Comparison of Shear Modulus Test Methods

S. Kate Harrison

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

Master of Science
In
Wood Science and Forest Products

Dr. Daniel P. Hindman
Dr. Joseph R. Loferski
Dr. Surot Thangjitham

March 31, 2006
Blacksburg, Va.

Keywords:

Shear modulus
Test methods
Machine-stress-rated lumber
Laminated veneer lumber

Comparison of Shear Modulus Test Methods

S. Kate Harrison

ABSTRACT

This research compared the results of three tests: ASTM D 198 torsion, ASTM D 198 three-point bending and the five-point bending test (FPBT) using machine-stress-rated (MSR) lumber and laminated veneer lumber (LVL) to determine if the shear properties evaluated by the different test methods were equivalent. Measured *E:G* ratios were also compared to the *E:G* ratio of 16:1 commonly assumed for structural wooden members.

The average shear moduli results showed significant differences between the three test methods. For both material types, the shear moduli results determined from the two standard test methods (ASTM D 198 three-point bending and torsion), both of which are presently assumed to be equivalent, were significantly different.

Most average *E:G* ratios from the two material types and three test methods showed differences from the *E:G* ratio of 16:1 commonly assumed for structural wooden members. The average moduli of elasticity results for both material types were not significantly different. Therefore, the lack of significant difference between moduli of elasticity terms indicates that differences between *E:G* ratios are due to the shear modulus terms.

This research has shown differences in shear moduli results of the three test types (ASTM D 198 torsion, ASTM D 198 three-point bending, and the FPBT). Differences in the average *E:G* ratios per material and test type were also observed.

Acknowledgements

I would like to acknowledge the Wood-Based Composites Center and Georgia-Pacific Resins, Inc. for their financial support of this project. I would also like to thank Rigidply Rafters, Inc. for their lumber donation and Virginia Frame Builders and Supply, Inc. for use of their facility to temporarily store this material. I would also like to express appreciation to Timber Truss Housing Systems, Inc., for supplying discounted laminated veneer lumber.

My committee chairman, Dr. Daniel Hindman provided invaluable guidance and encouragement throughout his project. His counsel, and that of my committee members, Dr. Joseph Loferski and Dr. Surot Thangjitham, was instrumental to the success of this project. The technical expertise of the Wood Engineering Lab’s manager, Rick Caudill, also played an essential role in this project. Rick, Kenny Albert, and David Jones also assisted in the fabrication and testing phases of this project. I am grateful of not only their labor, but also their friendship and support throughout this project.

Most importantly, I want to thank my father and mother, Gary and Kay Harrison, and brother, Andy Harrison, for their patience, love, and support. I would not be where I am today without your words of encouragement.

Table of Contents

List of Figures

List of Tables

List of Equations

Chapter 1 Introduction

1.1 Justification

Structural composite lumber (SCL) is a type of engineered wood product designed to replace solid-sawn structural lumber. This family of engineered wood products includes laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL). The use of SCL in light frame construction has increased substantially in recent years. These building materials not only possess the advantage of being manufactured from small-diameter timber, but also have enhanced strength and stiffness properties in comparison to their solid-sawn counterparts.

In order to obtain reliable assessments of the material properties of SCL, the methods used in determining their values must be examined. Many different test methods for evaluating the elastic properties of solid-sawn wood and engineered wood products have been explored in the past. Elastic constants determined using the different test methods are generally considered to be equivalent. However, different test setups may contain inherent test bias. Though test bias is assumed to be small, limited research has been conducted to verify this assumption**.**

Presently, the testing methods used to evaluate the material properties of structural sized engineered wood composites are identical to those used for solid-sawn wood. Though SCL products are evaluated according to their own standard, ASTM D 5456, Standard Specification for Evaluation of Structural Composite Lumber Products (2003f), the test methods listed in this standard largely reference those listed in ASTM D 198, Standard Test Methods of Static Tests of Lumber in Structural Sizes (2003a). Of particular interest are the test methods used to determine the shear moduli of both solid wood and wood-based composites. However, no specific guidelines for evaluating this material property are mentioned in ASTM D 5456 (2003f).

Lack of a standardized method to evaluate the shear moduli of SCL has resulted in a deficient understanding of this material property. Differences between the test methods used by various researchers have also produced values that are not easily compared. In particular, the present shear moduli data for SCL have proven inadequate in the design equations for lateral torsional stability and torsional rigidity (Hindman 2003).

A better understanding of the shear moduli of SCL would improve the predictive power of such design equations while also allowing for the use of these products in more demanding structural applications. This expanded knowledge may also assist in the development of new wood-based composites with enhanced performance characteristics.

A comprehensive study of some of the tests used for shear moduli determination, including a quantitative and statistical comparison of the shear moduli values obtained by the various methods, would be beneficial to both the design community and the wood-based composites industry. Therefore, the main goal of this research is to evaluate the shear moduli of SCL and solid-sawn lumber using consistent test methods. Shear moduli values determined by the different test methods will be compared to determine if differences exist. The specific objectives of this research are:

1) To measure the shear moduli of solid sawn lumber and laminated veneer lumber according to: ASTM D 198 (2003a) three-point bending, ASTM D 198 (2003a) torsion, and the five-point bending test (FPBT). Differences among the results of the different test methods will be determined using statistical measures.
2) To measure the moduli of elasticity of solid sawn lumber and laminated veneer lumber according to: ASTM D 198 (2003a) three-point bending and the five-point bending test (FPBT). Differences among the results of the different test methods will be determined using statistical measures.
3) To determine and quantitatively compare the *E:G* ratios per material type and test type. The measured *E:G* ratios will also be compared to the 16:1 ratio commonly assumed for structural wooden members.
4) To combine qualitative data with the variability of measured results for each test method to determine the most appropriate test method to use for shear moduli determination.

Chapter 2 Literature Review

This literature review will provide a summary of elastic property definitions according to Hooke's three-dimensional law of elasticity. The discussion will concentrate on flexural, torsional, and plate twisting test methods available for shear moduli determination. Research involving shear moduli determination of wood and wood-based composites according to these test methods will be summarized.

2.1 Elasticity Definitions

Hooke's law of elasticity mathematically defines the relationship between stress and strain through the use of a constant known as the compliance coefficient. This relationship is described by the following (Bodig and Jayne 1982):

$$\gamma = S\sigma$$

Equation 2-1: Hooke's law of elasticity

where,

σ = stress

S = compliance coefficient

γ = strain.

Stresses and strains acting in three-dimensions require the direction and surface they act upon to be defined. Therefore, a subscript combination of a 1, 2, or 3 correlate the three-dimensional surface and direction the stress or strain act upon, respectively (Bodig and Jayne 1982). In the case of wood, axes are generally not labeled numerically, but are instead defined in terms of longitudinal (L), radial (R), and tangential (T) planes. These letters correlate to the 1, 2, and 3 directions of composites, respectively. For consistency within this research, the directional properties of solid sawn wood and SCL will be referred to according to the numerical labeling system. Figure 2-1 illustrates the axes of both solid-sawn wood and LVL according to this labeling system.

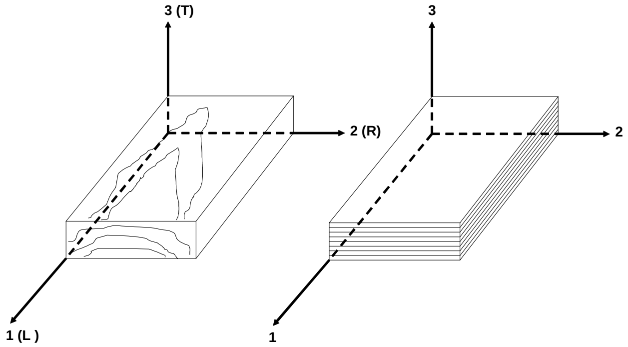


Figure 2-1: Three orthogonal directions labeled for solid-sawn wood and LVL. For solid-sawn wood, the longitudinal (L or 1-axis) is parallel to the grain direction. The radial (R or 2-axis) is perpendicular to the growth rings. The tangential (T or 3-axis) is tangent to the growth rings.

Based upon the numerical labeling system defining the surface and direction that stresses and strains act, respectively, Hooke's three-dimensional law may be written as the following tensor notation (Bodig and Jayne 1982):

$$\gamma_{ij} = S_{ijkl}\sigma_{kl}$$

Equation 2-2: Hooke's three-dimensional law of elasticity

where,

γ = strain

S = compliance coefficient

σ = stress

i, j, k, l = coordinate index (1, 2, or 3)

This tensor notation can be expanded to matrix form as the following:

$$\begin{Bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{12} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{13} & S_{23} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{14} & S_{24} & S_{34} & S_{44} & S_{45} & S_{46} \\ S_{15} & S_{25} & S_{35} & S_{45} & S_{55} & S_{56} \\ S_{16} & S_{26} & S_{36} & S_{46} & S_{56} & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix}$$

Equation 2-3: Matrix form of Hooke's Law

The subscripts of 1, 2, and 3 refer to normal stresses in the appropriate planes. The subscripts of 4, 5, and 6 refer to shear stresses applied over the 2-3, 1-3, and 1-2 surfaces, respectively. However, compliance coefficients (S_{ij}) are generally not used in engineering applications; instead a set of elastic parameters are substituted in their place. The parameters relating axial stress and strain in the same direction are termed moduli of elasticity, *E*. Those relating shear stress and shear strain applied in the same plane are termed shear moduli, *G*. Finally, axial stress and strain in different directions are related by Poisson's ratios, ν. The internal organization of a material dictates the number of elastic parameters needed to define all stress-strain relationships. Material organization is generally described as isotropic, orthotropic, or anisotropic (Bodig and Jayne 1982).

2.1.1 Isotopic Materials

Isotropic materials are the simplest materials to model according to Hooke's three-dimensional law of elasticity. Materials that display this type of behavior have a homogenous internal organization. Therefore, the stress-strain relations of isotropic materials are the same regardless of which surface and direction a force is applied. There are no interactions between normal stresses and shear strains or between shear stresses and normal strains. All possible stress-strain relationships can be defined using two independent constants, ν and *E*. The stress-strain relationship of an isotopic material is the following (Bodig and Jayne 1982):

$$\begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} = \frac{1}{E} \begin{bmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+\nu) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\nu) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+\nu) \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix}$$

Equation 2-4: Hooke's law of elasticity for isotropic materials

2.1.2 Anisotropic Materials

Anisotropic materials display directional properties though no internal symmetry is apparent. Therefore, material properties depend upon the direction they are applied. Lack of symmetry within this type of material requires all compliance terms, a total of 36, to completely describe stress-strain relations (Bodig and Jayne 1982).

2.1.3 Orthotropic Materials

Orthotropic material behavior is between isotropic and anisotropic behavior. Specifically, orthotropic materials are defined as those with directional properties about three mutually perpendicular planes that geometrically correspond to the material's axes. Wood is generally considered an orthotropic material as it displays material properties about its longitudinal, radial, and tangential axes. Specifically, the longitudinal (L or 1) axis is parallel to grain direction, the radial (R or 2) axis is perpendicular to the growth rings, and the tangential (T or 3) axis is tangent to the growth rings. However, the geometric and orthotropic axes of solid sawn wood products rarely coincide. Instead, a combination of radial and tangential grain orientations constitute both the 2 and 3 directions.

Orthotropic materials have each of the three elastic parameters (E, G, ν) defined in each orthogonal direction. The resulting three moduli of elasticity (E_1, E_2, E_3), three shear moduli (G_{12}, G_{13}, G_{23}), and three independent Poisson's ratios ($\nu_{12}, \nu_{13}, \nu_{23}$), are subscripted according to the surface and direction they are associated with, respectively. Therefore, Hooke's three-dimensional law of elasticity for orthotropic materials takes on the following form (Bodig and Jayne 1982):

$$\begin{Bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_2} & -\frac{\nu_{13}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{23}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix}$$

Equation 2-5: Hooke's law of elasticity for orthotropic materials

Though a total of nine elastic parameters are needed to completely solve Hooke's three-dimensional law of elasticity for wood materials, some elastic parameters are of greater importance to the design community than others. These parameters include: the modulus of elasticity in the 1-direction (E_1), the shear modulus in the 1-2 direction (G_{12}), and the shear modulus in the 1-3 direction (G_{13}). The modulus of elasticity in the 1-direction is also referred to as the longitudinal modulus of elasticity. The shear moduli in the 1-2 and 1-3 directions are referred to as the in-plane and through-the-thickness shear moduli, respectively. Often these parameters are referred to in the form of an *E:G* ratio, or a ratio of bending to shear stiffness. The E_1:G_{12} ratio represents the bending to shear stiffness of beams in an edgewise orientation. The E_1:G_{13} ratio represents the bending to shear stiffness of beams in a flatwise orientation. A lack of subscripts on an *E:G* ratio can be interpreted as representative of the E_1:G_{12} ratio.

2.1.4 Importance of *E:G* Ratio

E:G ratios are used in design equations to determine the torsional rigidity of structural wooden beams. The estimate of torsional rigidity is also used in the design equation that predicts the lateral torsional stability of structural beams (USDA 1999). If the modulus of elasticity and shear modulus are not explicitly defined for a wood product, the equations that predict torsional rigidity and lateral torsional stability assume an *E:G* ratio of 16:1. However, according to Hindman et al. (2001)'s analysis of the components used to predict lateral torsional stability, non-conservative values may result when predicting the responses of SCL materials that behave in a more orthotropic manner than the assumed *E:G* ratio of 16:1.

In most light frame construction, the torsional stability and rigidity of structural components are not a serious design concern. Angular deflections are generally prevented by bracing the beam's compression face with a structural panel product. However, forces that create uplift, such as a wind load upon roof joists, can cause the compression face of the beam to change position from above to below the neutral axis of the beam. This stress reversal results in the compression face no longer being reinforced by the sheathing, therefore leaving it vulnerable to lateral instability. Beams left without reinforcement during construction and other exposed beams that lack reinforcement are examples of situations where lateral instability is of concern (Hindman 2003).

Another scenario where lateral torsional stability is of importance is the design of long continuous spans. Stress reversals occur near the intermediate supports of the long span, leaving the beam susceptible to excessive angular deflection. This design issue is more of a concern under present construction practices as the sizes of SCL products allow for the design of long spans more than previously possible with solid-sawn members (Hindman 2003).

2.1.5 Evaluation of Shear Properties

The modulus of elasticity of wood materials is an easily evaluated and well documented material property. However, the testing of shear properties, and particularly the shear modulus, has long been a perplexing research topic. The presence of secondary stresses inherent to many test methods complicate the analysis of data used to predict shear properties, and the comparison of shear properties collected from different test methods. However, the presence of secondary stresses can also be considered more realistic as states of pure shear stress are uncommon in structural applications. Test methods that produce stress distributions similar to those observed during their use as a structural member could be considered most desirable. The use of such a loading essentially removes unrealistic test bias and provides the most appropriate estimate of shear properties.

2.2 Test Methods Used for Shear Moduli Determination

Many test methods have been developed to evaluate the shear modulus of wood products. A test formerly used for shear moduli determination of solid wood included twisting thin plates of wood (Bodig and Goodman 1973, Gunnerson et al. 1973). Much of the species-specific shear moduli data currently in use originated from these types of tests (Bodig and Goodman 1973). The *E:G* ratio of 16:1 used in the design equations to predict torsional rigidity and lateral torsional stability was also estimated from the plate twisting tests from Bodig and Goodman (1973). The test method used by these researchers is similar to that currently specified in ASTM D 3044 (2003d) for determining the shear moduli of wood-based panel products.

The present test method used to determine the material properties of structural sized lumber, listed in ASTM D 198 (2003a), Standard Test Methods of Static Tests of

Lumber in Structural Sizes, includes methods referenced by ASTM D 5456 (2003f), Standard Specification for Evaluation of Structural Composite Lumber Products. Though no specific reference to ASTM D 198 (2003a) is given in ASTM D 5456 (2003f) for determining the shear moduli of SCL, the guidelines for determining this material property for structurally sized solid-sawn lumber are included within ASTM D 198 (2003a). This standard specifies either a three-point bending or torsion test for determination of the shear modulus.

An additional test method available for determining the shear moduli of wood products is the five-point bending test (FPBT). This particular test method is not included as a standard for evaluating the shear modulus of wood, but it has shown success in the research of others (Hindman 2003, Janowiak et al. 2001, Hindman 1999, Bradtmueller et al. 1998, Bradtmueller et al. 1994). A survey of the FPBT method and other methods used in the work of previous researchers including: torsional, flexural, and plate twisting methods will be discussed in the following sections**.**

2.2.1 Torsion Test Methods

The following sections will describe torsional test methods used for the shear moduli determination of wood products. The two test methods include both an isotropic (ASTM D 198) and orthotropic method (torsional stiffness measurement test). Existing research efforts using these test methods will also be summarized.

2.2.1.1 ASTM D 198 Torsion

One test method described in ASTM D 198 (2003a) for shear moduli determination is the torsion method. This method restrains a specimen from rotating at one end while imposing a twisting moment at the other end. Troptometers are fastened along the length of the specimen to measure angular movement. The devices are symmetrically placed so that the length of the member between measurement locations is maximized. The portion of the span closest to the grips of the testing machine can experience end effects (Gupta and Siller 2005). Therefore, the devices can be no closer to the clamps than two times the largest cross sectional dimension of the member. Figure 2-2 is a schematic of the torsion test setup.

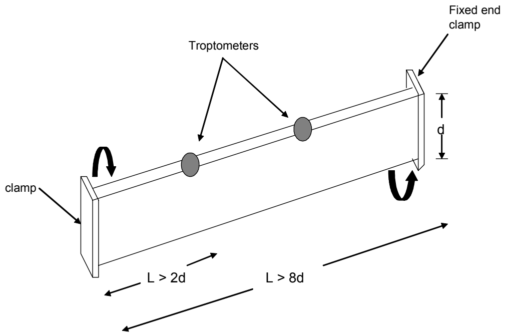


Figure 2-2: ASTM D 198 torsion test method setup.

A restriction of this test method is that the member's length be at least eight times its largest cross-sectional dimension. This method also assumes the beam is both homogenous and isotropic (Hindman 2003). The apparent shear modulus, which is a combination of the G_{12} and G_{13} terms, is calculated from the beam's dimensions, the measured angle of twist and torque applied at the proportional limit, and a Saint-Venant's constant given in Table X3.2 of ASTM D 198 (2003a). The equation for the relationship between these parameters is the following:

$$G = \frac{16LT}{bh^3\left[(16/3) - \lambda(h/b)\right]\theta}$$

Equation 2-6: Apparent shear modulus according to the ASTM D 198 torsion test

where,

G = shear modulus (psi or GPa)
L = length of member between clamps (in or mm)
T = torque at proportional limit (in-lb or mm-N)
b= width of specimen (in or mm)
h = height of specimen (in or mm)
λ= St. Venant constant, Table X3.2 in ASTM D 198 (2003a)
θ = angle of twist at proportional limit (radians).

Torsion test methods produce a pure state of shear stress in the specimen. A pure state of shear stress may be considered desirable in determining shear properties as complications due to secondary stresses are eliminated. However, the loading configuration used in the torsion test method does not reflect the condition that a beam experiences during its use as a structural element (Gupta and Siller 2000).

The shear modulus obtained from the ASTM D 198 (2003a) torsion test is termed apparent because it is a combination of both the in-plane (G_{12}) and through-the-thickness

(G_{13}) shear moduli. Consequently, the apparent shear modulus is most accurate when the ratio of the G_{12} and G_{13} shear moduli is unity, or the material displays isotropic behavior. However, the research of Hindman (2003) and Hindman (1999) has shown the G_{12} term of lumber and SCL products to be significantly higher than the G_{13} term. Therefore, the shear moduli of these products may not be obtained accurately using the ASTM D 198 torsion test method.

2.2.1.2 Torsional Stiffness Measurement Test

An alternative to the ASTM D 198 (2003a) torsion test method which accounts for orthotropic behavior is the torsional stiffness measurement test (TSMT). This method was first used by Janowiak and Pellerin (1992) to determine the in-plane (G_{12}) and through-the-thickness (G_{13}) shear moduli of particleboard, waferboard, and oriented strand board (OSB). An advantage of this testing procedure is that both G_{12} and G_{13} shear moduli can be determined from one specimen as opposed to the single apparent shear modulus determined by the torsion method specified in ASTM D 198 (2003a).

In order to calculate the shear modulus from the TSMT method, the same specimen is tested a minimum of four times over varying width to thickness (b/h, or slenderness ratios (Janowiak and Pellerin 1992). Torque versus angle of twist data is used to calculate torsional stiffness with respect to the slenderness ratio at which measurements were taken. The linear function resulting from a plot of torsional stiffness versus slenderness ratio is used to graphically determine the G_{12} shear modulus and to subsequently solve for the G_{13} shear modulus. Very high accuracy in determining the G_{12} shear modulus over the range of slenderness ratios is critical as it is raised to the cubic power to calculate the G_{13} shear modulus. The following equations are used for calculation of the G_{12} and G_{13} shear moduli according to the TSMT method (Hindman 2003):

$$G_{12} = \left(\frac{3}{bh^3}\right)K_x \qquad \textit{\textbf{if}} \qquad \frac{b}{h} \langle \frac{\pi}{4}\sqrt{\frac{G_{13}}{G_{12}}}$$

Equation 2-7: In-plane shear modulus according to TSMT

or

$$G_{13} = \left(\frac{0.3972 G_{12}^{3}}{k_s^{2}} \right) \qquad if \qquad \frac{b}{h} \rangle \frac{4}{\pi} \sqrt{\frac{G_{13}}{G_{12}}}$$

Equation 2-8: Through-the-thickness shear modulus according to TSMT

where,

G_{12} = shear modulus in the 1-2 plane (psi or GPa)
G_{13} = shear modulus in the 1-3 plane (psi or GPa)
K_x = torsional stiffness, TL’/θ ((in-lb/radian) or (mm-N/radian))
b= width of specimen (in or mm)
h = height of specimen (in or mm)
k_s = slope of the $(3/bh^3)K_x$ vs. (h/b) line
T = applied torque (in-lb or mm-N)
L'= L-ΔL = adjusted length (in or mm)
L = gage length between angular measurements (in or mm)
ΔL = clamp length adjustment (in or mm)
θ = angle of rotation caused by applied torque (radian).

Equations 2-7 and 2-8 assume the beam is free of end restraints. Therefore, by clamping the specimen’s cross-sections during torsion testing this assumption is violated (Janowiak and Pellerin 1992). Janowiak and Pellerin (1992) suggested angular measurements be taken a sufficient distance away from the clamps to eliminate clamping effects. A method discussed in Hindman (2003) can be used to determine the distance that eliminates clamping effects.

Originally developed by Tarnopol’skii and Kincis (1985), this method adjusts the gage length of a specimen by a correction factor, ΔL. The value of the correction factor is determined by subjecting a specimen of the same cross-sectional dimension to constant torque over several reduced gage lengths. The resulting angle of twist versus gage length data is regressed and the x-intercept of this data is used as the correction factor, ΔL. If the clamps restrained the specimen from deformation, the correction factor is positive. If the clamps warped under the applied torque, the correction factor is negative. The use of a correction factor is required when using equations 2-7 and 2-8 as the equations assume the specimen is free of clamping effects.

2.2.1.3 Existing ASTM D 198 Torsion and TSMT Research

Limited research has used torsional test methods to determine the shear moduli of solid-sawn lumber and SCL. A greater amount of research has concentrated on using torsion test methods to determine the shear strength of solid sawn lumber and SCL products. Only research that included shear moduli determination will be included in the following discussion.

Table 2-1 shows the shear moduli of various wood products determined by torsion test methods. The shear moduli of LVL, PSL, and LSL were determined by Trus Joist (1998) according to the torsion test method described in ASTM D 198 (2003a). The moduli of elasticity of the SCL materials tested by Trus Joist (1998) were not included within the research summary and therefore, the commercially rated modulus of elasticity provided by the manufacturer was used to calculate the *E:G* ratios found in Table 2-1. Specifically, the moduli of elasticity assumed for LVL and PSL were both 2.0×10^6 psi (13.9 GPa) while the LSL material was assumed to have a modulus of elasticity of 1.5×10^6 psi (10.3 GPa).

Doyle and Markwardt (1966) and Doyle (1968) also used a torsion test method to determine the shear modulus of various grades of southern pine dimension lumber. The moduli of elasticity of the specimens used to calculate *E:G* ratios included in Table 2-1 were determined by quarter-point bending tests. Hindman (1999) used the TSMT method to determine the shear moduli of LVL and LSL products. The moduli of elasticity used in the *E:G* ratios were taken from five-point bending test data corrected for shear. The results of this research are also summarized in Table 2-1.

Table 2-1: Average shear moduli and *E:G* ratios of materials tested under the torsion test method.

Material	Species Composition/ Scientific Name	Average Shear Moduli psi (GPa)	E:G Ratio	Researcher(s)
S. pine #2 Dense	*Pinus spp.*	1.35e5 (0.931)	13.5	Doyle 1968
S. pine lumber	*Pinus spp.*	1.40e5 (0.965)	11.6	Doyle and Markwardt 1966
S. pine LVL[1]	*Pinus spp.*	7.53e4 (0.519)	33.1	Hindman 1999
Douglas-fir LVL[1]	*Pseudotsuga menziesii*	8.69e4 (0.599)	28.4	Hindman 1999
Yellow-poplar LVL[1]	*Liriodendron tulipifera*	6.04e4 (0.416)	36.6	Hindman 1999
LVL	Unknown	1.02e5 (0.703)	19.6	Trus Joist 1998
PSL	Unknown	1.04e5 (0.717)	19.2	Trus Joist 1998
Aspen LSL[1]	*Populus spp.*	1.33e5 (0.917)	17.4	Hindman 1999
Yellow-poplar LSL[1]	*Liriodendron tulipifera*	1.05e5 (0.724)	14.8	Hindman 1999
LSL	Unknown	1.14e5 (0.786)	13.2	Trus Joist 1998

[1] *G* values determined by TSMT testing method.

2.2.2 Flexural Test Methods

The following sections will describe flexural test methods used for the shear moduli determination of wood products. Existing research efforts using these test methods will also be summarized.

2.2.2.1 ASTM D198 Three-Point Bending Test

The three-point bending test is currently the ASTM standard flexural test for shear moduli determination. This test method specifies that a beam is tested via center-point loading over multiple (a minimum of four) spans per specimen. Figure 2-3 illustrates the testing configuration specified by ASTM D 198 three-point bending.

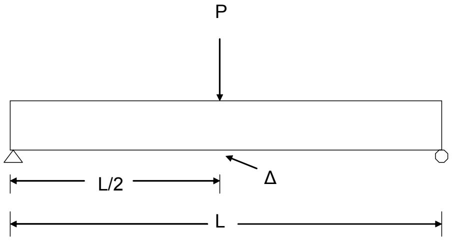


Figure 2-3: ASTM D 198 three-point bending test method configuration.

