Relationship between Tooth Withdrawal Strength and Specific Gravity for Metal Plate Truss Connections

by:

Brian K.Via

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the
degree of:

Master of Science

in

Wood Science and Forest Products

Approved:

Dr. Audrey Zink-Sharp, Chair

Dr. J. Daniel Dolan

Dr. Frank E. Woeste

Relationship between Tooth Withdrawal Strength and Specific Gravity for Metal Plate Truss Connections

Brian K.Via

(Abstract)

The objectives of this research were twofold: a) to define the relationship between tooth withdrawal and specific gravity for southern pine lumber and four different plate-to-wood load orientations, and b) to demonstrate how these relationships could be applied to new lumber grades to predict tooth withdrawal performance so that additional testing would not be necessary. The four orientations investigated were: a.)LRAA – plate axis parallel to load and wood grain parallel to load. b.) LREA – plate axis perpendicular to load and wood grain parallel to load. c.) LRAE – plate axis parallel to load and wood grain perpendicular to load. d.)LREE – plate axis perpendicular to load and wood grain perpendicular to load. For the LRAA, LREA, LRAE, LREE orientations, the following sample sizes were respectively: 27, 22, 27, and 29. Results showed specific gravity and embedment gap were excellent predictors of ultimate tooth withdrawal stress for the LRAA orientation. However, neither specific gravity nor percentage of latewood significantly influenced the location of tooth withdrawal. For the LREA orientation, specific gravity alone was a good predictor of ultimate tooth withdrawal stress. Furthermore, the side of the joint test specimen where tooth withdrawal initiated was dependent on the wood piece with the lowest mean specific gravity. For the LRAE orientation, specific gravity was a marginal predictor of ultimate tooth withdrawal stress. For the LREE orientation, specific gravity was a decent predictor of ultimate tooth-withdrawal stress.

Acknowledgements

The author would like to express appreciation to his major advisor, Dr. Audrey G. Zink, for going beyond the necessary guidance on both a professional and personal level. Appreciation is also extended to Drs. Frank E. Woeste and J. Daniel Dolan for their willingness to provide additional guidance on sometimes-short notice.

Acknowledgement is extended to Stu Lewis and Alpine Engineered Products Inc. for generous donations of advice, metal plate truss connectors, and high specific gravity lumber. TimberTruss Housing Systems of Salem, Virginia and Riverside Roof Truss of Danville, Virginia were also two companies that donated lumber and worked with the author to ensure satisfaction.

The author would also like to offer thanks to Kenneth L. Albert, Robert S. Carner, Carlile H. Price, and Harrison Sizemore for their contributions during both the experimental and test phase. Special thanks goes out to Phil O' Reagan who took days of his time to explain how the Mechanical Test System (MTS) works.

The author is also appreciative of Hong-mei Gu, Lilian Pita, Pete Uhrig, and Edgar Deomano who, as students of Dr. Audrey Zink, are always willing to help as both friends and colleagues. Other important friends were: Scott Bowe, Matt Bumgardner, Delton Alderman, Neil Tatum, Dan and Stacy Cumbo, Inez Johnson, Chris Surak, David Bailey, and Belinda Hargreaves.

Finally, Dale Via and Cathy Brown were two very important people. Dale Via is the author's father who, not only provided materials, but also was always there when needed. Cathy Brown deserves appreciation for her patience and encouragement through most of the study.

Table of Contents

List of Tables

List of Figures

1 Introduction

According to research conducted in laboratories on metal plate connectors, tooth withdrawal is the most common form of failure for truss tension joints (Wolfe, 1990; Gebremedhin et al., 1992; Gupta, 1990; Crovella, 1990; Gupta, 1994). For this project, tooth withdrawal is defined as the lateral tooth holding strength of a plated wood connection loaded laterally.

Specific gravity has been shown to influence other wood connections. Bolts, nails, and screws are common connectors in which joint strength depends on specific gravity. A full range of specific gravities for various species may be viewed in the National Design Specifications (AF&PA, 1991). AF & PA (1991) also listed the yield strength for connections in different species. Metal plate connections are not currently covered in the NDS (AF&PA, 1991), due, in part, to the lack of research for the affects of specific gravity on tooth withdrawal.

The affects of specific gravity on laterally loaded joints has been studied for only one type of loading orientation (Palka, 1984). Figure 1a gives the specimen geometry used in this study. For this orientation, the full range of specific gravity was not tested and extrapolation would be necessary.

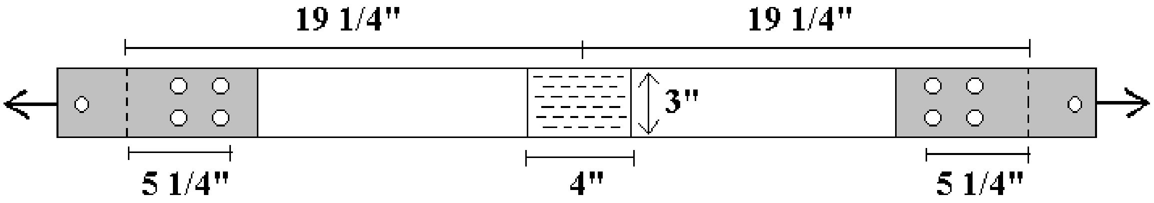


Figure 1a: Plate major axis parallel to the load and wood grain parallel to the load (LRAA).

However, there are three other orientations commonly tested (Figure 1b-d). TPI defines these orientations without the detailed specifications of Figures 1a-d (TPI 7.1.7.2a). For Figure 1b, the plate axis is perpendicular to the load and the wood grain is parallel to the load (LREA). For Figure 1c, the plate axis is parallel to the load and the wood grain is perpendicular to the load (LRAE). For Figure 1d, the plate axis is perpendicular to the load and the wood grain is perpendicular to the load (LREE). Since these four orientations are used for determining the lateral resistance of metal plate connected joints, it is important to understand the influence of specific gravity on tooth withdrawal for these four orientations.

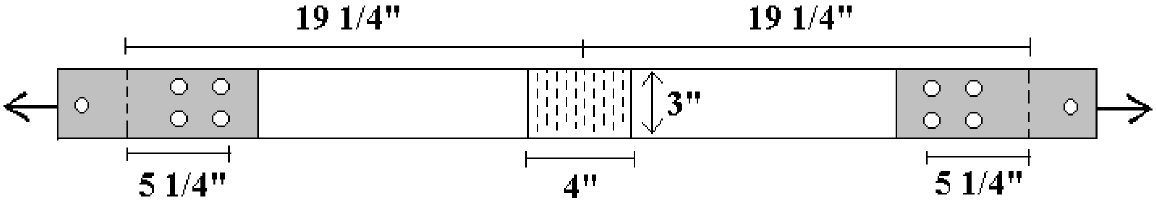


Figure 1b: LREA orientation and test specimen used in this study.

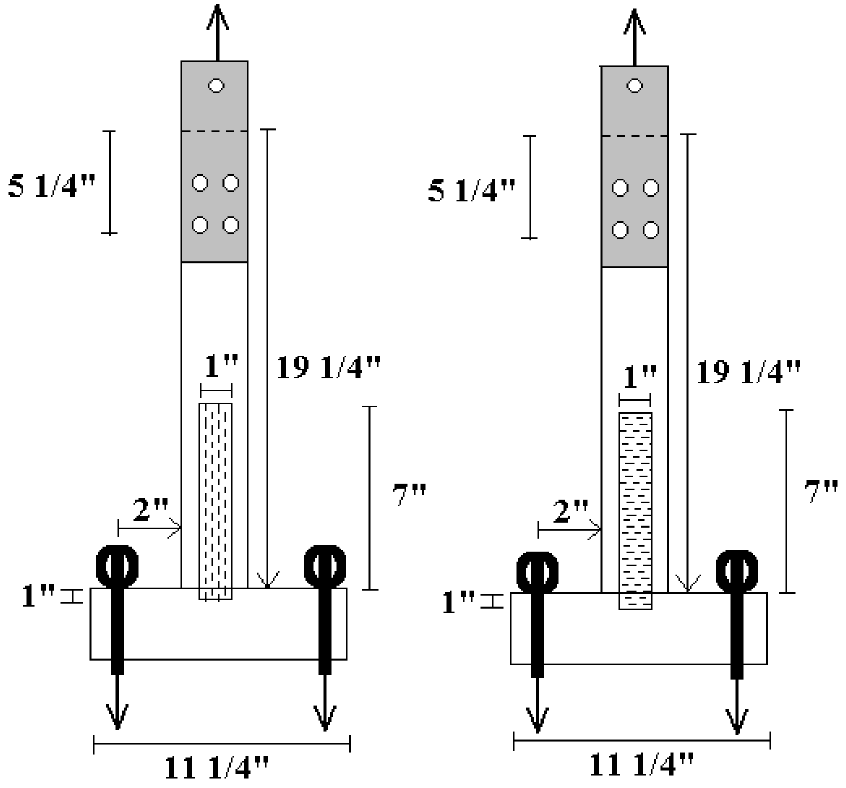


Figure1 (c) and (d): LREA and LREE orientations and test specimen geometry's used in this study.

Another major concern for structural applications is the increasing presence of juvenile wood. Juvenile wood is the wood formed during the early stages of a tree's life (Haygreen and Bowyer, 1989). It has been shown that most mechanical properties of juvenile wood are lower than mature wood due to the juvenile wood's inherent lower specific gravity, larger fibril angle, and shorter cell lengths. Since southern pine is commonly grown in plantations and harvested within 20 to 30 years, it is elemental that our current wood resource has a higher proportion of juvenile wood than in decades past. In the future, it will be important to understand the growing influence of this lower density wood resource and its effects on the lateral resistance of metal plate connected truss joints.

Finally, machine stress rated (MSR) lumber and machine evaluated lumber (MEL) are two technologies that make nondestructive measurements of the modulus of elasticity (MOE). Since it is well known that lumber strength correlates with specific gravity, it is possible to predict the mean specific gravity of a lumber grade. If statistically significant relationships between specific gravity and joint lateral strength for the four plate and lumber axis combinations are found, equations provided by this study would be useful in predicting the lateral tooth withdrawal capacity (as a function of specific gravity) of metal plated truss joints. The equations would be useful when new specific gravity grades of lumber are created and could save plate producers money because it would eliminate the need to test new machine grades of lumber for allowable lateral resistance values.

Finally, this research would develop a standardized procedure for testing the four plate and lumber axis orientations. Currently, TPI (Section, 7.1.7.2a) gives four orientations but lacks specifications for dimensions and reaction distances. Specifications are needed so that testing between plate manufacturers is consistent. The specimens developed in this research may be viewed in Figures 1a – 1d. These test geometries produced tooth withdrawal, as opposed to other failure modes.

2 Objectives

The objectives of this research were twofold:

a) to define the relationship between tooth withdrawal and specific gravity for southern pine lumber and four different plate-to-wood load orientations.

b) to demonstrate how these relationships can be applied to new lumber grades to predict tooth withdrawal allowable design values so that additional testing will not be necessary.

3 Justification and Rationale

Machine Stress Rated Lumber (MSR) and Machine Evaluated Lumber (MEL) are two methods used to stress-grade lumber in the truss industry. Lumber pieces are sorted according to various stiffness and strength characteristics. As a result, the customer can purchase different specific gravity classifications. For example, MSR southern pine having a modulus of elasticity (E) of 1.8 million-psi and less has a specific gravity of 0.55 (SPIB Supplement, 1994). However, when the modulus of elasticity is 1.9 million psi and greater, the specific gravity rating is assumed to be 0.57 (SPIB Supplement, 1994). Consequently, because specific gravity is not addressed in today's standards for truss plates (ANSI/TPI 1-1995), the truss designer is not allowed to adjust allowable design values for MSR southern pine with an E of 1.9 million psi or greater.

This research would be useful for new machine evaluated lumber grades. By understanding the influence of specific gravity on tooth withdrawal, each truss plate company could eliminate testing which is expensive and time consuming. This research could provide a universal equation for all truss plate companies to follow.

Innovations within the wood industry could also be a problem for the solid sawn wood truss industry. For example, laminated lumber could be used to construct truss members. Outer laminations could be controlled to a desired specific gravity. The point is, other engineered wood product sectors may develop dense new products that will perform better than solid wood. By understanding specific gravity effects, the truss industry will be better prepared to defend their products from a design standpoint.

4 Literature Review

4.1 General Background

Metal plate connectors (MPC) have been prevalent for roughly 4 decades (Gupta et al., 1996). Historically, mechanical fasteners have been used since the ancient days of Egypt and Rome (Patton-Mallory, 1986). Basically, a MPC is a piece of metal with teeth punched out and is used to join two wood members together (Figure 4.1a).

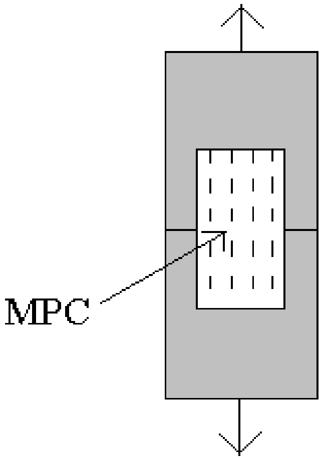


Figure 4.1a: A typical metal plate connector

Within a truss system, there are different modes of failure that could occur to connections such as: steel shear, steel tension, tooth withdrawal, and wood failure (Skaggs et al., 1994). Some other factors that affect plate performance would be: grain angle, metal plate axis direction, plate dimensions, plate thickness, number of teeth per plate (Moura et al., 1995), wood relaxation, tooth length (Crovella et al., 1990) and cyclic moisture patterns.

An important work was performed on bottom chord splice joints (O’Regan, 1997). This research determined a design method for the steel net-section capacity of the joint when subjected to tension and bending. Net cross-section steel failure can occur when axial forces and bending moments are applied to a joint.

It is important to notice the significance of plate withdrawal within the truss industry. Many research reports have stated that withdrawal is an important mode of failure within MPC trusses for laboratory experiments (Wolfe, 1990; Gebremedhin et al., 1992; Gupta, 1990; Crovella, 1990; Gupta, 1994). As a result, withdrawal is a foremost strength factor that can dictate joint performance.

Within the industry, there has been signs of interest towards the influence of specific gravity (SG) on tooth withdrawal performance. There has been little research performed on SG effects on tooth withdrawal and only for the LRAA orientation (Palka, 1984).

4.2 Specific Gravity Background

The equation for SG is (ASTM D2345, 1993):

$$SG = \frac{\text{ovendry weight of wood}}{\text{weight of displaced volume of water}} \qquad \textbf{[E4.2a]}$$

where: the weight of water displaced (grams)
equals the volume (cubic centimeters)

This index is used to indicate the ratio of solid wood material present for a specific volume. Since the dimensions of a specimen change with moisture change, the moisture content, at the dimensions recorded, should be reported (ASTM D2345, 1993).

For all wood species, SG has been shown to significantly influence mechanical properties. In general, as SG increases, the mechanical properties tend to increase. Some mechanical properties may include modulus of rupture, modulus of elasticity (E), work to maximum load, and hardness. Power functions usually provide the best representation of the relationship between mechanical properties and SG. For example, in softwoods, the equation for calculating E in static bending would be (USDA, 1990):

$$E = 2.44x(SG)^{0.81} \qquad \textbf{[E4.2b]}$$

where: E = modulus of elasticity in million psi
SG = specific gravity

SG has been shown to depend on: cell size, cell wall thickness, cell length, proportion of juvenile wood, geographic region, soil makeup, proportion of latewood, genetic inheritance, age of tree, and location within the tree (Szymanski et al., 1991; Bendtsen et al., 1986; Walton et al., 1986; Shepard et al, 1992; Gibson et al., 1986). As a result, a large variation in SG would be expected during the materials selection process.

Variation in SG occurs within a tree, between trees, and within a cross-section. Within most species, as tree height increases, so does SG. This has been shown particularly for most conifers (Panshin and de Zeeuw, 1970). Heger (1974) reported this for black spruce, balsam fir, and lodgepole pine. Within the southern pine group, Lenhart et al. (1977) confirmed this trend for loblolly pine and developed SG predictor equations given tree age and height. Likewise, this trend would be expected for 8 to 16 foot long pieces of lumber and would contribute to SG variability within a piece of lumber.

Within a cross-section, SG has been shown to vary from earlywood to latewood. Pernestal et al. (1995) developed a model assuming that the latewood specific gravity doubled that of earlywood for abrupt transition softwoods. Specifically, for longleaf pine, the density varied from 0.3 g/cm^3 to 0.9 g/cm^3 from earlywood to latewood respectively (Panshin and de Zeeuw, 1970). For metal plate truss connections, this characteristic could influence the tooth withdrawal strength of a joint. For example, if the teeth are located primarily in earlywood, then the SG in the vicinity of the teeth may be lower then the mean SG of the whole cross-section and thus lower the strength of the joint.

4.3 Major Works for Tooth Withdrawal Strength

Specifically for MPC wood trusses, there has been limited research relating SG to plate performance, especially tooth withdrawal. Palka has been a major force in establishing a relationship between MPC allowable design load and SG. In 1981, Palka first established a positive correlation between strength and stiffness of nailed and bolted timber versus specific gravity (Palka, 1981). However, the major work was reported three years later as Palka presented a report for the Science Council of British Columbia (Palka, 1984). This research established a sound relationship between wood specific gravity and truss-plate joint strength in pine and spruce (Palka, 1984).

The most important statement that Palka made was that an increase of 0.10 in SG would produce an approximate 25% increase in allowable design load within each grade of lumber (Palka, 1984). Moura et al. (1995) determined that high-density specimens had a 30% higher ultimate tooth holding strength than lower density specimens. Between grades, Palka suggested that relative density is not a major contributor to joint strength differences. Palka established that a significant correlation did not exist due to the inaccuracy of the Machine Stress Rating (MSR) procedure (Palka, 1984).

It may be possible that MSR is not the most accurate grading procedure for distinguishing grade differences. As a result, it may be possible for SG to relate to strength between grades. However, there may be another explanation for the differences. The best grade would present minimal knots and critical growth characteristics. Thus, it is easy to envision SG having a good correlation with strength and stiffness. However, with lower grades, more undesirable growth characteristics are present and may become the more important factor affecting strength and stiffness. Under this scenario, it is logical for SG to not correlate as well in lower grades of lumber. For today's standards, which are listed in ANSI/TPI 1-1995, teeth should only be embedded in clear wood (TPI 7.1.7.3). Therefore, no matter what grade of lumber, the area under question is clear wood.

In conclusion, Palka suggested that much research was needed within this area (Palka, 1984). However, for some reason, the idea seems to have been overlooked as other research was given priority.

The National Design Standard for Metal Plate Connected Wood Truss Construction (ANSI/TPI Commentary, 1995) shows SG to roughly linearly correlate (r^2 = 0.70) to tooth holding capacity in southern pine species. Furthermore, they expressed this concern (ANSI/TPI Commentary, 1995):

> *Research has not yet established a well-accepted relationship expressing the variation in tooth holding strength with wood density for all types of plates and woods.*

Lastly, Suddarth et al. (1981) reported that SG appeared to correlate with truss plate withdrawal strength and plate stiffness (Suddarth et al., 1981). For an earlier study, Suddarth et al.(1979) developed predictor equations for ultimate load and load at 0.03 inches of slip for tension specimens loaded parallel to grain (LRAA orientation). For southern pine, these equations were (Suddarth et al., 1979): **[E4.3a]**

$$P_u = 6109(SG) - 44.46(M) + 2751$$

where: P_u = ultimate load carried by the joint with most failures occurring in tooth withdrawal
SG = specific gravity

M = moisture content

with: multiple correlation coefficient R = 0.605
simple correlation P_u versus SG; r = 0.563
simple correlation P_u versus M; r = -0.317

$$P_s = 5093(SG) - 47.19(M) + 2712 \qquad \textbf{[E4.3b]}$$

where: P_s = load at 0.03 inches total slip;
with: multiple correlation coefficient R = 0.657
simple correlation P_s vs. SG; r = 0.589
simple correlation P_s vs. M; r = -0.389

Two hundred forty-five southern pine specimens were tested by Suddarth et al. (1979).

Similar equations were developed for spruce-pine-fir:

$$P_u = 12443(SG) - 596.85(M) + 4231 \qquad \textbf{[E4.3c]}$$

with: multiple correlation coefficient R = 0.745
simple correlation P_u versus SG; r = 0.737
simple correlation P_u versus M; r = -0.037

$$P_s = 9368(SG) - 482.02(M) + 4482 \qquad \textbf{[E4.3d]}$$

with: multiple correlation coefficient R = 0.767
simple correlation P_s vs. SG; r = 0.700
simple correlation P_s vs. M; r = -0.089

According to these equations, the correlation between SG and ultimate load for spruce-pine-fir was higher than that of southern pine. This result was indicative that ultimate strength for a joint connection was species dependent. Moisture did not have a significant effect because they were properly equilibrated to a similar moisture content (Suddarth et al., 1979).

4.4 Moisture Content

It has long been known that as moisture content increases, wood strength properties decrease. Furthermore, rates of water or vapor movement in wood are different for the three principle wood axes (Panshin and de Zeeuw, 1970). Moisture movement rates have been shown to be the fastest in the longitudinal direction (Panshin and de Zeeuw, 1970). Thus, in truss manufacturing, one would expect the butted ends of chords, where the end-grain had been previously exposed to the environment, to be closer to equilibrium than in the span of the chord where a web piece connects.

Dimensional change due to moisture fluctuations has been an even more influential factor for connections. Nails have been shown to “pop out,” with cyclic moisture conditions (Stelmokas et al., 1995). Specifically, Stelmokas showed that for nailed connections fabricated at 19% moisture content and then equilibrated to 12%, the axial withdrawal strength reduced nominal values by as much as 75% (Stelmokas et al., 1995). Friction loss due to both relaxation and dimensional change caused this strength reduction in nails and would likewise be expected to affect metal plate truss connectors.

