A NOVEL WOOD-STRAND COMPOSITE LAMINATE USING SMALL-DIAMETER TIMBER

By

SHILO WILLIS WEIGHT

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

WASHINGTON STATE UNIVERSITY
Department of Civil and Environmental Engineering

MAY 2007

To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of SHILO WILLIS WEIGHT find it satisfactory and recommend that it be accepted.

Chair

ACKNOWLEDGMENTS

I would like to express my gratitude to the many people who assisted with this project including the following:

- Advisor, Vikram Yadama, for invaluable insight, encouragement, and assistance along the way.
- Committee members, Bob Tichy and Don Bender, for their support and engineering expertise.
- CSREES/USDA PL 89-106, Inland Northwest Forest Products Research Consortium for funding this research.
- Bob Duncan and Scott Lewis for their assistance working in the lab.
- Friends and fellow graduate students for help constructing boards, and making the experience an enjoyable one.
- Family, especially Jeni, Dallin, Jeron, and my parents for their unfailing support and love throughout my studies.
- My Savior for his grace in my life.

A NOVEL WOOD-STRAND COMPOSITE LAMINATE USING SMALL-DIAMETER TIMBER

Abstract

by Shilo Willis Weight, MS
Washington State University
May 2007

Chair: Vikram Yadama

Our forest resources are changing due to fire prevention and depletion of increasing quantities of old growth forest. Applications for small-diameter juvenile timber, especially for low-value species such as ponderosa pine are needed. In this study, a novel thin wood strand composite 3.2 mm thick is introduced as a veneer substitute. In the first part of the study, optimization was performed for three processing parameters: PF resin content (3-6%), platen temperature (145-160º C), and strand length to thickness (L/t) aspect ratio (315, 430, and 750). Testing of the optimized formulation, consisting of 5.5% resin, platen temperature of 152º C, and a strand L/t aspect ratio of 430, yielded mean MOE and MOR values of 10.2 GPa and 79.1 MPa respectively. These values were approximately 2 to 2.5 times higher than the parent small-diameter ponderosa pine lumber.

In the next phase of this study, Young's modulus, Poisson's ratio, and shear modulus of thin plies were obtained for use in predicting laminate properties using classical lamination theory (CLT). Three laminate configurations formed of thin plies and one oriented strand composite (OSC) were then tested to compare mechanical and physical properties. Results showed that laminated strand ply (LSP) composites had

more uniform density throughout the ply, less thickness swell, and lower water absorption than the traditionally formed OSC. Elastic and strength properties of LSP composites compare favorably with plywood and LVL composites made of veneer, and exceeded those of OSB and particleboard. It was shown that the CLT model was useful in engineering composite lay-ups to give an approximation of LSP composites properties. Some of the observed advantages to using thin strand composites are high strength and stiffness, less variation in vertical and horizontal density distributions, continuous press manufacture, and utilization of low value small-diameter timber to form a value-added product.

.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

Introduction

The importance of engineered wood composites is increasing due to the changing nature of forest conditions in the United States. Much second growth forest land has been protected from fire and now contains undergrowth of dense, small diameter timber such as ponderosa pine, grand fir, and lodgepole pine. Lower density, smaller diameter, and non-uniformity of this timber make it unsuitable for lumber. LeVan (1997) estimates that excess biomass should be removed from at least 160,000 square kilometers of public lands at a cost of around $15 billion. A solution to help defray the costs incurred from thinning to foster healthy national forests is to produce value-added engineered wood products from small-diameter trees containing a large percentage of juvenile wood.

Currently engineered wood panels include plywood, medium density fiberboard (MDF), particleboard, and oriented strand board (OSB). However, disadvantages exist for each of these products particularly when using juvenile wood. Efficient plywood production requires the use of larger diameter logs, 0.3 m and larger, that are increasingly scarce and often excludes the use of faster growing timber. MDF is very sensitive to moisture, and warping can be more severe because of the high variation in vertical density (Genev et al. 2005). Poor fastener holding capacity and edge chipping can be problem areas for these composites as well (Buckner 1986). OSB has been all but excluded from some markets such as for furniture and case goods substrates due to customer objections, edge treatments, and fastener difficulties (Wu and Vlosky, 2000).

An engineered wood composite that could be produced from small diameter timber with consistent density, high strength and stiffness, good fastener holding properties, and smooth surfaces would be a valuable use of our changing forest resources.

The current study addresses the construction of a novel oriented strand composite composed of juvenile (0.1-0.2 m diameter) ponderosa pine (*Pinus ponderosa*) timber. This Laminated Strand Ply (LSP) composite is manufactured from thin strand plies (about 3.2 mm), made of oriented strands. These thin strand plies can in turn be laminated in different configurations/orientations to form a composite board (Figure 1.1). Various potential advantages exist for implementing LSP use as a wood composite as outlined next.

Figure 2.1. Thin strand plies and laminated strand ply (LSP) composites

Significance and Rationale

LSP composites create the opportunity for a more efficient usage of natural resources. By using small diameter, faster growing trees destruction of old growth forests and wildlife habitat is minimized. Techniques such as tree farming may be utilized more readily, enabling more efficient use of available renewable lumber resources. Fast-growing or small-diameter trees that predominately contain juvenile wood could be utilized in manufacturing LSP composites. Small-diameter ponderosa pine with low value was used to manufacture the strands for this study.

The term juvenile timber encompasses a range of tree sizes from approximately 0.1 to 0.3 m in diameter. Whereas trees that approach 0.3 m in diameter can be used for producing veneer or other products, trees with a diameter of 0.1 to 0.2 m can not be used in a cost effective manner. OSB can be and is manufactured from these smaller trees, but gains in specific performance are low, density variations are inevitable, and surface roughness is an issue. By substituting thin strand plies for veneer, a hybrid engineered wood composites similar in lay-up to laminated veneer lumber (LVL) or specialty grade plywood (commonly used as a furniture substrate), but formed of small-diameter timber strands like OSB, can be produced with significant gains in performance and density consistency. This novel technique of producing laminated strand composites using a hybrid of veneer- and strand-based technologies also results in smoother surfaces than traditional strand composites, as surface smoothness of a reconstituted wood product generally improves with decreasing wood constituent dimensions (Marra 1992).

One advantage of LSP composites is that thin plies lend themselves extremely well to production using a continuous press or multi-opening batch press similar to thin fiberboard. Heat can transfer more readily to the core allowing for faster production, eliminating bottlenecks at the hot press, and increasing energy efficiency for manufacturing processes. Also, manufacturing facilities for plywood and OSB already exist throughout North America (Miller and Voss 1998, Spelter et al. 2006), and implementation of LSP production would only require adjustments to current stranding, pressing, and lamination processes.

An additional benefit LSP offers is a reduction in horizontal density variations. As described by Xu and Steiner (1995), these variations in density can be attributed to variation in the number of strands through the board thickness. When pressing a strand board, localized areas of many or few strands result in high or low density through the full board thickness. With LSP, just like for plywood, defects or low density areas are localized within a single ply and adjacent plies are not affected. The result is a more uniform average horizontal density of the laminate than is possible for a typical strand composite board.

LSP would also have a more uniform vertical density profile. Typical vertical density profiles for OSB and MDF show that the core is less dense than the face (Andrews et al., 2001). This variation equates to lower fastener pullout strengths because the majority of the fastener is imbedded in the low density core. A further objection to using strand boards for furniture applications is the surface roughness according to Vlosky and Wu (2001). These problems are overcome with LSP. The vertical density variation is minimized with LSP because each layer has the same average density, creating uniformity through the thickness. This uniformity and consistency is particularly desired for furniture applications. Along with increased fastener strength, consistent density also means a material can be machined into a profile more easily.

A smoother surface is obtained in LSP production by using thinner strands which are much more pliable during pressing. This creates a much smoother surface for applying overlays, and minimizes issues with telegraphing. With these potential strengths, LSP could be a viable furniture substrate material as well as a performance rated engineered wood-strand composite for building construction.

One other strength of LSP is flexibility in designing the lay-up. For pure bending applications, the lay-up could be optimized by placing higher density plies on the faces for increased strength and stiffness. Thin strand plies could be used as stress skin layers for producing sandwich panels as well. Laminates can even be formed of plies with strand orientations other than 0 or 90 degrees; for example 45 degree strand orientation can be used to maximize shear strength of a panel. Indeed, this ability to engineer the composite lay-up according to the application is perhaps the greatest advantage to producing and using an LSP composite. However, to optimize engineering of LSP, it is critical to understand the effects of processing parameters on performance of thin strand plies.

This study examines some of the processing parameters involved in manufacturing thin strand plies and LSP composites, and evaluates their mechanical and physical properties. Results are compared with estimated values using classical lamination theory and with properties of other currently marketed wood composite panels.

Objectives

The objective of this study is to demonstrate a novel concept of producing high-performance thin oriented strand plies, similar to veneers, from small-diameter timber and engineer a performance rated composite laminate using these thin strand plies. Specific goals to attain this objective are to:

1. Determine optimum strand geometry, resin level, and press temperature necessary to produce an effective thin oriented strand ply, measured on the basis of internal bond (IB) strength, density variations, tensile strength, and bending strength and stiffness.
2. Characterize the optimum ply properties in terms of stiffness, Poisson's ratio, and shear modulus (E_1, E_2, ν_{12}, and G_{12}), for input into a classical lamination theory (CLT) model.
3. Manufacture and evaluate engineered laminated strand ply composites for physical and mechanical properties and compare to other wood composites.
4. Examine the applicability of CLT to predict laminate behavior based on ply properties.

Previous Research

Various studies on layered composites have been recorded in the literature. Plywood, as we know it, was first developed over 150 years ago (Perry 1948). It was found that for many applications, strength perpendicular to the length axis was important, so cross plies were included in the board lay-up. Equations used to engineer plywood according to the strength, elasticity, and orientation of each layer were only developed later (Norris 1942). Cross plies also help in dimensionally stabilizing the panel.

Studies performed on particleboard and strandboard with veneer overlays (Countryman 1975, Hse 1976, and Biblis and Mangalousis 1983) found that adequate board strengths can often be obtained. Vertically and horizontally oriented strand boards were overlaid with high-density flakeboard faces by Fyie (1977). Vertical core strand alignment required sawing the board into strips and rotating them 90 degrees before laminating the faces. Vertical core alignment, though not always practical, did increase shear and IB strengths. Often, however, the cores of these sandwich panels do not have high screw-holding capacity because of their lower, non-uniform density.

For structural sheathing applications, OSB, a multi-layer board with high strength consisting of oriented face strands and random or cross-oriented cores, was developed. By differing the orientation of face and core layers, properties approaching that of plywood can be obtained. OSB has become the dominant material used for structural panels in North America (Fuller 2001). One of the more recent applications for utilizing strands is in forming composite lumber products like laminated strand lumber (LSL) and parallel strand lumber (PSL). These products use strands or veneer clippings up to 0.3 m long to form a large structural laminate. The success of these products has demonstrated that high strength structural applications exist for oriented strand composites. However, no published work has been done on thin laminated strand ply composites.

Structure of Thesis

The following thesis is organized in the form of two stand alone articles preceded by this introductory chapter. Chapter two discusses the optimization and characterization of thin strand ply properties. Chapter three addresses the fabrication, testing, and analysis of laminated strand ply composites. These engineered laminates were also analyzed using a Classical Lamination Theory (CLT) model and compared with experimental results where appropriate. The final chapter summarizes the findings of the thesis, draws major conclusions, and provides some recommendations. Additional figures, statistical analysis, and raw data are included in the appendices.

References

1. Andrews, C. K., P. M. Winistorfer, and R. M. Bennett. 2001. The Influence of furnish moisture content and press closure rate on the formation of the vertical density profile in oriented strandboard. Forest Products Journal. 51(5): 32-39.

2. Biblis, E. J. and F. Mangalousis. 1983. Properties of ½-inch composite plywood with southern yellow pine veneer faces and unidirectionally oriented southern oaks strand core. Forest Products Journal. 33(2): 43-49.

3. Buckner, O. L. 1986. Medium density fiberboard and particleboard surface and edge qualities: attributes and problems. Proc. 20th Annual Particleboard/Composite Materials Symposium. Washington State University. Pullman, Washington. pp. 189-218.

4. Countryman, D. 1975. Research program to develop performance specifications for the veneer-particleboard panel. Forest Products Journal. 25(9): 44-48.

5. Fuller, B. 2001. Opportunities versus expectations: World market prospects for OSB and MDF. Proceedings of the International Particleboard/Composite Materials Symposium. pp. 75-83.

6. Fyie, J. A. 1977. Sandwich panel with vertically aligned fiber core. M. S. Thesis Washington State University.

7. Ganev, S. et al. 2005. Finite element modeling of the hygroscopic warping of medium density fiberboard. Wood and Fiber Science. 37(2): 337-354.

8. Hse, C. Y. 1976. Exterior structural composite panels with southern pine veneer faces and cores of southern hardwood flakes. Forest Products Journal. 26(7): 21-27.

9. LeVan, S. L. 1997. Benefits from wood engineering research. Wood Engineering in the 21st Century: Research Needs and Goals. ASCE. Reston, Virginia. 1-4.

10. Marra , A. A. 1992. Technology of wood bonding: Principles in practice. Van Nostrand Reinhold. New York, NY.

11. Miller, D. and O. Voss. 1998. Continuous Pressing of OSB: Products for the Future. Proceedings of the 32nd International Particleboard/Composite Materials Symposium. pp. 119-128.

12. Norris, C. B. 1942. <u>Technique of Plywood</u>. I. F. Laucks Inc. Seattle. pp. 249.

13. Perry, T. D. 1948. Modern Plywood. Pitman Publishing Corp. New York. pp. 458.

14. Wu, Q. and P. R. Steiner. 1995. A Statistical Characterization of the Horizontal Density Distribution in Flakeboard. Wood and Fiber Science. 27(2): 160-167.

15. Wu, Q. and R. P. Vlosky. 2000. Panel products: A perspective from furniture and cabinet manufacturers in the southern United States. Forest Products Journal. 50(9): 45-58.

CHAPTER TWO

OPTIMIZATION AND CHARACTERIZATION OF THIN STRAND PLY PROPERTIES

Introduction

The use of strands to form wood composite panels has increased significantly over the last several years with the development of oriented strand board (OSB) as sheathing material (Hansen, 2006). Some of the variables that have been examined that affect the mechanical and physical properties of strand composite panels include particle size, phenol formaldehyde (PF) resin content, platen temperature, furnish moisture content (MC) effects, and density variations (Geimer 1976, Kamke and Casey 1988, Suchsland 1962). In examining the effects of these variables, researchers have typically focused on boards with thicknesses greater than 13 mm.

This study examines laboratory manufactured thin strand veneers, referred to herein as plies, for use in producing a novel laminated strand ply (LSP) composite, consisting of engineered lay-ups of these thin plies. From preliminary testing it was found that using 0.38 mm thick strands, about half as thick as typical commercial strands, 3.2 mm plies could be produced with satisfactory properties. However, because of the high length to thickness ratio of these thinner strands, it was important to research what effect that would have and the required amount of PF resin. Also, it was necessary to understand the effect of platen temperature on mat thermodynamics during hot-pressing and on final ply properties to determine an optimum hot-pressing schedule for manufacturing thin strand plies.

Objective

The objective of this study was to determine optimum strand geometry, resin level, and press temperature necessary to produce an effective thin oriented strand ply suitable for engineered laminates. The optimal combination of variables was to be determined by performing the following tasks:

1. Analyzing the influence of strand geometry, resin level, and pressing temperature on mechanical and physical properties of thin strand plies, namely bending and tensile strength and stiffness, density variations, and internal bond strength.
2. Ranking these manufacturing parameters according to their effects on thin strand ply properties to obtain the thin strand ply configuration with the best qualities for use in an LSP composite.

Background

Particle Size Effects

Various researchers have examined the effects of particle geometry on optimizing properties of structural particleboards and strand composites (Stoffko, 1960; and Barnes, 2001). Lehmann (1974) found that optimum durability, strength, and dimensional stability were obtained for panels with densities from 600-680 kg/m^3, resin content from 5-6%, and with long, thin strands (0.51 mm thick). Thinner strands are more flexible and thus can more easily fill spaces during pressing, as well as provide a smoother surface which is important for furniture applications and overlays.

Effects of strand thickness have generally been examined in terms of a length/thickness slenderness ratio. Suchsland (1968) notes that bending or tensile strength of strand boards is limited by bond failure between strands until the bond surface area between strands reaches a point where the shear strength between strands is greater than the ultimate strength of the wood. A model by Simpson (1977) indicated that increasing the Length/thickness (L/t) ratio resulted in an initial increase in tensile strength which then began to level off at higher ratios. A study by Stoffko (1960) for L/t ratios ranging from 35-300 showed a similar trend with strength values beginning to level off at higher ratios.

