MECHANICAL CONNECTION PROPERTIES AND TECHNIQUES FOR LIGHTWEIGHT WOOD-STRAND SANDWICH PANELS

By

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MECHANICAL CONNECTION PROPERTIES AND TECHNIQUES FOR

LIGHTWEIGHT WOOD-STRAND SANDWICH PANELS

ABSTRACT

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Lightweight wood-strand sandwich panels (LWPs) have shown improvement upon the structural, thermal and hygrothermal properties of oriented strand board (OSB). In order to use LWPs as a replacement for OSB, their adequacy in connection systems and capacities must be developed. This study establishes the connection capacity of LWPs, particularly when utilized as skins for structural insulated panels (SIPs).

LWPs demonstrated an increase of 21%-40% when measuring mechanical properties needed for connection design, including density, nail withdrawal, head pull-through, lateral resistance and dowel bearing. Using dowel bearing strength and withdrawal resistance, equivalent specific gravities of 0.57 and 0.43, respectively, were assigned. Further, by applying connection yield theory, analysis showed that LWPs have the potential for an 11% increase in connection yield capacity over OSB.

Eight single fastener connection scenarios were investigated and the methods of connecting LWPs around the perimeter of a SIP were evaluated. Using nails and to fasten through the full thickness of the panel was evaluated as well as partial panel fastening with nails only. In addition to strength capacity, connection methods were scored on cost, robustness, ease of installation and contribution to hygrothermal performance. Overall, both nailed and screwed connections proved sufficiently strong to use LWPs as skins for structural insulated panels.

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Dedication

This thesis is dedicated to my dad for encouraging me to be an engineer before I even knew I wanted to be one, and for giving me the practical knowledge for it to all make sense.

CHAPTER 1: INTRODUCTION TO LIGHTWEIGHT SANDWICH PANELS

1.1 Introduction

There is an increasing interest in implementing sustainable design techniques for new construction. Sustainable design is generally defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs"(WCED 1987). One way to decrease the effect on future generations is to more efficiently use natural resources when manufacturing building materials. Since higher quality, large diameter timber for plywood is at a premium, using lower value, small diameter timber for panel products is more economical. One such species is lodgepole pine, with rapid juvenile growth and superior drought tolerance. Lodgepole also has a lower specific gravity than other lumber species normally used in construction, making it less desirable for use in structural components. A common method of utilizing lower value species is in the production of composite lumber products such as Oriented Strand Board (OSB). When the low density timber is cut into small strands, combined with resin and pressed together, the final product is denser and stronger than the original materials.

Another method of reducing the environmental impact of a design is to conserve the amount of energy used by the building. Increasing the insulation capacity and reducing thermal losses can reduce the energy usage associated with heating and cooling. The thermal resistance, or R-value, of a building assembly is used to rate the buildings thermal efficiency. R-values for a wood framed wall are commonly estimated at the center-of-cavity, which does not account for the thermal bridging that occurs at framing members and possible gaps in insulation (ORNL 2005). Instead a whole wall measurement should be used, which more accurately represents the insulation capabilities of a real building. A relatively new development in the housing industry is to use structural insulated panels (SIPs) to increase the thermal efficiency of the wall systems (Mullens and Arif 2006). SIPs are typically constructed by sandwiching layers of 7/16” OSB on either side of a foam core, commonly expanded polystyrene. SIPs can be as large as the OSB used for their skins, up to 2.4m x 7.3m (8’x24’). Using monolithic panels reduces the thermal bridging associated with repetitive framing and increases the whole wall R-value. When comparing a traditional wood framed wall with 90 mm of R-11 fiberglass insulation and a SIP wall with 90 mm of foam insulation, the whole wall R-value of the SIP wall was 64% greater than the wood framed wall (Krarti and Hildreth 2006).

SIP construction greatly benefits from creating a tightly sealed building envelope. In blower door testing, the air tightness of SIP homes was 53% better than conventional wood frame homes (Rudd 1998). While this air tightness is good for preventing thermal loss it has a negative effect of trapping moisture within the inside of the building envelope. An investigation of 20 homes in Juneau, Alaska revealed that warm, moist air from inside the building had penetrated seams in the SIPs and condensed when contacting cooler exterior air allowing moisture to collect in the OSB skins and damaging the panel joints, OSB panel edges and the roofing materials (SIPA 2002). Using lightweight wood-strand sandwich panels developed by Voth and Yadama (2010) as SIP skins allow internal air currents to convey moisture out of the panel and can prevent microbial growth and damage to the panels and building envelope (Brown 2012).

1.2 Background

1.2.1 Development of sandwich panels

Sandwich panels are not new to the materials industry. They are commonly used where a high strength-to-weight ratio is desired. Although typically used in the aerospace industry, they are becoming increasingly popular in the residential and commercial construction fields. Composite sandwich panels allow the use of undervalued small diameter trees, require less resin and embodied energy to manufacture (Voth and Yadama 2010) and are lightweight resulting in lower transportation costs. For this study small diameter, 100-200 mm, lodgepole pine was selected as the raw material. Lodgepole, because of its low specific gravity, averaging 0.40 (USDA 2007), is not favored for solid-sawn structural products.

1.2.2 Manufacture of Sandwich Panels

The lightweight wood-strand panels used in this study utilize a stranding and pressing technique developed by Weight and Yadama (2008). Building on this work, a core was designed by Voth and Yadama to increase the load bearing capacity while reducing overall panel weight (2010). Lodgepole pine logs were processed into 0.36 mm x 13 mm x 150 mm (0.014 in. x 0.5 in. x 6 in.) strands and dried to <3% moisture content. The dried strands were then blended with an 8% concentration of phenol formaldehyde resin and evenly distributed in a mat for pressing. The skins and cores that comprise LWPs were pressed using schedules developed by Voth in an oil heated press at 160° C (Voth 2009). A LWP core after removal from the press is shown in Figure 1.2.1

Figure 1.2.1: LWP core after removal from press

After pressing, a skin is adhered to either side of the core panel using a liquid polyurethane adhesive applied to the contact surfaces of the core. The final panel assemblies were trimmed square and stored in an environmental control room, at 20 °C and 65% relative humidity, until used as test specimens.

1.3 Scope of Thesis

Lightweight wood-strand sandwich panels (LWP) have shown promise for bending stiffness (Voth 2009), thermal barrier (White 2011), and hygrothermal performance with respect to use in structural insulated panels (SIPs) (Brown 2012). To effectively utilize LWPs in SIPs, connection techniques and structural capacities need to be quantified. Basic panel properties related to connections that require testing are specific gravity, dowel bearing strength, nail head pull through, nail withdrawal and lateral resistance to tear out. Once dowel bearing strength is quantified, an equivalent specific gravity can be assigned to permit usage of standard design tables. Dowel bearing can also be used to apply yield theory equations to predict connection behavior. In addition to basic connection properties, six panel-to-framing connections were tested with nails and two with wood screws. Using the results of connection testing, racking performance for SIP assemblies can be estimated.

The body of this paper is divided into two main chapters. Chapter 2 covers lightweight wood-strand sandwich panels and their properties related to connection design – i.e. dowel bearing strength, nail withdrawal, head pull-through and lateral resistance. Using dowel bearing strength and nail withdrawal values, equivalent specific gravity for lateral resistance and withdrawal are calculated. Equivalent specific gravity allows a designer to use standard design value tables to specify connections of proprietary materials. Further, using dowel bearing strength capacity of connections can be calculated using the yield theory equations presented in Chapter 11 of the National Design Specification for Wood Construction (AWC 2012).

In Chapter 3, single-shear fastener connections were tested and the applicability of LWPs as SIP skins is examined. Six single shear connections were tested with nails and two with screws with sample sizes ranging from five to ten. Using the 5% offset method the yield strength of the connections can be determined. By comparing the yield strengths of various connection types, the best method for connecting LWP skinned SIPs to the structural components can be judged. Using equations specific for perimeter nailed panels only, the racking strength of a SIP panel can be estimated (Tuomi and McCutcheon 1978).

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CHAPTER 2: CHARACTERIZATION OF MECHANICAL PROPERTIES OF LIGHTWEIGHT WOOD-STRAND SANDWICH PANELS NEEDED FOR CONNECTION DESIGN

2.1 Introduction

In the interest of pursuing more sustainable designs for building construction, techniques have been developed to reduce the amount of natural raw materials consumed in their manufacture. By producing strandboard that utilizes lower value, small diameter logs, instead of producing plywood with high value, larger diameter timber, natural resources are more efficiently utilized. Lodgepole pine is an excellent example of optimizing low value timber as a raw material for strand board production. As a native North American species it grows plentiful and because of its high drought tolerance, thrives where higher value species such as Douglas fir may not (USDA 2007). Although low density, lodgepole pine strands can be combined with resin into a panel product with a specific gravity up to 50% greater than the original value.

New developments in manufacturing technologies have created sandwich panels that optimize their strength to weight ratio. One product, developed at Washington State University, utilizes lower value timber by compressing the strands to create panels with a greater density than the source material. Combined with a new 3-dimensional core design, lightweight wood-strand sandwich panels (LWPs) were created as an alternative to other strand boards where a reduction in weight is desired without sacrificing strength (Voth 2009).

2.2 Background

The lightweight sandwich panels used in this study were developed by Voth and Yadama (2010) and utilize a strand board pressing technique from Weight and Yadama (2008a; 2008b). The potential for structural use of the panels have been demonstrated by testing flexural capacity and found that, when compared on a weight percentage basis, LWPs have a specific bending capacity 88% greater than OSB panels of comparable density (Voth 2009). Voth also performed a case study showing that LWPs could be used as floor sheathing, supporting a live load of 1915 Pa (40 psf) and dead load of 957 Pa (20 psf) when spaced 1.2 m (48 in.) on center.

Lightweight wood-strand sandwich panels are constructed of a three-dimensional core sandwiched between two thin outer skins. The core has an overall thickness of 19 mm (0.75 in.) with a layer thickness of 6.4 mm (0.25 in.). LWP skins are 3.2 mm (0.125 in.) thick. A cross section of one corrugation width of 108 mm (4.25 in.) is shown in Figure 2.2.1. Due to the alternating interface between the core and skins, a “thick skin” and “thin skin” will be referred to throughout the course of this study.

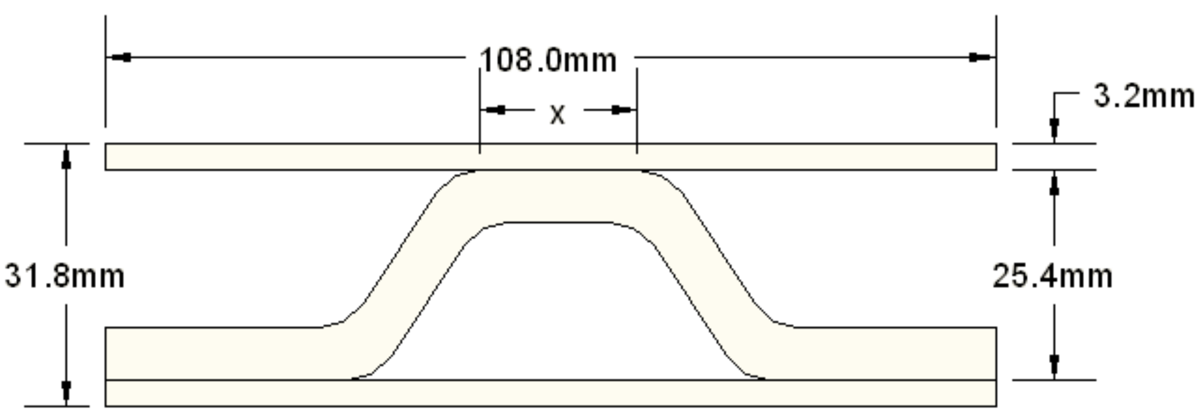

Figure 2.2.1: Cross section showing one corrugation of a LWP

White (2011) explored the thermal capabilities of LWPs by replacing a 12.7 mm (0.5 in.) thick sheet of OSB with a 32 mm (1.25 in.) LWP. The thermal resistance of a wall increased by 6%, and filling the hollow core with foam insulation resulted in a 20% increase in thermal resistance. In addition to improved thermal properties, LWPs have shown potential for increasing the hygrothermal performance of a building. By using LWPs as skins for structural insulated panels (SIPs), moisture evaporation could be increased by allowing passive ventilation through the core of the LWP. Modeling simulations show that this ventilation can mitigate microbial growth in the panel (Brown 2012).

With promising results in the areas of structural, thermal and hygrothermal performance, LWPs show great potential as a new building material. To facilitate structural design with LWPs, their connection capacity must be determined, which is the intent of this study.

2.3 Objectives

The goal of this study was to characterize strength properties related to connection design of lightweight wood-strand sandwich panels. Specific objectives were to characterize.

1. specific gravity and dowel bearing strength for eventual use in yield theory to predict connection behavior
2. nail withdrawal and
3. measuring nail head pull-through and lateral tear out resistance.

This study relies on work previously performed by Weight and Yadama (2008a), Voth and Yadama (2010) and White(2011) with regard to wood strand geometry and core design. It should be noted that in the previously mentioned studies ponderosa pine was used as the raw material and lodgepole pine is used for this study. The decision to use lodgepole pine was based primarily on availability as both trees are closely related western yellow pines, and have similar specific gravities, anatomy and mechanical properties (USDA 2007).

2.4 Materials and Methods

2.4.1 Nails

In conjunction with dowel bearing strength, the yield strength of nails is a required material property for prediction of connection capacity using yield equations (Johansen 1949; American Wood Council 2012). Nail diameters were chosen for each test performed depending on what was called for in the relevant ASTM standard. In performing nail head pull-through, nail withdrawal and lateral resistance, ASTM D 1037 recommends using a sixpenny (6d) common wire nail with a diameter of 2.9 mm (0.131 in) (ASTM 2006). Collated framing nails were selected for this study because it was desired that they be typical of the type driven by pneumatic nail guns during installation. The nails chosen have a diameter of 2.9 mm (0.113 in.) and length of 60 mm (2.375 in.), which correlates to a 6d common nail (AWC American Wood Council 2012). For lateral resistance, a 6d nail was insufficient, for reasons explained in Section 2.4.4, and larger 3.3 mm x 75 mm (0.131 in. x 3 in.), correlating to an eightpenny (8d) common, nails were used. The larger, 8d nails were also used for testing dowel bearing strength, in part because the increased length will be required to meet the requirements of ten-times-the-diameter penetration per the National Design Specification (NDS) (AWC2012) when nailing through the full thickness of the panels.

Nail yield moment was tested in accordance with ASTM F 1575 for both nail sizes (ASTM 2007b). The average yield strength was 683.9 MPa (99.2 ksi) for 6d nails and 788.0 MPa (114.3 ksi) for 8d nails, with a coefficient of variation of 4.1% and 3.8%, respectively.

2.4.2 Dowel Bearing Strength and Specific Gravity

In order to use yield theory for connection predictions as well as assign an equivalent specific gravity, the dowel bearing strength and specific gravity of LWPs were tested according to ASTM D 5764 (ASTM 2007c). Two rounds of testing were conducted to record dowel bearing strength of the LWPs. The first test setup used 50.4 mm x 50.4 mm (2 in. x 2 in.) specimen and a 6.4 mm (0.25 in.) diameter dowel, as can be seen in Figure 2.4.1. The larger diameter dowel was initially chosen for testing because of difficulty creating a bearing surface for the smaller diameter dowel when following the methods prescribed in the standard. A diameter of 6.4 mm (0.25 in.) also represents the dividing point between what is considered a nail and a bolt by the NDS (AWC 2012). The average dowel bearing strength for the 6.4 mm (0.25 in.) diameter dowel was 39.6 MPa (5746 psi).

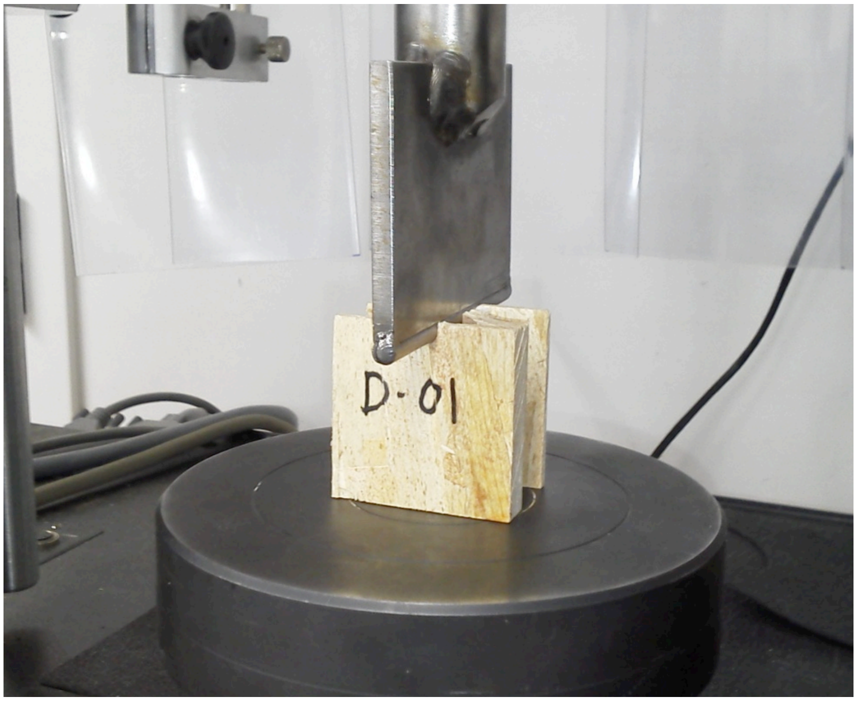

Figure 2.4.1: Dowel bearing test setup with 6.4 mm dowel and 50.4 mm square specimen.

To be consistent with later testing it was also desired to use 8d nails for determining dowel bearing strength. The latter tests were conducted using specimens 50.4 mm x 108 mm (2 in. x 4.25 in.). The wider specimens represent a full corrugation width of the core and helped keep the sample squarely aligned during testing. However, testing the full thickness of the panel proved to be problematic as well. During testing the thinner panel skin crushed more easily than the thicker side allowing the pressing fixture to tilt. Because of the premature crushing of the thinner panel the results were deemed to be inaccurate. A third round of dowel bearing tests was initiated using just the thicker panel skin as the bearing surface, as shown in Figure 2.4.2. As expected, the pressing fixture stayed square with the bearing surface and the calculated dowel bearing strength was greater. The final dowel bearing strength for LWPs was found to be 41.0 MPa (5942 psi).