4.5 Anatomical Considerations

Moving to the anatomical scale, wood specific gravity varies based on the proportion of tracheids, rays, and resin canals present. Furthermore, because wood is orthotropic, the direction of the load with respect to the grain is critical. For example, for split rings, shear plates, bolts, or lag screw connections, loaded at an angle to the grain between 0 and 90 degrees, the design values shall be determined using the Hankinson formula (AF&PA, 1991):

$$F'\theta = \frac{(F'_g \; F'_{c\perp})}{(F'_g \sin^2\theta + F'_{c\perp} \cos^2 \theta)} \qquad \textbf{[E4.4a]}$$

where: F'_g = allowable bearing design value parallel-to-grain
$F'_{c\perp}$ = allowable compression design value perpendicular-to-grain
F'_θ = allowable bearing design value at an angle-to-grain
θ = angle between direction of grain and direction of load

In wood joints, tooth embedment proved more influential for a load oriented in the radial direction than a load oriented in the tangential direction (Moura, 1995). Ring orientation therefore appears to play a factor in tooth withdrawal (Moura, 1995).

In general, there is a higher variation of specific gravity in earlywood sections of wood. However, latewood sections have a higher per cell specific gravity and are less variable in specific gravity. As a result, the latewood proportion is an important predictor of density in conifers (Wimmer, 1994) Based on this knowledge, the proportion of latewood at the joint area may affect the withdrawal performance of MPC's.

Lower specific gravity may also be attributed to the proportion of juvenile wood within a tree (Bendtsen et al., 1986). Juvenile wood may be defined as the wood formed during the early stages of a tree's life (Haygreen and Bowyer, 1989). The lower density in juvenile wood may be attributed to thinner cell walls and shorter cell lengths created by the cambial layer during the early stages of a tree's life. The age at which a tree begins to mature is variable even within species. Bendtsen et al. (1986) concluded that juvenile wood formation ended after the first 13 to 20 years for southern pine. Zobel and McElwee (1958) concluded that juvenile wood of loblolly pine grew within the first 7 years. For the next 3 years, transition wood occurred which is the gradual approach toward cell maturity (Zobel et al., 1958) Along with juvenile wood formation variation, the lack of agreement on how to define transition wood among wood scientists contributes to the debate.

Other characteristics of juvenile wood exist that have been shown to influence wood strength. For example, the larger fibril angle of the S2 layer contributed to lower tensile strength (Page et al., 1972). Also, the lignin and hemicellulose content for juvenile wood was higher than mature wood which lowers the strength of solid wood (Haygreen, 1989). As shown, specific gravity was not the only significant factor that contributed to strength loss. Nonetheless, specific gravity has been a significant factor in strength reductions for juvenile wood.

4.6 Nails

An area where significant research has been conducted is with nails. Nails may be good indicators of plate performance with regard to withdrawal. Emerson considers nail connections to be similar to metal plate connections (Emerson et al., 1996). In fact, Foschi developed a nonlinear monotonic model that determines load / slip characteristics for nail connections (Fridley et al., 1994). Furthermore, Foschi showed this model to be an excellent predictor for MPC joints (Foschi, 1977).

For nail withdrawal strength, there is a relationship between SG and dowel bearing strength (AF&PA, 1991). More importantly, there is a relationship between withdrawal and SG (AF&PA, 1991). USDA has developed an equation for nail withdrawal resistance is (USDA, 1990): **[E4.6a]**

$$p = 7850 \text{ x } (SG)^{5/2} \text{ x } D$$

where: p = maximum load in pounds
D = diameter of the nail in inches.

Common wire nails range in diameter from 0.113 inches to 0.263 inches, and they range in length from 2 inches to 6 inches (AF&PA, 1991). A plate tooth differs from a nail in that a plate tooth is punched from a sheet of metal. The length of penetration is also very important. MPC's usually penetrate less than half-inch into the wood. Nails usually penetrate through the lumber. This is important because moisture fluctuations would affect the wood surface most. Thus, surface moisture content may have more of an effect for metal plate truss connectors than nails.

4.7 Plate Characteristics

Plate embedment gaps are an important variable that affects joint strength. An embedment gap occurs when the plate's teeth are not fully embedded into the lumber (Triche, 1995). As a result, there is a gap between the metal plate and wood surface. According to Triche (1995), the magnitude of this gap had considerable effects on joint strength. For southern pine, a 1/32 inch gap decreased joint strength by an average of 17 percent (Triche, 1995). Furthermore, for those plates intended to be fully embedded, small gaps still existed due to variations in lumber thickness and wood deformation during pressing (Triche, 1995).

5 Methods and Procedures

5.1 Pilot Study

A preliminary study was conducted to evaluate and determine the necessary test fixtures, hold down distances, loading rates, plate sizes and plate coverage needed for final testing. Common failure modes were identified and categorized according to hold down distance, plate size, and plate coverage.

Eleven different specimens for the LRAE and LREE orientations were tested. Each specimen had a different hold down distance, loading rate, plate size and plate coverage combination. It was determined that as the hold down distance increased, the tension perpendicular to grain failure appeared to be more prominent. Based on these tests, a 2” hold down distance for the LRAE and LREE orientation appeared to yield tooth withdrawal failure more so than the longer hold down spans (Figures 1c and 1d).

For the LRAE and LREE orientations, as plate coverage increased on the main member, the failure modes gradually changed in this order: tooth withdrawal failure, tension perpendicular to grain failure, steel tension failure. It was found that for the LREE and LRAE orientations, 1x1 inch plate coverage per plate and on the main member, caused tooth withdrawal failure to be the dominant failure mode.

For the LRAA and LREA orientations, twenty-five different specimens were tested using three by four and four by three plates respectively. Tooth withdrawal failure occurred for each specimen. The orientation used to yield tooth withdrawal failure can be seen in Figure 1a and 1b.

The appropriate displacement rate for all four orientations was determined such that the average failure time would occur in about 10 minutes. For the LRAA and LREA orientations, the appropriate displacement rate was 0.07 inches per minute. For the

LRAE and LREE orientations, the appropriate displacement rate was 0.02 inches per minute.

5.2 Final Study

5.2.1 Sampling and preparation

5.2.1.1 Wood materials selection

Southern pine was the species combination selected due to its common use in the truss industry. The southern pine (Pinus spp.) combination group consists mainly of: loblolly (P. taeda), shortleaf (P. echinata), longleaf (P. palustris), slash (P. elliottii), and pitch pine (P. rigida) (Hoadley, 1990). Southern pine was identified mostly by a distinct uneven/wavy grain attributable to the dense latewood. Classification with an eyepiece was not necessary in most situations. However, when needed, abrupt transition and the presence of many large resin canals on the transverse surface identified southern pine.

Wood material was selected based on specific gravity criteria. Parameters were set for the lower 5th percentile, μ (average) specific gravity, and for the upper 95th percentile**.** A specific interval criterion is located on Table 5.2.2.1a. Preliminary research showed for this study, that rings per inch roughly correlates with specific gravity of lumber. This equation was derived:

$$\text{SG} = \left(\frac{\text{Rings per inch}}{21.7} \right)^{0.442} \qquad \textbf{[E5.2.2.1a]}$$

Table 5.2.2.1a: Specific gravity criteria for specimen selection

	Below 5th percentile	Average value (+/- 0.02 SG)	Above 95th percentile
Specific Gravity range	≤0.41	0.53 to 0.57	≥0.69
Approximate rings per inch	< 2.9	5.2 to 6.1	>9.4

A more accurate method to estimate mean (μ) specific gravity was to weigh each piece. The specific gravity intervals in Table 5.2.2.1a were met by converting specific gravity to a weight in pounds using this equation for 2X4's (Haygreen, 1989):

$$W = (5.25xL)x(SG)x(0.03611)x(1+\frac{MC}{100})$$

[E5.2.2.1b]

where: W = weight
L = length of nominal 2x4 cut off

An example of the weight listing is located in Table 5.2.2.1b.

Table 5.2.2.1b: Specific gravity determination for given lengths, weights, and at 16% moisture content.

SG	Weight (LB) for 24 inches	Weight (LB) for 23 inches	Weight (LB) for 22 inches	Weight (LB) for 21 inches	Weight (LB) for 20 inches	Weight (LB) for 19 inches	Weight (LB)for 18 inches	Weight (LB) for 17 inches	Weight (LB) for 16 inches
0.3	1.6	1.5	1.5	1.4	1.3	1.3	1.2	1.1	1.1
0.32	1.7	1.6	1.6	1.5	1.4	1.3	1.3	1.2	1.1
0.34	1.8	1.7	1.6	1.6	1.5	1.4	1.3	1.3	1.2
0.36	1.9	1.8	1.7	1.7	1.6	1.5	1.4	1.3	1.3
0.38	2.0	1.9	1.8	1.8	1.7	1.6	1.5	1.4	1.3
0.4	2.1	2.0	1.9	1.9	1.8	1.7	1.6	1.5	1.4
0.42	2.2	2.1	2.0	1.9	1.8	1.8	1.7	1.6	1.5
0.44	2.3	2.2	2.1	2.0	1.9	1.8	1.7	1.6	1.5
0.46	2.4	2.3	2.2	2.1	2.0	1.9	1.8	1.7	1.6
0.48	2.5	2.4	2.3	2.2	2.1	2.0	1.9	1.8	1.7
0.5	2.6	2.5	2.4	2.3	2.2	2.1	2.0	1.9	1.8
0.52	2.7	2.6	2.5	2.4	2.3	2.2	2.1	1.9	1.8
0.54	2.8	2.7	2.6	2.5	2.4	2.3	2.1	2.0	1.9
0.56	3.0	2.8	2.7	2.6	2.5	2.3	2.2	2.1	2.0
0.58	3.1	2.9	2.8	2.7	2.6	2.4	2.3	2.2	2.0
0.6	3.2	3.0	2.9	2.8	2.6	2.5	2.4	2.2	2.1
0.62	3.3	3.1	3.0	2.9	2.7	2.6	2.5	2.3	2.2
0.64	3.4	3.2	3.1	3.0	2.8	2.7	2.5	2.4	2.3
0.66	3.5	3.3	3.2	3.1	2.9	2.8	2.6	2.5	2.3
0.68	3.6	3.4	3.3	3.1	3.0	2.8	2.7	2.5	2.4
0.7	3.7	3.5	3.4	3.2	3.1	2.9	2.8	2.6	2.5

Specimens for lower and middle specific gravity intervals were selected at TimberTruss Housing Systems in Salem, Virginia. Cut-offs to be used as floor joist webs were available for selection. Pieces between 16 and 30 inches were measured for specific gravity approximation using tables like Table 5.2.2.1b. A digital scale with a readability of ± 0.1 pounds and accuracy of ± 0.2 pounds was used. A zeroing factor of +0.1 pounds was added to the scale reading because preliminary tests showed the scale to be off set by –0.1 pounds. For borderline pieces, both weight and rings per inch were used for selection. A pin resistance moisture meter was used to measure the moisture content for each piece with a penetration of 1/4 inch. The moisture content was needed to reference the proper weight table. Moisture content was measured 3 times along each piece to account for moisture variability. Over 1300 pieces were sampled to find the pieces that were intended to meet the lower 5th and upper 95th percentile parameters.

Alpine Engineered Products Inc. donated the dense lumber pieces that met the specific gravity criteria listed in Table 5.2.2.1a. Thirty-five eight-foot pieces were pulled and measured for weight to approximate specific gravity by Alpine Engineered Products Inc employees. These pieces were then shipped by truck to the Brooks Forest Products Laboratory in Blacksburg, Virginia.

5.2.1.2 Material Preparation

The high specific gravity lumber was weighed by Alpine Engineered Products Inc. and the heaviest pieces were shipped for testing. In Blacksburg, each lumber piece was re-weighed and measured with a moisture meter. The lumber was then cut to proper sizes, categorized by specific gravity, and placed in an equilibrium chamber. Sixteen cross-sectional specimens from thirty pieces of lumber were selected to measure moisture using the ovendry method. These measurements were then compared to the pin meter measurements.

Most medium and low specific gravity chords and webs (Figure 5.2.1.2a) were obtained from Timber Truss Housing Systems in Salem, Virginia. Some lower specific gravity pieces were selected from Riverside Truss in Danville, Virginia.

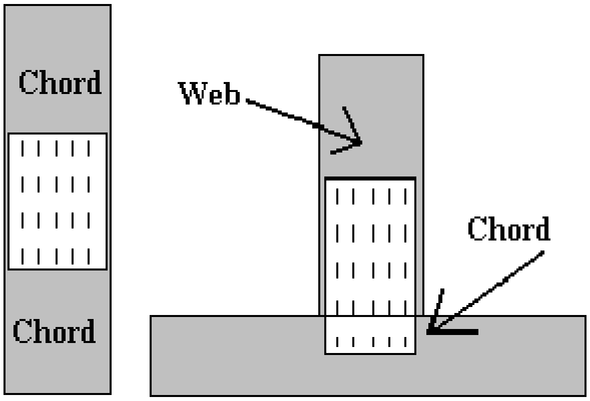


Figure 5.2.1.2a: Web and chord.

Chord and web pieces selected from TimberTruss Housing Systems were of varying lengths. All web and chord pieces were cross cut to proper length. The LRAA and LREA chords were cut to 19 ¼ inches. Likewise, all web pieces were cut to 19 ¼ inches. Chord pieces for the “t-joints” were cut to 11 ¼ inches (Figure 5.2.1.2a). Initial weight (grams), ovendry weight (grams), and ovendry volume (cubic centimeters) were measured for wood blocks taken from each chord and web piece. ASTM D4442-92 (1992) was followed for moisture content measurements using the ovendry procedure. ASTM D2395-93 (1993) was followed for the specific gravity measurements using the wax immersion method. Ovendry volume specific gravity and initial moisture content for each specimen piece were calculated. Specimens were then sorted according to pretest specific gravity so that chord to chord and web to chord pairs would have similar specific gravities. A list of the pretest specific gravity data is listed in Appendices A,B,C. Specimens were then placed in the conditioning chamber set at approximately 16% target equilibrium moisture content for 3 to 4 months. Three to four months storage time was allowed to minimize the moisture variation between pieces.

5.2.1.3 Fabrication

For the LRAA and LREA orientations (Figure 1a and 1b), each piece was crosscut to 19 ¼ inches in length. After cutting to length, a sample block was taken from each piece to pre-measure the specific gravity. Four holes (25/32” diameters) were then drilled for the hold down plates for each piece. The gross area method was used (TPI 7.1.7.5a) and each piece was ripped to 3 inches in width. All specimens were placed back in the conditioning chamber until plate pressing.

For the LREE and LRAE orientations (Figure 1c and 1d), webs were cut to 19 ¼ inches in length and the main members (chords) were cut to 11 ¼ inches in length. After cutting to length, a sample block was taken from each piece to pre measure the specific gravity. Four holes were drilled into each web piece for the hold down plates. All specimens were placed back in the conditioning chamber until plate pressing.

In the conditioning chamber, the specific gravity of each piece was marked and the pieces were categorized by specific gravity. Specimens were chosen and components were paired according to specific gravity with a ± 0.04 margin of error. Paired specimens were taken to the air press. The air tank reached a maximum pressure of 110 psi but the pressure at the press due to the cylinder size were over 1000 psi at the press point. Most specimens were clamped to the press table to prevent lateral movement of the specimen during pressing. Sometimes clamps were not used due to slight cup in the wood specimens. When the specimens were cupped, the plates would press in better without clamps. First, the plates were pressed in partially by the press head. Then a metal block with dimensions slightly larger than the plate were used to concentrate the load to a smaller area. Plates were pressed until either the plate was fully embedded or until the wood resisted further embedment. After pressing each specimen, the test specimens were placed into the conditioning chamber and allowed to relax for 7 to 14 days after fabrication (TPI, 7.1.6.3(b)).

5.2.2 Mechanical Testing

To allow for wood relaxation, each specimen was tested between 7 and 14 days after fabrication (TPI Section 7.1.8.1(b)). A constant crosshead speed of 0.07 inches per minute was used for the LRAA and LREA orientations. For the LRAE and LREE orientations, a constant crosshead speed of 0.0125 inch per minute and 0.0136 inch per minute, respectively, were used to obtain maximum load between 5 and 20 minutes (TPI 7.1.8.2 (a)).

Longitudinal joint separation was measured using two linear variable differential transducers (LVDT) for all orientations and the average of the two LVDT's was used to determine slip values. The data acquisition system acquired data values two times per second as described in the next section. Trial tests were performed to determine an appropriate data acquisition rate. Furthermore, trial tests yielded preliminary data, which ensured that the entire system produced usable data. Ultimate load was recorded from the MTS digital monitor, and these readings were compared to computer data acquisition values to assure consistency. Crosshead displacement was monitored from the digital monitor and was also compared to data acquisition readings for consistency. Prior to each test (4 times total), the LVDTs were calibrated to insure accuracy. The calibration results are listed in the Instrument Evaluation section (5.2.4).

5.2.3 Data Collection Methodology

For the LRAA and LREA orientations, the following data were recorded: Start and end time of test, ultimate load, ramp speed, total crosshead displacement, embedment gap (Appendix D), site of tooth withdrawal (Appendix E) (Figure 5.2.3a), latewood percent (an area measurement near each plate surface), volume (both green and ovendry), weight (green and ovendry), and immersed weight of waxed specimen (Appendices F and G). For the LRAE and LREE orientations, the same measurements were made except for embedment gap since none of the specimens showed any embedment gaps.

Ultimate load was recorded from the digital display of the MTS and compared to values obtained from the data acquisition computer values to ensure consistency (Appendix H). Likewise, crosshead displacement was measured with the MTS and compared to the data acquisition computer. Time to failure was recorded by both a watch and the data acquisition computer to ensure that failure occurred within 5 to 20 minutes (TPI 7.1.8.2a).

Just before testing, the embedment gap at each surface was measured with calipers with an accuracy of ± 0.001 (Appendix D). After failure, the location of tooth withdrawal was identified from 1 of 4 surfaces (Figure 5.2.3a).

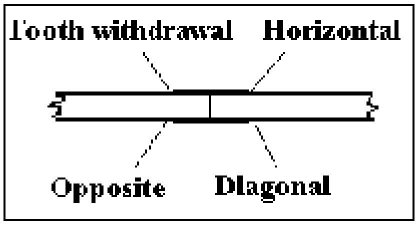


Figure 5.2.3a: Possible locations of withdrawal for LRAA and LREA orientations

Specific gravity and moisture content were measured by cutting two sample blocks from each specimen; block 1 contained surfaces 1 and 2 and block 2 contained surface 3 and 4. Initial weight of the block at the time of test was measured in grams. Initial volume of the block was also measured with digital calipers. The green volume was defined as the volume of the test block at time of test. Latewood percentage at each surface was then calculated using a laminated grid transparency (Figure 5.2.3b).

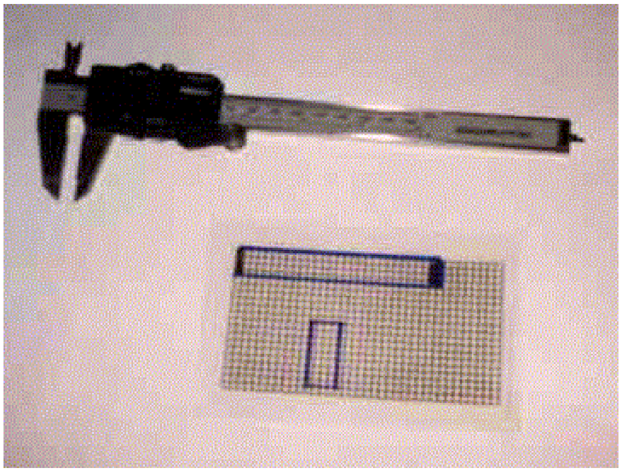


Figure 5.2.3b: (Top) Calipers used to measure block dimensions; (Bottom) Laminated transparency grid used to measure latewood point count.

5.2.4 Instrument Evaluation

To measure the initial weight and ovendry weight for specific gravity and moisture content calculations, a PB3002 laboratory weight scale was used. Instron calibration weights of 10, 50, and 60g were used as known input values to gain accuracy and repeatability information (Appendix I). Thirty data points for each known input weight were measured for a total of 90 observations at three weight classes.

A battery powered weight scale was used for wood piece selection from a local truss manufacturer. Calibration weights of 1, 1.5, 2, 4.5, 10, 11.5, 15, 23, 20.3, 50, and 100 lbs. were used as known input values to gain accuracy and repeatable statistics. Fifty data points for each known input weight were measured for a total of 550 observations at 11 weight classes. A summary of the results can be viewed in Table 5.2.4a.

Table 5.2.4a: Weight scales reliability and accuracy.

	Reliability at the 95% Confidence Level	Calibration for Accuracy	Range of input data
Lab Scale	[Input value + - 0.0021]	Add 0.01 to input value	10 grams to 60 grams
Lumber Scale	[Input value + - 0.1]	Add 0.01 to input value	1 pound to 100 pounds

Linear variable differential transducers (LVDT) were used to measure wood-to-wood slip differential at the joint. For calibration purposes, the instrument was deflected to known distances and the output voltage was measured (Appendix J). Linear equations were developed for the data acquisition computer for each LVDT. Each LVDT was checked four times during the testing phase to ensure consistency. The second, third, and fourth checks were only performed to ensure proper readings. However, if needed, all data were recorded for future adjustments. Ten data points for each LVDT at each check were recorded. A summary of the results can be viewed in Table 5.2.4b.

Table 5.2.4b: Calibration equations obtaining 'y' (volts) for four checks for known 'x' (inch displacements).

	LVDT Serial -- 2959		LVDT Serial -- 3031	
	Linear Equation Y (volts) =	R^2	Linear Equation Y (volts) =	R^2
First Check	15.376x+0.0072	0.9999	16.01x-0.0256	0.9999
Second Check	15.359x-0.0075	0.9999	16.319x+0.0041	0.9999
Third Check	15.443x-0.0106	0.9999	16.432x+0.0001	0.9999
Fourth Check	15.333x-0.0136	0.9999	16.38x+0.006	0.9999

The MTS was used to control displacement rates, acquire loads and displacement data, and start and stop the test. To insure proper functioning, a proving ring was positioned under the load head. This ring had the ability to measure high loads. One thousand-pound increment loads were applied from approximately 1,000 to 10,000 pounds (Appendix K). The deformations of the proving ring were then recorded for each 1,000-pound increment. A linear equation of $y = 0.0372x$ with an r^2 value of 0.9997 was derived where y represented the predicted load in pounds and x represented the displacement of the proving ring. The intercept was set for zero since at zero pounds, one would expect zero ring displacement.

