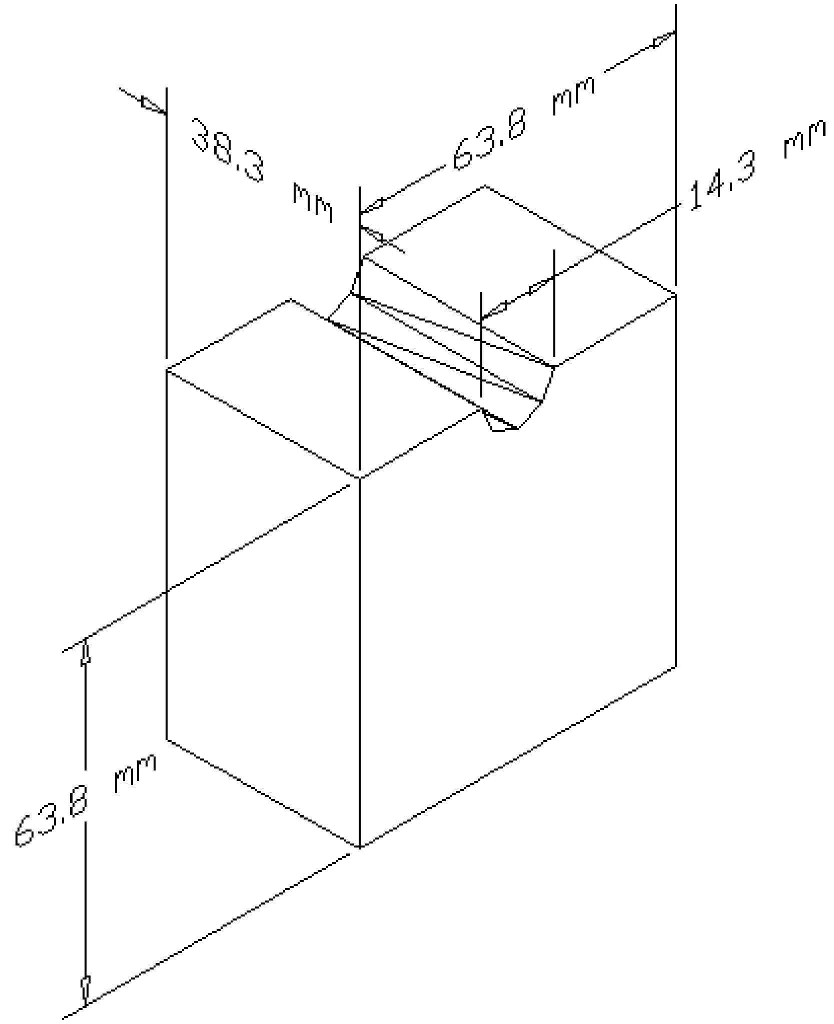

Figure 3.4: Illustration of dowel bearing sample

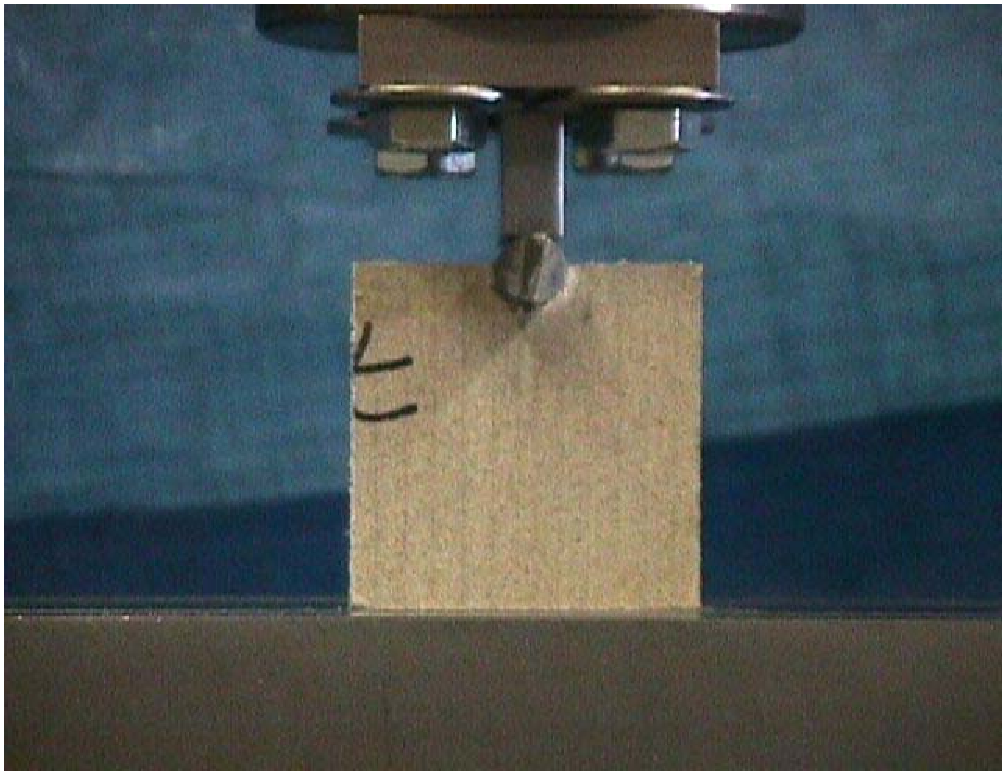

Figure 3.5: Dowel bearing strength test assembly

where:

F_e = dowel bearing strength

P = yield load

D = bolt diameter

t = thickness of dowel bearing specimen

Load Rate Testing

Load rate tests in dowel bearing were conducted on both composites. Six different dowel bearing displacement rates were tested at 196 mm/s, 26 mm/s, 6.4 mm/s, 2.6 mm/s, 0.51 mm/s, and 0.02 mm/s. Tests were conducted both parallel and perpendicular to the extrusion direction. Three specimens were tested at each loading rate for each case. Samples were of the same dimensions listed above. Tests were run to a maximum displacement of 6.4 mm. The tests were run on a MTS hydraulic testing machine with a 97.8 kN load cell. Data was recorded from the load cell and internal LVDT at a rate ranging from 2 to 2000 Hz depending on the testing speed.

Full Connection Testing

The connection tests followed the general provisions set forth in ASTM D-5562-95, ”Standard test methods for bolted connections in wood and wood-base products”. All connections tested were in double shear and were loaded in tension. The bolts that were used in this configuration came from the same population as the bolt bending yield strength tests. Two different connection geometries were tested for both composites. The first geometry for the LDPE composite was designed for a mode I yielding, and will be referred to as the mode I connection tests. Tests listed as mode I had member thickness of 38.3 and 19.1 mm for main and side members, respectively. The HDPE test designated mode IIIa has the same dimensions as the LDPE mode I test. The second test setup was designed for a mode III yielding state in both materials. The mode IIIb tests consisted of a 76.5 mm main member and 38.3 mm side members. These two cases provided data for relatively brittle and ductile modes of failure. Ten tests for each case were conducted. A schematic of the boards used in testing can be found in Figure 3.6. The edge and end distances of the assembly were designed using the 1997 NDS criteria for maximum fastener capacity. The tests performed for each composite are summarized in Table 3.1.

Figure 3.7 shows test setup for the double shear connection test. The fixture is composed of four A-36 steel brackets that are bolted into T-slotted tables. The T-slots enabled the brackets to be adjusted appropriately for each connection tested. Four 19.1 mm diameter high strength bolts were used to hold the specimen in the brackets. The bolts were a mixture of SAE Grade 8 with a minimum tensile strength of 1034.2 MPa, and 4140 steel bolts with a tensile strength of 1379 MPa. A spacer block was implemented at the base between two side members to keep the connection square. The bolt was placed in the connection so that the threads of the bolt did not come into contact with the WPC. The bolt was then "hand tightened" to secure the connection.

Tests were run at displacement rates for failure to occur in the 10 to 20 minute range to comply with the testing standard. Both of the LDPE composite and the mode IIIb HDPE composite tests were run at a rate of 0.04 mm/s. The mode IIIa HDPE test was run at a rate of 0.02 mm/s. The displacement rate was controlled by the internal LVDT of the test machine.

Two external displacement transducers were mounted directly on the specimens to measure the localized displacement on both sides of the connection. The transducers were placed as close to the 12.7 mm bolt as possible without interfering with the test. A picture of the transducer is shown in Figure 3.8 The displacement data from the transducers were then averaged for analysis. The test was run on the 245 kN hydraulic test machine. The internal load

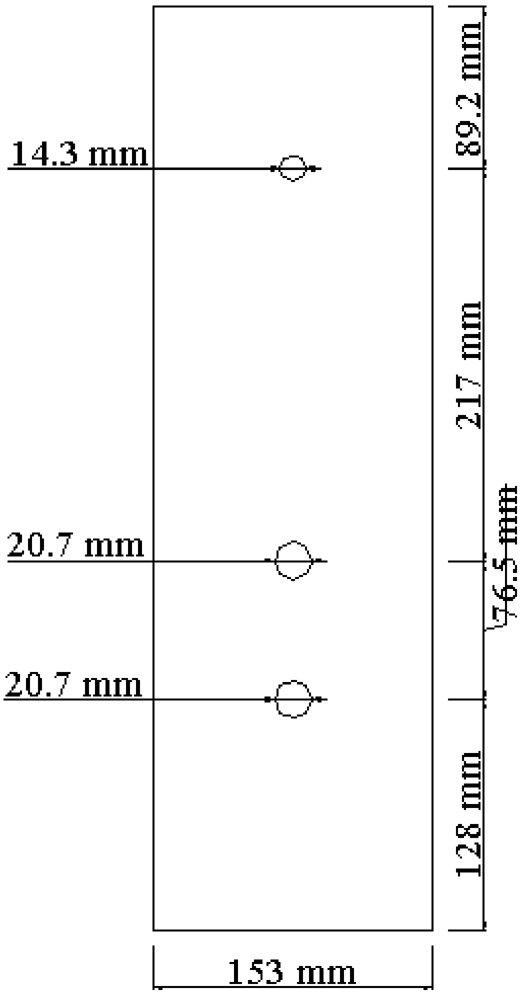

Figure 3.6: Drawing of full connection board sample

Table 3.1 Summary of performed tests

Material	Dowel Bearing Tests	Mode I Yield	Mode III Yield	Unconstrained Tests
50/50 wood to low density polyethylene composite	4 tests per board (24 boards were used)	10 tests	10 tests	3 tests per yield mode

Material	Dowel Bearing Tests	Mode IIIa Yield	Mode IIIb Yield	Unconstrained Tests
HDPE (High Density Polyethylene) Extruded Wood Composite	10 samples	10 tests	10 tests	3 tests per yield mode