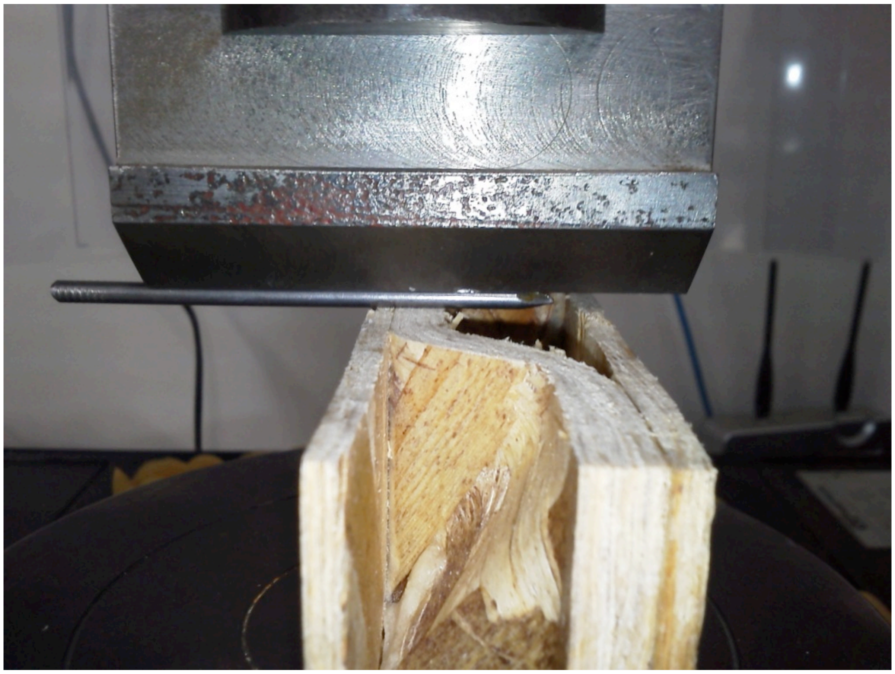

Figure 2.4.2: Dowel bearing test on thick side of panel only with 3.3 mm dowel

Once dowel bearing was determined, the specific gravity was tested using the volume by water immersion procedure outlined in ASTM D2395 (ASTM 2007d). After weighing the specimens they were oven dried and re-weighed again to determine moisture content. Each 50.4 mm x 108 mm (2 in. x 4.25 in.) specimen was then dipped in melted paraffin to seal any voids and submerged in a pan of water, with the mass known, and the increase in mass after submersion was recorded. The volume of paraffin was subtracted from the volume measured by displacement, resulting in the volume of the specimen. An average specific gravity of 0.645 and average moisture content of 9.2% was recorded for the full thickness of the panel. It was assumed that since the core and skins were pressed using the same raw materials and pressing schedules, the specific gravities of the individual pieces would be similar. Also since the dowel bearing test was performed using a combination of one skin and the core, an average of the two was desired.

2.4.3 Nail withdrawal and head pull-through

Nail Withdrawal and head pull-through were both performed according to ASTM D 1037 (ASTM 2006). Five nail withdrawal tests, using 6d nails, were conducted for each panel orientation, thin side up, and thick side up, shown in Figure 2.4.3. Since nail withdrawal is dependent primarily on the thickness of panel penetrated, panel orientation did not have a statistically significant effect on the mean withdrawal strength, as confirmed by using Students t-test to compare the data from each panel orientation. The average force per unit of panel thickness required to withdraw the nail from the panel was 291.4 N/cm (95.17 lb/in.)

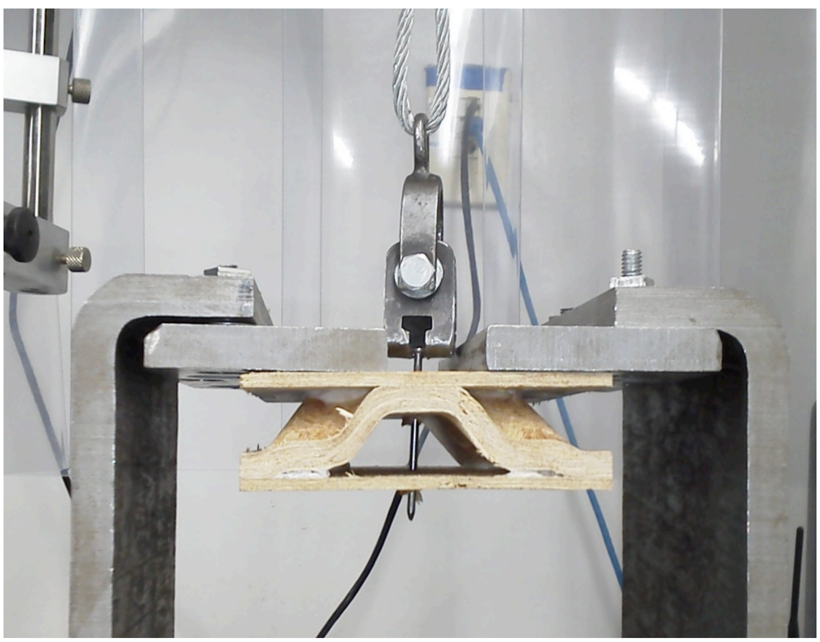

Figure 2.4.3: Nail withdrawal testing with thick side of panel up.

Head pull-through was performed with ten tests in each panel orientation, nail head against the thin side, Figure 2.4.4, and against the thick side, Figure 2.4.5. 6d nails with an average head diameter of 7.0 mm (0.274 in) were used. As expected the thicker side of the panel provided proportionally more resistance than the thinner side.

By dividing the average pull-through force by the panel thickness, the force per unit thickness could be determined and compared using Students t-test, and was determined to be no significant difference. A full summary of statistical analysis can be found in Appendix C. Average pulling force and the normalized force per unit thickness can be seen in Table 2.4.1.

Table 2.4.1: Pulling force require to pull nail head through panel

	Pulling Force N (lb)	Normalized Force N/mm (lb/in)	COV
Thick Side	2202 (495.0)	197 (1125.0)	18.6%
Thin Side	684 (153.8)	204 (1165.2)	24.9%

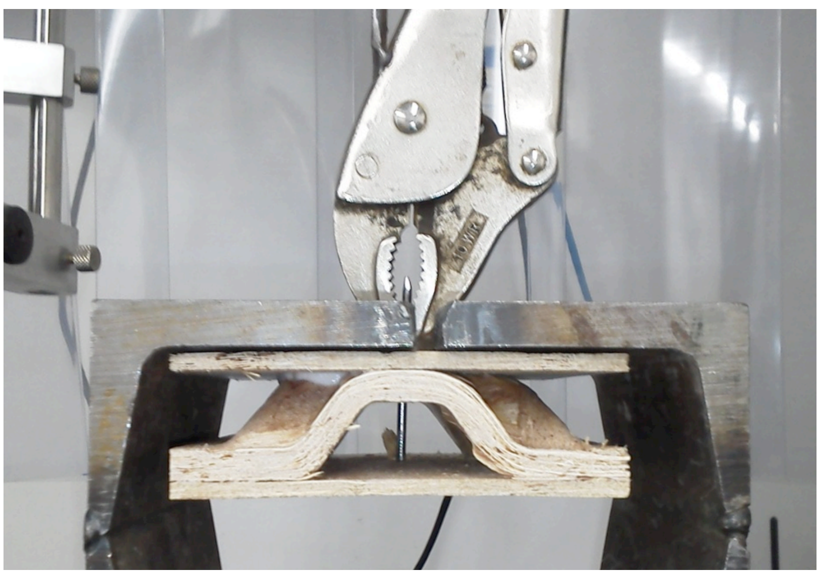

Figure 2.4.4: Nail head being pulled through thin panel skin by a custom loading fixture.

Figure 2.4.5: Nail head being pulled through thick panel skin by a custom loading fixture.

2.4.4 Lateral Tear-Out Resistance

As a precursor to single fastener connection testing, lateral tear out resistance was measured following the procedure detailed in ASTM D 1037 (ASTM 2006). The procedure was modified to use 8d nails instead of the 6d nails specified because the smaller diameter nails were not strong enough to tear-out the panel before the nail yielded. Two versions of the lateral resistance test were performed. First, five test were performed on the full thickness of the panel, shown in Figure 2.4.6, followed by five tests using just the thicker skin of the panel, shown in Figure 2.4.7. By statistical comparison, the results each of tests were determined to not be significantly different, the mean ultimate load of full and partial panel testing were 1408 N (316.6 lbs) and 1642 N (369.2 lbs), respectively. Although there was little difference in the ultimate load capacity, the failure modes were different. During the full thickness test, as the nail began to yield, the force was concentrated on the outer panel skins. By inspecting the panels after testing it was apparent that the failure typically occurred in both outer skins first, followed by failure of the core as shown in Figure 2.4.6. When the tear-out resistance of the partial panel was tested, both the skin and the core failed in unison, as shown in Figure 2.4.7

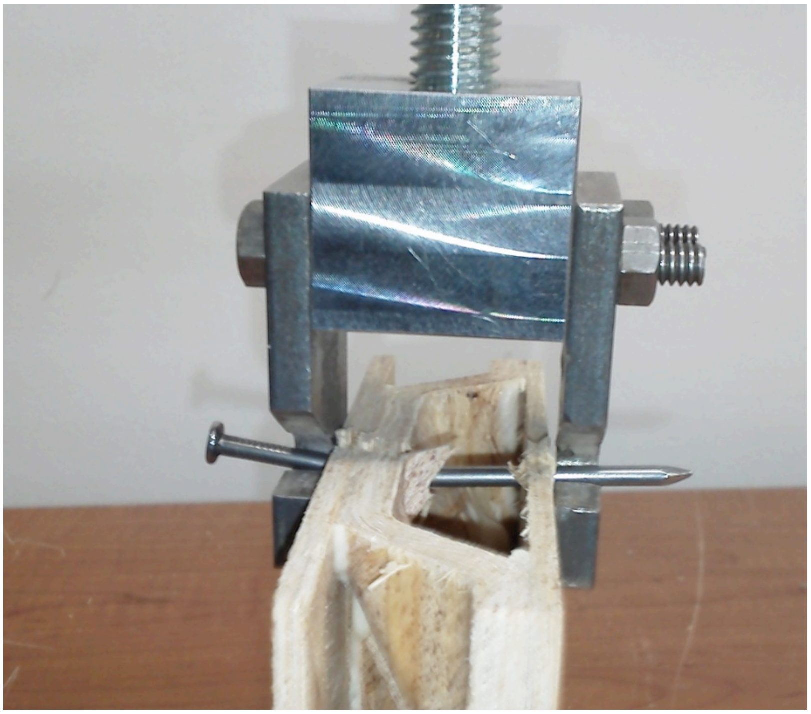

Figure 2.4.6: Lateral resistance test of full panel thickness.

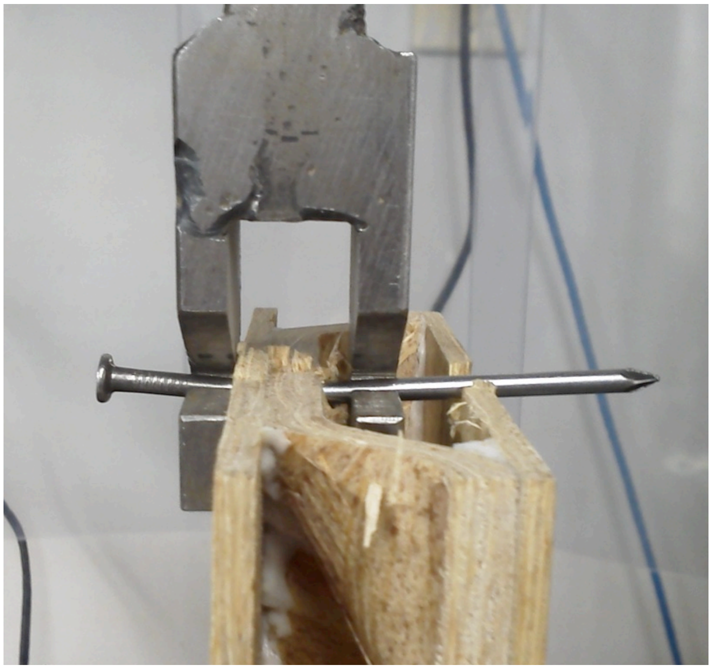

Figure 2.4.7: Lateral resistance tested on thick panel skin only causing uniform failure.

2.5 Results and Discussion

2.5.1 Comparison to OSB properties

LWP connection property performance was compared to published OSB specimens, since OSB is currently the industry standard for structural sheathing. The results of this comparison are summarized in Table 2.5.1. OSB tests performed with panel thicknesses comparable to the thickness of the actual LWP, minus air void in the core, were used for the comparison. Data were not available for OSB in a 3.35 mm (0.132 in) thickness but based on the force/thickness comparison made earlier, it can be assumed that the thinner panel would have similar results to the thicker cross section. The LWP outperformed OSB in every category.

Table 2.5.1: Summary of mechanical connection properties

	LWP (COV)	OSB (COV)	% Increase
Density (as tested)	0.74 g/cm^3	0.60 g/cm^3 (1)	23.3%
Nail Withdrawal	166 N/cm (39.9%)	132 N/cm (29.3%) (1)	25.8%
Head Pull-through – Thick	2202 N (18.6%)	1568 N (17.6%) (1)	40.0%
Lateral Resistance	1642 N (22.3%)	1360 N (14%) (2)	20.7%
Dowel Bearing	41.0 MPa (26.3%)	32.1 MPa (3	27.8%

[1] - (Herzog and Yeh 2006), Head pull-through performed on 11 mm OSB with as received density of 0.60 g/cm^3
[2]- (Davids, Dagher et al. 2003), results of 14 mm OSB with 9.5 mm edge distance
[3]- (American Wood Council 2012)

The increase in nail withdrawal, lateral resistance and dowel bearing is consistent with the increase in the as tested panel density. However, when testing a head pull-through resistance on a wide range of OSB and plywood specimens, Herzog and Yeh (2006) found that panel density did not have a significant affect, but that there was a linear correlation between capacity and panel thickness. The theory was that the non uniform panel density profile of OSB makes it difficult to predict the pull through capacity of a panel. Conversely, the 40% increase in pull-through capacity could be attributed to the more uniform density profile of the LWP.

2.5.2 Calculation of equivalent specific gravity

To easily facilitate connection capacity design of manufactured wood products by engineers, equivalent specific gravity (ESG) is used. By following the procedures of ASTM D 7033 (ASTM 2007a), Annex A, equivalent specific gravity can be determined for withdrawal and lateral resistance purposes. Withdrawal equivalence can be calculated by either interpolating between the values given in Table 11.2c of the NDS (AWC 2012) or by using the equation given in ASTM D 7033(ASTM 2007a). Lateral resistance equivalence can be calculated by using the equation listed in the footnote of

Table 11.3.3 of the NDS or interpolation of table values is allowed (ASTM 2007a; AWC2012). By using the equation methods equivalent specific gravities of 0.43 and 0.57 can be calculated for withdrawal and lateral resistance, respectively. By comparison, OSB is assigned an ESG of 0.50 for lateral resistance, or 32.1 MPa (4650 psi) of dowel bearing strength (AWC 2012) and 0.40 for withdrawal resistance (Herzog and Yeh 2006). LWP shows an increase of 7.5% for withdrawal resistance and 14% for lateral bearing resistance over OSB. This increase is similar to the 10% increase in the actual specific gravities of LWP over OSB, 0.64 and 0.58, respectively (Herzog and Yeh 2006)

2.5.3 Calculation of connection capacity by yield limit equations

The yield limit equations presented in Table 11.3.1A of the NDS (AWC 2012) were used to estimate connection capacity. Yield equations can calculate theoretical loads for both single and double shear connections, but for the purposes of this study only single shear will be investigated because it is the most likely method of connection for LWPs. Because the yield equations do not account for a void in the side member, it will be assumed that the panel has been nailed only through the thicker side of the panel. This could be accomplished by drilling a hole in the thinner skin or any other means of allowing nailing access. Assuming an 8d nail with a yield strength of 787.9 MPa (114.3 ksi), and Douglas Fir-Larch as the main member the design values shown in Table 2.5.2 were calculated. Full calculations can be found in Appendix B.

Table 2.5.2: Yield equation results for single shear connections

	I_m	I_s	II	III_m	III_s	IV
Newtons	3178	661	1114	2188	372	489
Pounds	714	149	250	492	84	110

The lowest value from the yield equations will control design, Mode III_s in this case, giving a maximum design load of 372 N (84 lbs) per connection. Yielding of the connection during crushing of the side member is to be expected since the thickness of the panel is much less than the penetration depth into the main member.

A number of studies have established that the racking resistance of wall sections linearly correlates to the lateral resistance of the individual nails (Tuomi and McCutcheon 1978; McCutcheon 1985; Salenikovich 2000). By using this correlation the increase in capacity of a wall segment can be estimated by comparing the results of Yield Mode III_s to published values for a comparable thickness of OSB sheathing nailed to a Douglas Fir-Larch main member. From the NDS Table 11Q (AWC 2012), the capacity of an 8d common nail through 11 mm (0.438 in.) OSB is 325 N (73 lb), indicating a 15% increase in capacity.

2.6 Conclusions

In order for LWPs to be competitive as a building material it must show improvements over the currently used materials, such as OSB. Voth demonstrated that LWP could match the span ratings of OSB at a fraction of the weight (2009). Research into the thermal and hygrothermal properties of LWPs showed that they have the potential to increase the thermal resistance and decrease risk of damage from moisture (White 2011; Brown 2012). By evaluating the mechanical properties related to connection design of lightweight wood-strand sandwich panels the viability of LWPs as structural sheathing is validated.

The results of nail withdrawal, head pull-through, lateral resistance and dowel bearing strength show that LWPs have the potential for a 21%-40% increase in connection capacity depending on failure mode. The predicted increase in LWP connection capacity is consistent with the increase in panel density over OSB. The more uniform density profile could also be a contributing factor and should be investigated further. By assigning an equivalent specific gravity to LWPs, connection design can be conveniently performed using the reference design value tables in Chapter 11 of the NDS (AWC 2012). Using connection yield theory and comparing to published design values for OSB, analysis showed that at least a 15% increase in diaphragm capacity can be expected. Further investigation of connection capacity by single shear fastener testing will be covered in Chapter 3 of this paper.

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CHAPTER 3: CONNECTION TECHNIQUES FOR LIGHTWEIGHT WOOD-STRAND SANDWICH PANELS UTILIZED AS STRUCTURAL INSULATED PANEL SKINS

3.1 Introduction

Reducing the environmental impact of new construction not only calls for the more efficient usage of raw materials but also a higher level of energy efficiency. Space heating and cooling accounts for 54% of residential energy use in the United States (D&R International Ltd. 2012). Increasing the thermal resistance, or R-value, by increasing the insulation capacity and reduce thermal losses, reduces the amount of energy used for heating and cooling (ORNL 2005). Structural insulated panels (SIPs) utilize oriented strand board (OSB) skins and a solid foam core, typically expanded polystyrene, to increase the R-value of a wall system. In addition to increased insulation, SIPs panels require fewer framing members which reduce the opportunities for thermal bridging and can increase the whole wall R-value by as much as 64% (Krarti and Hildreth 2006).

The sealed building envelope created by SIPs also greatly increases the hygrothermal performance of a building by reducing drafts and air leakage. However, the air tightness can have an adverse affect on the ability of a structure to release moist air that can rise and collect near roof ridges. An investigation into the cause of moisture damaged SIP roof systems in Juneau, Alaska revealed that the lack of a complete air flow network allowed moist air to rise to the roof ridge and saturate the OSB skins. One recommended solution for providing the airflow network is to include an air gap between the impermeable foam core and the OSB skin (Lstiburek 2009). A more elegant solution would be to include air flow channels *inside* the skin. Lightweight wood-strand sandwich panels (LWPs), developed at Washington State University, incorporate a three-dimensional core that has been shown to improve the hygrothermal performance of SIPs by allowing moisture to evaporate from within the panels (Brown 2012).

In SIP construction monolithic panels are typically used as infill between load bearing members, such as in heavy timber construction. The panel connections are usually only made around the perimeter by fastening the outer skins to a lumber plate, of equal thickness as the foam core, that is attached to the foundation or framing system. A typical SIP construction detail for a sill plate is shown in Figure 3.1.1.