Next of concern was proper measurement of specific gravity. To ensure that proper measurements were taken, both the caliper and the immersion method was used (ASTM D2395, 1993). For all test specimens, the immersion method was used to measure ovendry volume. Also, 32 of the specimens were randomly selected during testing and the ovendry volume was measured with calipers. The 32 caliper measurements were then compared to the corresponding immersion measurements for the same block. Figure 5.2.4a shows the linear regression line and the r-square value of the volume measurements.

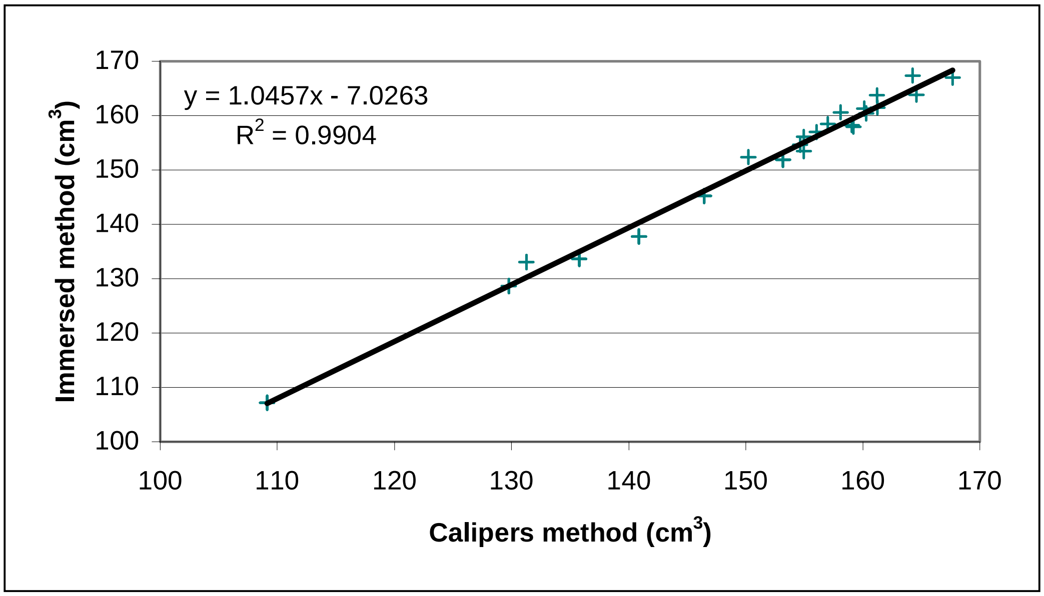


Figure 5.2.4a: Comparison of two volume measurement techniques

Next, the conditioning chamber was of concern. All specimens needed to be equilibrated to 15 ± 4% (TPI .7.1.6.3(b)). There were two measuring devices for humidity. Both consistently showed different humidity readings. The computer-controlled device was set for approximately 12 percent moisture content. This was achieved by setting the temperature and relative humidity for the room to 20 ^{o}C and 65% respectively. However, the relative humidity on the spring gage consistently read 75%. To determine the actual moisture content, 7 blocks were placed in the conditioning chamber and 17 data points (in grams) per block in a span of 96 days were registered (Appendix L). By day 12, all four blocks reached equilibrium and 14 data points (in grams) per block were measured under equilibrium until day 96. After 96 days, the blocks were oven-dried and weighed. The data points were then converted to moisture contents. The average moisture content was approximately 16%. This was unexpected since the room was set for 12%. The repeatability was 16% ± 0.05% at the 95% confidence level. Since the real average humidity was unknown, the accuracy was assumed to be 14.1% ± 0.05%.

5.2.5 Truss Plate Criteria

For the LRAA and LREA orientations, a 3X4 plate size was used because 3 inches is a common plate width and exhibits a high occurrence of tooth withdrawal based on our previous pilot study. Plate Specifications listed in Table 5.2.5a were used.

Table 5.2.5a: Plate Specifications for 4 plate and lumber axis orientations tested

Orientation	LRAA	LREA	LRAE	LREE
Size	3"x4"	3"x4"	1"x8"	1"x8"
Gauge	20	20	20	20
Number of Teeth	4 per square inch of plate surface area	4 per square inch of plate surface area	4 per square inch of plate surface area	4 per square inch of plate surface area
Plate Allowable	206 psi	158 psi	163 psi	170 psi
Safety Factor	3.2	3.2	3.2	3.2
Average Lateral Resistance	SizexRatingx3.2	SizexRatingx3.2	SizexRatingx3.2	SizexRatingx3.2

5.2.6 Statistical Analysis Model

Both linear and non-linear regression analyses were used to analyze specific gravity and tooth withdrawal data for all four orientations. The final regression technique used for each orientation depended on which technique best fit the data. Hypothesis testing of slopes was performed to determine the significance of the trend(s). Tooth withdrawal resistance was further defined by comparing ultimate load and longitudinal average slip to ovendry specific gravity. Percent latewood data were used to estimate the percentage of high specific gravity material within the volume of teeth penetration. For the LRAA and LREA orientations, a randomized complete block design was used to test the null hypothesis that tooth withdrawal was dependent on the lumber surface with the lowest percentage of latewood.

For the LRAA orientation, the Wilcoxon t-test statistic was used to test the null hypothesis that the lower specific gravity section would fail in tooth withdrawal. For the LREA orientation, a paired t-test of the mean was used to test the same null hypothesis. Proper test statistics were chosen based on the level of normality of the paired distribution curve. For the LRAA and LREA orientations, the difference was defined as tooth withdrawal minus lack of tooth withdrawal. Finally, embedment gaps, specific gravity, and percentage latewood data were analyzed with linear, linear weighted least squares and non-linear regression. Hypothesis testing of slopes was performed to determine the significance of the trend(s).

6 Results and Discussion

6.1 Load at critical slip versus ultimate load

Two criteria were used to determine allowable design loads for the connections (E6.1a and E6.1b) (TPI, Section 7.1.9(a)(b)).

$$\frac{\text{Load at critical slip (0.03'')}}{\text{1.6 safety factor}} \qquad \textbf{[E6.1a]}$$

$$\frac{\text{Ultimate load}}{\text{3.2 safety factor}} \qquad \textbf{[E6.1b]}$$

The lesser of the two equations determined whether load at critical slip or ultimate load controlled. For all four lumber and plate orientations, ultimate load controlled for every specimen tested. The mean values can be observed in Table 6.1a. Consequently, all independent variables were used to predict ultimate load and not load at critical slip.

Table 6.1a: Mean values for ultimate load, load at critical slip, and slip at ultimate load.

Lumber and plate orientation	Mean ultimate load (psi) ÷ 3.2	Mean load (psi) at 0.03 inch slip ÷ 1.6	Mean slip at Ultimate load (inches)
LRAA	187	328	0.0564
LREA	151	285	0.0458
LRAE	132	256	0.0377
LREE	153	300	0.0302

For the LRAA and LREA orientations, the occurrence of embedment gaps increased the importance of checking whether load at critical slip or ultimate load controlled (E6.1a and E6.1b). With embedment gaps, there was an increased chance for load at 0.03-inch slip to control. This was attributable to the rotation that occurred at the wood surface level of the non-fully embedded tooth (Figure 6.1a).

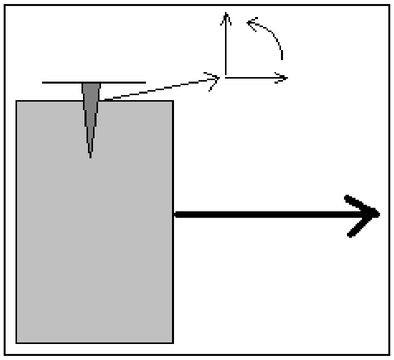


Figure 6.1a: Increased embedment gap allowed for bending of the tooth at the wood surface level instead of at the plate surface level.

For the LRAA orientation, the mean allowable lateral design value was 187 psi and the mean slip at ultimate load was 0.0564 inches (Table 6.1a). The 187 psi value compared well with previous research where a mean lateral allowable design value of

176 psi was found for southern pine joints loaded in the LRAA orientation (Suddarth et al., 1972). However, Suddarth did not test the same truss plate design tested in this study.

The mean allowable lateral design value of 186.5 psi was lower than the mean allowable lateral design value published by Alpine Engineered Products, Inc. This lower design value was attributed to the embedment gap of some test specimens, and sampling variability. The average embedment gap for all test specimens in the LRAA orientation was 0.0377 inches. The ANSI/TPI 1-1995 standard requires a 60% reduction in allowable load for all embedment gaps between 0.0313 and 0.0625 inches (TPI, Section 4.5.4.4) The research experimental mean allowable lateral resistance design values were 10% below Alpine Engineered Products, Inc. values which was much better than the 60% reduction required (TPI, Section 4.5.4.4) However, it should be realized that many test specimens had plates that were fully embedded.

For the LREA orientation, the mean allowable lateral design was 151psi and the mean slip at ultimate load was 0.0458 inches. The LREA orientation mean allowable lateral design value was lower than the LRAA orientation, which is consistent with the plate manufacturers code design values.

For the LRAE and LREE orientations, the mean allowable lateral resistance values were 132 psi and 152 psi, respectively. The LRAE orientation had the higher mean slip and lower allowable lateral resistance design values due to plate orientation. For the LRAE orientation, the tooth width during pressing was pressed in parallel to grain. It is theorized that the fibers were then spread open just enough to begin a crack at the cell level. During testing, this crack propagated at the macro level and contributed to failure. The resultant tension perpendicular to grain crack occurred along the first row

(Figure 6.1b) of teeth in the main member and explained why the LRAE orientation had higher slip and lower ultimate load.

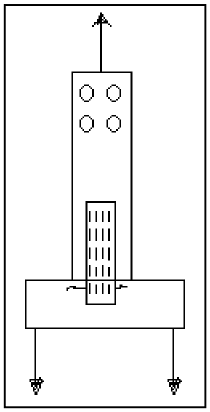


Figure 6.1b: Crack propagation for the LRAE orientation

Nevertheless, the failure mode for the LRAE orientation was a combined tension perpendicular to grain and tooth withdrawal failure. For most test specimens, tooth withdrawal occurred before the tension perpendicular to grain crack was observed.

6.2 Relationship between specific gravity and ultimate load

The mean and range of specific gravities for all four lumber and plate orientations are listed in Table 6.2a. For each orientation, the sample specific gravity range exceeded the 90% confidence interval (Green et al., 1989)

Table 6.2a: Range and mean specific gravity for all four lumber and plate orientations

			Green et al. (1989)	
Lumber and plate orientation	SG range	SG mean	SG 90% confidence interval	SG mean
LRAA	0.38 to 0.83	0.56	0.41 to 0.69	0.55
LREA	0.38 to 0.74	0.57	0.41 to 0.69	0.55
LRAE	0.38 to 0.75	0.55	0.41 to 0.69	0.55
LREE	0.36 to 0.75	0.55	0.41 to 0.69	0.55

Currently, it would be impractical to create new grades of lumber with a mean specific gravity that exceeds the tails. As a result, regression equations derived were considered representative for the population of southern pine.

For the four lumber and plate orientations, three possible hypothesis were checked:

$\mathbf{H_{6.2a}}$: No significant least squares linear trend between SG and ultimate load.
$\mathbf{H_{6.2b}}$: No significant weighted least squares linear trend between SG and ultimate load.
$\mathbf{H_{6.2c}}$: No significant quadratic trend between SG and ultimate load

The alternative hypothesis was accepted when a $p\text{-value} \leq 0.05$ existed.

For the LRAA orientation, a type III sum of squares ANOVA table was computed to determine the significance of a quadratic trend ($H_{6.2c}$). The first order variable SG had a p-value of 0.1118 and the second order variable SG^2 had a p-value of 0.3154. Thus, $H_{6.2c}$ was accepted and no quadratic relationship existed.

Since a quadratic relationship did not significantly exist, a linear regression model was developed to test $H_{6.2a}$. Due to a p-value of 0.0001 (Table 6.2_b), $H_{6.2a}$ was rejected and a linear trend proved to be a good fit. A linear equation was thus derived (Table 6.2_b) and the resultant plot was graphed (Figure 6.2a).

Table 6.2b: Specific gravity equations, respective r^2, and independent variable p-values for all four lumber and plate orientations.

Lumber and plate orientation	Equation predicting ultimate load	r^2	P-values of independent variables computed in an ANOVA table	
			SG	SG^2
LRAA	$U_{LRAA} = 430(SG)+361$	0.578	0.0001	----
LREA	$U_{LREA} = 991(SG)-662(SG^2)+147$	0.834	0.0076	0.0431
LRAE	$U_{LRAE} = 326(SG)+240$	0.391	0.0004	----
LREE	$U_{LREE} = 737(SG)+86.9$	0.606	0.0001	----

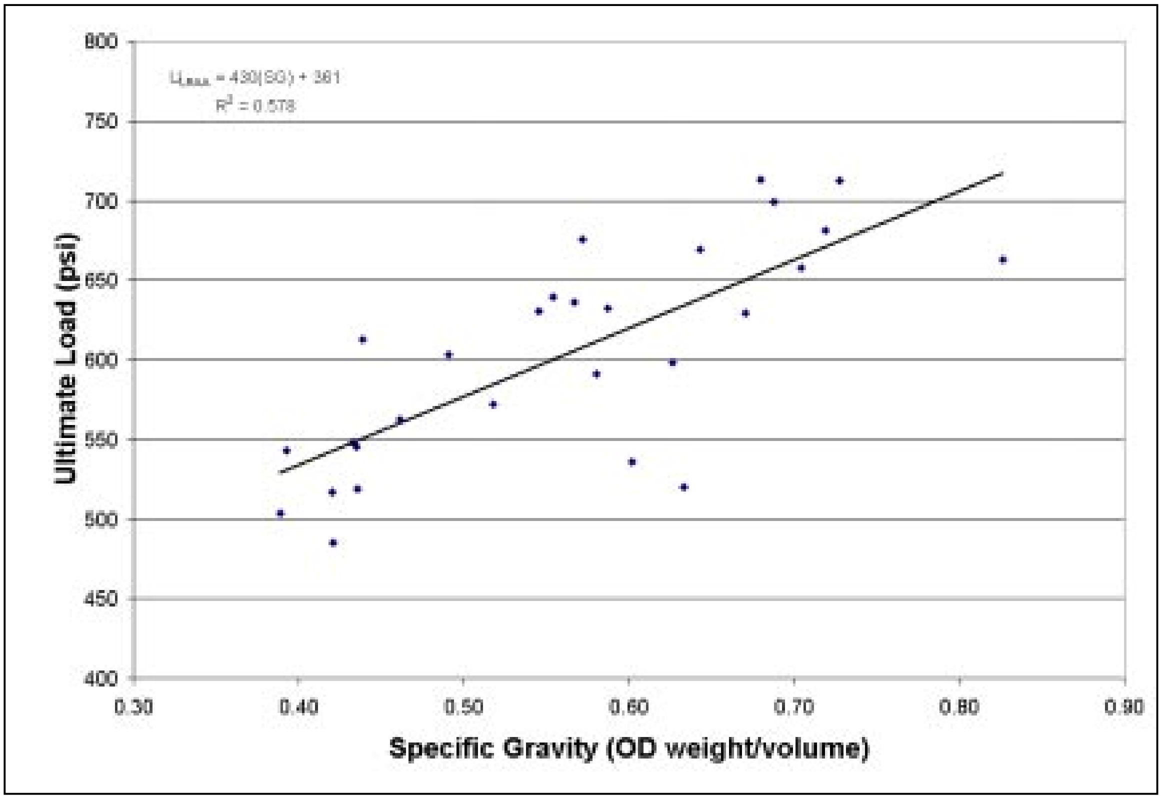


Figure 6.2a: Specific gravity versus Ultimate load for the LRAA orientation.

For the LRAA orientation, the r^2 of 0.578 was similar to the results of Suddarth et al. (1979). The reason for a moderate correlation was attributed to embedment gap.

By using the U_{LRAA} equation (Table 6.2b), a 0.10 increase in specific gravity caused the ultimate load to increase by 7%. This was different than Palka's study where a 25% increase in strength occurred for a 0.10 increase in specific gravity (Palka, 1984). However, Palka did account for embedment gap which could explain the larger (25%) increase in strength. Moura et al. (1995) determined that high specific gravity specimens had a 30% higher ultimate tooth holding strength than the lower specific gravity test specimens. For this study, a low specific gravity was defined as being less than 0.41 while a high specific gravity was considered greater than 0.69 for southern pine. By using the U_{LRAA} equation (Table 6.2b), when going from low to high specific gravity, a

22% increase in strength occurred. Once again, Moura et al. (1995) did not take embedment gaps into account, which may have explained the different result.

For all lumber and plate orientations, it was evident that all test specimens with higher specific gravities were stronger. For the same deflection and before the proportional limit, the load was higher for the high specific gravity specimens. This was observed by looking at the load versus deflection real time plot and was attributable to the lateral resistance of fibers to slip.

For the LREA orientation, a type III sum of squares ANOVA table was computed and the hypothesis $H_{6.2c}$ was checked for significance. The first order SG and second order SG^2 variables were significant at a p-value of 0.0076 and 0.0431 respectively (Table 6.2b). Therefore, $H_{6.2c}$ was rejected and a significant quadratic trend was determined to exist. An equation was derived (Table 6.2b) and the trend can be seen in Figure 6.2b.

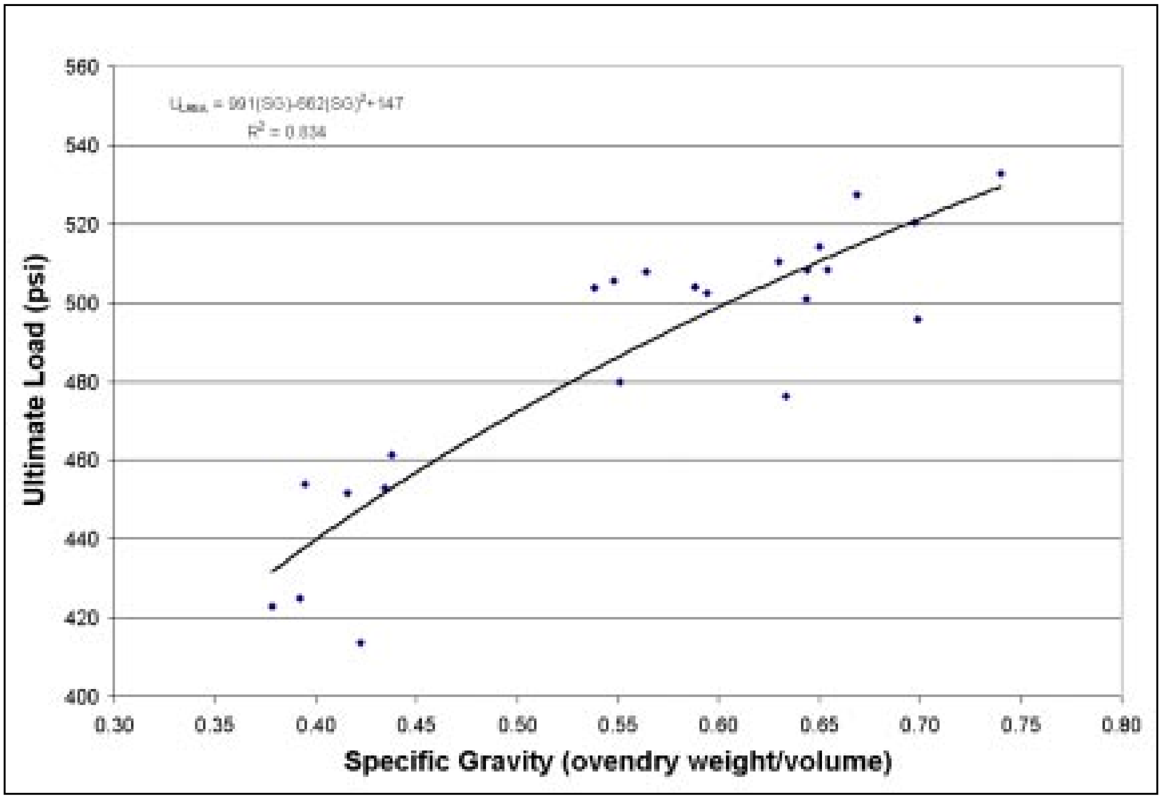


Figure 6.2b: Specific gravity versus Ultimate load for the LREA orientation.

The reason for such a strong correlation was attributable to the lower occurrence of embedment gap. It was determined that embedment gap was not a significant variable to include in a multiple regression model at a p-value of 0.8523. As a result, there was no need to include embedment gap in any prediction equations.

For the LRAA and LREA orientations, tooth axis direction was important. For the LREA orientation, the teeth cut parallel to the fibers during pressing (Figure 6.2c). During loading, there was increased opportunity for slip in the LREA orientation. For the LRAA orientation, the teeth cut across the fibers during pressing. As a result, there was apparently more resistance to slip during loading.

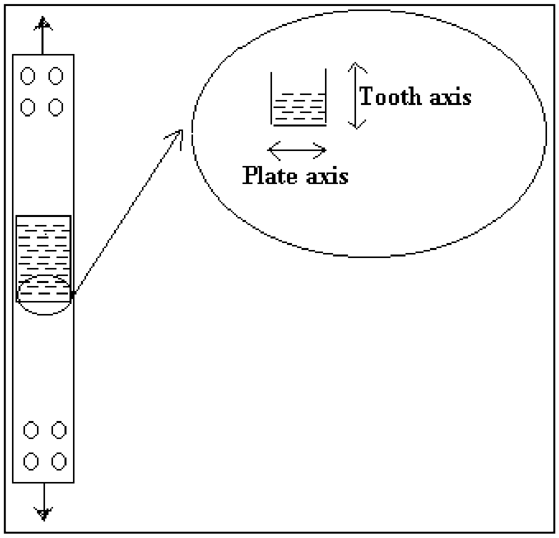


Figure 6.2c: Plate and tooth axis where the fiber axis is parallel to the tooth axis for the LREA orientation.

For the LRAE and LREE orientations, a weighted least squares linear regression model was developed to predict the ultimate load for a given specific gravity (Table 6.2b). The weighted least squares method was chosen because as the independent variable specific gravity increased, the variability of the residuals appeared to increase. This model helped to account for the increased residual variability with increasing specific gravity. For the LRAE and LREE orientations, the p-values for the independent variable SG was 0.0004 and 0.0001 respectively (Table 6.2b). Thus, there was a significant weighted least squares linear trend and the null hypothesis $H_{6.2b}$ was rejected. The resulting trends for the LRAE and LREE can be seen in Figure 6.2d and 6.2e respectively.