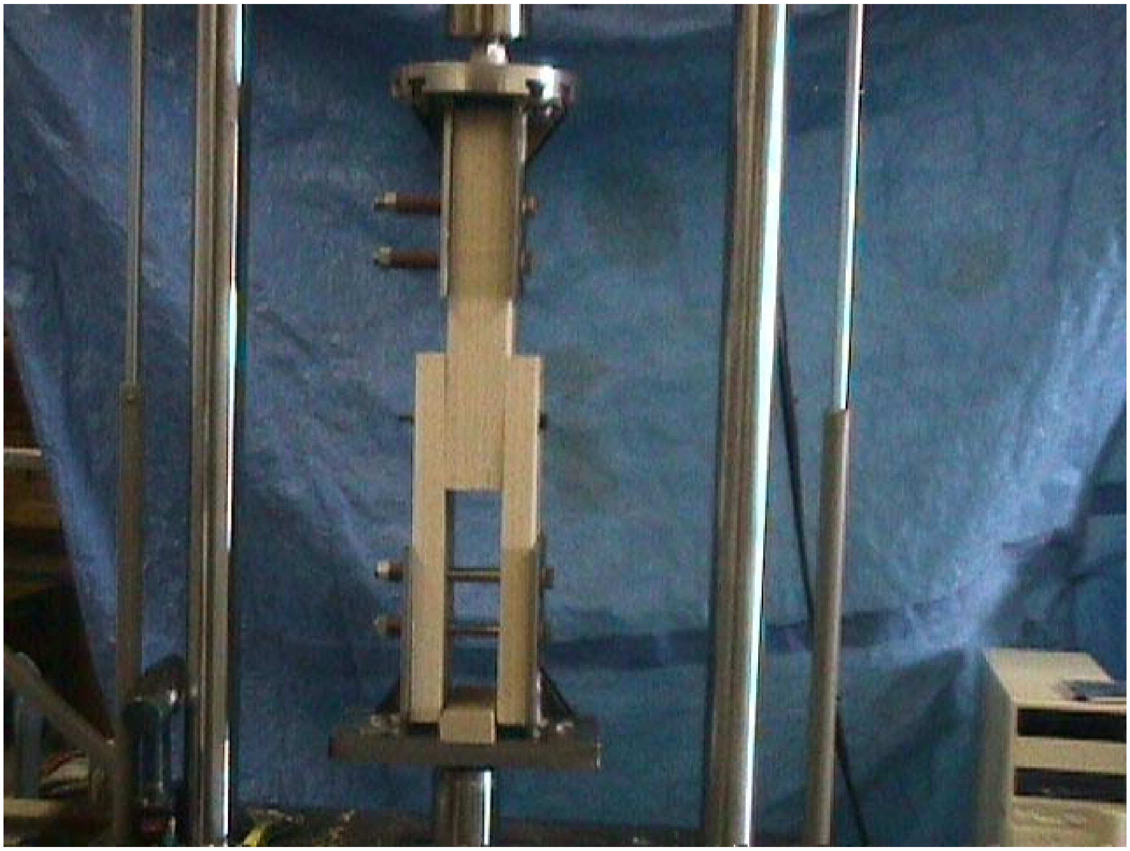

Figure 3.7: Full connection test setup

Figure 3.8: Picture of linear transducer mounted on connection sample

cell was used to record the resistance of the connection. The type of failure and behavior of the material was recorded as well.

Unconstrained Connection Tests

Three samples from each testing group were tested in an unconstrained setup. There is currently no standard for this type of procedure. The unconstrained tests were conducted in the same way as the other connection tests except for the absence of nuts and washers, and a longer bolt. A picture of the unconstrained connection test is shown in Figure 3.9. The bolt was centered loosely in the specimen. The displacement rate implemented for all tests was 0.04 mm/s. The tests were stopped after peak load or at 12 mm deflection.

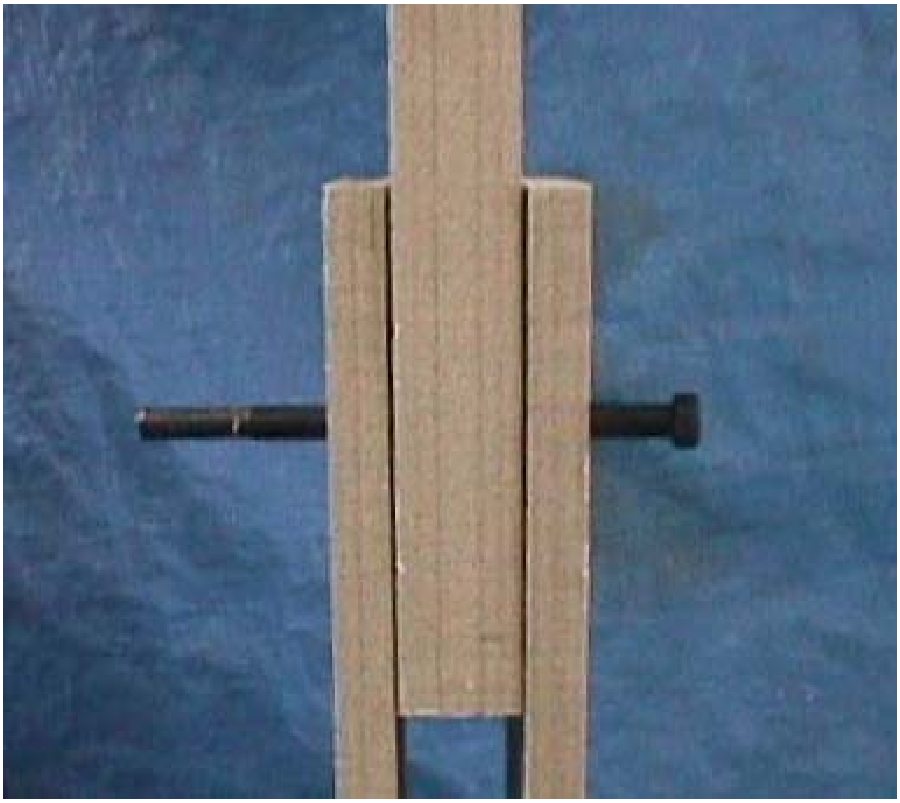

Figure 3.9: Unconstrained connection test setup

CHAPTER IV

RESULTS AND DISCUSSION

Dowel Bearing Results

The average dowel bearing strength of the LDPE composite was 23.4 MPa for parallel to the extruded direction. The coefficient of variation (COV) was 3.4 % for all samples, and the within-piece COVs averaged under 2 % per board. The dowel bearing load displacement curve for WPCs appears to follow an almost perfect elastic-plastic model, as shown in Figure 4.1. The deformation of the LDPE composite in dowel bearing was localized around the bolt hole and perpendicular to the loading plane. Figure 4.2 illustrates this behavior in several pictures. The dowel bearing specimens never reached a distinct failure point despite deflections of over 12 mm.

The average dowel bearing strength of the HDPE composite parallel to the extruded direction was 35.7 MPa for the ten samples tested, and had a COV of 2.6 %. A typical load-displacement curve for dowel bearing of the HDPE composite is shown in Figure 4.3. This material failed shortly after yielding as can be seen in the curve. The failure surface appeared to occur between the hexagonal strands that formed the material as shown in Figure 4.4. A zig-zag pattern was observed at the base of the sample where the failure occurred. Out of plane deformation that was similar to the LDPE composite was observed, but not to the same extent.

The dowel bearing values for several common species groupings of timber are shown in Table 4.1. The LDPE composite dowel bearing strength is lower than any of the major species for parallel to grain orientation, but is equivalent in strength for perpendicular to the grain

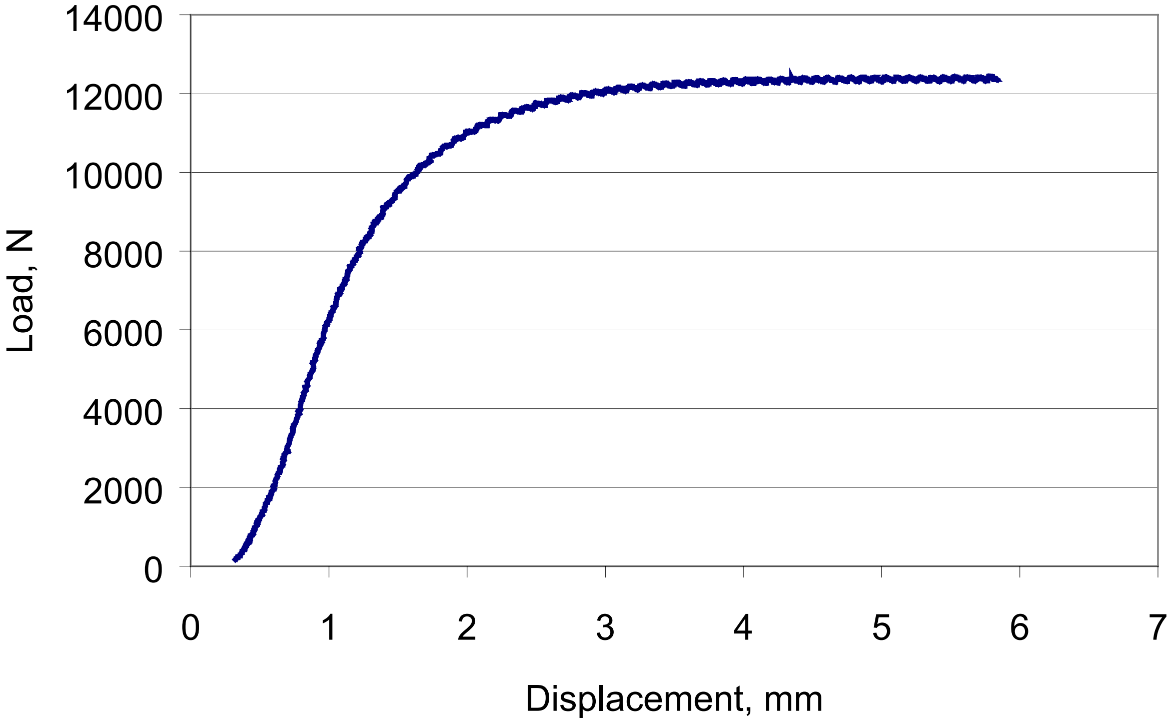

Figure 4.1: Typical dowel bearing curve for LDPE composite loaded parallel to extruded direction