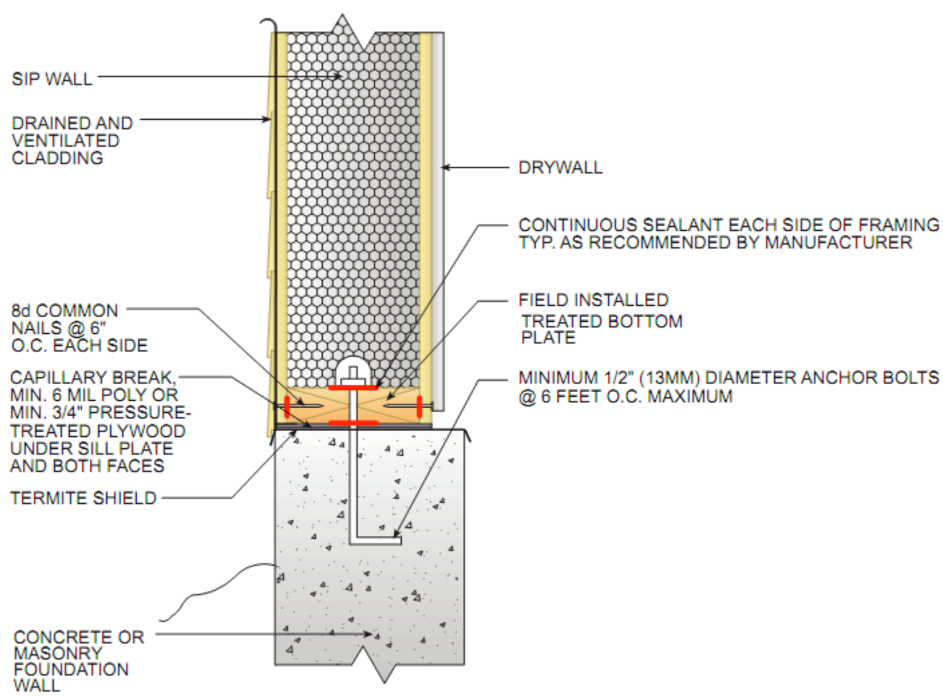

Figure 3.1.1: Typical SIP to sill plate connection detail. Used with permission (SIPA 2011b)

Connection details from panel-to-top plate and panel-to-panel are similar to the panel-to-sill plate connections. Panels are usually connected to one another with a spline bridging the two panels, either made of OSB or lumber (ICC 2011). One thing all these connections have in common is that the panels are nailed to another member and not directly to another panel. During testing this was modeled using a single fastener connection with a piece of Stud grade Douglas Fir-Larch representing the sill, top plate or spline connector.

3.2 Objectives

This study will examine the yield and ultimate capacity of single fastener connections between lightweight wood-strand sandwich panels and Douglas fir-larch lumber by accomplishing the following objectives:

1. establish connection capacity of nailed and screwed single fastener connection tests in a variety of configurations,
2. validate test results by comparing to previously determined yield theory calculations,
3. estimate racking capacity of full size LWP wall by applying test results to capacity equations developed for perimeter nailed panels (Tuomi and McCutcheon 1978) and
4. evaluate connection techniques considering yield strength, ultimate strength, ease of installation and hygrothermal benefits.

3.3 Methods and Materials

3.3.1 Terminology

For the purposes of simplifying discussion, the following terminology will be used in describing the panel orientation and fastening schedule. The term “thick skin” refers to the portion of the panel where the core and one of the outer skins are glued together and “thin skin” refers to just the outer skin by itself. Due to the alternating profile of the core, this is not always the same side of the panel. Nailing configurations are described by which panel skin is first penetrated by the nail point and whether the nail penetrates the full thickness of the panel or just the partial thickness of the thicker side. Two different nailing and panel configurations are shown in Figure 3.3.1.

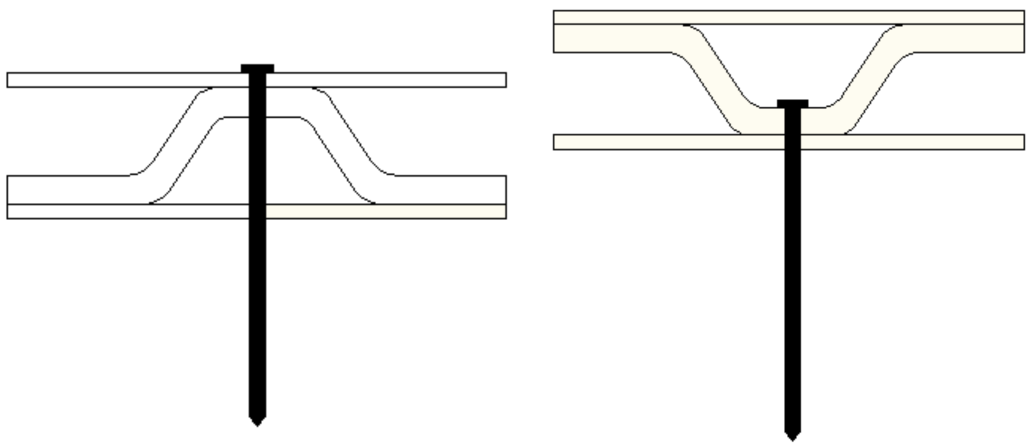

Figure 3.3.1: Full depth panel nailing, through thick side first (left) and Partial nailing through the thick side only (right)

3.3.2 Testing Setup

Eight single fastener connection tests, six with nails and two with screws, were devised to simulate the connection scenarios of installing a LWP SIP. For the nailed connections, 3.3 mm (0.131 in.) diameter nails, correlating to an eightpenny common (8d), were primarily used with the exception of 2.9 mm (0.113 in.) diameter nails, correlating to a six penny common (6d), for partial thickness nailing since the ten-times-the-diameter minimum penetration requirement could be met with the smaller nail (AWC 2012). Another reason for using a larger diameter nail in place of a smaller diameter nail is the increased yield strength of the nail made it more likely that the panel would fail instead of the fastener.

The tests were setup and specimens prepared using a modified version of ASTM D 1761 (ASTM 2006). The panel specimens (prism) were cut to 105mm (4.125 in) widths instead of the recommended 50.8 mm (2 in) width to include one full corrugation of the core in each prism. Prism length of 305 mm (12 in) was maintained as recommended by the standard. A 20.6 mm (0.813 in.) hole was drilled 50.8 mm (2 in.) from the top edge of the prism to accept a 19 mm (0.75 in.) bolt attaching it to the moveable crosshead of the Instrom 30k testing machine. A Stud grade Douglas Fir-Larch cleat, 38 mm x 89 mm x 150 mm (2 in. x 4 in. x 6 in.), was secured to the machine base with a piece of angle iron bolted across the cleat behind the prism. The testing setup can be seen in Figure 3.3.2 and is typical for all nail and screw lateral resistance tests.

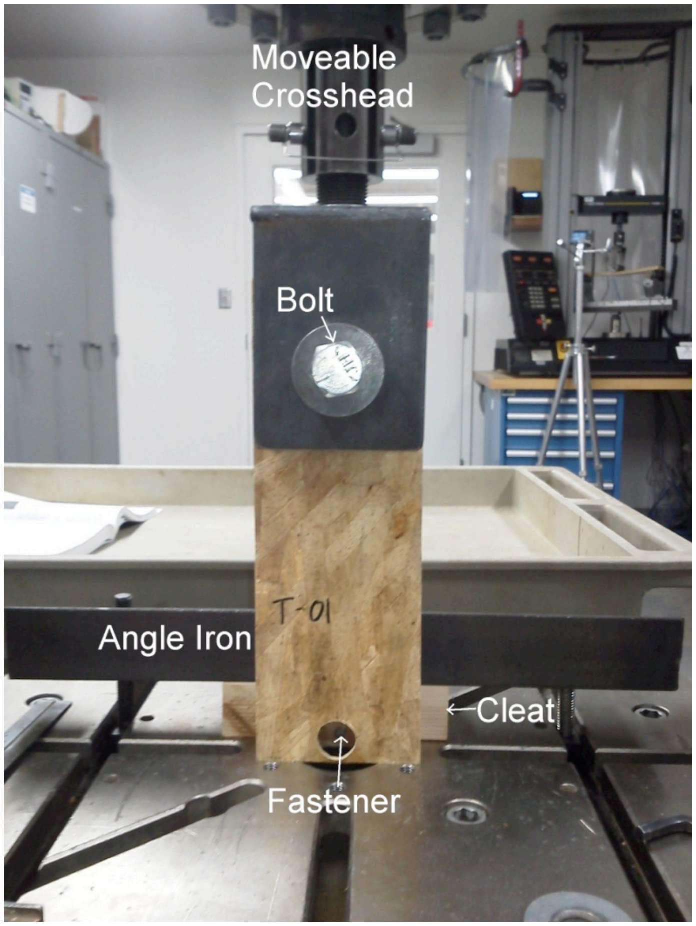

Figure 3.3.2: Lateral resistance test setup in 30k Instron

For testing, nails and screws were installed 12.7 mm (0.5 in) from the edge of the panel. This distance was chosen because the smallest practical edge distance was desired but closer edge distances caused unpredictable behavior during nail installation with panel blowout and nails curving out the side of the main member. Nails were driven with a Bostich 21° framing nail gun operating at 620 kPa (90 psi). Closer edge distances could have been tested if pilot holes were predrilled and nails were driven by hand, however this would not be an accurate representation of actual installation conditions. A bubble level was attached to the nail gun to ensure the nails were installed perpendicular to the panel face.

Specimens were tested at a loading rate of 2.54 mm/min (0.10 in/min) until panel failure or the loading rate reached a plateau and it was apparent that the fastener was withdrawing from the cleat. By using the 5% of the fastener diameter offset method, a yield strength was calculated and recorded along with the ultimate strength of the connection. Figure 3.3.3 graphically illustrates finding the 5% offset value for a panel nailed through the full thickness, thin side first.

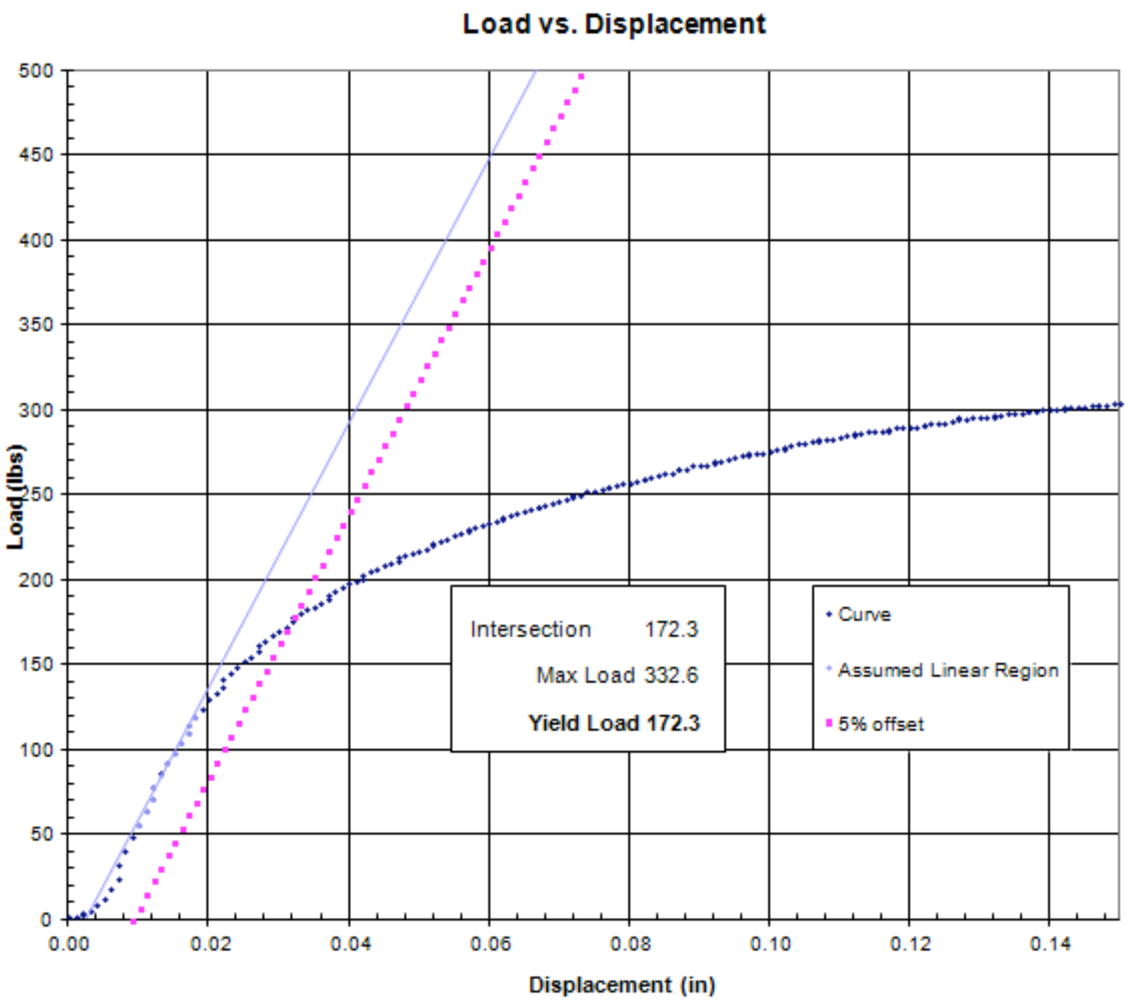

Figure 3.3.3: Obtaining 5% offset yield strength from panel nailed through the full thickness, thin side first.

After dowel bearing tests, the specific gravity and moisture content of each prism and cleat was determined and recorded. The average specific gravity of the LWP prisms was 0.685, and the average moisture content was 9%, with coefficient of variations of 6.4% and 3.0%, respectively. The cleats had an average specific gravity of 0.51 and an average moisture content of 14.3%, with coefficient of variations of 7.3% and 10.2%, respectively.

3.3.3 Full Panel Thickness Nailing

Ten tests were conducted fastening the prism to the cleat by nailing through the full depth of the panel with the point of the nail going through the thin side first. Care had to be taken while shooting the nails from the gun to not crush the thin outer skin. Using a regulator in line with the gun, the air pressure was kept to a maximum of 80 psi and the gun was held firmly against the panel so it would not bounce. Some compression of the outer skins occurred during nailing, as shown in Figure 3.3.5, but they were not visibly fractured. With a coefficient of variation of 8.6%, this fastening method produced the most consistent results, as visible in Figure 3.3.4: Load-displacement curves for full thickness nailing through the thin side Figure 3.3.4 through the elastic range to the yield limit, but ultimate strength was limited by the head pull-through resistance of the thinner panel.

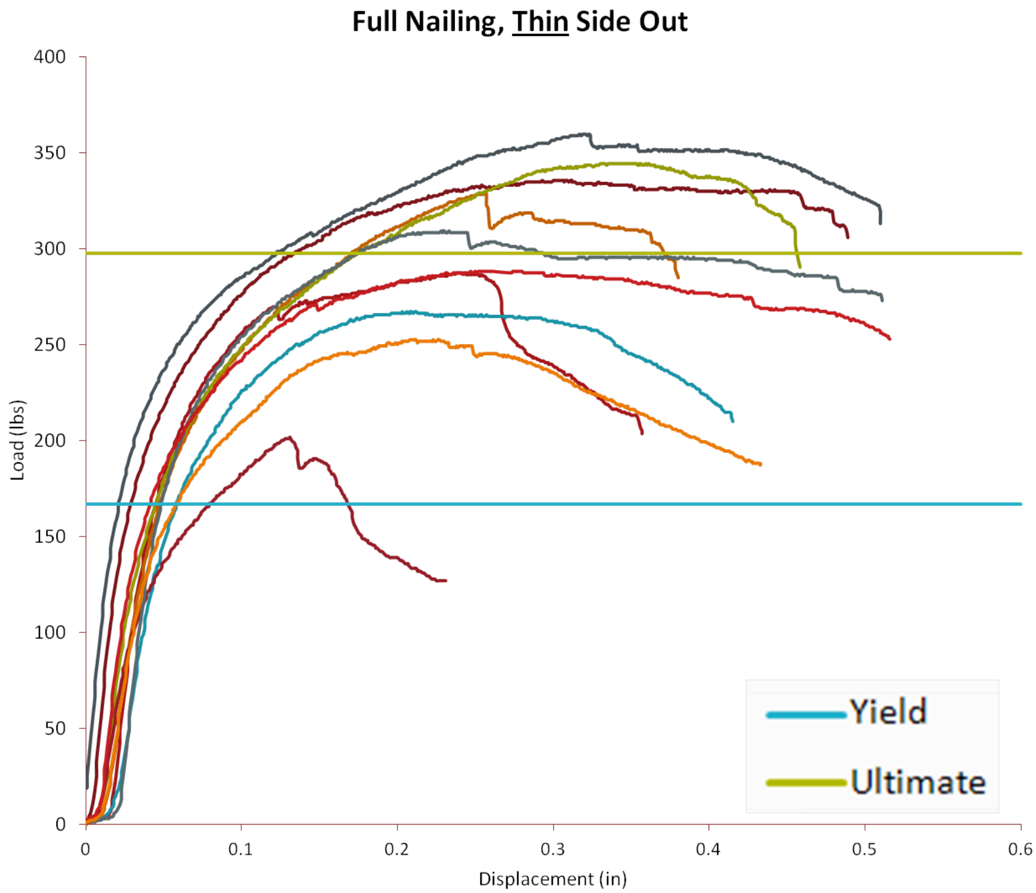

Figure 3.3.4: Load-displacement curves for full thickness nailing through the thin side

Figure 3.3.5: Compressed panel skin resulting from nailing through thin skin first.

The full depth nailing test was then repeated with the panel arrangement reversed and the nail point was driven through the thicker side first which protected the panel from damage by the nail gun. This arrangement placed the thinner skin against the cleat and as the displacement increased, the thinner skin failed by localized crushing before the thicker outer skin was compromised. The localized failure is noted by the momentary drop in capacity around 3.8 mm (0.15 in) of displacement, as shown in Figure 3.3.6. The thicker skins were still intact but due to the permanent damage to the thin skins, the panels were considered failed. Once the thin skin failed the load dropped significantly or ceased to increase, indicating that the nail was in withdrawal from the cleat.

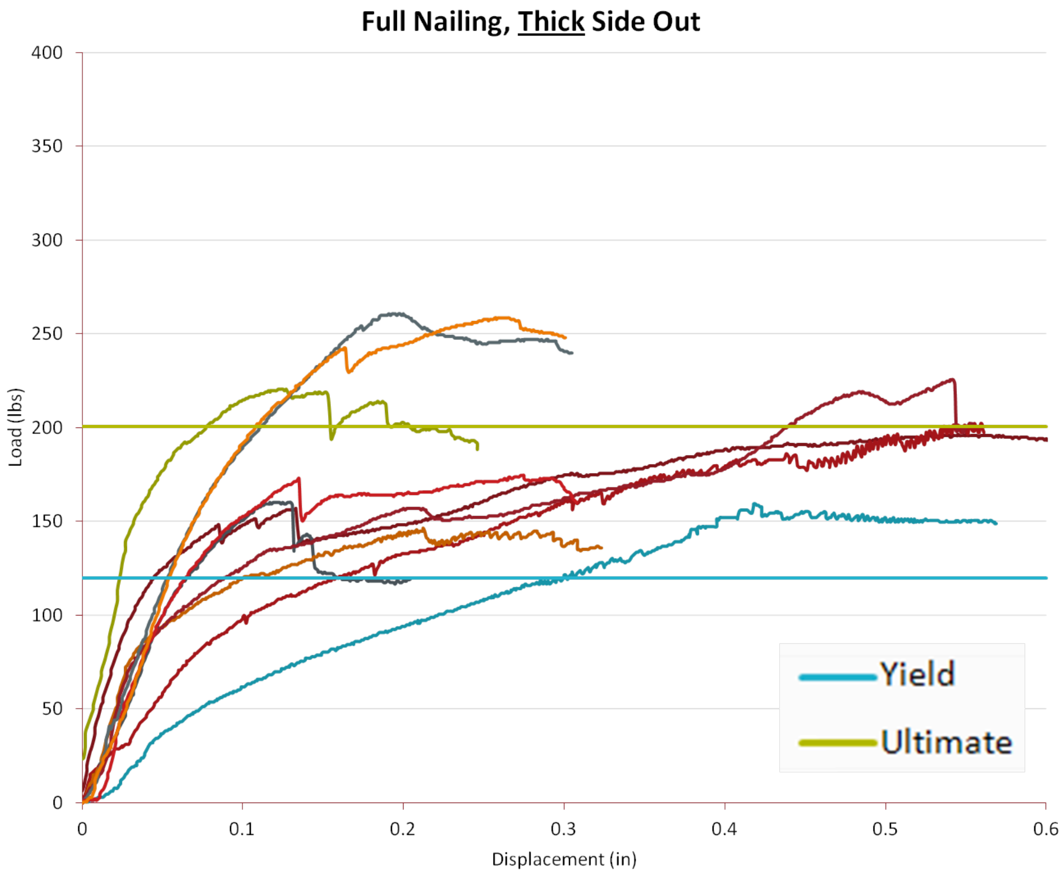

Figure 3.3.6: Load displacement curves for full thickness nailing through the thick skin

Of the eight configurations tested, full panel thickness, nailed through the thick side produced the lowest average yield and ultimate loads. This reversed arrangement, with the thin skin out, resulted in a 39.4% to 48.4% increase in yield and ultimate capacity, respectively, when compared to full nailing with the thick side out. Results of full thickness nailing are presented in Table 3.3.1.