The shear modulus obtained from the three-point bending test is determined by a procedure based on the apparent modulus of elasticity and the specimen dimensions. Within this procedure, the apparent modulus of elasticity is determined at multiple aspect ratios, $(h/L)^2$. The equation used to calculate the apparent modulus of elasticity is the following:

$$E_f = \frac{L^3}{48I}\left(\frac{P}{\Delta}\right)$$

Equation 2-9: Apparent modulus of elasticity according to ASTM D 198 three-point bending

where,

E_f = apparent modulus of elasticity (psi or GPa)
L = span (in or mm)
I = moment of inertia (in^4 or mm^4)
P/Δ = slope of load-deflection data (lb/in or N/mm).

The term apparent is used to describe the modulus of elasticity defined in Equation 2-9 because deflection due to both bending and shear are included in its calculation. The true modulus of elasticity differs from the apparent modulus of elasticity because it ignores deflection due to shear. In order to determine the true moduli of elasticity, a linear regression of the apparent moduli of elasticity and the aspect ratios at which they were measured is performed. The resulting intercept is the inverse of the true modulus of elasticity. The inverse slope of the data, modified by a shape factor, is the shear modulus. The equation used to relate these parameters is the following:

$$\frac{1}{E_f} = \frac{1}{E} + \frac{1}{KG}(h/L)^2$$

Equation 2-10: Solution for the true modulus of elasticity and shear modulus according to ASTM D 198 three-point bending

where,

E_f = apparent modulus of elasticity (psi or GPa)
E = true modulus of elasticity (psi or GPa)
K = shape factor (5/6 for rectangular beams)
G = modulus of rigidity (psi pr GPa)
h = height of beam (in or mm)
L = length of beam (in or mm).

An example of the solution is illustrated in Figure 2-4. ASTM D 198 (2003a) also provides a discussion on the solution of elastic properties according to three-point bending.

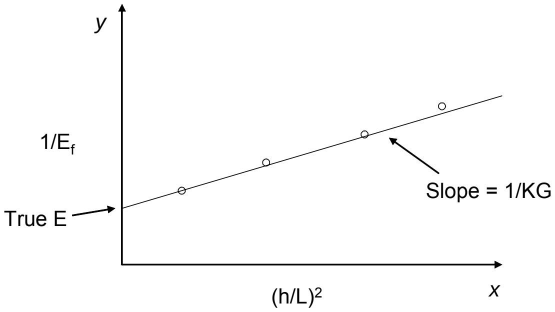


Figure 2-4: Graphical solution for shear modulus and true modulus of elasticity according to ASTM D 198 three-point bending.

Gromala (1985) noted that an accurate shear modulus approximation can result from center-point loading because shear stresses encompass the entire length of the beam. Gromala (1985) also pointed out that the ASTM D 198 (2003a) requirement of testing a minimum of four spans per specimen allows for an improvement in determining the shear modulus as data from multiple regions of the beam are incorporated into the overall shear modulus estimation. However, Chui (1991) realized that if the specimen being tested according to this method is not homogeneous, variability is captured in the individual measurements taken at the various spans. In addition, higher loads are needed to produce even small deflections at reduced span lengths, thereby making the measurements subject to error (Chui 1991).

2.2.2.2 Existing Three-point Bending Research

Some of the existing research on the shear moduli of wood and wood-based composites determined by the three-point bending test includes a survey completed by Yoshihara et al. (1998). In this study, the shear moduli of several hardwood and softwood species, including spruce (*Picea sitchensis*) and yellow-poplar (*Liriodendron tulipifera*), were determined via center-point loading over a range of length/depth (l/d) ratios. The resulting shear moduli decreased as the l/d ratios decreased, indicating to Yoshihara et al. (1998) that the deflection measurements of specimens in the lower l/d ratio range were possibly biased. The source of bias was attributed to the stress disturbance induced at the loading point from which deflection measurements were taken. The additional deflection caused by this stress disturbance was hypothesized to falsely decrease the calculation of the specimen's shear modulus. Generally, a yoke is used to eliminate this bias by taking measurements relative to the neutral axis of the beam. However, Yoshihara et al. (1998) modified the equation used to determine the shear modulus in order to calculate the shear moduli values found in Table 2-2.

Additional research by Samson and Sotomayor-Castellanos (1991) determined the shear moduli of various grades of visually and machine-stress-rated spruce-pine-fir (SPF) dimension lumber. Though the method used by these researchers is not identical to ASTM D 198 (2003a) standards, it has been included for comparative purposes. The method used by Samson and Sotomayor-Castellanos (1991) included subjecting specimens to pure bending to determine their true moduli of elasticity. The apparent moduli of elasticity were calculated from load-deflection data of a three-point bending test taken at a single span. The true and apparent moduli of elasticity values were then inserted into equation 2-10 of ASTM D 198 (2003a) to calculate the shear modulus. The resulting *E:G* ratios determined by this research are summarized in Table 2-2**.**

Biblis (2001) also used a three-point bending test to evaluate the shear modulus of two types of non-commercial LVL, each constructed with either grade C or grades C and D southern pine (*Pinus spp.*) plies. The high *E:G* ratios reported by Biblis (2001) could be related to the non-commercial manufacture of the LVL, or the result of biased deflection measurements. No mention of the method used to obtain deflection measurements was included in the research summary. An average of the *E:G* ratios determined by Biblis (2001) is included in Table 2-2.

The research of Palka and Barret (1985) also determined the *E:G* ratios of various species of softwood dimension lumber. The researchers found most *E:G* ratios determined from three-point bending tests differed from the commonly used *E:G* ratio estimate of 16:1. The *E:G* ratio of Palka and Barret (1985)'s three-point bending tests on white spruce 2 in x 8 in clear dimension lumber is included in Table 2-2.

Table 2-2: Average shear moduli and *E:G* ratios of materials tested under the three-point bending test method.

Material	Species Composition/ Scientific Name	Average Shear Moduli psi (GPa)	E:G Ratio	Researcher(s)
Solid Sawn Spruce	*Picea sitchensis*	1.29e5 (0.890)	10.5	Yoshihara et al. (1998)
Solid Sawn Yellow-Poplar	*Liriodendron tulipifera*	1.41e5 (0.970)	11.6	Yoshihara et al. (1998)
Glulam	SPF	1.60e5 (1.10)	11.7	Samson and Sotomayor-Castellanos (1991)
Select[1]	SPF	9.79e4 (0.675)	15.9	Samson and Sotomayor-Castellanos (1991)
1650f-1.5E[1]	SPF	2.07e5 (1.43)	10.6	Samson and Sotomayor-Castellanos (1991)
No. 1[1]	SPF	9.79e4 (0.675)	19.3	Samson and Sotomayor-Castellanos (1991)
Clear W. Spruce	*Picea Gluaca*	1.46e5 (1.01)	8.7	Palka and Barret (1985)
S. pine LVL[1]	P*inus spp.*	3.07e4 (0.211)	61.6	Biblis (2001)

[1] *E/G* ratios are an average of reported values.

2.2.2.3 Five-Point Bending Test

The five-point bending test (FPBT) is not included as an ASTM accepted testing procedure, but it has proven effective in determining the shear properties of structural wood and wood-based composites (Hindman 2003, Janowiak et al. 2001, Hindman 1999, Bradtmueller et al. 1998, Bradtmueller et al. 1994). The FPBT method requires two different flexural test setups per specimen, a four-point and a five-point loading configuration. Illustrations of the configurations used in the FPBT are provided in Figure 2-5.

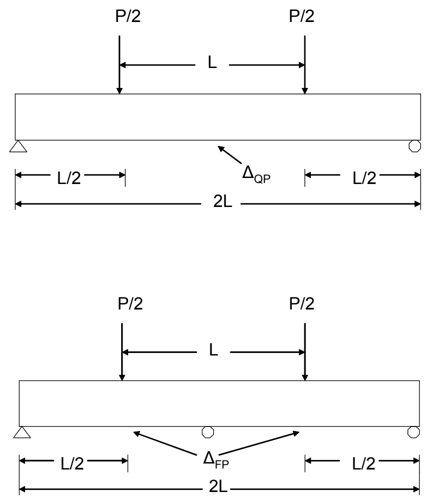


Figure 2-5: Quarter-point (top) and five-point (bottom) test configurations for the FPBT.

According to a derivation provided by Bradtmueller et al. (1994), the deflection equations of the two loading configurations can be simultaneously solved to provide equations for the shear free modulus of elasticity and the shear modulus. The deflection measurement of the four-point loading configuration is taken at midspan while deflection measurements for the five-point loading configuration are taken at both ¼ and ¾ of the span length. The resulting equations are the following:

$$\Delta_{QP} = \frac{11PL^3}{96EI} + \frac{PL}{4KGA} \qquad E = \frac{249L^3}{\left\{4096I\left[\frac{73}{128}Y_{QP} - Y_{FP}\right]\right\}}$$

Equation 2-11: Quarter-point bending deflection equation and solution for modulus of elasticity according to the FPBT

$$\Delta_{FP} = \frac{7PL^3}{1536EI} + \frac{73PL}{512KGA} \qquad G = \frac{747L}{\left\{5632KA\left[Y_{FP} - \frac{7}{176}Y_{QP}\right]\right\}}$$

Equation 2-12: Five-point bending deflection equation and solution for shear modulus according to the FPBT

where,

P = applied load (lb or N)
E = modulus of elasticity (psi or GPa)
L = five-point span that is one-half of the quarter-point beam span (in or mm)
A = cross sectional area (in^2 or mm^2)
Δ_{QP} = deflection of quarter-point bending (in or mm)
Δ_{FP} = deflection of five-point bending (in or mm)
G = shear modulus (psi or GPa)

I = moment of inertia (in^4 or mm^4)
K = shape factor (5/6 for rectangular beams)
Y_{QP} = inverse slope of the load vs. deflection curve for quarter-point bending
Y_{FP} = inverse slope of the load vs. deflection curve for five-point bending.

Bradtmueller et al. (1994) determined that errors in deflection measurements made during the FPBT could be related to compressive stresses at the loading heads and supports. It was also realized that the increase in measured deflection due to compressive stresses was the probable source of over estimating the modulus of elasticity and under estimating the modulus of rigidity calculated from this data. To alleviate this source of error, Bradtmueller et al. (1994) suggested taking deflection measurements relative to the neutral axis of the specimen with the use of a yoke. Bradtmueller et al. (1994) also recommended adjusting the l/d ratio so that at least 40% of the total five-point loading deflection results from shear stress.

Finite element model (FEM) analysis of the five-point loading configuration of the FPBT was performed by Leichti et al. (1996). In this research it was determined that by maintaining a sufficient distance between the loading points and supports, the presence of compressive stresses perpendicular to grain could be minimized. If these stresses are present in excess, the calculated shear stresses could be falsely increased. Tingley and Kent (1996) verified that compressive stresses perpendicular to grain near the supports could be minimized by maintaining a ratio of half of the shear span to specimen height (a/d) of 3.0.

2.2.2.4 Existing FPBT Research

The FPBT method was first used to determine the interlaminar shear strength of oriented strand board (OSB) by Bateman et al. (1990). Bradtmueller et al. (1994) successfully extended the FPBT to evaluate the elastic and shear moduli of OSB. Other researchers, such as Hunt et al. (1993) and Bradtmueller et al. (1998), have found the FPBT useful in determining the shear properties of laminated veneer lumber (LVL). Hindman (2003) and Hindman (1999) also utilized the FPBT to determine the elastic and shear moduli of several types of LVL, PSL, and LSL. The aforementioned researchers whose studies included shear moduli determination via the FPBT are summarized in Table 2-3.

Table2-3: Average shear moduli and *E:G* ratios of materials tested under the FPBT method.

Material	Species Composition/ Scientific Name	Average Shear Moduli psi (GPa)	E:G Ratio	Researcher(s)
S. pine LVL	*Pinus spp.*	1.03e5 (0.710)	23.4	Hindman 2003
S. pine LVL	*Pinus spp.*	4.53e4 (0.312)	36.2	Hindman 1999
S. pine LVL	*Pinus spp.*	1.31e5 (0.903)	20.8	Bradtmueller et al. 1998
Douglas-fir LVL	*Pseudotsuga menziesii*	5.48e4 (0.378)	37.2	Hindman 1999
Yellow-poplar LVL	*Liriodendron tulipifera*	3.58e4 (0.247)	61.7	Hindman 1999
S. pine PSL	*Pinus spp.*	1.06e5 (0.731)	18.8	Hindman 2003
S. pine PSL	*Pinus spp.*	7.27e4 (0.501)	30.0	Hindman 1999
Yellow-poplar PSL	*Liriodendron tulipifera*	3.66e4 (0.252)	57.4	Hindman 1999
Aspen LSL	*Populus spp.*	9.87e4 (0.681)	19.8	Hindman 1999
Yellow-poplar LSL	*Liriodendron tulipifera*	1.51e5 (1.04)	11.5	Hindman 2003
Yellow-poplar LSL	*Liriodendron tulipifera*	5.41e4 (0.373)	33.4	Hindman 1999
S. pine MSR lumber	*Pinus spp.*	1.09e5 (0.752)	21.4	Hindman 2003

2.2.3 Plate Twisting Test Methods

The following section will describe plate twisting test methods used for the shear moduli determination of wood products. Existing research efforts using these test methods will also be summarized.

2.2.3.1 ASTM D 3044 Test Method

An additional test method previously used for shear moduli determination is similar to ASTM D 3044 (2003d), Standard Test Method for Shear Modulus of Wood-based Structural Panels. This test method specifies twisting a square panel section by applying two loads on the diagonal corners of a specimen while simultaneously supporting the other two corners. Though this method is not currently used for structural lumber it is used for panel products. A schematic of this test method is illustrated in Figure 2-6.

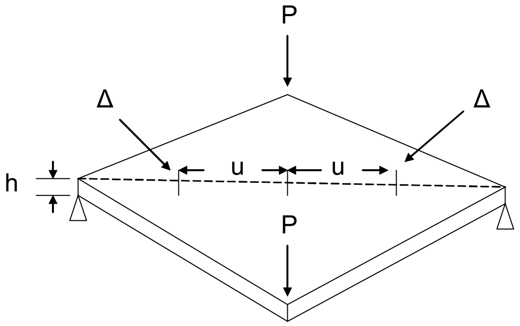


Figure 2-6: ASTM D 3044 plate twisting test method setup.

Deflections are measured relative to the center of the plate at approximate quarter-point locations from the two loaded corners. The shear modulus though-the-thickness of the panel is calculated from load-deflection data according to the following relationship defined in ASTM D 3044 (2003d):

$$G = \frac{3u^2 P}{2h^3 \Delta}$$

Equation 2-13: Shear modulus according to ASTM D 3044

where,

G = shear modulus (psi or GPa)
P = load applied to each corner (lbf or N)
h = thickness of plate (in or mm)
Δ = deflection relative to center (in or mm)
u = distance from the center of the panel to the point where the deflections are measured (in or mm).

The plate twisting test method requires the test specimen to be relatively thin as both its length and width dimensions are limited to 25 to 40 times the thickness. Due to this constraint, it is also necessary that the specimen be of relative constant thickness. Obviously, the geometry of the specimen used in this test method facilitates the shear modulus determination of panel products more than solid wood products. In fact, it was originally designed for plywood panel products (Liu et al. 1999). However, a version of the plate twisting method has also been used for shear moduli determination of solid wood products (Bodig and Goodman 1973).

2.2.3.2 Existing Plate Twisting Research

Bodig and Goodman (1973) predicted the shear moduli of solid wood according to a method similar to that described in ASTM D 3044 (2003d). To obtain the shear moduli in the orthogonal directions of interest, Bodig and Goodman (1973) milled thin strips of wood with specific grain orientations and edge glued them into a square plate of the required dimensions. Though this task is rather time consuming, Gunnerson et al. (1973) noted that after fabrication is complete, the shear properties of the specimen can be readily evaluated. However, only one shear modulus can be evaluated per specimen.

Bodig and Goodman (1973) tested a total of 18 softwood species in a series of plate bending and twisting tests to obtain estimates of the elastic parameters of each species. The resulting data is the source of the solid wood average *E:G* ratio of 16:1 that is commonly used in design equations for wooden beams. The average *E:G* ratios as determined by Bodig and Goodman (1973) are reported in Table 2-4. Sliker and Yu (1993) also used a series of plate twisting tests to define the shear properties of 18 hardwood species. The moduli of elasticity included in the *E:G* ratios of this research were determined by off-axis tension tests. The average *E:G* ratio determined by Sliker and Yu (1993) is included in Table 2-4.

Table 2-4: Average shear moduli and *E:G* ratios of materials tested under the plate twisting test method.

Material	Species Composition/ Scientific Name	Average Shear Moduli psi (GPa)	E:G Ratio	Researcher(s)
Southern Pine[1]	*Pinus spp.*	1.27e5 (0.873)	16.5	Bodig and Goodman 1973
Sitka Spruce	*Picea sitchensis*	7.73e4 (0.533)	20.2	Bodig and Goodman 1973
Engleman spruce	*Picea engelmannii*	9.36e4 (0.645)	10.7	Bodig and Goodman 1973
Yellow-poplar	*Liriodendron tulipifera*	1.27e5 (0.873)	11.6	Sliker and Yu 1993
Sliker and Yu Average	various hardwoods	1.58e5 (1.09)	10.0	Sliker and Yu 1993

[1] Southern pine averaged from values reported for loblolly, slash, longleaf and shortleaf pines.

2.2.4 Summary of Existing Research

In general, the inconsistencies between the *E:G* values determined for the solid-sawn wood and SCL products included in sections 2.2.1-2.2.3 are expected due to the wide variability of material types and test methods used for the reported values. Many of the test methods produce different shear moduli values as a result of the stress distributions inherent to the test setups. However, ASTM D 198 (2003a) three-point bending and torsion test results are considered equivalent. Hindman (2004)'s research on the shear moduli of solid sawn lumber has shown significant differences in shear moduli values measured by these two test methods.

Differences in the shear moduli of different material types are also expected due to the intrinsic organizational structure of the materials. Janowiak et al. (2001) noted that the properties of certain composite types can be influenced by differences in the processes used in their manufacture. Therefore, with differences among the material types and test methods used for shear moduli determination it is difficult to make direct comparisons between the results of individual research efforts. However, the following discussion will compare the most similar research efforts included in sections 2.2.1-2.2.3.

2.2.4.1 Differences among Test Methods for Similar Material Types

Southern pine (*Pinus spp.*) LVL is an example of a common species and material choice used in many research efforts. To illustrate the differences in shear moduli values obtained from different test setups, research that has been conducted on southern pine LVL is summarized in Table 2-5.

Table 2-5: Average shear moduli and *E:G* ratios of southern pine LVL tested under various test methods.

Material	Average Shear Moduli psi (GPa)	E:G Ratio	Percent Difference[1]	Test Method	Researcher(s)
S. pine LVL	7.53e4 (0.519)	31.5	49.3	TSMT	Hindman 1999
S. pine LVL	3.07e4 (0.211)	61.6	74.0	3-pt. bending	Biblis 2001
S. pine LVL	1.03e5 (0.710)	23.4	31.6	FPBT	Hindman 2003
S. pine LVL	4.53e4 (0.312)	36.2	55.8	FPBT	Hindman 1999
S. pine LVL	1.31e5 (0.903)	20.8	23.1	FPBT	Bradtmueller et al. 1998

[1] Percent difference = (*E:G* ratio – 16)/ *E:G* ratio *100

The test methods found in Table 5 include a version of three-point bending similar to that described in ASTM D 198 (2003a), the torsional stiffness measurement test (TSMT), and the five-point bending test (FPBT). Differences among reported *E:G* values of southern pine LVL range from 61.6, as determined by three-point bending tests conducted by Biblis (2001), to a minimum of 20.8 as determined by the FPBT conducted by Bradtmueller et al. (1998). Such variation results in a maximum of 66% difference between the highest and lowest *E:G* ratios determined for southern pine LVL. When these ratios are compared to the common *E:G* ratio estimate of 16:1 differences ranging from 23.1% to 74.0% result. Therefore, these research efforts show that considerable variation in the measured *E:G* ratios exist. In addition, these results show that the typical *E:G* ratio estimate of 16:1 may not be appropriate for LVL.

Included in Table 2-6 are shear moduli values determined for southern pine (*Pinus spp.*) dimension lumber. The shear moduli values determined from torsion testing by Doyle (1968) and Doyle and Markwardt (1966) are most similar to those determined by the plate twisting tests of small, clear specimens performed by Bodig and Goodman (1973). The reported *E:G* value for small, clear southern pine plate tests was 16.5 while larger-sized specimens tested via torsion by Doyle (1968) and Doyle and Markwardt (1966) produced *E:G* values of 13.5 and 11.4, respectively. This results in a maximum 31% difference in *E:G* ratios determined by torsion and small, clear plate twisting tests.

Table 2-6: Average shear moduli and *E:G* ratios of southern pine lumber and small clear specimens tested under torsion, FPBT and plate twisting test methods.

Material	Average Shear Moduli psi (GPa)	E:G Ratio	Percent Difference[1]	Test Method	Researcher(s)
S. pine #2 Dense	1.35e5 (0.931)	13.5	-18.5	ASTM D198 Torsion	Doyle 1968
S. pine lumber	1.40e5 (0.965)	11.4	-40.2	ASTM D198 Torsion	Doyle and Markwardt 1966
S. pine MSR lumber	1.09e5 (0.752)	21.4	25.2	FPBT	Hindman 2003
S. pine[2]	1.27e5 (0.873)	16.5	2.9	ASTM D3044 Plate Twisting	Bodig and Goodman 1973

[1] Percent difference = (*E:G* ratio – 16)/ *E:G* ratio *100

[2] Southern pine averaged from values reported for loblolly, slash, longleaf and shortleaf pines.

When the *E:G* ratio of Bodig and Goodman's small, clear specimens are compared to the *E:G* ratio determined by FPBTs of Hindman (2003) a difference of approximately -30% results. Differences ranging from 2.9% to -40.2% result when the test methods are compared to the commonly used *E:G* ratio of 16:1. Though the ratio of

16:1 appears to be a better estimate on the basis of some of these research efforts, differences in the *E:G* ratios determined by the different test methods still exist.

The southern pine lumber specimens tested by Doyle (1968), Doyle and Markwardt (1966), and Hindman (2003) are not identical to the small, clear southern pine specimens tested by Bodig and Goodman (1973). However, a comparison of the research is included as the *E:G* ratio determined from the small, clear specimens is similar to that commonly used in structural design equations for wooden beams. The differences in the *E:G* ratios determined in these research efforts question the validity of using small, clear specimens to determine the material properties of a structurally sized member. Hindman (1999) also found most elastic constant ratios of full-sized SCL determined by FPBT and TSMT methods differ from those published for solid wood. Therefore, this research also questions the appropriateness of estimating the elastic properties of SCL from solid wood specimens of the parent species.

The research of Hindman (1999) is one of the few examples of research that directly compares different test methods used for shear moduli determination. Hindman (1999) statistically compared the shear moduli values of SCL determined from the FPBT and TSMT. The results of this study noted differences in the shear moduli values determined by the different test setups.

Though the research of Riyanto and Gupta (1998) did not include shear moduli determination, the researchers compared the shear strength of structural sized solid-sawn lumber by various test methods including: three-point bending, four-point bending, five-point bending, and a torsion method. The results of this research verified that the shear strength of lumber is highly dependent upon the method used for its determination. Therefore, based on the results of Hindman (1999), Riyanto and Gupta (1998), and loose comparisons of *E:G* ratios determined by the various methods as reported by other researchers through sections 2.2.1-2.2.4, it can be hypothesized that shear moduli values are also highly dependent upon the test method used in their determination.

2.2.4.2 Differences among Material Types for Similar Test Methods

The differences between shear moduli values of solid-sawn wood and LVL determined by torsional test methods are apparent in Table 2-7.

Table 2-7: Average shear moduli and *E:G* ratios of southern pine lumber and LVL tested under torsion test methods.

Material	Average Shear Moduli psi (GPa)	E:G Ratio	Percent Difference[1]	Test Method	Researcher(s)
S. pine #2 Dense	1.25e5 (0.931)	13.5	-18.5	ASTM D198 Torsion	Doyle (1968)
S. pine lumber	1.40e5 (0.965)	11.4	-40.2	ASTM D198 Torsion	Doyle and Markwardt (1966)
S. pine LVL	7.53e4 (0.519)	31.5	49.3	TSMT	Hindman 1999

[1] Percent difference = (*E:G* ratio – 16)/ *E:G* ratio *100

Doyle (1968) and Doyle and Markwardt (1966) found *E:G* ratios of 13.5 and 11.4, respectively, for southern pine lumber according to ASTM D 198 (2003a) torsion testing. In comparison to the TSMT, which is the most similar test method available to compare to the torsion test method described in ASTM D 198 (2003a), the *E:G* ratio found by Hindman (1999) for LVL is almost triple the value found for solid wood at 31.5. The large difference in *E:G* ratios of the two materials can likely be attributed to intrinsic differences between LVL and solid-sawn lumber as the two test methods produce similar stress distributions. However, the TSMT and ASTM D 198 (2003a) torsion test methods also differ in the assumption of orthotropic or isotropic behavior used in their analyses. A more direct comparison of the *E:G* ratios of the two materials determined by the same test method would provide for a more definitive comparison of the two material types.

The differences among MSR lumber, LVL, and PSL tested under Hindman (2003)'s FPBT method are shown in Table 2-8. Much smaller differences between material types were realized in this research. The percent differences between MSR lumber and the SCL products were only 9% and -12%, for LVL and PSL, respectively. The difference among the *E:G* ratios of the two types of SCL was greater with LVL's *E:G* ratio being almost 20% higher than that determined for PSL. The lower variability in Hindman's (2003) *E:G* ratios could be related to the use of more consistent test methods as the same researcher conducted the testing for all material types.

Table 2-8: **Average shear moduli and *E:G* ratios of southern pine MSR lumber, LVL, and PSL tested under the FPBT method.**

Material	Average Shear Moduli psi (GPa)	E:G Ratio	Test Method	Researcher(s)
S. pine MSR lumber	1.09e5 (0.752)	21.4	FPBT	Hindman 2003
S. pine LVL	1.03e5 (0.710)	23.4	FPBT	Hindman 2003
S. pine PSL	1.06e5 (0.731)	18.8	FPBT	Hindman 2003

A comparison of the *E:G* ratio of only southern pine LVL determined by the FPBT conducted by Bradtmueller et al. (1998), Hindman (2003), and Hindman (1999) shows greater variability than observed in Table 2-8. The *E:G* ratios of these researchers are summarized in Table 2-9.

Table 2-9: **Average shear moduli and *E:G* ratios of southern pine LVL tested under the FPBT method.**

Material	Average Shear Moduli psi (GPa)	E:G Ratio	Test Method	Researcher(s)
S. pine LVL	4.53e4 (0.312)	36.2	FPBT	Hindman 1999
S. pine LVL	1.31e5 (0.903)	20.8	FPBT	Bradtmueller et al. 1998
S. pine LVL	1.03e5 (0.710)	23.4	FPBT	Hindman 2003

The *E:G* ratios as determined by the FPBT reported by Bradtmueller et al. (1998), Hindman (2003), and Hindman (1999) were 20.8, 23.4, and 36.2, respectively. These results show as much as a 74% difference between *E:G* values determined for the same material type and by the same test method. This variability can likely be attributed to the use of inconsistent test methods among the researchers.