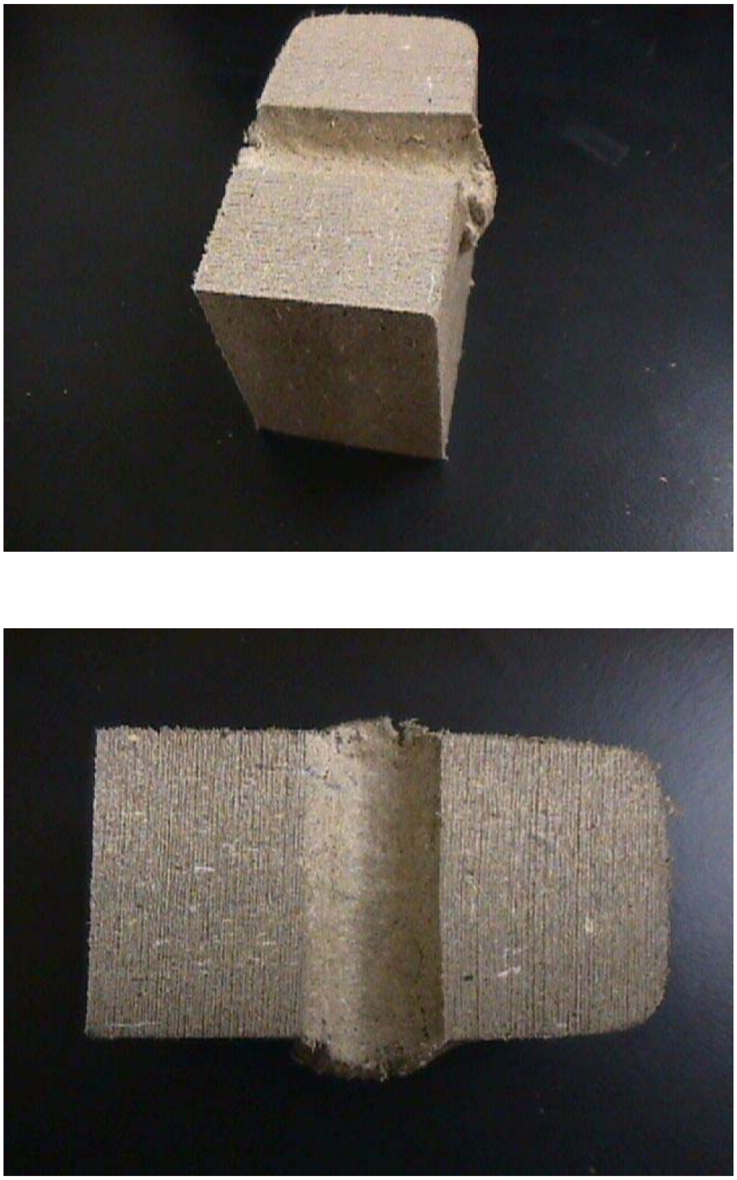

Figure 4.2: Pictures of "failed" LDPE composite dowel bearing sample

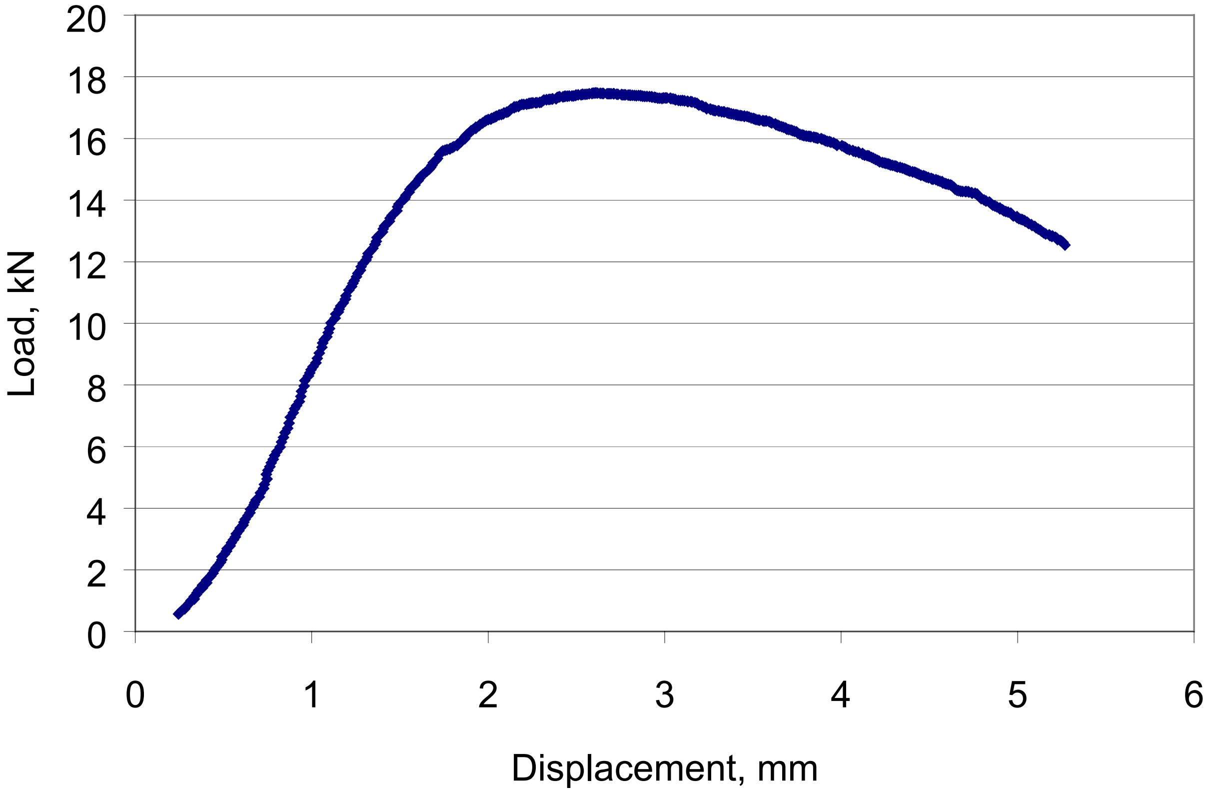

Figure 4.3: Typical dowel bearing curve for HDPE composite loaded parallel to extruded direction

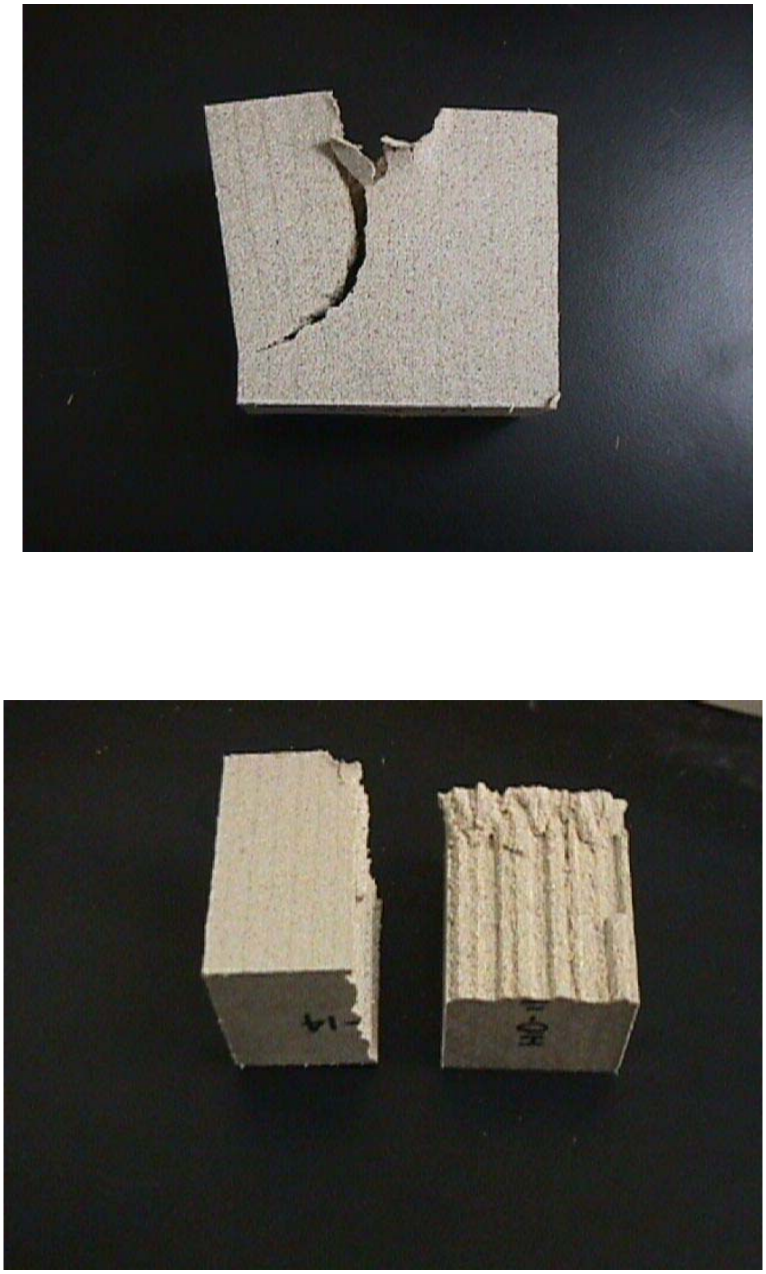

Figure 4.4: Pictures of failed HDPE dowel bearing samples

Table 4.1: Dowel bearing strength values from NDS (1997) and testing

	Douglas Fir-Larch	Hem-Fir	Spruce-Pine-Fir	Southern Pine	LDPE composite	HDPE composite
Parallel	38.6 MPa	33.1 MPa	32.4 MPa	42.4 MPa	23.4 MPa	35.7 MPa
Perpendicular for 12.7 mm bolts	21.7 MPa	17.6 MPa	16.9 MPa	25.2 MPa	27.8 MPa	41.8 MPa

applications. The HDPE composite is higher than hem-fir and spruce-pine-fir groupings for parallel to grain values, and lower than douglas fir-larch and southern pine. For perpendicular dowel bearing strength values the HDPE composite was at least twice as high as three of the four species group listed

Displacement Rate Study

Figure 4.5 shows the results from the dowel bearing load rate study, and Figure 4.6 illustrates this data on a semi-logarithmic plot. A regression analysis was performed on the logarithm of load rate verse dowel bearing strength. The analysis showed a good fit with an R^2 of 0.98 for parallel and 0.99 for perpendicular to the extruded direction for the LDPE composite. This exponential relationship of displacement rate to dowel bearing strength is similar to that reported for wood by Girnhammar and Andersson (1986), although the specific parameters of the curves are different. The slope of the semi-logarithmic curve is steeper for WPCs than is published for wood by the NDS (1997), showing that WPCs are more sensitive to load rate than wood. The regression analysis on the HDPE composite showed a well fitting exponential regression with an R^2 of 0.99 for parallel and 0.98 for perpendicular to the extruded direction. Both WPCs showed a similar response to load rate effects.

The reason for examining load rate effects was to determine how changing the deflection rate would effect the results in later testing. The wood standards use a time to failure criteria for testing instead of a common load or displacement rate. This time to failure criteria also covers a broad time range; for example, ASTM standard D5764-95 for dowel bearing states that the maximum load should be reached in 1 to 10 minutes. This range of testing times could cause significant variation in dowel bearing results. In the LDPE composite, the dowel bearing

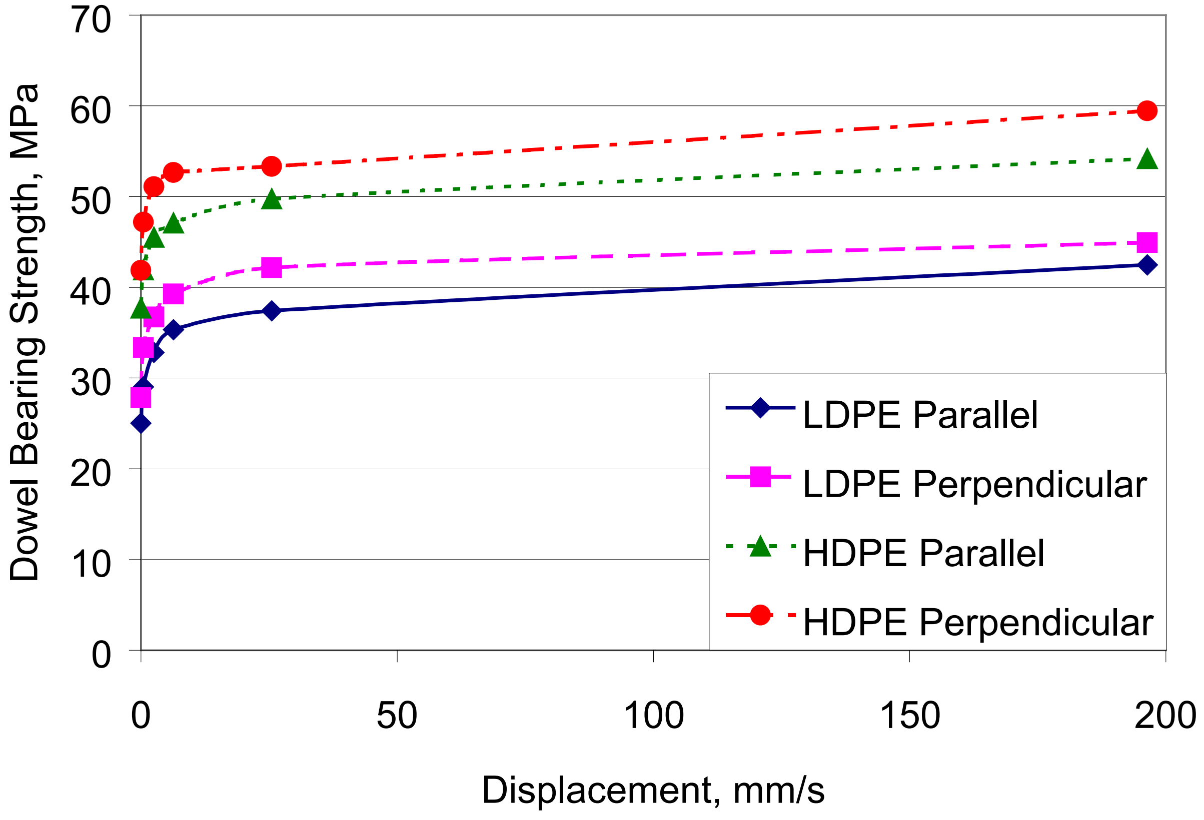

Figure 4.5: LDPE composite displacement rate verse 5% diameter offset dowel bearing strength curves