Table 3.3.1: Comparison of yield and ultimate load capacity for full thickness nailing

Panel Orientation	Yield			Ultimate		
	N	lb	COV	N	lb	COV
Full, Thick	532	120	32.6%	892	201	20.3%
Full, Thin	742	167	8.6%	1324	298	16.2%

3.3.4 Partial nailing through thick side only

As demonstrated during full thickness nailing, the thin skin of LWPs alone could not withstand the impact force produced by a pneumatic nail gun. Even restricting the maximum air pressure to 550 kPa (80 psi), collapsing the skin could not be reliably prevented. Clearly an alternative method is needed to create a more robust connection. It was theorized that with the inner and outer skin separated by 25.4 mm (1 in) the force would be concentrated on the skin closest to the main member, as was demonstrated in the full thickness nailing scenarios. To allow the nail gun to fasten the thick side of the panel directly to the cleat, a 25.4 mm (1in) access hole was drilled in the thin side as shown in Figure 3.3.7. This access hole had the added advantage of creating a pathway for passive ventilation of the LWP to remove unwanted moisture buildup.

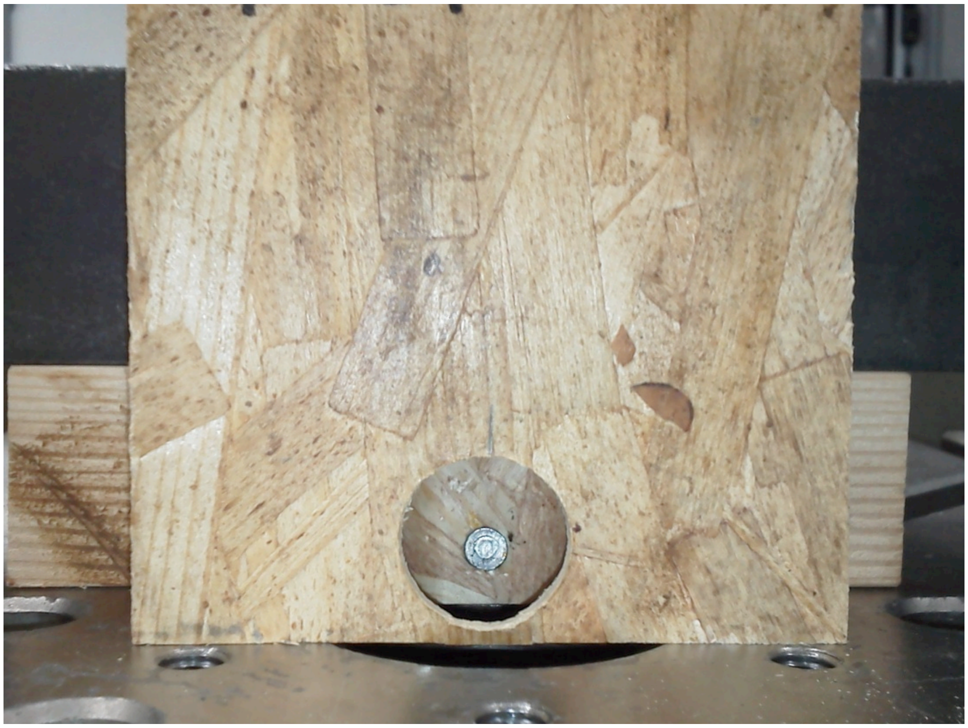

Figure 3.3.7: Hole drilled in outer thin skin of panel to allow direct nailing of thick skin to main member.

Two rounds of ten tests, first using 6d and then 8d, smooth shank, round head nails were performed with partial nailing through the thick side of the prism only. Partial panel nailing also produced consistent results for yield strength, with the second lowest coefficient of variations of the nail tests. The increased head pull-through capacity of the thicker skin increased the ultimate capacity 27% when comparing the 8d tests to full thickness nailing through the thin side. Average yield strength is presented along with the ultimate strength in Table 3.3.2 for both nail sizes. When comparing 6d and 8d partial panel connection tests there was a significant decrease in ultimate capacity. This difference could be explained by the larger, longer nail not achieving its full withdrawal capacity by splitting or curving out the side of the cleat. The uniform loading of 6d nails can be contrasted with the loading curves of 8d nails in Figure 3.3.8 and Figure 3.3.9, respectively.

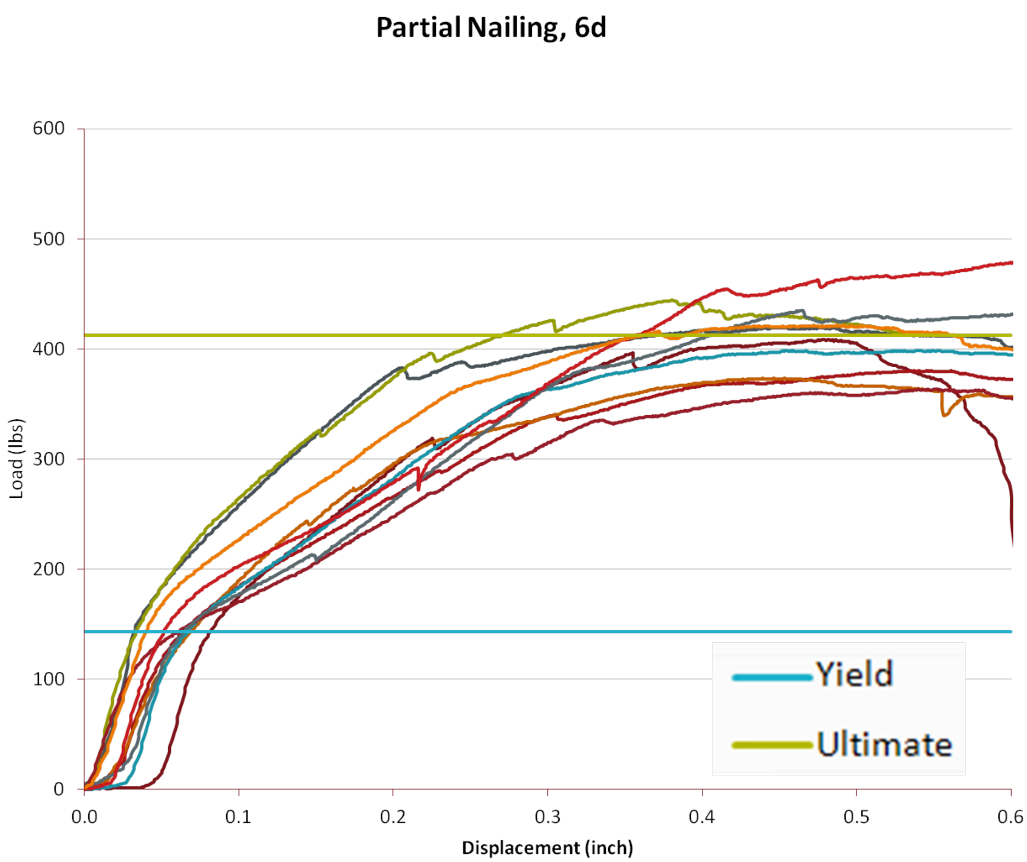

Figure 3.3.8: Load-displacement curves for partial panel fastening with 6d nails

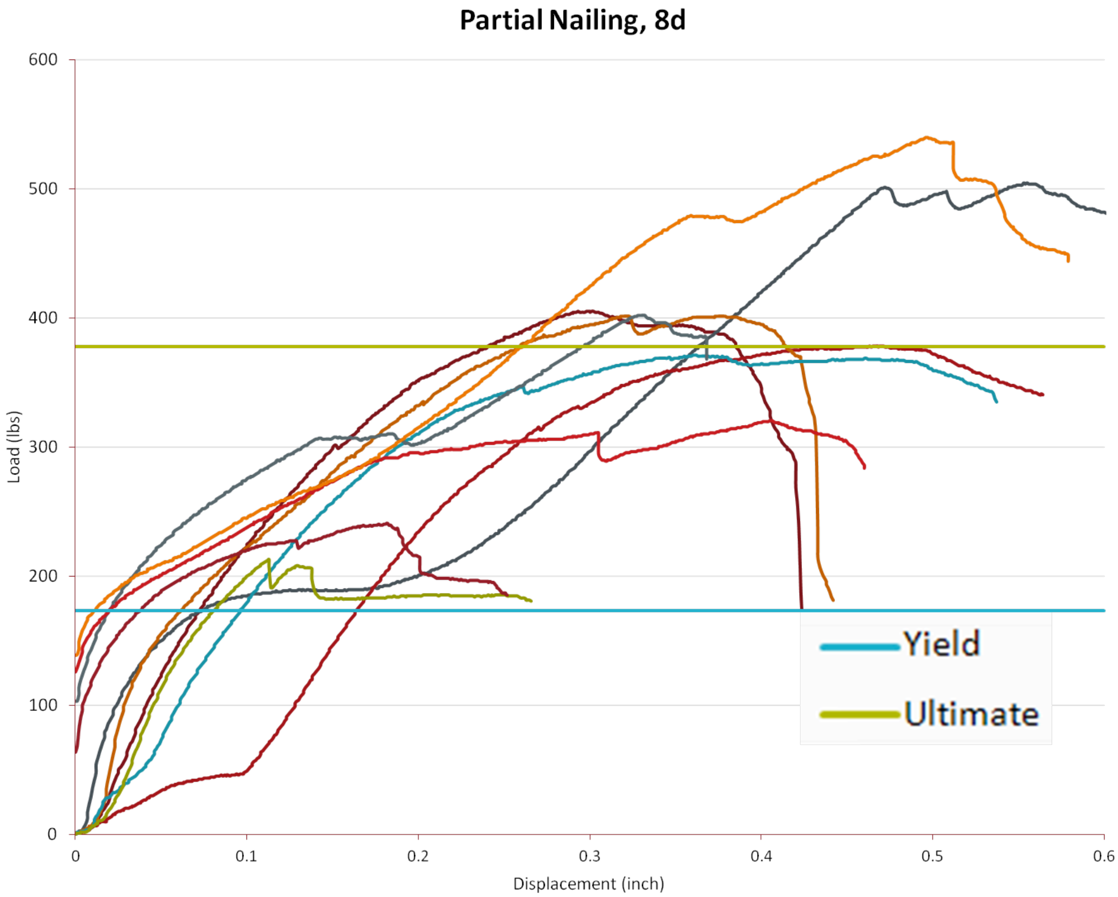

Figure 3.3.9: Load-displacement curves for partial panel fastening with 8d nails

Fastener Type	Yield			Ultimate		
	N	lb	COV	N	lb	COV
6d nail	638	144	12.7%	1835	413	8.6%
8d nail	770	173	18.0%	1517	341	20.3%

Table 3.3.2: Connection yield and ultimate strength for partial thickness nailing.

3.3.5 Load Applied Perpendicular to Strand Orientation

Although orientation of grain is considered to be insignificant in nailed connections (AWC 2012), a short series of tests were performed to check if angle to strand orientation has an effect on the connection performance. Two tests, with five samples each, were performed with the load applied perpendicular to the strand orientation. The tests chosen for comparison were full thickness nailing through the thin side and partial thickness nailing because they represented the highest connection yield capacities thus far. The issues with nailing through the thin side first were exacerbated when the skin was not supported on both sides of the nailed area, as shown in Figure 3.3.10. Even with the compression of the outer skin, there was no statistically significant effect of strand orientation on yield capacity. A comparison of yield and ultimate strength for loading parallel and perpendicular to the strand orientation are shown in Table 3.3.3 and full statistical analysis is included in Appendix C.

Table 3.3.3: Effect of loading parallel and perpendicular to strand orientation.

Fastener	Connection	Yield			Ultimate		
		N	lb	COV	N	lb	COV
8d nail	Partial, Thick	769	173	18.0%	1680	378	27.0%
8d nail	Partial, Thick Perp.	821	185	28.4%	1517	341	20.3%

Figure 3.3.10: Full panel nailing perpendicular to strand orientation. Also illustrates the effect of nailing through the thin skin.

Drilling an access hole in the thin skin to drive the fastener directly through the thick skin again worked well as a solution to the issue of thin skin collapse. Partial thickness nailing, both parallel and perpendicular to strand orientation, resulted in the highest yield capacity of any of the nailed connection techniques. Changing the direction of load application did not have a statistically significant effect on the yield or ultimate capacity of the partial thickness connection. The results of applying the load perpendicular strand orientation are summarized in Table 3.3.4. Graphical illustration of the load-displacement curves are presented in Appendix C.

Table 3.3.4: Comparison of full thickness panel testing, loaded parallel and perpendicular to strand orientation.

Fastener	Connection	Yield			Ultimate		
		N	lb	COV	N	lb	COV
8d nail	Full Thin Perp	741	167	19.0%	1295	291	11.4%
8d nail	Full, Thin	742	167	8.6%	1324	298	16.2%

3.3.6 Screws as fasteners

Since some of the test results indicated that the ultimate capacity of the connections was limited by fastener withdrawal from the cleat, two rounds of testing were conducted using #10 all purpose wood screws with a root diameter of 3.4 mm (0.132 in.). Screws were chosen as a fastener instead of threaded nails with the assumption that the installation would be less damaging to the thin skin of the panel when installed with that side facing out. To insure that the screws were installed perpendicular to the panel face a pilot hole 90% of the screw root diameter was drilled with a drill press prior to screw installation. Care still had to be taken not to over-tighten the screws and collapse the outer skin but it was much easier to control than with a nail gun. Figure 3.3.11 shows the slight depression in the panel skin caused by screw installation. Since the head is not countersunk into the panel, it would be advisable to use a pan head screw during installation to prevent the head from interfering with cladding.

Figure 3.3.11: Screw installed through thin side first. Picture taken post-testing.

As expected, using screws as a fastener increased the yield strength and ultimate capacity of the connection. When comparing screws versus nails installed full thickness through the thin side first, screws increased the yield and ultimate strength by 36% and 37%, respectively. Screws had the biggest effect on the ultimate capacity when fastening the full panel thickness with the thick side out, increasing 116%. The increase in ultimate capacity is illustrated in Figure 3.3.12 for full thickness fastening with #10 screws through the thick side. The load-displacement curves for full thickness fastening with screws through the thin side are presented in Appendix C.

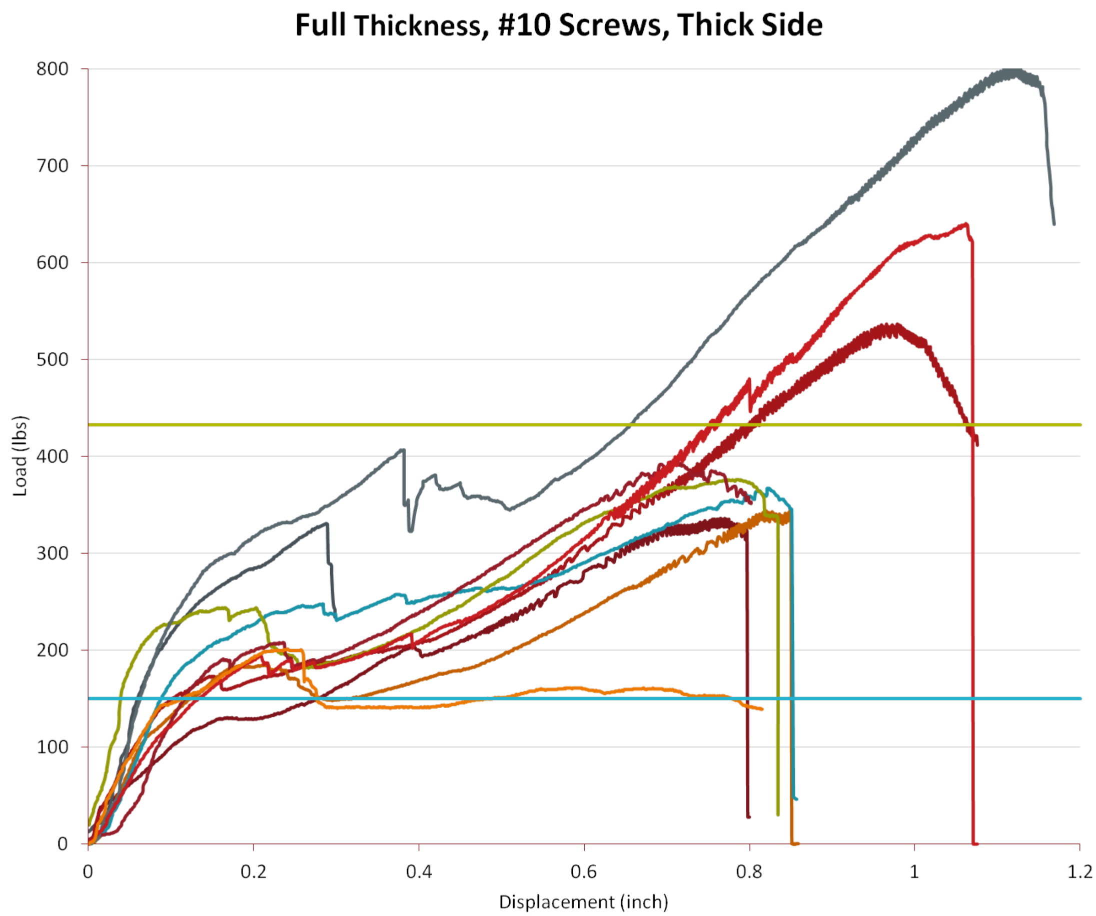

Figure 3.3.12: Load-displacement curves for full thickness fastening with #10 screws through the thick side

3.4 Results and Analysis

3.4.1 Comparison of Connection Techniques

Connection testing of lightweight wood-strand sandwich panels resulted in a wide range or results nearly doubling the yield strength when comparing nailing full thickness through the thick skin and screwing full thickness through the thin skin, as can be seen in Table 3.4.1. It becomes apparent that panel orientation and fastener type play a large role in deciding what connection configuration to utilize when installing SIPs with LWP skins.

Table 3.4.1: Summary of connection capacity, sorted by yield strength, in ascending order.