Barnes (2000), when examining wood strand composite bending specimens found that for *in situ* strands (compacted within the board), 90% of the maximum modulus of rupture (MOR) was reached with L/t ratios of 450-650 and that modulus of elasticity (MOE) values tend to level off more quickly. For a compaction ratio of about 55%, as used in this study, this corresponds to uncompressed L/t ratios of 250-350. Therefore, optimum values should be obtained for strands with L/t ratios at or above this level (Figure 2.1).

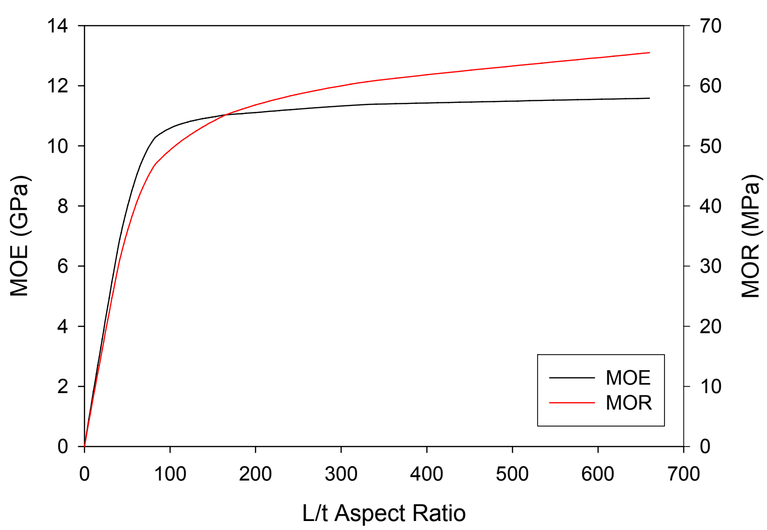


Figure 2.3. Modified Hankinson curves showing increase in MOE and MOR with L/t aspect ratio (adapted from Barnes, 2001)

Barnes (2001) reasoned that this could be because as the L/t ratio increases, the stress transfer angle between strands decreases, resulting in a more efficient stress transfer between strands.

Strand length also has a significant effect on strand orientation, leading to increased board strength and stiffness in the direction of orientation. This study used strands with a constant mean length of 0.15 m and thicknesses of 0.20 mm, 0.36 mm, and 0.48 mm to test L/t ratios at 750, 430, and 315 respectively. Width was held constant at an average value of 0.013 m. Another effect of raising the slenderness ratio is that the total surface area of strands within a ply increases. As surface area increases, the amount of resin required to transfer stress to adjacent strands also increases. For the high L/t ratios used in this study, the relationship between surface area and PF resin content may be more significant than the effect of stress transfer angle described by Barnes (2001) especially since a good bond is required for stress transfer.

PF Resin

Board strength depends on the distribution, cure, and amount of resin that is used. Several studies have shown that the amount of moisture present as PF resin cures correlates to board properties (Wang et al. 1995, Wang et al. 1996). Geimer and Christiansen (1996) reported that incomplete resin cure and bonding do not always translate into reduced board properties. Even though the resin was fully cured, extended press times or higher temperature were necessary to produce boards with good properties so that the moisture could be removed. It was also reported that boards made with low MC (7%) had higher bending and IB strengths compared to 12% MC boards even though individual strand bond strength developed more quickly at the higher moisture level. It was suggested that the number of bonding sites appeared to be more important for board strength properties than developing full resin cure strengths of the bonds during pressing (Geimer and Christiansen 1996).

Larmore (1959) reported a negative correlation between particleboard mechanical properties and the specific gravity of the wood species used to manufacture the boards. In other words, higher composite board properties resulted when low-density wood was used. This effect was attributed to a greater volume of wood being required to make up a board of the same density, resulting in higher compaction and plasticization during hot-pressing. In addition, there could be an increase in glue line contact between particles. As Suchsland (1968) found, increasing the length to thickness ratio of particles in a mat increases the amount of strand overlap within boards, as well as the number of potential bonding sites between strands.

The amount of resin required for good bonding depends on particle geometry. In a study by Maloney (1970), results indicated that much less resin was required for finer particles in high-density surface zones than for lower density core areas with coarser particles. Lehmann (1965 and 1968) found that there was a more uniform resin spread with finer atomization and longer spraying times resulting in increased strength. Bonding was found to be effective for a PF resin content of 4%.

Another study by Generalla et al. (1989) showed that resin content also affects the moisture resistance. Boards made with 4.5% and 6.5% resin content originally had comparable strength and dimensional stability. However, in tests of soaked specimens, significantly better properties were observed for those with higher resin content. Linville (2000) found that increases in resin content decreased the thickness swell of strand boards and increased the mechanical properties. The quantity of resin used is significant because of higher cost; commonly about 17% of production cost goes towards resin in an OSB plant (Spelter et al. 2006).

Temperature and Moisture Effects

Many studies have evaluated the effects of press temperature and moisture content of wood furnish (Strickler 1959, Kamke and Casey 1988, Wang et al. 1995). Temperature and moisture affect heat and mass transfer within the mat. Heat causes plasticization of the mat, removes moisture, and cures the resin. Therefore, the rate at which heat and mass transfer occur, due to press closure rate and platen temperature, significantly influences board properties. A study by Strickler (1959) showed that the rate that temperature increased in the interior of the mat rose with increasing moisture content. However, higher moisture content resulted in more non-uniform density profiles. Studies by Kamke and Casey (1988) confirmed these results and showed that mat gas pressure increases with temperature as well. High internal pressure due to moisture in the form of steam within boards can lead to blows as the press is opened.

Wang et al. (1995) studied the strength of lap-shear bonds cured at temperatures from 110°C to 140°C and relative humidities from 41% to 90%. At the lower temperatures, a high relative humidity had a tendency to retard bonding. However, for higher temperatures, the difference in bonding strength appeared not to differ significantly due to moisture levels. Therefore, as long as a sufficiently high platen temperature (>140°C) is used, differences in strength due to temperature and moisture variations could be small.

Vertical density profile

The location of maximum and minimum density and their variations are important because of the effects on strength, stiffness, and uniformity within a board. Two accepted measures of variability in strandboards are the vertical and horizontal density distributions. The vertical density profile through the board thickness has been shown by Smith (1982) to affect the strength properties significantly. Boards with a faster press closing time and higher overall board density resulted in higher bending strength from face densification of panels. Variation in vertical density, especially lower core density, results in decreased properties such as internal bond and fastener holding strengths (Wang and Winistorfer 2000). Andrews et al. (2001) found that increasing the furnish moisture content was related to steeper surface density peaks in the vertical density profile. They also found that speeding up the press closure time caused the location of maximum density to move closer to the surface.

Suchsland (1959) reported that vertical density profile is affected by temperature, board thickness, and moisture introduced through strands and resin. This is because of the difference in heat transfer at the face through direct platen contact and the slower heat transfer to the core as moisture becomes steam. This plasticization of the mat is a dynamic process, changing even after the press reaches a constant holding thickness, and results in a differential densification through the board thickness. Using thinner boards means that the heat transfer from the platen through the board occurs more quickly and with smaller density variations between the face and the core of the board.

One of the advantages of a uniform vertical density profile within plies is having consistent and predictable properties for each ply. This makes prediction of the composite properties for an engineered laminate more accurate. Consistency and uniformity within a ply doesn't mean that all the plies within a laminate need to have equal properties. Face plies of higher density and strength may often be desirable for bending applications, while this may be less important for core plies.

Horizontal density distribution

Minimizing variations in horizontal density within a board is also important because of the direct correlation between density and the panel strength and stiffness. In a paper by Xu and Steiner (1995), it was shown that the horizontal density varied depending on the size of the specimen. Equations were developed that show that the smaller the specimen size is, the larger the standard deviation of density. Bozo (2002) showed that localized density measurements correlate more closely with specimen properties than average board densities. The horizontal density distribution is affected mainly by the uniformity of deposition, strand geometry, and strand orientation (Suchsland 1962, Dai and Steiner 1993).

Horizontal density variation is an inherent attribute of strand boards due to non-uniform strand distribution during the mat formation process. Longer strands tend to bridge between high points in the mat leaving voids underneath. As reported by Linville (2000), decreasing the horizontal density variation can limit the damaging effects of thickness swell by decreasing the differential stresses induced with moisture contact. Dai and Steiner (1993) suggest that horizontal density variations may be decreased by increasing the strand orientation. The presence of voids, the primary reason for horizontal density variation, can be minimized with good orientation in thin strand plies due to better packing of the elements and fewer chances to bridge between high points.

Strand Alignment

The effects of strand alignment on strandboard performance have been well documented. McNatt et al. (1992) and Zhou (1990) both found that strength and stiffness of boards in the aligned direction was approximately twice that of boards with random orientation. In the direction perpendicular to the alignment, there was a corresponding drop in strength and stiffness properties; properties of boards with random orientation were 50-70% greater than aligned boards. Additionally, Geimer (1979) found that MOE values could be directly correlated to the percentage of flake alignment. His definition of percent alignment is given in Equation 2.1.

$$PercentAlignment = \frac{45 - \theta}{45} \qquad \text{Equation 2.1}$$

Where, θ, the average alignment angle, is the mean of the absolute value of the measured alignment angles.

Three of the important factors that determine the distribution of strand alignment are strand geometry, vane or disc spacing, and height of freefall distance above the mat (Barnes 2000). Meyers (2001) found that strand geometry (especially length) was important in that it determined the degree of strand orientation in a board. For strands with a constant length to width ratio, variations on strand width had no significant effect on board properties. Obviously, the gap spacing between orienting vanes or discs also affects the degree of orientation. Geimer (1976) found that increasing the freefall height for strands increased the angular deviation of strands, which could be an important factor in the case of thin strands. In fact, Barnes (2000) has shown that a positive linear relationship exists between increasing height of freefall and angular deviation.

In industrial settings, use of cores with randomly oriented flakes is common due to the ease of forming. However, this method results in increased variation in strength and density properties. The ideal case for individual strand plies is to have a high degree of orientation, so that properties are uniform and easily predictable. In reality a less than ideal distribution of oriented strand ply properties will be obtained for use in engineering composite strand ply laminates, but attempts should be made to minimize variation.

Methods and Materials

Manufacturing

From preliminary analysis it was found that commercially produced strands with an average thickness of about 0.76 mm could be used to manufacture 6.4 mm oriented strand plies, but were inadequate for manufacturing thinner plies. This was due to less strands being packed through the thickness of the ply, resulting in higher void volume. Initial testing showed that with 0.38 mm thick strands manufactured in the laboratory, 3.2 mm plies could be produced with satisfactory properties.

Forty ponderosa pine (*pinus ponderosa*) logs 0.10 – 0.18 m in diameter and 2.4 m long were obtained from northwest Washington for stranding. To obtain consistent strand width, logs were ripped into boards 0.013 m thick using a band saw. Boards were then trimmed to remove bark and cross cut into 0.15 m lengths. These smaller boards were put into stacks of 10 and fed into a CAE strander operating at a rotation speed of 500 rpm. The projection of the strander blades was adjusted manually so that three different strand thicknesses 0.20 mm, 0.36 mm, and 0.48 mm could be obtained. A constant strand width of 0.013 m and a constant strand length of 0.15 m were targeted. This resulted in nominal length to thickness (L/t) aspect ratios of 750, 430, and 315.

Boards were kept moist until processed to prevent splintering and to reduce fines during the stranding process. Strands were then removed from the strander and immediately placed in circulating air driers to reduce moisture content to about 15%. Strands were then dried to 6% moisture content in a heated drum drier and stored in large plastic bags until use in order to prevent moisture absorption. The 0.20 mm strands had more breakage and fines content after drum drying than the thicker flake sizes, so these were screened after being dried.

One hundred strands of each thickness type were taken randomly from different areas of the bags, and thickness was measured with digital calipers in the middle of each strand. A lognormal probability density function was found to best fit the strand thickness distributions (Appendix A). Lengths and widths were also measured to determine consistency of strands. The mean strand length was 0.150 m with a coefficient of variation (COV) of 1.1% and mean width was found to be 0.013 m with a COV of 6.2%.

Phenol formaldehyde (PF) OSB face resin with 57% solids content was utilized when making all plies. The resin cure kinetics were studied using a differential scanning calorimeter (DSC). Tests showed that the peak cure rate occurred at 145º C and that over 90% of resin cure was achieved in about 2.5 minutes. Test panels were then made to determine an appropriate pressing schedule. All plies were pressed using a hydraulic 0.914 m square oil-heated press in conjunction with the Pressman™ (2006) control system. A thermocouple wire was placed in the middle of test plies to measure the length of time required to reach curing temperature. A typical graph of core temperature, mat thickness, and ram pressure is shown in Figure 2.2. The press closing, holding, and release times for each of the 3.2 mm thick plies manufactured in this study were kept constant. Additional details are included in Appendix B.

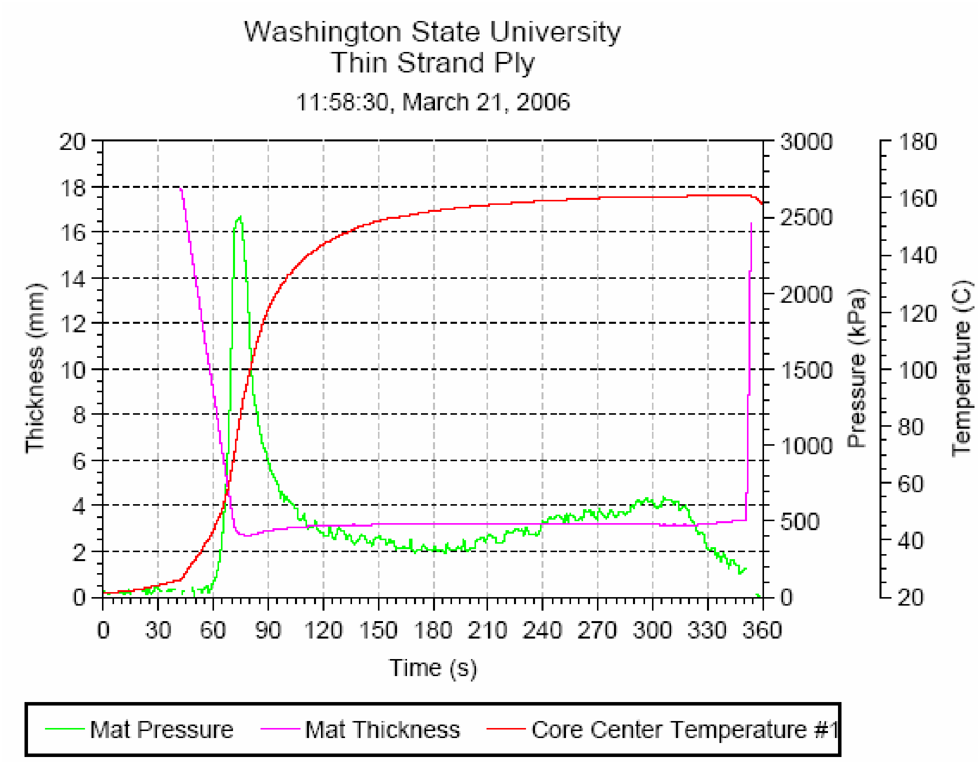


Figure 2.4. Pressing data for 3.2 mm ply at a platen temperature of 160º C

A response surface D-optimal factorial experiment design was set up using Design-Expert® (2007) software in order to optimize plies for maximum bending and tensile strength and stiffness, maximum internal bond strength, and minimum density variations. Three process variables were investigated in this study: resin content, press temperature, and aspect ratio (strand length-to-thickness (L/t) ratio). The quadratic model was implemented with a total of 32 runs with 9 replicates and 10 runs to minimize error and estimate lack of fit of the model. Resin content was varied from 3-6%, temperatures ranged from 145-160º C, and aspect ratios of 750, 430, and 315 were included. One oriented strand ply was made for each run, thus a total of 32 plies were fabricated for testing. A list of the runs and corresponding variable values is included in Appendix C.

PF resin was applied to the strands using an air atomized resin sprayer in a rotating drum mixer. Strands were distributed by hand into a forming box placed on an aluminum caul sheet. Orientation was accomplished using vanes with staggered heights and a spacing of 0.038 m on center. Freefall distance of strands was minimized to less than .025 m. The forming box was set on an oscillating table to provide a uniform distribution of flakes passing through the vanes. Once the ply was formed, it was placed in the hot press and pressed with a holding time of 210 seconds at target thickness. Plies were then removed, labeled, and trimmed to about 0.61m x 0.61m. The target density for each ply was 640 kg/m^3 with a ply thickness of 3.2 mm.