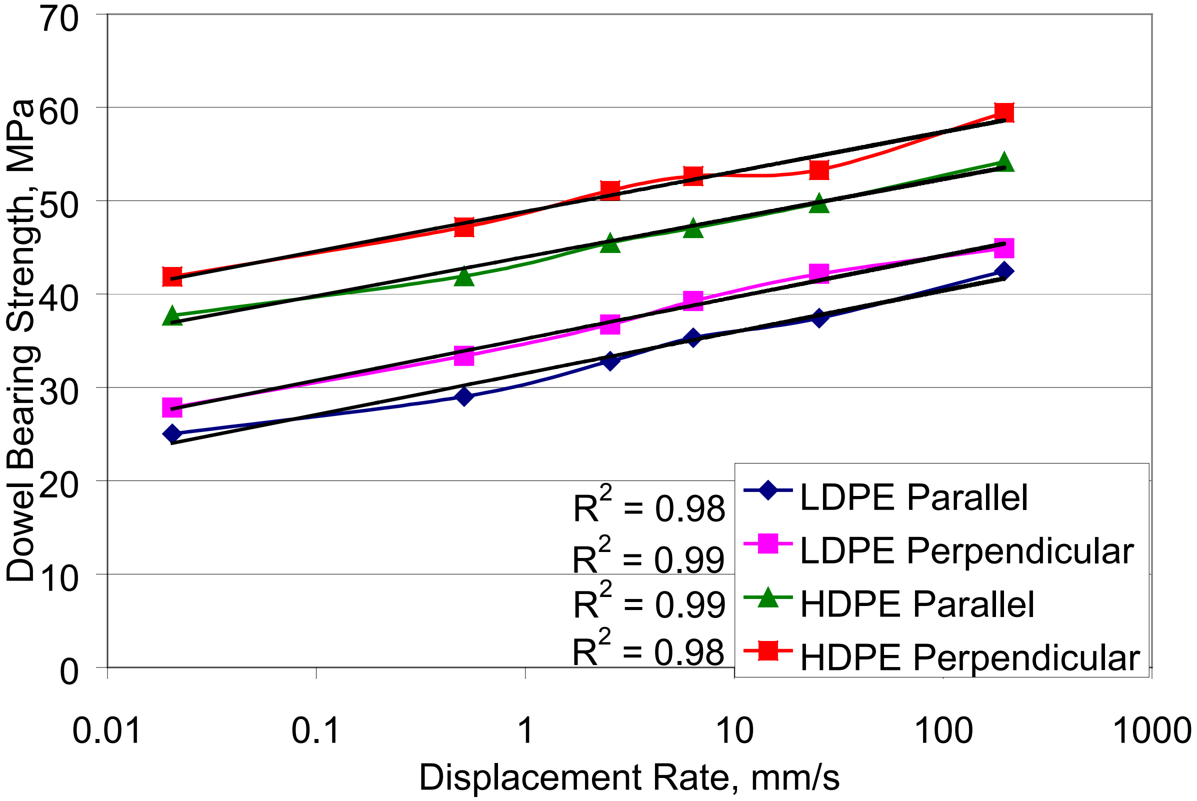

Figure 4.6: LDPE composite semi-logarithmic graph of displacement rate verse 5% diameter offset rate dowel bearing strength with regression curves superimposed.

strength could range from 21.8 MPa to 26.2 MPa using the testing range specified in the standard.

For both composites dowel bearing strength was higher perpendicular than parallel to the extruded directions by about 10%. This result is most likely caused from the extrusion process. The LDPE had nearly identical behavior for both the perpendicular and parallel dowel bearing tests; however, the HDPE composite failed quite differently. The parallel test failed in shear as described in the results above, but the perpendicular tests failed in delamination of the glued slats after yielding. The delamination was caused by the prying action of the out of plane deformation right under the dowel. Part of the reason for the higher strength for the perpendicular tests were that it could not fail as easily in shear due to the orientation of the strands in the material. A similar effect may have been present in the LDPE composite, but it was not observable in the tests that were run. The LDPE manufacturer reported a higher compression strength perpendicular to the extruded direction than parallel. The perpendicular compression strength was reported as 13.4 MPa, and the parallel to the extruded direction compression strength was 12.5 MPa. This correlates with the findings of a higher perpendicular than parallel dowel bearing strength value.

Bolt Yielding Results

Average bolt bending yield strength was 365 MPa with a COV of 1.7%. This is higher than the value published in the NDS of 310 MPa for ASTM 307 bolts (AF&PA, 1997). A typical bolt bending load verse displacement curve can be seen in figure 4.7. The low COV for this population was achieved by sampling bolts from the same lot by a single manufacturer. It

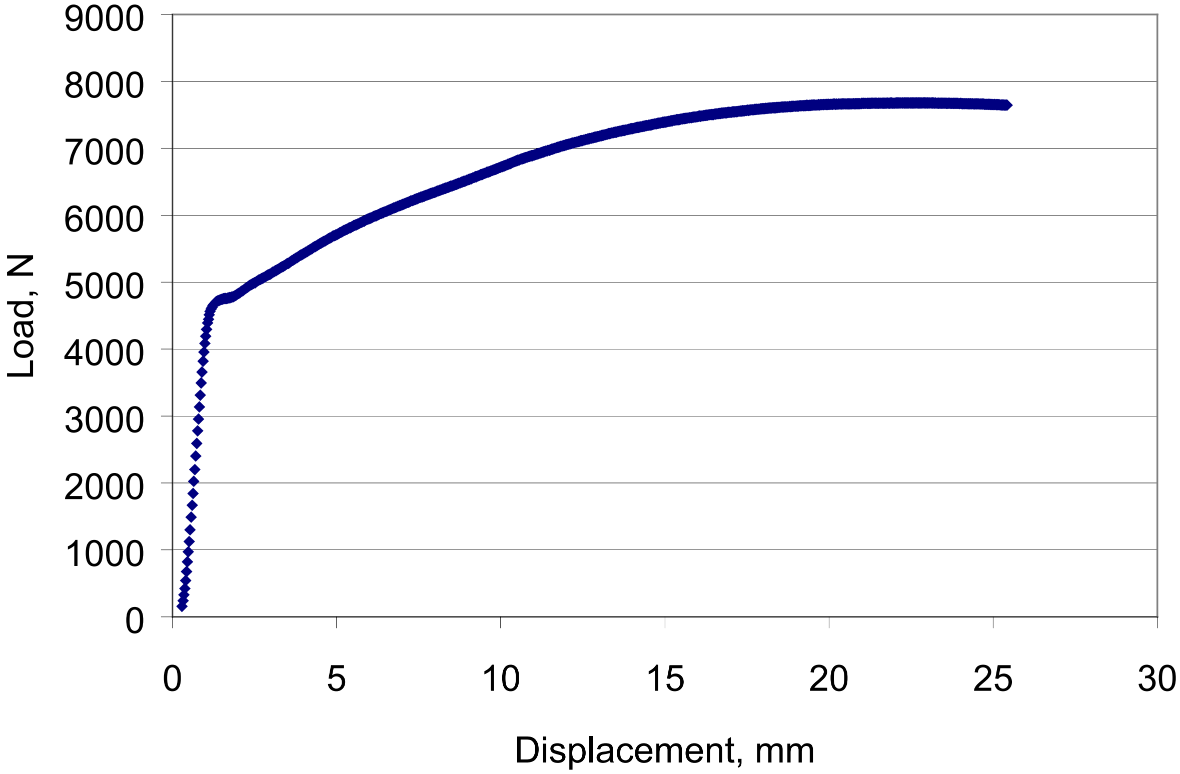

Figure 4.7: Typical bolt bending yield strength graph for ASTM 307 bolts

also facilitates an accurate estimate for bolt yielding strength in the EYM, and a better prediction for connection yield.

Full Connection Testing Results

A typical load-displacement curve for the LDPE mode I tests is shown in figure 4.8a. An initial linear region is clearly present in this curve before the yielding point. Results of connection testing are summarized in Table 4.2. Average ultimate load for the mode I connections was 22.9 kN, and the average displacement at failure was 23 mm. These specimens all failed through the cross section of the member in tension due to the concentrated stress at the bolt hole. An unexpected observation was that the mode I connections actually yielded in mode III at failure. The reasons for this mode change are likely due to the constraining effect of the nut and washers. The average 5% diameter offset yield value for the connections was 11.1 kN and the predicted yield was 11.4 kN.

Figure 4.8b shows a typical load-displacement curve for the LDPE connections configured in the mode III geometry. Average ultimate load for the mode III connections was 38.1 kN, and displacement at failure averaged 28 mm. Every connection failed in tension through the member cross section at the bolt hole due to concentrated stresses. The test yield mode at failure was also different than the predicted yield mode. All of the connections were mode IV at failure with two hinges per shear plane instead of mode III with only one plastic hinge per shear plane. The average 5% diameter offset yield value was 10.1 kN and a predicted value of 13.2 kN. The experimental value for yield is nearly 30% lower than the predicted value. It is also noteworthy that the COV for this particular experiment group was much higher than any other group tested. This high COV was caused by an outlier that had a 5% offset yield

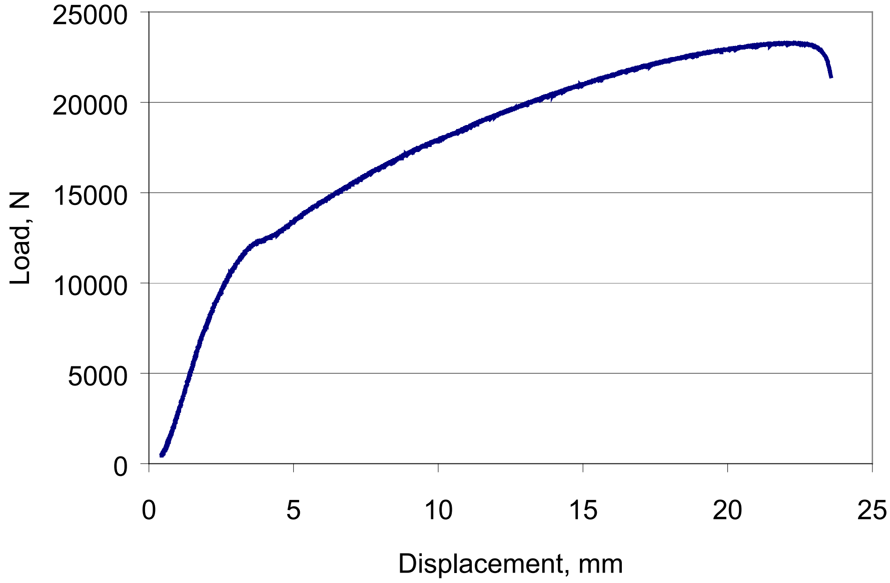

Figure 4.8a: Typical load-displacement curve for LDPE mode I connection

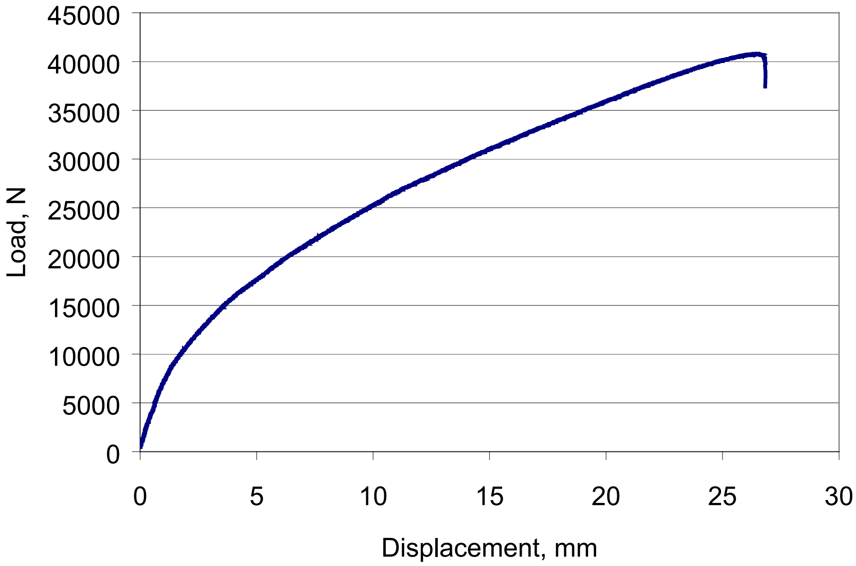

Figure 4.8b: Typical load-displacement curve for LDPE mode III connection

Table 4.2: Summary of full connection testing results

	LDPE Mode I	LDPE Mode III	HDPE Mode IIIa	HDPE Mode IIIb
Average Yield	11150 N	10050 N	14300 N	14900 N
Standard Deviation	719	1559	111	270
COV	6.5%	15.5%	3.5%	8%
Minimum	9800 N	6700 N	13600 N	13800 N
Maximum	11800 N	11800 N	15200 N	17300 N
Mode at Failure	Mode III	Mode IV	Mode III	Mode IV
Predicted Yield	11400 N	13200 N	14900 N	17400 N
Predicted Yield Mode	Mode I	Mode III	Mode III	Mode III

strength of 6.7 kN. When the two lowest yield values are discarded the average experimental yield was 10.7 kN. This value is still 23% lower than the prediction. This outlying result led to the investigation of how bolt containment affected yielding. The results of this study are discussed later in this chapter.