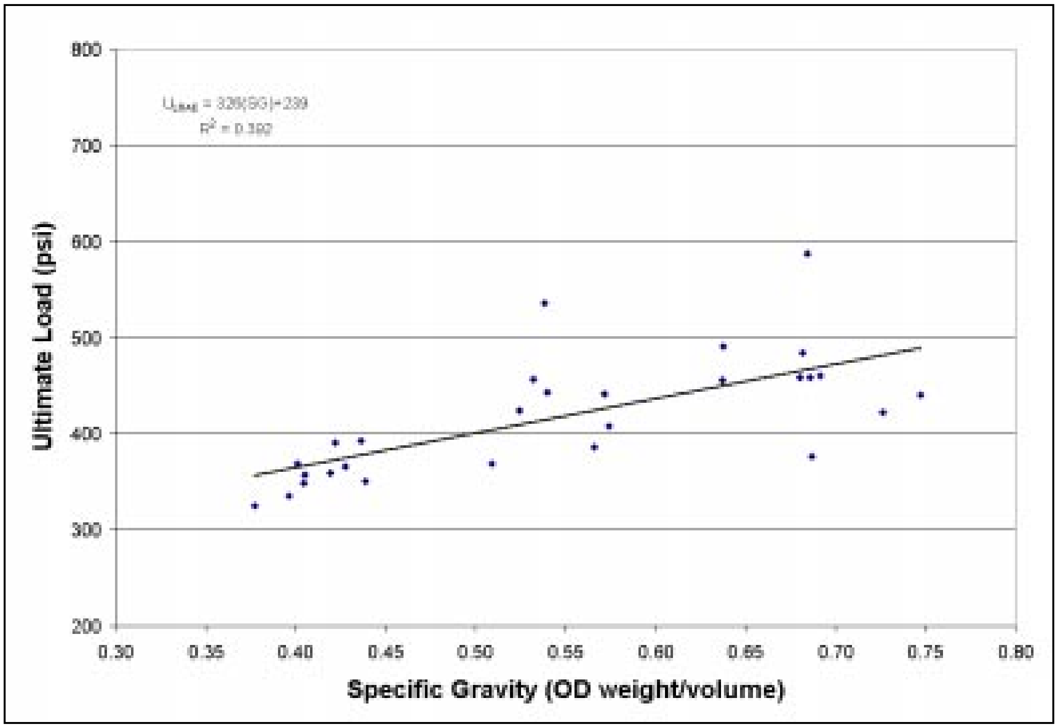


Figure 6.2d: Specific gravity versus Ultimate load for the LRAE orientation.

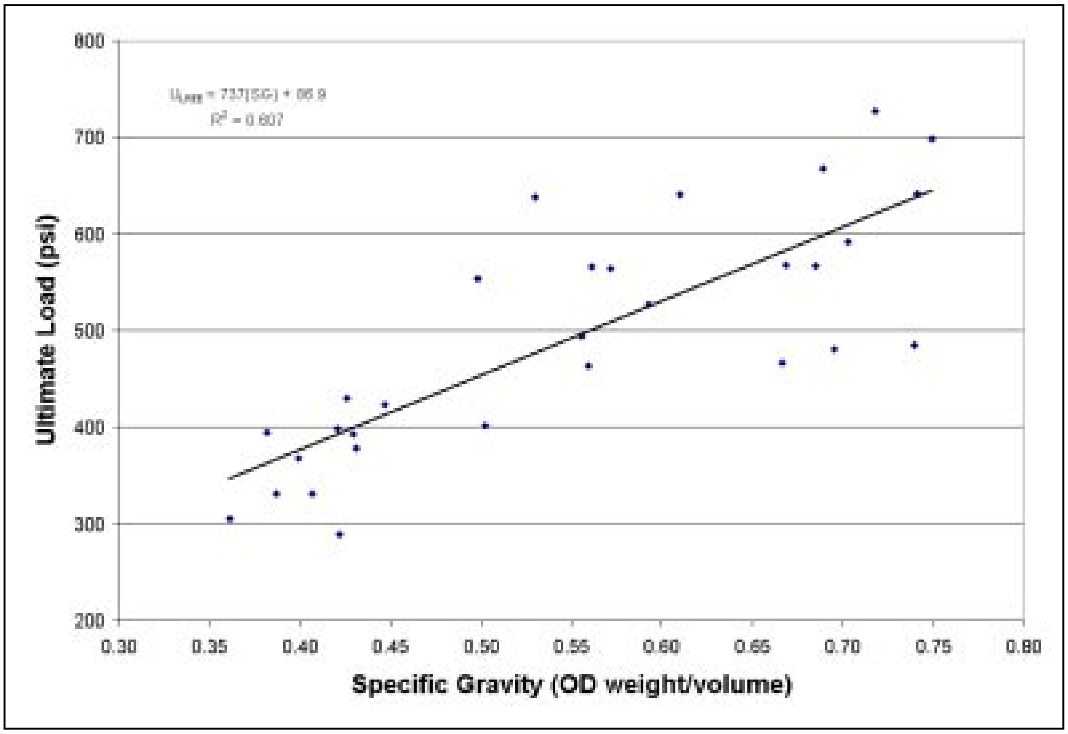


Figure 6.2e: Specific gravity versus Ultimate load for the LREE orientation.

Once again, plate orientation appeared to be important. For the LRAE orientation, the tooth width was pressed in parallel to grain. It was theorized that fibers were then wedged open and a crack at the cell level began. During testing, this crack propagated at the macro level and contributed to failure. Ultimately, the teeth withdrew but undoubtedly, tension perpendicular to played a role. As a result, the LRAE orientation had higher slip values and lower ultimate loads than the LREE orientation.

During the test, since the LREE orientation did not experience any visible cracks due to tension perpendicular to grain, specific gravity was a better predictor of ultimate load for the LREE orientation than for the LRAE orientation (Table 6.2b).

6.3 Relationship between percent latewood at tooth depth and ultimate load

For the four lumber and plate orientations, two possible hypothesis were checked:

$H_{6.3a}$: No significant weighted least squares linear trend between percent latewood and ultimate load.
$H_{6.3b}$: No significant quadratic trend between percent latewood and ultimate load

The alternative hypothesis was accepted when a $p\text{-value} \leq 0.05$ existed.

For the LRAA and LREA orientation, a type III sum of squares ANOVA table was computed to determine the significance of $H_{6.3b}$. For the LRAA and LREA orientation, the variable (LW) had a p-value of 0.2287 and 0.0015 respectively. Likewise, for the variable (LW^2), the LRAA orientation had a p-value of 0.6561 while the LREE orientation had a p-value of 0.0464 (Table 6.3a). The hypothesis $H_{6.3b}$ was accepted for the LRAA orientation while for the LREA orientation, the hypothesis was rejected and a quadratic trend was adequate. Since $H_{6.3b}$ was accepted for the LRAA orientation, no equation was derived (represented by dashed lines for Table 6.3a).

Table 6.3a: Latewood equations, respective r^2,and independent variable p-values for all four lumber and plate orientations.

Lumber and plate orientation	Equation predicting ultimate load	r^2	P-values of independent variables computed in an ANOVA table	
			LW	LW^2
LRAA	----	----	0.2287	0.6561
LREA	$U_{LREA} = 6.1(\%LW)-0.05(\%LW^2)$	0.81	0.0015	0.0464
LRAE	$U_{LRAE} = 3.2(\%LW)+291$	0.41	0.0002	----
LREE	$U_{LREE} = 5.5(\%LW)+290$	0.45	0.0001	----

For the LRAA and LREA orientation, specific gravity of the cross section was a better predictor of lateral resistance than percentage of latewood at tooth depth. Since the whole cross section was a better predictor, it indicated that the whole cross section of wood between the two metal plate truss connectors was important in distributing stresses. More importantly, significant embedment gaps, especially for the LRAA orientation, probably increased the variability of the ultimate load for a given latewood percentage.

However, based on the r^2 and p-values for the LREA orientation, percentage of latewood was almost comparable to specific gravity in predicting ultimate load (Tables 6.2b and 6.3a). Percentage latewood at tooth depth was probably an adequate predictor of ultimate load because most pieces of lumber appeared consistent in latewood percentage throughout the cross-section. Due to this consistency, percentage of latewood at tooth depth was related to specific gravity of the whole cross-section. Thus, specific gravity appeared to be the best variable for ultimate load ($U_{LRAA\text{ or }LREA}$) prediction.

For the LRAE and LREE orientations, the hypothesis $H_{6.3a}$ was checked for significance, and a linear weighted least squares regression model was developed if $H_{6.3a}$ was rejected. For the LRAE and LREE orientations, the variable (LW) had p-values of

0.0002 and 0.0001 respectively (Table 6.3a). The resultant plots can be seen in Figures 6.3a and 6.3b.

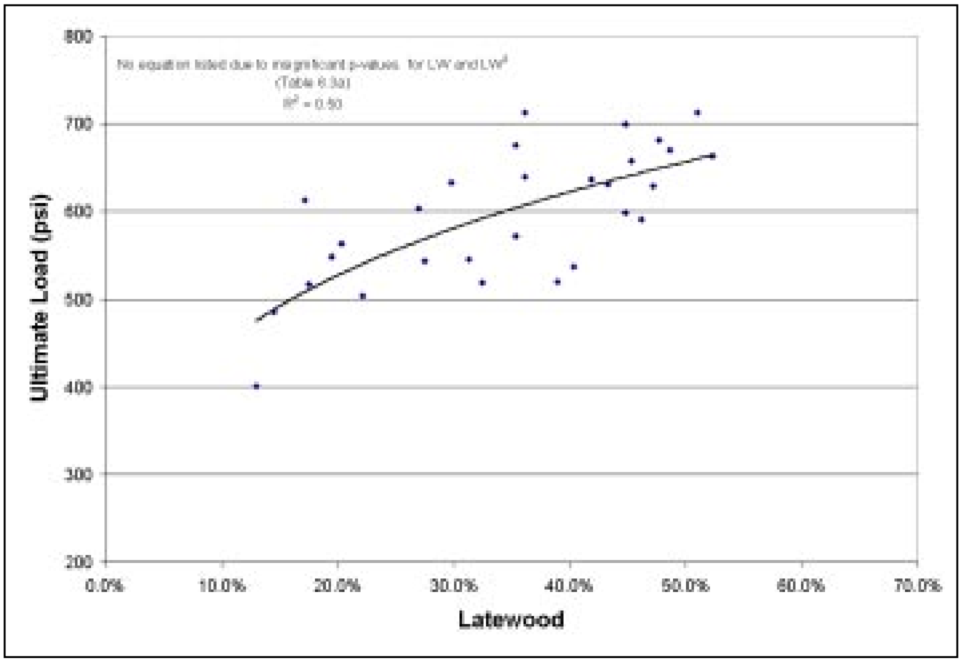


Figure 6.3a: Percent latewood at tooth depth versus Ultimate load for the LRAA orientation.

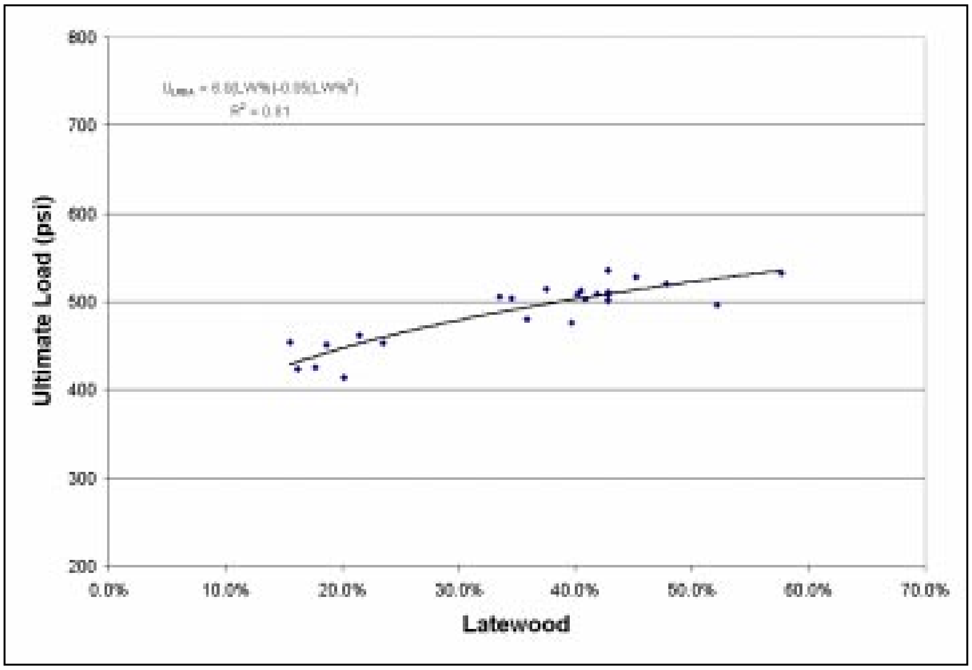


Figure 6.3b: Percent latewood at tooth depth versus Ultimate load for the LREA orientation.

For the LRAE orientation, the higher r^2 and p-value for the latewood percentage statistically showed latewood percentage was a better predictor of ultimate load than specific gravity (Table 6.3a). However, for the LREE orientation, specific gravity appeared to be a better predictor of ultimate load.

For the LRAE orientation, latewood percentage may have been a better predictor of ultimate load due to the partial tension perpendicular to grain failure. Increased earlywood to latewood transition would have increased the chance that a crack would propagate along the earlywood to latewood transition layer. Since only tooth withdrawal failure occurred in the LREE orientation, the earlywood to latewood transition would not have been as important.

6.4 Relationship between specific gravity and tooth withdrawal location

Specific gravity measurements were taken from two blocks on both sides of the joints for the LRAA and LREA orientations. One block was taken from the site of tooth withdrawal and the other block from the site where tooth withdrawal was not as prevalent (Figure 6.4a).

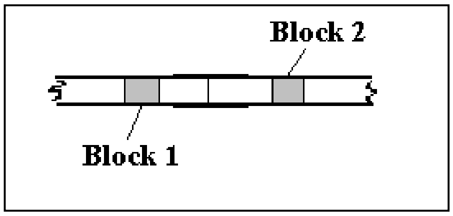
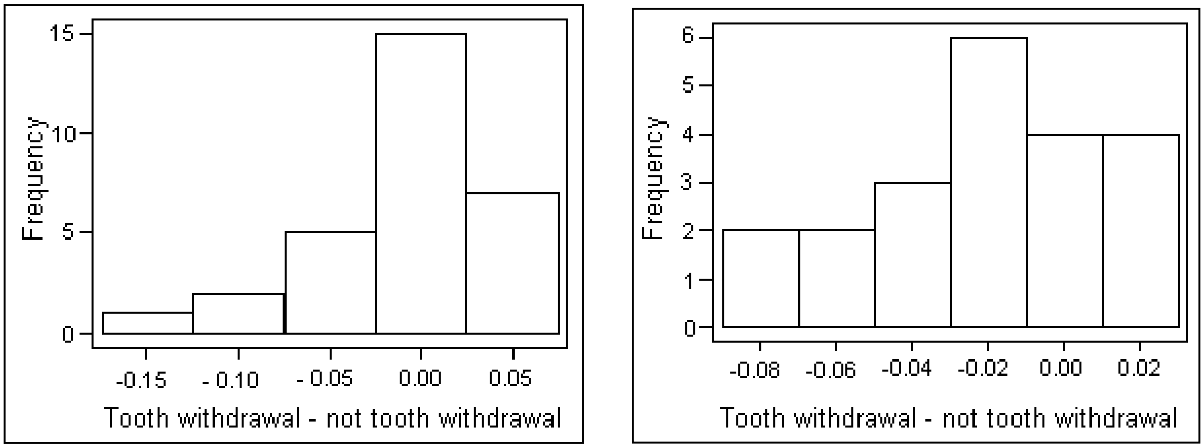


Figure 6.4a: Two blocks were taken from each specimen

The following null hypothesis was posed:

$H_{6.4}$: There was not a significant difference between the mean specific gravity on side of tooth withdrawal versus the mean specific gravity on the side of lesser withdrawal.

To test this hypothesis, the blocks were categorized as either tooth withdrawal or not tooth withdrawal. Blocks within each test specimen were considered to be dependent of one another. For the LRAA orientation, a conservative Wilcoxon test was used since the data were skewed (Figure 6.4b). For the LREA orientation, a paired t-test was used since the data were not skewed (Figure 6.4c).



Figures 6.4b and 6.4c: Paired distribution for the LRAA and LREA orientation respectively.

For the LRAA and LREA orientations, p-values of 0.366 and 0.012 were obtained respectively and the null hypothesis ($H_{6.4}$) was accepted and rejected respectively. Thus, for the LRAA orientation, there was not a significant difference between the mean specific gravity of the two blocks while the LREA orientation did show a significant difference between the two blocks.

For the LRAA orientation, embedment gap was more severe than the LREA orientation. With increased embedment gap, a decrease in tooth depth occurred. As a result, it was expected that the influence of specific gravity would decrease when predicting ultimate load. Since the severity of embedment gap was less for the LREA orientation that would explain why tooth withdrawal became more dependent on specific gravity.

For both LRAA and LREA orientations, separate lumber was used to construct each test specimen. It was interesting that the LREA orientation showed a significant difference in mean specific gravities between blocks because the separate pieces of lumber used to construct the test specimens were pre matched by specific gravities. Had there been a larger mean specific gravity difference between matched specimens, an even higher significance would have been expected. However, with an increase in mean difference specific gravity, the possibility of embedment might have increased and would have counteracted the influence of specific gravity on tooth withdrawal. On the other extreme, had the matched pieces come from the same piece of lumber, the difference might have been so minimal that a significant difference would not have been found. This was the reason why test specimens where matched from two pieces of lumber but with similar specific gravities.

For the LRAE and LREE orientations, tooth withdrawal occurred with equal magnitude for both surfaces on most test specimens. Therefore, there was no need to perform a statistical test and null hypothesis $H_{6.4}$ was accepted. It was understandable that tooth withdrawal occurred equally on both surfaces since tooth withdrawal could only occur on the main member where the specific gravity was approximately the same. In other words, the sites of tooth withdrawal were 1.5 inches from each other in the same piece of wood; thus, specific gravity would not vary much.

6.5 The relationship between percent latewood and tooth withdrawal location

There were four possible surfaces capable of tooth withdrawal for the LRAA and LREA orientations (Figure 6.5a).

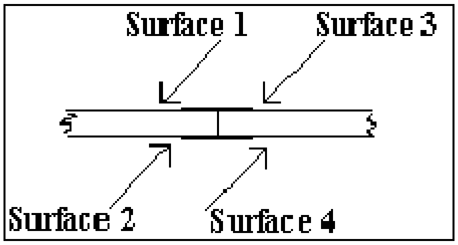


Figure 6.5a: Four possible surfaces for withdrawal.

To determine the relationship of percent latewood and tooth withdrawal, the following hypothesis was formed:

$H_{6.5a}$: $\mu_{tw} = \mu_{opposite} = \mu_{diagonal} = \mu_{horizontal}$

where: μ represents the mean latewood percent at tooth depth for each surface.

To test this hypothesis, a randomized complete block design was constructed where each specimen was treated as a block and each surface was treated as a treatment. By using a randomized complete block design, the experimental error variance was reduced. The percent latewood data were organized into four categories: tooth withdrawal, opposite, horizontal, and diagonal (Figure 6.5b) (Appendix M).

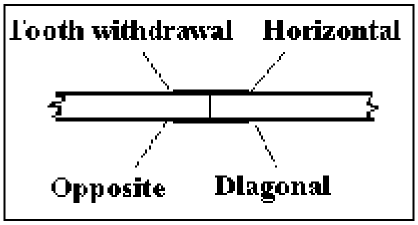


Figure 6.5b: Reorganization of percent latewood data

For the LRAA and LREA orientations, the p-values were 0.6615 and 0.9884 and thus the null hypothesis ($H_{6.5a}$) was accepted.

For the LRAA and LREA orientations, specific gravity statistically had a stronger relationship with the site of tooth withdrawal than percent latewood and was further evidence that the whole cross-section was more important in resisting lateral loads than just the wood fibers at tooth depth.

There were several factors that may have dictated why there was no difference in mean latewood percentage for the four surfaces. Embedment gap was the primary reason in that the level of gap significantly contributed to the strength of the joint. Secondly, the whole cross section appeared important in redistributing stresses. Also, ring orientation sometimes differed between wood pieces where flat sawn might have been more effective than quarter-sawn. Finally, the wood pieces within a test specimen were dependent. In other words, if one part of the joint lacked lateral resistance, stresses would redistribute to other joint parts. The dynamic redistribution of stresses during the test probably influenced tooth withdrawal more than the percentage of latewood.

As discussed in section 6.4, the tooth withdrawal magnitude appeared equal on both surfaces for the LRAE and LREE orientations. The null hypothesis $H_{6.5}$ was thus accepted for both orientations.

6.6 Influence of moisture

In past research dealing with nails, the withdrawal strength of the nail was strongly dependent on the moisture content of the test specimen (Stelmokas et al., 1995). Since metal plate connectors may behave similar to nails, the specimens were placed in a conditioning chamber for 3 to 4 months. However, a noticeable variance in specimen moisture content still existed once tested. Since it is a know fact that moisture content and specific gravity are linearly related, only one hypothesis was formed:

$H_{6.6}$: In addition to specific gravity, moisture did not significantly account for residual variability when predicting ultimate load.

Table 6.6a: Linear regression ANOVA analysis for the independent variables moisture and specific gravity.

Lumber and plate orientation	P-values of independent variables computed in an ANOVA table	
	Moisture	Specific gravity
LRAA	0.3268	0.0001
LREA	0.6920	0.0001
LRAE	0.1233	0.0007
LREE	0.6927	0.0001

For all four orientations, moisture content did not significantly contribute to the residual variability and thus the null hypothesis was accepted ($H_{6.6}$) (Table 6.6a).