Fastener Type	Connection Type	Yield			Ultimate		
		N	lb	COV	N	lb	COV
8d nail	Full, Thick	532	120	32.6%	892	201	20.3%
6d nail	Partial, Thick	638	144	12.7%	1835	413	8.6%
#10 Screw	Full Thick	670	151	23.3%	1926	433	40.7%
8d nail	Full Thin Perp	741	167	19.0%	1295	291	11.4%
8d nail	Full, Thin	742	167	8.6%	1324	298	16.2%
8d nail	Partial, Thick	770	173	18.0%	1680	378	27.0%
8d nail	Partial, Thick Perp	821	185	28.4%	1517	341	20.3%
#10 Screw	Full, Thin	1006	226	14.7%	1818	409	14.0%

For simplicity of installation, installing a #10 screw through the thin side of the panel would provide the highest yield strength while requiring the least amount of installation preparation when compared to partial panel nailing. Since there is little risk of collapsing the thin skin, screws may be installed anywhere, simplifying layout. However, if panels are prepared at a factory, as SIPs usually are, and access holes are pre-drilled for partial panel nailing, then the increased installation speed of a pneumatic nail gun would help keep labor cost of a project down. Full panel thickness nailing should also be considered because of the ease of installation. Because of their distinct advantages, the three aforementioned connection types will be the only ones considered for further comparisons.

3.4.2 Optimizing Connections for Hygrothermal Performance

When evaluating the three remaining connection techniques a number of variables must be taken into consideration. The yield capacity of each connection type is of the utmost importance, but even a connection of high strength is not of much use if it is too complicated or prohibitively expensive to install. Also considered in this study are the unique benefits available because of the hollow core of LWPs. It has been demonstrated that allowing convection inside the panels can alleviate mold issues (Brown 2012) but by following installation recommendations of SIPA, SIP skins shall be fully supported by framing members (SIPA 2011a), effectively blocking airflow into the panels. By using the connection method of drilling an access hole in the outer skin of a LWP and fastening through the thicker skin, a strong connection is developed and it takes advantage of the moisture evaporative capabilities LWPs offer. Building scientists' recommendation to avoid the roof rot that occurred in SIP roofs in Juneau, Alaska is to "provide a mechanism for moisture removal (Lstiburek 2009)" and LWPs have the benefit of providing the mechanism while acting as the structural skin. The decision matrix, shown in Table 3.4.2, was used to determine which connection should be utilized for installing SIPs with LWP skins. Connections are ranked 1 (best) through 3 (worst) with the lowest total score having the most advantages.

Table 3.4.2: Decision matrix comparing connection techniques.

	Strength	Cost	Hygrothermal	Rugged	Intallation	Total
Full, Thin, 8d nail	3	1	3	3	1	11
Partial Thick, 8d nail	2	2	1	1	2	**8**
Full Thin, #10 Screw	1	3	3	2	3	12

3.4.3 Estimating Strength of Full-Size SIPs

Due to size limitations of the laboratory press and custom mold for producing the cores, the maximum panel size produced was 635 mm x 800 mm (25 in. x 31.5 in.). Performing a miniature shear wall type test with these panels was rejected due to scaling inaccuracies that would be encountered. Instead, it was decided that it would be most beneficial to estimate the capacity of a full system using single fastener connection capacities.

Two comparisons will be made. First, using connection ultimate strength values, the racking capacity of a single panel will be calculated for comparison with shear wall design values from the Special Design Provisions for Wind and Seismic (SDPWS) (AF&PA 2005). Then, using allowable strength values from connection testing, the capacity of a SIP with LWP skins will be calculated and compared to a published study on SIP racking capacity.

To establish allowable design values, yield strength must be adjusted by applying the reduction term, R_d, of 2.2 from yield limit equations (AWC 2012). Table 3.4.3 compares allowable design values as well as listing the ultimate strength values from single shear connection testing.

Table 3.4.3: Allowable and ultimate design values of fasteners for use in calculations

Fastener	Connection	Allowable		Ultimate	
		N	lb	N	lb
8d nail	Full Thin	337	76	1326	298
8d nail	Partial, Thick	350	79	1681	378
#10 Screw	Full, Thin	457	103	1819	409

The allowable yield capacity for an 8d nailed connection can be validated by comparing to the connection capacity calculated with yield limit equations in Chapter 2. Table 3.4.4 gives the mean yield capacity and 95% confidence interval associated with lateral resistance and partial thickness connection testing. The lateral resistance tests are representative of a Mode I_s failure while partial panel thickness represents a Mode III_s failure. It can be seen that the mean yield limit prediction for each failure mode falls well within the confidence interval indicating that the yield limit equations provide an accurate prediction of connection capacity.

Table 3.4.4: Comparison of yield limit prediction with tested fastener capacity

	Yield Limit Prediction	Tested Yield Capacity Mean	Tested Yield Capacity 95% CI	Difference
Lateral Resistance	663 N	632 N	605-845 N	5%
8d nails, Partial Panel Thickness	374 N	351 N	302-396 N	6%

Equation 3.4.1, was developed by Tuomi and McCutcheon (1978) for comparing calculated strength values of sheeted wall assemblies and was verified by full scale testing. Due to having a similar construction method, the same equation can be used to estimate the racking capacity, *R*, of a full size LWP SIP.

$$R = r \sin\alpha \left[n + m - \frac{2}{3}\left(\frac{n^2 - 1}{n} \cos^2\alpha + \frac{m^2 - 1}{m} \sin^2\alpha \right) \right] \qquad (3.4.1)$$

Where *r* represents the resistance of an individual nail, *m* and *n* are the number of nail spaces along the vertical and horizontal edges respectively, and *α* is determined by the panel width/height ratio, B/H = tan α. The usage of this equation is dependent on meeting the following assumptions (Tuomi and McCutcheon 1978):

- The load/displacement ratio for a single nail is linear
- The frame is allowed to distort while the sheathing material remains rectangular
- Sheathing is continuous from the top to the bottom of the frame

- Nails are evenly and symmetrically spaced around the panel perimeter
- Loading is static, or applied slowly to eliminate dynamic or impact effects
- Distortions and deflections are small

The previous assumptions work well with SIP construction, particularly since SIPs are monolithic (continuous sheathing) and fastened only around the perimeter of the panel. Assuming a LWP wall of 1.2 m x 2.4 m (4 ft x 8 ft), nails spaced 180 mm (4.25 in.) on center (o.c.), then n = 12, m = 23 and α=0.46. Spacing the fasteners 180 mm o.c. ensures that each one is centered on the core corrugation, i.e. the same as tested conditions. By applying Equation 3.4.1 to the ultimate strength values in Table 3.4.3 ultimate racking resistance and unit shears for a LWP wall panel can be calculated. For comparison, the unit shear of a 11 mm (0.438 in.) OSB wall with 8d nails 102 mm (4 in.) o.c. around the perimeter and every 12 in. in the field, is tabulated as well (AF&PA 2005). Comparison of the 11 mm OSB and Partial, Thick LWP capacities results in a 10% increase for LWP over OSB. This increase is to be expected as it is consistent with the percentage increase predicted by application of the yield limit equations (AWC 2012)

Table 3.4.5: Ultimate racking strength prediction for LWP SIPs

Fastener	Connection	Racking Resistance per 1.2m x 2.4m Panel		Unit Shear	
		N	Lb	N/m	lb/ft
8d nail	Full, Thin	15166	3410	12440	852
8d nail	Partial, Thick	19238	4325	15779	1081
#10 Screw	Full, Thin	20815	4680	17073	1170
8d nail	11 mm OSB	17437	3920	14302	980

To best evaluate the applicability of LWP as SIP skins they should be compared to an existing study on SIP racking performance. Work performed by Kermani and Hairstans (2006) evaluating the racking strength of SIP walls will be used for the comparison. The wall details from the latter study are as follows: 2.65 mm diameter screws installed 250 mm o.c. (m=10) for vertical edges and 200 mm o.c. (n=6) for horizontal edges. Since one of the requirements of Equation 3.3.4 is that all fasteners be equally spaced, a distance of 225 mm o.c. will be assumed for the calculation resulting in the same number of fasteners per panel and the same values for n and m. 1.2 m x 2.4 m panels were also assumed, therefore α=0.46 remains the same. The equation was solved using the allowable design values from Table 3.4.3, and Table 3.4.6 gives a comparison of racking calculation results to full size SIP racking tests. The results show that LWPs can be used as a suitable OSB replacement for SIP skins.

Table 3.4.6: Comparison of racking resistance values vs. Kermani and Hairstans (2006).

Fastener	Connection	Unit Shear N/m	Unit Shear lb/ft
2.9 mm nail	Partial, Thick	2864	196
3.3 mm nail	Partial, Thick	2969	203
#10 Screw	Full, Thin	3882	266
2.65 mm screw	Kermani	3100	211

3.5 Conclusions

When analyzing the results, screws become the obvious choice for installing SIPs with LWP skins when ultimate strength is the priority. In addition to the higher load capacity, using screws alleviates the concern of damaging the thin outer skin with a nail gun. Also, since driving the fastener through either the thick or thin skin has a minimal affect on performance, fastener spacing can be modified as needed during installation.

Partial panel nailing had comparable capacity to screwed connections but the requirement of drilling a hole through the outer skin to access the thicker side could add cost to SIP installation. However, in order to take advantage of the hygrothermal improvements discovered by Brown (2012) exposing the core of the LWP to air flow will be necessary. In high humidity climates, the added installation cost might be a worthy investment when considering the cost of roof repair and replacement in Juneau, Alaska is estimated at up to $120,000 per home (Andrews 2001).

The results of this study, when combined with the hygrothermal benefits (Brown 2012) and increased specific bending stiffness (Voth and Yadama 2010),indicate that compared to typical OSB, lightweight wood strand sandwich panels have significant promise to improve the sustainable design impact of SIP construction.

3.6 Literature Cited

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CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

In order for lightweight wood-strand sandwich panels to be used as skins for structural insulated panels, they must meet or exceed the structural and hygrothermal properties of the oriented strand board they would replace. Their ability meet the requirements of bending stiffness (Voth 2009) and improve upon the hygrothermal performance (Brown 2012) has already been demonstrated. The connection properties evaluated in this study shows that LWPs can meet the connection capacity demands of SIPs.

LWPs have been shown to exceed the dowel bearing capacity of OSB by 28% and outperform its nail withdrawal and head pull-though resistance by 26% and 40% respectively. These results indicate that they have the potential to outperform OSB not only in its capacity as structural sheathing but also when attaching exterior cladding and interior fixtures.

Using yield limit equations and tested dowel bearing strength, single shear connection capacity was estimated at 732 N (84 lbs) per fastener. When the results of single shear connection tests were compared to yield limit calculations, the calculated and tested capacities differ by only 6%. This illustrates that the dowel bearing capacity can be reliably used to predict connection capacity of lightweight wood-strand sandwich panels. With further development of the energy yield model for hollow members the capacity of different connection techniques can be determined.

4.2 Recommendations for Future Research

Future research on LWPs should include testing of full size wall configurations to verify the racking resistance calculations performed in Chapter 3. Also threaded nails should be evaluated to determine if the additional withdrawal resistance can significantly improve the ultimate load capacity similar to screwed connections without resulting in brittle failures.

Since full thickness panel nailing would provide the easiest installation, a technique should be developed to minimize thin skin collapse. Testing of panels with the edges filled with an expanded foam, similar to the foam filled LWPs created by White (2011). Although this would not take full advantage of the hygrothermal benefits of the panel, it could be useful for implementation as floor sheathing since hygrothermal benefits would not be as important.

To encourage the adoption of LWPs studies should be performed to emphasize their long term benefits. The advantages of LWPs would be promoted by means of a life cycle analysis (LCA) study. A LCA combined with a market demand study would help promote LWPs as a viable replacement for OSB.

4.3 Literature Cited

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Appendix A

A.1 Production of LWPs

For this study 30 lodgepole pine logs, pre-cut into 13 mm (0.5 in.) thick slats by a lumber mill, were used for the raw material. The slats were then cut into 150 mm (6 in.) lengths and sliced to 0.36 mm (0.014 in.) thick strands using a CAE stranding machine. The dimensions selected reflect the optimum length to thickness aspect ratio of 430 as determined by Weight and Yadama (2008). To enhance the stranding process, the raw material was saturated with water to maintain a high moisture content similar to that of green lumber. The wood strands then had to be dried to approximately 9% moisture content in a box dryer, Figure A.1.1, to prevent mold and stain from forming.

Figure A.1.1: Lodgepole pine strands drying to 9% M.C. in box dryer.

The LWPs consist of a 3-D core sandwiched between two thin outer skins. Both the core and the skin are fabricated using the same strands and resins with similar pressing schedules as developed by Voth and Yadama (2010). Prior to pressing the strands were oven dried to <3% moisture content to reduce the effects of vapor pressure in the thin panels. The moisture content target was reduced from Voth's target of <5% to reduce the production of excess steam inside the panel resulting in trapped gas pockets or de lamination of the strand layers. Strands were spread out in trays and placed in an oven at 105 °C. This approach was used instead of a drum drier because, although faster, the drum drier is known to create more fines than stationary drying techniques. Instead of sieving the material after drying the fines were allowed to settle to the bottom of the bag during handling and later discarded.

The dried strands were then mixed in a rotating drum with Momentive Cascophen AM1661 phenol formaldehyde resin containing 55.8% solids by weight. The resin was applied at a ratio of 8% solids by weight, compared to wood furnish, using a three nozzle sprayer system with 40 psi air pressure to spray the resin inside the rotating drum ensuring even coating of all strands. The coated strands were then weighed according to furnish calculations to achieve the desired density of 0.64 g/cm^3. Using a screening box mounted over a shake table the strands were evenly distributed over a caul sheet and with a +/- 15° orientation. The caul sheet was then placed in a hydraulic press with oil heated platens, preheated to 160 °C, and pressed using the pressing schedule previously mentioned. Pressing of the cores followed the same process as the 3.2 mm skins except contoured aluminum caul sheets were used to mold the strands into the final shape while being heated to cure the resin as shown in Figure A.1.2.

Figure A.1.2: LWP core being pressed

After pressing, cores and skins were placed in an environmental control room at 50% relative humidity and 20 °C to equalize the panels at 9.0% MC. Once equilibrium moisture content was attained, the panels were bonded together with one skin on either side of a core using Daubond U6040 liquid polyurethane adhesive. To ensure good bonding, the panels were prepped by misting with water. Adhesive was applied to only the contact points of the contoured core using a 76 mm low nap mohair roller. Panels were assembled three at a time and clamped using a dimensional lumber frame to evenly spread the clamping force over the surface of the panels.

Figure A.1.3: LWPs assembled three at a time and clamped

A.2 LWP Skin Composition

Panel Properties				
Target Density	40	lb/ft^3	0.64	g/cm^3
Width	26	in	660.4	mm
Length	38	in	965.2	mm
Thickness	0.125	in	3.175	mm
Solids per panel	2.86	lb.	1.297	kg

Phenol Formaldehyde Resin		**S.G.**	**1.240**	
% content	8%			
Solids content	55.35%			
Total solids weight	0.229	lb.	0.104	kg
Total resin weight	0.413	lb.	0.187	kg

Lodgepole Pine		**S.G.**	**0.37**	
Strands, OD	2.63	lb	1.193	kg
Target MC of strands	3%			
Strand weight @ Target MC	2.71	lb	1.230	kg
Water weight	0.08	lb	0.04	kg

Recipe for Blender (per panel)				
Waste Factors (%)	110%			
Wood	2.98	lb	1.353	kg
Resin	0.45	lb	0.206	kg
Wood+Resin for Forming	3.12	lb	1.417	kg

HCP Recipe Adjusted for Moisture Content and Double Batch Quantities

	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%
Wood	1325.5 g	1332.3 g	1339.1 g	1345.9 g	1352.9 g	1359.9 g
Resin	206.2 g	206.2 g	206.2 g	206.2 g	206.2 g	206.2 g
Wood x2	2651.1 g	2664.5 g	2678.1 g	2691.9 g	2705.8 g	2719.8 g
Resin x2	412.3 g	412.3 g	412.3 g	412.3 g	412.3 g	412.3 g
Wood+Resin for Forming	1392.5 g	1398.6 g	1404.8 g	1411.0 g	1417.3 g	1423.7 g

A.3 LWP Core Composition

Panel Properties				
Target Density	40	lb/ft^3	0.64	g/cm^3
Width	27	in	685.8	mm
Length	36	in	914.4	mm
Thickness	0.25	in	6.35	mm
Solids per panel	5.63	lb.	2.551	kg

Phenol Formaldehyde Resin		**S.G.**	**1.240**	
% content	8%			
Solids content	55.35%			
Total solids weight	0.450	lb.	0.204	kg
Total resin weight	0.813	lb.	0.369	kg

Lodgepole Pine		**S.G.**	**0.37**	
Strands, OD	5.18	lb	2.347	kg
Target MC of strands	3%			
Strand weight @ Target MC	5.34	lb	2.420	kg
Water weight	0.16	lb	0.07	kg

Recipe for Blender (per panel)				
Waste Factors (%)	110%			
Wood	5.87	lb	2.662	kg
Resin	0.89	lb	0.406	kg
Wood+Resin for Forming	6.15	lb	2.789	kg

LWP Recipe Adjusted for Moisture Content and Double Batch Quantities

	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%
Wood	2608.2 g	2621.4 g	2634.8 g	2648.3 g	2661.9 g	2675.7 g
Resin	405.7 g	405.7 g	405.7 g	405.7 g	405.7 g	405.7 g
Wood+Resin for Forming	2739.8 g	2751.9 g	2764.0 g	2776.3 g	2788.7 g	2801.3 g

A.4 LWP Pressing Schedule

A.4.1 LWP Core – Imperial Units

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------------------------------------------------------------------------------»
° PressMAN v7.8 Press Control  rel. 06/14/2000 SK Software Copyright 1990-2000 °
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  Proj. Ref.: LWP Core      Date......: 06-27-2012    Time......: 11:44:11
  Prod. Ref.: 380f          Panel ID..: 1/4           File Name.: DO_C25.REG
  Press ID..: WSU300        Mat Length: 31.5 in.      Mat Width.: 27.0 in.
  Density...: 40.00 lb/ft3  Thickness.: 0.250 in.     Caul Thick: 3.250 in.