Testing

The top and bottom surface of ten strand plies were photographed to characterize the strand orientation. About ten strands were chosen at random from the top and bottom surfaces of each ply and using image analysis software, orientation angles were measured and percent alignment was calculated.

Plies were conditioned at 20º C (68º F) and 65% relative humidity and then cut into specimens to determine density and conduct bending, tension, and internal bond strength tests according to ASTM D1037-99 (1999). Bending and tension specimens were cut with orientation both parallel and perpendicular to the strong-axis of the plies. The sampling scheme shown in Appendix D was used to obtain test specimens, resulting in the number of specimens given in Table 2.1 for the 32 plies used. An Instron testing machine with a capacity of 8.9 kN was used to perform internal bond, tension, and bending tests.

Table 2.1. Sampling scheme for thin strand ply tests

Test performed	# of Specimens per Ply	Total # of Specimens
Tension parallel	3	96
Tension perpendicular	3	96
Bending parallel	4	128
Bending perpendicular	3	96
Internal bond	6	192
Horizontal density	13	416

The mid-section of the tension specimens were dog-boned as specified in ASTM D1037-99 (1999) using a router. For tensile tests, an extensometer with a gage length of 0.051m was used to gather strain data. The resulting stress and strain data were then used to calculate ultimate tensile strength and Young's modulus for each specimen.

For the bending tests, a laser extensometer was used to measure deflection by measuring the gap between a reflective reference tape below the specimen and a small strip of reflective tape applied at mid-span of each specimen, with the bottom edge of the tape aligned with the bottom of the specimen. Modulus of elasticity (MOE) and modulus of upture (MOR) were then calculated from the resulting load deflection curves.

Vertical density profiles were measured nondestructively on the IB samples using an X-ray vertical density profiler. Density variations through the thickness of each specimen were obtained from these measurements and the range between maximum and minimum densities was used as a measure of the vertical density variation. Horizontal density samples were weighed, measured, dried, and then weighed again to determine density and moisture content for different locations in each ply.

The mean and coefficient of variation (COV) of test results for specimens from each ply were calculated. For example, the average of the 6 internal bond results for ply 1 was 646 kPa with a COV of 14.7%. Mean values were entered into the Design-Expert software program to determine the significance of results and to develop response surfaces. Because the density of each ply had a significant effect on tension and bending results, it was included as a covariate in the analysis to remove its effect. From these models, an optimum combination of variables was chosen to maximize bending and tensile properties and minimize density variations.

A couple of run results were omitted from the analysis. For example, the internal bond results for run number 9 showed that bonding was very poor between strands and so results were omitted. Additionally, run 29 experienced some blows through certain sections of the ply, therefore some specimens from this ply were omitted from the analysis as well.

The optimum combination of variables, as described above, was used to manufacture additional plies for use in making laminates. Four of these plies were chosen at random for testing to determine their mechanical and physical properties. Experimental values were then compared to those predicted by the Design-Expert model.

Results and Discussion

Examining the orientation of strands determined using plies of each aspect ratio indicated that the average strand angle, θ, for the plies was 9.8º with a COV of 71%. Entering this angle into Geimer's formula (Equation 2.1) resulted in a percent strand alignment of 78%. The ratio of average bending modulus in the parallel versus perpendicular directions of the plies was 7.9 due to the high orientation. Similarly, for the tension modulus the ratio was 7.2. In comparison, Bodig and Jayne (1982) report an average ratio of parallel to perpendicular direction moduli for solid wood to be between 12 and 20. Meyers (2002), in her testing of unidirectional oriented strand composites, reported an average ratio of moduli between 7 and 37 when tested in tension.

Density, tension, and bending test results were input into the Design-Expert software as effects and an analysis of variance (ANOVA) was performed. After examining the influence of ply density, it was determined that density needed to be included as a covariate to eliminate its effects. Therefore, an analysis of covariance (ANCOVA) was used to determine significance of results. Table 2.2 shows which variables were included in the model to get the best fit and which were significant using a significance level, α, of 5%. Complete results of the statistical analyses are included in Appendix E.

Table 2.2. Significance of factors

Model Effect	**Resin Content**		**Temperature**		**Aspect Ratio**	
	Significant?	P-Value	Significant?	P-Value	Significant?	P-Value
HD Variation						
VD Variation	X	0.0041	O		O	
Internal Bond	X	0.0030	O		X	<0.0001
Tensile E Par.*	O		O		O	
Tensile Stress Par.*	O		O		O	
Tensile E Perp.*	X	0.0253	O		X	0.0086
Tensile Stress Perp.*	X	0.0031	O		X	0.0002
MOE Par.*	X	0.0280	X	0.0110	O	
MOR Par.*	X	0.0009	O		X	0.0330
MOE Perp.*	X	0.0333	O		X	0.0004
MOR Perp.*	X	0.0010	O		X	0.0076

X = Significant at 5% level; O = Insignificant at 5% level.
*Density was considered as a covariate and effects were removed from model.

The influence of variables on mechanical properties is presented graphically in Figures 2.3 and 2.4. Some general trends were observed from these results for each variable tested. Increasing resin content caused a significant positive effect on nearly all ply properties measured. The effect of varying aspect ratio was significant for all properties of specimens oriented perpendicular to the strong axis, with higher L/t ratio strand plies having higher values for this orientation. However, other properties of high L/t strand plies were lower or insignificant. The effect of varying the platen temperature, within the range tested in this study, was insignificant for nearly all of the properties except MOE parallel. Vertical density variation is measured as the range between the maximum density at the surface and the minimum density at the core.

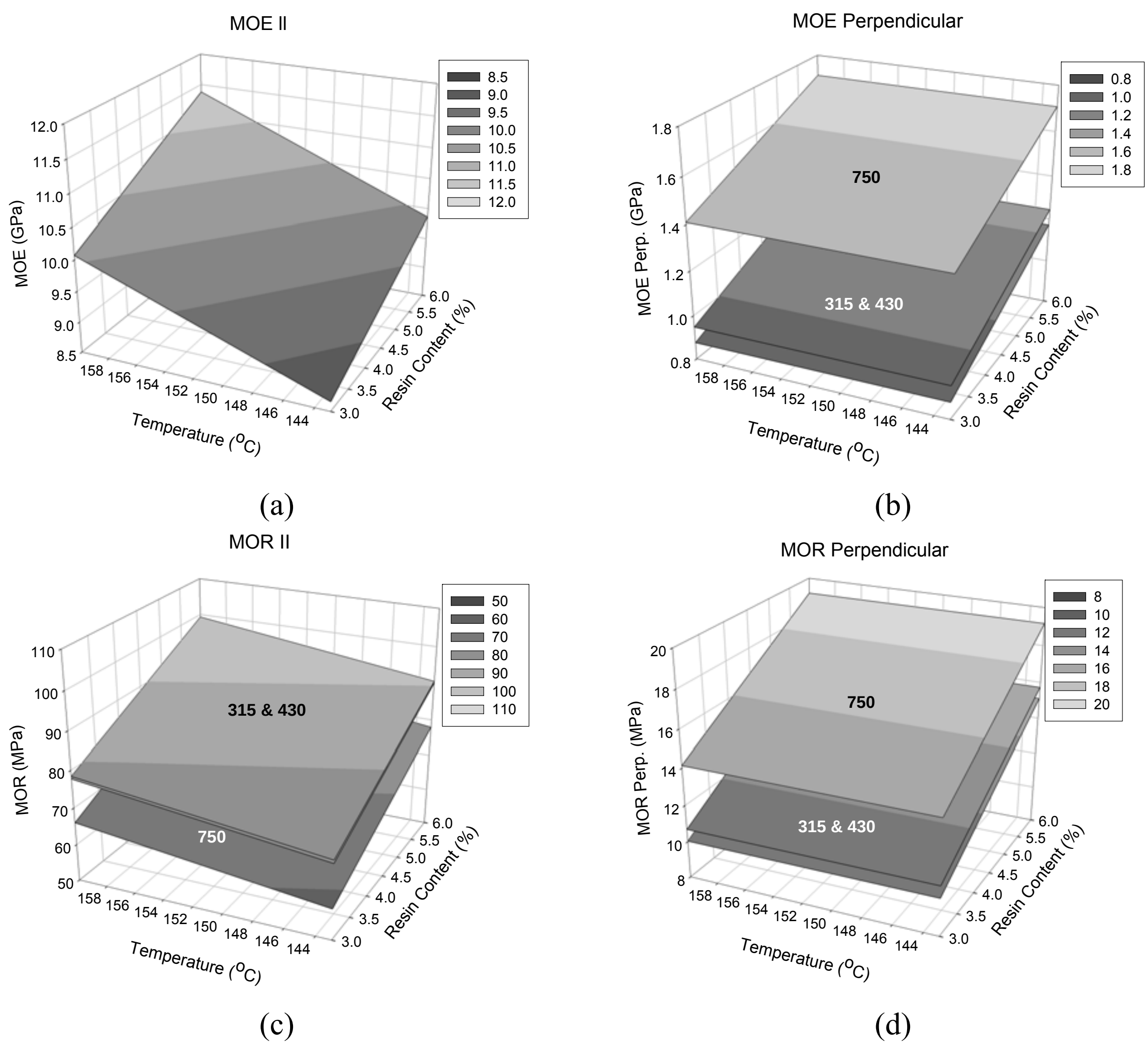


Figure 2.3. Effect of resin content, platen temperature, and aspect ratio on ply properties: a) MOE parallel, b) MOE perpendicular, c) MOR parallel, and d) MOR perpendicular. Where aspect ratio was not significant, only 1 graph including all aspect ratios is shown.

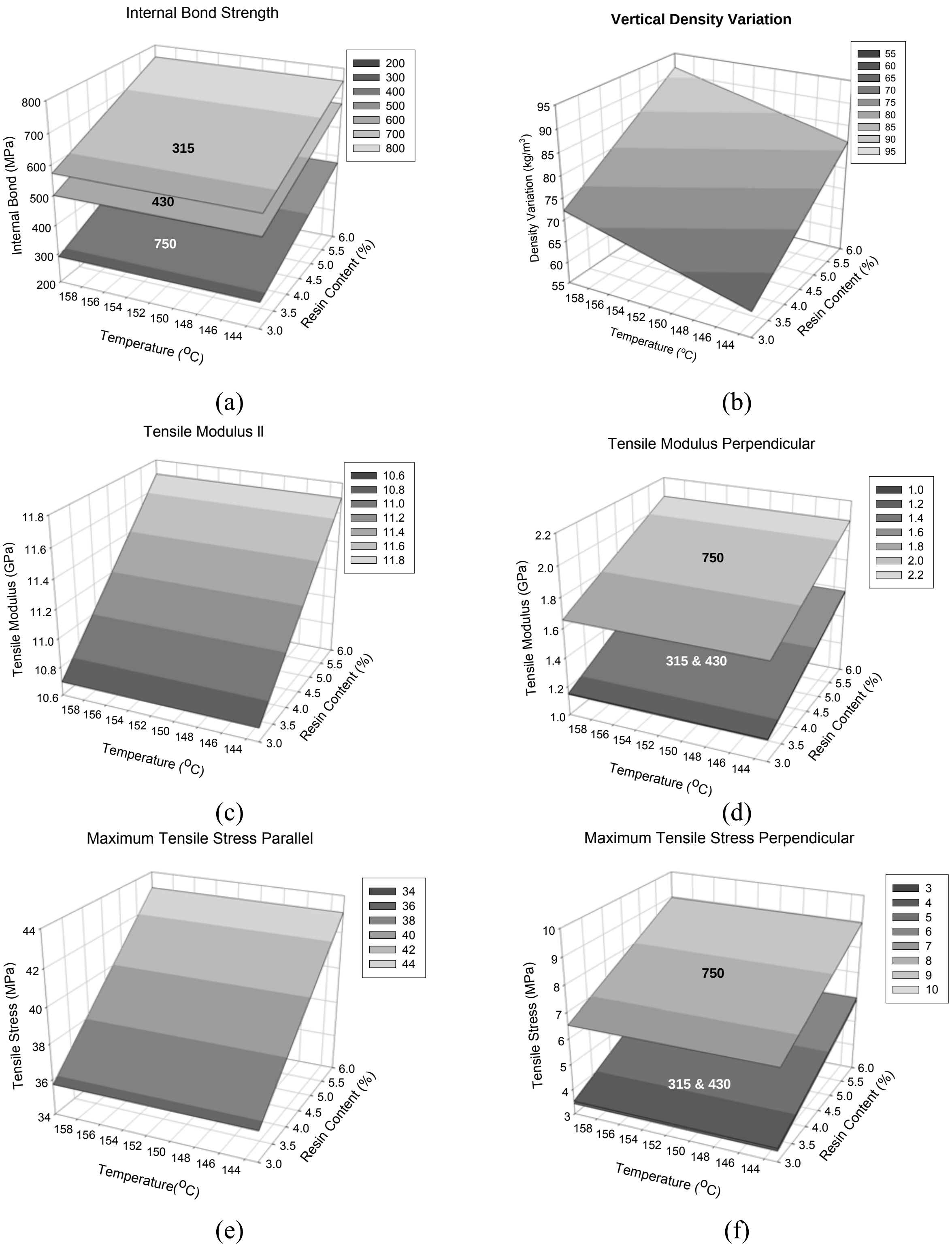


Figure 2.4. Effect of resin content, platen temperature, and aspect ratio on ply properties: a) Internal bond strength, b) Vertical density range, c) Tensile modulus parallel, d) Tensile modulus perpendicular, e) Maximum tensile stress parallel, and f) Maximum tensile stress perpendicular. Where aspect ratio was not significant, only 1 graph is shown for all aspect ratios.

Elastic properties of bending and tension specimens were similar. In the parallel direction, the average MOE was 10.4 GPa with a COV of 10.5% and the elastic modulus in tension was 11.9 GPa with a COV of 12.6%. In the perpendicular direction the average MOE was 1.32 GPa with a COV of 20.6%, while in tension the mean was 1.66 GPa with a COV of 22.2%. Alignment of strands seemed to have a greater influence on properties perpendicular to the strong axis: in the parallel direction a misaligned strand has a small effect; whereas, in the perpendicular direction one misaligned strand can impart significant strength to the ply.

Resin Content

Increasing the resin content significantly increased the vertical density variation, internal bond strength, bending properties parallel to the strong axis, and both tensile and bending properties perpendicular to the strong axis. The reason for the increase in the vertical density profile variation may be because of the higher moisture from the resin. During pressing, heat transfer adjacent to the platens occurs first so moisture can be removed and cure can take place more quickly at the surface. In the core, higher moisture results in increased steam pressure causing more resistance to densification and a larger vertical density variation.

The most significant effect of higher resin content within the plies was better resin coverage on strand surfaces and more bonding sites. The improved bonding within plies was reflected in a significant increase in internal bond strength, bending properties, and tensile properties in the perpendicular direction with increasing resin content (Figures 2.3 and 2.4). Using bending stiffness for example, there was an average increase of about

400 MPa in Young's modulus parallel to the strong axis and about 100 MPa in the perpendicular direction for every 1% increase in resin content. However, with an increase in resin content, moisture content also increases and mechanical properties may not continue to improve linearly for resin levels above 6% (Geimer and Christiansen 1996).

Aspect Ratio

The effect of aspect ratio was significant for internal bond strength, tension and bending in the perpendicular direction, and MOR in the parallel direction. Internal bond strength increased as aspect ratio decreased; a primary reason for this could be the increase in ratio of resin quantity to total strand surface area. The different aspect ratio strands had constant surface areas, but thickness differed, so 2.4 times as many 750-L/t strands as 315-L/t strands were required to make a ply and 1.4 times as many 430-L/t strands as 315-L/t strands.

Increasing the strand aspect ratio caused a significant increase in bending and tension properties perpendicular to the strength axis (Figures 2.3 and 2.4). One reason for this is because of the increase in width to thickness ratio. In the perpendicular direction, the strand width in effect becomes the length, and for the strands used, the ratio of width to thickness yields values of about 26, 36, and 63. As shown in Figure 2.1, for values in this range the effect of increasing the L/t ratio (decreasing the stress transfer angle) is a steep increase in strength and stiffness (Barnes 2000 and 2001). As mentioned above, this effect was not observed in the parallel direction because the curves have leveled out and values are relatively constant at the larger ratios (Figure 2.1).

Another reason for increased perpendicular strength and stiffness of plies made with higher aspect ratio strands can be attributed to strand misalignment. As mentioned above, a single misaligned strand can impart significant strength when tested in the perpendicular direction. Due to the higher number of 750 aspect ratio strands required to make up a ply, the probability of a misaligned strand being present is higher in these plies than in those composed of lower aspect ratio strands.