It is apparent from previous research efforts that inconsistencies exist between shear moduli determined from different test methods and different researchers. Discrepancies between the *E:G* ratios of different material types determined by the same test method have also been observed. In order for wood-based composites, such as SCL, to be utilized to their full potential, the differences between test types and the effect these differences have on material properties should be understood.

Chapter 3 Materials and Methods

The extent of research necessary to examine the shear properties of all SCL materials according to all available test methods necessitated more time than was available for this project. Therefore, this research focused on the shear moduli determination of a single type of SCL and solid-sawn lumber according to three different test methods. This section describes the materials, experimental test methods, and quantitative/statistical analyses needed to fulfill the objectives.

3.1 Materials

Test specimens included a set of 1.9E southern pine LVL specimens and a set of southern pine MSR (machine-stress-rated) lumber rated 2400f-2.0E. LVL specimens were purchased from Timber Truss Housing Systems, Inc of Salem, VA. and were manufactured by Trus Joist, A Weyerhaeuser Business, mill number 49 in Evergreen, AL. MSR lumber specimens were donated from Rigid Ply Rafters of Richland, Pa. and were manufactured by Tolleson Lumber Company, Inc. of Georgia. Material with nominal dimensions of 2 in x 8 in (1.5 in x 7.5 in actual) was chosen to satisfy the aspect ratio requirements of the ASTM D 198 (2003a) three-point bending test. All specimens were a minimum of twelve feet in length due to limitations of the torsion testing apparatus.

Specimens were not conditioned in an environmental chamber due to space constraints. However, the specimens were stored in the Engineering Laboratory of the Brooks Forest Products Center for approximately one month prior to testing to reduce moisture content variation between samples. A temperature and relative humidity data logger was used to monitor the environmental conditions of the laboratory.

3.1.1 Determination of Sample Size

Specimen sample size was determined according to the following equation provided in ASTM D 2915, Standard Practice for Evaluating Allowable Properties for Grades of Structural Lumber (2003c):

$$n = \left(\frac{ts}{0.05\overline{X}} \right)^2 = \left(\frac{t}{0.05} COV \right)^2$$

Equation 3-1: Determination of sample size according to ASTM D 2915

where,

n = sample size
s = standard deviation of specimen values
$\overline{X}$ = specimen mean value
COV = coefficient of variation
0.05 = precision of estimate
t = value of t statistic from Table 1 in ASTM D 2915 (2003c).

A coefficient of variation (COV) of 10% was assumed for LVL materials at a confidence level of 95% resulting in a sample size of 16 specimens. A COV of 25% can be assumed for solid sawn lumber (Smulski 1997). This knowledge combined with the decreased variability generally observed for MSR lumber products, led to an assumed COV of 15% for the MSR lumber. This resulted in a sample size of 24 specimens at a confidence level of 90%.

3.2 Test Methods

The test methods used in this research project included ASTM D 198 (2003a) (both three-point bending and torsion), and the FPBT, along with moisture content and specific gravity sampling according to ASTM D 4442 (2003e) and ASTM D 2395 (2003b), respectively. Sequential testing of each specimen under the aforementioned test methods was used to quantify the shear properties of each specimen according to each test method. Figure 3-1 is a flow chart of the experimental design displaying the sequential order of testing.

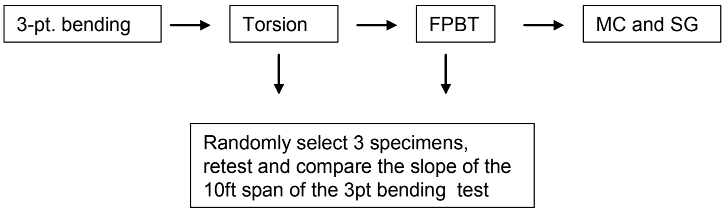


Figure 3-1: Flowchart of the experimental design displaying the sequential order of testing.

Test specimens were first subjected to the ASTM D 198 (2003a) three-point bending test followed by the ASTM D 198 (2003a) torsion test. After completion of the torsion test, three randomly selected specimens were retested according to the three-point bending test at a 10 ft span. A comparison (paired t-test, $\alpha = 0.05$) of load-deflection data before and after the torsion test ensured no permanent damage was inflicted on the specimens. Specimens were then evaluated according to the FPBT. Another comparison (paired t-test, $\alpha = 0.05$) of three-point bending load-deflection data of three randomly selected specimens before and after the FPBT ensured no permanent damage had been inflicted on the specimens. The moisture content and specific gravity of the specimens were determined according to ASTM D 4442 (2003e) and ASTM D 2395 (2003b), respectively.

3.2.1 Flexural Test Methods

All bending specimens were tested in edgewise bending to determine E_1 and G_{12} properties. When testing LVL in the edgewise orientation, the geometric and orthotropic axes aligned nearly perfectly, and therefore measured shear properties corresponded solely to the 1-2 orientation. However, for solid sawn wood perfect of alignment of the geometric and orthotropic axes required perfectly flatsawn or quarter sawn pieces of lumber. Such an occurrence is a rarity and therefore, the labeling of the G_{12} shear modulus for solid sawn lumber must not be considered a material property, but a property of the board as an element.

Bending tests in the edgewise orientation required the use of lateral restraints. The use of at least one lateral restraint approximately halfway between the supports and loading head was required per ASTM D 198 (2003a) recommendations. Lateral restraints were covered in high density polyethylene (HDPE) to eliminate as much friction as possible. The radius of curvature of the loading points was 11 inches for all bending tests. The supports were 0.5 in thick steel plates with dimensions (width x length) of 5.75 in x 8 in.

All flexural test specimens were loaded to no more than 60% of their allowable stress design (ASD) value (NDS 2001). This stress level was deemed well within the elastic range of the specimens. Limiting the stress level to this threshold ensured no permanent damage was inflicted on the specimens. The calculated load limitations for each flexural test configuration are included in Appendix A.

3.2.1.1 ASTM D 198 Three-Point Bending Tests

Three-point bending tests were conducted on a 55,000 lb. capacity servo-hydraulic Material Testing System (MTS) universal testing machine with a 5,000 lb. load range card and ±2.5 inch displacement range card. Deflection measurements were made relative to the neutral axis with a yoke suspended from two screws fastened above the supports of the testing machine. A linear variable differential transformer (LVDT) (2 inch range, ±0.001 inch sensitivity) was attached to the yoke at midspan with an aluminum bracket. Electronic data from the MTS actuator with a load cell (5,000 lb., ±50 lb. sensitivity) and LVDT were processed through LabVIEW^{TM} 7 *Express* data acquisition software. Figure 3-2 depicts the loading configuration used for ASTM D 198 (2003a) three-point bending tests.

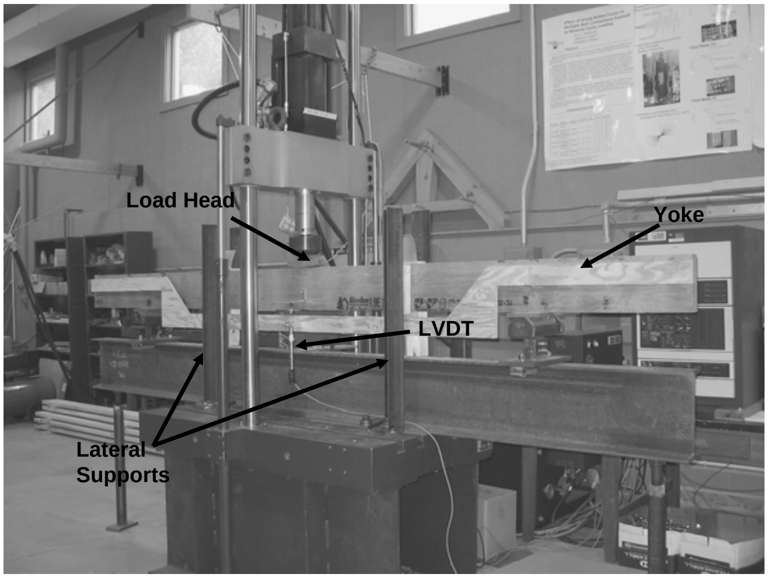


Figure 3-2: ASTM D 198 three-point bending test setup.

A total of five successive spans were used to comply with ASTM D 198 (2003a) requirements. The tested spans were chosen to provide aspect ratios, $(h/L)^2$, within the permissible range of 0.035 to 0.0025, as specified by ASTM D 198 (2003a). The spans were also selected so that the most constant difference between aspect ratios was maintained per ASTM D 198 (2003a) recommendations. Table 3-1 depicts the lengths and corresponding aspect ratios of the materials tested in an edgewise orientation.

Table 3-1: Aspect ratios used for three-point bending tests in edgewise orientations[1].

Material	length (ft) 11	10	9	8	7
PSL	0.0032	0.0039	0.0048	0.0061	0.0080
MSR	0.0030	0.0037	0.0045	0.0057	0.0074

[1] ASTM D 198 (2003a) recommends aspect ratios between 0.0025 to 0.035.

Aspect ratio requirements for specimens tested in a flatwise orientation permitted spans of no more than 30 inches and no fewer than 8 inches. Such small spans were considered unreasonable for determining the material properties of a twelve foot long specimen. The span differences between edgewise and flatwise tests (7 to 11 feet edgewise versus 2.5 to ~1 foot flatwise) were also believed to likely complicate future comparisons of the data sets as the presence of defects in the longer spans was inevitable. Therefore, flatwise testing was not pursued in these research efforts.

Loading rates consistent with ASTM D 198 recommendation's of a constant outer fiber strain rate of 0.001 in/in/minute were calculated according to elementary beam mechanics equations. However, maintaining the prescribed constant rate of outer fiber strain required that the loading rate change per span. Altering the loading rate per span was deemed to be unreasonable and therefore, a rate of 0.25 in/minute was used for all edgewise three-point bending tests. The effect of loading rate on elastic property determination was deemed insignificant based on the review of research performed by Brokaw and Foster (1952) and Liska (1950).

Spans were tested sequentially beginning with the longest span. After all testing of one group of specimens at an individual span was completed; the supports were repositioned to the next appropriate span. Backspan was not eliminated because the specimen's original dimensions were needed to complete shear moduli determinations according to alternative test methods.

Three repetitions of load-deflection data were collected at each of the five spans tested, resulting in a total of fifteen load-deflection measurements per specimen. The average apparent modulus of elasticity at each span was calculated according to equation 2-9. These values were plotted versus the aspect ratios at which they were measured. The resulting linear relationship was used to calculate the shear modulus and true modulus of elasticity for each specimen according to equation 2-10.

3.2.1.2 FPBT Testing

The FPBT method requires two consecutive flexural loading configurations per specimen, both a quarter-point and five-point setup. Both loading configurations were conducted on a 55,000 lb. capacity servo-hydraulic Material Testing System (MTS) universal testing machine. Bending tests in the quarter-point and five-point arrangement were tested using a 5,000 lb. load range card and ±2.5 inch displacement range card. In accordance with recommendations of Bradtmueller et al. (1994), all deflection measurements were made with either one or a pair of LVDTs (2 inch range, ±0.001 inch sensitivity) relative to the neutral axis of the beam. The LVDT(s) were attached to a yoke suspended from two screws fastened above the supports of the testing machine.

Each specimen was first tested in the quarter-point loading configuration. Figure 3-3 depicts the loading configuration used for the quarter-point bending test of the FPBT.

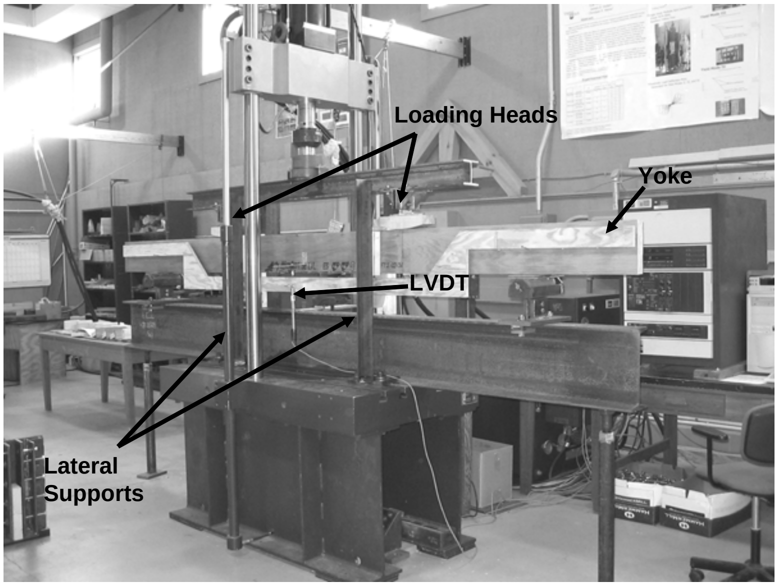


Figure 3-3: Quarter-point bending test configuration of the FPBT.

One deflection measurement for the quarter-point arrangement was made at the beam's midspan. After completing the quarter-point bending tests for all specimens in a material group, the additional middle support necessary for the five-point bending configuration was added to the test setup. Figure 3-4 illustrates the loading configuration used in the five-point bending tests of the FPBT.

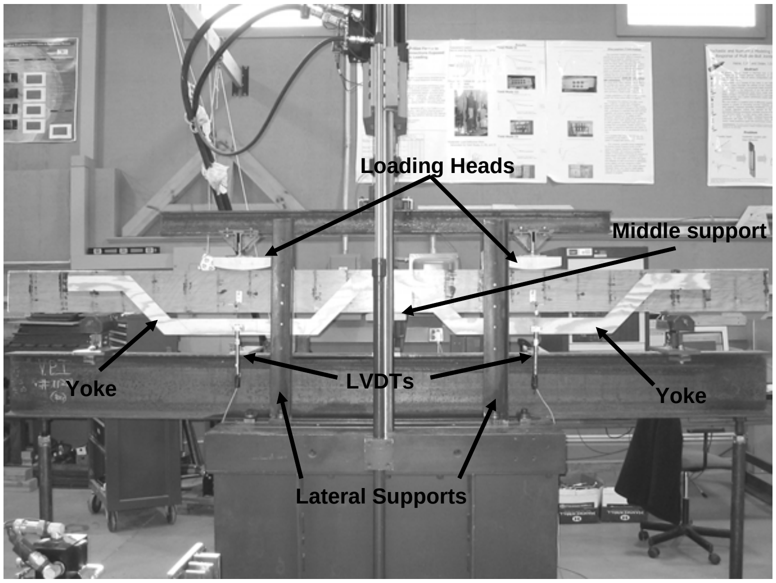


Figure 3-4: Five-point bending test configuration of the FPBT.

Deflection measurements for the five-point bending configuration were taken with the use of two yokes relative to the neutral axis of the beam at quarter point locations (¼ and ¾ of the span). The shear span used for edgewise loading configurations was 54 inches, allowing for a minimum of 40% shear deflection in the five-point configuration per recommendations of Bradtmueller et al. (1994). The use of a 54 inch shear span also allowed for a half shear span to depth (a/d) ratio above the minimum value of 3.0, as recommended by Tingley and Kent (1996).

A loading rate of 0.25 in/minute was used for quarter-point bending tests. A slower loading rate of 0.125 in/minute was used for five-point bending tests to ensure adequate data acquisition. Electronic load-deflection data collected from the LVDTs and load cell (5,000 lb. capacity, ±50 lb. sensitivity) was processed using LabVIEW *Express* 7 software. The average inverse slopes of the load-deflection data collected for three repetitions of the quarter-point and five-point bending tests were used in equations 2-11 and 2-12 to solve for both the shear modulus and shear free modulus of elasticity.

3.2.2 ASTM D 198 Torsion Tests

ASTM D 198 (2003a) torsion testing was conducted using a MTS universal testing machine torsion actuator with torque cell (50,000 in.-lb., ±500 in.–lb. sensitivity) and end grip as illustrated in Figure 3-5. Torsion tests were performed using a 5,000 in-lb. load range card and ±50 degrees displacement range card. The gage length between end grip and actuator for all specimens was 135.5 inches. The actuator and end grip were both bolted to the laboratory floor eliminating movement and the possibility of any change in gage length.

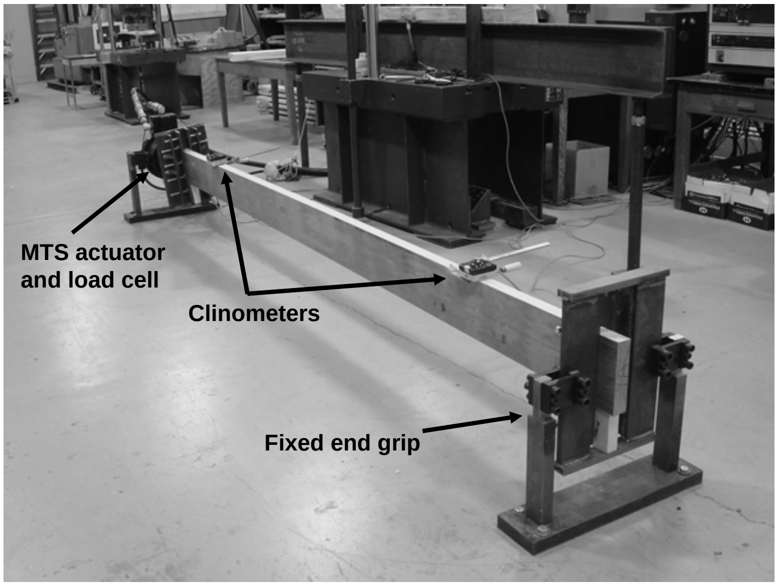


Figure 3-5: ASTM D 198 torsion test configuration with specimen under load.

ASTM D 198 (2003a) requires symmetrical angular deflection measurements be taken as far apart as possible along the length of the specimen. However, these measurements must be at least a distance of two times the largest cross sectional dimension from either clamp. Therefore, two angular deflection measurements were taken 20 inches from each clamp using two Accustar® II/DAS 20 Dual Axis Clinometers (20 degrees range, ±0.01 degrees sensitivity). The gage length between the clinometers measured 95.5 inches.

The loading rate recommended by ASTM D 198 (2003a) was 0.2325 degrees/in per minute. For a gage length of 95.5 inches, this recommendation corresponds to a loading rate of 22.2 degrees per minute. Due to the possibly of this loading rate inflicting strain beyond the proportional limit and the inadequacy of data acquisition at such a high rate, ASTM D 198 (2003a) recommendations were not followed. Previous research of Hindman (2004) has shown angular deflections of seven degrees are within the elastic range of test specimens. The results of this research coupled with the knowledge of the slowest bending tests taking approximately two minutes to achieve their designated loads resulted in a desired torsional loading rate of 3.5 degrees per minute. This loading rate was only used until angular deflections reached a maximum of seven degrees to ensure no permanent damage was inflicted on the test specimens.

Electronic torque data from the torque cell and angular deflection data from the two clinometers were processed using LabVIEW *Express* 7 software. Each specimen was loaded to seven degrees of angular deflection a total of three times. The average slope of the torque–angle deflection data was used in equation 2-6 to predict the apparent shear modulus of each specimen.

3.2.3 Moisture Content and Specific Gravity Sampling

Moisture content and specific gravity samples were cut after completion of all flexural and torsional testing. Procedures in accordance with ASTM D 4442, Method A (2003e) were followed for moisture content determination. After moisture content determination was complete, procedures in accordance with ASTM D 2395, Method B, Mode II (2003b) were followed for specific gravity determination.

3.3 Statistical Methods

The following statistical block diagram displays the number of specimens evaluated per material and test type. Each test type was repeated a total of three times.

Table 3-2: Statistical block diagram displaying the number of specimens evaluated per material and test type. Each test was also repeated a total of three times.

Material	**Test Type**		
	ASTM D 198 3-pt bending	ASTM D 198 Torsion	FPBT
LVL	16	16	16
MSR	24	24	24

Differences among material types were investigated per test method. Differences among the test methods were also investigated per material type. Differences in the calculated *E:G* ratios per test and material type were compared to the assumed *E:G* ratio of 16:1. Correlation of shear moduli and moduli of elasticity test results was attempted through linear regression modeling. All statistical calculations were made using a combination of SAS version 9.1 software and Microsoft® Excel.

3.3.1 Differences among Material Types

Differences among LVL and MSR lumber material types were evaluated by comparing average *E:G* ratios per test type. Percent differences were computed for each test method and the results for LVL and MSR lumber were compared to determine if differences in *E:G* values existed between the two material types.

3.3.2 Differences among Test Methods

Differences between test methods were analyzed according to a single-factor repeated measures experimental design. Tests were carried out with size $\alpha = 0.05$. Randomizing the order that test methods were applied to specimens was logistically impossible. However, any “ordering or carryover effect” was avoided by ensuring all testing remained within the elastic range of the specimens (Neter et al. 1996). The variability between LVL and MSR lumber material groups was not equal, thereby limiting an analysis of each test method over all material types. Upon recognition that at least one mean was significantly different, Tukey’s Honestly Significant Difference (HSD) multiple comparison analyses were performed.

3.3.3 Differences from Assumed *E:G* Ratio

The average *E:G* ratio of each test method per material type was compared to the *E:G* ratio of 16:1 commonly assumed of structural wooden members. Differences among the ratios were evaluated by comparing the percent differences between average *E:G* ratios of each test method per material type with the assumed *E:G* ratio of 16:1.

3.3.4 Regression Modeling

Correlation of shear moduli and moduli of elasticity test results per material type was attempted through linear regression modeling. Correlation of the shear moduli and moduli of elasticity results over both material types was also attempted. The success of the model was evaluated by examining the strength of relationship between variables (R^2 value). This method is similar to that previously used by Doyle (1968) and Doyle and Markwardt (1968) to compare the elastic properties of visually-graded solid-sawn lumber.

Chapter 4 Results and Discussion

The following chapter will discuss the results of the experimental methods described in Chapter 4. All testing for this research project was conducted in the Wood Engineering Laboratory of the Thomas M. Brooks Forest Products Research Center at Virginia Polytechnic Institute and State University. LVL specimens were obtained in late August 2005 with testing beginning in early October. MSR specimens were obtained in early October 2005 with testing beginning in early November. All testing was completed by late January of the following year. This chapter will discuss the results of each test method (three-point bending, torsion, and FPBT) described in Chapter 4 as well as the results of moisture content and specific gravity sampling. Comparisons of the elastic constants collected from the different test methods will also be included.

4.1 Moisture Content and Specific Gravity Results

Conditioning of the specimens under controlled environmental conditions was logistically impossible due to their large size. However, the specimens were stored a minimum of one month prior to testing in the Engineering Laboratory of the Brooks Forest Products Center to reduce moisture content variability between specimens. Temperature and relative humidity data were also periodically monitored throughout the conditioning and testing phases of the project. Ambient conditions of the laboratory were fairly constant at 71.4° Fahrenheit (21.9° Celsius) and 29.1 % relative humidity. An equilibrium moisture content of 4.7% was calculated for these environmental conditions. Figure 4-1 shows the temperature and relative humidity data collected throughout the conditioning and testing phases of the experiment.

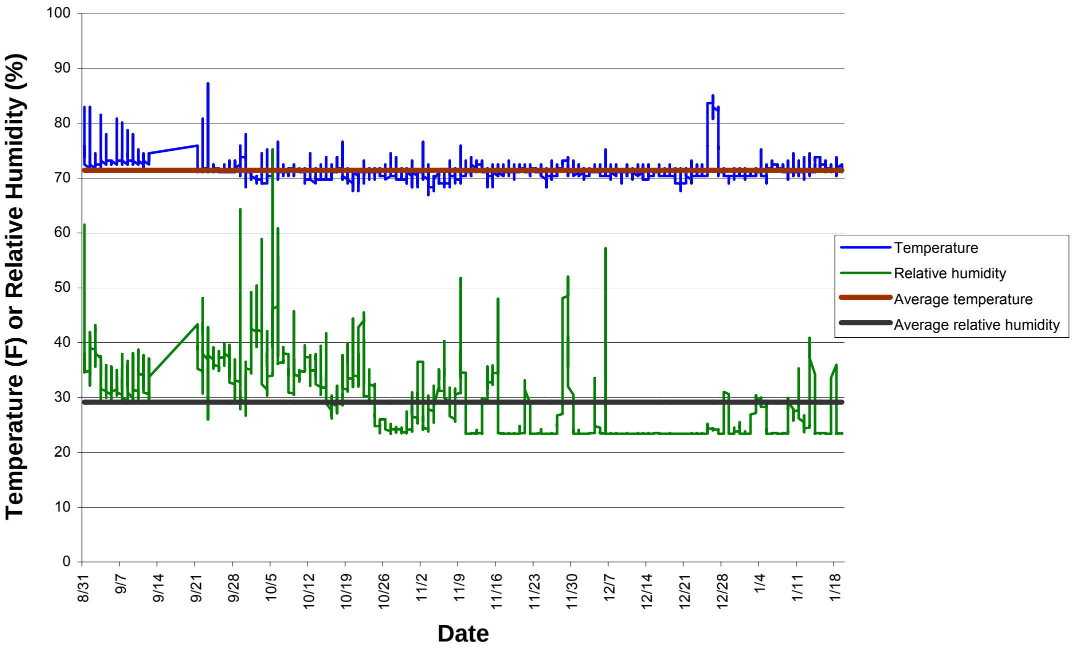


Figure 4-1: Temperature and relative humidity conditions of the testing laboratory throughout conditioning and testing phases of the experiment.

After the completion of testing, specific gravity and moisture content samples were cut from the center of a section one inch from the end of each specimen. The sample was cut to approximately 1”x 2” dimensions. An effort to retain the original dimensions of the specimens was made to facilitate their use in future tests. However, a sacrificial specimen was taken from each material group to determine if a moisture gradient was present along the length of the specimen. The results of this study showed no moisture gradient effect.

Table 4-1 summarizes the average moisture content and specific gravity of the LVL and MSR lumber specimens. The COV of the moisture content and specific gravity are also included. A complete summary of all data collected for moisture content and specific gravity sampling is included in Appendix B.

Table 4-1: Summary of average moisture content and specific gravity results for LVL and MSR lumber specimens.

Material	Moisture Content (COV)	Specific Gravity (COV)
LVL	4.9% (6.3%)	0.67 (2.4%)
MSR	5.8% (4.4%)	0.62 (9.1%)

The average moisture content of LVL specimens was 4.9% with a COV of 6.3%. The average moisture content of MSR lumber specimens was 5.8% with a COV of 4.1%. The equilibrium moisture content (EMC) calculated for the ambient conditions of the testing laboratory was 4.7%. The average moisture contents of LVL and MSR specimens were both within approximately one percent of the EMC. The lower initial moisture content of the LVL specimens may have contributed to their ability to attain a moisture content closer to EMC than the MSR lumber specimens.

The average specific gravity of the LVL specimens was 0.67 with a COV of 2.4%. The average specific gravity of the MSR specimens was 0.62 with a COV of 9.1%. The specific gravity of the LVL was expected to be higher than the specific gravity of the MSR lumber due to the presence of adhesive bond lines between veneer layers.

4.2 ASTM D 198 Three-Point Bending Results

An example of load-deflection data collected during the ASTM D 198 three-point bending test is provided in Appendix C. Load-deflection data for the three-point bending test was collected at five different spans per specimen. The resulting slopes calculated from this data were highly variable. In order to reduce the variability of data collected for a specimen, the load-deflection data from one span, or in some cases, two spans, were excluded from the regression analysis. The decision to exclude data was made if these points were considered outliers and a significant improvement in the fit (R^2 values) of the data was observed upon its removal.