  Units.....: IMPERIAL      Pressure..: MAT           Position..: THICKNESS

------------------------------------------------------------------------------»
°SEG.³CONTROL   ³SETPOINT      ³SEG. TIME³END CONDITION           ³EVENTS      °
°  1 ³ FASTPOSN ³ -0.500 in./s ³    10 s ³ POSITION <=  1.000 in. ³1          1 °
°  2 ³ POSITION ³  50.00 %     ³     1 s ³                        ³           2°
°  3 ³ POSITION ³  0.750 in.   ³    10 s ³                        ³            °
°  4 ³ POSITION ³  0.250 in.   ³    30 s ³                        ³            °
°  5 ³ POSITION ³  0.250 in.   ³   240 s ³                        ³            °
°  6 ³ POSITION ³  0.275 in.   ³    40 s ³                        ³            °
°  7 ³ POSITION ³  0.300 in.   ³    30 s ³                        ³            °
°  8 ³ POSITION ³  0.500 in.   ³    30 s ³                        ³            °
°  9 ³ FASTPOSN ³  0.500 in./s ³    20 s ³ POSITION >= 20.000 in. ³1          1 °
° 10 ³          ³              ³         ³                        ³            °
° 11 ³          ³              ³         ³                        ³            °
° 12 ³          ³              ³         ³                        ³            °
° 13 ³          ³              ³         ³                        ³            °
° 14 ³          ³              ³         ³                        ³            °
° 15 ³          ³              ³         ³                        ³            °
° 16 ³          ³              ³         ³                        ³            °
° 17 ³          ³              ³         ³                        ³            °
° 18 ³          ³              ³         ³                        ³            °
° 19 ³          ³              ³         ³                        ³            °
° 20 ³          ³              ³         ³                        ³            °
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 EVENT Listing:

 EVENT 1: Fast Position Control         EVENT 2: Not Used
 EVENT 3: Follow Density Rate Profile   EVENT 4: Not Used
 EVENT 5: Begin Steam Injection Program EVENT 6: Run Steam Injection Program
 EVENT 7: Not Used                      EVENT 8: Not Used
 EVENT 9: Decelerate from Set Rate to 0 EVENT 10: Accelerate from 0 to Set Rate
 EVENT 11: Setpoint is Given as Rate    EVENT 12: PID Control is Manual

------------------------------------------------------------------------------»
° PRESS PRESSURE/POSITION          ³  LOOP 1  ³  LOOP 2  ³  LOOP 3  ³  LOOP 4  °
° PID PARAMETERS                   ³ PRESSURE ³ POSITION ³FAST POSTN³ NOT USED °
° Gain                             ³   3.00 % ³  40.00 % ³  15.00 % ³   N/A    °
° Reset                            ³   0.20 % ³   2.00 % ³   0.00 % ³   N/A    °
° Rate                             ³   0.00 % ³   0.00 % ³   0.00 % ³   N/A    °
° Bias                             ³  50.00 % ³  50.00 % ³  50.00 % ³   N/A    °
° Dead Band                        ³   0.00 % ³   0.00 % ³   0.00 % ³   N/A    °
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A.4.2 LWP Core – Metric Units

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° PressMAN v7.8 Press Control  rel. 06/14/2000 SK Software Copyright 1990-2000 °
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  Proj. Ref.: LWP Core      Date......: 06-27-2012    Time......: 11:44:11
  Prod. Ref.: 380f          Panel ID..: 1/4           File Name.: DO_C25.REG
  Press ID..: WSU300        Mat Length: 0.80 m        Mat Width.: 0.69 m
  Density...: 641 kg/m3     Thickness.: 6.35 mm       Caul Thick: 82.55 mm

  Units.....: METRIC        Pressure..: MAT           Position..: THICKNESS

-------------------------------------------------------------------------------»
°SEG.³CONTROL   ³SETPOINT      ³SEG. TIME³END CONDITION          ³EVENTS      °
°  1 ³ FASTPOSN ³ -12.70 mm/s  ³    10 s ³ POSITION <=  25.40 mm  ³1         1 °
°  2 ³ POSITION ³  50.00 %     ³     1 s ³                        ³           2°
°  3 ³ POSITION ³  19.05 mm    ³    10 s ³                        ³            °
°  4 ³ POSITION ³   6.35 mm    ³    30 s ³                        ³            °
°  5 ³ POSITION ³   6.35 mm    ³   240 s ³                        ³            °
°  6 ³ POSITION ³   6.99 mm    ³    40 s ³                        ³            °
°  7 ³ POSITION ³   7.62 mm    ³    30 s ³                        ³            °
°  8 ³ POSITION ³  12.70 mm    ³    30 s ³                        ³            °
°  9 ³ FASTPOSN ³  12.70 mm/s  ³    20 s ³ POSITION >= 508.00 mm  ³1         1 °
° 10 ³          ³              ³         ³                        ³            °
° 11 ³          ³              ³         ³                        ³            °
° 12 ³          ³              ³         ³                        ³            °
° 13 ³          ³              ³         ³                        ³            °
° 14 ³          ³              ³         ³                        ³            °
° 15 ³          ³              ³         ³                        ³            °
° 16 ³          ³              ³         ³                        ³            °
° 17 ³          ³              ³         ³                        ³            °
° 18 ³          ³              ³         ³                        ³            °
° 19 ³          ³              ³         ³                        ³            °
° 20 ³          ³              ³         ³                        ³            °
È----Ï----------Ï--------------Ï---------Ï------------------------Ï------------¼

 EVENT Listing:

 EVENT 1: Fast Position Control         EVENT 2: Not Used
 EVENT 3: Follow Density Rate Profile   EVENT 4: Not Used
 EVENT 5: Begin Steam Injection Program EVENT 6: Run Steam Injection Program
 EVENT 7: Not Used                      EVENT 8: Not Used
 EVENT 9: Decelerate from Set Rate to 0 EVENT 10: Accelerate from 0 to Set Rate
 EVENT 11: Setpoint is Given as Rate    EVENT 12: PID Control is Manual

-------------------------------------------------------------------------------»
° PRESS PRESSURE/POSITION          ³  LOOP 1  ³  LOOP 2  ³  LOOP 3  ³  LOOP 4  °
° PID PARAMETERS                   ³ PRESSURE ³ POSITION ³FAST POSTN³ NOT USED °
° Gain                             ³   3.00 % ³  40.00 % ³  15.00 % ³   N/A    °
° Reset                            ³   0.20 % ³   2.00 % ³   0.00 % ³   N/A    °
° Rate                             ³   0.00 % ³   0.00 % ³   0.00 % ³   N/A    °
° Bias                             ³  50.00 % ³  50.00 % ³  50.00 % ³   N/A    °
° Dead Band                        ³   0.00 % ³   0.00 % ³   0.00 % ³   N/A    °
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A.4.3 LWP Skin – Imperial Units

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º PressMAN v7.8 Press Control  rel. 06/14/2000 SK Software Copyright 1990-2000 º
È-------------------------------------------------------------------------------¼


  Proj. Ref.: LWP Skin      Date......: 09-11-2012    Time......: 12:53:34
  Prod. Ref.: 160C          Panel ID..: 1/8           File Name.: DO_S125.REG
  Press ID..: WSU300        Mat Length: 38.0 in.      Mat Width.: 26.0 in.
  Density...: 40.00 lb/ft3  Thickness.: 0.125 in.     Caul Thick: 0.190 in.

  Units.....: IMPERIAL      Pressure..: MAT           Position..: THICKNESS

-------------------------------------------------------------------------------»
ºSEG.³CONTROL   ³SETPOINT      ³SEG. TIME³END CONDITION          ³EVENTS      º
º  1 ³ FASTPOSN ³ -0.500 in./s ³    10 s ³ POSITION <=  1.000 in. ³1         1 º
º  2 ³ POSITION ³  50.00 %     ³     1 s ³                        ³          2º
º  3 ³ POSITION ³  0.750 in.   ³    20 s ³                        ³            º
º  4 ³ POSITION ³  0.250 in.   ³    20 s ³                        ³            º
º  5 ³ POSITION ³  0.250 in.   ³    10 s ³                        ³            º
º  6 ³ POSITION ³  0.125 in.   ³    10 s ³                        ³            º
º  7 ³ POSITION ³  0.130 in.   ³    80 s ³                        ³            º
º  8 ³ POSITION ³  0.125 in.   ³    10 s ³                        ³            º
º  9 ³ POSITION ³  0.125 in.   ³   210 s ³                        ³            º
º 10 ³ POSITION ³  0.135 in.   ³    40 s ³                        ³            º
º 11 ³ FASTPOSN ³  2.000 in./s ³    20 s ³ POSITION >=  5.000 in. ³1         1 º
º 12 ³          ³              ³         ³                        ³            º
º 13 ³          ³              ³         ³                        ³            º
º 14 ³          ³              ³         ³                        ³            º
º 15 ³          ³              ³         ³                        ³            º
º 16 ³          ³              ³         ³                        ³            º
º 17 ³          ³              ³         ³                        ³            º
º 18 ³          ³              ³         ³                        ³            º
º 19 ³          ³              ³         ³                        ³            º
º 20 ³          ³              ³         ³                        ³            º
È----Ï----------Ï--------------Ï---------Ï------------------------Ï------------¼

 EVENT Listing:

 EVENT 1: Fast Position Control         EVENT 2: Not Used
 EVENT 3: Follow Density Rate Profile   EVENT 4: Not Used
 EVENT 5: Begin Steam Injection Program EVENT 6: Run Steam Injection Program
 EVENT 7: Not Used                      EVENT 8: Not Used
 EVENT 9: Decelerate from Set Rate to 0 EVENT 10: Accelerate from 0 to Set Rate
 EVENT 11: Setpoint is Given as Rate    EVENT 12: PID Control is Manual

-------------------------------------------------------------------------------»
º PRESS PRESSURE/POSITION          ³  LOOP 1  ³  LOOP 2  ³  LOOP 3  ³  LOOP 4  º
º PID PARAMETERS                   ³ PRESSURE ³ POSITION ³FAST POSTN³ NOT USED º
º Gain                             ³   3.00 % ³  40.00 % ³  15.00 % ³   N/A    º
º Reset                            ³   0.20 % ³   2.00 % ³   0.00 % ³   N/A    º
º Rate                             ³   0.00 % ³   0.00 % ³   0.00 % ³   N/A    º
º Bias                             ³  50.00 % ³  50.00 % ³  50.00 % ³   N/A    º
º Dead Band                        ³   0.00 % ³   0.00 % ³   0.00 % ³   N/A    º
È----------------------------------Ï----------Ï----------Ï----------Ï----------¼
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A.4.4 LWP Skin – Metric Units

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-----------------------------------------------------------------------------»
° PressMAN v7.8 Press Control  rel. 06/14/2000 SK Software Copyright 1990-2000 °
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  Proj. Ref.: LWP Skin       Date......: 09-11-2012    Time......: 12:53:34
  Prod. Ref.: 160C           Panel ID..: 1/8           File Name.: DO_S125.REG
  Press ID..: WSU300         Mat Length: 0.97 m        Mat Width.: 0.66 m
  Density...: 641 kg/m3      Thickness.: 3.18 mm       Caul Thick: 4.83 mm

  Units.....: METRIC         Pressure..: MAT           Position..: THICKNESS

-----------------------------------------------------------------------------»
°SEG.³CONTROL   ³SETPOINT      ³SEG. TIME³END CONDITION          ³EVENTS      °
°  1 ³ FASTPOSN ³ -12.70 mm/s  ³    10 s ³ POSITION <=  25.40 mm  ³1          1 °
°  2 ³ POSITION ³  50.00 %     ³     1 s ³                        ³           2°
°  3 ³ POSITION ³  19.05 mm    ³    20 s ³                        ³            °
°  4 ³ POSITION ³   6.35 mm    ³    20 s ³                        ³            °
°  5 ³ POSITION ³   6.35 mm    ³    10 s ³                        ³            °
°  6 ³ POSITION ³   3.18 mm    ³    10 s ³                        ³            °
°  7 ³ POSITION ³   3.30 mm    ³    80 s ³                        ³            °
°  8 ³ POSITION ³   3.18 mm    ³    10 s ³                        ³            °
°  9 ³ POSITION ³   3.18 mm    ³   210 s ³                        ³            °
° 10 ³ POSITION ³   3.43 mm    ³    40 s ³                        ³            °
° 11 ³ FASTPOSN ³  50.80 mm/s  ³    20 s ³ POSITION >= 127.00 mm  ³1          1 °
° 12 ³          ³              ³         ³                        ³            °
° 13 ³          ³              ³         ³                        ³            °
° 14 ³          ³              ³         ³                        ³            °
° 15 ³          ³              ³         ³                        ³            °
° 16 ³          ³              ³         ³                        ³            °
° 17 ³          ³              ³         ³                        ³            °
° 18 ³          ³              ³         ³                        ³            °
° 19 ³          ³              ³         ³                        ³            °
° 20 ³          ³              ³         ³                        ³            °
È----Ï----------Ï--------------Ï---------Ï------------------------Ï------------¼

 EVENT Listing:

 EVENT 1: Fast Position Control          EVENT 2: Not Used
 EVENT 3: Follow Density Rate Profile    EVENT 4: Not Used
 EVENT 5: Begin Steam Injection Program  EVENT 6: Run Steam Injection Program
 EVENT 7: Not Used                       EVENT 8: Not Used
 EVENT 9: Decelerate from Set Rate to 0  EVENT 10: Accelerate from 0 to Set Rate
 EVENT 11: Setpoint is Given as Rate     EVENT 12: PID Control is Manual

-----------------------------------------------------------------------------»
° PRESS PRESSURE/POSITION          ³  LOOP 1  ³  LOOP 2  ³  LOOP 3  ³  LOOP 4  °
° PID PARAMETERS                   ³ PRESSURE ³ POSITION ³FAST POSTN³ NOT USED °
° Gain                             ³   3.00 % ³  40.00 % ³  15.00 % ³   N/A    °
° Reset                            ³   0.20 % ³   2.00 % ³   0.00 % ³   N/A    °
° Rate                             ³   0.00 % ³   0.00 % ³   0.00 % ³   N/A    °
° Bias                             ³  50.00 % ³  50.00 % ³  50.00 % ³   N/A    °
° Dead Band                        ³   0.00 % ³   0.00 % ³   0.00 % ³   N/A    °
È----------------------------------Ï----------Ï----------Ï----------Ï----------¼
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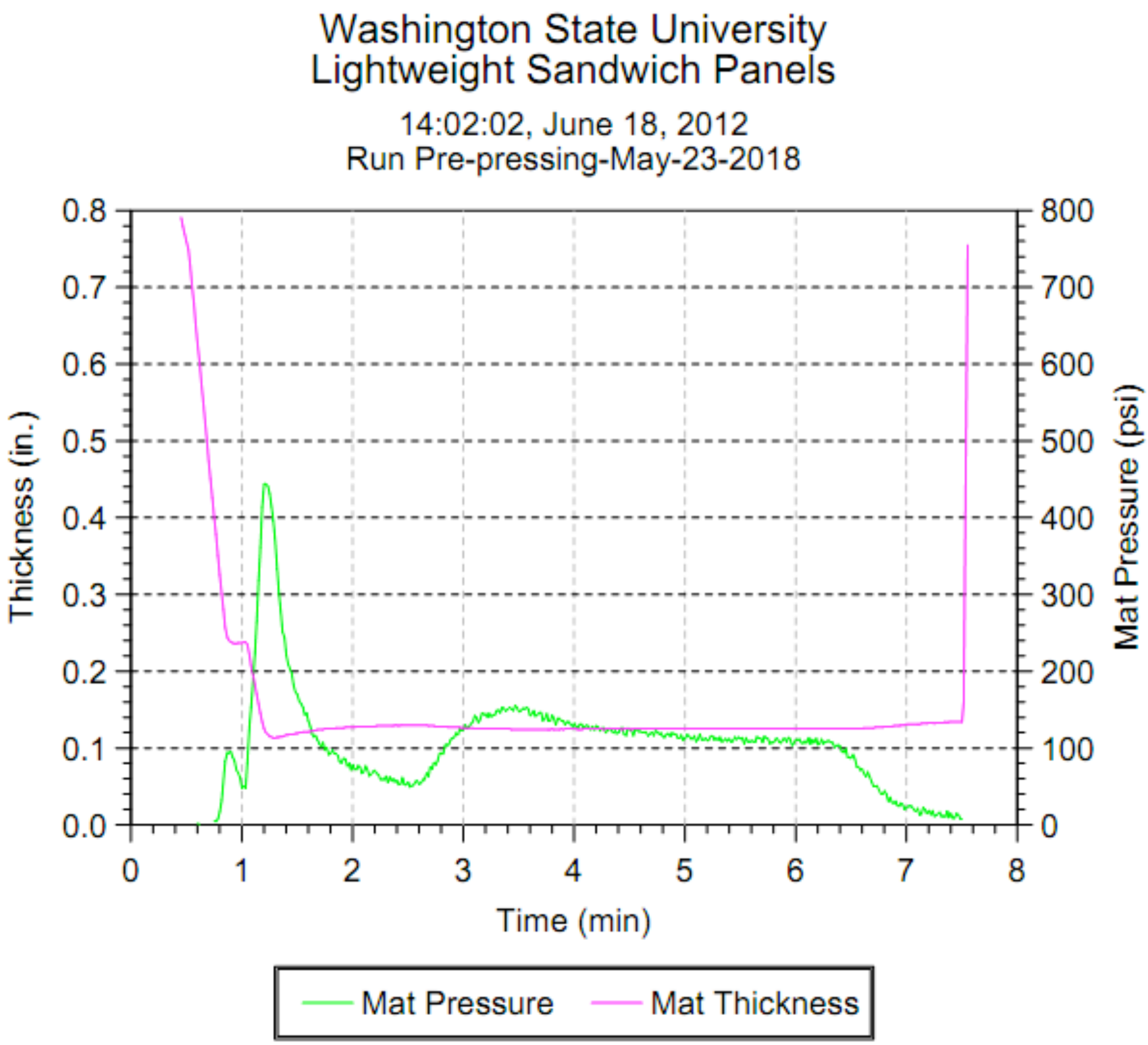


Figure A.4.1: Mat pressure and thickness during skin pressing

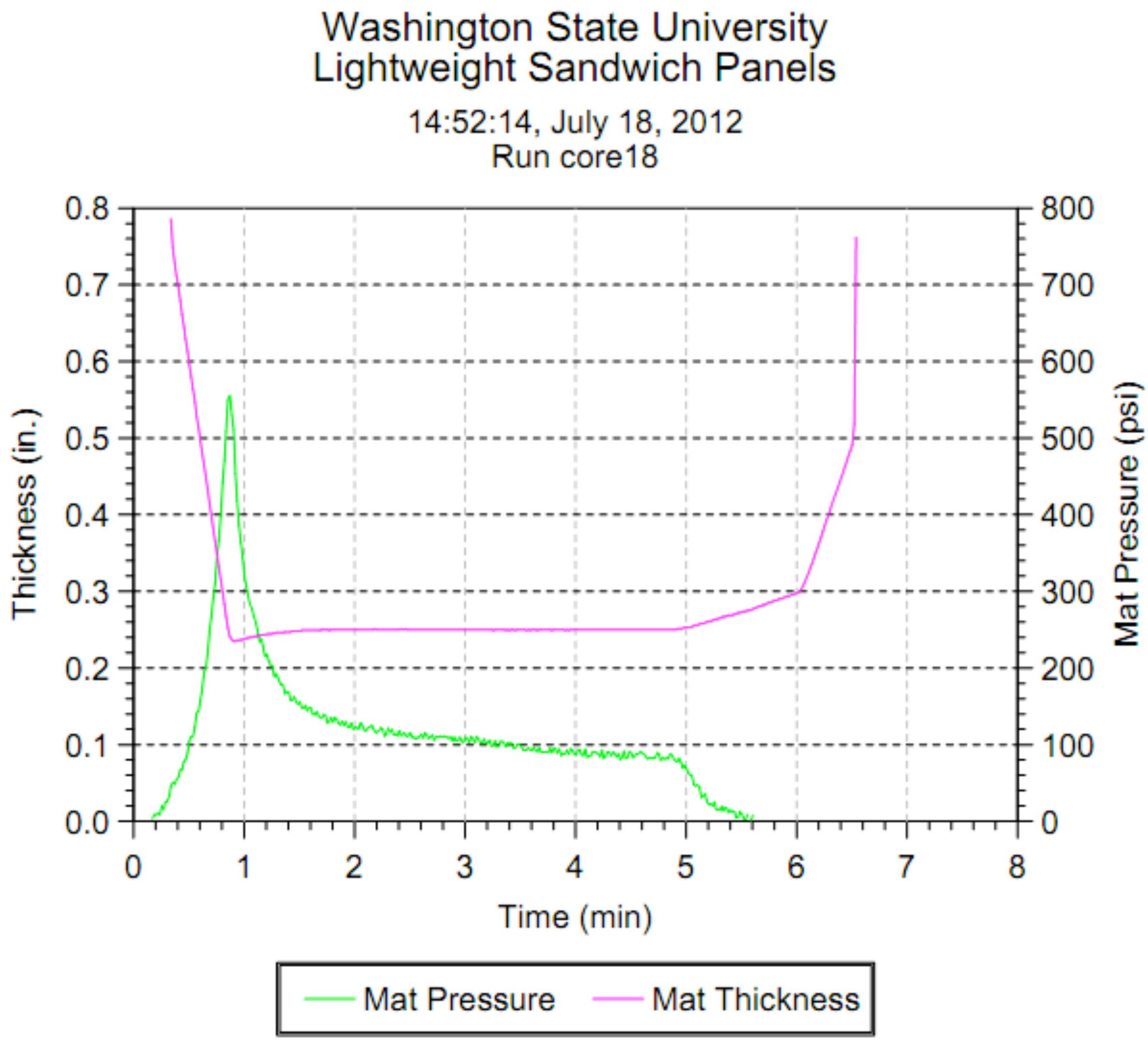


Figure A.4.2: Mat pressure and thickness during core pressing

Appendix B : Yield Capacity Calculations

B.1 : European Yield Calculations

Yield Mode	Single Shear	
I_m	$Z = \frac{D \ell_m F_{em}}{R_d}$	(11.3-1)
I_s	$Z = \frac{D \ell_s F_{es}}{R_d}$	(11.3-2)
II	$Z = \frac{k_1 D \ell_s F_{es}}{R_d}$	(11.3-3)
III_m	$Z = \frac{k_2 D \ell_m F_{em}}{(1+2R_e) R_d}$	(11.3-4)
III_s	$Z = \frac{k_3 D \ell_s F_{em}}{(2+R_e) R_d}$	(11.3-5)
IV	$Z = \frac{D^2}{R_d}\sqrt{\frac{2 F_{em} F_{yb}}{3(1+R_e)}}$	(11.3-6)