Figure 4.9a illustrates the typical load-displacement curve for the mode IIIa HDPE connections. The shape is similar to the LDPE Mode I curve where a clear initial linear region is present before the yield point. The average ultimate load for the connection was 25.1 kN, and displacement at failure was 11 mm. The connection failed in the predicted mode III yielding. Every connection failed in tension through the member cross section due to concentrated stress at the bolt hole. The experimental yield point was 14.3 kN and the predicted yield was 14.9 kN.

Figure 4.9b illustrates the typical load-displacement curve for the mode IIIb HDPE connections. The shape of this curve is similar to that of the Mode III LDPE curve. The curve appears to follow a logarithmic function, however there is no distinct yield point similar to that observed in the mode IIIa HDPE curve. The average ultimate load for the connection was 47.6 kN, and the displacement at failure was 24 mm. All of the connections were in mode IV at failure instead of mode III as predicted. The failure mechanism for every connection was due to concentrated tensile stresses at the bolt hole. The average 5% diameter offset yield point was 14.8 kN, and the EYM predicted yield point was 17.2 kN. The experimental value was 16.2 % lower than the EYM prediction.

There appears to be a correlation in geometry effects between the two materials. The LDPE mode I and the HDPE mode IIIa connections which had the same geometry appear to follow the EYM predictions extremely well. The HDPE mode IIIa test in fact was originally

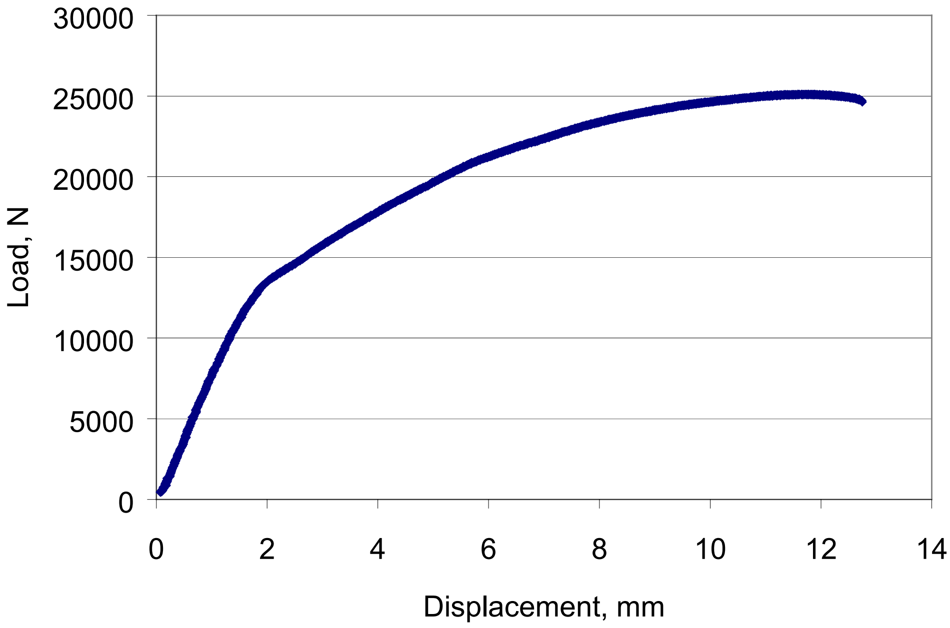

Figure 4.9a: Typical load-displacement curve for HDPE mode IIIa connection

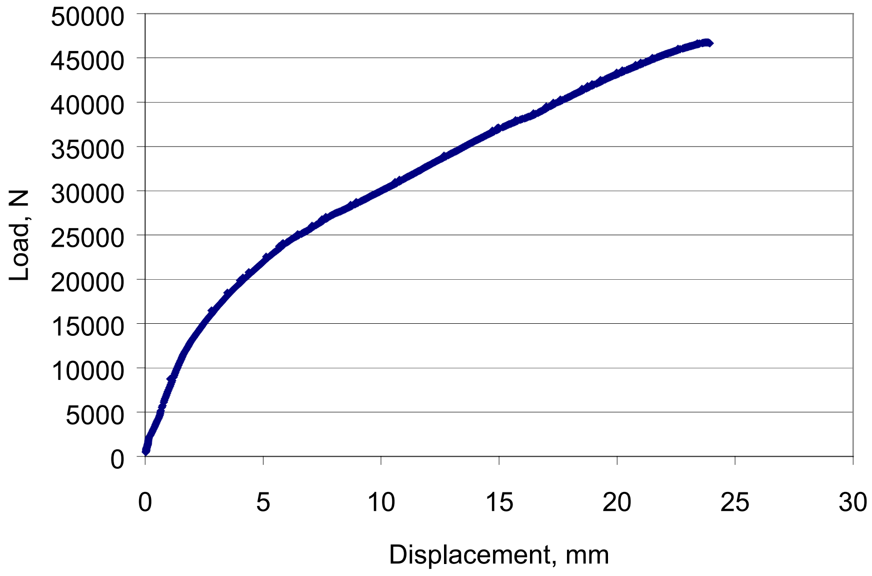

Figure 4.9b: Typical load-displacement curve for HDPE mode IIIb connection

intended to be a mode I failure, but the HDPE composite was stronger in dowel bearing than anticipated. The prediction is in fact on the border of the two modes. The various yield predictions for the test groups can be found in Table 4.3. This means that the yield mechanism was most likely similar in these two test groups. The similar shape of the two test curves supports this. The major factor of yielding in both of these tests was the bearing strength of the material. This means that the connection behavior at yielding was like the material in a simple dowel bearing test. The EYM only uses dowel bearing strength in the calculation of yielding for mode I, so there should be an accurate approximation of the experimental yielding point by the EYM. These load displacement curves also appear to correspond to what McLain and Thangjitham (1983) classifies as a type A curve. McLain and Thangjitham (1983) describe these curves as having two distinct regions. The initial region is described as generally linear below the proportional limit, and the load displacement curve tends to be linear after the point of inflection as well. This type of curve usually indicates a mode III failure of the connection (McLain and Thangjitham, 1983).

The LDPE mode III and the HDPE mode IIIb connections also appear to behave in a similar manner. Both of the curves for these materials do not have a clear yielding point, and the 5% offset approximations for both test groups are significantly lower than the predictions. These two tests are more of a combination of bolt yielding and material crushing than the previous two tests due to connection geometry. The free body diagram of a bolt in mode III failure is shown in figure 4.10. The edges of the side members of the wood plastic composite are what causes the initial yield of the material as seen from the figure. Finite element modeling research of connections by Patton Mallory et. al. (1998) found that the stress in the edges of a connection with larger aspect ratios are unevenly distributed, and tend to be higher than the yield limit that is

Table 4.3: Average yield predictions for each yield mode

		EYM Predictions		
Connection	5% offset test value	Mode I	Mode III	Mode IV
LDPE I	11150 N	11400 N	12200 N	17200 N
LDPE III	10050 N	20400 N	13200 N	17200 N
HDPE IIIa	14300 N	17100 N	14900 N	21000 N
HDPE IIIb	14900 N	33000 N	17400 N	21000 N

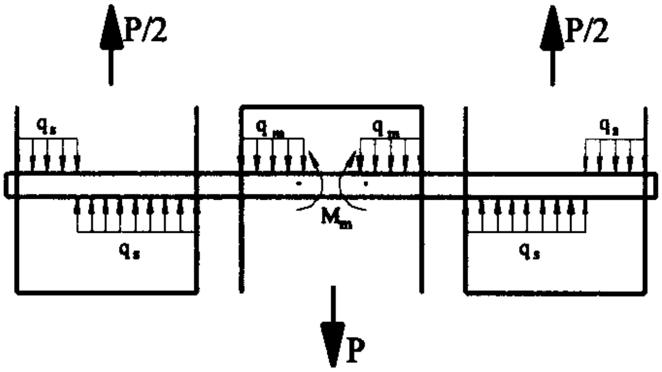

Figure 4.10: Free body diagram if double shear mode III yielding (AF&PA)

assumed in the EYM. The stresses in the connection shift when the displacement increases, and a larger proportion of the WPC is subjected to plastic yielding. The bolt is also yielding in Mode III simultaneously. Unaccounted for tensile stresses are then introduced by the combination of bolt bending and out of plane deformation of the WPC. This containment factor and friction are most likely the cause of the high ultimate loads seen in this connection geometry. The effects of containment are discussed in greater detail in a later section. The low 5% diameter offset yield value for this geometric setup is most likely caused by the early yielding of the WPC described above. These two test group load displacement curves do not seem to be a type A curve because there is not a clear deflection point.

Unconstrained Connection Results

Three tests were run per test group without nuts and washers to determine the effect that constraint had on a WPC bolted connection. It was found that the constraint provided by the nuts and washers in the connection tests had a significant effect on the maximum loads. Table 4.4 quantifies the effects that constraints had upon the connections. Constraints increased the average maximum load for mode I LDPE connections by 75% and mode III LDPE by 290%. Constraints increased the maximum load for the HDPE composite by a slightly smaller margin with a 64% and a 178% increase for the HDPE mode IIIa and HDPE mode IIIb test groups respectively. Gattesco (1998) examined the effects of bolt constraints in wood and found that constraints increased parallel-to-grain ultimate loads by 10% and perpendicular to grain ultimate loads by 40%. The unconstrained LDPE mode III and the unconstrained HDPE mode IIIb connections yielded in mode III instead of the mode IV yielding that was seen in the constrained tests of the same geometry; however, the unconstrained mode I connections still yielded in mode

Table 4.4: Summary of unconstrained connection results

	LDPE Mode I	LDPE Mode III	HDPE Mode IIIa	HDPE Mode IIIb
Average Unconstrained Yield	8500 N	9900 N	12800 N	12100 N
Average Unconstrained Maximum Load	12900 N	13600 N	15300 N	17100 N
Average Constrained Yield	11150 N	10050 N	14300 N	14900 N
Average Constrained Maximum Load	22900 N	38100 N	25100 N	47600 N
Predicted	11400 N	13200 N	14900 N	17400 N

III. The unconstrained HDPE mode IIIa connections still yielded in mode III. The 5% diameter offset values were lower for all unconstrained groups when compared to the constrained connections as illustrated in figure 4.11. The tests did not reach a failure point despite excessive deflections. The side members peeled away from the main member and slid down the bolt after the maximum load was achieved.

The maximum load of the unconstrained connection does not represent the ultimate load of the connection due to the fact that the side members started to slide down the bolt. This maximum load can be termed as a fully yielded connection, meaning that by the time the connections starts to come apart that the bolt and member have yielded completely. This concept of full yielding is supported by the finding that the maximum unconstrained connection load matches fairly closely to the EYM predicted value, with an average error of 5%.