The criteria set for data exclusion included specimens with an R^2 value of less than 80%. If the R^2 value of the specimen reached 80% upon removal of one data point further modification was considered unnecessary. With removal of only one data point, the

ASTM D 198 three-point bending requirement of a minimum of four tested spans was still met. However, if the removal one data point was insufficient in raising the R^2 value to the 80% cutoff value, two data points were eliminated. Though the minimum requirement of four spans was no longer satisfied when two data points were excluded from the regression analysis, significant improvement in the R^2 value and reasonableness of the data deemed such exclusion appropriate. A complete summary of all collected data for the ASTM D 198 three-point test is provided in Appendix D.

4.2.1 Shear and Elastic Property Determination for LVL: Three-point Bending

The edgewise shear moduli (G_{12}) and moduli of elasticity (E_1) of LVL specimens as determined by ASTM D 198 (2003a) three-point bending are presented in Table 4-2. The average and COV of the collected data are also included. The average edgewise shear modulus (G_{12}) of the LVL specimens was 1.05×10^5 psi (0.724 GPa) with a COV of 36.3%. Such a large COV is evidence of the amount of variability observed when evaluating the shear modulus according to ASTM D 198 three-point bending. The average edgewise modulus of elasticity (E_1) was 2.84×10^6 psi (19.6 GPa), a total of 49.5% greater than the manufacturer's moduli of elasticity rating of 1.9×10^6 psi (13.1 GPa). The COV of the moduli of elasticity determined according to ASTM D 198 three-point bending was 12.2%. A COV of this magnitude is reasonable for LVL (Smulski 1997).

Table 4-2: Summary of edgewise shear moduli (G_{12}), moduli of elasticity (E_1), and R^2 values of LVL specimens as determined by ASTM D 198 (2003a) three-point bending.

Specimen	G_{12} psi (Gpa)	E_1 psi (Gpa)	R^2	Specimen	G_{12} psi (Gpa)	E_1 psi (Gpa)	R^2
LVL-1[1]	1.01e5 (0.693)	2.79e6 (19.2)	94.4%	LVL-10[1]	1.60e5 (1.10)	2.35e6 (16.2)	83.0%
LVL-2	8.21e4 (0.566)	2.97e6 (20.5)	94.3%	LVL-11[1]	6.51e4 (0.449)	3.30e6 (22.7)	97.7%
LVL-3	5.91e4 (0.407)	3.33e6 (23.0)	99.4%	LVL-12	8.98e4 (0.618)	3.11e6 (21.5)	88.7%
LVL-4	6.53e4 (0.450)	3.31e6 (22.8)	94.6%	LVL-13	9.22e4 (0.636)	3.10e6 (21.4)	91.0%
LVL-5[1]	9.87e4 (0.680)	2.74e6 (18.9)	95.4%	LVL-14[1]	8.13e4 (0.561)	3.00e6 (20.7)	84.7%
LVL-6[1]	1.28e5 (0.881)	2.80e6 (19.3)	95.6%	LVL-15[1]	1.14e5 (0.783)	2.69e6 (18.6)	80.8%
LVL-7[1]	1.52e5 (1.05)	2.43e6 (16.8)	89.3%	LVL-16	8.53e5 (0.588)	2.69e6 (18.5)	96.9%
LVL-8	1.09e5 (0.748)	2.55e6 (17.6)	90.7%	**Average**	**1.05e5 (0.724)**	**2.84e6 (19.6)**	**92.2%**
LVL-9[1]	1.98e5 (1.37)	2.26e6 (15.6)	98.8%	**COV**	**36.3%**	**12.2%**	**6.2%**

[1] Load-deflection data from one of the five tested spans is excluded from the analysis. The point was excluded due to a significant improvement in the fit of the data upon its removal.

The COV of the shear moduli data was much greater than the COV of the moduli of elasticity data. It is possible that the large difference in the observed COV between the two material properties indicates that the three-point bending test configuration does not permit enough shear deflection to effectively isolate the shear modulus.

The regression analyses of the data used to determine the shear moduli and true moduli of elasticity had an average R^2 value of 92.2% with a COV of 6.2%. R^2 values ranged from a minimum of 80.8% to a maximum of 99.4%. As mentioned previously, the load-deflection data from one span of a particular specimen may have been excluded from the regression analysis in order to improve the fit of the data. The specimens with excluded data are so noted in Table 4-2. A summary of all data used in the solution of each specimen's material properties, including those excluded from the determination of elastic properties in the above summary, are included in Appendix E.

4.2.2 Shear and Elastic Property Determination for MSR: Three-point Bending

The edgewise shear moduli (G_{12}) and moduli of elasticity (E_1) of MSR lumber specimens as determined by ASTM D 198 (2003a) three-point bending are presented in Table 4-3. The average and COV of the collected data are also included.

Table 4-3: Summary of edgewise shear moduli (G_{12})[3], moduli of elasticity (E_1), and R^2 values of MSR lumber specimens as determined by ASTM D 198 (2003a) three-point bending.

Specimen	G_{12} psi (Gpa)	E_1 psi (Gpa)	R^2	Specimen	G_{12} psi (Gpa)	E_1 psi (Gpa)	R^2
MSR-1[1]	1.05e5 (0.724)	2.36e6 (16.3)	96.0%	MSR-14[2]	1.85e5 (1.28)	2.11e6 (14.6)	86.9%
MSR-2[2]	2.07e5 (1.43)	3.18e6 (21.9)	89.6%	MSR-15[2]	1.92e5 (1.32)	3.01e6 (20.7)	87.5%
MSR-3	1.49e5 (1.03)	2.27e6 (15.6)	90.6%	MSR-16	8.39e4 (0.579)	3.02e6 (20.8)	93.0%
MSR-4	1.31e5 (0.901)	2.32e6 (16.0)	82.5%	MSR-17[1]	1.23e5 (0.848)	3.08e6 (21.3)	82.5%
MSR-5[1]	1.08e5 (0.746)	2.20e6 (15.2)	98.8%	MSR-18[1]	1.21e5 (0.832)	3.10e6 (21.4)	99.9%
MSR-6	8.52e4 (0.588)	2.79e6 (19.2)	80.9%	MSR-19[1]	4.64e4 (0.320)	3.47e6 (23.9)	89.3%
MSR-7	2.26e5 (1.56)	2.07e6 (14.3)	87.5%	MSR-20	1.27e5 (0.876)	2.16e6 (14.9)	97.4%
MSR-8[1]	6.58e4 (0.454)	2.47e6 (17.1)	95.5%	MSR-21	8.104e4 (0.559)	2.85e6 (19.6)	87.8%
MSR-9	1.22e5 (0.838)	2.38e6 (16.4)	93.5%	MSR-22[2]	2.12e5 (1.46)	2.18e6 (15.1)	93.8%
MSR-10	7.13e4 (0.492)	2.35e6 (16.2)	99.2%	MSR-23[1]	1.09e5 (0.752)	2.25e6 (15.5)	91.8%
MSR-11	9.07e4 (0.625)	2.32e6 (16.0)	94.5%	MSR-24	7.58e4 (0.522)	2.26e6 (15.6)	96.7%
MSR-12[2]	3.77e5 (2.60)	2.31e6 (15.9)	88.4%	**Average**	**1.31e5 (0.903)**	**2.53e6 (17.4)**	**91.8%**
MSR-13[2]	5.05e4 (0.348)	2.20e6 (15.2)	98.9%	**COV**	**56.0%**	**16.2%**	**6.1%**

[1] Load-deflection data from one of the five tested spans is excluded from the analysis.

[2] Load-deflection data from two of the five tested spans is excluded from the analysis used in material property determination.

[3] G_{12} property for solid sawn lumber is not a material but an element property due to the lack of alignment between orthotropic and geometric axes.

The average edgewise shear modulus (G_{12}) of the MSR lumber specimens was 1.31x10^5 psi (0.903 GPa) with a COV of 56.0%. This large COV again demonstrates the variability of shear moduli data calculated from ASTM D 198 three-point bending test data. The COV collected for MSR lumber specimens (56.0%) was higher than the COV collected for LVL specimens (36.3%). A larger COV was expected due to the greater variability of solid sawn wood in comparison to wood-based composite materials (Smulski 1997).

The average edgewise modulus of elasticity (E_1) was 2.53x10^6 psi (17.4 GPa), a total of 26.5% higher than the manufacturer's rating of 2.0x10^6 psi. The COV of the moduli of elasticity data (16.2%) collected from ASTM D 198 three-point bending was much lower than the COV calculated for the collected shear moduli data (56.0%). For moduli of elasticity data, a COV of this magnitude is reasonable. Similar to the results for LVL specimens, a large difference in COVs calculated for moduli of elasticity and shear moduli terms was observed. This result could possibly indicate that the amount of shear deflection observed in the ASTM D 198 three-point bending is inadequate to use in shear property evaluation.

The regression analyses of the data used to determine the material properties had an average R^2 value of 91.8% with a COV of 6.1%. R^2 values ranged from a minimum of 80.9% to a maximum of 99.9%. As mentioned previously, the outliers from one or in some cases, two spans, may have been excluded from the regression analysis to improve the fit of the data. The specimens with data excluded from the regression analyses are so noted in Table 4-3. A summary of all data used in the solution of each specimen's material properties, including those excluded from the determination of elastic properties in the above summary, are included in Appendix E.

4.3 ASTM D 198 Torsion Results

The torsion test configuration posed no problems in the shear moduli determination of LVL specimens. However, many of the MSR lumber specimens had varying degrees of twist and cup. The occurrence of such defects did not allow the specimens to be easily fastened into the end grips. Provisions to straighten the boards in the fixture were avoided due to the possibility of damaging the specimens. It was also recognized that straightening a board in the fixture induced a large amount of internal stress within the specimen. Therefore, some of the MSR lumber specimens were not able to be fastened into the torsion fixture with both ends perpendicular to the grip. An example of torque-angular deflection data collected during the ASTM D 198 torsion test is provided in Appendix C. A complete summary of all collected data for ASTM D 198 torsion testing is provided in Appendix F.

4.3.1 Shear Property Determination for LVL: Torsion

The apparent shear moduli as determined by the ASTM D 198 (2003a) torsion test for LVL specimens are presented in Table 4-4. The average and COV of the collected data are also included. It should be noted that the shear moduli determined by ASTM D 198 is termed apparent because it is combination of both G_{12} and G_{13} shear moduli. The research of Hindman (2003) and Hindman (1999) has shown the G_{13} material property to be significantly lower than the G_{12} material property.

Table 4-4: Summary of apparent shear moduli for LVL specimens as determined by the ASTM D 198 torsion test.

Specimen	Apparent Shear Moduli psi (Gpa)	Specimen	Apparent Shear Moduli psi (Gpa)
LVL-1	1.60e5 (1.10)	LVL-10	1.51e5 (1.04)
LVL-2	1.57e5 (1.08)	LVL-11	1.45e5 (1.00)
LVL-3	1.53e5 (1.05)	LVL-12	1.54e5 (1.06)
LVL-4	1.57e5 (1.08)	LVL-13	1.41e5 (0.970)
LVL-5	1.45e5 (0.998)	LVL-14	1.45e5 (1.00)
LVL-6	1.50e5 (1.03)	LVL-15	1.55e5 (1.07)
LVL-7	1.53e5 (1.05)	LVL-16	1.47e5 (1.01)
LVL-8	1.48e5 (1.02)	**Average**	1.51e5 (1.04)
LVL-9	1.54e5 (1.06)	**COV**	3.5%

The average apparent shear modulus for LVL specimens as determined by the ASTM D 198 torsion test was 1.51×10^5 psi (1.04 GPa). The COV of LVL shear moduli determined by the torsion test was 3.5%, by far the lowest of the three test methods. The low variability of torsion shear moduli results is likely related to this particular test producing a pure state of shear stress in the specimen. Moduli of elasticity values for the specimens are not included in Table 4-4 because this property could not be determined from the torsion test method alone. The manufacturer's rating for the average modulus of elasticity for the LVL was 1.9×10^6 psi (13.1 GPa).

4.3.2 Shear Property Determination for MSR: Torsion

The apparent shear moduli of the MSR lumber specimens as determined by the ASTM D 198 (2003a) torsion test are presented in Table 4-5. The average and COV of the collected data are also included.

Table 4-5: Summary of apparent shear moduli for MSR lumber specimens as determined by the ASTM D 198 torsion test.

Specimen	Apparent Shear Modulus psi (Gpa)	Specimen	Apparent Shear Modulus psi (Gpa)
MSR-1	1.66e5 (1.15)	MSR-14	1.72e5 (1.18)
MSR-2	1.58e5 (1.09)	MSR-15	1.70e5 (1.17)
MSR-3	1.58e5 (1.09)	MSR-16	1.69e5 (1.17)
MSR-4	1.65e5 (1.14)	MSR-17	1.52e5 (1.05)
MSR-5	1.61e5 (1.11)	MSR-18	1.68e5 (1.16)
MSR-6	1.50e5 (1.03)	MSR-19	1.62e5 (1.11)
MSR-7	1.41e5 (0.974)	MSR-20	1.71e5 (1.18)
MSR-8	1.86e5 (1.28)	MSR-21	1.67e5 (1.15)
MSR-9	1.84e5 (1.27)	MSR-22	1.81e5 (1.25)
MSR-10	1.73e5 (1.19)	MSR-23	1.99e5 (1.37)
MSR-11	1.82e5 (1.25)	MSR-24	1.79e5 (1.23)
MSR-12	1.62e5 (1.12)	**Average**	1.68e5 (1.16)
MSR-13	1.56e5 (1.07)	**COV**	7.5%

The average apparent shear modulus of the MSR lumber specimens as determined by the ASTM D 198 torsion test was 1.68x10^5 psi (1.16 GPa). The COV of the shear moduli was 7.5%, which was lower than the flexural test method COV values. Again, the low variability of measured shear moduli values is likely related to the torsion test inducing a state of pure shear stress within the specimen. The COV of MSR lumber specimens was higher than that determined for LVL specimens. This result was expected due to the greater uniformity of wood-based composite materials (Smulski 1997). Moduli of elasticity values are not included in Table 4-5 because this property could not be determined from the torsion test method alone. The manufacturer's modulus of elasticity rating for the MSR lumber was 2.0x10^6 psi (13.8 GPa).

4.4 Test for Material Damage during Torsion Testing

After the completion of torsion testing, three specimens were randomly selected from each material group and retested in the three-point bending test configuration at the 10 foot span. The slopes of load-deflection data before and after torsion testing were compared to determine if any non-elastic stress levels were attained during torsion testing. Results of a paired t-test ($\alpha = 0.05$) for each material type determined that neither the LVL nor the MSR lumber specimens experienced stress levels above their proportional limits. Specifically, as noted in Table 4-6, the resulting p-values were 0.194 and 0.209 for the LVL and MSR lumber specimens, respectively. The magnitude of these test statistics were initially considered suspect, but upon examination it was determined that in most cases the retested slopes were higher than the original slopes. Had the retested slopes been lower than the original slopes, additional investigation and possible omission of the specimen from further testing may have been warranted.

Table 4-6: Summary of paired t-test results for the original and retested slopes of load-deflection data taken prior to and after torsion testing ($\alpha = 0.05$).

Specimen	Original Slope of Load-Deflection Data lb/in (N/m)	Retested Slope of Load-Deflection Data lb/in (N/m)	p-value
LVL-9	3984.9 (697870)	4220.9 (739200)	0.194
LVL-10	4062.6 (711480)	4262.5 (746470)	
LVL-14	4822.5 (844550)	4818.4 (843820)	
MSR-7	2434.2 (426290)	2447.0 (428540)	0.209
MSR-8	2647.7 (463680)	2674.7 (469410)	
MSR-12	2848.2 (498800)	2937.7 (514470)	

4.5 Five-Point Bending Test (FPBT) Results

Testing according to the FPBT posed no problem for LVL or MSR lumber specimens. An example of quarter-point and five-point bending load-deflection data collected during the FPBT is provided in Appendix C. A complete summary of all collected data for the FPBT is provided in Appendix G.

4.5.1 Shear and Elastic Property Determination for LVL: FPBT

The edgewise shear moduli (G_{12}) and moduli of elasticity (E_1) of the LVL specimens as determined by the FPBT are presented in Table 4-7. The average and COV of the collected data are also included. The average edgewise shear modulus (G_{12}) of the LVL specimens was 1.80x10^5 psi (1.14GPa) with a COV of 14.2%. The COV of the shear moduli was considered within a reasonable range (Smulski 1997).

Table 4-7: Summary of edgewise shear moduli (G_{12}) and moduli of elasticity (E_1) of LVL specimens as determined by the FPBT method.

Specimen	G_{12} psi (Gpa)	E_1 psi (Gpa)	Specimen	G_{12} psi (Gpa)	E_1 psi (Gpa)
LVL-1	1.58e5 (1.09)	3.28e6 (22.6)	**LVL-10**	1.56e5 (1.08)	2.69e6 (18.5)
LVL-2	1.99e5 (1.37)	2.79e6 (19.2)	**LVL-11**	2.05e5 (1.41)	3.04e6 (21.0)
LVL-3	1.79e5 (1.23)	2.94e6 (20.3)	**LVL-12**	1.92e5 (1.32)	3.44e6 (23.7)
LVL-4	1.71e5 (1.18)	3.26e6 (22.4)	**LVL-13**	1.36e5 (0.934)	3.24e6 (22.4)
LVL-5	1.89e5 (1.30)	2.67e6 (18.4)	**LVL-14**	2.39e5 (1.65)	2.98e6 (20.5)
LVL-6	1.97e5 (1.36)	2.98e6 (20.5)	**LVL-15**	1.57e5 (1.08)	2.84e6 (19.6)
LVL-7	1.55e5 (1.07)	2.71e6 (18.7)	**LVL-16**	1.65e5 (1.14)	2.68e6 (18.4)
LVL-8	1.97e5 (1.36)	2.54e6 (17.5)	**Average**	1.80e5 (1.14)	2.91e6 (20.1)
LVL-9	1.90e5 (1.31)	2.53e6 (17.5)	**COV**	14.2%	9.6%

The average edgewise modulus of elasticity (E_1) was 2.91x10^6 psi (20.1 GPa) with a COV of 9.6%. The average modulus of elasticity was 53.1% higher than the manufacturer's rating of 1.9x10^6 psi (13.1 GPa). Hindman (2003) also found the moduli of elasticity of LVL to be higher than the manufacturer's rating when testing according to the FPBT. The COV of the moduli of elasticity data (9.6%) was within a reasonable range (Smulski 1997).

4.5.2 Shear and Elastic Property Determination for MSR: FPBT

The edgewise shear moduli (G_{12}) and moduli of elasticity (E_1) of the MSR lumber specimens as determined by the FPBT are presented in Table 4-8. The average and COV of the collected data are also included. The average edgewise shear modulus (G_{12}) of the MSR lumber specimens was 1.14x10^5 psi (0.789 GPa) with a COV of 24.1%. The COV of the measured shear moduli was considered to be within a reasonable range (Smulski 1997).

Table 4-8: Summary of edgewise shear moduli (G_{12})[1] and moduli of elasticity (E_1) of MSR lumber specimens as determined by the FPBT method.

Specimen	G_{12} psi (Gpa)	E_1 psi (Gpa)	Specimen	G_{12} psi (Gpa)	E_1 psi (Gpa)
MSR-1	1.43e5 (0.988)	2.36e6 (16.3)	**MSR-14**	1.72e5 (1.18)	2.22e6 (15.3)
MSR-2	9.11e4 (0.628)	3.43e6 (23.6)	**MSR-15**	5.89e4 (0.406)	3.42e6 (23.6)
MSR-3	1.19e5 (0.823)	2.29e6 (15.8)	**MSR-16**	8.68e4 (0.599)	3.11e6 (21.5)
MSR-4	1.21e5 (0.837)	2.38e6 (16.4)	**MSR-17**	1.34e5 (0.924)	3.15e6 (21.7)
MSR-5	7.69e4 (0.530)	2.34e6 (16.1)	**MSR-18**	1.18e5 (0.811)	3.03e6 (20.9)
MSR-6	1.20e5 (0.826)	2.51e6 (17.3)	**MSR-19**	1.53e5 (1.06)	2.64e6 (18.2)
MSR-7	7.34e4 (0.506)	2.73e6 (18.8)	**MSR-20**	1.23e5 (0.850)	2.32e6 (16.0)
MSR-8	1.17e5 (0.809)	2.15e6 (14.8)	**MSR-21**	1.21e5 (0.831)	2.68e6 (18.5)
MSR-9	1.05e5 (0.723)	2.33e6 (16.0)	**MSR-22**	1.09e5 (0.753)	2.24e6 (15.4)
MSR-10	1.19e5 (0.818)	2.19e6 (15.1)	**MSR-23**	1.10e5 (0.756)	2.47e6 (17.0)
MSR-11	1.06e5 (0.734)	2.39e6 (16.5)	**MSR-24**	1.61e5 (1.11)	2.05e6 (14.1)
MSR-12	1.27e5 (0.877)	2.34e6 (16.1)	**Average**	1.14e5 (0.789)	2.54e6 (17.5)
MSR-13	7.99e5 (0.551)	2.19e6 (15.1)	**COV**	24.1%	15.8%

[1] G_{12} property for solid sawn lumber is not a material but an element property due to the lack of alignment between orthotropic and geometric axes.

The average edgewise modulus of elasticity (E_1) was 2.54x10^6 psi (17.5 GPa), a total of 27.0% higher than the manufacturer's rating of 2.0 x 10^6 psi (13.8 GPa). Hindman (2003) also found the modulus of elasticity of MSR lumber to be higher than the manufacturer's rating when tested according to the FPBT. The COV of the moduli of elasticity data (15.8%) was considered to be reasonable for MSR lumber (Smulski 1997).

4.6 Test for Material Damage during the FPBT

After completion of the FPBT, three specimens were randomly selected from each material group and retested in the three-point bending test configuration at the 10 foot span. The slopes of load-deflection data before and after the FPBT were compared to determine if any non-elastic stress levels were attained during the testing. Results of a paired t-test (α = 0.05) for each material type determined that neither the LVL nor MSR lumber experienced stress levels above their proportional limits. Specifically, as noted in Table 4-9, the resulting p-values for LVL and MSR lumber specimens were 0.784 and 0.875, respectively. Therefore, the results of statistical comparisons made before and after the FPBT and the torsion test (Section 5.4) indicate no material damage occurred during the sequential testing phases of this experiment.

Table 4-9: Summary of ANOVA results for the original and retested slopes of load-deflection data taken prior to and after the FPBT (α = 0.05).

Specimen	Original Slope of Load-Deflection Data lb/in (N/m)	Retested Slope of Load-Deflection Data lb/in (N/m)	p-value
LVL-3	4944.2 (865860)	5011.9 (877710)	0.784
LVL-6	4713.0 (825380)	4762.0 (833960)	
LVL-13	5099.8 (893110)	4903.3 (858700)	
MSR-3	2609.5 (456990)	2687.2 (470600)	0.875
MSR-9	2716.9 (475800)	2780.2 (486880)	
MSR-10	2585.6 (452800)	2476.5 (433700)	

4.7 Differences among Material Types

The average *E:G* ratios of LVL and MSR lumber specimens based on the test method used for evaluation are summarized in Table 4-10. The percent difference between the *E:G* ratios of LVL and MSR lumber are also included. A complete listing of all *E:G* ratios are provided in Appendix H.

Table 4-10: Summary of average *E:G* ratios for LVL and MSR lumber specimens based on the test method used for evaluation.

Test Type	LVL	MSR	Percent Difference[1]
ASTM D 198 Three-point bending	27.1	19.3	-40%
ASTM D 198 Torsion[2]	18.8	15.1	-25%
FPBT	16.0	22.2	28%

[1] Percent Difference = (MSR-LVL)/MSR *100

[2] The average moduli of elasticity used in the *E:G* ratio for ASTM D 198 torsion was determined by ASTM D 198 three-point bending.

The average *E:G* ratios for MSR lumber and LVL specimens tested via ASTM D 198 three-point bending were 19.3 and 27.1, respectively. The average MSR lumber *E:G* ratio was 40% lower than the average LVL *E:G* ratio. The average *E:G* ratios for MSR lumber and LVL specimens tested via the FPBT were 22.2 and 16.0, respectively, with the average LVL *E:G* ratio 28% lower than the average MSR lumber *E:G* ratio. According to flexural test results, the trend in *E:G* ratios between LVL and MSR lumber material groups was not consistent. This result was unexpected as the stress distributions of the flexural tests are similar. However, it should be noted that the FPBT span remained constant at 9 feet while the spans used in ASTM D 198 three-point bending ranged from 7 to 11 feet.

The average *E:G* ratios of MSR lumber and LVL specimens tested via ASTM D 198 torsion were 15.1 and 18.8, respectively. The moduli of elasticity terms used in these ratios were determined by ASTM D 198 three-point bending tests. According to the results of ASTM D 198 torsion testing, the average MSR *E:G* ratio was 25% lower than the LVL *E:G* ratio. This result is not intuitive when the stress distribution of the torsion test and the intrinsic nature of the two material types are considered.

The location of maximum shear stress in a torsion test is along the perimeter of the cross section closest to the center axis of the specimen (Hibbeler 2000). A common practice in the construction of LVL is to incorporate a gradient of veneer stiffness through the thickness of the composite. Generally, veneers with the highest stiffness are stacked to the outside with veneers of lower stiffness ratings comprising the middle of the composite (Smulski 1997). Therefore, the presence of the stiffest veneers at a location of maximum shear stress would act to increase the measured shear modulus, thereby decreasing the *E:G* ratio. No gradient of stiffness is incorporated into solid sawn lumber specimens, and therefore, an increase in the shear modulus would not likely be observed. With the modulus of elasticity held constant, the resulting *E:G* ratio would be larger. However, the results of this research did not follow this reasoning. The LVL *E:G* ratio was measured to be 25% higher than the MSR *E:G* ratio.

Figure 4-2 is a graphical representation of the average *E:G* ratios of LVL and MSR lumber specimens based on the test method used for evaluation. The difference in the *E:G* ratios of LVL and MSR lumber when evaluated by the standard ASTM D three-point bending test and the FPBT are apparent. According to the non-standard FPBT, the MSR lumber *E:G* ratio was higher than the LVL *E:G* ratio. However, when evaluated by ASTM D 198 three-point bending and ASTM D 198 torsion, the MSR lumber had a lower average *E:G* ratio than the LVL. This result is more intuitive than the former when the intrinsic nature of MSR lumber is considered.