D = diameter, in. (see 11.3.6)
F_{yb} = dowel bending yield strength, psi
R_d = reduction term (see Table 11.3.1B)
R_e = F_{em}/F_{es}
R_t = ℓ_m/ℓ_s
ℓ_m = main member dowel bearing length, in.
ℓ_s = side member dowel bearing length, in.
F_{em} = main member dowel bearing strength, psi (see Table 11.3.3)
F_{es} = side member dowel bearing strength, psi (see Table 11.3.3)

$$k_1 = \frac{\sqrt{R_e + 2R_e^2(1+R_t+R_t^2)+R_t^2R_e^3} - R_e(1+R_t)}{(1+R_e)}$$

$$k_2 = -1 + \sqrt{2(1+R_e) + \frac{2F_{yb}(1+2R_e)D^2}{3F_{em}\ell_m^2}}$$

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

Yield Equations as entered in Excel Spreadsheet

	A	B
1	D	0.131
2	Fyb	114276.957649846
3	Rd	2.2
4	Re	=fem/fes
5	Rt	=lm/ls
6	lm	=3-ls
7	ls	0.42
8	Fem	4650
9	Fes	5942
10	k1	=(SQRT(re+2*re^2*(1+rt+rt^2)+rt^2*re^3)-re*(1+rt))/(1+re)
11	k2	=-1+SQRT((2*(1+re))+(2*fyb*(1+2*re)*d^2)/(3*fem*ls^2))
12	k3	=-1+SQRT((2*(1+re))/re+(2*fyb*(2+re)*d^2)/(3*fem*ls^2))
13		
14	Im	=d*lm*fem/(rd)
15	Is	=d*ls*fes/rd
16	II	=B10*d*ls*fes/rd
17	IIIm	=B11*d*lm*fem/((1+2*re)*rd)
18	IIIs	=B12*d*ls*fem/((2+re)*rd)
19	IV	=(d^2/rd)*SQRT((2*fem*fyb)/(3*(1+re)))

B.2 Equivalent Dowel Bearing Strength

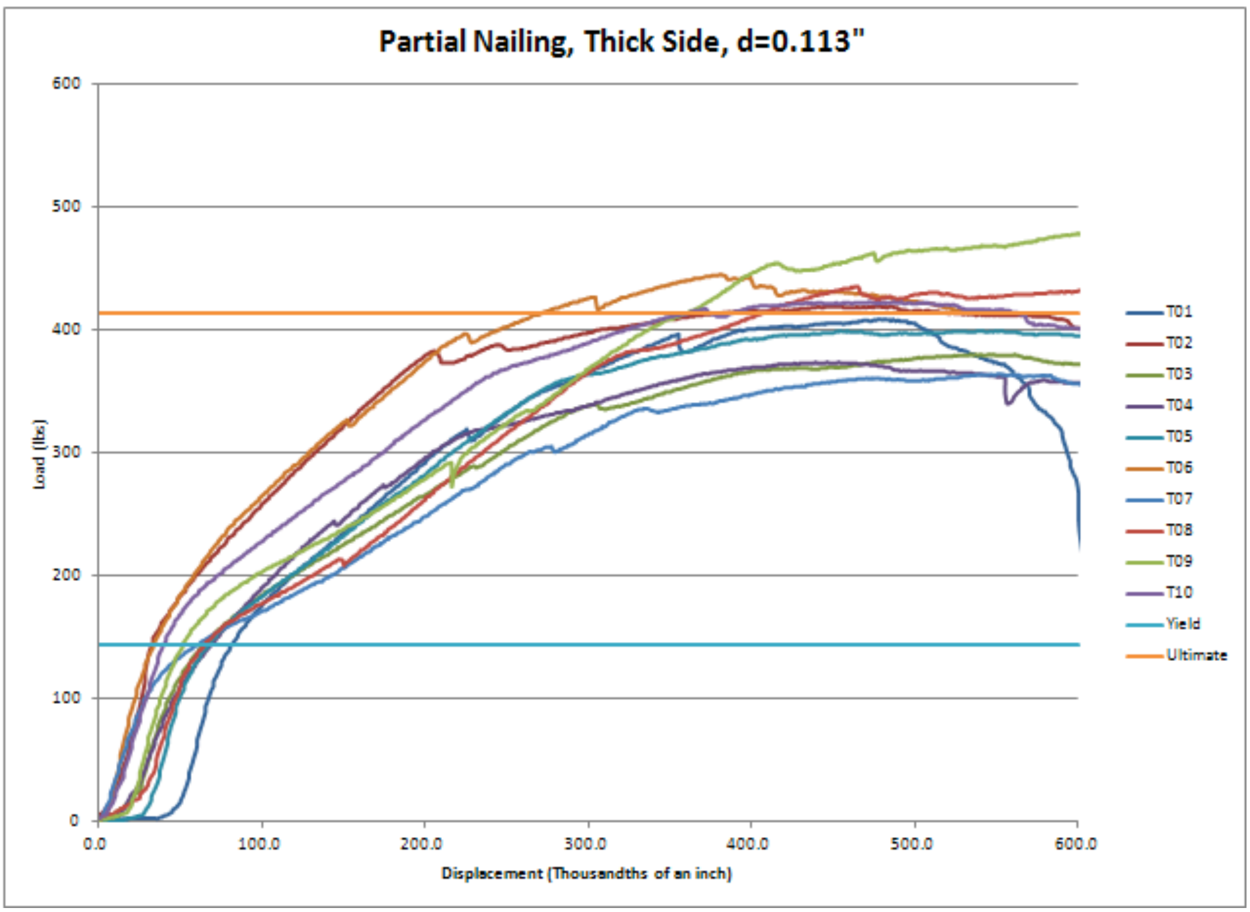
	A	B	C	D
1	**Withdrawal Equivalence**			
2				
3		$G_{eq} = \left(\frac{\frac{W}{5}}{1380d} \right)^{0.4}$		(A1.1)
4				
5				
6	where:			
7				
8	G_{eq}	= equivalent specific gravity		
9	W	= withdrawal capacity per inch of penetration, lbf/in.		
10	d	= nail diameter, in.		
11	W	95.17	lb/in	
12	d	0.113	in	
13	Geq=	=((B11/5)/(1380*B12))^0.4	=0.43	
14				
15	**Lateral Resistance Equivalence**			
16	D < 1/4" = 16600 $G^{1.84}$; Tabulated values are rounded to the nearest 50 psi.			
17	Fe=	5950		
18	Geq=	=(B17/16600)^(1/1.84)	=0.57	

Appendix C Single Fastener Test Results and Statistical Analysis

C.1 : Test Results

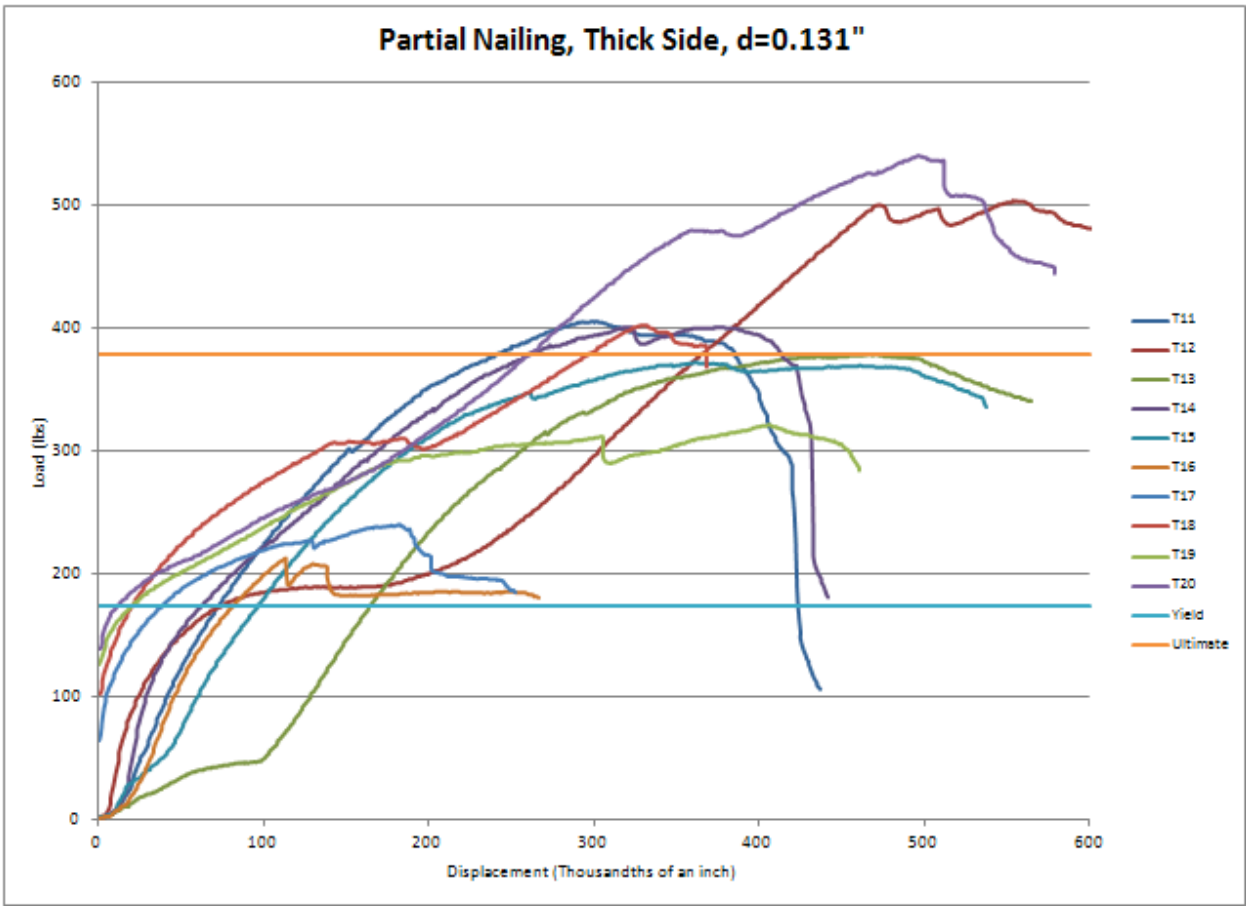
Partial Nailing, Thick Side, d=0.113"

Panel ID	Max Load (lb)	Disp. At Max Load (in)	Yield (lb)
T01	408.3	0.475	141.7
T02	419.6	0.484	177.2
T03	380.1	0.534	128.1
T04	373.7	0.439	126.4
T05	398.6	0.452	132.9
T06	444.6	0.38	153
T07	363.2	0.54	121.6
T08	434.9	0.461	138.5
T09	480	0.611	147.4
T10	422	0.472	168.3
Mean	412.5	0.4848	143.51
COV	8.6%	13.1%	12.7%



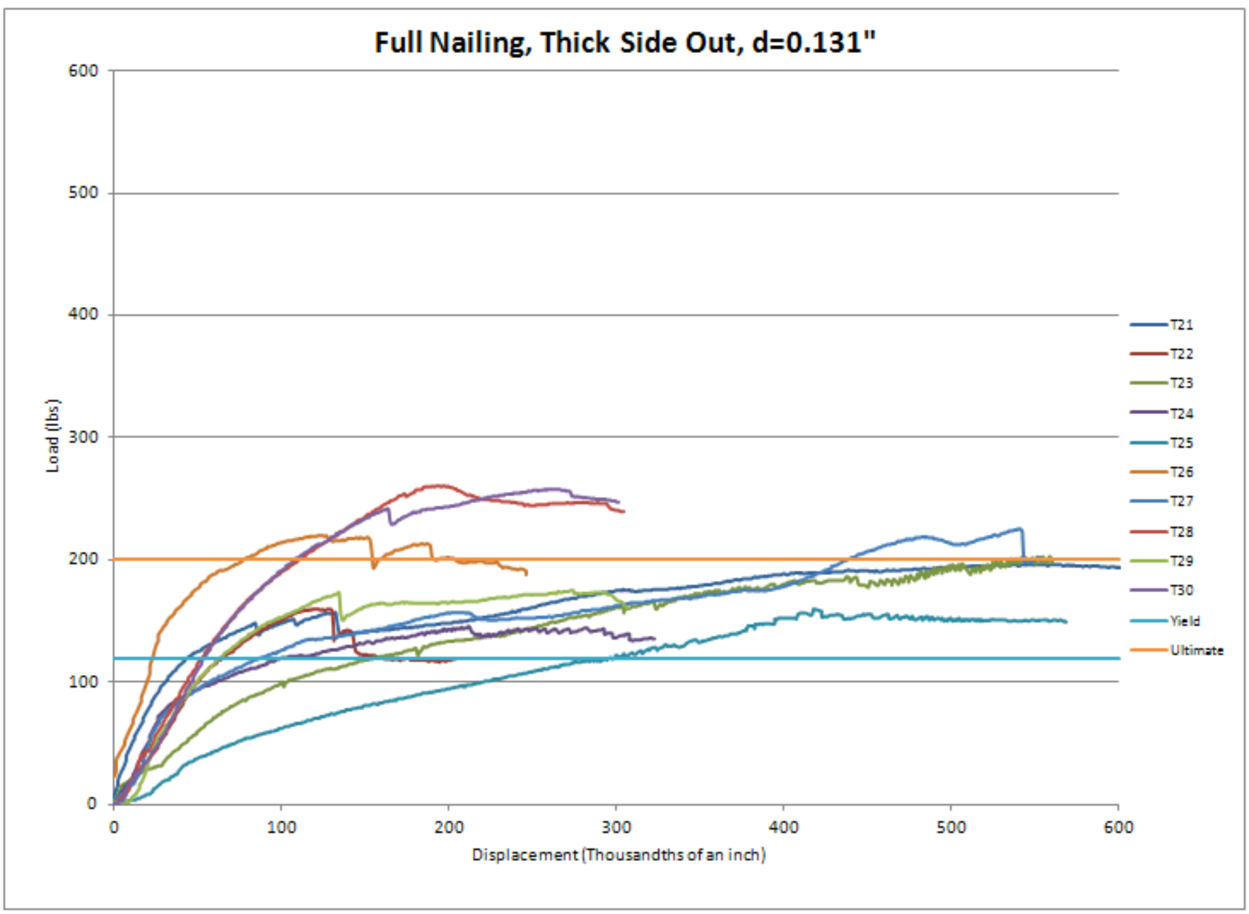
Partial Nailing, Thick Side, d=0.131"

Panel ID	Max Load (lb)	Disp. At Max Load (in)	Yield (lb)
T11	405.1	0.293	165.9
T12	504.2	0.553	149
T13	378.5	0.463	253.7
T14	401.1	0.318	147.4
T15	371.3	0.36	161.9
T16	212.6	0.113	156.2
T17	240.8	0.182	154.6
T18	401.9	0.328	184.4
T19	320.5	0.405	174.8
T20	539.6	0.496	182
Mean	377.56		172.99
COV	27.0%		18.0%



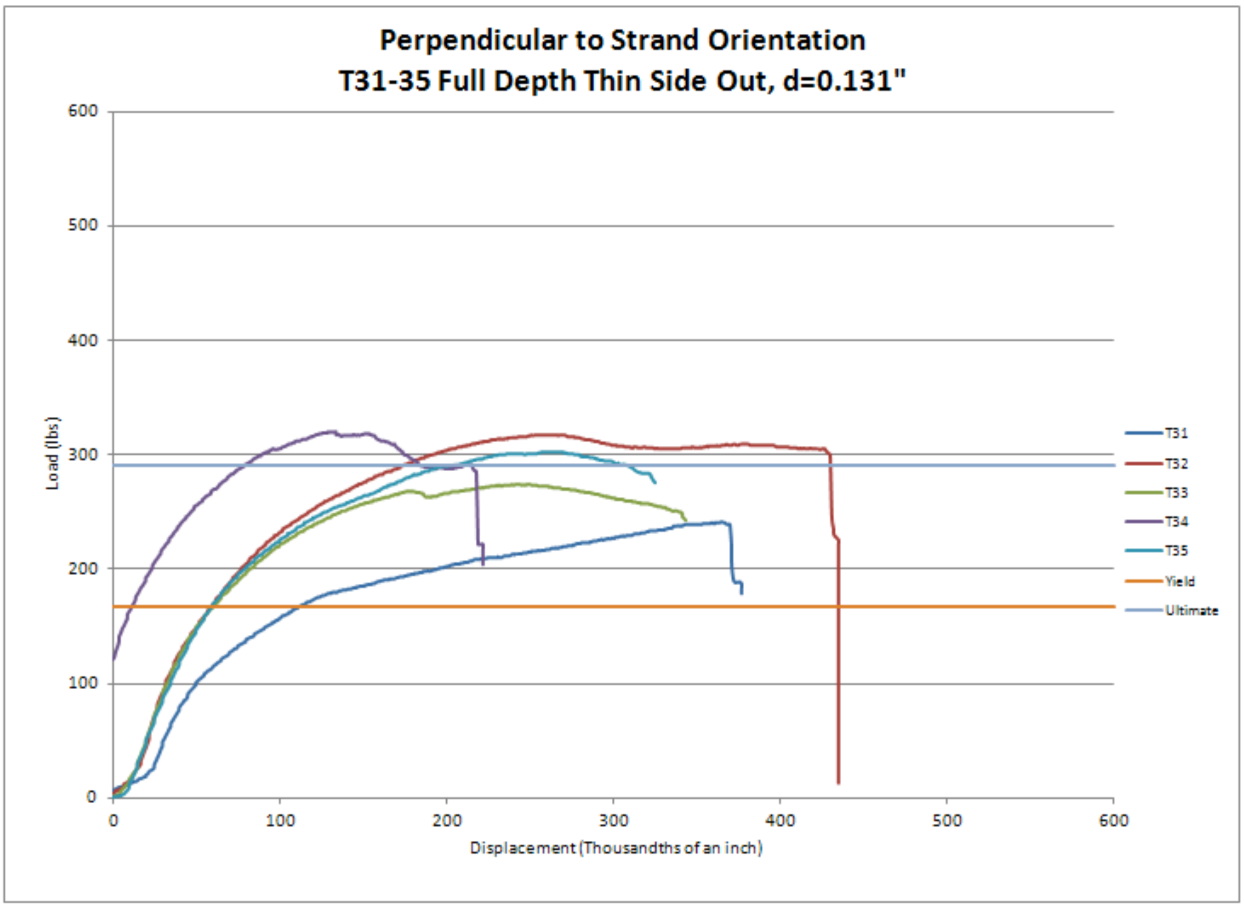
Full Nailing, Thick Side Out, d=0.131"