These results support the notion that the constraints were partially responsible for the change in yield mode. A second possible factor for the yield mode shift is the high ductility of WPCs when compared to wood. The influence of bolt containment also helps to explain the outlier from the mode III connection test mentioned in the previous section. This outlier yielded at almost the same value as the unconstrained tests. Hence, the cause for the lower yield value could have been due to an improperly tightened nut.

Alternate Yield Definitions

Several different approaches were taken to examine how the definition of yield point affected the prediction accuracy of the EYM. Table 4.5 shows the average yield loads for the different yield definitions. These data were compiled by first using the 5% diameter offset line as described previously, and then changing the percentage offset of the diameter of the bolt used

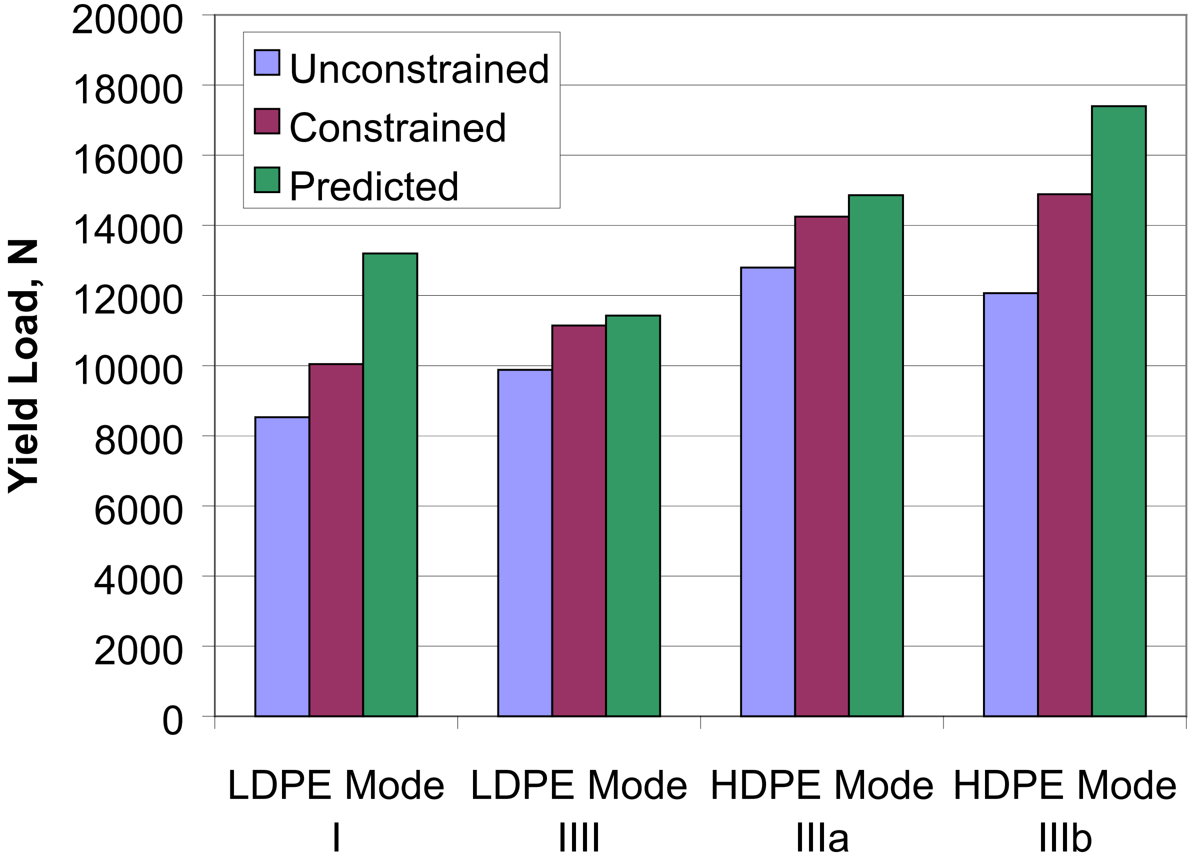

Figure 4.11: 5% diameter offset values for unconstrained tests, constrained test, and predictions

Table 4.5: Yield load for WPCs at several different offsets

	5% offset	8% offset	10% offset	12% offset	Predicted
LDPE Mode I	11148 N	11919 N	12222 N	12512 N	11430 N
LDPE Mode III	10045 N	11536 N	12503 N	13217 N	13202 N
HDPE Mode IIIa	14254 N	15485 N	16379 N	16800 N	14860 N
HDPE Mode IIIb	14887 N	17125 N	18293 N	19397 N	17400 N

in the model. The yield predictions were calculated using the offset listed for the dowel bearing and bolt yielding strengths. The different offsets that were examined were 5%, 8%, 10%, and 12% of bolt diameter.

A second definition was used for yield analysis based on displacement instead of an offset criterion. Table 4.6 shows the average yield loads using different displacements. The test data were calibrated so that a line fitting the elastic region would pass through zero. Yield load was then recorded for corresponding displacements on the shifted curve. The four displacements that were examined included 1.28 mm, 2.55 mm, 3.83 mm, and 7.65 mm.

Figure 4.12 illustrates how several of the alternative yield definitions compare to the predicted value. When considering the LDPE composite, the test value seems to most closely match the 3.83 mm displacement definition of yield. Theilen et al. (1998) also found that a displacement of 3.83 mm was best for predicting yield for ring-shank nail connections in southern pine. This yield definition does not hold true for the HDPE composite where the test values exceed the predicted yield by 23% and 17% for the mode IIIa and mode IIIb tests respectively. The predicted yield appears to approximate the 8% diameter offset better than the other yield definitions that were tried, but the predicted did not consistently match this offset. The predicted yield was slightly under the 8% diameter offset test value for the LDPE mode I and the HDPE mode IIIa connection, but the predicted yield was higher for the LDPE mode III and HDPE mode IIIb tests. This suggests that the reason for test yields being lower for the LDPE mode III and HDPE mode IIIb tests is due to a geometry effect as mentioned earlier instead of yield definition. Using the 8% diameter offset merely averages the difference empirically between the two different connection geometries.

Table 4.6: Yield Load of WPCs at several different displacements

	1.28 mm displacement	2.55 mm displacement	3.83 mm displacement	7.65 mm displacement	Predicted
LDPE Mode I	7426 N	11282 N	12754 N	16185 N	11430 N
LDPE Mode III	6827 N	10243 N	13104 N	20027 N	13202 N
HDPE Mode IIIa	11266 N	15248 N	18344 N	23663 N	14860 N
HDPE Mode IIIb	10536 N	16305 N	20306 N	28778 N	17400 N

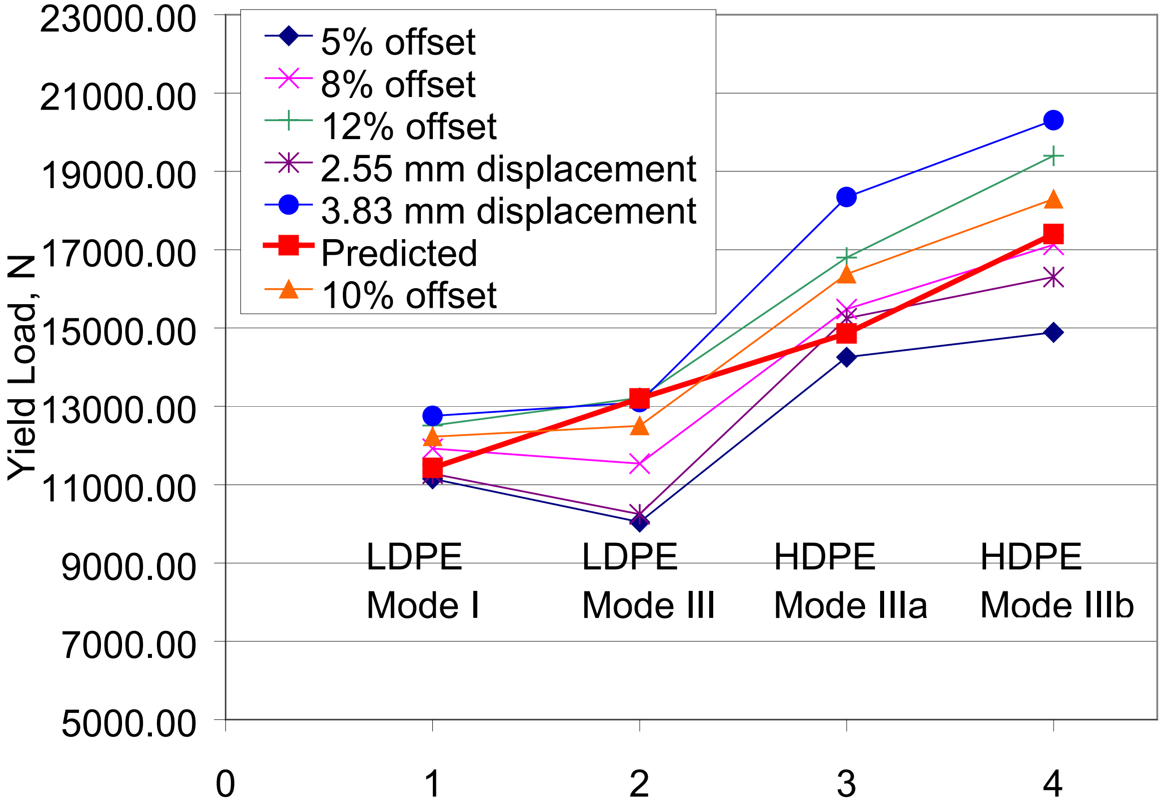

Figure 4.12: Several alternative definitions of yield compared to predicted values

A modification of the EYM model itself is probably required to account for these geometry effects. This modification may lie in the ratio between the thickness of the main member and bolt diameter. This ratio is already accounted for in the EYM equations (McLain and Thangjitham, 1993), but an additional factor may be required for WPCs that take their ductility into account. Figure 4.13a and Figure 4.13b show how the test values match up with the predicted values for WPCs over a range of aspect ratios. The aspect ratio is the comparison of the relative connection yield normalized by full dowel bearing strength to the ratio of main member thickness and bolt diameter. The assumptions behind these figures include that the bolts used for this prediction have the same properties as the bolts tested, side members were exactly half the thickness of main members, and the uncalibrated (without safety factors) EYM values were used. These figures further illustrate the point that the model over-predicts the test data due to geometry issues. There is currently not enough data to establish the complete relationship between tested and predicted data over a wide range of aspect ratios, and future research should be directed at this issue.