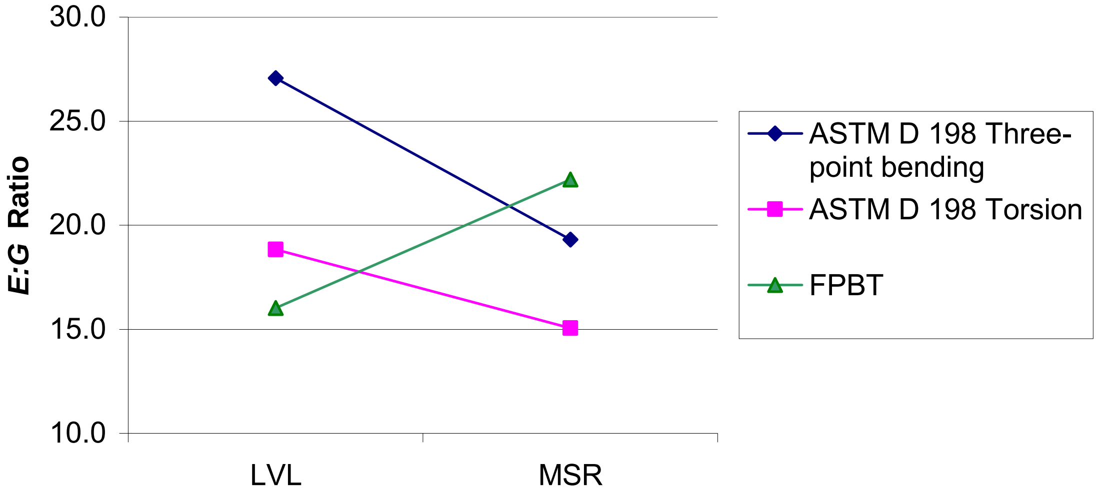


Figure 4-2: Summary of average E:G ratios for LVL and MSR specimens based on the test method used for evaluation.

The present resource base of solid sawn wood is of relatively small diameter. The lumber sawn from smaller diameter trees is more prone to defects such as the occurrence of pith and juvenile wood. Most of the MSR lumber tested in this research effort either contained pith or were taken from regions of the stem that were within a close proximity to the pith. Therefore, it is also likely that the majority of the tested lumber also contained some proportion of juvenile wood. Conversely, the majority of the veneer used in the manufacture of the LVL tested in this project did not contain pith. LVL veneer is rotary peeled, indicating that the pith of the log would remain in the peeler core and not be included in the veneer.

The occurrence of juvenile wood and pith generally negatively impact the overall mechanical properties of wood. In fact, the presence of pith in sawn lumber is generally indicative of a high proportion of knots because many knots originate from the pith (Haygreen and Bowyer 1996). Though the presence of knots and juvenile wood has been shown to decrease the modulus of elasticity, the occurrence of knots has been shown to increase the shear modulus of wood in the research of Chui (1991). Therefore, the occurrence of knots in solid sawn lumber could increase the measured shear modulus while simultaneously decreasing the measured modulus of elasticity. Such an effect would decrease the *E:G* ratio as was observed for the MSR lumber tested via the ASTM D 198 three-point bending test and the ASTM D 198 torsion test. An increase in the measured shear modulus of LVL would not be apparent because its manufacture does not permit the concentration of knots in any one location.

4.8 Comparison of Test Method Results

4.8.1 Shear Moduli Comparison of LVL

The average shear moduli results for the LVL specimens are listed in Table 4-11. A single-factor repeated measures analysis of variance (ANOVA) ($\alpha = 0.05$) statistical analysis with the test types as treatments factors and specimens as blocking factors showed a significant difference between the shear moduli determined from the different test types (p-value = 0.0001). Subsequent multiple comparison analysis according to Tukey's Honestly Significant Difference (HSD) showed a significant difference in the mean shear moduli determined by all of the test methods. According to this analysis, the average shear modulus determined by ASTM D 198 torsion was significantly higher than that determined by ASTM D 198 three-point bending. Furthermore, the average shear modulus determined by the FPBT was significantly higher than the average shear modulus determined by the torsion test method.

Graphically, this relationship can be expressed as the following:

FPBT > ASTM D 198 torsion > ASTM D 198 three-point bending.

Table 4-11: Summary of LVL average shear moduli determined by the three test methods.

Material	Test Method	Average Shear Modulus psi (Gpa)	COV	p-value
LVL	ASTM D 198 three-point bending	1.05e5 (0.724)	36.3%	0.0001
	ASTM D 198 torsion	1.51e5 (1.04)	3.5%	
	FPBT	1.80e5 (1.24)	14.2%	

The shear modulus measured by the ASTM D 198 torsion test is an apparent shear modulus, which is not equivalent to G_{12} measured by the flexural test methods. The apparent shear modulus measured by the torsion test is actually a combination of both G_{12} and G_{13} material properties. The research of Hindman (2003) and Hindman (1999), has shown G_{13} to be significantly smaller than G_{12}. Therefore, the G_{13} contribution to the apparent shear modulus measured by the torsion test is likely to decrease the magnitude of the apparent shear modulus. It is also probable that if the G_{12} component of the apparent shear modulus was isolated, it would be higher in magnitude than the apparent shear modulus reported in Table 4-11.

4.8.2 Shear Moduli Comparisons of MSR

The average shear moduli results for the MSR lumber specimens are listed in Table 4-12. A single-factor repeated measures ANOVA ($\alpha = 0.05$) statistical analysis with the test types as treatment factor levels and specimens as blocking factors showed a significant difference among the shear moduli determined by the different test types (p-value = 0.001).

Table 4-12: Summary of MSR lumber average shear moduli determined by the three test methods.

Material	Test Method	Average Shear Modulus psi (Gpa)	COV	p-value
MSR	ASTM D 198 three-point bending	1.31e5 (0.903)	56.0%	0.001
	ASTM D 198 torsion	1.68e5 (1.16)	7.5%	
	FPBT	1.14e5 (0.789)	24.1%	

Subsequent multiple comparison analysis according to Tukey's HSD showed a significant difference in the mean shear moduli determined by the FPBT and ASTM D 198 torsion test methods and also between the ASTM D 198 three-point bending and torsion tests. No significant difference in the average shear moduli as determined by ASTM D 198 three-point bending and the FPBT was observed. The large COV (56%) calculated for the ASTM D 198 three-point bending test is likely the cause of this lack of significance. However, the average shear moduli determined by the FPBT and ASTM D 198 three-point bending test were significantly lower than the average shear moduli determined by the torsion test method. Graphically, this relationship can be expressed as the following:

ASTM D 198 torsion > (FPBT = ASTM D 198 three-point bending).

4.8.3 Moduli of Elasticity Comparisons of LVL

The average moduli of elasticity results for the LVL specimens as determined by the two flexural tests are listed in Table 4-13. A pairwise t-test ($\alpha = 0.05$) of the moduli of elasticity for the LVL specimens as determined by ASTM D 198 three-point bending and the FPBT indicated no significant difference between the means (p-value = 0.227). Therefore, no significant difference in the average moduli of elasticity results for LVL specimens was observed.

Table 4-13: Summary of LVL average moduli of elasticity determined by ASTM D 198 three-point bending and the FPBT.

Material	Test Method	Average Modulus of Elasticity psi (Gpa)	COV	p-value
LVL	ASTM D 198 Three-point Bending	2.84e6 (19.6)	12.2%	0.227
	FPBT	2.91e6 (20.1)	9.6%	

4.8.4 Moduli of Elasticity Comparisons of MSR Lumber

The average moduli of elasticity of the MSR lumber specimens as determined by the two flexural tests are listed in Table 4-14. A pairwise t-test ($\alpha = 0.05$) of the moduli of elasticity results for the MSR lumber specimens as determined by ASTM D 198 three-point bending and the FPBT indicated no significant difference between the means (p-value = 0.850). Therefore, no significant difference in the average moduli of elasticity results for MSR lumber specimens was observed.

Table 4-14: Summary of MSR lumber specimens average moduli of elasticity determined by ASTM D 198 three-point bending and the FPBT.

Material	Test Method	Average Modulus of Elasticity psi (Gpa)	COV	p-value
MSR	ASTM D 198 Three-point Bending	2.53e6 (17.4)	16.2%	0.850
	FPBT	2.54e6 (17.5)	15.8%	

The high magnitude of the moduli of elasticity results for both LVL and MSR lumber specimens was initially considered suspect. However, the lack of a significant difference between the moduli of elasticity results of the two flexural tests for both material types helped verify their accuracy. In addition, a small accelerometer study performed on the LVL specimens also produced moduli of elasticity within the same range as those reported in Table 4-13.

Figure 4-3 shows the percent difference between measured MOE values and the manufacturer's rated MOE value. The results of this comparison show that measured MOE values of the LVL specimens were consistently ~50% higher than the manufacturer's rating for MOE when measured by both the ASTM D 198 three-point bending test and the FPBT. Likewise, the measured MOE values of the MSR lumber specimens were consistently ~27% higher than the manufacturer's MOE when measured by these two test methods. The similarity of the percent differences between measured and manufacturer's rated MOE values further contests to the accuracy of the measured MOE values.

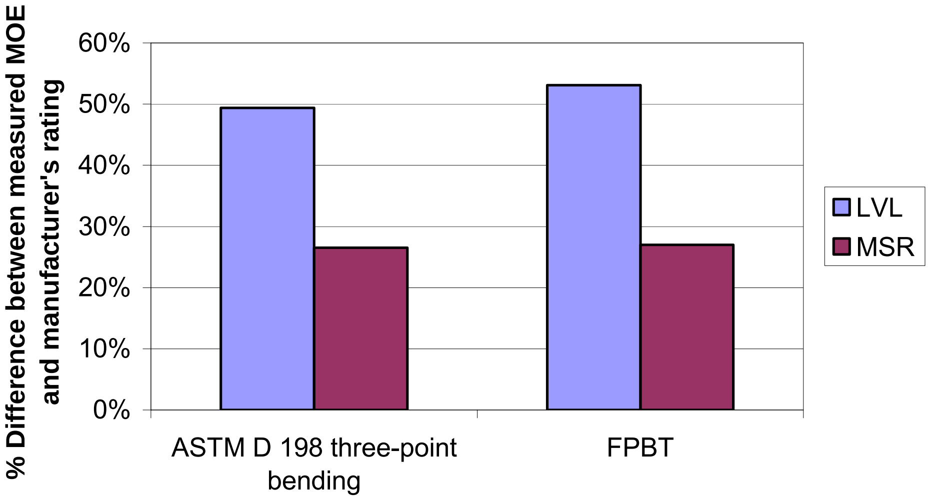


Figure 4-3: Percent difference between measured and manufacturer's rated MOE values.

Though the moduli of elasticity results determined by the flexural test methods showed no significant statistical difference for either material type, the shear moduli of the LVL specimens evaluated by these same test methods were significantly different. In fact, the LVL shear moduli were as much as 42% different when the moduli of elasticity were equal. Therefore, any difference in the *E:G* ratios determined by ASTM D 198 three-point bending and the FPBT for LVL specimens are contained only in the shear moduli term.

4.8.5 COV Comparison of Flexural Test Methods

Figure 4-4 displays the COV of shear moduli and moduli of elasticity data determined for the LVL by the flexural test methods. The COV of the modulus of elasticity data sets is relatively stable for both test methods. However, the variability present in the COV of the shear modulus data set determined by ASTM D 198 three-point bending is much greater than is observed for the FPBT. This result could possibly indicate that ASTM D 198 three-point bending does not produce an adequate amount of shear deflection to estimate the shear modulus.

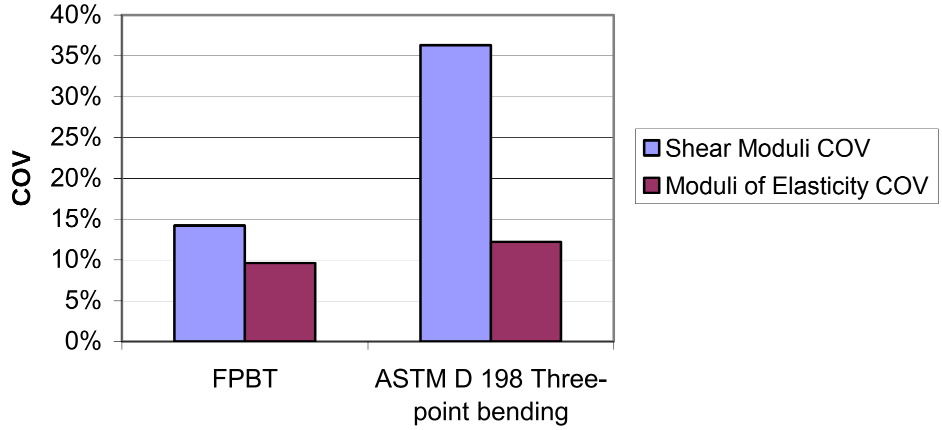


Figure 4-4: Summary of the COVs calculated for flexural shear moduli and moduli of elasticity for LVL specimens.

Figure 4-5 displays the COV of shear moduli and moduli of elasticity data determined for the MSR lumber by the flexural test methods. The COV of both moduli of elasticity data sets are similar. However, the variability present in the COV of shear moduli data sets determined by ASTM D 198 three-point bending is again much greater than is observed for the FPBT. This result is more evidence that ASTM D 198 three-point bending may not produce an adequate amount of shear deflection to estimate the shear modulus.

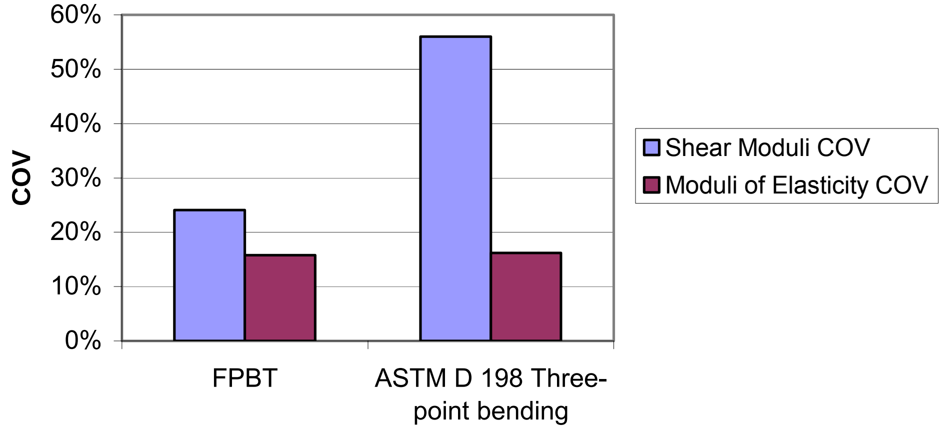


Figure 4-5: Summary of the COVs calculated for flexural shear moduli and moduli of elasticity for MSR specimens.

Table 4-15 displays the percentage of shear deflection produced by the flexural test setups at a nine foot span. Only 11% and 16% of the total beam deflection was due to shear in the ASTM D 198 three-point loading configuration for the MSR lumber and LVL, respectively. Approximately 55% and 52% of the total beam deflection was due to shear in the FPBT's five-point loading configuration for MSR and LVL, respectively. Therefore, the FPBT method produced approximately 35-40% more shear deflection than the three-point bending configuration.

Table 4-15: Percentage shear deflection produced by the flexural test methods at a nine foot span.

Material	ASTM D 198 Three-point bending	FPBT: Five-point configuration
MSR	11%	55%
LVL	16%	52%

An increased percentage of shear deflection could result in the measurement being less error prone. Therefore, the increase in measured shear deflection of the five-point loading configuration of the FPBT could have decreased the variability of the measured shear moduli data. Furthermore, the smaller percentage of shear deflection produced during the three-point bending test could be related to the increase in variability of the shear moduli data measured from this test method. The percentage of shear deflection measured from the ASTM D 198 three-point bending test remained low despite following aspect ratio recommendations. Therefore, imposing a minimum shear deflection requirement may be more appropriate than the aspect ratio constraints currently used in the ASTM D 198 (2003a) three-point bending test. However, in order to do so the tested spans would have to be reduced, which limits the applicability of this test on structurally sized specimens.

The variability of three-point bending test data may also be related to location of maximum stress induced in this loading configuration. The shear and moment diagram of the three-point bending test is illustrated in Figure 4-6.

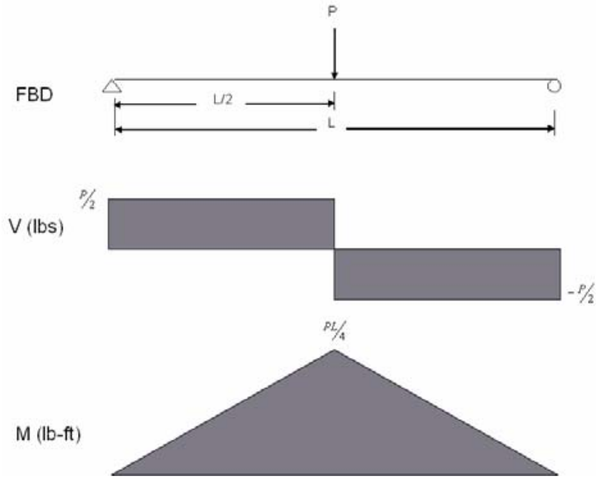


Figure 4-6: Shear and moment diagram of three-point bending test configuration.

As apparent in the Figure 4-6, the three-point loading configuration exposes only a small portion of the beam's midspan to maximum stress. If a defect is present at this location its impact on measured material properties could be significant. The shear and moment diagram of the FPBT's quarter-point and five-point configurations are shown in Figure 4-7a and 4-7b, respectively.

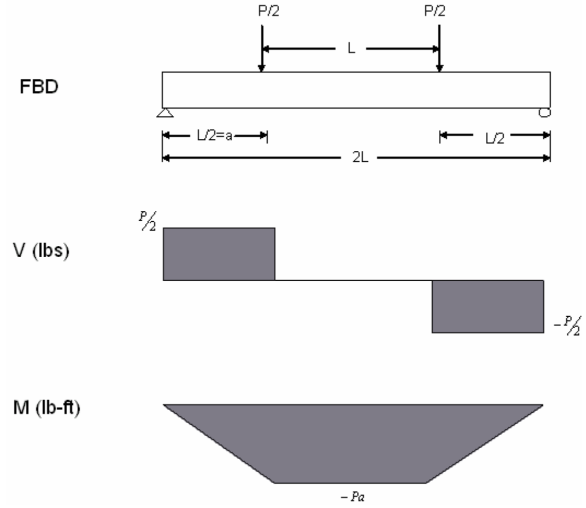


Figure 4-7a: Shear and moment diagram of quarter-point bending test configuration of the FPBT.

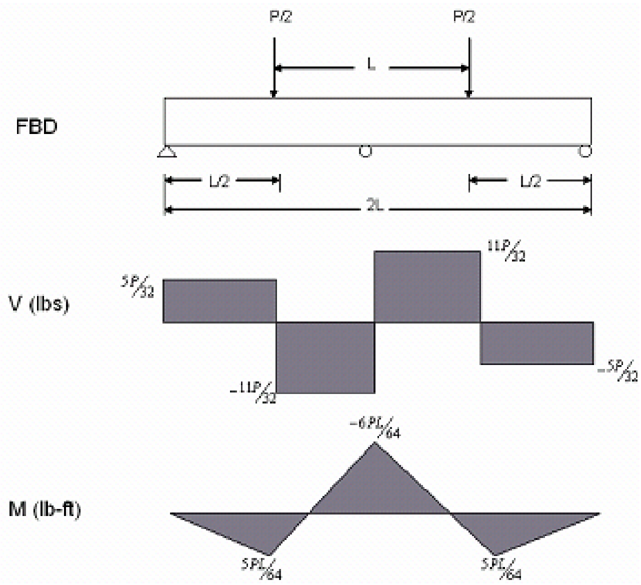


Figure 4-7b: Shear and moment diagram of five-point bending test configuration of the FPBT.

As apparent in Figure 4-7a and 4-7b, the quarter-point and five-point bending configurations of the FPBT expose larger portions of the beam to maximum stress. Therefore, by not concentrating the maximum stress at a point, the quarter and five-point loading configurations provide an averaged material response to the maximum stress. This averaged effect could reduce the variability of the measured response in the presence of defects.

4.9 Differences from Assumed *E:G* Ratio

The *E:G* ratios determined from this research were not expected to be equivalent to the *E:G* ratio of 16:1 commonly assumed for structural wooden members. The experimental work that is the basis for the *E:G* ratio of 16:1 was performed in the 1970's on small, clear specimens (Bodig and Goodman 1973). It has been well documented that tests of small, clear specimens produce mechanical property estimates that are different from the properties determined for structurally sized wooden members (Madsen 1992). Additionally, today's forest resource base is different from thirty years ago. In fact, wood products are currently manufactured from primarily second, third, or even fourth-generation forests (Schuler 2001). The occurrence of strength and stiffness compromising defects such as juvenile wood and pith is much greater than observed in the old-growth forests of the past. Therefore, one would not expect for the material of today to have mechanical properties identical to small, clear specimens tested in the past.

4.9.1 Comparisons of LVL to Assumed *E:G* Ratio

The *E:G* ratio of 16:1 commonly assumed for structural wooden members was compared to the average *E:G* ratios measured for the LVL specimens. Table 4-16 displays the percent difference between the assumed value and those determined from experimental testing.

Table 4-16: Percent difference comparison between the assumed *E:G* ratio of 16:1 and those determined from experimental testing.

Test Type	LVL	% Difference
ASTM D 198 Three-point bending	27.1	69.4%
ASTM D 198 Torsion[1]	18.8	17.5%
FPBT	16.0	0.1%

[1] The average moduli of elasticity used in the *E:G* ratio for ASTM D 198 torsion was determined by the ASTM D 198 three-point test.

The average *E:G* ratio determined from the FPBT was found to approximately equal the assumed *E:G* ratio of 16:1. However, both standard test methods, ASTM D 198 three-point bending and ASTM D 198 torsion, showed significant variation from the assumed *E:G* ratio. The *E:G* ratio for ASTM D 198 three-point bending was calculated at 27.1, a total of 69.4% different from the assumed value. The *E:G* ratio calculated for ASTM D 198 torsion test method was 18.8, a total of 17.5% different from the assumed value. The lack of consistency in the average *E:G* ratios determined by the flexural test methods was unexpected as these test methods produce similar stress distributions.

4.9.2 Comparison of MSR Lumber to Assumed *E:G* Ratio

The *E:G* ratio of 16:1 commonly assumed for structural wooden members was compared to the average *E:G* ratios measured for the MSR lumber specimens. Table 4-17 displays the percent differences between the assumed values and those determined from experimental testing.

Table 4-17: Percent difference comparison between the assumed *E:G* ratio of 16:1 and those determined from experimental testing.

Test Type	MSR	% Difference
ASTM D 198 Three-point bending	19.3	20.7%
ASTM D 198 Torsion[1]	15.1	-5.9%
FPBT	22.2	38.7%

[1] The average moduli of elasticity used in the *E:G* ratio for ASTM D 198 torsion was determined by the ASTM D 198 three-point test.

The average *E:G* ratio determined from the ASTM D 198 torsion test was 15.1, which was most similar to the assumed *E:G* ratio of 16:1. A difference of only 5.9% between the measured and assumed *E:G* ratios was observed for this particular test. However, both flexural tests included in Table 4-17, ASTM D 198 three-point bending and the FPBT, showed significant variation from the assumed *E:G* ratio. The average *E:G* ratio for ASTM D 198 three-point bending was calculated at 19.3, a total of 20.7% different from the assumed value. The average *E:G* ratio calculated for the FPBT was 22.2, a total of 38.7% different from the assumed value. Consistency between the *E:G* ratios determined by flexural test methods was expected as the two test methods produce similar stress distributions.

4.9.3 *E:G* Ratios Derived from Different Test Methods

The differences between calculated and assumed *E:G* ratios were not consistent between material types or test types. Figure 4-8 graphically illustrates the percent difference between calculated and assumed *E:G* ratios for each material type per test method.

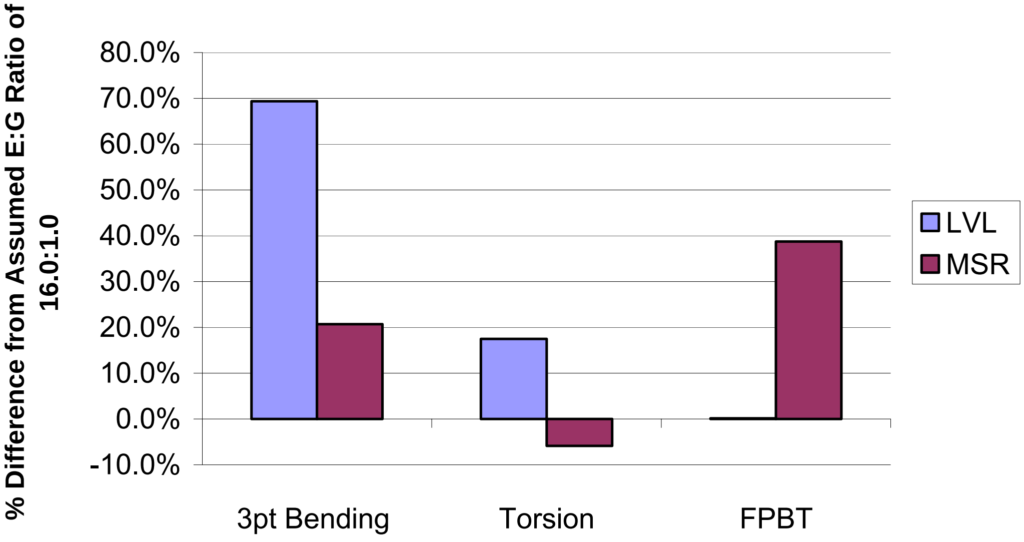


Figure 4-8: Comparison of average *E:G* ratios to the assumed E:G ratio of 16:1.

Figure 4-8 shows that only the *E:G* ratios calculated for the ASTM D 198 three-point bending test were higher for both material types. This result could be further evidence of the inability of ASTM D 198 three-point bending configuration to produce enough shear deflection to effectively measure the shear modulus. However, the LVL *E:G* ratio showed approximately 50% more deviation from the assumed *E:G* ratio than displayed by the MSR lumber specimens.

The *E:G* ratios determined by the ASTM D 198 torsion test were significantly higher than the assumed *E:G* ratio for LVL specimens, yet slightly lower for the MSR lumber specimens. Conversely, in the case of the FPBT, the calculated *E:G* ratio for MSR lumber specimens was approximately 40% higher than the assumed *E:G* ratio, while the calculated *E:G* ratio for the LVL specimens was approximately equal to the assumed value.

4.10 Regression Modeling

The presence of a significant relationship between the material properties determined by different test methods would improve the ability to make comparisons between the results of existing and future research efforts. Such a relationship may indicate that the data of one test method could be used to predict the data from another test method.

4.10.1 Shear Moduli Modeling

An investigation into the dependence of the shear moduli for MSR lumber and LVL showed no significant relationships between any test methods. Figures 4-9a and 4-9b show the results of such analysis between the shear moduli of LVL and MSR lumber as determined by ASTM D 198 three-point bending and ASTM D 198 torsion tests. Similar results of paired data sets from the other test methods can be found in Appendix I.