Temperature

Temperature was seen to have only a small influence on the resulting ply properties for the pressing schedule used. Bending modulus parallel to the strong axis was the only significant effect observed (Figure 2.3). A faster and more complete resin cure at the face of the ply with higher temperature could have resulted in an increase in bending stiffness. Geimer and Christiansen (1996) noted that high temperature was needed to remove moisture and promote good resin bonding. The effects of temperature were probably small in this case because the holding time was sufficient for the press cycle used; therefore, it appears that a good resin cure developed for all temperatures in the range studied (145-160°C). For all the plies manufactured in this study, the core temperature was approximately equal to the platen temperature by the end of the pressing cycle (Figure 2.2). One of the advantages to using thin strand ply therefore is a quicker heat and mass transfer through the ply.

Wang et al. (1995) found that for low temperatures (110°C), the effects of moisture are significant, but at higher temperatures (140°C) the bond strength develops quickly and isn't affected as much by the moisture in the board. Therefore, for pressing schedules with shorter holding times or temperatures lower than those used for this study, the effect of temperature might influence ply properties more significantly.

Other Effects

Horizontal density variation within plies was not significant for any of the variables used. Horizontal density was measured by taking the mean and COV of measured densities from thirteen different specimens per ply. The COV of density for specimens within each ply was taken as a measure of the density variation and the average COV value was 10.4%. For comparison, Bozo (2002) reported a COV of density within OSB panels of 6.5%. However, the boards studied in that case were 19 mm thick and the increased quantity of strands per specimen reduced the variability. The overall average density of all plies was 663 kg/m^3 with a coefficient of variation (COV) of 7.7%. The percent alignment, as mentioned above, was not found to differ significantly for any of the variables tested.

Optimization

In order to optimize the strand ply properties considering the three processing variables examined in this study, a goal was set for each effect along with an importance factor ranging from 1 to 5, with 5 being the highest. Table 2.3 presents the criteria used to establish the omptimality of each effect.

Table 2.3. Optimization criteria for plies with importance rated from 1 to 5

Optimization Criteria		
Variable / Effect	Goal	Importance
Resin Content	Minimize	2
Temperature	Minimize	2
Aspect Ratio	None	-
HD Variation	Minimize	3
VD Variation	Minimize	3
Internal Bond	Maximize	4
Tensile Mod. II	Maximize	5
Tensile Stress II	Maximize	5
Tensile Mod. Perp.	Maximize	1
Tensile Stress Perp.	Maximize	1
MOE II	Maximize	5
MOR II	Maximize	5
MOE Perp.	Maximize	1
MOR Perp.	Maximize	1

The numerical value for each effect multiplied by its importance was used to calculate omptimality using the Design-Expert model predictions. The combinations of variables were ranked by their maximum optimality. The top three optimization results showed that there was little difference in optimality between different aspect ratios due to offsetting influences of different effects. The variable levels and optimality for the top three combinations are given in Table 2.4.

Table 2.4. Variable combinations resulting in three highest optimality values

Rank	Resin content	Temperature	Aspect ratio	Optimality
1	5.59%	151.7°C	315	0.430
2	5.61%	151.8°C	430	0.423
3	5.59%	152.5°C	750	0.418

One factor that was not considered in the optimization was surface roughness. The 315 aspect ratio strands had more surface voids than the other aspect ratios because fewer of these strands were required to make up the ply thickness. As described by Dai (2005), a higher number of strands per board thickness results in more compaction and a lower probability of voids. Due to the similarity in optimality between the aspect ratios and the fact that the 430-aspect ratio strands were easiest to form, strands with nominal 430-aspect ratio were chosen over nominal 315-aspect ratio strands. Therefore, the optimum ply formulation chosen consisted of the following variable levels: Resin Content = 5.5%; Temperature = 152°C; and Aspect Ratio = 430. Values were rounded because optimality was not greatly affected by small variations.

Plies were then fabricated using this combination of variables for for a subsequent study of laminated composites. These specimens were tested and mean experimental values were compared to the predicted properties as shown in Table 2.3. Density variations, internal bond strength, and stiffness results parallel to the strong axis were generally close to predicted values, but in the perpendicular direction the model tended to over-predict strength and stiffness. One reason for this discrepancy could be differences in forming of the mat, as a different operator with less experience assisted in forming the second batch of strand mats. It is theorized that in the perpendicular direction plies are more sensitive to non-uniformity of deposition because of the low number of strands through the ply thickness and a smaller overlap between strands in the width direction.

Table 2.5. Predicted ply properties for optimum configuration

Variable / Effect	Predicted Value	Units	Experimental Value	Units	P/E Ratio
HD Variation	10.3	%	10.2	%	1.01
VD Variation	83.30	kg/m^3	79.13	kg/m^3	0.95
Internal Bond	653.14	kPa	615.0	kPa	1.06
Tensile Mod. II	11.53	GPa	10.89	GPa	1.06
Tensile Stress II	41.98	MPa	30.83	MPa	1.36
Tensile Mod. Perp.	1.50	GPa	1.05	GPa	1.43
Tensile Stress Perp.	5.46	MPa	3.27	MPa	1.67
MOE II	10.42	GPa	10.22	GPa	1.02
MOR II	91.13	MPa	79.09	MPa	1.15
MOE Perp.	1.12	GPa	.873	GPa	1.28
MOR Perp.	14.27	MPa	10.61	MPa	1.34

Comparing the strand ply properties to reported mechanical properties for small-diameter ponderosa pine timber demonstrates a two to three fold increase in strength and stiffness. Erikson et al. (2000) reported that small diameter ponderosa pine solid wood specimens taken from northern Idaho had a mean MOE of about 5.9 GPa and an MOR of about 30 MPa. His study determined that properties were low enough for this species, that it was unsuitable for mechanical grading of lumber. Therefore, potential utilization of this species for producing strand plies that have significantly improved strength and stiffness properties with low variation could be of commercial significance.

Summary and Conclusions

A novel thin strand ply composite was developed and tested to determine optimum mechanical and physical properties. The manufacturing variables considered for ply optimization were resin content, temperature, and strand aspect ratio. Increasing the resin content was shown to significantly increase nearly all of the properties tested, including bending, tension, internal bond, and density variation. Aspect ratio had a significant effect on internal bond, as well as bending and tensile properties perpendicular to the strong axis. Temperature was seen to influence significantly only the bending modulus parallel to the strong axis for the pressing schedule used. Using the test results, the optimum manufacturing parameters for thin strand ply were determined to be 5.5% resin content, 152°C platen temperature, and 430 L/t aspect ratio strands.

The major conclusions from thin strand ply testing were that:

1. Thin strand ply veneers of consistent quality can be produced from low-value, small-diameter timber.

2. Strand-based veneers were produced that were 2-3 times stronger and stiffer than the parent wood.
3. An optimum combination of resin, platen temperature, and strand aspect ratio was determined for hot-pressing thin strand plies that could then be used to engineer layered strand-based composite laminates.

References

1. Alberta Research Council. 2006. PressMAN. Alberta, Canada. http://www.arc.ab.ca/Index.aspx/ARC/7501.

2. American Society for Testing and Materials (ASTM). 1999. Standard test methods for evaluating properties of wood-base fiber and particle panel materials. ASTM D 1037-99. ASTM, West Conshohocken, Pa.

3. Andrews, C. K., P. M. Winistorfer, and R. M. Bennett. 2001. The Influence of furnish moisture content and press closure rate on the formation of the vertical density profile in oriented strandboard. Forest Products Journal. 51(5): 32-39.

4. Barnes, D. 2000. A model of the effect of strand angle and grain angle on the strength properties of oriented veneer and strand wood composites. Forest Products Journal. 52(4): 39-47.

5. Barnes, D. 2001. A model of the effect of strand length and strand thickness on the strength properties of oriented wood composites. Forest Products Journal. 51(2): 36-46.

6. Bodig, J. and B. A. Jayne. 1982. Mechanics of wood and wood composites. Van Nostrand. New York. 712 pp.

7. Bozo, A. 2002. Spatial variation of wood composites. Ph.D dissertation. Washington State University. Pullman, WA.

8. Dai, C., and P. R. Steiner. 1994. Spatial structure of wood composites in relation to processing and performance characteristics, Part 3. Modeling the formation of multi-layerd random flake mats. Wood Science and Technology. 28: 229-239.

9. Dai, C., C. Yu, and X. Zhou. 2005. Heat and mass transfer in wood composite panels during hot-pressing. Part II. Modelling void formation and mat permeability. Wood and Fiber Science. 37(2): 242-257.

10. Erikson, R. G., T. M. Gorman, D. W. Green, and D. Graham. 2000. Mechanical grading of lumber sawn from small-diameter lodgepole pine, ponderosa pine, and grand fir trees from northern Idaho. Forest Products Journal. 50(7/8):59-65.

11. Garcia, P. J., S. Avramidis, and F. Lam. 2001. Internal temperature and pressure responses to flake alignment during hot-pressing. Holz als Roh- und Werkstoff. 59:272-275.

12. Geimer, R. L. 1976. Flake alignment in particleboard as affected by machine variables and particle geometry. USDA Forest Service, Research Paper FPL 275, Forest Products Laboratory, Madison, WI.

13. Geimer, R. L. 1979. Data basic to the engineering design of reconstituted flakeboard. Proc. 13th Annual Particleboard Symposium. Washington State University. Pullman, Washington. pp. 105-125.

14. Geimer, R. L. and A. W. Christiansen. 1996. Critical variables in the rapid cure and bonding of phenolic resins. Forest Products Journal. 46(11/12): 67-72.

15. Generalla, N. C., E. J. Biblis, and H. F. Carino. 1989. Effect of two resin levels on properties of commercial southern OSB. Forest Products Journal. 39(6): 64-68.

16. Hansen, E. 2006. Structural Panel Industry Evolution: Implications for Innovation and New Product Development. Forest Policy and Economics. 8(7):774-783.

17. Jones, R. M. 1999. Mechanics of composite materials. 2nd Edition. Taylor and Francis. Philadelphia, PA.

18. Kamke, F. A., and L. J. Casey. 1988. Gas pressure and temperature in the mat during flakeboard manufacture. Forest Products Journal. 38(3): 41-43.

19. Kamke, F. A., and L. J. Casey. 1988. Fundamentals of flakeboard manufacture: internal-mat conditions. Forest Products Journal. 38(6): 38-44.

20. Larmore, F. D. 1959. Influence of specific gravity and resin content on properties of particleboard. Forest Products Journal. 9(4): 131-134.

21. Lehmann, W. F. 1965. Improved particleboard through better resin efficiency. Forest Products Journal. 15(4): 155-161.

22. Lehmann, W. F. 1968. Resin distribution in flakeboard shown by ultraviolet light photography. Forest Products Journal. 18(10): 32-34.

23. Lehmann, W. F. 1974. Properties of structural particleboards. Forest Products Journal. 24(1): 19-26.

24. Linville, J. D. 2000. The influence of a horizontal density distribution on moisture-related mechanical degradation of oriented strand composites. Master's Thesis. Dept. of Civil and Environmental Engineering. Washington State University. 121 pp.

25. Maloney, T. 1970. Resin distribution in layered particleboard. Forest Products Journal. 20(1): 43-52.

26. McNatt, J. D., L. Bach, and R. W. Wellwood. 1992. Contribution of flake alignment to performance of strandboard. Forest Products Journal. 42(3): 45-50.

27. Meyers, K. 2001. Impact of strand geometry and orientation on mechanical properties of strand composites. M.S. Thesis. Washington State University. Pullman, WA.

28. Saliklis, E. P. and R. H. Falk. 2000. Correlating off-axis tension tests to shear modulus of wood-based panels. Journal of Structural Engineering. 126(5): 621-625.

29. Sekino, N. et al. 2000. Effect of manufacturing parameters on the linear expansion of densified wood composite panels. I. Effect of element size and press temperature. Journal of the Japan Wood Research Society. 46(4): 334-341.

30. Simpson, W. T. 1977. Model for tensile strength of oriented flakeboard. Wood Science 10(2): 68-71.

31. Smith, D. C. 1982. Waferboard press closing strategies. Forest Products Journal. 32(3): 40-45.

32. Spelter, H. et al. 2006. Status and trends: Profile of structural panels in the United States and Canada eh. USDA Forest Products Lab Research Paper FPL-RP-636. 45 pp.

33. Stat-Ease. 2007. Design-Expert® 7.1 for Windows – Software for Design of Experiments (DOE). Minneapolis. http://www.statease.com/dx71descr.html

34. Stoffko, J. 1960. The relationship between the dimensions and geometry of wood particles and the mexhanical poperties of wood-particle boards. Drearsky Vyskum. 5(2):241-261.

35. Strickler, M. D. 1959. Effect of press cycles and moisture content on properties of Douglas-Fir flakeboard. Forest Products Journal. 9(7): 203-215.

36. Suchsland, O. 1959. An analysis of the particle board process. Michigan Quarterly Bulletin. 42:2 (350-372).

37. Suchsland, O. 1962. The density distribution in flake boards. Michigan Quarterly Bulletin. 45(1): 104-121.

38. Suchsland, O. 1968. Particle-board from southern pine. Southern Lumberman. December 15: 139-144.

39. UTHSCA ImageTool. 2002. UTHSCA ImageTool Version 3.0 Final is Here. http://ddsdx.uthscsa.edu/dig/itdesc.html.

40. Wang, S. and P. M. Winistorfer. 2000. Fundamentals of vertical density profile formation in wood composites. Part II. Methodology of vertical density formation under dynamic conditions. Wood and Fiber Science. 32(2): 220-238.

41. Wang, X. M., B. Reidl, A. W. Christiansen, and R. L. Geimer. 1995. The effects of temperature and humidity on phenol-formaldehyde resin bonding. Wood Science and Technology. 29(4):253-266.

42. Wang, X. M., B. Reidl, R. L. Geimer, and A. W. Christiansen. 1996. Phenol-formaldehyde resin curing and bonding under dynamic conditions. Wood Science and Technology. 30(6):423.

43. Xu, W. and P. R. Steiner. 1995. A statistical characterization of the horizontal density distribution in flakeboard. Wood and Fiber Science. 27(2): 160-167.

44. Zhou, D. 1990. A study of oriented structural board made from hybrid poplar: Physical and mechanical properties of OSB. Holz als Roh- und Werkstoff. 48:293-296.

CHAPTER THREE

PROPERTIES OF LAMINATED STRAND PLY (LSP): AN ENGINEERED LAMINATE OF THIN STRAND PLIES

Introduction

Laminated Strand Ply (LSP) is a novel engineered wood composite consisting of thin (3 mm) plies formed with oriented strands (Weight 2007). These plies are laminated to form a composite board. Advantages include utilization of low density small-diameter timber, manufacture of a composite with smooth surface, consistent density, good mechanical properties, and the ability to engineer laminates for specific applications. Some of the critical information needed to commercialize such a product is mechanical and physical properties of these laminates for comparison with currently used wood composites. In addition, the ability to predict stiffness and strength properties using an analytical model like Classical Lamination Theory (CLT) would help limit the extent of testing needed to identify optimum ply lay-ups for individual applications.

Objective

The primary objective of this proof of concept study is to investigate the feasibility of engineering laminated composites of thin strand-based plies produced from small-diameter timber of low value. Several tasks were formulated to attain this objective.

1. Using a previously optimized formulation, fabricate and test thin strand plies to determine elastic moduli (E_1, E_2), Poisson's ratio (ν_{12}), and shear modulus (G_{12}), for input into a classical lamination theory (CLT) model.

2. Manufacture engineered strand laminates using these plies (LSP) evaluate physical and mechanical properties, and compare these with properties of similar wood composites marketed currently.
3. Predict laminate elastic and strength properties using CLT, and compare results with experimentally obtained laminate properties.

Background

Classical Lamination Theory

Flexibility of engineering a laminate using CLT for specific end uses has been utilized for decades with synthetic fiber composites like carbon, fiberglass, aramid, and others (Jones 1999, Barbero 1999, Chen and Sun 1989), especially in space and aircraft applications. One significant advantage to this method is the ability to engineer the end product to meet design criteria. In the field of wood composites, plywood has long employed lay-ups of wood veneer to form composites with properties that can be predicted using the individual ply properties and their orientation (Perry 1948). Evaluation by Panago (1970) of an exact solution versus a CLT model for a pinned end wood composite laminate validated use of a CLT model showing that the error of the model is insignificant compared to the property variability in plies and laminates. Other layered wood composites that have been studied include panels consisting of strand or particleboard cores overlaid with veneer faces (Biblis et al. 1996, Hse 1976, Countryman 1975).