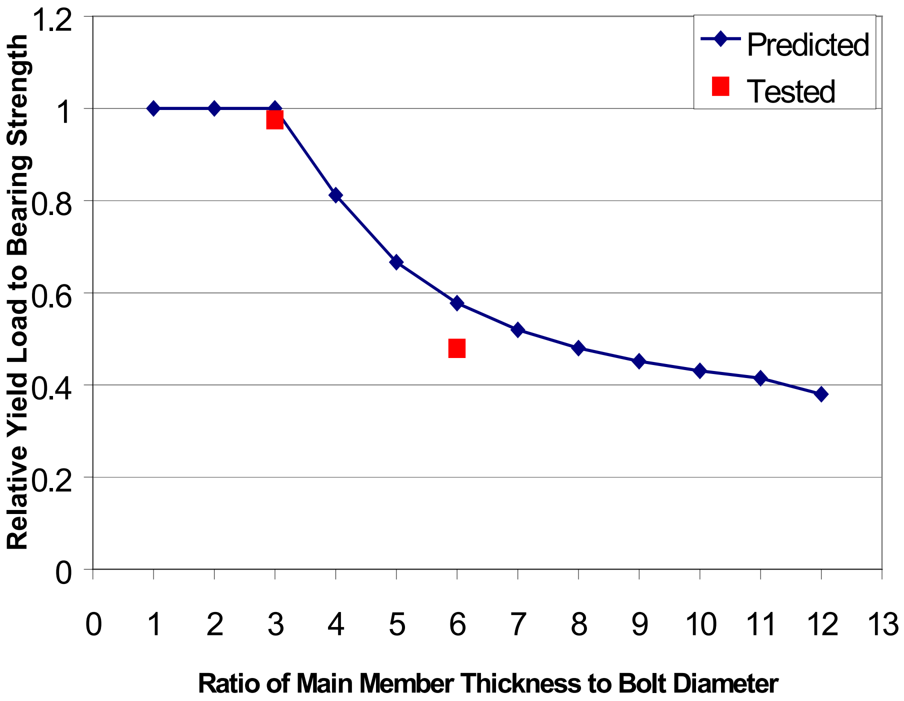

Figure 4.13a: A graph of the relationship between the aspect ratio to yield load relative to the full dowel bearing strength of the LDPE composite for predicted and tested values

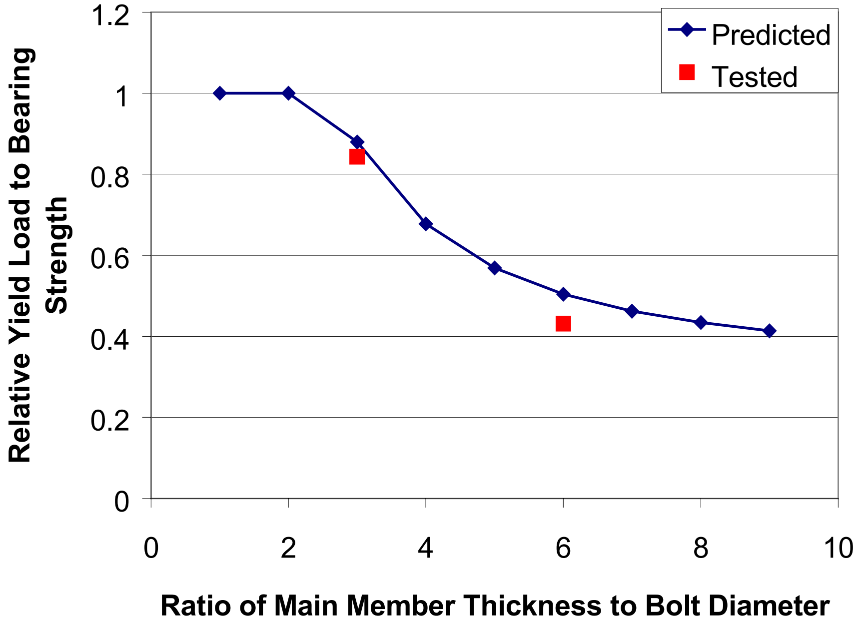

Figure 4.13b: A graph of the relationship between the aspect ratio to yield load relative to the full dowel bearing strength of the HDPE composite for predicted and tested values

CHAPTER V

SUMMARY AND CONCLUSIONS

Wood plastic composites (WPCs) are relatively new materials that are being increasingly used in building applications such as deck boards, railings, moldings and window frames. The U. S. navy also is evaluating this material for use in fendering systems on waterfront structures. Engineering properties of WPCs need to be determined before they are implemented into structures or as structural components. One of the key properties is connection behavior. The European yield model (EYM) is the current design model for wood connections in the United States. The EYM is based on the interaction of wood crushing and dowel yielding in a connection. The goal of this project was to evaluate the EYM for WPCs. ASTM 307 12.7 mm diameter bolts were examined with two different formulations of WPCs. The first formulation was an extruded wood plastic composite with a 50/50 ratio of wood particles to low-density polyethylene, and the second formulation had a 70/30 ratio of wood flour to high-density polyethylene. There were two different geometries tested for each formulation.

WPC dowel bearing strengths and bolt bending yield strengths were measured. WPC dowel bearing strengths were sensitive to displacement rate, which has practical implications for standardization of test methods. A logarithmic relationship was observed between WPC displacement rate and dowel bearing strength. The dowel bearing strength of the composite was approximately 10% higher perpendicular to the extruded direction than parallel. Bolt bending yield strength was found to be higher than the value listed in the NDS (1997). The COV for bolt bending yield strength was low (less than 2%) since all of the bolts came from the same lot from the same manufacturer. The values from the bolt bending yield strength and the dowel bearing tests were then used to determine the EYM predicted yield load.

Two different double shear geometries were tested for both WPC formulations. The smaller main member type that was predicted to fail in mode I, or on the border between a mode I and a mode III, had a good agreement between the EYM and the 5% diameter offset with a maximum error of 4%. All of these connections failed in mode III even though the LDPE composite was predicted to be mode I with the crushing of wood being the failure mechanism. The second geometry did not match the predicted yield to the 5% diameter offset test value as well with a maximum error of 21%. These connections were all predicted to yield in a mode III configuration with one hinge per shear plane, but at failure the bolts had two plastic hinges per plane indicating mode IV yielding. It has not been determined what the yielding mode was at the 5% diameter offset yield point for these connections. Several alternative yield methods were examined for defining the yield points of the connections. Model predictions were in better agreement with the 8% diameter offset test values for all four groups of connection tests, as compared to the 5% diameter offset yield definition. Another approach for improving the accuracy of EYM predictions may be to better account for the ratio of main member thickness to bolt diameter, and the resulting stress distributions. This ratio was a major consideration in the literature for the verification of the EYM for timber. More information is required before this relationship of main member thickness to bolt diameter can be ascertained for WPC connections.

Full double shear connection tests were also conducted without nuts and washers to determine the effects of constraint on connections. It was found that the unconstrained tests yielded at a marginally lower 5% diameter offset load than constrained tests of the same geometry. It is believed that confinement of the bolt was responsible for increasing WPC connections load capacity. The full yielding value of the unconstrained tests closely approximated the predicted EYM capacity with errors ranging from 2% to 10% for all four test groups.

Conclusions

The following conclusions were reached from this research:

1. The EYM with a 5% diameter offset accurately predicts yielding accurately for WPC connections that have low aspect ratios, with a maximum error of 4%.
2. The EYM over-predicts the yielding of WPC connections with higher aspect ratios of around 6, with a maximum error of 21%. One explanation for this is that an initial yielding occurs in the WPC due an uneven distribution of stress under the dowel. The EYM assumes a uniform stress distribution.
3. WPCs have higher dowel bearing strength properties in the perpendicular than in the parallel extrusion orientation by about 10%. By comparison, wood has a 40% to 45% decrease of dowel bearing strength in the perpendicular to grain orientation when compared to the parallel orientation.
4. Unconstrained connections , i. e. without nuts and washers, had lower yield loads than the constrained connections. The maximum load of the unconstrained connections, also termed as fully yielded connections, was in close agreement with the EYM prediction with the error ranging from 2% to 10%.

5. The failure loads of the connection tests were at least twice that of both the predicted and actual yield loads. One explanation for the strength increase is the effects of nuts and washers confining out-of-plane deformation of the WPC.
6. Displacement rates have a significant effect on dowel bearing strength of WPCs. These effects are similar to that seen in wood with a linear relationship between dowel bearing strength and the logarithm of displacement rate; however, the slope is of this curve is steeper than published for wood in the NDS.

Recommendations

Future recommendations for research include:

1. Characterize the effects of creep and temperature on wood plastic composite connection yielding.
2. Establish a consistent displacement rate standard for WPC connections, and a modification for existing standards on wood connection displacement rate.
3. Establish the exact relationship of the ratio of bolt diameter length to main member thickness for WPC connections.
4. Modification of the EYM or a new model developed for the design of net section connections.
5. Evaluation of new formulations of WPCs for connection performance.
6. Evaluation of such parameters as end and edge distances, fastener diameter effects, and multiple bolt performance for WPC connections.
7. Evaluation of other types of fasteners such as nails and lag screws for WPCs.

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APPENDIX A

DOWEL BEARING DATA

Board and Sample	Yield lbs	P-DSLOPE	thickness in	Dowel Bearing Strength psi	Stiffness			
1 A	2487	57694	1.46	3416	79250	Bd Avg	Bd st dev	Bd COV
1 B	2554	54122	1.47	3472	73585	3411.503	45.49185	1.333484
1 C	2501	62321	1.48	3391	84503			
1 D	2496	57292	1.48	3366	77265			
2 A	2543	63831	1.46	3479	87320	Bd Avg	Bd st dev	Bd COV
2 B	2609	61121	1.46	3581	83900	3510.508	49.44434	1.408466
2 C	2545	59525	1.47	3474	81263			
2 D	2571	58414	1.47	3508	79692			
3 A	2635	62556	1.47	3587	85168	Bd Avg	Bd st dev	Bd COV
3 B	2678	49907	1.51	3545	66058	3531.255	76.52691	2.167131
3 C	2563	59691	1.50	3420	79641			
3 D	2646	62494	1.48	3573	84394			
4 A	2470	57209	1.47	3354	77677	Bd Avg	Bd st dev	Bd COV
4 B	2546	57052	1.47	3464	77622	3427.269	55.35091	1.615015
4 C	2545	57776	1.49	3416	77552			
4 D	2570	60450	1.48	3475	81744			
5 A	2434	55982	1.47	3307	76063	Bd Avg	Bd st dev	Bd COV
5 B	2551	59362	1.47	3473	80820	3429.344	95.50826	2.78503
5 C	2573	62272	1.46	3529	85421			
5 D	2520	59847	1.48	3408	80929			
6 A	2577	61951	1.47	3518	84575	Bd Avg	Bd st dev	Bd COV
6 B	2580	63688	1.48	3489	86123	3468.863	42.95312	1.238248
6 C	2530	59425	1.47	3447	80960			
6 D	2544	60080	1.49	3422	80807			
7 A	2519	58014	1.47	3439	79200	Bd Avg	Bd st dev	Bd COV
7 B	2663	65831	1.47	3633	89810	3530.017	81.6092	2.311864
7 C	2635	59474	1.49	3546	80046			
7 D	2558	56926	1.46	3502	77927			
8 A	2593	58991	1.48	3516	79988	Bd Avg	Bd st dev	Bd COV
8 B	2523	55129	1.48	3414	74599	3457.003	42.80585	1.238236
8 C	2514	58923	1.46	3444	80716			
8 D	2525	65258	1.46	3454	89272			

Board and Sample	Yield lbs	P-DSLOPE	thickness in	Dowel Bearing Strength psi	Stiffness			
9 A	2593	58991	1.468	3532.698	80369.21	Bd Avg	Bd st dev	Bd COV
9 B	2523	55129	1.487	3393.41	74147.95	3440.32	66.44129	1.931253
9 C	2514	58923	1.483	3390.425	79464.6			
9 D	2525	65258	1.466	3444.748	89028.65			
10 A	2516	59279	1.468	3427.793	80761.58	Bd Avg	Bd st dev	Bd COV
10 B	2535	55920	1.469	3451.327	76133.42	3367.937	121.3615	3.603436
10 C	2372	50933	1.488	3188.172	68458.33			
10 D	2521	57198	1.481	3404.456	77242.4			
11 A	2517	59078	1.471	3422.162	80323.59	Bd Avg	Bd st dev	Bd COV
11 B	2611	59391	1.466	3562.074	81024.56	3444.321	123.1562	3.57563
11 C	2415	43753	1.472	3281.25	59447.01			
11 D	2604	62162	1.483	3511.8	83832.77			
12 A	2366	53188	1.483	3190.829	71730.28	Bd Avg	Bd st dev	Bd COV
12 B	2454	52545	1.496	3280.749	70247.33	3235.769	66.60988	2.058548
12 C	2352	48721	1.485	3167.677	65617.51			
12 D	2463	53216	1.491	3303.823	71382.96			
13 A	2490	61279	1.457	3417.982	84116.68	Bd Avg	Bd st dev	Bd COV
13 B	2576	61522	1.455	3540.893	84566.32	3441.571	82.63024	2.400945
13 C	2466	57991	1.475	3343.729	78631.86			
13 D	2551	53036	1.473	3463.68	72010.86			
14 A	2577	47246	1.481	3480.081	63802.84	Bd Avg	Bd st dev	Bd COV
14 B	2492	58513	1.466	3399.727	79826.74	3420.352	44.63464	1.304972
14 C	2540	57496	1.483	3425.489	77540.12			
14 D	2473	55324	1.465	3376.109	75527.65			
15 A	2344	56517	1.49	3146.309	75861.74	Bd Avg	Bd st dev	Bd COV
15 B	2431	46896	1.46	3330.137	64241.1	3213.069	81.58245	2.539081
15 C	2358	52602	1.487	3171.486	70749.16			
15 D	2360	53079	1.473	3204.345	72069.25			
16 A	2454	57048	1.483	3309.508	76935.94	Bd Avg	Bd st dev	Bd COV
16 B	2442	49260	1.482	3295.547	66477.73	3281.62	59.17794	1.803315
16 C	2385	54483	1.493	3194.91	72984.59			
16 D	2440	53469	1.467	3326.517	72895.71			