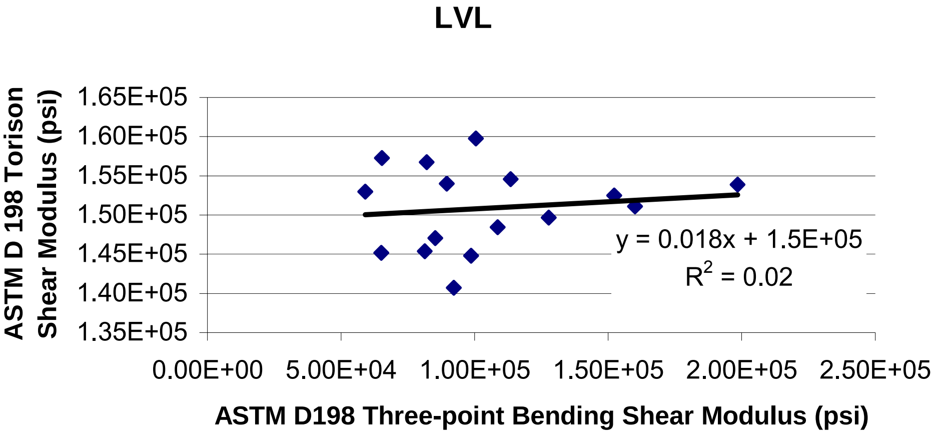


Figure 4-9a: Linear regression of ASTM D 198 three-point bending and ASTM D 198 torsion shear moduli results for LVL.

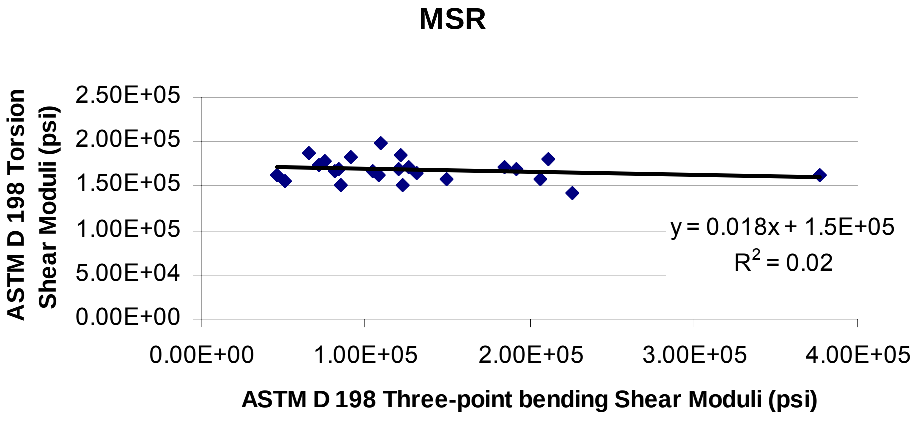


Figure 4-9b: Linear regression of ASTM D 198 three-point bending and ASTM D 198 torsion shear moduli results for MSR.

The lack of a significant relationship between the results of the different test methods may be related to the small range of measured shear moduli values. If the range of measured shear moduli values were increased by testing a broader range of material, the presence of a more significant relationship may become apparent.

When MSR lumber and LVL shear moduli data were combined, the relationship between the paired data sets deteriorated further. The lack of correlation between the results of the paired data sets contests to the wide variability of the test data. This result also reiterates the difficulty of evaluating the shear moduli of wood products.

4.10.2 Moduli of Elasticity Modeling

Though shear moduli results of the test methods could not be modeled in terms of one another, the moduli of elastic results of the two flexural test methods showed a marginal relationship. A linear trend between the moduli of elasticity was observed, with an increase in the moduli of elasticity determined according to one method also resulting in an increase in the moduli of elasticity determined by the alternate method. Figure 4-10a shows the linear relationship ($R^2 = 0.52$) between the moduli of elasticity results of ASTM D 198 three-point bending and the FPBT for LVL specimens. The relationship between the moduli of elasticity as determined for the MSR lumber specimens also showed a marginal relationship ($R^2 = 0.59$) as apparent in Figure 4-10b. Again, a linear and positively correlated relationship among the moduli of elasticity determined by the flexural test methods was observed.

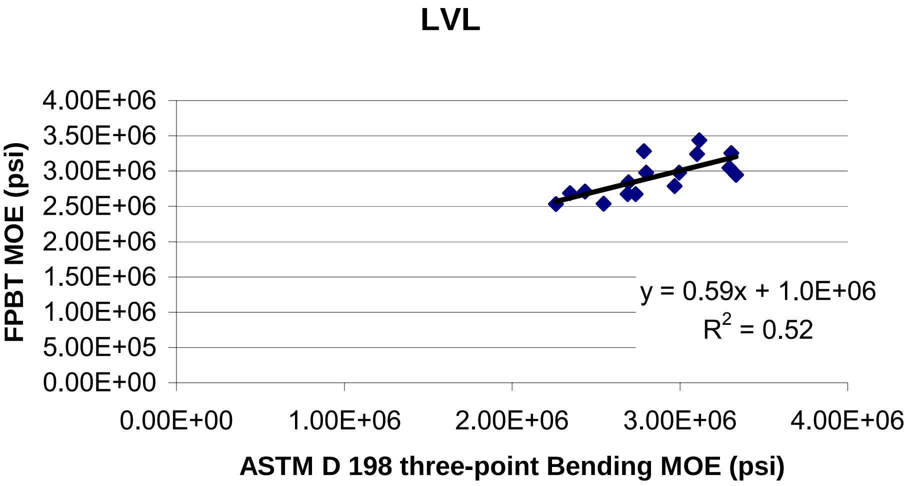


Figure 4-10a: Linear regression of ASTM D 198 three-point bending and FPBT moduli of elasticity results for LVL.

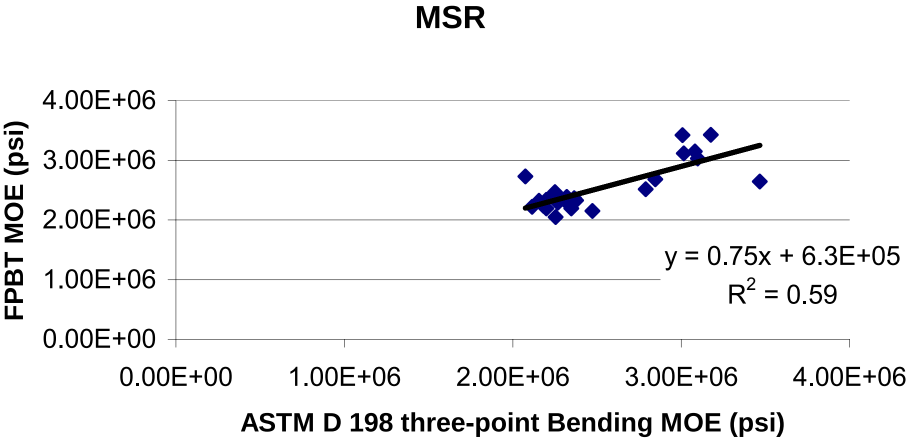


Figure 4-10b: Linear regression of ASTM D 198 three-point bending FPBT moduli of elasticity results for MSR lumber.

When MSR lumber and LVL moduli of elasticity data were combined, the relationship between the moduli of elasticity determined by the flexural methods improved further. As apparent in Figure 4-11, the relationship remained linear and positively correlated.

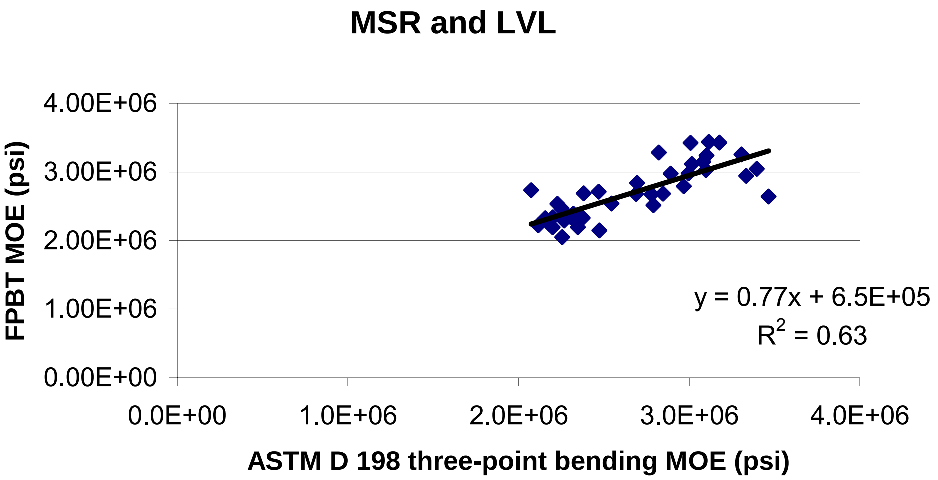


Figure 4-11: Linear regression of ASTM D 198 three-point bending and FPBT moduli of elasticity results for MSR lumber and LVL combined.

Chapter 5 Summary and Conclusions

The results of this research have shown differences in the shear moduli of LVL and MSR lumber specimens determined by ASTM D 198 (torsion and three-point bending) and the FPBT. However, discrepancies between the results between material types complicate the formulation of overall generalizations. Nevertheless, the following conclusions were drawn from this research:

- The average shear moduli of LVL specimens as determined by ASTM D 198 three-point bending, ASTM D 198 torsion, and the FPBT were significantly different. The average shear modulus determined by the FPBT was the highest followed by the ASTM D 198 torsion test. The lowest average shear modulus was determined by ASTM D 198 three-point bending.
- The average shear moduli of MSR lumber specimens determined by the FPBT and ASTM D 198 three-point bending were significantly lower than the average shear modulus determined by ASTM D 198 torsion. The average shear modulus determined by the ASTM D 198 three-point bending test was not significantly different than the average shear modulus determined by the FPBT.
- For both material types, the average shear moduli determined by ASTM D 198 three-point bending and torsion, both of which are presently assumed to be equivalent, were found significantly different. ASTM D 198 torsion shear moduli values were higher than ASTM D 198 three-point bending shear moduli values in both cases.
- The average moduli of elasticity as determined by the flexural test methods were not significantly different for either material type. The percent difference between measured and manufacturer rated moduli of elasticity values were consistent between the flexural test methods.
- The COV of shear moduli data evaluated by ASTM D 198 three-point bending was much larger than the COV of shear moduli data evaluated by the FPBT. The percentage of shear deflection induced in the ASTM D 198

three-point bending test was also much lower than observed for the five-point loading configuration of the FPBT. Therefore, to ensure accurate shear deflection measurement, flexural test methods should be chosen with consideration of the percentage of shear deflection induced during loading.

- The average *E:G* ratio of LVL was higher than the *E:G* ratio of MSR lumber when tested according to the FPBT. The average *E:G* ratios of the MSR lumber were higher than the *E:G* ratio of LVL when tested according to the standard ASTM D 198 torsion and three-point bending tests.
- The average *E:G* ratios calculated for each test method per material type showed differences from *E:G* ratio of 16:1 commonly assumed for structural wooden members. Exceptions were noted for the *E:G* ratios calculated for MSR lumber ASTM D 198 torsion tests and for those measured by the FPBT for LVL specimens.
- The shear modulus COV as determined by the torsion test was the lowest for both material types. This test was also easily performed though the loading condition is not observed in real-life situations. The shear modulus COV as determined by the ASTM D 198 three-point bending test was the highest for both material types. This test was also the most labor intensive with a required minimum of four tested spans per specimen. The shear modulus COV of the FPBT was consistent with expectations for both material types. The test is also the most representative of real life loading conditions.

5.1 Recommendations for Further Research

This research quantified the shear moduli and moduli of elasticity of MSR lumber and LVL according to consistent test methods. Future research efforts that could be based upon the results of this research include the following:

- The response of solid wood and wood-based composites is generally characterized as orthotropic. However, the ASTM D 198 torsion test method assumes isotropic material behavior. The determination of shear moduli values according to a test method that accounts for orthotropic behavior, such as the TSMT, may provide more accurate predictions of shear moduli values than the ASTM D 198 torsion test. Therefore, a comparison of shear moduli values obtained from both orthotropic and isotropic test methods would be beneficial.
- The results of this research indicate that shear moduli values measured from the ASTM D 198 three-point bending test are the least consistent of the three test methods. The percentage of shear deflection measured from the ASTM D 198 three-point bending tests remained low despite following recommended aspect ratios requirements. Therefore, investigation into the effect of imposing a minimum shear defection requirement in place of the current aspect ratio recommendation may provide for a more consistent shear moduli measurement.

Literature Cited

ASTM D 198-02. 2003a. Standard Test Methods of Static Tests of Lumber in Structural Sizes. American Society of Testing and Materials, West Conshohocken, PA.

ASTM D 2395-02. 2003b. Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials. American Society of Testing and Materials, West Conshohocken, PA.

ASTM D 2915-03. 2003c. Standard Practice for Evaluating Allowable Properties for Grades of Structural Lumber. American Society of Testing and Materials, West Conshohocken, PA.

ASTM D 3044-94. 2003d. Standard Test Methods for Shear Modulus of Wood-Based Structural Panels. American Society of Testing and Materials, West Conshohocken, PA.

ASTM D 4442-92. 2003e. Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials. American Society of Testing and Materials, West Conshohocken, PA.

ASTM D 5456-03. 2003f. Standard Specification for Evaluation of Structural Composite Lumber Products. American Society of Testing and Materials, West Conshohocken, PA.

Bateman, J.H., M.O. Hunt, and C.T. Sun. 1990. New interlaminar shear test for structural wood composites. Forest Prod. J. 40(3) 9-14.

Biblis, E.J. 2001. Edgewise flexural properties and modulus of rigidity of different sizes of southern pine LVL and plywood. Forest Prod. J. 51(1):81-84.

Bodig, J. and B.A. Jayne. 1982. Mechanics of Wood and Wood Composites. Van Nostrand Reinhold Company, New York. 714 p.

Bodig, J. and J.R. Goodman. 1973. Prediction of elastic parameters for wood. Wood Sci. 5(4):249-264.

Bradtmueller, J.P., M.O. Hunt, and S.R. Shook. 1998. Mechanical properties of laminated veneer lumber via five-point bending test. Journal of Testing and Evaluation. 26(2): 132-137.

Bradtmueller, J.P., M.O. Hunt, K.J. Fridley, and G.P. McCabe. 1994. Development of the five point bending test to determine shear moduli of wood composites. Forest Prod. J. 44(5): 17-26.

Brokaw, M.P., and G.W. Foster. 1952. Effect of rapid loading rate and duration of stress on the strength properties of wood tested in compression and flexure. Mimeo. No. 1518. Madison, WI: USDA, For. Serv., Forest Products Laboratory. 17p.

Chui, Y.H. 1991. Simultaneous evaluation of bending and shear moduli of wood and the influence of knots on these parameters. Wood Sci. Technol. 25:125-134.

Doyle, D.V. 1968. Properties of No. 2 dense kiln-dried southern pine dimension lumber. Res. Pap. FPL-96. Madison, WI: USDA For. Serv., Forest Products Laboratory. 24 p.

Doyle, D.V. and L.J. Markwardt. 1966. Properties of southern pine in relation to strength grading of dimension lumber. Res. Pap. FPL-64. Madison, WI: USDA For. Serv., Forest Products Laboratory. 62 p.

Gromala, D.S. 1985. Determination of modulus of rigidity by ASTM D 198 flexural methods. ASTM Journal of Testing and Evaluation. 13(5): 352-355.

Gupta, R. and T. Siller. 2005. Stress distributions in structural composite lumber under torsion. Forest Prod. J. 55(2):51-56.

Gupta, R. and T. Siller. 2000. Evaluation of the torsion test as a method to determine shear strength of structural composite lumber. ASAE Annual International Meeting, Sacramento, CA, July 30-August 1, 2001. Paper Number: 01-4015.

Gunnerson, R.A., J.R. Goodman, and J. Bodig 1973. Plate tests for determination of elastic parameters of wood. Wood Sci. 5(4):241-248.

Haygreen, J.G., and J.L. Bowyer. 1996. Forest Products and Wood Science, an Introduction. Iowa State University Press, Ames, IA. 484 p.

Hibbeler, R.C. 2000. Mechanics of Materials. Fourth Edition. Prentice Hall, Inc., Upper Saddle River, NJ. 848 p.

Hindman, D.P. 2004. Comparison of shear modulus from bending and torsion tests. ASAE Annual International Meeting, Ottawa, Ontario, Canada, August 1-4, 2004 Paper Number: 044117

Hindman, D.P. 2003. Torsional rigidity and lateral stability of structural composite lumber and I-joist members. Ph.D. dissertation, The Pennsylvania State University. University Park, PA. 222 p.

Hindman, D.P. 1999. Elastic constant ratios of selected engineered wood products, M.S. Thesis, The Pennsylvania State University. University Park, PA. 238 p.

Hindman, D.P., H.B. Manbeck, and J.J. Janowiak. 2001. Effects of E:G ratios of SCLs on structural performance. ASAE Annual International Meeting, Sacramento, CA, July 30-August 1, 2001. Paper Number: 01-4014.

Hunt, M.O., S.R. Shook and J.P. Bradtmueller. 1993. Longitudinal shear strength of LVL via the five-point bending test. Forest Prod. J. 43(7/8): 39-44.

Janowiak, J.J. and R.F. Pellerin. 1992. Shear moduli determination using torsional stiffness measurements. Wood and Fiber Sci. 24(4):392-400.

Janowiak, J.J., D.P. Hindman, H.B. Manbeck. 2001. Orthotropic behavior of lumber composite materials. Wood and Fiber Sci. 33(4): 580-594.

Leichti, R., M. Vatovec and P. Cheng. 1996. An appraisal of stress interactions in the five-point bending specimen. Presented at the ASTM Working Group Meeting. Madison, WI.

Liska, L.A. 1950. Effect of rapid loading on the compressive and flexural strength of wood. Res. Pap. No. R1767. Madison, WI: USDA, For. Serv., Forest Products Laboratory. 10p.

Liu, J.Y., D.D. Flach, R.J. Ross, and G.J. Lichtenberg. 1999. An improved shear test fixture using the Iosipescu specimen. Mech. Cellulosic Mater. AMD-VOl. 231/MD-VOL. 85:139-147.

Madsen, Borg. 1992. *Structural behavior of timbe*r. Timber Engineering Ltd. Vancouver, BC, Canada. 405 p.

NDS. 2001. Allowable Stress Design (ASD) Manual for Engineered Wood Construction. American Forest and Paper Association. Washington, DC., USA. 700p.

Neter, J., M.H. Kutner, C.J. Nachtsheim, W. Wasserman. 1996. Applied Linear Statistical Models. Fourth Edition. Times Mirror Higher Educational Group, Inc., Chicago, IL. 1408 p.

Palka, L.C. and J.D. Barrett. 1985. An examination of E/G ratios for Canadian spruce lumber. Report to ASTM task group investigating the validity of Table 2 of ASTM D 2915-74. Forintek Canada Corp. Report on file at ASTM headquarters.

Riyanto, D.S. and R. Gupta. 1998. A comparison of test methods for evaluating shear strength of structural lumber. Forest Prod J. 48(2):83-90.

Samson, M. and J.R. Sotomayor-Castellanos. 1991. Constant bending method for determining modulus of elasticity of lumber in structural size. Wood and Fiber Sci. 23(4): 520-532.

Schuler, A., C. Adiar, and E. Elias. 2001. Engineered lumber products, taking their place in the global market. Journal of Forestry. December 2001.

Sliker, A. and Y. Yu. 1993. Elastic constants for hardwoods measured from plate and tension tests. Wood and Fiber Sci. 25(1): 8-22.

Smulski, S. 1997. *Engineered wood products, a guide for specifiers, designers and users.* PFS Research Foundation. Madison, WI. 294 p.

Tarnopol'skii, Y.M. and T. Kincis. 1985. *Static test methods for composites.* Van Nostrand Reinhold Company. New York, New York USA. 301 p.

Tingley, D.A., S.M. Kent. 1996. The effects of test setup and apparatus on full-scale glue laminated timber beam shear strength. Presented at ASTM D07 Conference.

Trus Joist, A Weyerhauser Business. 1998. The shear modulus and torsional rigidity of Parallam^{TM}, Timberstrand^{TM}, and Microllam^{TM}. Report prepared by J.R. Loferski. Boise, ID. 22p.

U.S. Dept. of Agriculture, Forest Products Laboratory. 1999. Wood Handbook: Wood as an engineering material. Forest Products Society. Madison, WI, USA.463 p.

Appendix A: Calculations for Maximum Flexural Loads

Calculations for Maximum Loads Used for ASTM D 198 Three-point Bending

LVL:

$F_{b=}$ 2772 psi
d= 7.5 in
w= 1.75 in
Section Modulus= 16.4 in^3

Max Moment= 45472 in-lb

Max moment = (PL)/4

Span (in)	Max Load (lb)	60 % of Max Load (lb)
132	1378	827
120	1516	909
108	1684	1010
96	1895	1137
84	2165	1299

MSR Lumber:

$F_{b=}$ 2400 psi
d= 7.25 in
w= 1.5 in
Section Modulus= 13.1 in^3

Max Moment= 31538 in-lb

Max moment = (PL)/4

Span (in)	Max Load (lb)	60 % of Max Load (lb)
132	956	573
120	1051	631
108	1168	701
96	1314	788
84	1502	901

Calculations for Maximum Loads Used for FPBT Quarter-point Configuration

LVL:

$F_{b=}$ 2772 psi
d= 7.5 in
w= 1.75 in
Section Modulus= 16.4 in^3

Max Moment= 45472 in-lb

Max moment = Pa where a=L/4

Span (in)	Max Load (lb)	60 % of Max Load (lb)
108	1684	1010

MSR Lumber:

$F_{b=}$ 2400 psi
d= 7.25 in
w= 1.5 in
Section Modulus= 13.1 in^3

Max Moment= 31538 in-lb

Max moment = Pa where a=L/4

Span (in)	Max Load (lb)	60 % of Max Load (lb)
108	1168	701

Calculation for Maximum Loads used in FPBT Five-point Configuration

LVL:

$F_{b=}$ 2772 psi
d= 7.5 in
w= 1.75 in
Section Modulus= 16.4 in^3

Max Moment= 45472 in-lb

Max moment = (3PL)/64

Span (in)	Max Load (lb)	60 % of Max Load (lb)
108	8982	5389

MSR Lumber:

$F_{b=}$ 2400 psi
d= 7.25 in
w= 1.5 in
Section Modulus= 13.1 in^3

Max Moment= 31538 in-lb

Max moment = (3PL)/64

Span (in)	Max Load (lb)	60 % of Max Load (lb)
108	6230	3738

Appendix B: Moisture Content and Specific Gravity Data Tables

Moisture content and specific gravity results for LVL specimens.

Specimen	Wet weight (g)	OD weight (g)	Volume (cm^3)	MC (%)	SG
LVL-1	43.70	41.70	60.79	4.8%	0.69
LVL-2	40.59	38.74	59.82	4.8%	0.65
LVL-3	44.70	42.73	64.15	4.6%	0.67
LVL-4	42.72	40.81	59.20	4.7%	0.69
LVL-5	46.01	43.83	66.55	5.0%	0.66
LVL-6	47.11	44.94	68.52	4.8%	0.66
LVL-7	43.83	41.90	61.72	4.6%	0.68
LVL-8	45.60	43.57	64.48	4.7%	0.68
LVL-9	36.23	34.39	50.65	5.4%	0.68
LVL-10[1]	---	---	---	---	---
LVL-11	50.31	47.67	68.23	5.5%	0.70
LVL-12	42.78	40.56	59.03	5.5%	0.69
LVL-13	42.54	40.59	61.89	4.8%	0.66
LVL-14	39.37	37.54	57.28	4.9%	0.66
LVL-15	40.49	38.69	56.40	4.7%	0.69
LVL-16	43.64	41.59	63.65	4.9%	0.65
			Average	**4.9%**	**0.67**
			COV	**6.3%**	**2.4%**

[1] Specimen was used to determine if a moisture gradient was present along the length of specimens.

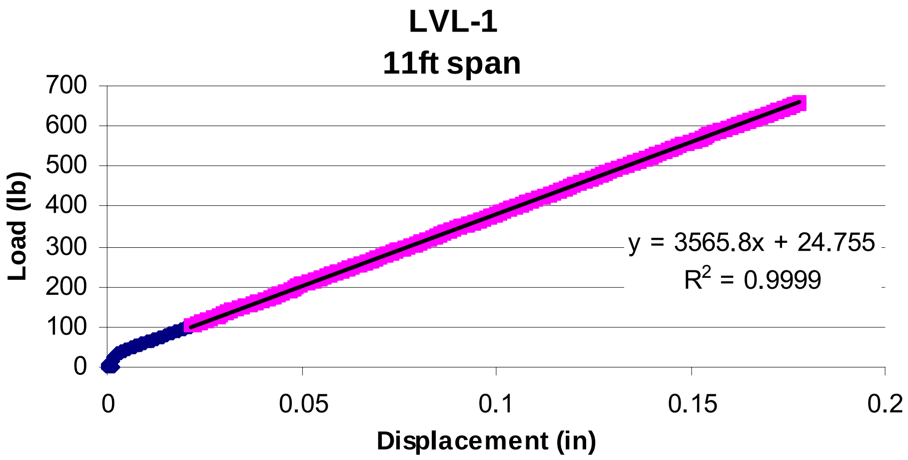
Moisture content and specific gravity results for MSR specimens.