Panel ID	Max Load (lb)	Disp. At Max Load (in)	Yield (lb)
T21	197.3	0.965	114.4
T22	160.3	0.117	118.4
T23	202.1	0.552	99.05
T24	146.6	0.212	92.61
T25	159.5	0.418	57.98
T26	220.7	0.122	178
T27	225.5	0.54	86.97
T28	260.9	0.191	163.5
T29	174.8	0.273	118.4
T30	258.5	0.257	167.5
Mean	200.62		119.681
COV	20.3%		32.6%



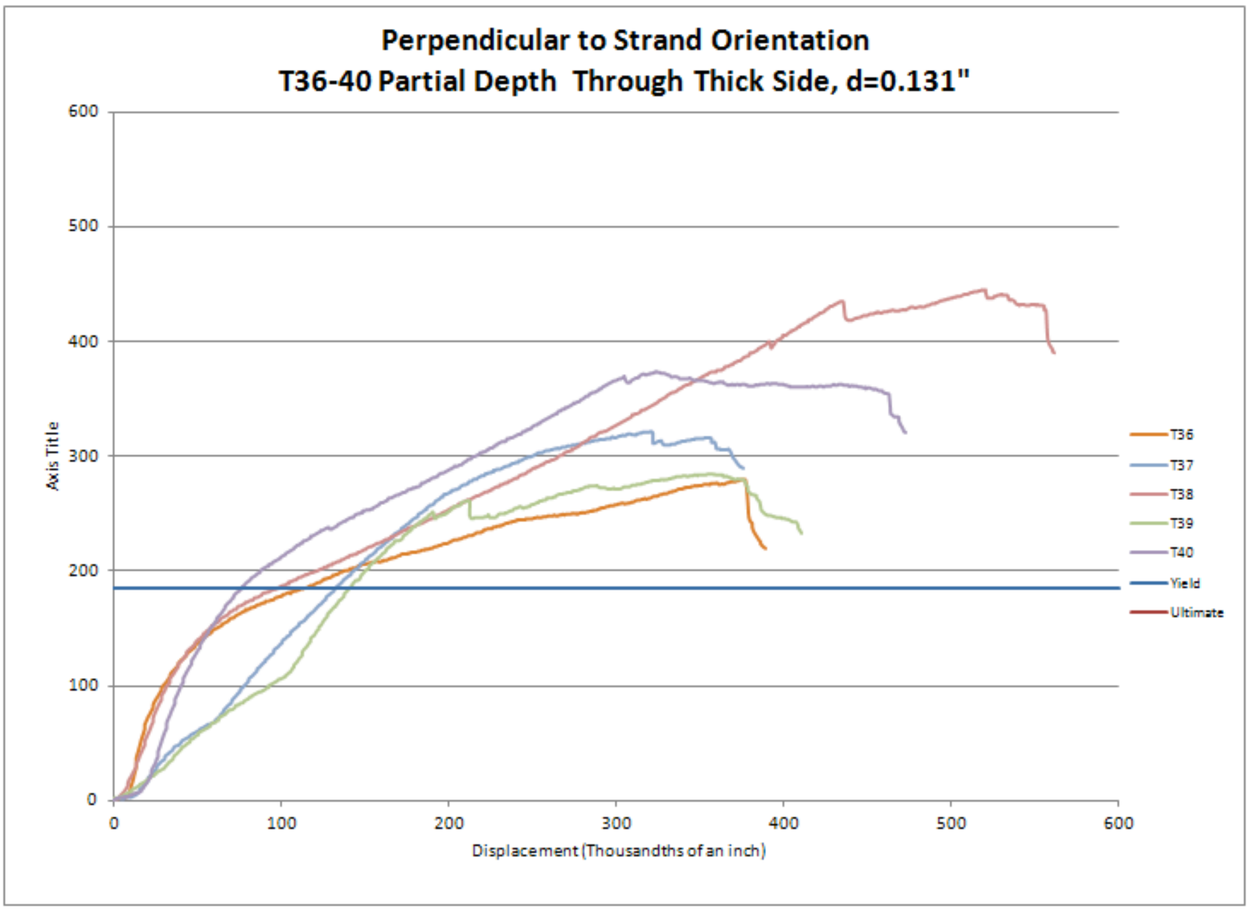
Full Nailing, Thin Side Out, d=0.131" - Perpendicular

Panel ID	Max Load (lb)	Disp. At Max Load (in)	Yield (lb)
T31	241.6	0.365	130.5
T32	317.3	0.251	155.4
T33	273.8	0.239	157
T34	320.5	0.129	215.8
T35	302	0.257	174
Mean	291.04		166.54
COV	11.4%		19.0%



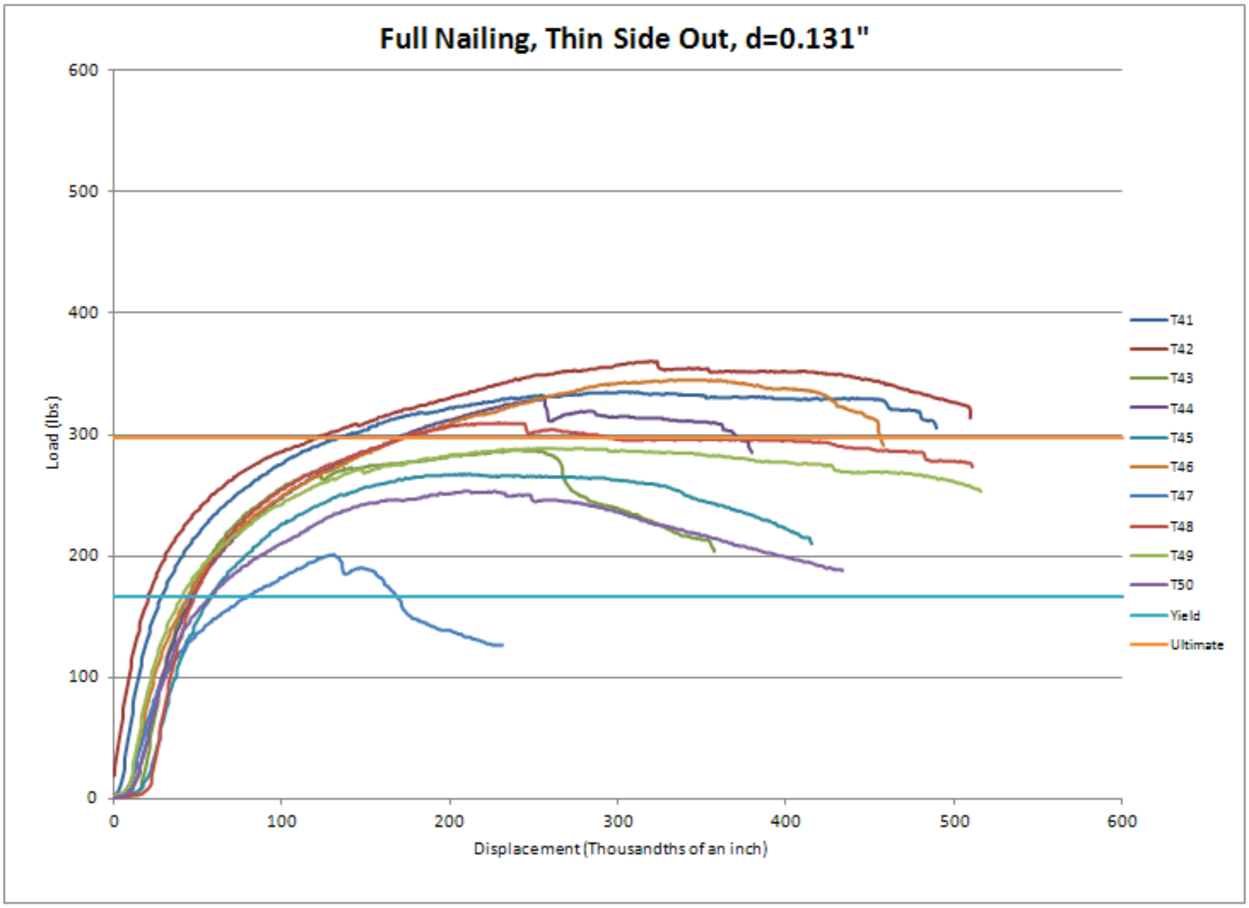
Partial Nailing, Through Thick Side, d=0.131" - Perpendicular

Panel ID	Max Load (lb)	Disp. At Max Load (in)	Yield (lb)
T36	279.5	0.374	137.7
T37	322.1	0.321	233.6
T38	444.6	0.519	140.9
T39	284.3	0.355	248
T40	374.5	0.324	162.7
Mean	341		184.58
COV	20.3%		28.4%



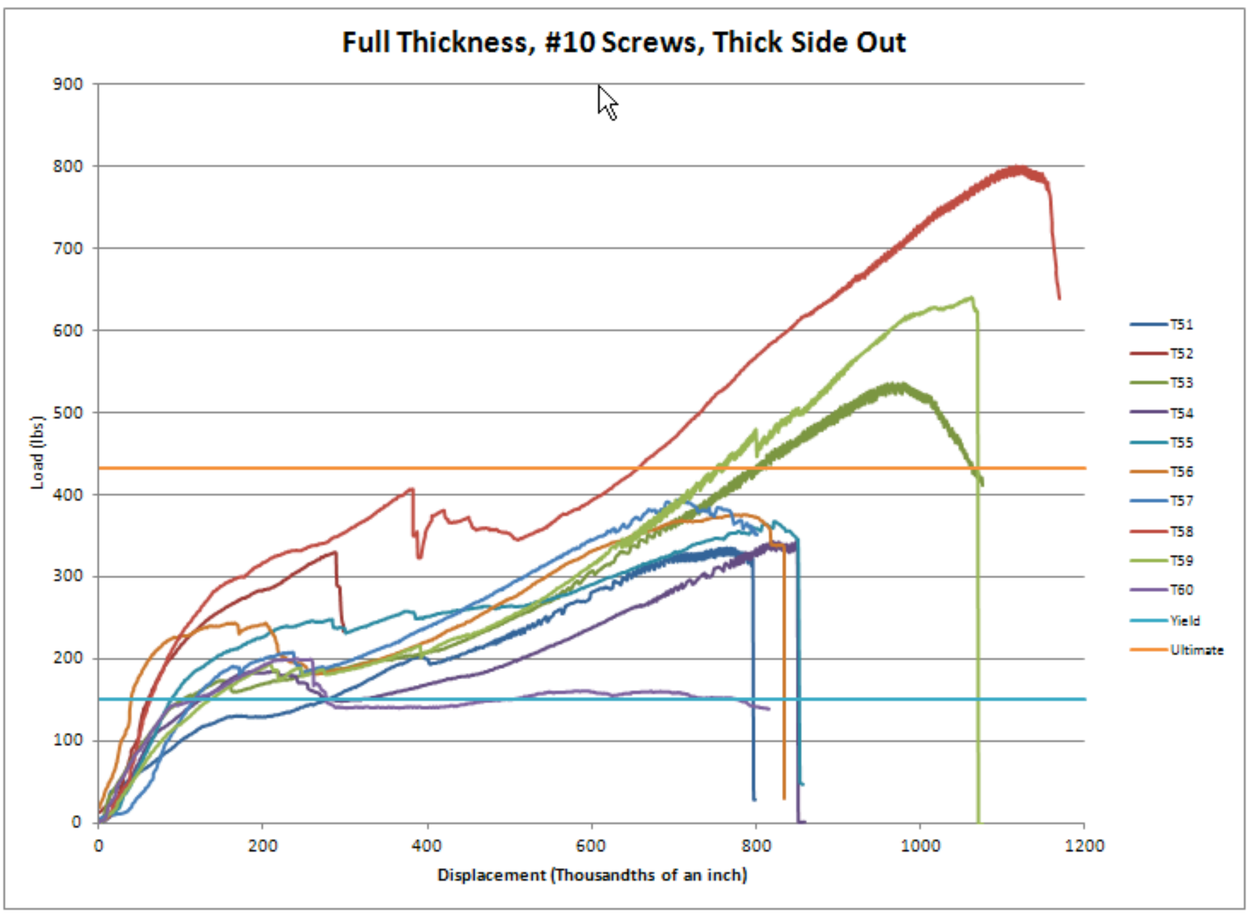
Full Nailing, Thin Side Out, d=0.131"

Panel ID	Max Load (lb)	Disp. At Max Load (in)	Yield (lb)
T41	335.8	0.293	172.3
T42	360	0.317	182.8
T43	287.5	0.236	177.2
T44	329.4	0.256	173.2
T45	267.4	0.203	161.1
T46	344.7	0.33	161.9
T47	202.1	0.131	136.9
T48	309.3	0.228	183.6
T49	288.3	0.247	165.9
T50	252.9	0.208	153.8
Mean	297.74		166.87
COV	16.2%		8.6%



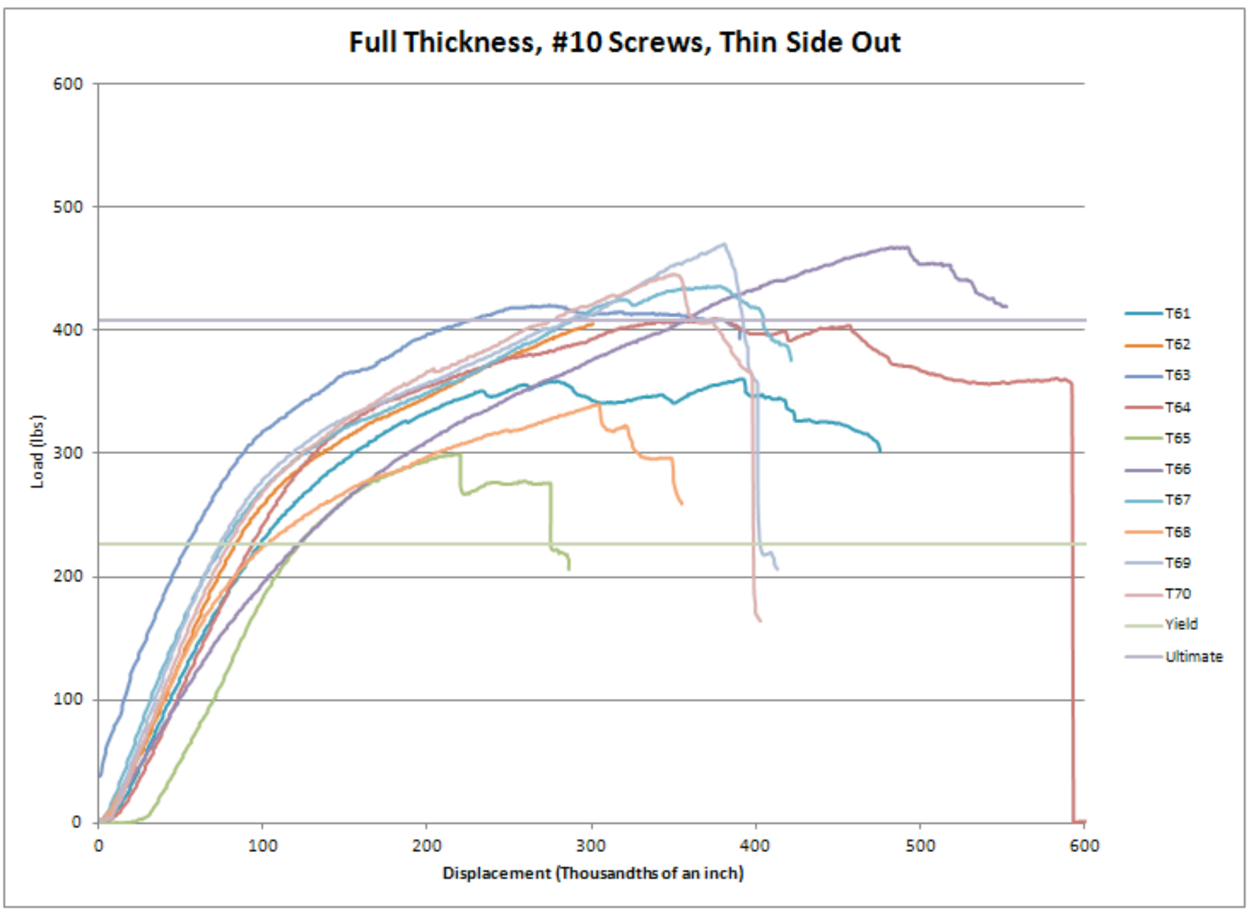
Full Screwing, Thick Side Out, #10 Screw

Panel ID	Max Load (lb)	Disp. At Max Load (in)	Yield (lb)
T51	335.8	0.765	119.2
T52	331	0.287	196.5
T53	536.4	0.966	130.5
T54	344.7	0.849	115.2
T55	367.2	0.821	175.6
T56	376.1	0.773	206.2
T57	394.6	0.709	124.8
T58	801.3	1.116	177.2
T59	640.3	1.062	116.8
T60	201.3	0.241	143.4
Mean	432.87		150.54
COV	40.7%		23.3%



Full Screwing, Thin Side Out, #10 Screw

Panel ID	Max Load (lb)	Disp. At Max Load (in)	Yield (lb)
T61	360	0.39	185.2
T62	438.1	0.411	257.7
T63	421.2	0.274	244.8
T64	409.1	0.374	268.2
T65	299.6	0.216	245.6
T66	467.9	0.482	182
T67	436.5	0.371	206.2
T68	339.1	0.303	183.6
T69	470.3	0.38	248
T70	445.4	0.349	240.8
Mean	408.72		226.21
COV	14.0%		14.7%



C.2 Statistical Comparison

C.2.1 Nail Withdrawal – Comparison of Panel Orientation

t-Test: Two-Sample Assuming Equal Variances

	Thin Skin Up	*Thin Skin Down*
Mean	42.704	66.172
Variance	205.64	515.34567
Observations	5	5
Pooled Variance	360.49	
Hypothesized Mean Difference	0	
df	8	
t Stat	-1.9543	
P(T<=t) one-tail	0.0432	
t Critical one-tail	1.8595	
P(T<=t) two-tail	**0.0864**	
t Critical two-tail	2.3060	

C.2.2 Lateral Resistance Comparison

t-Test: Two-Sample Assuming Equal Variances

	Full Thickness	*Partial Thickness*
Mean	316.58	369.2
Variance	2186.54	6814.39
Observations	5	5
Pooled Variance	4500.46	
Hypothesized Mean Difference	0	
df	8	
t Stat	-1.240	
P(T<=t) one-tail	0.125	
t Critical one-tail	1.860	
P(T<=t) two-tail	**0.250**	
t Critical two-tail	2.306	

C.2.3 Partial Panel Nailing – Parallel vs. Perpendicular to Strand Orientation

t-Test: Two-Sample Assuming Equal Variances

	Parallel	*Perpendicular*
Mean	172.99	184.58
Variance	972.50	2752.367
Observations	10	5
Pooled Variance	1520.149	
Hypothesized Mean Difference	0	
df	13	
t Stat	-0.543	
P(T<=t) one-tail	0.298	
t Critical one-tail	1.771	
P(T<=t) two-tail	0.597	
t Critical two-tail	2.160	

C.2.4 Full Thickness Nailing – Parallel vs. Perpendicular to Strand Orientation

t-Test: Two-Sample Assuming Equal Variances

	Parallel	*Perpendicular*
Mean	166.87	166.54
Variance	204.209	999.048
Observations	10	5
Pooled Variance	448.77	
Hypothesized Mean Difference	0	
df	13	
t Stat	0.028	
P(T<=t) one-tail	0.489	
t Critical one-tail	1.771	
P(T<=t) two-tail	0.978	
t Critical two-tail	2.160	