Since the wood materials were stored in the conditioning chamber for 3 to 4 months, the variability in moisture content was narrow enough such that moisture did not significantly deserve to be in the multiple regression model. One reason that moisture was insignificant was due to the probable moisture content of the surfaces. Three to four months was enough time to equilibrate the surface where tooth penetration would occur. Had tooth length been longer, moisture variation at tooth depth between specimens would have increased. This would have increased the chance for moisture to influence ultimate load.

6.7 Embedment gap

Embedment gap only occurred in the LRAA and LREA orientations and the LRAA orientation experienced embedment gap most often. For both orientations, two quadratic regression models were developed to predict embedment gap for a given specific gravity or latewood percentage. Also, for both orientations, a multiple linear regression was performed to see if both specific gravity and embedment gap were needed to predict ultimate load (U_{LRAA} and U_{LREA}) and thus the three null hypotheses were:

$H_{6.7a}$: No significant quadratic trend between the independent variable specific gravity and embedment gap.

$H_{6.7b}$: No significant quadratic trend between the independent variable percent latewood and embedment gap.

$H_{6.7c}$: Embedment gap did not account for most of the residual variability when specific gravity was accounted for using a multiple regression.

The null hypothesis $H_{6.7a}$ and $H_{6.7b}$ was checked for the LRAA and LREA orientations. As shown in 6.2a, the variables SG and SG^2 were not significant in predicting embedment gap and $H_{6.7a}$ was not accepted for either orientation. Likewise, for both orientations, LW and LW^2 were not significant in predicting embedment gap (Table 6.2a). Even though none of the four variables were statistically significant, SG and SG^2 was a stronger predictor of embedment gap than LW and LW^2. It made sense that SG was a stronger predictor since the whole cross section would be involved in transferring press forces to the press table.

Table 6.7a: Quadratic regression ANOVA analysis for the independent variables specific gravity and latewood.

Lumber and plate orientation	P-values of independent variables computed in an ANOVA table	
	SG	SG^2
LRAA	0.373	0.3728
LREA	0.6225	0.8904
	LW	LW^2
LRAA	0.921	0.7022
LREA	0.5317	0.7934

Subsequently, a multiple regression ANOVA analysis was used to determine the importance of embedment gap ($H_{6.7c}$). As shown in Table 6.7a, for the LRAA orientation, both specific gravity and embedment gap had 0.0001 p-values. Thus, $H_{6.7c}$ was rejected and the two variables significantly predicted ultimate load (U_{LRAA}). For the LREA orientation, $H_{6.7c}$ was accepted and only specific gravity was needed to predict the ultimate load (U_{LREA}) (Table 6.7b).

Table 6.7b: Specific gravity and embedment gap equations, respective r^2,and independent variable p-values for all four lumber and plate orientations

Lumber and plate orientation	Equation predicting ultimate load	r^2	P-values of independent variables computed in an ANOVA table	
			SG	Embedment gap (EG)
LRAA	U_{LRAA} = 564(SG)-655(EG)+307	0.90	0.0001	0.0001
LREA	----	----	0.0001	0.8523

For the LRAA and LREA orientations, the average maximum embedment gap was 0.0377 and 0.0322 inches respectively. For both orientations, the lower specific gravity specimens rarely experienced embedment gap.

For the LRAA orientation, with the occurrence 0.03125 (1/32)-inch gaps, there was an 8% average decrease in ultimate load. Triche (1995) showed a 17% decrease in strength with a 0.03125 inch embedment gap. However, for Triche's experiment, embedment gaps were purposely created and the experiment targeted high specific gravity specimens. For this experiment, most of the low specific gravity test specimens did not have embedment gap. Based on the experience of the author, low to mid specific gravity southern pine lumber makes up the truss industry. Thus, an 8% decrease in strength would be more appropriate for most of the lumber used in the truss industry.

For both orientations, the increase in embedment gap with increased specific gravity was partially due to the amount of latewood close to the surface. Even though the percentage of latewood at tooth depth alone did not statistically correlate with embedment gap, it was apparent during pressing that this was an important variable. During pressing, latewood would resist the perpendicular to grain forces and crushing would occur in the next few earlywood layers. As a result, a lumber thickness differential occurred between the two wood pieces that made up the joint. Thus, the more latewood present toward the surface, the greater the resistance of the latewood and the greater the occurrence of earlywood crushing. After removal of the press load, the wood would partially "spring," back but not to original thickness, which was attributable to the viscoelastic response of wood. Further pressing did not narrow the embedment gaps due to either continued crushing of the earlywood fibers or resistance to further pressing.

Lumber manufacturing imperfections may have been the reason why specific gravity did not statistically correlate with embedment gap. Quite often, when two wood pieces were paired together, there was a considerable difference in lumber thickness (up to 0.04 inches). Since lumber pieces were paired by specific gravity, it was impractical to pair by thickness. No statistical data were collected to quantify the pre-press thickness differential of the paired wood pieces.

Finally, not all wood pieces lay flat on the press table due to slight: twist, cup, or warp. For example, in this experiment, 0.04 inches of cup added to the experimental error of the pressing procedure.

6.8 Elimination of plate testing for new specific gravity grades

The equations derived in this research could be incorporated into the Truss Plate Institute standards (TPI, 1995). Currently, metal plate manufactures have to retest all their plate products whenever a new specific gravity grade of lumber is approved and produced. With the equations from this research, plate manufacturers could simply adjust their plate allowable for a new grade of lumber with the new specific gravity rating.

For example, for a new grade of southern pine lumber with an average specific gravity of 0.57 (versus the population species average of 0.55), how could a plate manufacturer use the derived equation to adjust their LRAA plate allowable (206 psi for example) originally tested at 0.55 specific gravity? First, one would use the proper equation for the adjustment (E6.1.6.2a).

$$U_{LRAA} = 430(SG) + 361$$

The new plate rating would be calculated as such:

$$U'_{LRAA} = \text{Base value in code report (psi) x } \frac{(U_{LRAA\,@\,0.57\ SG})}{(U_{LRAA\,@0.55\ SG})}$$

$$U'_{LRAA} = 206 \text{ psi x } \frac{(430(0.57) + 361)}{(430(0.55) + 361)}$$

$$U'_{LRAA} = 209 \text{ psi}$$

Therefore, the new allowable lateral resistance value is 209 psi.

Table 6.8a shows the same calculations for all four plate and lumber orientations.

Table 6.8a: Adjusted allowable lateral resistance calculations for all four plate and lumber orientations for the Alpine plate tested in this study.

Lumber and plate orientation	Published SG	New grade SG	Published allowable at published SG (psi)	Derived equation	Adjustment calculation $U'_{orientation}$	Adjusted allowable lateral resistance value (psi)
LRAA	0.55	0.57	206	$U_{LRAA} = 430(SG)+361$	$206{*}U_{LRAA@\ 0.57\ SG} \div U_{LRAA@\ 0.55\ SG}$	209
LREA	0.55	0.57	158	$U_{LREA} = 991(SG)-662(SG)^2 +147$	$158{*}U_{LREA@\ 0.57\ SG} \div U_{LREA@\ 0.55\ SG}$	164
LRAE	0.55	0.57	163	$U_{LRAE} = 326(SG)+239$	$163{*}U_{LRAE@0.57} \div U_{LRAE@0.55}$	165
LREE	0.55	0.57	170	$U_{LREE} = 737(SG)+86.9$	$170{*}U_{LREE@0.57} \div U_{LREE@0.55}$	175

7 Conclusions

Results showed specific gravity alone to be a good predictor of ultimate load (r^2 = 0.578). However, with the addition of embedment gap and specific gravity, an r^2 value of 0.904 showed both these independent variables together to be excellent predictors of ultimate load for the LRAA orientation. Also, neither specific gravity nor percentage of latewood significantly influenced the location of tooth withdrawal. For the LREA orientation, specific gravity alone was a good predictor (r^2 = 0.834) of ultimate load. Furthermore, the location of tooth withdrawal significantly occurred first in the wood piece with the lowest mean specific gravity. For the LRAE orientation, specific gravity was a marginal predictor (r^2 = 0.392) of ultimate stress. For the LREE orientation, specific gravity was a good predictor (r^2 = 0.607) of ultimate stress.

For both the LRAE and LREE orientation, the magnitude of tooth withdrawal could not be accurately distinguished. As a result, it was concluded that neither percent latewood nor specific gravity influenced the location of tooth withdrawal since tooth withdrawal magnitude was approximately equal for both locations. Finally, it was shown that the predictor equations for the four plate and wood orientations could be used to adjust the truss plate allowable lateral resistance values as demonstrated in Section 6.8.

8 Limitations

Embedment gaps at the metal plate truss connector occurred for the LRAA and LREA orientation and could not be eliminated. This was due to compression perpendicular to grain and had to be allowed as a potential covariant. Embedment gap measurements were made to quantify and evaluate the embedment problem.

Moisture was another variable that was monitored and partially controlled. Three to four months were allowed for conditioning so that moisture would not affect ultimate load results. However, after 3 to 4 months, a range of moisture content of 12 to 17 percent was still common. It is a known relationship that moisture differences may influence strength. This research did not account for the 12 to 17% variation in moisture content.

Due to time constraints, a sample size of 120 for all four groups was chosen with 30 specimens per group. However, every group had specimens that had to be eliminated from data analysis. Three groups had an outlier data point that was recorded to have an abnormal failure. For the LRAA and LREA, failure in the wood at the bolts before ultimate load was reached which eliminated more specimens. Nevertheless, enough specimens were tested to yield information with 95 percent confidence.

Full sized trusses and typical full sized loads were not tested. Instead, each specimen consisted of one joint loaded to ultimate load. It is possible that steel failures in the truss plates will occur in a truss system. This research did not address the issue of steel failure modes.

Next, the plate coverage of the specimens was not representative of most metal plate connected joints. For this research, a 1-inch by 1-inch plate coverage was used on the main member for the LRAE and LREE orientations. Yet, most trusses observed in construction had more plate coverage. With more plate coverage, other connection failure modes are possible.

Finally, only southern pine lumber was used for this research and all equations derived are applicable to southern pine with the specified plate coverage and joint specifications as described in this report. Additional testing would be needed for other species to derive empirical equations for adjusting truss plate allowable withdrawal values based on new specific gravity grades.

9 Recommendations

For future research, other species need to be tested for lateral resistance (withdrawal) and similar equations developed. This would enable metal plate manufactures to use equations to determine joint capacities each time a new grade of lumber is developed. The equations developed in this research should not be used for other species groups and should be limited to southern yellow pine. Furthermore, the equations derived in this research (Table 6.8a) should be submitted to the next revision of the standards of Truss Plate Institute (TPI). By introducing these equations, companies would no longer have to retest their truss metal plate connectors for new grades of southern pine lumber.

The specification scheme and dimensions developed and tested in this research should also be submitted to TPI (Figures 1a-1d). By testing with different specifications, other failure modes would be possible. Using the same specifications would ensure consistency between plate manufacturers during lateral resistance testing.

The relationship between specific gravity and embedment gap appeared very important. Embedment gap was significant enough to include in the predictor model for the LRAA orientation. Since embedment gap reduced the strength with all other variables staying equal, it deserves further investigation.

Also, the effects of roller pressing instead of vertical pressing could be evaluated. In the literature, only the relationship between tooth withdrawal strength and SG has been reported for vertical pressing.

Finally, future researchers should consider some of the following suggestions. For specific gravity estimation, it is important to also estimate moisture content and weight. To measure moisture content , pin meters with pins that penetrate to core depth (3/4 inches) should be used instead of the ¼ inch pins that only measure surface moisture content which is usually significantly lower. To measure the weight, a scale that reads in increments of 0.1 pounds is vital for estimating the 5th and 95th percentile. Sample size is another important variable that needs to be properly estimated. If small pieces of wood are to be selected (15 to 30 inches in length), knots can sometimes fall in unacceptable places and should be considered when estimating how many wood pieces one would have to go through to reach the desired number of low and high specific gravity specimens. Finally, for the LRAA and LREA orientations, some high specific gravity specimens experienced wood fracture at plate fixture bolts. To eliminate this problem, a larger end-distance (greater than 4 inches) would be helpful. Figure 5.2.7a shows proper distances probably needed to eliminate wood fracture at plate hold down bolts. Since wood fracture only occurred in specimens with a high specific gravity (>0.69), this specification would not need to be adopted by TPI standards (TPI 7.1.6.3).

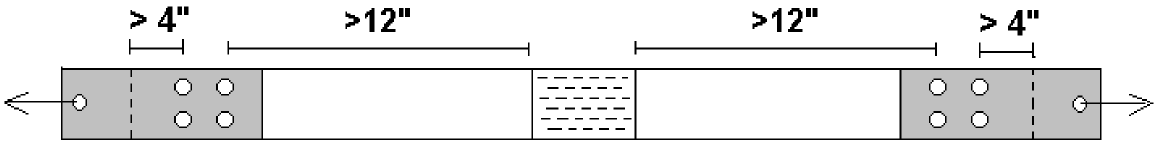


Figure 9.1a: The 4-inch length prevents wood fracture at the bolts for LRAA and LREA orientations.

References

American Forest and Paper Association (AF&PA). 1991. National Design Specification for Wood Construction (NDS). Washington D.C.

American Society for Testing and Materials (ASTM). 1993. ASTM D2395. Test methods for specific gravity of wood and wood-base materials. Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992. ASTM D4442. Test methods for direct moisture content measurement of wood and wood-base materials. Philadelphia, PA.

Bendtsen, B.A. and Senft, J. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood and Fiber Science 18(1): 23-38.

Crovella, P.L. and Gebremedhin, K.G. 1990. Analysis of light frame wood truss tension joint stiffness. Forest Products Journal 40(4): 41-47.

Emerson, RN. and Fridley, K.J. 1996. Resistance of metal-plate-connected truss joints to dynamic loading. Forest Products Journal 46(5): 83-90.

Foschi, R.O. 1977. Analysis of wood diaphragms and trusses. Part II: Truss-plate connections. Canadian Journal of Civil Engineering 4:353-362.

Fridley, K.J., Roberts, K.A., and Mitchell, J.B. 1994. Estimating ground snow loads using local climatological data. Journal of Structural Engineering 120(12): 3567-3576.

Gebremedhin, K.G., Jorgensen, M.C., and Woelfel, C.B. 1992. Load-slip characteristics of metal plate connected wood joints tested in tension and shear. Wood and Fiber Science 24(2): 118-132.

Gibson, M.D., McMillin, C.W., and Shoulders, E. 1986. Moisture content and specific gravity of the four major southern pines under the same age and site conditions. Wood and Fiber Science 18(3): 428-435.

Green, David W. and Evans, J.W. 1989. Specific Gravity of Visually Graded Lumber. U.S. Department of Agriculture Forest Service, Forest Products Laboratory. Madison, WI.

Gupta, R. 1990. Destructive testing of metal-plate-connected wood truss joints. J. of Structural Engineering 116(7): 1971-1977.

Gupta, R. 1994. Metal-plate connected tension joints under different loading conditions. Wood and Fiber Science 26(2):212-222.

Gupta, R., Vatovec, M, and Miller, T.H. April 1996. Metal-Plate Connected Wood Joints: A Literature Review. Oregon State University / Forest Research Laboratory. Research Contribution 13.

Haygreen, J.G.; and Bowyer, J.J. 1989. Forest Products and Wood Science: An Introduction. Second Edition. Iowa State University Press. Ames Iowa.

Heger, L. 1974. Longitudinal variation in specific gravity in stems of black spruce, balsum fir, and lodgepole pine. Canadian Journal of Forestry Resources. Volume 4: 321-326.

Hoadley, B.R. 1990. Identifying Wood: Accurate results with simple tools. The Taunton Press. Newtown, Connecticut.

Lenhart, J.D., Shinn, K.H., and Cutter, B.E. 1977. Specific gravity at various positions along the stem of planted loblolly pine trees. Forest Products Journal 27(9):43-44.

Moura, J.D., Bastian, C., and Triboulot, P. 1995. The influence of wood density on metal-plate connector mechanical behavior under cyclic loading. Forest Products Journal 45(11/12): 74-82.

O'Regan, P.J. 1997. Combined tension and bending loading in bottom chord splice joints of metal-plate-connected wood trusses. Masters Thesis, Virginia Polytechnic Institute and State University. Blacksburg, Virginia.

Page, D.H., El-Hosseiny, F., Winkler, K., and Bain, R. 1972. The mechanical properties of single woodpulp fibers: A new approach. Pulp and Paper Magazine of Canada 73(8):72-76.

Panshin and de Zeeuw. 1970. Textbook of wood technology. Third edition. McGraw-Hill Book Company. New York, New York.

Patton-Mallory, M. 1986. Strength of mechanically fastened wood connections. in Proceedings, Current Topics in Forest Research: Emphasis on contributions by women scientists. USDA Forest Service, Asheville, North Carolina. General Technical Report SE-46, pp. 92-95.

Palka, L.C. 1981. Effect of load duration upon Timber Fasteners: A selective literature review. Report submitted by Forintek Canada Corp., Western Laboratory, to Canadian Forestry Service, Ottawa, Ont., pp.58

Palka, L.C. 1984. Effect of wood density on truss-plate joint strength. Forintek Canada Corp. Western Laboratory. Prepared for Science Council of British Columbia. British Columbia.

Pernestal, K., Jonsson, B., and Larsson, B. 1995. A simple model for density of annual rings. Wood Science and Technology. V29: 441-449.

Shepard, R.K. and Shottafer, J.E. 1992. Specific gravity and mechanical property-age relationships in red pine. Forest Products Journal 42(7/8): 60-65.

Skaggs, T.D., Woeste, F.E., Dolan, J.D., and Loferski, J.R. 1994. Safety factors for metal-plate-connected wood trusses: theoretical design versus test specifications. Forest Products Journal. 44(9): 11-18.

Southern Pine Inspection Bureau (SPIB). 1994. Supplement No.10 to SPIB Standard Grading Rules For Southern Pine Lumber. Pensacola, Fl. pp4.

Stelmokas, J.W. and Dolan, J.D. 1995. Variability of axial withdrawal resistance of smooth, plain-shank nails in wet, wet-dry, and dry lumber. Virginia Polytechnic Institute and State University Timber Engineering. Report No. TE-1995-001. Blacksburg, Va.

Suddarth, S. K., Percival, D.H., and Comus, Q.B. 1979. Variability in tension performance of metal plate connections. In Proceedings of Metal Plate Wood Truss Conference, November, 1979, St. Louis, MO. FPRS Proceedings P-79-28, Forest Products Research Society. Madison, Wi.

Suddarth, S.K., Percival, D.H., and Comus, Q.B. 1981. Testing and analysis of 4x2 parallel-chord metal-plate-connected trusses. Research Report 81-1, Small Homes Council, University of Illinois, Urbana-Champaign, Il.

Szymanski, M.B. and Tauer, C.G. 1991. Loblolly pine provenance variation in age of transition from juvenile to mature wood specific gravity. Forest Science 37(1): 160-174.

Triche, M.H. 1995. Effect of partially embedded metal plate connector plates on joint strength. Wood Design Focus. Winter: 19-25.

Truss Plate Institute (TPI). 1995. ANSI / TPI 1-1995 National design standard for metal plate connected wood truss construction. TPI: Madison, WI.

Truss Plate Institut (TPI). 1995. Commentary to ANSI / TPI 1-1995 National design standard for metal plate connected wood truss construction. TPI: Madison, WI.

United States Forest Products Laboratory (USDA). 1990. Wood Handbook: Second Edition. Englewood Cliffs, NJ: Prentice-Hall.

Walton, D.R. and Armstrong, J.P. 1986. Taxonomic and gross anatomical influences on specific gravity-mechanical property relationships. Wood and Fiber Science 18(3): 413-420.

Wimmer, R. 1995. Intra-annual cellular characteristics and their implications for modeling softwood density. Wood and Fiber Science 27(4): 413-420.

Wolfe, R.W. 1990. Metal-plate connections loaded in combined bending and tension. Forest Products Journal 40(9):17-23.

Zobel, B.J. and McElwee, R.L. 1958. Natural variation in wood specific gravity of loblolly pine and an analysis of contributing factors. Tappi 41(2):158-161.