Specimen	Wet weight (g)	OD weight (g)	Volume (cm^3)	MC (%)	SG
MSR-1	33.86	32.00	47.81	5.8%	0.67
MSR-2	33.27	31.44	46.34	5.8%	0.68
MSR-3	33.91	31.94	52.58	6.2%	0.61
MSR-4	29.10	27.62	51.23	5.4%	0.54
MSR-5	29.08	27.60	51.20	5.4%	0.54
MSR-6	33.29	31.30	50.51	6.4%	0.62
MSR-7	27.86	26.44	49.50	5.4%	0.53
MSR-8	35.17	33.38	50.30	5.4%	0.66
MSR-9	26.92	25.44	47.64	5.8%	0.53
MSR-10[1]	---	---	---	---	---
MSR-11	38.20	36.10	55.35	5.8%	0.65
MSR-12	33.46	31.60	50.04	5.9%	0.63
MSR-13	29.51	27.95	50.25	5.6%	0.56
MSR-14	29.82	28.19	54.04	5.8%	0.52
MSR-15	38.50	36.38	53.35	5.8%	0.68
MSR-16	34.41	32.53	51.73	5.8%	0.63
MSR-17	37.29	35.27	51.90	5.7%	0.68
MSR-18	32.67	30.80	49.37	6.1%	0.62
MSR-19	37.88	35.77	59.85	5.9%	0.60
MSR-20	29.59	27.94	48.06	5.9%	0.58
MSR-21	43.55	41.16	61.43	5.8%	0.67
MSR-22	36.11	34.16	50.00	5.7%	0.68
MSR-23	38.29	36.27	54.41	5.6%	0.67
MSR-24	33.68	31.89	49.55	5.6%	0.64
			Average	**5.8%**	**0.62**
			COV	**4.4%**	**9.1%**

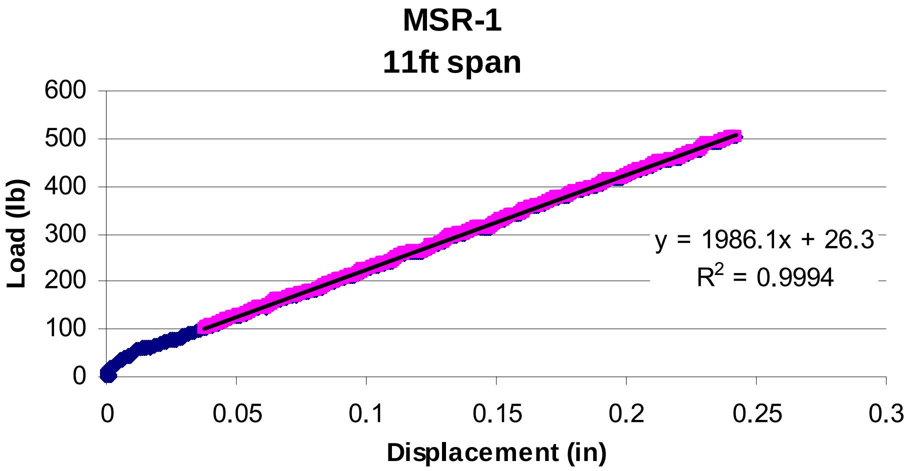
[1] Specimen was used to determine if a moisture gradient was present along the length of specimens

Appendix C: Example Load-Deflection Curves

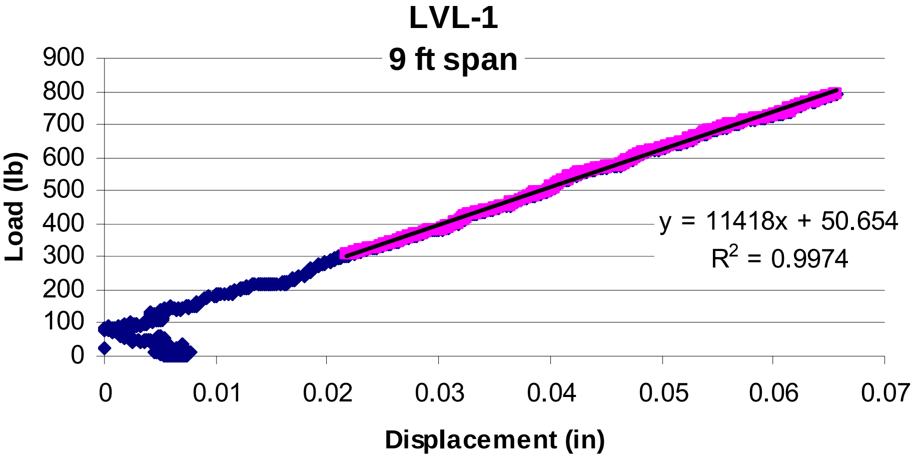
ASTM D 198 Three-point Bending Load-Deflection Curve: LVL



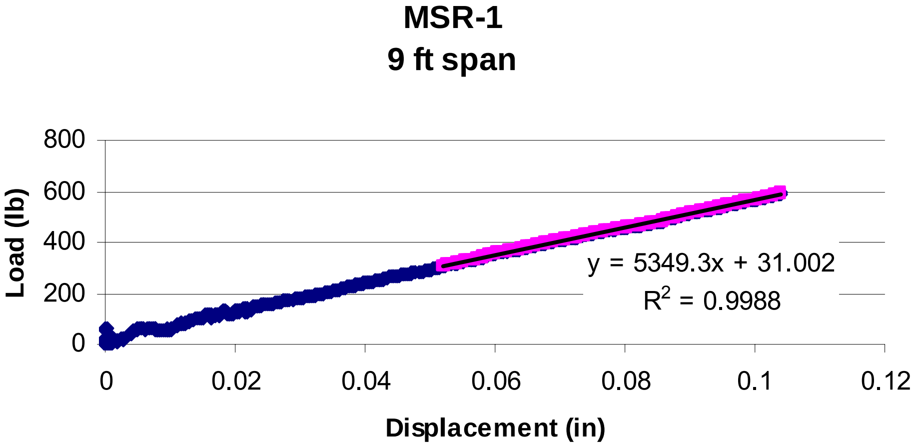
ASTM D 198 Three-point Bending Load-Deflection Curve: MSR



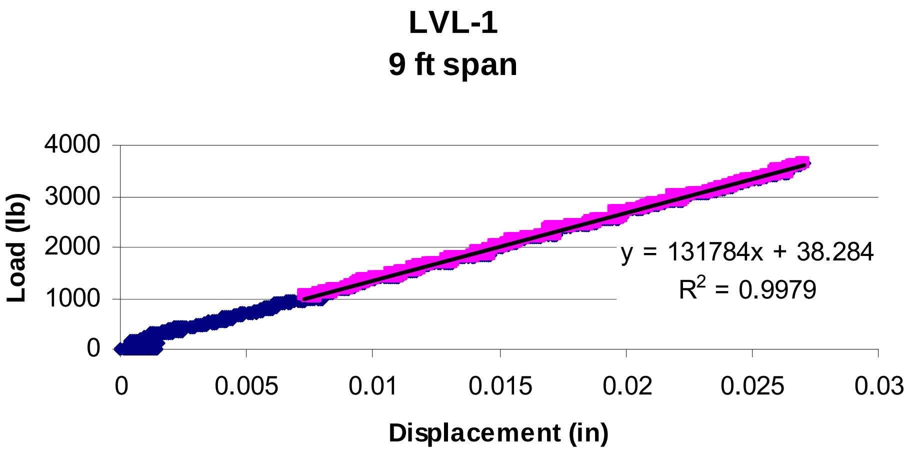
FPBT: Quarter-point Configuration Load-Deflection Curve: LVL



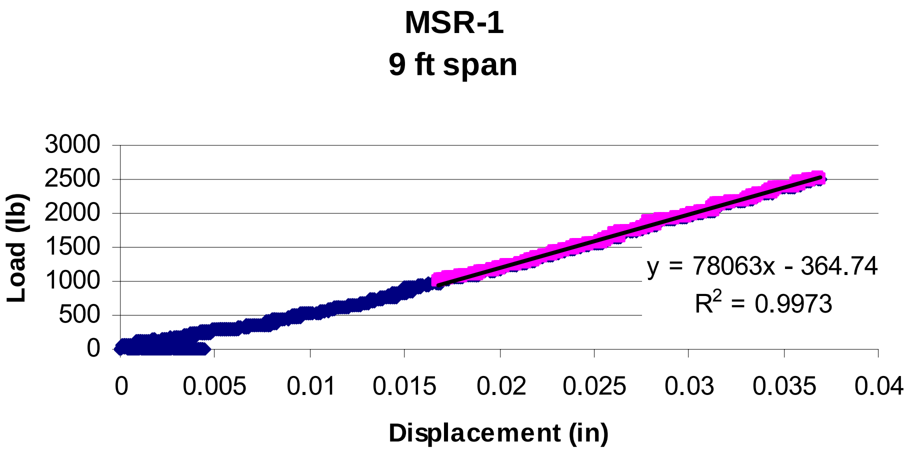
FPBT Quarter-point Configuration Load-Deflection Curve: MSR



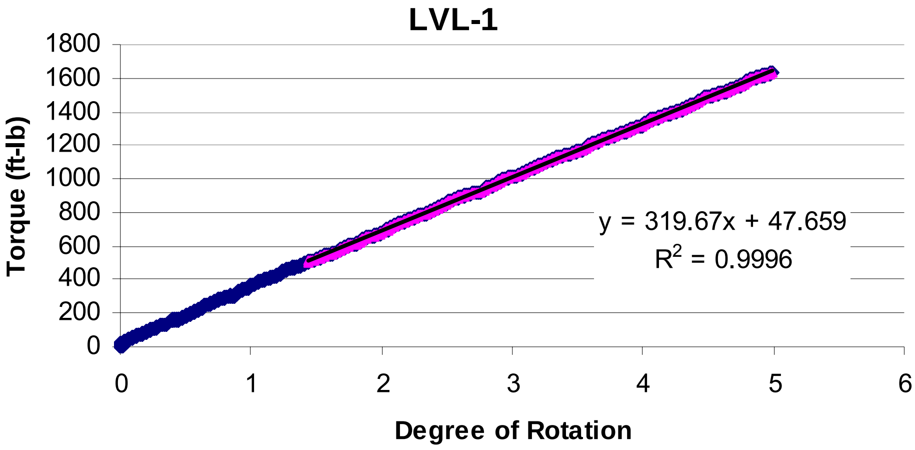
FPBT: Five-point Configuration Load-Deflection Curve: LVL



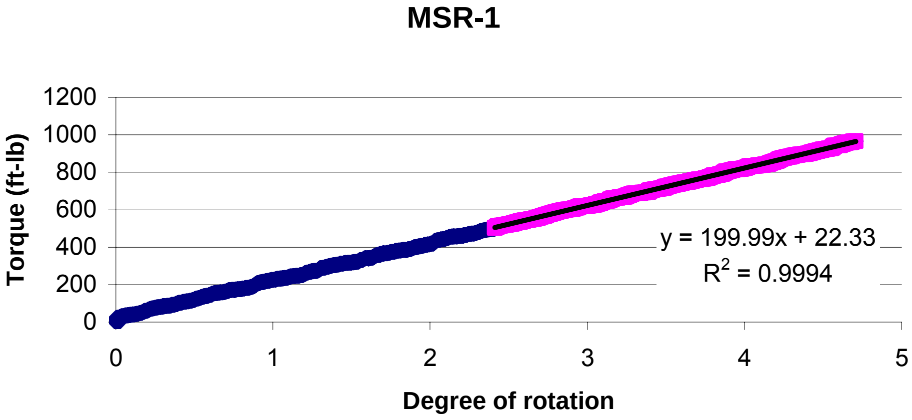
FPBT: Five-point Configuration Load-Deflection Curve: MSR



ASTM D 198 Torsion Torque-Angular Displacement Curve: LVL



ASTM D 198 Torsion Torque-Angular Displacement Curve: MSR



Appendix D: ASTM D 198 Three-point Bending Test Data

Collected Data for ASTM D198 Three-Point Bending: LVL

Specimen	Dimensions			Slope at span (in)				
	depth (in)	thickness (in)	Moment of Inertia (in^4)	132	120	108	96	84
LVL-1	7.915	1.695	70.017	3582.0	4771.4	6515.2	8792.1	12055.3
LVL-2	7.838	1.695	68.020	3565.4	4731.5	6373.1	8745.2	11617.7
LVL-3	7.931	1.681	69.888	3784.2	4944.2	6658.3	9139.5	11365.6
LVL-4	7.835	1.672	67.020	3697.7	4868.5	6564.1	8867.0	11441.6
LVL-5	7.919	1.678	69.444	3516.3	4574.7	6391.0	8675.6	11675.3
LVL-6	7.842	1.688	67.833	3604.8	4713.0	6933.2	8990.8	12335.0
LVL-7	7.889	1.674	68.493	3290.5	4227.1	5995.6	8010.5	11566.7
LVL-8	7.875	1.670	67.970	3235.8	4250.6	5829.7	8093.5	11032.7
LVL-9	7.892	1.675	68.591	3094.0	3984.9	5513.7	7636.3	11259.2
LVL-10	7.848	1.681	67.690	3129.2	4062.6	5765.4	7813.3	11075.6
LVL-11	7.885	1.695	69.219	3888.9	4967.0	7026.7	9086.1	11823.5
LVL-12	7.889	1.691	69.201	3844.4	5024.7	6886.7	9318.7	12531.8
LVL-13	7.889	1.691	69.201	3816.7	5099.8	6831.8	9403.7	12567.1
LVL-14	7.864	1.685	68.294	3578.8	4822.5	6403.2	8825.4	11682.8
LVL-15	7.886	1.674	68.392	3460.9	4493.5	6210.7	8556.7	11749.5
LVL-16	7.872	1.683	68.438	3358.7	4417.1	5813.9	8076.6	11099.9
Average	**7.879**	**1.683**	**68.607**	**3528.0**	**4622.1**	**6357.0**	**8626.9**	**11680.0**
St Dev	**0.029**	**0.009**	**0.829**	**250.8**	**349.3**	**464.4**	**544.3**	**488.4**
COV	**0.4%**	**0.5%**	**1.2%**	**7.1%**	**7.6%**	**7.3%**	**6.3%**	**4.2%**

Specimen	Apparent E (psi)					Aspect ratio (in/in)^2				
	132	120	108	96	84	132	120	108	96	84
LVL-1	2.45E+06	2.45E+06		2.31E+06	2.13E+06	0.0036	0.0044	0.0054	0.0068	0.0089
LVL-2	2.51E+06	2.50E+06	2.46E+06	2.37E+06	2.11E+06	0.0035	0.0043	0.0053	0.0067	0.0087
LVL-3	2.59E+06	2.55E+06	2.50E+06	2.41E+06	2.01E+06	0.0036	0.0044	0.0054	0.0068	0.0089
LVL-4	2.64E+06	2.62E+06	2.57E+06	2.44E+06	2.11E+06	0.0035	0.0043	0.0053	0.0067	0.0087
LVL-5	2.43E+06	2.37E+06		2.30E+06	2.08E+06	0.0036	0.0044	0.0054	0.0068	0.0089
LVL-6	2.55E+06	2.50E+06		2.44E+06	2.25E+06	0.0035	0.0043	0.0053	0.0067	0.0087
LVL-7	2.30E+06	2.22E+06		2.16E+06	2.09E+06	0.0036	0.0043	0.0053	0.0068	0.0088
LVL-8	2.28E+06		2.25E+06	2.19E+06	2.00E+06	0.0036	0.0043	0.0053	0.0067	0.0088
LVL-9	2.16E+06	2.09E+06		2.05E+06	2.03E+06	0.0036	0.0043	0.0053	0.0068	0.0088
LVL-10	2.22E+06	2.16E+06		2.13E+06	2.02E+06	0.0035	0.0043	0.0053	0.0067	0.0087
LVL-11	2.69E+06	2.58E+06	2.66E+06	2.42E+06	2.11E+06	0.0036	0.0043	0.0053	0.0067	0.0088
LVL-12	2.66E+06	2.61E+06	2.61E+06	2.48E+06	2.24E+06	0.0036	0.0043	0.0053	0.0068	0.0088
LVL-13	2.64E+06	2.65E+06	2.59E+06	2.50E+06	2.24E+06	0.0036	0.0043	0.0053	0.0068	0.0088
LVL-14	2.51E+06	2.54E+06	2.46E+06	2.38E+06	2.11E+06	0.0035	0.0043	0.0053	0.0067	0.0088
LVL-15	2.42E+06	2.37E+06	2.38E+06	2.31E+06	2.12E+06	0.0036	0.0043	0.0053	0.0067	0.0088
LVL-16	2.35E+06	2.32E+06	2.23E+06	2.18E+06	2.00E+06	0.0036	0.0043	0.0053	0.0067	0.0088
Average	**2.46E+06**	**2.44E+06**	**2.47E+06**	**2.32E+06**	**2.10E+06**	**0.0036**	**0.0043**	**0.0053**	**0.0067**	**0.0088**
St Dev	**1.66E+05**	**1.75E+05**	**1.48E+05**	**1.38E+05**	**8.20E+04**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0001**
COV	**6.7%**	**7.2%**	**6.0%**	**6.0%**	**3.9%**	**0.7%**	**0.7%**	**0.7%**	**0.7%**	**0.7%**

Specimen	Results		
	E (psi)	G (psi)	R-sq
LVL-1	2.79E+06	1.01E+05	94.4%
LVL-2	2.97E+06	8.21E+04	94.3%
LVL-3	3.33E+06	5.91E+04	99.4%
LVL-4	3.31E+06	6.53E+04	94.6%
LVL-5	2.74E+06	9.87E+04	95.4%
LVL-6	2.80E+06	1.28E+05	95.6%
LVL-7	2.43E+06	1.52E+05	89.3%
LVL-8	2.55E+06	1.09E+05	90.7%
LVL-9	2.26E+06	1.98E+05	98.8%
LVL-10	2.35E+06	1.60E+05	83.0%
LVL-11	3.30E+06	6.51E+04	97.7%
LVL-12	3.11E+06	8.96E+04	88.7%
LVL-13	3.10E+06	9.22E+04	91.0%
LVL-14	3.00E+06	8.13E+04	84.7%
LVL-15	2.69E+06	1.14E+05	80.8%
LVL-16	2.69E+06	8.53E+04	96.9%
Average	**2.84E+06**	**1.05E+05**	**0.922**
St Dev	**3.41E+05**	**3.81E+04**	**0.057**
COV	**12.0%**	**36.3%**	**6.1%**

Collected Data for ASTM D198 Three-Point Bending: MSR

Specimen	Dimensions			Slope at span (in)					Results		
	depth (in)	thickness (in)	Moment of Inertia (in^4)	132	120	108	96	84	E (psi)	G (psi)	Rsquared
MSR-1	7.186	1.470	45.453	1986.6	2698.0	3693.5	5078.6	7242.5	2.36E+06	1.05E+05	96.0%
MSR-2	7.140	1.485	45.034	2852.9	3698.3	5310.9	7058.7	12545.5	3.18E+06	2.07E+05	89.6%
MSR-3	7.130	1.471	44.449	1999.5	2599.9	3609.0	4958.5	7200.2	2.27E+06	1.49E+05	90.6%
MSR-4	7.126	1.477	44.549	2008.4	2689.1	3663.9	4913.4	7290.8	2.32E+06	1.31E+05	82.5%
MSR-5	7.065	1.463	43.009	1840.7	2439.3	3253.6	4742.2	6538.1	2.20E+06	1.08E+05	98.8%
MSR-6	7.165	1.489	45.632	2347.2	3208.9	4148.7	5460.2	8156.4	2.79E+06	8.52E+04	80.9%
MSR-7	7.122	1.475	44.387	1864.8	2441.8	3361.2	4749.5	6875.9	2.07E+06	2.26E+05	87.5%
MSR-8	7.144	1.495	45.434	1926.4	2652.5	3634.0	4900.0	6826.4	2.47E+06	6.58E+04	95.5%
MSR-9	7.176	1.470	45.277	2118.4	2720.2	3712.7	5213.2	7414.3	2.38E+06	1.22E+05	93.5%
MSR-10	7.132	1.484	44.873	1971.2	2567.9	3407.4	4729.8	6619.9	2.35E+06	7.13E+04	99.2%
MSR-11	7.113	1.475	44.239	1947.6	2584.4	3458.9	4844.8	6750.0	2.32E+06	9.07E+04	94.5%
MSR-12	7.169	1.477	45.366	2143.9	2821.2	3923.5	5458.5	8133.4	2.31E+06	3.77E+05	88.4%
MSR-13	7.146	1.481	45.026	1797.4	2312.8	3077.6	4430.7	8134.6	2.20E+06	5.05E+04	98.9%
MSR-14	7.147	1.457	44.331	1827.4	2428.3	3353.7	4766.4	6885.2	2.11E+06	1.85E+05	86.9%
MSR-15	7.071	1.478	43.535	2604.0	3279.1	4571.8	6479.2	9627.7	3.01E+06	1.92E+05	87.5%
MSR-16	7.057	1.465	42.912	2383.1	3112.7	4178.3	5845.8	7915.0	3.02E+06	8.39E+04	93.0%
MSR-17	7.075	1.461	43.113	2571.0	3268.7	4631.1	6383.8	8745.6	3.08E+06	1.23E+05	82.5%
MSR-18	7.190	1.465	45.367	2682.7	3522.4	4715.0	6875.0	9284.1	3.10E+06	1.21E+05	99.9%
MSR-19	7.141	1.475	44.743	2639.7	3196.3	4156.3	5713.4	8675.2	3.47E+06	4.64E+04	89.3%
MSR-20	7.221	1.473	46.218	1953.2	2568.8	3500.1	4874.4	6980.2	2.16E+06	1.27E+05	97.4%
MSR-21	7.185	1.481	45.761	2336.5	3214.7	4241.1	5786.1	7952.4	2.85E+06	8.10E+04	87.8%
MSR-22	7.163	1.490	45.638	1909.3	2637.4	3624.0	5273.2	7393.0	2.18E+06	2.12E+05	93.8%
MSR-23	7.165	1.480	45.356	1983.3	2626.6	3473.8	4886.1	7343.4	2.25E+06	1.09E+05	91.8%
MSR-24	7.203	1.493	46.503	1996.0	2569.3	3403.6	4788.1	6717.5	2.26E+06	7.58E+04	96.7%
Average	**7.143**	**1.476**	**44.842**	**2153.8**	**2827.4**	**3837.7**	**5342.1**	**7802.0**	**2.53E+06**	**1.31E+05**	**91.8%**
St Dev	**0.044**	**0.010**	**0.965**	**314.5**	**381.2**	**549.4**	**726.4**	**1320.9**	**4.10E+05**	**7.33E+04**	**5.6%**
COV	**0.6%**	**0.7%**	**2.2%**	**14.6%**	**13.5%**	**14.3%**	**13.6%**	**16.9%**	**16.2%**	**56.0%**	**6.1%**

Specimen	Apparent E (psi)					Aspect Ratio (in/in)^2				
	132	120	108	96	84	132	120	108	96	84
MSR-1		2.14E+06	2.13E+06	2.06E+06	1.97E+06	0.0030	0.0036	0.0044	0.0056	0.0073
MSR-2	3.04E+06	2.96E+06		2.89E+06		0.0029	0.0035	0.0044	0.0055	0.0072
MSR-3	2.16E+06	2.11E+06	2.13E+06	2.06E+06	2.00E+06	0.0029	0.0035	0.0044	0.0055	0.0072
MSR-4	2.16E+06	2.17E+06	2.16E+06	2.03E+06	2.02E+06	0.0029	0.0035	0.0044	0.0055	0.0072
MSR-5	2.05E+06	2.04E+06	1.99E+06		1.88E+06	0.0029	0.0035	0.0043	0.0054	0.0071
MSR-6	2.46E+06	2.53E+06	2.39E+06	2.21E+06	2.21E+06	0.0029	0.0036	0.0044	0.0056	0.0073
MSR-7	2.01E+06	1.98E+06	1.99E+06	1.97E+06	1.91E+06	0.0029	0.0035	0.0043	0.0055	0.0072
MSR-8		2.10E+06	2.10E+06	1.99E+06	1.86E+06	0.0029	0.0035	0.0044	0.0055	0.0072
MSR-9	2.24E+06	2.16E+06	2.15E+06	2.12E+06	2.02E+06	0.0030	0.0036	0.0044	0.0056	0.0073
MSR-10	2.10E+06	2.06E+06	1.99E+06	1.94E+06	1.82E+06	0.0029	0.0035	0.0044	0.0055	0.0072
MSR-11	2.11E+06	2.10E+06	2.05E+06	2.02E+06	1.88E+06	0.0029	0.0035	0.0043	0.0055	0.0072
MSR-12	2.26E+06	2.24E+06		2.22E+06		0.0029	0.0036	0.0044	0.0056	0.0073
MSR-13	1.91E+06	1.85E+06	1.79E+06			0.0029	0.0035	0.0044	0.0055	0.0072
MSR-14			1.99E+06	1.98E+06	1.92E+06	0.0029	0.0035	0.0044	0.0055	0.0072
MSR-15	2.87E+06		2.76E+06	2.74E+06		0.0029	0.0035	0.0043	0.0054	0.0071
MSR-16	2.66E+06	2.61E+06	2.56E+06	2.51E+06	2.28E+06	0.0029	0.0035	0.0043	0.0054	0.0071
MSR-17	2.86E+06	2.73E+06		2.73E+06	2.50E+06	0.0029	0.0035	0.0043	0.0054	0.0071
MSR-18	2.83E+06	2.80E+06	2.73E+06		2.53E+06	0.0030	0.0036	0.0044	0.0056	0.0073
MSR-19	2.83E+06	2.57E+06	2.44E+06	2.35E+06		0.0029	0.0035	0.0044	0.0055	0.0072
MSR-20	2.02E+06	2.00E+06	1.99E+06	1.94E+06	1.86E+06	0.0030	0.0036	0.0045	0.0057	0.0074
MSR-21	2.45E+06	2.53E+06	2.43E+06	2.33E+06	2.15E+06	0.0030	0.0036	0.0044	0.0056	0.0073
MSR-22		2.08E+06	2.08E+06		2.00E+06	0.0029	0.0036	0.0044	0.0056	0.0073
MSR-23	2.10E+06	2.08E+06	2.01E+06	1.99E+06		0.0029	0.0036	0.0044	0.0056	0.0073
MSR-24	2.06E+06	1.99E+06	1.92E+06	1.90E+06	1.78E+06	0.0030	0.0036	0.0044	0.0056	0.0074
Average	**2.36E+06**	**2.27E+06**	**2.18E+06**	**2.20E+06**	**2.03E+06**	**0.0029**	**0.0035**	**0.0044**	**0.0055**	**0.0072**
St Dev	**3.58E+05**	**3.09E+05**	**2.66E+05**	**3.00E+05**	**2.19E+05**	**0.0000**	**0.0000**	**0.0001**	**0.0001**	**0.0001**
COV	**15.2%**	**13.6%**	**12.2%**	**13.6%**	**10.8%**	**1.2%**	**1.2%**	**1.2%**	**1.2%**	**1.2%**

Appendix E: Original and Excluded ASTM D 198 Three-point Bending Data

ASTM D 198 three-point bending data for LVL specimens. Inverse apparent moduli of elasticity and corresponding aspect ratios are included. Shaded inverse apparent moduli of elasticity cells indicate exclusion of the data point. Results for the moduli of elasticity, shear moduli, and R^2 values of the data before and after data exclusion are also included.