Recently, strand composites have been evaluated using a CLT model (Moses et al. 2003, Yadama et al. 2006). Moses et al. (2003) described one application of CLT in a study performed on laminated strand lumber (LSL). Approximately 0.23 m long strands were used to form laminates suitable for beam or column structural members. Specimens were constructed of fully oriented layers as well as completely random layers to determine the strengths, modulus of elasticity, and shear properties of each case. The properties of oriented (0° and 45°) and random (R) layers were then used to predict the overall properties of three lay-ups: [0°, R, 0°], [R,0°,R], and $[0°/45°/-45°/0°]_{sym}$. Distributions in the layer properties were then used in a prediction of the range of properties for the complete laminate. The program that was developed predicted the effects of stacking sequence on panel behavior. The influence of strand alignment and the variability of results were shown to be predictable to varying degrees using CLT. A similar technique should be viable for LSP composites as well. Yadama et al. (2006) applied CLT, which incorporated the effects of out-of-plane undulation of strands, to predict the elastic properties of oriented strand composites as well.

Determination of Shear and Elastic Properties

Shear and elastic properties of individual ply layers must be obtained to apply a CLT model,. From tensile testing of plies in which strain data are collected in both longitudinal and transverse directions, elastic moduli and Poisson's ratios can be calculated. By testing specimens with strands oriented at 0 degrees, 90 degrees, and 45 degrees, as shown in Figure 3.2, one can obtain E_1, E_2, ν_{12}, ν_{21}, and E_x.

The shear modulus may then be calculated using a transformation equation such as presented by Jones (1999) (Equation 3.1) and inserting the experimentally obtained elastic moduli and Poisson's ratios.

$$\frac{1}{E_x} = \frac{1}{E_1}\cos^4\theta + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1}\right)\sin^2\theta\cos^2\theta + \frac{1}{E_2}\sin^4\theta \qquad \text{Equation 3.1}$$

Solving Jones' equation for G_{12} we obtain an equation for the shear modulus:

$$G_{12} = \left[\frac{2\nu_{12}}{E_1} + \frac{\frac{1}{E_x} - \frac{\cos^4\theta}{E_1} - \frac{\sin^4\theta}{E_2}}{(\sin^2\theta)(\cos^2\theta)} \right]^{-1} \quad \text{Equation 3.2}$$

Saliklis and Falk (2000) also have proposed an empirical equation for G_{12} using results of tension tests performed on parallel, perpendicular, and off-axis specimens:

$$G_{12} = \frac{(\sin^2\theta)(\cos^2\theta)}{\left(A^{2A}\right) * \left[\frac{1}{E_x} - \left(\frac{\cos^4\theta}{E_1} + \frac{\sin^4}{E_2} \right) \right]} \quad \text{Equation 3.3}$$

Where: $A = E_2/E_1$.

Once the elastic moduli, Poisson's ratio, and shear modulus of individual plies have been obtained, all of the necessary properties for input into a CLT model are known. From this information, elastic properties of laminates may be predicted and compared with experimental test data.

In addition, maximum stress values for σ_1 and σ_2 can be obtained from ply tension testing for use in CLT strength predictions. Assuming a linear stress/strain relationship, a load N_x, N_y, M_x, or M_y may be input into the model. Then, the resulting stress calculated for each ply may be examined and compared to the maximum stress to determine if failure has occurred. Through an iterative process of incrementally increasing the applied load and comparing the predicted stresses, a prediction of the failure load can be made based on failure of the critical ply. Comparisons can then be made between predicted and experimental tension and bending values as a first approximation.

Currently Marketed Wood Composite Panels

It is important to compare the mechanical and physical properties of LSP to other wood composites such as OSB, MDF, particleboard, and plywood to determine if values are comparable, inferior, or superior. The results of these tests will help to determine what potential exists and what additional research should be performed on this new laminated composite concept. Additionally, comparisons with oriented strand composite boards hot-pressed from the same material to approximately the same thickness as the laminates would give insight into the effects of utilizing this new concept and its potential benefits.

Methods and Materials

Thin Strand Ply Manufacturing

Using an optimal formulation as determined previously (Weight, 2007), thin oriented strand plies were manufactured with strands having a length/thickness aspect ratio of 430; other processing parameters included a resin content of 5.5% and a press temperature of 152°C. The 0.15 m long strands were generated in the lab from small-diameter (top diameter of 0.10-0.15 m) ponderosa pine (*Pinus ponderosa*). Plies were formed using vanes spaced at 0.076 m on center for orientation resulting in an average strand alignment of 78%. Strand alignment is defined in Equation 3.4 as first presented by Geimer (1979).

$$PercentAlignment = \frac{45 - \theta}{45} \qquad \text{Equation 3.4}$$

Where, θ, the average alignment angle, is the mean of the absolute value of the measured alignment angles.

A total of 66 plies were manufactured for this study including 46 plies with strands oriented at 0 degrees with respect to the longitudinal axis and 20 plies oriented at 45 degrees with respect to the longitudinal axis. In order to orient strands at an angle to the longitudinal axis, a plywood form was designed to overlay the forming box as shown in Figure 3.1. The number of plies used for each stage of the study is listed in Table 3.1 and the specimen sampling scheme may be found in Appendix D.

Figure 3.5. Forming box for 45 degree strand plies

The mechanical and physical properties of the plies were determined by selecting individual plies at random from the set of manufactured plies. Internal bond, tension, and thickness swell specimens were cut from each ply and tested to determine ply properties.

Table 3.1. Plies manufactured for the study

Orientation Angle	# of Plies Needed for Laminates	# of Plies Needed for Ply Testing	Total # of Plies Needed
0 degrees	42	4	46
45 degrees	16	4	20
Total	58	8	66

Ply testing

All ply testing followed the guidelines of ASTM D 1037-99 (1999). Tension specimens were cut with strands oriented at 0º, 90º, and 45º from the longitudinal axis as shown in Figure 3.2. A 25 mm gauge length extensometer was used to measure strain in the longitudinal direction and a 13 mm gauge length extensometer was used to measure strain in the transverse direction. Due to instrumentation limitations, extensometers could not be synchronized to gather strain data simultaneously. Therefore, specimens were loaded to about 30% of maximum capacity, staying within the linear elastic region, while strain data were gathered in the longitudinal direction and then unloaded. Next, the transverse strain data were gathered while the specimen was loaded to failure. The combined stress-strain data were used to calculate the elastic moduli and Poisson's ratios for each specimen. From the values of E_1, E_2, ν_{12}, and E_x, the shear modulus, G_{12}, was then calculated using Equations 3.2 and 3.3.

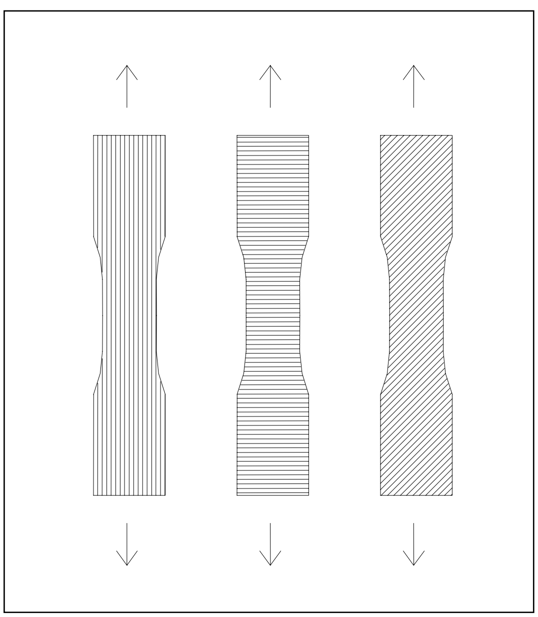


Figure 3.6. Tension specimens for obtaining elastic moduli and Poisson's ratios

Water soak tests for the plies were performed using 0.152 m square specimens with data collected after 2 hours and 24 hours after initial submersion as outlined in ASTM D1037-99. The short-term measurements were included to determine how quickly the specimens gained moisture.

Laminate Manufacture

Three different laminate configurations were manufactured from the remaining plies. The lay-up for each laminate was balanced and symmetric to eliminate coupling between bending and tension. Laminate A was composed of six plies all bonded with their strong axes parallel to each other (0º, 0º, 0º, 0º, 0º, 0º) and had four replicates. Laminate B also consisted of six plies with a parallel ply on each face and plies oriented at ±45 degrees in the center (0º, +45º, -45º, -45º, +45º, 0º) with four replicates. Laminate C was a five-ply laminate with three plies oriented at 0 degrees and two at 90 degrees (0º, 90º, 0º, 90º, 0º) with only two replicates due to the limited supply of strands and strand plies. The three configurations are shown in Figure 3.3.

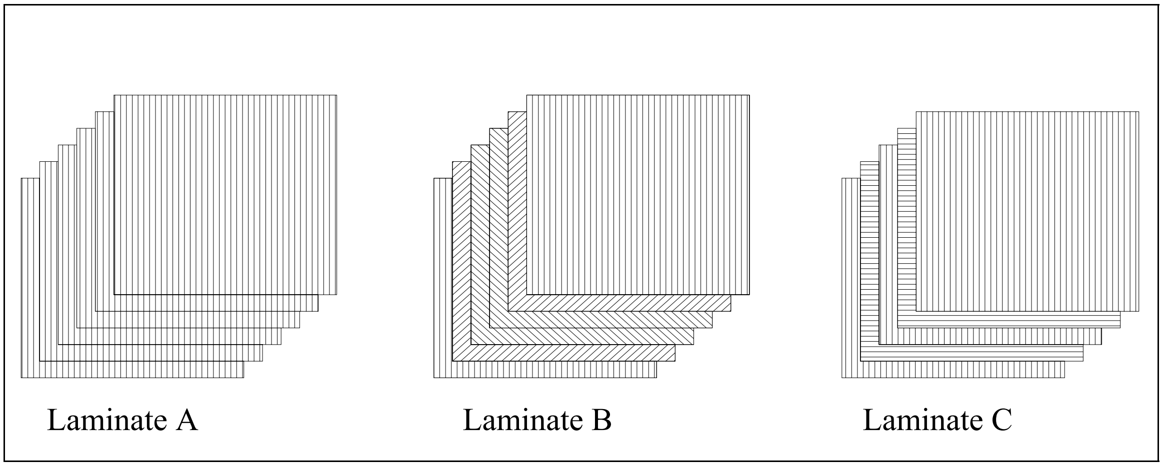


Figure 3.7. Laminate lay-up configuration: Laminate A (0, 0, 0, 0, 0, 0), Laminate B (0, +45, -45, -45, +45, 0) and Laminate C (0, 90, 0, 90, 0)

Plies were bonded together using phenol resorcinol resin applied at a loading of 37 kg per 100 m^2 of bond line. Laminates were cured in a hydraulic press at a pressure of 860 kPa and a platen temperature of 35ºC for about 6 hours according to the glue manufacturer's instructions.

In addition to the laminates, three 19 mm thick unidirectional strand composite (OSC) panels were manufactured using the same strands for comparison of properties. A previously developed pressing schedule (Meyers 2001) was used for these boards. Due to the slow closing time for the OSC panels some "pre-cure" occurred on the faces. After the thin strand laminates and OSC panels were formed, test specimens were cut from each board for bending, tensile, internal bond, and thickness swell testing (test specimen sampling schemes are included in Appendix D.)

Laminate Testing

Bending, tensile, internal bond, and thickness swell tests were performed on laminate and OSC specimens according to ASTM D1037-99 (ASTM 1999). Specimens were conditioned at 21ºC and 65% relative humidity. Bending and internal bond tests were performed using an 8.9 kN capacity screw driven testing machine. Strain data for the bending tests were obtained using a laser extensometer.

Tension tests of "dog-bone" specimens were performed on a similar testing machine with a capacity of 133 kN. It was observed that failure initiated at the grips in 18 of 24 specimens tested parallel to the strong axis. Self tightening grips with teeth were used as prescribed in the standard, and it appeared that the surface fibers were severed by the contraction of these grips (Figure 3.4). Two specimens also experienced a shear failure within the grips, and the remaining specimens all failed in the necked-down portion of the specimen. This likely truncated the resulting maximum stress values.

Figure 3.8. Failure of tension specimen initiating at the grips

Water soak tests of laminates and OSC specimens were carried out in the same manner as for the ply specimens. Short-term effects were measured after two hours, and then specimens were re-weighed and measured after twenty-four hours to determine water absorption and thickness swell properties.

Results and Discussion

Ply Properties

The mean values resulting from ply tensile testing are reported in Table 3.2. Using these values and Equation 3.2, the shear modulus, G_{12}, was calculated to be 1.364 GPa. Using Equation 3.3 a value of 2.355 GPa was obtained for G_{12}, however the paper by Saliklis and Falk (2000) recommended using various off-axis angles in addition to the 0 and 90 degree moduli. To be conservative, since in this study only one additional off-axis angle (at 45 degrees) was tested, the shear modulus value determined from the transformation equation (Equation 3.2) was used. This shear modulus, along with the experimentally obtained elastic moduli, maximum stresses, and Poisson's ratios listed in Table 3.2 were used as input for the CLT model to predict laminate properties.

Table 3.2. Ply tensile properties

Average Ply Properties

Ply orientation	Property	# of Specimens Tested	Mean Value (COV)
0 Degrees	Young's Modulus (Gpa)	16	10.89 (20.2%)
	Max Stress (Mpa)	16	30.83 (41.5%)
	Poisson's Ratio	16	0.358 (28.6%)
90 Degrees	Young's Modulus (Gpa)	16	1.05 (39.8%)
	Max Stress (Mpa)	16	3.27 (40.2%)
	Poisson's Ratio	16	0.030 (34.2%)
45 Degrees	Young's Modulus (Gpa)	32	2.31 (17.6%)
	Max Stress (Mpa)	32	6.03 (18.7%)

The variation in ply properties was quite high because of the difficulty in distributing strands evenly by hand for the thin plies; thereby contributing to imprecision in laminate property predictions. Uniform distribution of strands becomes especially critical in forming mats to construct thin plies as fewer layers of strands are present in a given thickness. The ply directional properties were high due to the strand alignment. Ratios of parallel to perpendicular stiffness and strength were 10.4 and 9.4 respectively.

Three different measures of ply density variations were measured: vertical density variations through the ply thickness, horizontal density variation in the plane of the ply, and average overall ply density variation between plies. Vertical densities using an X-ray density profiler were measured in increments of 0.13 mm through the ply thickness and resulted in relatively constant density profiles (Figure 3.5). The mean ply density was

730 kg/m^3 with a COV of 12.1%. Horizontal density variation in a ply was measured using the COV of density of 5 specimens per ply. The average COV of horizontal density across the plane of the plies was 10.2%. Therefore, variations of density within a ply were almost as great as the difference from one ply to another.

Internal bond (IB) strengths of the plies were high for the 0-degree plies with an average capacity of 615 kPa and a COV of 14.3%. The IB strength of the 45 degree plies was lower but still fairly good with an average capacity of 576 kPa and a COV of 16.5%. Differences in values may be attributed to differences in forming the plies. The strands were spread a little thinner (average ply thickness was 0.119" rather than 0.127") for the 45 degree plies because of the absence of a forming box to contain strands. Therefore, a slightly less uniform ply quality may account for the lower internal bond strength of these plies.

The water soak specimens were conditioned before submersion to an average moisture content (MC) of 11.4%. After 2 hours of soaking, the mean MC had increased to 82.9% and after 24 hours had reached 99.6%. The percent of water absorbed with respect to the initial weight was 64.2% and 79.1% respectively. Mean thickness swell was measured at 19.5% after 2 hours and 22.0% after 24 hours. A large percentage of the thickness swell and water absorption occurred within the first two hours of submersion. Some specimens split at locations along the edges after soaking.

Laminate Properties

As with individual plies, variations in vertical density, horizontal density, and overall density were also obtained for the three laminates and the unidirectional OSC. Laminate vertical density tests showed that variation through the thickness was approximately equal to the variation between plies except at the laminate interface between plies where the density "spiked". By comparison, the OSC board had a much higher vertical density profile variation. Mean density of OSC was 672 kg/m^3 with a range of 483 kg/m^3 (71.9%) between the high-density face and the low-density core (Figure 3.5). In contrast, LSP specimens averaged 707 kg/m^3 with a density range of about 20%.