Appendix A: Pre specific gravity data measured for specimen pairing (19 ¾ inches)

Pre specific gravity data for 19-3/4 inch long specimens					
Specimen	Initial weight (g)	Ovendry Weight (g)	Immersed cm3	Moisture content	Specific gravity (od volume and weight)
cd	38.39	32.8	94.5	17.0%	0.35
t	32.05	28.2	78.52	13.7%	0.36
j	26.65	23.25	60.61	14.6%	0.38
da	40.68	35.45	90.45	14.8%	0.39
ci	41.73	36.74	93.25	13.6%	0.39
bm	44.64	39.37	99.65	13.4%	0.40
cw	38.1	33.63	83.52	13.3%	0.40
al	45.95	39.88	98.91	15.2%	0.40
ab	44.45	39.19	96.77	13.4%	0.40
af	67.51	58.17	142.5	16.1%	0.41
h	36.38	31.78	77.55	14.5%	0.41
aq	24.54	21.19	51.55	15.8%	0.41
s	39.77	34.99	84.5	13.7%	0.41
ad	41.26	35.65	85.8	15.7%	0.42
br	27.29	23.62	56.72	15.5%	0.42
ck	44.37	38.15	91.4	16.3%	0.42
ct	14.98	13.23	31.48	13.2%	0.42
g	47.73	41.69	98.65	14.5%	0.42
bn	39.38	34.55	81.55	14.0%	0.42
bz	42.41	36.64	86.22	15.7%	0.42
ca	43.55	38.49	90.42	13.1%	0.43
as	43.4	37.14	86.95	16.9%	0.43
a	40.25	35.76	83.59	12.6%	0.43
bx	38.91	34.23	79.96	13.7%	0.43
bk	27.73	24.6	57.25	12.7%	0.43
cm	8.41	7.3	16.95	15.2%	0.43
bw	45.1	38.47	89.13	17.2%	0.43
cl	42	36.13	83.08	16.2%	0.43
cv	42.63	37.62	86.45	13.3%	0.44
cc	42.77	36.88	83.74	16.0%	0.44
cy	43.58	38.4	86.7	13.5%	0.44
aa	52.37	45.91	102.85	14.1%	0.45
bh	50.81	43.32	96.9	17.3%	0.45
m	69.07	61	135.9	13.2%	0.45
bo	46.08	40.99	91.19	12.4%	0.45
cx	43.78	38.78	85.61	12.9%	0.45
ag	54.33	46.88	102.91	15.9%	0.46
bf	48.29	41.69	91.31	15.8%	0.46
bu	49.56	43.26	94.25	14.6%	0.46
bl	43.55	38.41	83.19	13.4%	0.46
cu	46.84	40.55	85.64	15.5%	0.47
f	47.38	41.77	87.2	13.4%	0.48
bj	46.2	40.34	83.13	14.5%	0.49
ch	44	39.14	80.47	12.4%	0.49

av	43.16	37.42	76.63	15.3%	0.49
cb	72.9	63.57	128.2	14.7%	0.50
bv	54.49	48.46	97.23	12.4%	0.50
I	49.82	44.23	86.66	12.6%	0.51
x	50.09	43.03	82.93	16.4%	0.52
p	55.52	50.14	94.84	10.7%	0.53
cg	71.79	61.39	114.56	16.9%	0.54
an	56.89	49.4	91.6	15.2%	0.54
at	101.2	86.45	159.8	17.1%	0.54
az	52.07	45.35	83.81	14.8%	0.54
ak	57.39	49.7	91.45	15.5%	0.54
y	48.23	42.72	78.44	12.9%	0.54
bp	51.03	43.84	79.98	16.4%	0.55
e	49.77	44.04	80.12	13.0%	0.55
cp	54.64	47.13	85.67	15.9%	0.55
r	61.85	53.74	97.68	15.1%	0.55
bb	77.93	66.77	120.92	16.7%	0.55
ac	35.29	31.14	56.23	13.3%	0.55
cj	57.05	50.48	91.14	13.0%	0.55
ay	67.45	57.8	102.48	16.7%	0.56
ae	62.15	54.07	95.6	14.9%	0.57
ba	57.84	50.01	87.73	15.7%	0.57
bq	65.57	57.1	98.49	14.8%	0.58
k	41.52	36.38	62.68	14.1%	0.58
be	58.9	51.37	88.39	14.7%	0.58
cn	46.77	40.63	69.73	15.1%	0.58
db	59.22	51.18	87.62	15.7%	0.58
ao	56.82	48.64	82.8	16.8%	0.59
cz	57	50.48	85.8	12.9%	0.59
am	67.14	59.28	100.73	13.3%	0.59
cs	56.49	49.22	82.56	14.8%	0.60
bd	56.05	48.78	81.68	14.9%	0.60
bs	31.8	27.76	46.33	14.6%	0.60
z	62.98	55.01	91.3	14.5%	0.60
ar	64.82	57.34	94.89	13.0%	0.60
aw	71.78	63.81	105.52	12.5%	0.60
ap	77.15	67.99	112.12	13.5%	0.61
bg	120.23	103.48	170.44	16.2%	0.61
by	94.19	80.83	132.6	16.5%	0.61
ce	50.95	45.1	73.91	13.0%	0.61
u	69.84	60.19	97.73	16.0%	0.62
et	84.7	75.67	120.16	11.9%	0.63
o	62.48	55.95	88.59	11.7%	0.63
bi	56.32	49.11	77.7	14.7%	0.63
eb	69.64	61.92	97.75	12.5%	0.63
dj	85	76.52	120.6	11.1%	0.63
dv	62.3	55.55	87.28	12.2%	0.64
aj	64.29	54.94	86.3	17.0%	0.64
fa	77.83	68.2	107.03	14.1%	0.64
n	21.82	19.24	30.19	13.4%	0.64
cf	54.96	48.87	76.55	12.5%	0.64
dh	81.46	71.68	112.16	13.6%	0.64

cq	63.49	56.14	87.77	13.1%	0.64
v	62.66	53.76	84.03	16.6%	0.64
eo	93.49	82.82	128.62	12.9%	0.64
dt	82.79	71.13	110.45	16.4%	0.64
eg	65.08	57.5	88.58	13.2%	0.65
er	57.81	50.68	78.02	14.1%	0.65
dx	81.4	73.3	112.04	11.1%	0.65
ai	73.33	63.91	97.42	14.7%	0.66
ea	103.6	93.1	141.72	11.3%	0.66
fb	90.75	79.25	120.08	14.5%	0.66
de	64.55	57.32	86.7	12.6%	0.66
w	95.1	86.33	130.5	10.2%	0.66
eq	111.78	97.48	147.32	14.7%	0.66
es	105.56	93.9	141.59	12.4%	0.66
dg	92.09	81.65	122.88	12.8%	0.66
ep	85.75	74.52	111.5	15.1%	0.67
ed	99.05	87.81	130.63	12.8%	0.67
ez	111.96	99.24	146.6	12.8%	0.68
cr	69.73	62.42	91.96	11.7%	0.68
di	96.35	84.83	124.87	13.6%	0.68
dm	86.58	76.65	112.71	13.0%	0.68
em	93.91	83.79	122.83	12.1%	0.68
dz	76.07	68.26	99.65	11.4%	0.68
do	84.41	73.73	107.34	14.5%	0.69
eu	99.28	87.3	126.9	13.7%	0.69
dd	84.43	74.92	108.86	12.7%	0.69
dp	99.98	88.33	127.83	13.2%	0.69
ax	69.32	61.5	89	12.7%	0.69
dy	97.04	85.96	124.1	12.9%	0.69
bt	78.36	70.23	101	11.6%	0.70
ec	62.48	54.76	78.55	14.1%	0.70
el	89.92	79.55	114.1	13.0%	0.70
du	91.6	79.72	114.19	14.9%	0.70
bc	53.33	47.31	67.7	12.7%	0.70
dk	88.11	76.76	109.8	14.8%	0.70
dw	91.27	80.6	115.25	13.2%	0.70
ey	98.96	86.38	123.43	14.6%	0.70
ev	109.25	95.41	135.92	14.5%	0.70
dl	92.8	79.91	113.75	16.1%	0.70
ee	67.28	59.02	83.91	14.0%	0.70
dc	42.16	38.01	53.97	10.9%	0.70
df	68.56	60.27	85.55	13.8%	0.70
q	66.49	58.45	82.36	13.8%	0.71
ds	84.42	74.53	104.98	13.3%	0.71
dr	26.14	23.09	32.52	13.2%	0.71
dn	86.99	78.37	110.28	11.0%	0.71
ef	68.15	59.52	83.75	14.5%	0.71
dq	114.81	101.83	142.35	12.7%	0.72
ah	81.22	70.8	98.28	14.7%	0.72
ei	96.64	85.87	118.69	12.5%	0.72
en	110.01	97.02	133.87	13.4%	0.72
ek	68.22	60.77	82.78	12.3%	0.73

ex	76.07	67.66	91.93	12.4%	0.74
ej	116.16	105.47	141.6	10.1%	0.74
eh	117.99	103.43	129.58	14.1%	0.80
ew	116.59	102	124.43	14.3%	0.82

Appendix B: Pre specific gravity data measured for specimen pairing (11 ¼ inches)

	Pre specific gravity 11-1/4 inch specimens				
Specimen	Initial weight (g)	Ovendry weight (g)	Immersed cm3	Moisture content	Specific gravity (od volume and weight)
a	24	20.88	56.9	14.9%	0.37
f	32.48	28.83	76.32	12.7%	0.38
af	97.14	83.23	217.24	16.7%	0.38
aj	112.4	95.57	243.96	17.6%	0.39
bi	79.66	68.34	173.01	16.6%	0.40
h	71.62	62.41	155.82	14.8%	0.40
e	49.96	44.07	108.89	13.4%	0.40
1st	63.21	58.11	142.26	8.8%	0.41
bf	74.96	64.4	157	16.4%	0.41
bp	37.53	32.36	78.79	16.0%	0.41
t	98.99	85.6	205.48	15.6%	0.42
ah	60.81	52.92	126.94	14.9%	0.42
av	73.59	62.93	150.55	16.9%	0.42
u	57.91	50.55	119.62	14.6%	0.42
bl	77.78	67.64	159.5	15.0%	0.42
az	42.19	36.75	86.64	14.8%	0.42
ab	69.13	59.77	138.7	15.7%	0.43
w	59.5	51.57	118.96	15.4%	0.43
n	132.72	117.61	268.42	12.8%	0.44
o	101.12	89.94	204.67	12.4%	0.44
r	125.48	108.71	247.13	15.4%	0.44
m	103.05	91.61	206.41	12.5%	0.44
as	81.61	70.76	156.4	15.3%	0.45
bn	84.69	75.46	162.89	12.2%	0.46
k	42.57	37.49	80.47	13.6%	0.47
br	74.08	64.37	137.65	15.1%	0.47
bh	104.41	90.9	193.59	14.9%	0.47
g	67.31	58.16	122.3	15.7%	0.48
I	45.78	40.88	81.03	12.0%	0.50
q	80.78	68.83	135.13	17.4%	0.51
al	89.21	78.32	152.67	13.9%	0.51
bb	73.68	65.4	125.78	12.7%	0.52
ap	171.7	152.69	291.3	12.5%	0.52
v	137.45	119.67	227.7	14.9%	0.53
bd	31.04	26.39	49.73	17.6%	0.53
bm	72.44	63.32	118.42	14.4%	0.53
bo	78.16	68.79	126.3	13.6%	0.54
co	108.99	95.41	172.2	14.2%	0.55
x	137.25	118.33	213.53	16.0%	0.55
aa	102.75	89.54	161.55	14.8%	0.55
ad	116.29	99.34	179.12	17.1%	0.55
ak	107.41	93.78	168.5	14.5%	0.56
bq	131.63	114.54	200.3	14.9%	0.57
j	148.9	128.68	224.5	15.7%	0.57

bk	110.17	94.79	164.97	16.2%	0.57
ai	164.25	146.62	254.97	12.0%	0.58
c	35.8	31.1	54.06	15.1%	0.58
z	133.37	115.55	199.49	15.4%	0.58
y	47.59	42.67	73.31	11.5%	0.58
ba	115.59	103.37	177.27	11.8%	0.58
bj	104.49	89.27	152	17.0%	0.59
bg	76.47	66.76	113.39	14.5%	0.59
ay	173.34	147.68	249	17.4%	0.59
aq	75.28	64.66	109	16.4%	0.59
cj	109.92	96.42	160.94	14.0%	0.60
ac	95.79	82.38	136.37	16.3%	0.60
s	81.22	70.81	116.82	14.7%	0.61
be	115.83	99.15	163.41	16.8%	0.61
ae	142.53	123.47	203.21	15.4%	0.61
cd	120.57	107.04	174.18	12.6%	0.61
au	120.69	105.06	169.52	14.9%	0.62
cm	116.74	103.37	166.08	12.9%	0.62
aw	113.42	99.79	157.35	13.7%	0.63
ag	164.6	147.35	232.3	11.7%	0.63
ax	149.13	131.43	206.3	13.5%	0.64
cl	133.59	118.94	183.93	12.3%	0.65
bw	115.89	100.83	155.04	14.9%	0.65
an	81.58	70.9	108.85	15.1%	0.65
bx	121.07	105.27	160.93	15.0%	0.65
bs	124.9	109.81	167.7	13.7%	0.65
ch	125.26	109.75	166.84	14.1%	0.66
ce	133.33	117.99	178.51	13.0%	0.66
bt	142.32	123.43	184.49	15.3%	0.67
bu	123.66	107.88	159.79	14.6%	0.68
cg	112.67	98.41	145.43	14.5%	0.68
ci	140.37	122.7	180.27	14.4%	0.68
ck	140.56	122.58	179.95	14.7%	0.68
cs	130.12	114.62	168.25	13.5%	0.68
by	115.56	100.52	147.11	15.0%	0.68
cf	131.07	114.62	165.33	14.4%	0.69
bz	155.4	135.32	194.97	14.8%	0.69
bv	133.62	117.12	166	14.1%	0.71
cr	164.78	146.06	206.83	12.8%	0.71
bc	143.63	124.39	174.5	15.5%	0.71
ar	228.54	199.14	279.3	14.8%	0.71
cn	126.52	111.6	154.41	13.4%	0.72
ct	143.14	125.84	172.33	13.7%	0.73
cp	125.53	110.2	150.14	13.9%	0.73
p	85.35	72.82	98.95	17.2%	0.74
cq	148.41	129.67	173.7	14.5%	0.75

Appendix C: Pre specific gravity data measured for specimen pairing (web specimens)

	Pre specific gravity data for web specimens				
Specimen	Initial weight (g)	Ovendry weight (g)	Immersed cm^3	Moisture content	Specific gravity (od volume and weight)
w69	7.36	6.94	18.08	6.1%	0.38
w68	64.04	60.42	154.48	6.0%	0.39
w67	27.15	25.62	63.95	6.0%	0.40
w12	40.29	35.62	87.05	13.1%	0.41
w10	56.51	49.58	120.26	14.0%	0.41
w41	44.64	39.7	96.12	12.4%	0.41
w63	64.89	61.14	147.05	6.1%	0.42
w35	69.81	60.06	143.55	16.2%	0.42
w65	68.58	64.67	153.97	6.0%	0.42
w62	63.73	60.15	143.15	6.0%	0.42
w52	75.6	66.33	157.59	14.0%	0.42
w66	64.24	60.56	140.8	6.1%	0.43
w13	40.36	35.07	81.2	15.1%	0.43
w21	63.56	53.68	122.23	18.4%	0.44
w2	53.76	46.18	104.68	16.4%	0.44
w30	44.51	38.74	87.75	14.9%	0.44
w4	16	13.45	30.37	19.0%	0.44
w20	44.37	33.99	76.4	30.5%	0.44
w15	9.75	8.33	18.66	17.0%	0.45
w27	37.29	32.2	72.11	15.8%	0.45
w48	101.19	89.73	200.71	12.8%	0.45
w29	42.83	37.54	83.69	14.1%	0.45
w34	117.77	72.9	162.22	61.6%	0.45
w33	74.81	62.58	138.7	19.5%	0.45
w28	20.41	17.5	38.7	16.6%	0.45
w32	63.92	56.8	125.17	12.5%	0.45
w24	113.11	92.08	201.83	22.8%	0.46
w42	41.07	36.45	78.09	12.7%	0.47
w44	108.63	94.79	203.07	14.6%	0.47
w22	88.16	75.7	161.91	16.5%	0.47
w25	96.48	82.89	176.18	16.4%	0.47
w71	63.97	60.26	128.06	6.2%	0.47
w37	39.54	33.85	71.8	16.8%	0.47
w3	44.86	38.88	81.65	15.4%	0.48
w61	66.05	62.24	130.39	6.1%	0.48
w46	38.06	33.17	69.25	14.7%	0.48
w64	66.84	63.03	131.17	6.0%	0.48
w26	67.91	54.16	112.26	25.4%	0.48
w70	72.14	67.99	139.41	6.1%	0.49
w17	84.88	64.85	132.81	30.9%	0.49
w14	43.71	33.61	68.82	30.1%	0.49
w31	65.82	57.08	116.36	15.3%	0.49
w5	84.07	73.17	148.92	14.9%	0.49
w56	123.07	102.38	204.5	20.2%	0.50

w50	111.48	92.23	184.18	20.9%	0.50
w55	130.61	95.09	184.33	37.4%	0.52
w47	85.95	73.24	141.66	17.4%	0.52
w39	43.46	36.83	71.23	18.0%	0.52
w9	50.51	41.81	80.63	20.8%	0.52
w19	86.74	69.99	132.66	23.9%	0.53
w49	54.17	43.29	81.82	25.1%	0.53
w53	69.74	61.37	115.1	13.6%	0.53
w45	51.39	41.5	77.81	23.8%	0.53
w7	63.59	55.63	102.51	14.3%	0.54
w1	98.99	84.38	155.21	17.3%	0.54
w43	161.24	118.64	216.24	35.9%	0.55
w8	69.23	57.15	104.02	21.1%	0.55
w18	55.44	47.43	82.94	16.9%	0.57
w91	100	86.92	147.06	15.0%	0.59
w82	98.99	87.68	147.98	12.9%	0.59
w23	90.76	71.15	119.66	27.6%	0.59
w95	91.74	79.93	129.89	14.8%	0.62
w76	30.1	26.82	42.85	12.2%	0.63
w74	101.55	88.6	139.4	14.6%	0.64
w96	94.74	82.81	129.81	14.4%	0.64
w75	103.06	91.05	142.39	13.2%	0.64
w80	65.28	58.36	89.15	11.9%	0.65
w51	18.61	16.79	25.6	10.8%	0.66
w72	92.87	81.74	123.94	13.6%	0.66
w92	95.06	80.02	121.3	18.8%	0.66
w90	27.34	24.03	36.37	13.8%	0.66
w88	94.83	82.1	124.08	15.5%	0.66
w85	104.22	89.64	134.58	16.3%	0.67
w77	85.12	74.7	112.13	13.9%	0.67
w86	94.64	81.68	122.55	15.9%	0.67
w87	93.99	81.36	121.01	15.5%	0.67
w84	108.15	95.98	141.94	12.7%	0.68
w11	81.52	70.97	103.5	14.9%	0.69
w79	38.6	33.47	47.66	15.3%	0.70
w73	101.78	89.84	126.1	13.3%	0.71
w78	115.72	103.26	143.07	12.1%	0.72
w83	35.08	31.08	42.95	12.9%	0.72

Appendix D: Embedment gap data for LRAA and LREA orientations

Specimen	Maximum embedment gap (inches)	Latewood percent at maximum embedment gap	Specific gravity at maximum embedment gap
LRAA1	0.062	44.0	0.70
LRAA2	0.022	37.3	0.57
LRAA3	0.008	36.0	0.55
LRAA4	0.032	45.3	0.69
LRAA7	0.064	58.7	0.58
LRAA8	0.027	40.7	0.68
LRAA9	0.082	50.0	0.63
LRAA10	0.060	45.3	0.44
LRAA11	0.021	20.7	0.46
LRAA12	0.058	44.7	0.57
LRAA13	0.104	38.0	0.60
LRAA14	0.045	44.7	0.55
LRAA15	0.033	60.0	0.64
LRAA16	0.014	32.0	0.39
LRAA17	0.011	12.0	0.38
LRAA18	0.044	35.3	0.59
LRAA19	0.067	51.3	0.83
LRAA21	0.065	53.3	0.73
LRAA23	0.067	44.7	0.52
LRAA25	0.063	55.3	0.72
LRAA26	0.062	48.7	0.67
LRAA28	0.044	43.3	0.63
LRAA30	0.044	12.7	0.42
LREA1	0.020	36.7	0.55
LREA2	0.047	44.0	0.64
LREA3	0.000	32.0	0.59
LREA5	0.067	62.0	0.74
LREA6	0.000	20.7	0.39
LREA7	0.000	36.7	0.42
LREA8	0.037	43.3	0.63
LREA9	0.000	18.7	0.43
LREA10	0.034	20.0	0.66
LREA11	0.034	32.0	0.54
LREA12	0.022	19.3	0.42
LREA14	0.033	43.3	0.67
LREA15	0.033	43.3	0.69
LREA16	0.024	56.0	0.68
LREA17	0.023	48.0	0.70
LREA18	0.062	34.7	0.55
LREA19	0.072	43.3	0.64
LREA20	0.039	36.0	0.57
LREA21	0.000	10.7	0.42
LREA23	0.024	16.7	0.41

LREA24	0.036	47.3	0.63
LREA25	0.068	48.0	0.70
LREA26	0.053	46.0	0.59
LREA27	0.025	18.7	0.44
LREA28	0.046	54.7	0.69

Appendix E: Tooth withdrawal data for LRAA and LREA orientations

Specimen	Surface of tooth withdrawal	Block 1 specific gravity	Block 2 specific gravity	Specific gravity at site of withdrawal	Specific gravity at site without withdrawal
LRAA1	4	0.72	0.70	0.70	0.72
LRAA2	2	0.57	0.55	0.57	0.55
LRAA3	3	0.50	0.55	0.55	0.50
LRAA4	4	0.70	0.69	0.69	0.70
LRAA7	4	0.60	0.58	0.58	0.60
LRAA8	3	0.66	0.68	0.68	0.66
LRAA9	3	0.57	0.63	0.63	0.57
LRAA10	1	0.44	0.54	0.44	0.54
LRAA11	1	0.46	0.42	0.46	0.42
LRAA12	4	0.55	0.57	0.57	0.55
LRAA13	4	0.59	0.60	0.60	0.59
LRAA14	3	0.61	0.55	0.55	0.61
LRAA15	4	0.71	0.64	0.64	0.71
LRAA16	2	0.39	0.45	0.39	0.45
LRAA17	4	0.41	0.38	0.38	0.41
LRAA18	3	0.53	0.59	0.59	0.53
LRAA19	4	0.80	0.83	0.83	0.80
LRAA21	1	0.73	0.66	0.73	0.66
LRAA23	1	0.52	0.58	0.52	0.58
LRAA25	3	0.66	0.72	0.72	0.66
LRAA26	4	0.65	0.67	0.67	0.65
LRAA28	1	0.63	0.65	0.63	0.65
LRAA30	4	0.44	0.42	0.42	0.44
LREA1	1	0.55	0.63	0.55	0.63
LREA2	4	0.65	0.64	0.64	0.65
LREA3	4	0.59	0.59	0.59	0.59
LREA5	1	0.74	0.74	0.74	0.74
LREA6	4	0.39	0.38	0.38	0.39
LREA7	2	0.43	0.42	0.43	0.42
LREA8	4	0.63	0.56	0.56	0.63
LREA9	4	0.45	0.42	0.42	0.45
LREA10	4	0.66	0.65	0.65	0.66
LREA11	4	0.57	0.54	0.54	0.57
LREA12	2	0.42	0.42	0.42	0.42
LREA14	2	0.70	0.67	0.70	0.67
LREA15	3	0.69	0.61	0.69	0.61
LREA16	2	0.67	0.68	0.67	0.68
LREA18	2	0.55	0.54	0.55	0.54
LREA19	2	0.64	0.62	0.64	0.62
LREA20	1	0.69	0.57	0.57	0.69
LREA21	4	0.45	0.39	0.39	0.45
LREA23	3	0.41	0.39	0.39	0.41
LREA24	1	0.63	0.68	0.63	0.68
LREA25	3	0.71	0.70	0.70	0.71

LREA26	2	0.59	0.60	0.59	0.6
LREA27	3	0.42	0.44	0.44	0.42
LREA28	2	0.65	0.69	0.65	0.69

Appendix F: Block 1 specific gravity and moisture content data for all four orientations.