	Apparent E (psi) at span (in.)					Aspect ratio at span (in)				
Specimen	**132**	**120**	**108**	**96**	**84**	**132**	**120**	**108**	**96**	**84**
LVL-1	2.45E+06	2.45E+06	2.44E+06	2.31E+06	2.13E+06	0.0036	0.0044	0.0054	0.0068	0.0089
LVL-2	2.51E+06	2.50E+06	2.46E+06	2.37E+06	2.11E+06	0.0035	0.0043	0.0053	0.0067	0.0087
LVL-3	2.59E+06	2.55E+06	2.50E+06	2.41E+06	2.01E+06	0.0036	0.0044	0.0054	0.0068	0.0089
LVL-4	2.64E+06	2.62E+06	2.57E+06	2.44E+06	2.11E+06	0.0035	0.0043	0.0053	0.0067	0.0087
LVL-5	2.43E+06	2.37E+06	2.42E+06	2.30E+06	2.08E+06	0.0036	0.0044	0.0054	0.0068	0.0089
LVL-6	2.55E+06	2.50E+06	2.68E+06	2.44E+06	2.25E+06	0.0035	0.0043	0.0053	0.0067	0.0087
LVL-7	2.30E+06	2.22E+06	2.30E+06	2.16E+06	2.09E+06	0.0036	0.0043	0.0053	0.0068	0.0088
LVL-8	2.28E+06	2.25E+06	2.25E+06	2.19E+06	2.00E+06	0.0036	0.0043	0.0053	0.0067	0.0088
LVL-9	2.16E+06	2.09E+06	2.11E+06	2.05E+06	2.03E+06	0.0036	0.0043	0.0053	0.0068	0.0088
LVL-10	2.22E+06	2.16E+06	2.24E+06	2.13E+06	2.02E+06	0.0035	0.0043	0.0053	0.0067	0.0087
LVL-11	2.69E+06	2.58E+06	2.66E+06	2.42E+06	2.11E+06	0.0036	0.0043	0.0053	0.0067	0.0088
LVL-12	2.66E+06	2.61E+06	2.61E+06	2.48E+06	2.24E+06	0.0036	0.0043	0.0053	0.0068	0.0088
LVL-13	2.64E+06	2.65E+06	2.59E+06	2.50E+06	2.24E+06	0.0036	0.0043	0.0053	0.0068	0.0088
LVL-14	2.51E+06	2.54E+06	2.46E+06	2.38E+06	2.11E+06	0.0035	0.0043	0.0053	0.0067	0.0088
LVL-15	2.42E+06	2.37E+06	2.38E+06	2.31E+06	2.12E+06	0.0036	0.0043	0.0053	0.0067	0.0088
LVL-16	2.35E+06	2.32E+06	2.23E+06	2.18E+06	2.00E+06	0.0036	0.0043	0.0053	0.0067	0.0088
AVG	**2.46E+06**	**2.42E+06**	**2.43E+06**	**2.32E+06**	**2.10E+06**	**3.56E-03**	**4.31E-03**	**5.32E-03**	**6.74E-03**	**8.80E-03**
COV	**6.7%**	**7.2%**	**7.0%**	**6.0%**	**3.9%**	**0.7%**	**0.7%**	**0.7%**	**0.7%**	**0.7%**

	Before Removal			After Removal		
Specimen	**E (psi)**	**G (psi)**	**R^2**	**E (psi)**	**G (psi)**	**R^2**
LVL-1	2.66E+06	1.59E+05	77.3%	2.79E+06	1.01E+05	94.4%
LVL-2	2.72E+06	1.53E+05	94.3%	2.97E+06	8.21E+04	94.3%
LVL-3	2.84E+06	1.33E+05	99.4%	3.33E+06	5.91E+04	99.4%
LVL-4	2.94E+06	1.19E+05	94.6%	3.31E+06	6.53E+04	94.6%
LVL-5	2.55E+06	2.08E+05	63.7%	2.74E+06	9.87E+04	95.4%
LVL-6	2.64E+06	3.82E+05	7.6%	2.80E+06	1.28E+05	95.6%
LVL-7	2.44E+06	1.64E+05	51.8%	2.43E+06	1.52E+05	89.3%
LVL-8	2.38E+06	2.39E+05	90.7%	2.55E+06	1.09E+05	90.7%
LVL-9	2.26E+06	1.86E+05	75.9%	2.26E+06	1.98E+05	98.8%
LVL-10	2.29E+06	2.86E+05	30.3%	2.35E+06	1.60E+05	83.0%
LVL-11	3.03E+06	1.06E+05	68.1%	3.30E+06	6.51E+04	97.7%
LVL-12	2.89E+06	1.49E+05	88.7%	3.11E+06	8.96E+04	88.7%
LVL-13	2.86E+06	1.70E+05	91.0%	3.10E+06	9.22E+04	91.0%
LVL-14	2.73E+06	1.54E+05	84.7%	3.00E+06	8.13E+04	84.7%
LVL-15	2.54E+06	2.08E+05	80.8%	2.69E+06	1.14E+05	80.8%
LVL-16	2.61E+06	1.04E+05	96.9%	2.69E+06	8.53E+04	96.9%
AVG	**2.65E+06**	**1.83E+05**	**74.7%**	**2.84E+06**	**1.05E+05**	**92.2%**
COV	**8.7%**	**39.3%**	**34.4%**	**12.0%**	**36.3%**	**6.1%**

ASTM D 198 three-point bending data for MSR lumber specimens. Inverse apparent moduli of elasticity and corresponding aspect ratios are included. Shaded inverse apparent moduli of elasticity cells indicate exclusion of the data point. Results for the moduli of elasticity, shear moduli, and R^2 values of the data before and after data exclusion are also included.

Specimen	Apparent E (psi) at span (in)					Aspect Ratio $(in/in)^2$ at span (in)				
	132	120	108	96	84	132	120	108	96	84
1	2.09E+06	2.14E+06	2.13E+06	2.06E+06	1.97E+06	0.0030	0.0036	0.0044	0.0056	0.0073
2	3.04E+06	2.96E+06	3.09E+06	2.89E+06	3.44E+06	0.0029	0.0035	0.0044	0.0055	0.0072
3	2.16E+06	2.11E+06	2.13E+06	2.06E+06	2.00E+06	0.0029	0.0035	0.0044	0.0055	0.0072
4	2.16E+06	2.17E+06	2.16E+06	2.03E+06	2.02E+06	0.0029	0.0035	0.0044	0.0055	0.0072
5	2.05E+06	2.04E+06	1.99E+06	2.03E+06	1.88E+06	0.0029	0.0035	0.0043	0.0054	0.0071
6	2.46E+06	2.53E+06	2.39E+06	2.21E+06	2.21E+06	0.0029	0.0036	0.0044	0.0056	0.0073
7	2.01E+06	1.98E+06	1.99E+06	1.97E+06	1.91E+06	0.0029	0.0035	0.0043	0.0055	0.0072
8	2.03E+06	2.10E+06	2.10E+06	1.99E+06	1.86E+06	0.0029	0.0035	0.0044	0.0055	0.0072
9	2.24E+06	2.16E+06	2.15E+06	2.12E+06	2.02E+06	0.0030	0.0036	0.0044	0.0056	0.0073
10	2.10E+06	2.06E+06	1.99E+06	1.94E+06	1.82E+06	0.0029	0.0035	0.0044	0.0055	0.0072
11	2.11E+06	2.10E+06	2.05E+06	2.02E+06	1.88E+06	0.0029	0.0035	0.0043	0.0055	0.0072
12	2.26E+06	2.24E+06	2.27E+06	2.22E+06	2.21E+06	0.0029	0.0036	0.0044	0.0056	0.0073
13	1.91E+06	1.85E+06	1.79E+06	1.81E+06	2.23E+06	0.0029	0.0035	0.0044	0.0055	0.0072
14	1.98E+06	1.97E+06	1.99E+06	1.98E+06	1.92E+06	0.0029	0.0035	0.0044	0.0055	0.0072
15	2.87E+06	2.71E+06	2.76E+06	2.74E+06	2.73E+06	0.0029	0.0035	0.0043	0.0054	0.0071
16	2.66E+06	2.61E+06	2.56E+06	2.51E+06	2.28E+06	0.0029	0.0035	0.0043	0.0054	0.0071
17	2.86E+06	2.73E+06	2.82E+06	2.73E+06	2.50E+06	0.0029	0.0035	0.0043	0.0054	0.0071
18	2.83E+06	2.80E+06	2.73E+06	2.79E+06	2.53E+06	0.0030	0.0036	0.0044	0.0056	0.0073
19	2.83E+06	2.57E+06	2.44E+06	2.35E+06	2.39E+06	0.0029	0.0035	0.0044	0.0055	0.0072
20	2.02E+06	2.00E+06	1.99E+06	1.94E+06	1.86E+06	0.0030	0.0036	0.0045	0.0057	0.0074
21	2.45E+06	2.53E+06	2.43E+06	2.33E+06	2.15E+06	0.0030	0.0036	0.0044	0.0056	0.0073
22	2.00E+06	2.08E+06	2.08E+06	2.13E+06	2.00E+06	0.0029	0.0036	0.0044	0.0056	0.0073
23	2.10E+06	2.08E+06	2.01E+06	1.99E+06	2.00E+06	0.0029	0.0036	0.0044	0.0056	0.0073
24	2.06E+06	1.99E+06	1.92E+06	1.90E+06	1.78E+06	0.0030	0.0036	0.0044	0.0056	0.0074
AVG	2.30E+06	2.27E+06	2.25E+06	2.20E+06	2.15E+06	2.93E-03	3.54E-03	4.37E-03	5.54E-03	7.23E-03
COV	15.2%	13.9%	14.8%	14.2%	17.2%	1.2%	1.2%	1.2%	1.2%	1.2%

Specimen	Before Removal			After Removal		
	E (psi)	G (psi)	R^2	E (psi)	G (psi)	R^2
1	2.26E+06	1.45E+05	75.3%	2.36E+06	1.05E+05	96.0%
2	2.76E+06	-1.53E+05	39.6%	3.18E+06	2.07E+05	89.6%
3	2.27E+06	1.49E+05	90.6%	2.27E+06	1.49E+05	90.6%
4	2.32E+06	1.31E+05	82.5%	2.32E+06	1.31E+05	82.5%
5	2.19E+06	1.26E+05	72.2%	2.20E+06	1.08E+05	98.8%
6	2.79E+06	8.52E+04	80.9%	2.79E+06	8.52E+04	80.9%
7	2.07E+06	2.26E+05	87.5%	2.07E+06	2.26E+05	87.5%
8	2.29E+06	9.29E+04	72.4%	2.47E+06	6.58E+04	95.5%
9	2.38E+06	1.22E+05	93.5%	2.38E+06	1.22E+05	93.5%
10	2.35E+06	7.13E+04	99.2%	2.35E+06	7.13E+04	99.2%
11	2.32E+06	9.07E+04	94.5%	2.32E+06	9.07E+04	94.5%
12	2.30E+06	5.18E+05	60.5%	2.31E+06	3.77E+05	88.4%
13	1.66E+06	-7.12E+04	42.1%	2.20E+06	5.05E+04	98.9%
14	2.02E+06	3.84E+05	53.9%	2.11E+06	1.85E+05	86.9%
15	2.85E+06	4.95E+05	27.3%	3.01E+06	1.92E+05	87.5%
16	3.02E+06	8.39E+04	93.0%	3.02E+06	8.39E+04	93.0%
17	3.12E+06	1.19E+05	77.7%	3.08E+06	1.23E+05	82.5%
18	3.07E+06	1.41E+05	73.6%	3.10E+06	1.21E+05	99.9%
19	2.98E+06	8.92E+04	64.2%	3.47E+06	4.64E+04	89.3%
20	2.16E+06	1.27E+05	97.4%	2.16E+06	1.27E+05	97.4%
21	2.85E+06	8.10E+04	87.8%	2.85E+06	8.10E+04	87.8%
22	2.07E+06	2.03E+06	0.6%	2.18E+06	2.12E+05	93.8%
23	2.16E+06	2.04E+05	67.9%	2.25E+06	1.09E+05	91.8%
24	2.26E+06	7.58E+04	96.7%	2.26E+06	7.58E+04	96.7%
AVG	2.44E+06	2.23E+05	72.1%	2.53E+06	1.31E+05	91.8%
COV	16.0%	184.3%	34.3%	16.2%	56.0%	6.1%

Appendix F: Collected data for ASTM D 198 Torsion

Collected Data for ASTM D 198 Torsion: LVL

Specimen	**thickness (in)**	**width (in)**	**Gage Length (in)**	**Average Slope**	**G (psi)**
LVL-1	1.695	7.915	95.5	324.4	1.60E+05
LVL-2	1.695	7.838	95.5	315.0	1.57E+05
LVL-3	1.681	7.931	95.5	304.4	1.53E+05
LVL-4	1.672	7.835	95.5	303.8	1.57E+05
LVL-5	1.678	7.919	95.5	286.1	1.45E+05
LVL-6	1.688	7.842	95.5	297.1	1.50E+05
LVL-7	1.674	7.889	95.5	298.0	1.53E+05
LVL-8	1.670	7.875	95.5	287.5	1.48E+05
LVL-9	1.675	7.892	95.5	300.9	1.54E+05
LVL-10	1.681	7.848	95.5	296.6	1.51E+05
LVL-11	1.695	7.885	95.5	293.4	1.45E+05
LVL-12	1.691	7.889	95.5	309.8	1.54E+05
LVL-13	1.691	7.889	95.5	283.0	1.41E+05
LVL-14	1.685	7.864	95.5	288.4	1.45E+05
LVL-15	1.674	7.886	95.5	301.6	1.55E+05
LVL-16	1.683	7.872	95.5	291.1	1.47E+05
Average	**1.683**	**7.879**	**95.5**	**298.8**	**1.51E+05**
St Dev	**0.009**	**0.029**	**0**	**11.1**	**5.28E+03**
COV	**0.5%**	**0.4%**	**0.0%**	**3.7%**	**3.5%**

Collected Data for ASTM D 198 Torsion: MSR

Specimen	thickness (in)	width (in)	Gage Length (in)	Average Slope	G (psi)
MSR-1	1.470	7.186	95.5	201.2	1.66E+05
MSR-2	1.485	7.140	95.5	195.8	1.58E+05
MSR-3	1.471	7.130	95.5	190.2	1.58E+05
MSR-4	1.477	7.126	95.5	200.6	1.65E+05
MSR-5	1.463	7.065	95.5	189.2	1.61E+05
MSR-6	1.489	7.165	95.5	187.7	1.50E+05
MSR-7	1.475	7.122	95.5	170.9	1.41E+05
MSR-8	1.495	7.144	95.5	235.3	1.86E+05
MSR-9	1.470	7.176	95.5	222.9	1.84E+05
MSR-10	1.484	7.132	95.5	213.0	1.73E+05
MSR-11	1.475	7.113	95.5	220.0	1.82E+05
MSR-12	1.477	7.169	95.5	198.8	1.62E+05
MSR-13	1.481	7.146	95.5	191.5	1.56E+05
MSR-14	1.457	7.147	95.5	201.7	1.72E+05
MSR-15	1.478	7.071	95.5	204.8	1.70E+05
MSR-16	1.465	7.057	95.5	198.9	1.69E+05
MSR-17	1.461	7.075	95.5	177.2	1.52E+05
MSR-18	1.465	7.190	95.5	201.7	1.68E+05
MSR-19	1.475	7.141	95.5	196.2	1.62E+05
MSR-20	1.473	7.221	95.5	209.8	1.71E+05
MSR-21	1.481	7.185	95.5	206.4	1.67E+05
MSR-22	1.490	7.163	95.5	226.6	1.81E+05
MSR-23	1.480	7.165	95.5	244.6	1.99E+05
MSR-24	1.493	7.203	95.5	227.2	1.79E+05
Average	**1.476**	**7.143**	**95.5**	**204.7**	**1.68E+05**
St Dev	**0.010**	**0.044**	**0**	**17.8**	**1.29E+04**
COV	**0.7%**	**0.6%**	**0.0%**	**8.7%**	**7.5%**

Appendix G: Collected Data for FPBT

Collected Data for FPBT: LVL

Specimen	thickness (in)	width (in)	Moment of Inertia (in^4)	Area (in^2)	Y-QP	Y-FP	E (psi)	G (psi)
LVL-1	1.695	7.915	70.017	13.413	8.62E-05	7.48E-06	3.28E+06	1.58E+05
LVL-2	1.695	7.838	68.020	13.287	1.01E-04	7.28E-06	2.79E+06	1.99E+05
LVL-3	1.681	7.931	69.888	13.334	9.45E-05	7.36E-06	2.94E+06	1.79E+05
LVL-4	1.672	7.835	67.020	13.102	8.99E-05	7.40E-06	3.26E+06	1.71E+05
LVL-5	1.678	7.919	69.444	13.289	1.04E-04	7.54E-06	2.67E+06	1.89E+05
LVL-6	1.688	7.842	67.833	13.235	9.55E-05	7.09E-06	2.98E+06	1.97E+05
LVL-7	1.674	7.889	68.493	13.208	1.05E-04	8.38E-06	2.71E+06	1.55E+05
LVL-8	1.670	7.875	67.970	13.153	1.11E-04	7.73E-06	2.54E+06	1.97E+05
LVL-9	1.675	7.892	68.591	13.215	1.10E-04	7.81E-06	2.53E+06	1.90E+05
LVL-10	1.681	7.848	67.690	13.189	1.07E-04	8.43E-06	2.69E+06	1.56E+05
LVL-11	1.695	7.885	69.219	13.362	9.15E-05	6.78E-06	3.04E+06	2.05E+05
LVL-12	1.691	7.889	69.201	13.343	8.22E-05	6.62E-06	3.44E+06	1.92E+05
LVL-13	1.691	7.889	69.201	13.343	8.94E-05	8.31E-06	3.24E+06	1.36E+05
LVL-14	1.685	7.864	68.294	13.253	9.38E-05	6.44E-06	2.98E+06	2.39E+05
LVL-15	1.674	7.886	68.392	13.198	1.01E-04	8.14E-06	2.84E+06	1.57E+05
LVL-16	1.683	7.872	68.438	13.252	1.06E-04	8.13E-06	2.68E+06	1.65E+05
Average	**1.683**	**7.879**	**68.607**	**13.261**	**9.80E-05**	**7.56E-06**	**2.91E+06**	**1.80E+05**
St Dev	**0.009**	**0.029**	**0.829**	**0.084**	**8.83E-06**	**6.24E-07**	**2.80E+05**	**2.56E+04**
COV	**0.5%**	**0.4%**	**1.2%**	**0.6%**	**9.0%**	**8.3%**	**9.6%**	**14.2%**

Collected Data for FPBT: MSR

Specimen	thickness (in)	width (in)	Moment of Inertia (in^4)	Area (in^2)	Y-QP	Y-FP	E (psi)	G (psi)
MSR-1	1.470	7.186	45.453	10.562	1.79E-04	1.28E-05	2.36E+06	1.43E+05
MSR-2	1.485	7.140	45.034	10.601	1.34E-04	1.42E-05	3.43E+06	9.11E+04
MSR-3	1.471	7.130	44.449	10.491	1.90E-04	1.44E-05	2.29E+06	1.19E+05
MSR-4	1.477	7.126	44.549	10.527	1.83E-04	1.40E-05	2.38E+06	1.21E+05
MSR-5	1.463	7.065	43.009	10.339	2.00E-04	1.88E-05	2.34E+06	7.69E+04
MSR-6	1.489	7.165	45.632	10.666	1.70E-04	1.35E-05	2.51E+06	1.20E+05
MSR-7	1.475	7.122	44.387	10.502	1.70E-04	1.79E-05	2.73E+06	7.34E+04
MSR-8	1.495	7.144	45.434	10.683	1.98E-04	1.47E-05	2.15E+06	1.17E+05
MSR-9	1.470	7.176	45.277	10.551	1.86E-04	1.52E-05	2.33E+06	1.05E+05
MSR-10	1.484	7.132	44.873	10.586	1.96E-04	1.46E-05	2.19E+06	1.19E+05
MSR-11	1.475	7.113	44.239	10.494	1.85E-04	1.51E-05	2.39E+06	1.06E+05
MSR-12	1.477	7.169	45.366	10.591	1.82E-04	1.36E-05	2.34E+06	1.27E+05
MSR-13	1.481	7.146	45.026	10.581	2.02E-04	1.82E-05	2.19E+06	7.99E+04
MSR-14	1.457	7.147	44.331	10.414	1.92E-04	1.25E-05	2.22E+06	1.72E+05
MSR-15	1.478	7.071	43.535	10.449	1.47E-04	1.98E-05	3.42E+06	5.89E+04
MSR-16	1.465	7.057	42.912	10.339	1.53E-04	1.57E-05	3.11E+06	8.68E+04
MSR-17	1.461	7.075	43.113	10.335	1.45E-04	1.20E-05	3.15E+06	1.34E+05
MSR-18	1.465	7.190	45.367	10.531	1.44E-04	1.27E-05	3.03E+06	1.18E+05
MSR-19	1.475	7.141	44.743	10.530	1.63E-04	1.18E-05	2.64E+06	1.53E+05
MSR-20	1.473	7.221	46.218	10.637	1.80E-04	1.37E-05	2.32E+06	1.23E+05
MSR-21	1.481	7.185	45.761	10.638	1.60E-04	1.30E-05	2.68E+06	1.21E+05
MSR-22	1.490	7.163	45.638	10.675	1.91E-04	1.50E-05	2.24E+06	1.09E+05
MSR-23	1.480	7.165	45.356	10.602	1.75E-04	1.44E-05	2.47E+06	1.10E+05
MSR-24	1.493	7.203	46.503	10.755	1.99E-04	1.28E-05	2.05E+06	1.61E+05
Average	**1.476**	**7.143**	**44.842**	**10.545**	**1.76E-04**	**1.46E-05**	**2.54E+06**	**1.14E+05**
St Dev	**0.010**	**0.044**	**0.965**	**0.112**	**2.007E-05**	**2.145E-06**	**4.024E+05**	**2.761E+04**
COV	**0.7%**	**0.6%**	**2.2%**	**1.1%**	**11.4%**	**14.7%**	**15.8%**	**24.1%**

Appendix H: *E:G* Ratios

E:G ratios: LVL

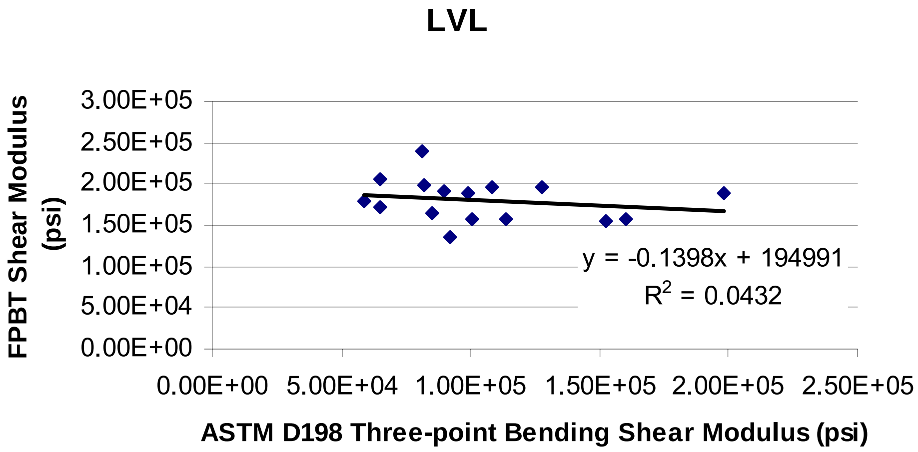
Specimen	E:G		
	3pt	**3pt/torsion**	**fpbt**
LVL-1	28.1	17.7	20.8
LVL-2	36.2	18.9	14.0
LVL-3	56.5	21.8	16.5
LVL-4	50.6	21.0	19.0
LVL-5	28.2	19.2	14.1
LVL-6	22.6	19.3	15.1
LVL-7	16.2	16.2	17.5
LVL-8	23.5	17.1	12.9
LVL-9	11.2	14.5	13.4
LVL-10	14.9	15.8	17.2
LVL-11	52.2	23.4	14.9
LVL-12	34.8	20.2	17.9
LVL-13	33.6	22.0	23.9
LVL-14	36.8	20.6	12.4
LVL-15	23.7	17.4	18.1
LVL-16	31.5	18.3	16.2
Average	**31.3**	**19.0**	**16.5**
St Dev	**13.2**	**2.5**	**3.1**
COV	**42.3%**	**13.0%**	**18.6%**

E:G ratios: MSR

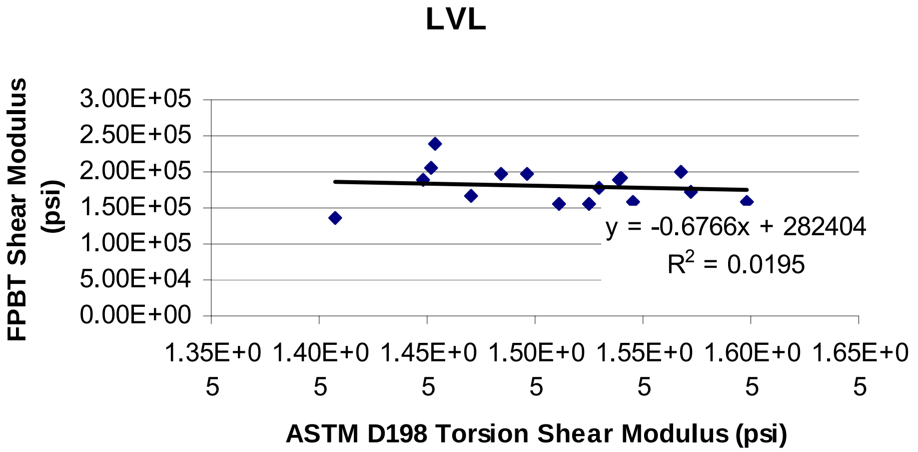
Specimen	**E:G**		
	3pt	**3pt/torsion**	**fpbt**
MSR-1	22.5	14.2	16.5
MSR-2	15.4	20.1	37.6
MSR-3	15.2	14.3	19.2
MSR-4	17.7	14.1	19.6
MSR-5	20.4	13.6	30.4
MSR-6	32.7	18.6	21.0
MSR-7	9.2	14.7	37.2
MSR-8	37.6	13.3	18.3
MSR-9	19.5	12.9	22.2
MSR-10	32.9	13.6	18.5
MSR-11	25.6	12.8	22.4
MSR-12	6.1	14.2	18.4
MSR-13	43.5	14.1	27.5
MSR-14	11.4	12.3	12.9
MSR-15	15.7	17.7	58.1
MSR-16	35.9	17.8	35.9
MSR-17	25.1	20.3	23.5
MSR-18	25.7	18.4	25.7
MSR-19	74.8	21.4	17.2
MSR-20	17.0	12.6	18.8
MSR-21	35.1	17.0	22.3
MSR-22	10.3	12.1	20.5
MSR-23	20.6	11.3	22.5
MSR-24	29.8	12.6	12.7
Average	**25.0**	**15.2**	**24.1**
St Dev	**14.5**	**2.9**	**9.9**
COV	**57.9%**	**19.4%**	**41.2%**

Appendix I: Regression Analyses between Shear Moduli Test Results

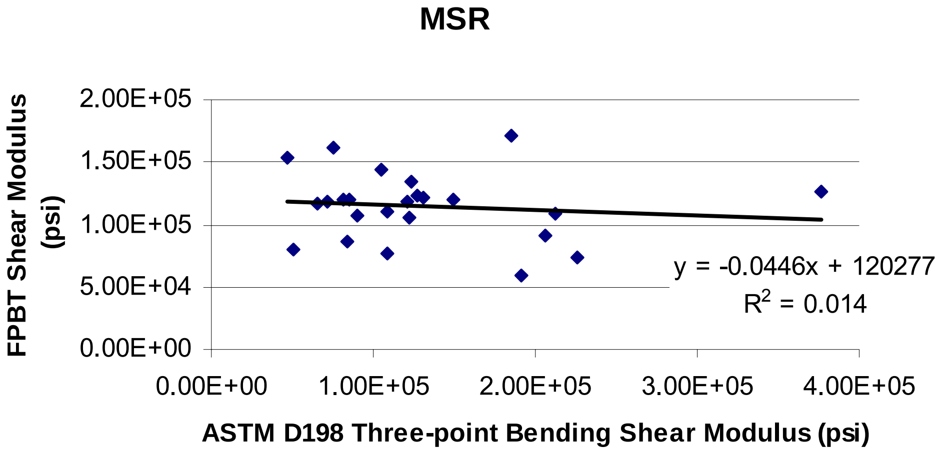
Regression Analysis of Shear Moduli Values Determined by ASTM D 198 Three-point Bending Test and the FPBT : LVL



Regression Analysis of Shear Moduli Values Determined by the ASTM D 198 Torsion Test and the FPBT: LVL



Regression Analysis of Shear Moduli Values Determined by ASTM D 198 Three-point Bending Test and the FPBT: MSR



Regression Analysis of Shear Moduli Values Determined by the ASTM D 198 Torsion Test and the FPBT: MSR