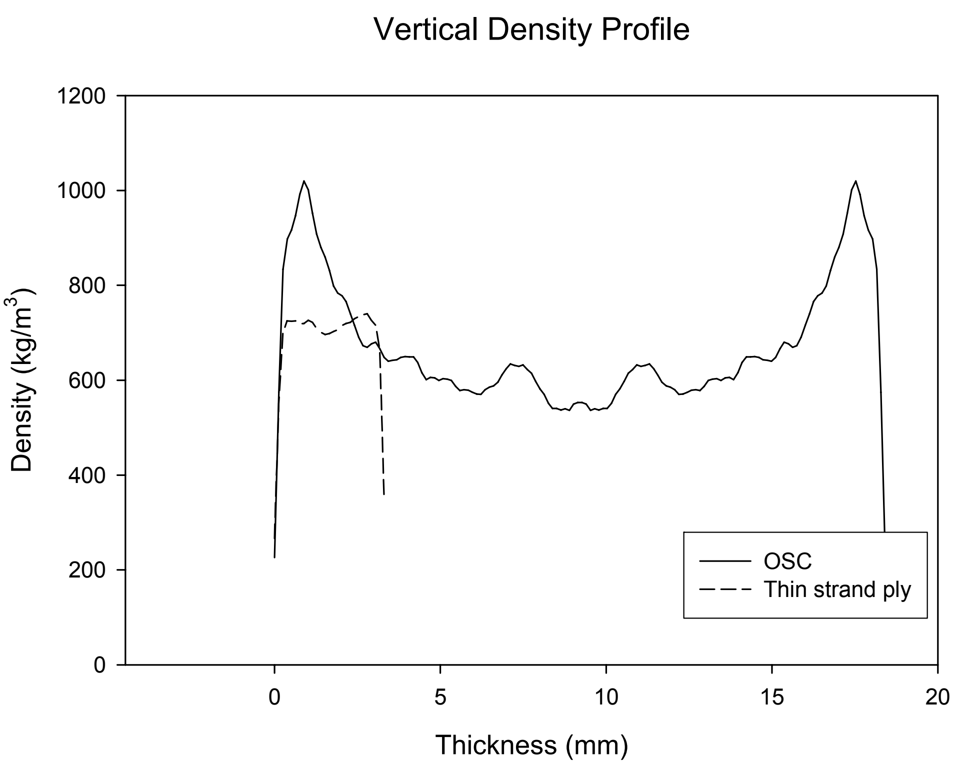


Figure 3.9. Vertical density profiles of thin strand ply and OSC

Horizontal density measurements of laminates resulted in a COV of density within laminates of 5.4%, whereas for OSC the value was 9.7%. Overall density variation, measured using the COV of density between boards, was 3.3% for the laminates and 6.1% for the OSC boards. Not enough specimens were measured to determine the significance of these differences in density variations; however, two observations that should be noted are that the density variations of the laminates appear to be about half the value of the OSC, and the variation within a board was observed to be higher than the variation between boards.

In order to compare the laminate and OSC property results, descriptive statistics were obtained including a Shapiro-Wilkes test for normality of data. Then, a general linear model (GLM) was used to perform analysis of variance (ANOVA) using SYSTAT software (2002). This method was used because of the unequal sample sizes. Relevance of results was determined using a level of significance (α) value of 0.05. A summary of ANOVA test results is presented in Table 3.3.

Table 3.3. ANOVA test results of significance of response variables

Significance of Response Variables with Board Configuration

Response Variable	Significant?	p-value
MOE II	Yes*	< 0.001
MOR II	Yes*	0.001
MOE ⊥	Yes*	< 0.001
MOR ⊥	Yes*	< 0.001
Young's Modulus II	Yes	< 0.001
Max Tensile Stress II	Yes*	< 0.001
Young's Modulus ⊥	Yes	< 0.001
Max Tensile Stress ⊥	Yes*	< 0.001
Internal Bond	Yes[†]	< 0.001
MC after 24h Soak	Yes[†]	0.015
Water Abs after 24h Soak	Yes[†]	0.001
Thickness Swell	Yes[†]	0.011

* One or more data sets failed Shapiro-Wilkes normality test.

[†] Density was included as a covariate to remove its effects.

Where significant effects were observed, multiple pairwise comparisons between the laminates and the OSC were made using the Scheffe test. This test was chosen because it was the most conservative, meaning the least likely to commit a Type I error and predict a significant difference between board types when none existed. Mean properties, COV's, and a summary of comparison of means for the effects examined are presented in Table 3.4. Complete statistical analysis output is included in Appendix F.

Table 3.4. Summary of board properties and pairwise comparison of different LSP configurations and OSC. Configurations with same symbol (A or B) are not significantly different from each other using Scheffe's test at a significance level (α) of 0.05. Values in parentheses are COVs.

Product	MOE II (GPa)		MOR II (MPa)		Young's Mod II (GPa)		Max Ten Str II (MPa)		IB (kPa)	
Lam A	9.46 (10.4%)	A	51.8 (15.0%)	A	9.52 (9.8%)	A	28.4 (9.7%)	A	370 (22.8%)	A
Lam B	7.22 (2.9%)	B	41.6 (13.2%)	B	5.32 (19%)	B	20.2 (9.9%)	B	300 (27.5%)	A
Lam C	7.59 (9.8%)	B	43.5 (7.8%)	A B	5.64 (23%)	B	22.5 (8.9%)	B	290 (38.8%)	A
OSC	10.24 (7.8%)	A	64.5 (7.0%)		9.66 (15.1%)	A	29.0 (14.2%)	A	480 (29.1%)	
Product	**MOE II (GPa)**		**MOR II (MPa)**		**Young's Mod II (GPa)**		**Max Ten Str II (MPa)**		**TS (%)**	
Lam A	1.16 (10.9%)	A	10.0 (13.1%)	A	1.30 (26.2%)	A	6.1 (15.4%)	A	17.8 (17.2%)	A
Lam B	1.72 (6.4%)	B	17.4 (11.0%)		2.24 (14.8%)		12.3 (7.9%)		18.9 (4.5%)	A
Lam C	2.87 (8.6%)		28.9 (9.5%)		4.37 (15.2%)		20.6 (18.4%)		19.3 (5.0%)	A B
OSC	1.47 (14.3%)	A B	12.7 (16.1%)	A	1.02 (16.5%)	A	5.6 (10.1%)	A	24.4 (13.7%)	B

It can be seen that in bending and tension, the differences between Lam A and OSC were insignificant in nearly every case in both parallel and perpendicular testing. This is because all strands were oriented parallel to the strength axis in both the OSC and Lam A with the only difference being in the way they were manufactured. The difference in MOR may be accounted for by the variation in vertical density profile of the OSC. The higher density face zones of the OSC appeared to have resulted in a higher MOR value. For pure bending applications, laminates could be improved by incorporating high density face plies into the lay-up. Least squares means data of elastic properties in bending and tension parallel and perpendicular to the strong axis are given in Figure 3.6.

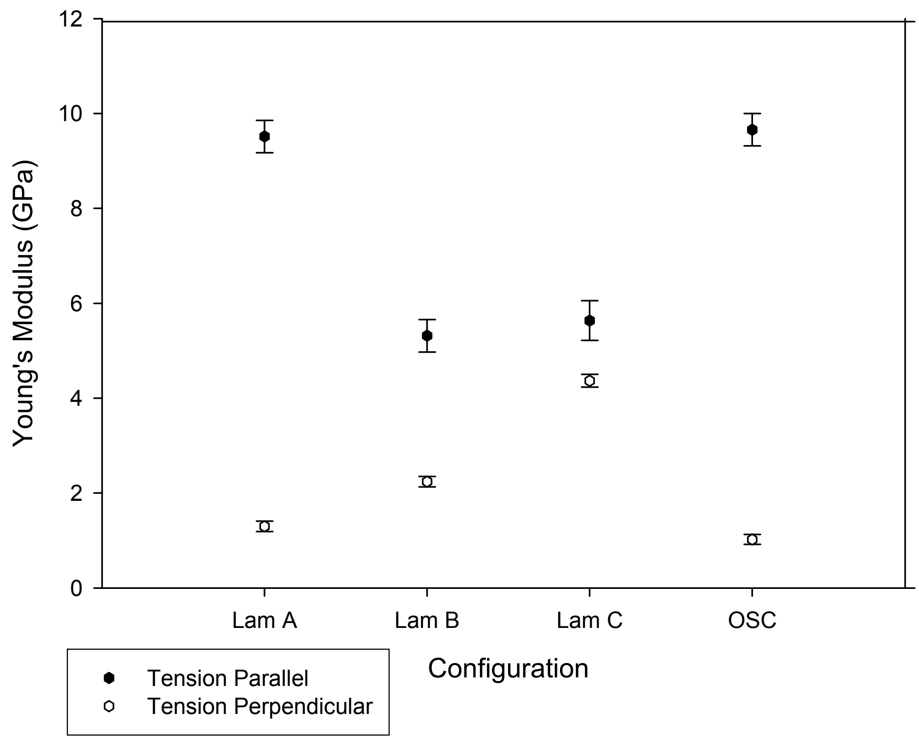


Figure 3.10. Least squares means results for Young's modulus parallel and perpendicular to the strong axis (in GPa)

Bending and tension results for Lam B and Lam C were very similar to each other in the parallel direction. This is mainly because of contributions to strength and stiffness from the two parallel face plies with some additional contribution from interior laminations. However, for bending in the perpendicular direction, the MOE and MOR of Lam C were significantly higher than Lam B due to the 90 degree cross plies in the lay-up. It was seen that some strength and stiffness was imparted to Lam B by its 45 degree plies, because perpendicular values were significantly higher than Lam A and OSC for most cases. Due to limited ply quantities, no specimens were tested at 45 degrees to the strong axis, where it is assumed that strength and stiffness of Lam B would exceed the others. Saliklis and Falk (2000) reported tensile moduli of plywood tested at various off-axis angles, and values were lowest at 45 degrees from the strong axis. For shear panel applications, a configuration like Lam B with high strength at 45 degrees may be more desirable than a typical plywood configuration with only 0 and 90 degree plies.

An analysis of covariance (ANCOVA) was performed for the IB results including density as a covariate, since otherwise its effects were found to be significant. Results showed that IB strength of OSC was significantly higher than that of the laminates. Comparing to the initial IB strengths of individual plies, which were higher than the OSC, significant strength was lost. The mean IB value of individual plies was 559 kPa with a COV of 20.7% compared to the laminate IB values of 320 kPa and 29.2%. This suggests that improvements could be made in the lamination process such as using different laminating glues to improve the IB strength of laminates.

Another way to increase IB strength is to increase the quantity of PF resin used. Increasing resin content has been shown to be one of the best methods to improve physical and mechanical properties of OSB (Chowdhury 2006). Ply properties, and in turn laminate properties, could be dramatically improved by increasing the amount of resin, making LSP an even more valuable wood composite material.

Density was again included as a covariate in analyzing the water soak test data to remove its effects. Thickness swell of specimens from Lam A and Lam B was significantly lower than specimens from OSC. The percent of water absorbed for OSC was significantly higher than for any of the laminates (24% higher on average). Use of resorcinol laminating resin between plies and less variation in laminate densities could have resulted in the lower water absorption and thickness swell values for LSP specimens compared to OSC specimens. Low density boards, due to higher void volumes, were affected more in water soak tests; and the cores of the OSC all had lower density.

Comparison with Currently Marketed Composite Properties

Direct comparison of laminates to other wood composites has some limitations because of the wide range of properties obtained through different manufacturing techniques, and various species and maturity of materials used to produce them. Also, allowable design stress values are often given rather than ultimate stresses. However, an attempt was made to obtain published property values of several wood composites to determine if LSP properties are in the same range, and what potential exists for further development and study. These values are listed in Table 3.5.

Table 3.5. Comparison of LSP properties to several wood composites currently on the market. Lam A was a 6-ply laminate with all plies oriented parallel to the strength axis. Lam B was a 5-ply laminate that had two cross plies like a plywood configuration.

Product	MOE II (GPa)	MOR II (MPa)	Ten Str II (MPa)	IB (MPa)
LSP Composite – Lam A	9.46	51.85	28.41	0.37
LSP Composite – Lam C	7.59	43.50	22.50	0.29
LVL*	10.34	~	~	~
Plywood †	10.00	34.47	18.96	~
OSB †	6.55	24.13	8.62	~
Particleboard †	2.25	13.75	~	0.4
MDF †	1.90	19.00	~	0.45

* LVL value taken from Nelson Pine Industries web site. Strength values were allowable stress values, inappropriate for direct comparisons. (http://www.icc-es.org/reports/pdf_files/ICC-ES/ESR-1633.pdf)
† Median of range of values given in the Forest Products Laboratory's Wood Handbook. (http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/ch10.pdf)

As can be seen here, the stiffness properties for a LSP composite lay-up are comparable to laminated veneer lumber (LVL) and plywood. In general, wood composites produced with strand plies appear to compare very favorably with those produced with veneers, particularly strength. Comparing LSP properties with lumber formed from small-diameter Ponderosa pine shows a large increase in strength and stiffness. Mackes et al. (2005) reported values of 5.6 GPa and 34 MPa for MOE and MOR of lumber from small-diameter ponderosa pine similar to that used in this study. For "open grown" specimens (trees taken from clearings allowing for faster growth) in this study, mean MOE and MOR values were 3.2 GPa and 23 MPa (Mackes 2005). These were not recommended for structural use; however, these types of trees could be utilized for LSP production.

CLT Model Predictions

Using the mean ply material properties from Table 3.2 as input, Young's moduli, E_1 and E_2, for LSP laminates A, B, and C were predicted using CLT. As an initial approximation, by including the values for maximum tensile stress of the plies and iteratively applying a load, a prediction of ultimate tensile load (UTL) and ultimate bending load (UBL) were made. Failure was considered to occur when the ultimate stress capacity of one of the plies in the laminate was reached. Predicted values are thus somewhat lower than experimental values because after the failure of the first ply there is often additional strength left in the remaining plies of the laminate. Table 3.6 lists the predicted / experimental (P/E) ratio for each of the laminate configurations.

Table 3.6. CLT predictions of elastic moduli (E), ultimate tensile load (UTL), and ultimate bending load (UBL) parallel and perpendicular to the strong-axis

Laminate Property	Lam A P/E Ratio	Lam B P/E Ratio	Lam C P/E Ratio
E par	1.13	1.18	1.24
E perp	0.82	1.35	1.15
UTL par	1.01	0.81	0.83
UTL perp	0.52	0.76	0.65
UBL par	0.81	0.78	0.64
UBL perp	0.45	0.92	0.57

As can be seen from Table 3.6, elastic properties were over-predicted by about 15% and strength properties were under-predicted by about 25%. This shows that the model is useful to give a general idea of what properties may be expected for a new laminate configuration, but not an accurate prediction. There are several reasons for the difference in predicted and experimental properties.

For strength properties perpendicular to the strong-axis, the ply stress was lower than the laminate stress due to the existence of voids within the plies. When tested individually, plies would fail at the spot with the most voids, whereas in the laminates stress could be transferred to adjacent layers giving the laminated composites a much higher strength. This can be seen in Table 3.6 where in the parallel direction, the predicted tensile strength of Lam A was almost equal to CLT predictions using ply strength. Predicted tensile strength in the perpendicular direction of Lam A using ply values was about half of the experimental laminate values, and other laminates exhibit combinations of these two effects.

The main reasons for differences in experimental and predicted were that the elastic and strength properties used in the model were mean values, with significant variation. In addition, the accuracy of the calculated value of G_{12}, which affected predictions, was not verified by experimentation. Other reasons could be due to the imperfect agreement with underlying CLT assumptions of perfect bonding between plies, linear elasticity of wood, and the existence of edge effects. The CLT model assumes a plane stress state and has been validated up to one laminate thickness away from the edge of a laminate (Jones 1975). However, as you approach the edge of a specimen some discrepancy in experimental and predicted values exists. This effect could be minimized by using larger test specimens. Despite some limitations, the advantage of CLT model predictions is the ability to obtain an approximation of laminate properties without the cost of manufacturing many different laminate configurations.

Summary and Conclusions

The purpose of this study was to examine the feasibility of engineering laminated composites of thin strand-based plies produced from small-diameter timber of low value. Properties of individual strand plies and laminates manufactured with strand plies were determined and compared with traditional wood composite panel properties and predictions using classical lamination theory (CLT). By measuring stiffness, strength, and Poisson's ratios of strand ply specimens oriented parallel and perpendicular to the strong-axis, the shear modulus was calculated and data were obtained for input into a CLT model. Remaining plies were then formed into three laminate configurations and evaluated using bending, tension, internal bond, and water soak tests. The following observations could be made from the results:

1. Advantages to using a LSP composite include more uniform density throughout the ply, approximately 23% less thickness swell, and lower water absorption than traditionally formed strand board.
2. Strength and stiffness of laminated strand ply (LSP) are 100-150% higher than that of the small-diameter parent wood from which it was formed.
3. LSP composite MOE of 9.46 GPa and MOR of 51.9 MPa compare favorably with plywood and LVL composites made of veneer.
4. Engineering of LSP composites may potentially be performed using a CLT model. Improved agreement between predicted and experimental values could be

obtained by more accurate determination of ply properties and testing of larger specimens to more closely approximate plane stress state conditions.

References

1. ASTM. 1999. Standard test methods for evaluating properties of wood-base fiber and particle panel materials. Standard D1037-99. American Society of Testing and Materials.

2. Barbero, E. J. 1999. Introduction to Composite Materials Design. Taylor & Francis. Philadelphia. pp. 336.

3. Biblis, E. J., A. Grigoriou, and H. Carino. 1996. Flexural properties of veneer-overlaid OSB composite panels from southern yellow pine. Forest Products Journal. 46(4):59-62.