	At test dimensions (cm)								
Specimen	Width	Height	Length	Volume cm^3	Ovendry volume cm^3	Test weight (g)	Ovendry weight (g)	Specific gravity ovendry weight (g) ovendry volume cm^3	Test moisture content
LRAA1	3.89	4.19	7.62	124.11	114.95	94.01	83.13	0.72	13.1%
LRAA2	3.76	4.29	7.65	123.37	112.24	74.9	64.16	0.57	16.7%
LRAA3	3.81	3.68	7.67	107.64	101.48	58.15	50.69	0.50	14.7%
LRAA4	3.81	3.68	7.67	107.64	97.42	78.47	67.98	0.70	15.4%
LRAA6	3.89	3.68	7.70	110.15	102.93	69.68	61.62	0.60	13.1%
LRAA7	3.89	4.19	7.70	125.35	116.6	78.36	70	0.60	11.9%
LRAA8	3.78	3.43	7.67	99.55	91.73	69.61	60.84	0.66	14.4%
LRAA9	3.89	3.51	7.75	105.53	96.5	62.44	54.84	0.57	13.9%
LRAA10	3.78	4.57	7.67	132.73	125.76	64.22	54.79	0.44	17.2%
LRAA11	3.81	3.18	7.67	92.79	86.2	45.85	39.77	0.46	15.3%
LRAA12	3.73	3.00	7.70	86.13	77.34	50.24	42.65	0.55	17.8%
LRAA13	3.76	3.78	7.67	109.13	100.64	69.15	59.5	0.59	16.2%
LRAA14	3.81	3.68	7.67	107.64	97.86	68.81	59.21	0.61	16.2%
LRAA15	3.81	3.78	7.72	111.34	101.48	81.52	71.6	0.71	13.9%
LRAA16	3.84	3.68	7.67	108.36	101.49	45.35	39.83	0.39	13.9%
LRAA17	3.78	3.58	7.67	103.97	98.29	47.49	40.78	0.41	16.5%
LRAA18	3.86	3.43	7.67	101.55	95.1	57.62	50.43	0.53	14.3%
LRAA19	3.78	3.84	7.65	110.98	100.3	92.03	80.32	0.80	14.6%
LRAA20	3.86	4.22	7.70	125.28	118.08	56.75	49.39	0.42	14.9%
LRAA21	3.76	3.96	7.70	114.64	104.93	87.22	76.36	0.73	14.2%
LRAA22	3.94	3.38	7.67	102.02	94.55	44.41	39.11	0.41	13.6%
LRAA23	3.76	4.04	7.70	116.84	106.53	64.27	55.18	0.52	16.5%
LRAA24	3.78	3.66	7.70	106.54	100.31	48.85	42	0.42	16.3%
LRAA25	3.84	3.76	7.65	110.23	102.85	76.98	68.05	0.66	13.1%
LRAA26	3.84	3.89	7.70	114.71	105.7	79.1	68.61	0.65	15.3%
LRAA27	3.73	4.11	7.67	117.85	110.38	55.73	48.04	0.44	16.0%
LRAA28	3.84	4.37	7.70	128.96	118.8	83.95	74.45	0.63	12.8%
LRAA29	3.84	3.58	7.70	105.72	101.36	46.69	41.04	0.40	13.8%
LRAA30	3.84	3.71	7.67	109.10	104.46	52.33	46.08	0.44	13.6%
LREA1	3.73	4.24	7.72	122.29	113.91	73.89	62.76	0.55	17.7%
LREA2	3.89	4.88	7.70	145.86	134.35	100.92	87.63	0.65	15.2%
LREA3	3.76	9.65	6.63	240.54	165.82	113.29	98.08	0.59	15.5%
LREA5	3.78	4.50	7.70	130.95	120.16	101.14	88.49	0.74	14.3%
LREA6	3.84	4.80	7.72	142.17	135.76	61.09	53.55	0.39	14.1%
LREA7	3.73	4.60	7.72	132.55	124.51	62.96	54.09	0.43	16.4%
LREA8	3.76	4.34	7.70	125.66	115.07	84.37	72.68	0.63	16.1%
LREA9	3.86	4.85	7.70	144.15	135.50	69.91	61.28	0.45	14.1%
LREA10	3.78	4.67	7.72	136.58	127.36	96.53	84.42	0.66	14.3%
LREA11	3.91	4.80	7.65	143.57	135.00	87.84	77.48	0.57	13.4%
LREA12	3.84	4.45	7.67	130.77	124.70	60.87	52.68	0.42	15.5%
LREA14	3.89	4.04	7.72	121.19	109.57	87.65	76.42	0.70	14.7%
LREA15	3.81	4.72	7.70	138.53	126.20	99.65	87.06	0.69	14.5%
LREA16	3.81	4.55	7.59	131.56	121.44	94.99	81.18	0.67	17.0%
LREA17	3.86	4.78	7.62	140.48	131.42	96.93	86.14	0.66	12.5%

LREA18	3.68	4.93	7.62	138.29	127.60	81.30	69.90	0.55	16.3%
LREA19	3.73	3.76	7.65	107.31	96.17	72.58	61.91	0.64	17.2%
LREA20	3.89	4.93	7.67	146.89	134.09	105.84	92.15	0.69	14.9%
LREA21	3.84	4.55	7.65	133.32	128.52	64.21	57.64	0.45	11.4%
LREA23	3.78	4.57	7.59	131.41	123.80	59.49	51.19	0.41	16.2%
LREA24	3.78	4.50	7.65	130.08	117.48	87.56	74.42	0.63	17.7%
LREA25	3.89	4.55	7.67	135.54	125.57	101.02	88.54	0.71	14.1%
LREA26	3.81	4.55	7.65	132.44	123.16	83.18	73.22	0.59	13.6%
LREA27	3.84	4.80	7.65	140.77	135.32	64.20	56.61	0.42	13.4%
LREA28	3.94	4.39	7.62	131.83	121.77	89.27	79.64	0.65	12.1%
LRAE1	3.81	4.95	8.89	167.76	157.21	73.15	63.34	0.40	15.5%
LRAE2	3.84	6.30	8.89	214.78	199.03	142.83	127.83	0.64	11.7%
LRAE4	3.76	5.36	8.86	178.60	167.53	82.17	70.96	0.42	15.8%
LRAE5	3.89	6.22	8.89	214.99	196.04	143.28	123.67	0.63	15.9%
LRAE6	3.81	6.10	8.94	207.66	192.65	94.36	81.87	0.42	15.3%
LRAE7	3.81	5.74	8.86	193.88	178.60	116.24	100.47	0.56	15.7%
LRAE8	3.89	4.93	8.92	170.73	159.61	99.75	86.98	0.54	14.7%
LRAE9	5.82	5.84	8.94	303.81	190.77	86.48	75.65	0.40	14.3%
LRAE10	3.78	4.85	8.92	163.69	156.06	77.98	67.58	0.43	15.4%
LRAE11	3.73	4.95	8.86	163.94	155.23	72.25	61.82	0.40	16.9%
LRAE12	3.78	4.98	8.97	168.93	154.82	78.26	67.56	0.44	15.8%
LRAE13	3.84	4.90	8.79	165.24	152.60	121.28	106.45	0.70	13.9%
LRAE14	3.89	4.90	8.94	170.33	157.71	115.70	101.91	0.65	13.5%
LRAE15	3.81	4.93	8.94	167.86	161.57	69.58	51.75	0.32	34.5%
LRAE16	3.91	4.93	8.97	172.82	160.75	103.28	91.93	0.57	12.3%
LRAE17	3.86	4.95	8.89	170.00	161.29	94.98	84.43	0.52	12.5%
LRAE18	3.89	4.95	8.84	170.14	156.82	120.16	104.36	0.67	15.1%
LRAE19	3.89	5.84	8.92	202.41	190.21	109.78	96.86	0.51	13.3%
LRAE20	3.76	4.95	8.89	165.53	154.33	72.03	62.13	0.40	15.9%
LRAE21	3.84	5.59	8.84	189.44	174.30	108.00	94.21	0.54	14.6%
LRAE22	3.76	4.98	8.76	164.00	149.65	123.42	109.44	0.73	12.8%
LRAE23	3.76	5.18	8.81	171.68	156.90	130.37	115.35	0.74	13.0%
LRAE24	3.91	5.44	8.99	191.18	173.40	126.41	111.73	0.64	13.1%
LRAE25	3.81	4.98	8.86	168.14	153.43	116.43	102.06	0.67	14.1%
LRAE26	3.81	4.95	8.97	169.20	162.90	78.06	69.30	0.43	12.6%
LRAE27	3.81	4.98	8.97	170.07	156.50	94.57	82.61	0.53	14.5%
LRAE28	3.73	4.95	8.76	162.06	147.82	95.73	83.11	0.56	15.2%
LRAE29	3.86	4.98	8.74	167.94	152.94	119.72	104.45	0.68	14.6%
LRAE30	3.76	5.00	8.79	165.31	153.51	120.44	106.09	0.69	13.5%
LREE1	3.73	5.05	8.81	166.34	160.38	74.88	65.83	0.41	13.7%
LREE2	3.78	5.08	8.84	169.94	160.58	78.79	68.54	0.43	15.0%
LREE3	3.81	5.13	8.86	173.29	158.21	135.20	118.45	0.75	14.1%
LREE4	3.76	5.08	8.84	168.80	159.25	77.92	66.99	0.42	16.3%
LREE5	3.84	5.13	8.76	172.44	158.46	124.97	109.34	0.69	14.3%
LREE6	3.78	5.08	8.74	167.99	155.30	129.96	114.97	0.74	13.0%
LREE7	3.78	5.05	8.79	168.12	154.64	88.68	75.58	0.49	17.3%
LREE8	3.76	5.05	8.84	167.96	160.04	75.08	64.54	0.40	16.3%
LREE9	3.81	5.08	8.89	172.06	163.73	74.13	64.64	0.39	14.7%
LREE10	3.73	5.21	8.81	171.36	154.07	133.84	114.08	0.74	17.3%
LREE11	3.81	5.18	8.74	172.50	157.97	123.80	108.00	0.68	14.6%

LREE12	3.84	5.08	8.94	174.20	163.14	98.78	87.02	0.53	13.5%
LREE13	3.86	5.11	8.92	175.73	166.93	82.92	72.96	0.44	13.7%
LREE14	3.84	5.13	8.79	172.94	158.44	124.70	108.50	0.68	14.9%
LREE15	3.71	5.05	8.76	164.26	151.06	97.87	85.38	0.57	14.6%
LREE16	3.84	5.08	8.81	171.73	156.03	103.58	88.49	0.57	17.1%
LREE17	3.73	5.08	8.81	167.18	156.05	77.34	66.07	0.42	17.1%
LREE18	3.86	5.11	8.97	176.73	164.19	102.34	90.08	0.55	13.6%
LREE19	3.84	5.18	8.92	177.18	160.53	104.20	90.67	0.56	14.9%
LREE20	3.81	4.98	8.94	169.59	162.86	73.64	65.53	0.40	12.4%
LREE21	3.76	5.13	8.76	169.02	154.29	109.59	94.42	0.61	16.1%
LREE22	3.84	5.11	8.99	176.07	162.04	132.10	115.77	0.71	14.1%
LREE23	3.84	5.13	8.84	173.94	158.75	121.94	106.55	0.67	14.4%
LREE24	3.78	5.03	8.81	167.76	153.59	106.74	91.63	0.60	16.5%
LREE25	3.73	5.05	8.81	166.34	157.11	66.09	56.59	0.36	16.8%
LREE26	3.78	5.08	8.92	171.41	160.93	78.80	68.50	0.43	15.0%
LREE27	3.86	5.11	8.86	174.73	158.50	128.33	112.09	0.71	14.5%
LREE28	3.86	5.11	8.86	174.73	163.87	122.46	108.85	0.66	12.5%
LREE29	3.94	5.05	8.97	178.43	168.61	97.40	86.82	0.51	12.2%
LREE30	3.84	5.00	8.92	171.10	161.45	83.18	72.23	0.45	15.2%

Appendix G: Block 2 specific gravity and moisture content data for of all four orientations.

	At test dimensions (cm)							Specific gravity	
Specimen	Width	Height	Length	Volume cm^3	Ovendry volume cm^3	Test weight (g)	Ovendry weight (g)	ovendry weight (g) ovendry volume cm^3	Test moisture content
LRAA1	3.81	3.94	7.72	115.82	103.60	83.72	72.95	0.70	14.8%
LRAA2	3.71	3.81	7.70	108.74	100.28	63.19	54.85	0.55	15.2%
LRAA3	3.73	3.43	7.65	97.89	91.07	59.34	50.45	0.55	17.6%
LRAA4	3.91	3.61	7.70	108.58	100.61	78.27	69.22	0.69	13.1%
LRAA6	3.84	3.96	7.72	117.35	110.82	61.29	54.4	0.49	12.7%
LRAA7	3.76	4.45	7.70	128.60	120.67	79.83	70.06	0.58	13.9%
LRAA8	3.81	3.89	7.67	113.58	102.58	80.34	69.73	0.68	15.2%
LRAA9	3.86	3.94	7.77	118.14	104.82	76.07	66.38	0.63	14.6%
LRAA10	3.78	3.61	7.70	105.06	95.78	59.59	51.4	0.54	15.9%
LRAA11	3.78	3.71	7.67	107.53	101.01	47.86	42	0.42	14.0%
LRAA12	3.66	3.58	7.67	100.48	96.42	63.03	54.66	0.57	15.3%
LRAA13	3.73	3.94	7.57	111.27	100.58	70.59	60.55	0.60	16.6%
LRAA14	3.73	3.89	7.70	111.67	103.56	66.12	56.5	0.55	17.0%
LRAA15	3.89	4.29	7.67	127.96	116.60	85.61	75	0.64	14.1%
LRAA16	3.86	3.61	7.65	106.46	101.30	51.47	45.35	0.45	13.5%
LRAA17	3.84	4.19	7.65	122.89	117.32	51.06	44.44	0.38	14.9%
LRAA18	3.78	3.89	7.67	112.82	104.27	71.46	61.23	0.59	16.7%
LRAA19	3.76	3.20	7.65	91.98	81.62	77.19	67.47	0.83	14.4%
LRAA20	----	----	----	----	99.69	51.26	43.72	0.44	17.2%
LRAA21	3.81	3.78	7.67	110.61	103.63	77.2	68.17	0.66	13.2%
LRAA22	3.71	3.86	7.59	108.73	102.65	50.6	43.14	0.42	17.3%
LRAA23	3.76	3.51	7.70	101.41	96.24	63.56	55.45	0.58	14.6%
LRAA24	3.76	3.23	7.70	93.33	86.32	43.64	37.36	0.43	16.8%
LRAA25	3.78	3.84	7.67	111.35	101.51	83.05	73	0.72	13.8%
LRAA26	3.81	3.38	7.70	99.06	89.11	69.06	59.75	0.67	15.6%
LRAA27	3.81	3.51	7.70	102.78	95.33	65.84	57.04	0.60	15.4%
LRAA28	3.84	3.25	7.72	96.29	91.10	66.35	58.82	0.65	12.8%
LRAA29	3.76	3.63	7.65	104.39	101.96	45.24	39.66	0.39	14.1%
LRAA30	3.84	3.76	7.67	110.60	106.32	50.5	44.72	0.42	12.9%
LREA1	3.89	4.34	7.70	129.91	122.00	86.25	76.69	0.63	12.5%
LREA2	3.78	4.39	7.72	128.41	117.58	87.31	75.73	0.64	15.3%
LREA3	3.84	4.47	7.75	132.83	122.05	82.72	71.8	0.59	15.2%
LREA5	3.94	4.98	7.72	151.34	137.70	117.24	101.38	0.74	15.6%
LREA6	3.86	5.13	7.72	152.96	145.24	62.97	54.98	0.38	14.5%
LREA7	3.51	4.78	7.72	129.24	133.03	64.95	55.28	0.42	17.5%
LREA8	3.78	4.78	7.72	139.55	128.58	83.4	72.51	0.56	15.0%
LREA9	3.76	4.50	7.70	130.07	121.48	58.8	50.52	0.42	16.4%
LREA10	3.94	3.89	7.70	117.75	107.20	79.41	70.1	0.65	13.3%
LREA11	3.84	5.59	7.65	163.86	151.91	92.44	81.78	0.54	13.0%
LREA12	3.73	4.42	7.65	126.16	118.12	57.97	49.69	0.42	16.7%
LREA14	3.86	4.83	7.70	143.40	130.27	101.22	87.49	0.67	15.7%
LREA15	3.94	4.62	7.72	140.53	121.12	83.44	74.39	0.61	12.2%
LREA16	3.40	4.80	7.65	124.92	130.52	100.5	88.51	0.68	13.5%
LREA17	3.91	5.31	7.67	159.29	147.79	118.61	104.17	0.70	13.9%

LREA18	3.78	3.91	7.62	112.81	104.18	65.64	56.21	0.54	16.8%
LREA19	3.91	4.98	7.70	149.87	139.29	97.01	86.55	0.62	12.1%
LREA20	3.81	4.93	7.65	143.54	135.08	88.36	77.08	0.57	14.6%
LREA21	3.81	5.18	7.65	150.93	143.47	65.91	56.58	0.39	16.5%
LREA23	3.84	3.58	7.70	105.72	100.65	45.09	39.44	0.39	14.3%
LREA24	3.78	4.83	7.62	139.18	132.20	101.65	89.82	0.68	13.2%
LREA25	3.89	4.75	7.67	141.59	126.81	101.89	88.65	0.70	14.9%
LREA26	3.61	4.65	7.67	128.60	133.64	89	79.63	0.60	11.8%
LREA27	3.68	4.95	7.65	139.47	134.82	67.79	59.04	0.44	14.8%
LREA28	3.86	3.84	7.65	113.21	102.51	81.1	70.32	0.69	15.3%
LRAE1	3.81	4.93	8.89	166.90	157.01	73.44	63.59	0.41	15.5%
LRAE2	3.78	5.36	8.86	179.80	169.49	121.09	108.09	0.64	12.0%
LRAE4	3.76	4.98	8.84	165.42	155.82	76.32	65.77	0.42	16.0%
LRAE5	3.86	5.31	8.89	182.20	166.45	115.51	99.64	0.60	15.9%
LRAE6	3.84	5.33	8.94	182.91	168.88	83.11	72.18	0.43	15.1%
LRAE7	3.78	5.36	8.86	179.80	166.67	110.22	95.29	0.57	15.7%
LRAE8	3.91	4.95	8.89	172.24	159.58	98.78	85.9	0.54	15.0%
LRAE9	3.86	5.31	8.94	183.25	172.92	79.18	69.35	0.40	14.2%
LRAE10	3.78	4.93	8.92	166.26	157.67	76.36	66.15	0.42	15.4%
LRAE11	3.76	4.90	8.92	164.30	154.75	71.71	61.32	0.40	16.9%
LRAE12	3.86	4.93	8.89	169.13	155.42	79.15	68.23	0.44	16.0%
LRAE13	3.81	4.95	8.79	165.85	153.89	121.18	106.38	0.69	13.9%
LRAE14	3.91	4.98	8.94	174.11	160.70	124.86	109.96	0.68	13.6%
LRAE15	3.86	4.95	8.94	170.97	163.75	69.4	61.79	0.38	12.3%
LRAE16	3.91	4.98	8.97	174.60	162.52	104.84	93.27	0.57	12.4%
LRAE17	3.84	4.98	8.86	169.26	161.78	97.06	86.06	0.53	12.8%
LRAE18	3.84	4.93	8.84	167.05	153.22	119.38	105.04	0.69	13.7%
LRAE19	3.89	5.31	8.92	183.93	175.51	100.58	89.3	0.51	12.6%
LRAE20	3.76	5.61	8.89	187.60	175.67	82.39	71.07	0.40	15.9%
LRAE21	3.78	5.64	8.86	189.18	174.05	107.84	93.96	0.54	14.8%
LRAE22	3.81	5.36	8.76	178.93	165.71	135.04	120.37	0.73	12.2%
LRAE23	3.78	5.61	8.79	186.70	172.47	144	128.88	0.75	11.7%
LRAE24	3.86	5.64	8.97	195.20	180.63	130.54	115.1	0.64	13.4%
LRAE25	3.84	4.98	8.84	168.78	156.06	120.79	106.15	0.68	13.8%
LRAE26	3.86	4.93	8.99	171.06	161.99	79.55	70.65	0.44	12.6%
LRAE27	3.76	4.98	8.94	167.33	155.33	93.19	81.46	0.52	14.4%
LRAE28	3.78	4.93	8.86	165.32	150.58	97.95	85.24	0.57	14.9%
LRAE29	3.86	4.95	8.74	167.09	153.01	119.51	104.27	0.68	14.6%
LRAE30	3.78	5.00	8.76	165.95	153.95	119.83	105.7	0.69	13.4%
LREE1	3.76	5.08	8.84	168.80	161.48	70.5	61.61	0.38	14.4%
LREE2	3.81	5.08	8.84	171.08	161.28	79.56	69.47	0.43	14.5%
LREE3	3.78	5.16	8.86	172.99	158.79	134.29	117.62	0.74	14.2%
LREE4	3.78	5.08	8.86	170.43	159.96	78.33	67.29	0.42	16.4%
LREE5	3.81	5.13	8.76	171.30	156.93	124.6	109.13	0.70	14.2%
LREE6	3.76	5.13	8.74	168.53	157.21	131.31	116.25	0.74	13.0%
LREE7	3.76	5.03	8.79	166.15	152.40	90.07	76.53	0.50	17.7%
LREE8	3.78	5.03	8.81	167.76	160.20	74.34	63.93	0.40	16.3%
LREE9	3.81	5.00	8.92	169.97	163.78	72.22	63.38	0.39	13.9%
LREE10	3.76	5.13	8.81	170.00	152.90	134.43	114.52	0.75	17.4%
LREE11	3.78	5.05	8.74	167.15	153.44	120.42	105.1	0.68	14.6%