Board and Sample	Yield lbs	P-DSLOPE	thickness in	Dowel Bearing Strength psi	Stiffness			
17 A	2410	55187	1.462	3296.854	75495.21	Bd Avg	Bd st dev	Bd COV
17 B	2447	41507	1.472	3324.728	56395.38	3304.973	32.2261	0.975079
17 C	2443	61026	1.465	3335.154	83311.95			
17 D	2418	57673	1.482	3263.158	77831.31			
18 A	2449	62351	1.479	3311.697	84315.08	Bd Avg	Bd st dev	Bd COV
18 B	2440	54755	1.47	3319.728	74496.6	3367.902	61.6346	1.830059
18 C	2494	56656	1.465	3404.778	77346.08			
18 D	2513	60046	1.463	3435.407	82086.12			
19 A	2372	57097	1.472	3222.826	77577.45	Bd Avg	Bd st dev	Bd COV
19 B	2336	51898	1.465	3189.078	70850.51	3247.316	53.01091	1.632453
19 C	2430	56664	1.488	3266.129	76161.29			
19 D	2447	57363	1.478	3311.231	77622.46			
20 A	2369	54323	1.473	3216.565	73758.32	Bd Avg	Bd st dev	Bd COV
20 B	2416	51849	1.483	3258.26	69924.48	3275.225	61.41003	1.874987
20 C	2454	58856	1.46	3361.644	80624.66			
20 D	2432	42617	1.49	3264.43	57204.03			

HDPE Dowel Bearing Tests

Sample	Thickness in	5% Load lbs	Max Ld lbs	5% Dowel l psi
1	1.476	3834	3901	5195.122
2	1.445	3549	3550	4912.111
3	1.446	3490	3520	4827.109
4	1.473	3785	3801	5139.172
5	1.475	3737	3787	5067.119
6	1.524	3862	3888	5068.241
7	1.407	3399	3402	4831.557
8	1.483	3784	3858	5103.169
9	1.426	3651	3711	5120.617
10	1.443	3683	3716	5104.643

APPENDIX B

BOLT BENDING YIELD TEST DATA

Sample	Diameter in	5% Yield Load lbs	Fyb psi
4by 1	0.5	1111	53343
4by 2	0.5	1111	53343
4by 3	0.5	1088	52210
4by 4	0.5	1114	53456
4by 5	0.5	1097	52663
4by 6	0.5	1125	54022
4by 7	0.5	1159	55608
4by 8	0.5	1090	52324
4by 9	0.5	1109	53230
4by 10	0.5	1133	54362
6by 1	0.5	1081	51871
6by 2	0.5	1074	51531
6by 3	0.5	1090	52324
6by 4	0.5	1100	52777
6by 5	0.5	1088	52210
6by 6	0.5	1090	52324
6by 7	0.5	1081	51871
6by 8	0.5	1102	52890
6by 9	0.5	1118	53683
6by 10	0.5	1085	52097
9by 1	0.5	1092	52437
9by 2	0.5	1095	52550
9by 3	0.5	1118	53683
9by 4	0.5	1104	53003
9by 5	0.5	1107	53116

APPENDIX C

FULL CONNECTION TEST DATA

LDPE composite designed for a Mode I Failure

Sample	tm	ts	5% offset	Ultimate Load	Failure Mode	Fe	Fyb	Z Values w/o Safety Factors					Predicted Mode
								Is	Im	III	IV	K3	
	in	in	lbs	lbs		psi	psi	lbs	lbs	lbs	lbs		
ld1-m1	1.505	0.803	2637	4932	III	3411	52900	2566.8	2739	2742	3877.7	3.0032	I
ld2-m1	1.49	0.807	2543	5063	III	3510	52900	2615	2832.6	2781.6	3933.6	2.946	I
ld5-m1	1.493	0.778	2338	5081	III	3429	52900	2559.7	2667.8	2749.5	3888	3.0919	I
ld6-m1	1.506	0.76	2300	4895	III	3468	52900	2611.4	2635.7	2765.5	3910	3.1478	I
ld7-m1	1.498	0.771	2589	5258	III	3530	52900	2644	2721.6	2789.6	3944.8	3.0749	I
ld8-m1	1.495	0.771	2655	5229	III	3457	52900	2584.1	2665.3	2760.8	3903.8	3.1075	I
ld9-m1	1.492	0.787	2580	5304	III	3440	52900	2566.2	2707.3	2753.7	3894.2	3.0514	I
ld10-m1	1.49	0.765	2561	5464	III	3367	52900	2508.4	2575.8	2725.3	3852.6	3.1741	I
ld11-m1	1.493	0.758	2650	5460	III	3444	52900	2570.9	2610.6	2756.2	3896.4	3.1673	I
ld20-m1	1.51	0.761	2209	4748	III	3275	52900	2472.6	2492.3	2688.5	3799.6	3.2363	I

LDPE composite designed for a Mode III failure

ld1-m3	2.45	1.501	2409	8005	IV	3411	52900	4178.5	5119.9	2949	3877.7	1.728	III
ld2-m3	2.72	1.495	2158	7209	IV	3510	52900	4773.6	5247.5	2999.9	3933.6	1.7151	III
ld3-m3	2.675	1.507	2652	9165	IV	3531	52900	4722.7	5321.2	3018.1	3945.4	1.7016	III
ld4-m3	2.738	1.495	2470	8094	IV	3427	52900	4691.6	5123.4	2954.6	3886.8	1.7301	III
ld5-m3	2.814	1.501	2405	9216	IV	3429	52900	4824.6	5146.9	2958.9	3888	1.7246	III
ld6-m3	2.79	1.506	1500	7105	IV	3468	52900	4837.9	5222.8	2983	3910	1.7134	III
ld7-m3	2.63	1.502	2397	9034	IV	3530	52900	4642	5302.1	3014.7	3944.8	1.7058	III
ld8-m3	2.751	1.496	2580	9683	IV	3457	52900	4755.1	5171.7	2971.5	3903.8	1.7237	III
ld9-m3	2.693	1.507	1890	9589	IV	3440	52900	4632	5184.1	2968.2	3894.2	1.7177	III
ld12-m3	2.847	1.517	2121	9243	IV	3236	52900	4606.4	4909	2860.4	3777	1.7481	III

HDPE composite designed for a Mode IIIa Yielding

Sample	tm	ts	5% offset	Ultimate Load	Failure Mode	Fe	Fyb	Z Values w/o Safety Factors					Predicted Mode
								Is	Im	III	IV	K3	
	in	in	lbs	lbs		psi	psi	lbs	lbs	lbs	lbs		
hd1-m1	1.517	0.764	3298	5645	III	5036	52900	3819.8	3847.5	3341.3	4711.7	2.6053	III
hd2-m1	1.521	0.761	3052	5604	III	5036	52900	3829.9	3832.4	3340.8	4711.7	2.6151	III
hd3-m1	1.512	0.76	3185	5860	III	5036	52900	3807.2	3827.4	3340.6	4711.7	2.6184	III
hd4-m1	1.52	0.762	3313	5596	III	5036	52900	3827.4	3837.4	3340.9	4711.7	2.6118	III
hd5-m1	1.523	0.77	3415	5930	III	5036	52900	3834.9	3877.7	3342.4	4711.7	2.5859	III
hd6-m1	1.547	0.771	3191	5520	III	5036	52900	3895.3	3882.8	3342.6	4711.7	2.5827	III
hd7-m1	1.555	0.764	3182	5520	III	5036	52900	3915.5	3847.5	3341.3	4711.7	2.6053	III
hd8-m1	1.564	0.768	3115	5520	III	5036	52900	3938.2	3867.6	3342	4711.7	2.5923	III
hd9-m1	1.575	0.765	3088	5650	III	5036	52900	3965.9	3852.5	3341.5	4711.7	2.602	III
hd10-m1	1.625	0.769	3207	5493	III	5036	52900	4091.8	3872.7	3342.2	4711.7	2.5891	III

HDPE composite designed for a Mode IIIb failure

hd1-m3	3.034	1.55	3116	10741	IV	5036	52900	7639.6	7805.8	3869.6	4711.7	1.4872	III
hd2-m3	2.875	1.542	3524	10969	IV	5036	52900	7239.3	7765.5	3861.4	4711.7	1.4918	III
hd3-m3	2.948	1.49	3116	10217	IV	5036	52900	7423.1	7503.6	3809.5	4711.7	1.523	III
hd4-m3	3.004	1.565	3896	11070	IV	5036	52900	7564.1	7881.3	3885	4711.7	1.4788	III
hd5-m3	2.928	1.554	3225	10761	IV	5036	52900	7372.7	7825.9	3873.7	4711.7	1.4849	III
hd6-m3	2.925	1.518	3203	10600	IV	5036	52900	7365.2	7644.6	3837.2	4711.7	1.5058	III
hd7-m3	2.923	1.592	3378	11157	IV	5036	52900	7360.1	8017.3	3913	4711.7	1.4642	III
hd9-m3	3.015	1.531	3105	10280	IV	5036	52900	7591.8	7710.1	3850.3	4711.7	1.4981	III
hd10-m3	3.007	1.532	3378	10580	IV	5036	52900	7571.6	7715.2	3851.3	4711.7	1.4976	III

Unconstrained Tests

Sample	tm	ts	5% offset	Ultimate Load	Failure Mode	Fe	Fyb	Z Values w/o Safety Factors				K3	Predicted Mode
								Is	Im	III	IV		
	in	in	lbs	lbs		psi	psi	lbs	lbs	lbs	lbs		
hd1m1-uc	1.518	0.767	2883	3325	III	5036	52900	3822.3	3862.6	3341.9	4711.7	2.5955	III
hd2m1-uc	1.521	0.767	2985	3456	III	5036	52900	3829.9	3862.6	3341.9	4711.7	2.5955	III
hd3m1-uc	1.53	0.775	2826	3554	III	5036	52900	3852.5	3902.9	3343.4	4711.7	2.5699	III
hd1m3-uc	2.945	1.526	2550	3850	III	5036	52900	7415.5	7684.9	3845.3	4711.7	1.5011	III
hd2m3-uc	2.997	1.519	2574	4076	III	5036	52900	7546.4	7649.7	3838.2	4711.7	1.5052	III
hd3m3-uc	2.965	1.552	2713	4091	III	5036	52900	7465.9	7815.9	3871.6	4711.7	1.4861	III
ld12m1-uc	1.517	0.752	2262	2981	III	3236	52900	2454.5	2433.5	2673.4	3777	3.2958	I
ld18m1-uc	1.482	0.765	2305	2856	III	3367	52900	2494.9	2575.8	2725.3	3852.6	3.1741	I
ld19m1-uc	1.503	0.762	2094	2914	III	3247	52900	2440.1	2474.2	2677.2	3783.4	3.2461	I
ld18m3-uc	3.001	1.488	1947	3153	III	3367	52900	5052.2	5010.1	2918.1	3852.6	1.7474	III
ld19m3-uc	2.981	1.502	2053	3129	III	3247	52900	4839.7	4877	2859.2	3783.4	1.7588	III
ld20m3-uc	3.01	1.509	1751	2926	III	3275	52900	4928.9	4942	2878.1	3799.6	1.7471	III