4. Chen J. L., and C. T. Sun. 1989. Modeling of orthotropic elastic-plastic properties of ARALL laminates. Composites Science and Technology. v. 36(4): 321-337.

5. Countryman, D. 1975. Research program to develop performance specifications for the veneer-particleboard composite panel. Forest Products Journal. 25(9):44-48.

6. Hse, C. 1976. Exterior structural composite panels with southern pine veneer faces and cores of southern hardwood flakes. Forest Products Journal. 26(7):21-27.

7. Jones, R. M. 1999. Mechanics of Composite Materials. 2nd ed. Taylor and Francis. Philadelphia. pp. 356.

8. Mackes, K., W. Shepperd, and C. Jennings. 2005. Evaluating the bending properties of clear wood specimens produced from small-diameter ponderosa pine trees. Forest Products Journal. 55(10):72-80.

9. Meyers, K. L. 2001. Impact of strand geometry and orientation on mechanical properties of strand composites. M.S. Thesis. Washington State University.

10. Moses, D. M. et al. 2003. Composite behavior of laminated strand lumber. Wood science and Technology. v. 37(1): 59-77.

11. Pagano, N. J. 1970. Exact solutions for rectangular bidirectional composites and sandwich plates. Journal of Composite Materials. 4 :20-34.

12. Perry, T. D. 1948. Modern Plywood. Pitman Publishing Corp. New York. pp. 458.

13. SYSTAT. 2002. SYSTAT Software Inc. http://www.systat.com/products/Systat.

14. Weight. S. W. 2007. A novel wood-strand composite laminate using small-diameter timber: Chapter 2. M.S. Thesis. Washington State University.

15. Yadama, V. et al. 2006. Elastic properties of wood-strand composites with undulating strands. Composites: Part A. 37:385-392.

CHAPTER FOUR

PROJECT SUMMARY AND CONCLUSIONS

Summary and Conclusions

A novel concept of using strands from small-diameter timber to produce thin plies (3 mm thick) which in turn can be used to engineer composite Laminated Strand Ply (LSP) is presented and demonstrated. This hybrid combination of two composite technologies, oriented strand board and veneer/plywood, was researched because of the potential to utilize small-diameter timber to produce a high-performance wood composite.

In the first part of the study, the effect of three processing variables, resin content (3-6%), press platen temperature (145-160º C), and strand aspect ratio (length/thickness ratios of 315, 430, and 750), on strand-based veneer or ply properties was tested to determine an optimum combination of variables. Increasing the resin content was shown to significantly increase nearly all of the properties tested. Aspect ratio had a significant effect on about half of the properties tested. Temperature was seen to influence significantly only the bending modulus parallel to the strong-axis for the pressing schedule used.

Using the test results, the optimum manufacturing parameters for thin strand ply were determined to be 5.5% resin content, 152°C platen temperature, and 430 L/t aspect ratio. Average MOE and MOR of plies with this formulation were 10.2 GPa and 79.1 MPa respectively, showing that thin strand ply veneers of good quality can be produced from low-value, small-diameter timber. Applications include use in laminates or as stress skins.

In the second part of the study, additional plies were produced using this optimum formulation. Some of the plies were tested to determine stiffness and strength properties parallel and perpendicular to the strong axis. Shear modulus was estimated using transformation equations. Remaining plies were then laminated to form three configurations of LSP and evaluated for bending, tension, internal bond, and water soak properties. A unidirectional oriented strand composite (OSC) configuration was also formed and tested for comparison. Comparisons were then made to currently manufactured wood composites and predicted classical lamination theory (CLT) model values.

Results showed that LSP composites had more uniform density throughout the ply, approximately 23 % less thickness swell, and lower water absorption than the traditionally formed OSC. LSP composite MOE of 9.46 GPa and MOR of 51.9 MPa compare favorably with plywood and LVL composites made of veneer, and exceeded those of OSB and particleboard. It was shown that the CLT model was useful in engineering composite lay-ups to give an approximation of LSP composites properties. Improved agreement with predicted and experimental values could be obtained by more accurate determination of ply properties and testing of larger specimens to more closely approximate plane stress state conditions.

Manufacture of LSP composites appears to be an excellent utilization of small-diameter timber which generally is of low value and low quality because of the high percentage of juvenile wood. Strength and stiffness of laminated strand ply (LSP) are

100-150% greater than that of the small-diameter parent juvenile ponderosa pine from which it was produced. LSP can be used as furniture substrate as it can be profiled. Strands can be used to form uniform and consistent veneers, the basis for producing high-performance laminates. It is concluded that utilization of laminated strand ply creates a value-added application for small-diameter timber that compares favorably with veneer composites.

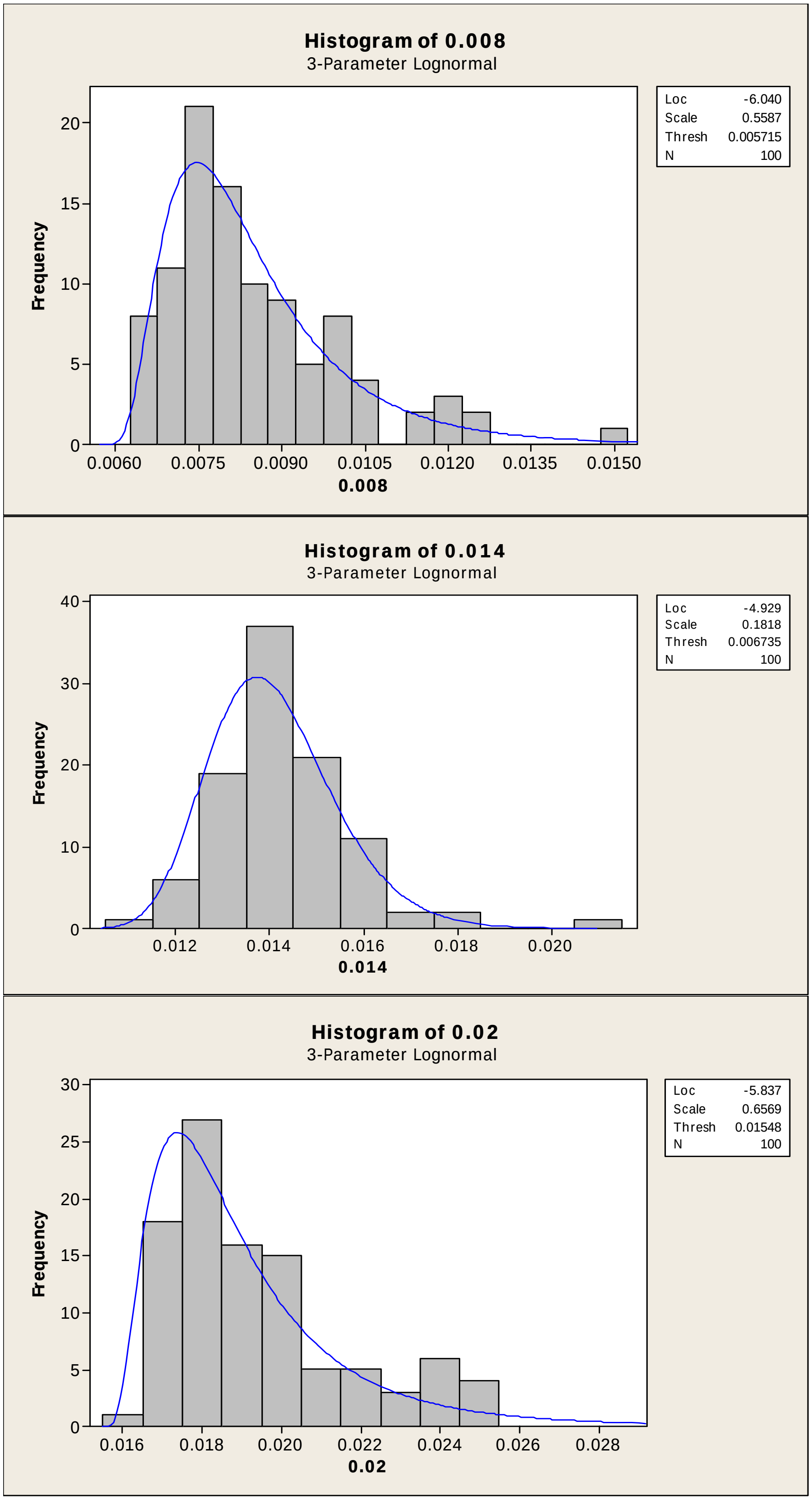
Recommendations

Based on the experimentally obtained LSP properties and the results of this study, it is recommended that further experimentation should be carried out to:

- Evaluate fastener holding properties. This may be especially significant as compared with other strand composites due to the more uniform density of LSP through its thickness.
- Determine dimensional stability of laminates.
- Characterize surface roughness and compare to other wood composites.
- Improve internal bond strength, perhaps by increasing PF resin content or by optimizing the lamination process.
- Evaluate the effects of increasing PF resin content above 6% as strength, stiffness, and water resistance properties all improved with increasing resin content
- Optimize press schedule.
- Test different laminate configurations and examine potential uses of thin strand plies as high strength skins or face plies.

Appendix A

Strand Thickness Distributions



Strand thickness histograms for N = 100. Nominal strand thickness is in inches.

Appendix B

Press Schedule Outline

Outline of pressing schedule for plies.

Pressing Schedule			
Step	**Control**	**Thickness/Rate**	**Time (s)**
1	FastPos	-0.5 in/sec	10
2	Position	50%	1
3	Position	0.75 in	20
4	Position	0.125 in	30
5	Position	0.125 in	210
6	Position	0.135 in	30
7	FastPos	0.5 in/sec	10
		Total	311

Appendix C

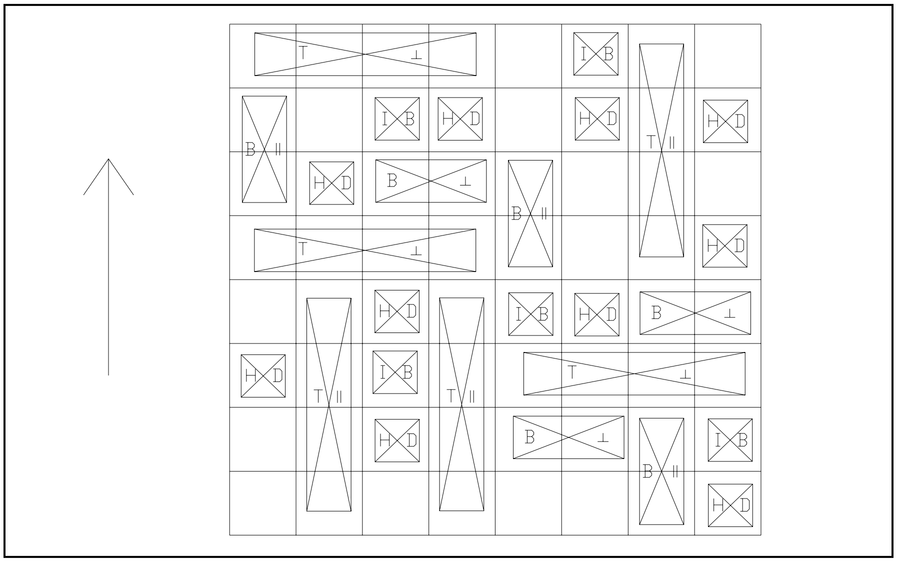
Ply input data for Design Expert analysis

Std	Run	Block	Resin Cont	Temp	Aspect Ratio	Density	IB	HD Var	VD Var	Ten Mod II	Max Ten Str II	Ten Mod Perp.	Max Ten Str Perp	MOE II	MOR II	MOE Perp.	MOR Perp.
			(%)	(Deg F)		(pcf)	(psi)	(%)	(pcf)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)
2	1	Block 1	6	290	430	39.16	93.73	11.71	4.38	1768431	6251	154830	512.0	1172757	10117.2	142799	1797.1
25	2	Block 1	6	290	430	46.60	93.40	8.45	4.32	2030563	7144	310919	909.1	1681256	15584.3	174660	2279.3
17	3	Block 1	5.5	305	430	44.70	93.67	9.08	3.21	1933506	4901	307201	1332.9	1669620	13816.3	260873	3286.6
21	4	Block 1	3	295	315	42.09	77.06	13.15	3.43	1518178	5672	151906	532.0	1520997	12351.1	152455	1579.9
23	5	Block 1	4.75	320	315	39.70	98.62	8.84	5.41	1699648	5914	146864	695.2	1597041	13685.1	159111	2341.4
20	6	Block 1	4.5	320	430	43.77	102.32	8.83	4.03	1956149	7229	188425	578.0	1745310	15159.4	174400	2214.4
26	7	Block 1	3	290	750	35.60	35.23	6.02	3.28	1097496	2894	141150	566.9	1071171	6889.4	141675	1596.4
13	8	Block 1	4.5	300	750	41.24	68.55	9.42	4.88	1607108	6667	307267	1203.0	1483414	11148.5	207233	2684.8
28	9	Block 1	3	320	430												
27	10	Block 1	6	305	315	37.68	99.94	16.10	5.74	1952807	6580	149341	489.2	1855419	16538.6	147889	1848.9
16	11	Block 1	3.75	305	750	40.76	21.48	15.20	5.08	1639154	5588	197684	699.4	1462853	7192.4	196816	1628.4
12	12	Block 1	4.25	290	315	43.34	96.33	12.60	3.95	1933791	6572	221419	774.6	1730612	12637	180220	2127.4
29	13	Block 1	6	320	750	38.47	66.55	11.26	4.62	1690392	7637	310088	1249.9	1594419	12742.1	216118	2464.7
3	14	Block 1	6	305	315	38.58	96.77	8.30	5.73	1259197	4119	251457	1082.6	1280890	10539.2	199032	2509.4
4	15	Block 1	5.5	290	750	42.96	83.16	6.78	4.32	1934606	7009	309718	1592.3	1240340	10847.7	338700	3589.9
1	16	Block 1	6	320	750	43.14	69.89	12.50	5.80	1486347	5411	325694	1628.5	1892713	15469.6	276220	3277.2

Std	Run	Block	Resin Cont	Temp	Aspect Ratio	Density	IB	HD Var	VD Var	Ten Mod II	Max Ten Str II	Ten Mod Perp.	Max Ten Str Perp	MOE II	MOR II	MOE Perp	MOR Perp
			(%)	(Deg F)		(pcf)	(psi)	(%)	(pcf)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)
10	17	Block 1	3	320	750	36.66	34.95	7.78	3.65	1218686	3564	260359	839.9	1093262	7491.6	232798	2049.3
5	18	Block 1	6	320	430	37.06	85.20	9.34	6.28	1556298	5036	228879	860.4	1506188	12180.6	146940	1703.5
32	19	Block 1	6	320	430	42.98	106.03	11.11	6.55	1857975	7544	217338	778.5	1947584	16419.3	152052	1931.5
14	20	Block 1	3.5	295	430	40.59	78.21	7.79	4.51	1877786	6106	175618	878.5	1270811	12186.1	148038	1640
19	21	Block 1	6	305	750	44.63	92.82	8.10	7.44	2106521	8478	416351	1767.5	1561484	13962.7	329261	3322
7	22	Block 1	3	290	750	44.12	46.30	8.75	3.73	1802875	7160	225675	988.1	1400164	10658.8	188650	2116.4
15	23	Block 1	4.45	305	315	41.58	108.71	9.62	5.70	1843899	7194	216927	619.0	1599274	12051.1	139471	1743.1
8	24	Block 1	3.75	315	430	43.72	76.08	12.48	4.23	2020559	7526	198079	815.1	1661873	13176.4	156850	1824.9
31	25	Block 1	5.5	290	750	34.12	79.25	8.79	6.01	1148635	4689	317632	1122.5	1242726	10696.1	222862	2574.4
11	26	Block 1	4.5	305	430	42.27	85.47	12.77	4.93	1678469	7556	260618	830.3	1528826	13972.5	172281	2317.4
30	27	Block 1	3	310	315	41.67	85.82	16.71	5.53	2208294	6783	233682	842.4	1467799	11703.6	222809	2039.9
22	28	Block 1	5	315	750	40.45	27.51	12.28	5.41	1660112	5725	213591	1006.7	1557931	10646.3	175988	1886.8
18	29	Block 1	5.5	290	315					1885176	5797	151990	459.0				
24	30	Block 1	3.5	295	430	42.14	81.89	11.18	4.33	1498479	4539	239656	772.0	1456449	11383.5	154968	1996.3
9	31	Block 1	4.75	320	315	46.88	95.88	9.32	4.20	2132046	8154	226214	804.6	1583332	13364.3	158076	2118.8
6	32	Block 1	3	310	315	45.13	97.54	8.13	4.80	1497404	4699	326107	950.8	1534116	12844.5	155582	1908.5

Appendix D

Test Specimen Sampling Scheme



Test specimen sampling scheme for manufactured thin strand plies. T || = tension parallel, T⊥ = tension perpendicular, B || = bending parallel, B⊥ = bending perpendicular, IB = internal bond (tension perpendicular to surface) and HD = horizontal density).