LREE12	3.78	5.05	8.89	170.06	160.24	98.57	56.65	0.35	74.0%
LREE13	3.86	5.11	8.92	175.73	167.38	80.72	71.28	0.43	13.2%
LREE14	3.86	5.16	8.79	174.95	159.66	126.18	109.99	0.69	14.7%
LREE15	3.73	5.13	8.76	167.88	153.62	99.79	85.38	0.56	16.9%
LREE16	3.84	5.08	8.79	171.23	157.03	103.04	88.12	0.56	16.9%
LREE17	3.73	5.08	8.79	166.70	156.99	77.57	66.2	0.42	17.2%
LREE18	3.84	5.08	8.94	174.20	160.85	102.87	89.92	0.56	14.4%
LREE19	3.84	5.03	8.94	172.46	159.38	104.47	91.07	0.57	14.7%
LREE20	3.84	5.00	8.94	171.59	162.71	74.24	66.17	0.41	12.2%
LREE21	3.76	5.03	8.79	166.15	153.59	108.71	93.67	0.61	16.1%
LREE22	3.84	5.08	8.99	175.19	160.53	131.72	115.27	0.72	14.3%
LREE23	3.84	5.08	8.84	172.22	159.00	121.43	106.33	0.67	14.2%
LREE24	3.81	5.08	8.81	170.59	155.26	107.11	92.01	0.59	16.4%
LREE25	3.76	5.03	8.81	166.63	157.60	66.52	56.88	0.36	16.9%
LREE26	3.78	4.78	8.92	161.12	160.00	78.88	68.69	0.43	14.8%
LREE27	3.84	5.11	8.81	172.59	158.73	127.86	111.59	0.70	14.6%
LREE28	3.84	5.13	8.89	174.94	163.94	121.84	109.25	0.67	11.5%
LREE29	3.94	5.00	8.94	176.13	166.63	93.8	82.98	0.50	13.0%
LREE30	3.86	5.08	8.92	174.86	163.30	84.08	72.98	0.45	15.2%

Appendix H: Ultimate load and allowable lateral resistance design value calculations

Specimen	Load at 0.03 inch slip	Load (psi) at 0.03 inch slip	Critical slip stress divided by 1.6 safety factor	Ultimate Load (pounds)	Ultimate Load (psi)	Ultimate load (psi) divided by 3.2 safety factor	Slip (inches) at ultimate load
LRAA1	7265.6	605.5	378.4	7900.4	658.4	205.7	0.048
LRAA2	6982.4	581.9	363.7	8115.2	676.3	211.3	0.071
LRAA3	6464.8	538.7	336.7	7675.8	639.7	199.9	0.065
LRAA4	7685.5	640.5	400.3	8388.7	699.1	218.5	0.064
LRAA6	6269.5	522.5	326.5	7246.1	603.8	188.7	0.054
LRAA7	6474.6	539.6	337.2	7099.6	591.6	184.9	0.043
LRAA8	7519.5	626.6	391.6	8554.7	712.9	222.8	0.063
LRAA9	5859.4	488.3	305.2	6240.2	520.0	162.5	0.040
LRAA10	5439.5	453.3	283.3	6230.5	519.2	162.3	0.051
LRAA11	5312.5	442.7	276.7	6757.8	563.2	176.0	0.071
LRAA12	6064.5	505.4	315.9	7646.5	637.2	199.1	0.075
LRAA13	5791.0	482.6	301.6	6435.5	536.3	167.6	0.054
LRAA14	6650.4	554.2	346.4	7578.1	631.5	197.3	0.054
LRAA15	7119.1	593.3	370.8	8037.1	669.8	209.3	0.060
LRAA16	5273.4	439.5	274.7	6523.4	543.6	169.9	0.065
LRAA17	4765.6	397.1	248.2	4804.7	400.4	125.1	0.033
LRAA18	6835.9	569.7	356.0	7597.7	633.1	197.9	0.055
LRAA19	7002.0	583.5	364.7	7959	663.3	207.3	0.055
LRAA20	5937.5	494.8	309.2	7353.5	612.8	191.5	0.081
LRAA21	7734.4	644.5	402.8	8554.7	712.9	222.8	0.061
LRAA22	5517.6	459.8	287.4	6201.2	516.8	161.5	0.050
LRAA23	5859.4	488.3	305.2	6875	572.9	179.0	0.058
LRAA24	5585.9	465.5	290.9	6572.3	547.7	171.2	0.063
LRAA25	7265.6	605.5	378.4	8183.6	682.0	213.1	0.070
LRAA26	6748.0	562.3	351.5	7558.6	629.9	196.8	0.051
LRAA27	6044.9	503.7	314.8	6543	545.3	170.4	0.047
LRAA28	6679.7	556.6	347.9	7187.5	599.0	187.2	0.043
LRAA29	5429.7	452.5	282.8	6044.9	503.7	157.4	0.047
LRAA30	5263.7	438.6	274.2	5820.3	485.0	151.6	0.044
LREA1	5605.5	467.1	292.0	5761.7	480.1	150.0	0.038
LREA2	5898.4	491.5	307.2	6103.5	508.6	158.9	0.043
LREA3	5888.7	490.7	306.7	6054.7	504.6	157.7	0.041
LREA5	6181.6	515.1	322.0	6396.5	533.0	166.6	0.048
LREA6	4785.2	398.8	249.2	5087.9	424.0	132.5	0.042
LREA7	4873.0	406.1	253.8	5449.2	454.1	141.9	0.062
LREA8	5468.8	455.7	284.8	6093.8	507.8	158.7	0.061
LREA9	5000.0	416.7	260.4	5419.9	451.7	141.1	0.047
LREA10	4912.1	409.3	255.8	4970.7	414.2	129.4	0.027
LREA11	5585.9	465.5	290.9	6044.9	503.7	157.4	0.049
LREA12	4628.9	385.7	241.1	4970.7	414.2	129.4	0.047
LREA14	5918.0	493.2	308.2	6250	520.8	162.8	0.050
LREA15	5918.0	493.2	308.2	6171.9	514.3	160.7	0.045
LREA16	6240.2	520.0	325.0	6328.1	527.3	164.8	0.041

LREA18	5507.8	459.0	286.9	6074.2	506.2	158.2	0.062
LREA19	5849.6	487.5	304.7	6015.6	501.3	156.7	0.043
LREA20	5908.2	492.4	307.7	6123	510.3	159.5	0.042
LREA21	5117.2	426.4	266.5	5459	454.9	142.2	0.044
LREA23	4755.9	396.3	247.7	5097.7	424.8	132.8	0.049
LREA24	5498.0	458.2	286.4	5712.9	476.1	148.8	0.039
LREA25	5742.2	478.5	299.1	5957	496.4	155.1	0.043
LREA26	5556.6	463.1	289.4	6035.2	502.9	157.2	0.055
LREA27	5117.2	426.4	266.5	5537.1	461.4	144.2	0.050
LREA28	5517.6	459.8	287.4	5615.2	467.9	146.2	0.033

LRAE1	695.8	347.9	217.4	712.9	356.5	111.4	0.040
LRAE2	927.7	463.9	289.9	986.3	493.2	154.1	0.044
LRAE4	761.7	380.9	238.0	781.3	390.7	122.1	0.045
LRAE5	1149.9	575.0	359.3	1320.8	660.4	206.4	0.051
LRAE6	712.9	356.5	222.8	730	365.0	114.1	0.036
LRAE7	832.5	416.3	260.2	878.9	439.5	137.3	0.054
LRAE8	1005.9	503.0	314.3	1044.9	522.5	163.3	0.034
LRAE9	712.9	356.5	222.8	742.2	371.1	116.0	0.040
LRAE10	634.8	317.4	198.4	634.8	317.4	99.2	0.022
LRAE11	659.2	329.6	206.0	668.9	334.5	104.5	0.034
LRAE12	693.4	346.7	216.7	700.7	350.4	109.5	0.047
LRAE13	900.9	450.5	281.5	913.1	456.6	142.7	0.028
LRAE14	1125.5	562.8	351.7	1171.9	586.0	183.1	0.044
LRAE15	603.0	301.5	188.4	625	312.5	97.7	0.035
LRAE16	795.9	398.0	248.7	815.4	407.7	127.4	0.036
LRAE17	886.2	443.1	276.9	910.6	455.3	142.3	0.038
LRAE18	881.3	440.7	275.4	881.3	440.7	137.7	0.029
LRAE19	700.7	350.4	219.0	734.9	367.5	114.8	0.048
LRAE20	690.9	345.5	215.9	695.8	347.9	108.7	0.033
LRAE21	869.1	434.6	271.6	881.3	440.7	137.7	0.034
LRAE22	830.1	415.1	259.4	842.3	421.2	131.6	0.033
LRAE23	839.8	419.9	262.4	878.9	439.5	137.3	0.047
LRAE24	896.0	448.0	280.0	910.6	455.3	142.3	0.029
LRAE25	896.0	448.0	280.0	915.5	457.8	143.0	0.036
LRAE26	776.4	388.2	242.6	783.7	391.9	122.5	0.033
LRAE27	844.7	422.4	264.0	849.6	424.8	132.8	0.028
LRAE28	754.4	377.2	235.8	771.5	385.8	120.5	0.034
LRAE29	947.3	473.7	296.0	966.8	483.4	151.1	0.035
LRAE30	722.7	361.4	225.8	752	376.0	117.5	0.045

LREE1	783.7	391.9	244.9	788.6	394.3	123.2	0.033
LREE2	737.3	368.7	230.4	754.4	377.2	117.9	0.028
LREE3	1267.1	633.6	396.0	1281.7	640.9	200.3	0.029
LREE4	788.6	394.3	246.4	795.9	398.0	124.4	0.027
LREE5	930.2	465.1	290.7	959.5	479.8	149.9	0.023
LREE6	----	----	----	969.1	484.6	151.4	----
LREE7	791.0	395.5	247.2	800.8	400.4	125.1	0.026
LREE8	730.0	365.0	228.1	732.4	366.2	114.4	0.027
LREE9	651.9	326.0	203.7	661.6	330.8	103.4	0.029
LREE10	1357.4	678.7	424.2	1396.5	698.3	218.2	0.039
LREE11	1120.6	560.3	350.2	1132.8	566.4	177.0	0.027

LREE12	1186.5	593.3	370.8	1274.4	637.2	199.1	0.041
LREE13	852.1	426.1	266.3	856.9	428.5	133.9	0.027
LREE14	1306.2	653.1	408.2	1335.4	667.7	208.7	0.038
LREE15	979.0	489.5	305.9	986.3	493.2	154.1	0.033
LREE16	1106.0	553.0	345.6	1132.8	566.4	177.0	0.037
LREE17	556.6	278.3	173.9	573.7	286.9	89.6	0.025
LREE18	915.5	457.8	286.1	927.7	463.9	145.0	0.027
LREE19	1118.2	559.1	349.4	1127.9	564.0	176.2	0.032
LREE20	656.7	328.4	205.2	661.6	330.8	103.4	0.024
LREE21	1250.0	625.0	390.6	1281.7	640.9	200.3	0.039
LREE22	1435.5	717.8	448.6	1452.6	726.3	227.0	0.034
LREE23	----	----	----	1136.0	568.0	177.5	----
LREE24	1042.5	521.3	325.8	1052.2	526.1	164.4	0.033
LREE25	605.5	302.8	189.2	607.9	304.0	95.0	0.035
LREE26	720.2	360.1	225.1	720.2	360.1	112.5	0.021
LREE27	1174.3	587.2	367.0	1181.6	590.8	184.6	0.029
LREE28	908.2	454.1	283.8	930.2	465.1	145.3	0.021
LREE29	1086.4	543.2	339.5	1098.6	549.3	171.7	0.032
LREE30	835.0	417.5	260.9	847.2	423.6	132.4	0.028

Appendix I: Weight data for laboratory scale

PB3002 Weight Scale		
Instron Calibration Weights		
10 grams	50 grams	60 grams
10.01	50	59.99
9.99	49.98	59.98
10	49.98	59.99
10	49.98	59.99
10	49.98	59.99
10	49.98	59.99
10	49.98	59.99
10	49.98	59.99
10	49.98	59.98
10	49.99	59.99
10	49.98	59.99
10	49.98	59.98
10	49.99	59.99
10	49.99	59.99
10	49.99	59.98
10	49.99	59.99
10	49.99	59.98
10	49.98	59.99
10	49.98	59.98
10	49.99	59.99
10	49.99	59.99
10	49.98	59.99
10	49.99	59.98
10	49.99	59.99
10	49.99	59.98
10	49.99	59.98
10	49.99	59.98
10	49.99	59.98
10	49.99	59.99
10.01	49.99	59.99

Appendix J : Linear variable differential transducer calibration data

	LVDT Serial 3031					LVDT Serial 2959			
Displacement (inches)	First calibration (volts)	Second calibration (volts)	Third calibration (volts)	Fourth calibration (volts)	Displacement (inches)	First calibration (volts)	Second calibration (volts)	Third calibration (volts)	Fourth calibration (volts)
0.2	3.259	3.301	3.282	3.281	0.2	3.1045	3.0453	3.0579	3.0297
0.175	2.8913	2.8913	2.878	2.8749	0.175	2.7109	2.671	2.6827	2.6563
0.15	2.4486	2.4781	2.4676	2.4659	0.15	2.3167	2.2935	2.3025	2.281
0.125	2.0407	2.0637	2.0547	2.0551	0.125	1.9249	1.9144	1.9199	1.9017
0.1	1.6307	1.6504	1.6427	1.6436	0.1	1.5367	1.53	1.5364	1.5213
0.075	1.2222	1.24	1.2305	1.2313	0.075	1.1524	1.148	1.1519	1.1403
0.05	0.8132	0.8271	0.8195	0.8201	0.05	0.7667	0.7647	0.7686	0.7593
0.025	0.4059	0.4128	0.4087	0.4102	0.025	0.3825	0.3816	0.3846	0.3843
0	0.0003	0.0003	0.0002	0.0002	0	0.0003	0.0002	0.0002	0.0003
-0.025	-0.4058	-0.4018	-0.4096	-0.4004	-0.025	-0.385	-0.3769	-0.3862	-0.3782
-0.05	-0.8124	-0.8162	-0.8219	-0.8098	-0.05	-0.7683	-0.7622	-0.773	-0.7643
-0.075	-1.2167	-1.2333	-1.2268	-1.2167	-0.075	-1.1515	-1.1485	-1.1617	-1.1531
-0.1	-1.6212	-1.6502	-1.6346	-1.6246	-0.1	-1.5336	-1.5356	-1.5473	-1.5381
-0.125	-2.0308	-2.067	-2.0485	-2.0368	-0.125	-1.917	-1.9233	-1.937	-1.927
-0.15	-2.4423	-2.4819	-2.4694	-2.4512	-0.15	-2.2967	-2.3163	-2.331	-2.3206
-0.175	-2.8529	-2.8945	-2.8829	-2.8643	-0.175	-2.673	-2.7098	-2.7262	-2.7138
-0.2	-3.26	-3.304	-3.288	-3.276	-0.2	-3.0484	-3.1033	-3.1218	-3.1109

Appendix K: Mechanical test system data for calibration

Load Head (pounds)	Ring units
1014	39
2004	77
3000	115
4011	152
5001	188
6004	224
7009	261
8008	297
9016	335
10006	373
9093	335
8000	298
7003	259
5998	222
4999	186
3999	150
3076	114
2013	72
995	37

Appendix L: Conditioning chamber block data for calibration

Day	Block 1 weight (g)	Block 2 weight (g)	Block 3 weight (g)	Block 4 weight (g)	Block 5 weight (g)	Block 6 weight (g)	Block 7 weight (g)
1	31.05	17.82	14.66	21.55	85.1	109.08	184.56
2	34.13	19.76	16.46	24.08	67.89	93.42	166.41
4	35.09	20.2	16.64	24.54	62.17	79.67	147.67
7	35.18	20.21	16.65	24.49	61.49	79.44	143.09
12	35.3	20.27	16.67	24.57	61.45	79.3	140.94
14	35.31	20.28	16.68	24.58	61.4	79.23	140.51
16	35.27	20.28	16.66	24.55	61.3	79.22	140.2
26	35.29	20.25	16.64	24.55	61.24	79.19	140.22
29	35.34	20.28	16.67	24.58	61.17	79.01	139.54
31	35.3	20.29	16.67	24.58	61.23	78.98	139.47
45	35.35	20.29	16.68	24.59	61.24	79.07	139.64
75	35.36	20.28	16.68	24.57	61.17	79.03	139.53
82	35.36	20.25	16.64	24.59	61.19	78.98	139.5
87	35.31	20.27	16.66	24.55	61.07	78.86	139.25
89	35.33	20.27	16.67	24.57	61.11	78.91	139.33
92	35.32	20.26	16.67	24.55	61.08	78.89	139.29
94	35.3	20.26	16.66	24.54	61.07	78.87	139.29
96	35.33	20.27	16.66	24.56	61.07	78.91	139.31

Appendix M: Reorganization of latewood data for randomized complete block design

		Pre-organized data				Reorganized data			
Specimen	Withdrawal	Surface 1	Surface 2	Surface 2	Surface 4	Tooth withdrawal surface	Vertical surface	Opposite surface	Opposite surface
LRAA1	4	42.7%	53.3%	44.0%	41.3%	41.3%	44.0%	53.3%	42.7%
LRAA2	2	43.3%	37.3%	33.3%	27.3%	37.3%	43.3%	27.3%	33.3%
LRAA3	3	29.3%	36.0%	37.3%	42.0%	37.3%	42.0%	29.3%	36.0%
LRAA4	4	49.3%	45.3%	42.7%	42.0%	42.0%	42.7%	45.3%	49.3%
LRAA7	4	32.7%	44.7%	48.7%	58.7%	58.7%	48.7%	44.7%	32.7%
LRAA8	3	20.7%	47.3%	40.7%	36.0%	40.7%	36.0%	20.7%	47.3%
LRAA9	3	39.3%	32.7%	50.0%	34.0%	50.0%	34.0%	39.3%	32.7%
LRAA10	1	27.3%	17.3%	45.3%	40.0%	27.3%	17.3%	45.3%	40.0%
LRAA11	1	22.0%	20.7%	20.0%	18.7%	22.0%	20.7%	20.0%	18.7%
LRAA12	4	43.3%	44.7%	48.0%	31.3%	31.3%	48.0%	44.7%	43.3%
LRAA13	4	34.0%	44.7%	44.7%	38.0%	38.0%	44.7%	44.7%	34.0%
LRAA14	3	49.3%	41.3%	38.0%	44.7%	38.0%	44.7%	49.3%	41.3%
LRAA15	4	47.3%	60.0%	41.3%	46.0%	46.0%	41.3%	60.0%	47.3%
LRAA16	2	32.0%	26.0%	17.3%	34.7%	26.0%	32.0%	34.7%	17.3%
LRAA17	4	18.7%	12.0%	10.0%	11.3%	11.3%	10.0%	12.0%	18.7%
LRAA18	3	19.3%	30.7%	34.0%	35.3%	34.0%	35.3%	19.3%	30.7%
LRAA19	4	50.0%	49.3%	58.7%	51.3%	51.3%	58.7%	49.3%	50.0%
LRAA21	1	53.3%	54.7%	44.7%	51.3%	53.3%	54.7%	44.7%	51.3%
LRAA23	1	26.0%	44.7%	44.7%	26.0%	26.0%	44.7%	44.7%	26.0%
LRAA25	3	56.7%	40.0%	55.3%	38.7%	55.3%	38.7%	56.7%	40.0%
LRAA26	4	48.7%	43.3%	48.0%	48.7%	48.7%	48.0%	43.3%	48.7%
LRAA28	1	43.3%	37.3%	45.3%	53.3%	43.3%	37.3%	45.3%	53.3%
LRAA30	4	15.3%	18.7%	11.3%	12.7%	12.7%	11.3%	18.7%	15.3%
LREA1	1	36.7%	40.0%	32.7%	34.0%	36.7%	40.0%	32.7%	34.0%
LREA2	4	44.7%	40.0%	44.0%	32.0%	32.0%	44.0%	40.0%	44.7%
LREA6	4	10.0%	14.7%	19.3%	20.7%	20.7%	19.3%	14.7%	10.0%
LREA7	2	28.7%	36.7%	20.7%	8.0%	36.7%	28.7%	8.0%	20.7%
LREA8	4	43.3%	48.7%	45.3%	34.0%	34.0%	45.3%	48.7%	43.3%
LREA9	4	16.0%	21.3%	18.7%	18.7%	18.7%	18.7%	21.3%	16.0%
LREA10	4	44.0%	20.0%	38.7%	50.0%	50.0%	38.7%	20.0%	44.0%
LREA11	4	31.3%	36.7%	32.0%	38.0%	38.0%	32.0%	36.7%	31.3%
LREA12	2	15.3%	24.0%	19.3%	22.0%	24.0%	15.3%	22.0%	19.3%
LREA14	2	39.3%	51.3%	43.3%	57.3%	51.3%	39.3%	57.3%	43.3%
LREA16	2	41.3%	39.3%	56.0%	44.0%	39.3%	41.3%	44.0%	56.0%
LREA18	2	34.7%	34.7%	38.7%	26.0%	34.7%	34.7%	26.0%	38.7%
LREA19	2	43.3%	42.7%	34.0%	51.3%	42.7%	43.3%	51.3%	34.0%
LREA21	4	22.7%	20.0%	8.7%	10.7%	10.7%	8.7%	20.0%	22.7%
LREA23	3	16.7%	27.3%	12.0%	14.7%	12.0%	14.7%	16.7%	27.3%
LREA24	1	47.3%	46.7%	36.7%	28.0%	47.3%	46.7%	36.7%	28.0%
LREA25	3	56.7%	58.0%	46.0%	48.0%	46.0%	48.0%	56.7%	58.0%
LREA26	2	46.0%	42.0%	34.7%	40.7%	42.0%	46.0%	40.7%	34.7%
LREA27	3	18.0%	28.7%	18.7%	20.7%	18.7%	20.7%	18.0%	28.7%
LREA28	2	34.0%	34.0%	44.7%	54.7%	34.0%	34.0%	54.7%	44.7%

Vita

Brian Kipling Via was born in Roanoke, Virginia on January 9th, 1972. He grew up in Collinsville and Ridgeway, Virginia where he graduated from Magna Vista High School in June of 1990.

College study was begun at Patrick Henry Community College where an Associates in Arts and Sciences degree was completed by 1993. The author then got his Bachelor of Science in Forest Products Marketing from Virginia Polytechnic Institute and State University in May of 1996. Upon completion of this research in May of 1998, the author received a Master of Science in Forest Products.