Appendix E

Design Expert Statistical Output for Plies

Response 1 IB

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Reduced Linear Model

Analysis of variance table [Classical sum of squares - Type II]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	11905.09	3	3968.36	22.69	< 0.0001
A-Resin Cont.	*3043.59*	*1*	*3043.59*	*17.40*	*0.0003*
C-Aspect rat.	*9247.52*	*2*	*4623.76*	*26.44*	*< 0.0001*
Residual	4547.55	26	174.91		
Cor Total	16452.64	29			

Std. Dev.	13.23	R-Squared	0.7236
Mean	79.28	Adj R-Squared	0.6917
C.V. %	16.68	Pred R-Squared	0.6426
PRESS	5879.51	Adeq Precision	14.050

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	79.24	1	2.44	74.22	84.27	
A-Resin Cont.	13.42	1	3.22	6.81	20.03	1.04
C[1]-0.16	1	0.022	-0.20	-0.11		
C[2]-1.194E-003	1	0.039	-0.082	0.079		

Final Equation in Terms of Coded Factors:

IB	=
+79.24	
+13.42	* A
-0.16	* C[1]
-1.194E-003	* C[2]

Response 2 HD Variation

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Reduced Linear Model

Analysis of variance table [Classical sum of squares - Type II]

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	1.464E-003	2	7.319E-004	1.01	0.3765
C-Aspect rat.	*1.464E-003*	*2*	*7.319E-004*	*1.01*	*0.3765*
Residual	0.020	27	7.224E-004		
Cor Total	0.021	29			

Std. Dev.	0.027	R-Squared	0.0698
Mean	0.10	Adj R-Squared	0.0009
C.V. %	25.81	Pred R-Squared	-0.1525
PRESS	0.024	Adeq Precision	2.004

Term	**Coefficient Estimate**	**df**	**Standard Error**	**95% CI Low**	**95% CI High**
Intercept	0.10	1	4.924E-003	0.095	0.11
C[1]	-5.748E-005	1	4.399E-005	-1.477E-004	3.279E-005
C[2]	4.944E-005	1	7.824E-005	-1.111E-004	2.100E-004

Final Equation in Terms of Coded Factors:

HD Variation =

+0.10

-5.748E-005 * C[1]

+4.944E-005 * C[2]

Response 3 VD Variation

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Reduced Linear Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	10.24	2	5.12	6.78	0.0041
A-Resin Cont.	*7.14*	*1*	*7.14*	*9.45*	*0.0048*
B-Temp.	*1.69*	*1*	*1.69*	*2.24*	*0.1462*
Residual	20.41	27	0.76		
Cor Total	30.65	29			

Std. Dev.	0.87	R-Squared	0.3342
Mean	4.85	Adj R-Squared	0.2849
C.V. %	17.94	Pred R-Squared	0.1860
PRESS	24.95	Adeq Precision	6.988

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	4.77	1	0.16	4.44	5.10	
A-Resin Cont.	0.65	1	0.21	0.21	1.08	1.03
B-Temp.	0.31	1	0.21	-0.12	0.75	1.03

Final Equation in Terms of Coded Factors:

VD Variation	=
+4.77	
+0.65	* A
+0.31	* B

Response 4 Ten Mod II

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Reduced Linear Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1.217E+012	2	6.087E+011	12.97	0.0001
A-Resin Cont.	*9.164E+010*	*1*	*9.164E+010*	*1.95*	*0.1737*
D-Density	*1.155E+012*	*1*	*1.155E+012*	*24.62*	*< 0.0001*
Residual	1.267E+012	27	4.693E+010		
Cor Total	2.484E+012	29			

Std. Dev.	2.166E+005	R-Squared	0.4900
Mean	1.721E+006	Adj R-Squared	0.4523
C.V. %	12.59	Pred R-Squared	0.3547
PRESS	1.603E+012	Adeq Precision	12.212

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	-2.620E+005	1	4.003E+005	-1.083E+006	5.594E+005	
A-Resin Cont.	72268.59	1	51713.85	-33839.47	1.784E+005	1.00
D-Density	2.516E+006	1	5.072E+005	1.476E+006	3.557E+006	1.00

Final Equation in Terms of Coded Factors:

Ten Mod II	=
-2.620E+005	
+72268.59	* A
+2.516E+006	* D

Response 5 Ten Stress II

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Reduced Linear Model

Analysis of variance table [Partial sum of squares - Type III]

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	2.324E+007	2	1.162E+007	9.62	0.0007
A-Resin Cont.	*5.032E+006*	*1*	*5.032E+006*	*4.16*	*0.0512*
D-Density	*1.913E+007*	*1*	*1.913E+007*	*15.83*	*0.0005*
Residual	3.263E+007	27	1.208E+006		
Cor Total	5.587E+007	29			

Std. Dev.	1099.25	R-Squared	0.4160
Mean	6144.63	Adj R-Squared	0.3728
C.V. %	17.89	Pred R-Squared	0.2674
PRESS	4.093E+007	Adeq Precision	11.182

Factor	**Coefficient Estimate**	**df**	**Standard Error**	**95% CI Low**	**95% CI High**	**VIF**
Intercept	-1948.46	1	2031.45	-6116.64	2219.72	
A-Resin Cont.	535.52	1	262.42	-2.93	1073.96	1.00
D-Density	10240.50	1	2573.73	4959.64	15521.35	1.00

Final Equation in Terms of Coded Factors:

Ten Stress II	=
-1948.46	
+535.52	* A
+10240.50	* D

Response 6 Ten Mod Perp

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Reduced Linear Model

Analysis of variance table [Classical sum of squares - Type II]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	5.995E+010	4	1.499E+010	5.25	0.0033
A-Resin Cont.	*1.616E+010*	*1*	*1.616E+010*	*5.66*	*0.0253*
C-Aspect rat.	*3.304E+010*	*2*	*1.652E+010*	*5.79*	*0.0086*
D-Density	*2.519E+010*	*1*	*2.519E+010*	*8.82*	*0.0065*
Residual	7.139E+010	25	2.856E+009		
Cor Total	1.313E+011	29			

Std. Dev.	53438.64	R-Squared	0.4565
Mean	2.410E+005	Adj R-Squared	0.3695
C.V. %	22.17	Pred R-Squared	0.1821
PRESS	1.074E+011	Adeq Precision	7.511

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	-70315.92	1	1.037E+005	-2.838E+005	1.432E+005	
A-Resin Cont.	30980.74	1	13023.21	4158.93	57802.54	1.04
C[1]	295.48	1	90.78	108.51	482.45	
C[2]	146.63	1	160.10	-183.09	476.36	
D-Density	3.895E+005	1	1.312E+005	1.194E+005	6.597E+005	1.10

Final Equation in Terms of Coded Factors:

Ten Mod Perp	=
-70315.92	
+30980.74	* A
+295.48	* C[1]
+146.63	* C[2]
+3.895E+005	* D

Response 7 Ten Stress Perp
These Rows Were Ignored for this Analysis.
29, 9

ANOVA for Response Surface Reduced Linear Model
Analysis of variance table [Classical sum of squares - Type II]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1.922E+006	4	4.805E+005	9.71	< 0.0001
A-Resin Cont.	*5.292E+005*	*1*	*5.292E+005*	*10.69*	*0.0031*
C-Aspect rat.	*1.252E+006*	*2*	*6.261E+005*	*12.65*	*0.0002*
D-Density	*5.357E+005*	*1*	*5.357E+005*	*10.83*	*0.0030*
Residual	1.237E+006	25	49479.47		
Cor Total	3.159E+006	29			

Std. Dev.	222.44	R-Squared	0.6084
Mean	924.05	Adj R-Squared	0.5458
C.V. %	24.07	Pred R-Squared	0.4276
PRESS	1.808E+006	Adeq Precision	10.215

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	-518.98	1	431.57	-1407.82	369.86	
A-Resin Cont.	177.28	1	54.21	65.63	288.93	1.04
C[1]	1.81	1	0.38	1.04	2.59	
C[2]	0.93	1	0.67	-0.44	2.30	
D-Density	1796.55	1	545.99	672.05	2921.04	1.10

Final Equation in Terms of Coded Factors:

Ten Stress Perp =
-518.98
+177.28 * A
+1.81 * C[1]
+0.93 * C[2]
+1796.55 * D

Response 8 MOE II

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Reduced Linear Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	7.650E+011	3	2.550E+011	10.03	0.0001
A-Resin Cont.	*1.377E+011*	*1*	*1.377E+011*	*5.41*	*0.0280*
B-Temp.	*1.909E+011*	*1*	*1.909E+011*	*7.51*	*0.0110*
D-Density	*3.677E+011*	*1*	*3.677E+011*	*14.46*	*0.0008*
Residual	6.613E+011	26	2.543E+010		
Cor Total	1.426E+012	29			

Std. Dev.	1.595E+005	R-Squared	0.5364
Mean	1.514E+006	Adj R-Squared	0.4829
C.V. %	10.54	Pred R-Squared	0.3581
PRESS	9.155E+011	Adeq Precision	12.321

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	3.860E+005	1	2.952E+005	-2.207E+005	9.927E+005	
A-Resin Cont.	89840.43	1	38610.61	10475.19	1.692E+005	1.03
B-Temp.	1.059E+005	1	38657.23	26450.23	1.854E+005	1.03
D-Density	1.422E+006	1	3.740E+005	6.532E+005	2.191E+006	1.01

Final Equation in Terms of Coded Factors:

MOE II =
+3.860E+005
+89840.43 * A
+1.059E+005 * B
+1.422E+006 * D

Response 9 MOR II

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Linear Model

Analysis of variance table [Classical sum of squares - Type II]

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	1.150E+008	5	2.300E+007	9.16	< 0.0001
A-Resin Cont.	*3.600E+007*	*1*	*3.600E+007*	*14.34*	*0.0009*
B-Temp.	*5.867E+006*	*1*	*5.867E+006*	*2.34*	*0.1394*
C-Aspect rat.	*1.981E+007*	*2*	*9.907E+006*	*3.95*	*0.0330*
D-Density	*2.678E+007*	*1*	*2.678E+007*	*10.67*	*0.0033*
Residual	6.024E+007	24	2.510E+006		
Cor Total	1.752E+008	29			

Std. Dev.	1584.27	R-Squared	0.6562
Mean	12248.51	Adj R-Squared	0.5846
C.V. %	12.93	Pred R-Squared	0.4384
PRESS	9.841E+007	Adeq Precision	11.748

Term	**Coefficient Estimate**	**df**	**Standard Error**	**95% CI Low**	**95% CI High**	**VIF**
Intercept	2165.20	1	3075.71	-4182.75	8513.16	
A-Resin Cont.	1486.04	1	392.36	676.25	2295.82	1.08
B-Temp.	590.38	1	386.16	-206.62	1387.38	1.04
C[1]	-7.40	1	2.70	-12.98	-1.83	
C[2]	-2.60	1	4.75	-12.41	7.21	
D-Density	12710.59	1	3891.37	4679.19	20741.98	1.10

Final Equation in Terms of Coded Factors:

MOR II	=
+2165.20	
+1486.04	* A
+590.38	* B
-7.40	* C[1]
-2.60	* C[2]
+12710.59	* D

Response 10 MOE Perp

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Reduced Linear Model

Analysis of variance table [Classical sum of squares - Type II]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	4.249E+010	4	1.062E+010	6.90	0.0007
A-Resin Cont.	*7.806E+009*	*1*	*7.806E+009*	*5.07*	*0.0333*
C-Aspect rat.	*3.394E+010*	*2*	*1.697E+010*	*11.03*	*0.0004*
D-Density	*9.530E+009*	*1*	*9.530E+009*	*6.19*	*0.0199*
Residual	3.847E+010	25	1.539E+009		
Cor Total	8.096E+010	29			

Std. Dev.	39229.90	R-Squared	0.5248
Mean	1.908E+005	Adj R-Squared	0.4487
C.V. %	20.56	Pred R-Squared	0.3144
PRESS	5.551E+010	Adeq Precision	8.605

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	-1713.29	1	76112.72	-1.585E+005	1.550E+005	
A-Resin Cont.	21532.02	1	9560.48	1841.84	41222.21	1.04
C[1]	288.37	1	66.64	151.11	425.62	
C[2]	203.13	1	117.53	-38.92	445.19	
D-Density	2.396E+005	1	96292.13	41298.23	4.379E+005	1.10

Final Equation in Terms of Coded Factors:

MOE Perp	=
-1713.29	
+21532.02	* A
+288.37	* C[1]
+203.13	* C[2]
+2.396E+005	* D

Response 11 MOR Perp

These Rows Were Ignored for this Analysis.

29, 9

ANOVA for Response Surface Reduced Linear Model

Analysis of variance table [Classical sum of squares - Type II]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	4.681E+006	4	1.170E+006	7.20	0.0005
A-Resin Cont.	*2.261E+006*	*1*	*2.261E+006*	*13.92*	*0.0010*
C-Aspect rat.	*1.939E+006*	*2*	*9.697E+005*	*5.97*	*0.0076*
D-Density	*1.452E+006*	*1*	*1.452E+006*	*8.93*	*0.0062*
Residual	4.062E+006	25	1.625E+005		
Cor Total	8.742E+006	29			

Std. Dev.	403.07	R-Squared	0.5354
Mean	2213.29	Adj R-Squared	0.4611
C.V. %	18.21	Pred R-Squared	0.3563
PRESS	5.627E+006	Adeq Precision	9.133

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	-162.50	1	782.03	-1773.12	1448.13	
A-Resin Cont.	366.45	1	98.23	164.14	568.76	1.04
C[1]	2.16	1	0.68	0.75	3.57	
C[2]	1.63	1	1.21	-0.86	4.12	
D-Density	2957.24	1	989.37	919.59	4994.88	1.10

Final Equation in Terms of Coded Factors:

MOR Perp	=
-162.50	
+366.45	* A
+2.16	* C[1]
+1.63	* C[2]
+2957.24	* D

Appendix F

SYSTAT Statistical Output for Laminates and OSC

▼Descriptive Statistics

Results for CONFIGURATION$ = Lam A

	NUMBER$	DENSITY	MOE	MOR
N of Cases	8	8	8	8
Minimum	1.000	690.376	7.868	40.569
Maximum	4.000	749.642	10.671	63.087
Median	2.500	720.810	9.761	50.101
Arithmetic Mean	2.500	720.009	9.459	51.847
Standard Deviation	1.195	22.079	0.982	7.752
Shapiro-Wilk Statistic	0.897	0.939	0.926	0.933
Shapiro-Wilk p-value	0.274	0.604	0.482	0.539

Results for CONFIGURATION$ = Lam B

	NUMBER$	DENSITY	MOE	MOR
N of Cases	8	8	8	8
Minimum	1.000	669.552	6.884	30.116
Maximum	4.000	699.987	7.450	46.974
Median	2.500	686.371	7.266	43.616
Arithmetic Mean	2.500	685.570	7.217	41.566
Standard Deviation	1.195	11.614	0.209	5.471
Shapiro-Wilk Statistic	0.897	0.928	0.923	0.834
Shapiro-Wilk p-value	0.274	0.496	0.451	0.065

Results for CONFIGURATION$ = Lam C

	NUMBER$	DENSITY	MOE	MOR
N of Cases	4	4	4	4
Minimum	1.000	685.570	6.925	41.486
Maximum	2.000	744.837	8.251	48.580
Median	1.500	704.792	7.600	41.993
Arithmetic Mean	1.500	709.998	7.594	43.513
Standard Deviation	0.577	25.474	0.748	3.392
Shapiro-Wilk Statistic	0.729	0.944	0.749	0.711
Shapiro-Wilk p-value	0.024	0.677	0.038	0.016

Results for CONFIGURATION$ = OSC

	NUMBER$	DENSITY	MOE	MOR
N of Cases	6	6	6	6
Minimum	1.000	631.109	9.255	59.481
Maximum	2.000	775.271	11.507	69.285
Median	1.500	639.919	10.053	64.556
Arithmetic Mean	1.500	665.281	10.244	64.484
Standard Deviation	0.548	55.982	0.794	4.485
Shapiro-Wilk Statistic	0.683	0.691	0.958	0.851
Shapiro-Wilk p-value	0.004	0.005	0.802	0.161

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	MOE
N	26
Multiple R	0.881
Squared Multiple R	0.777

Estimates of Effects B = (X'X)$^{-1}$X'Y

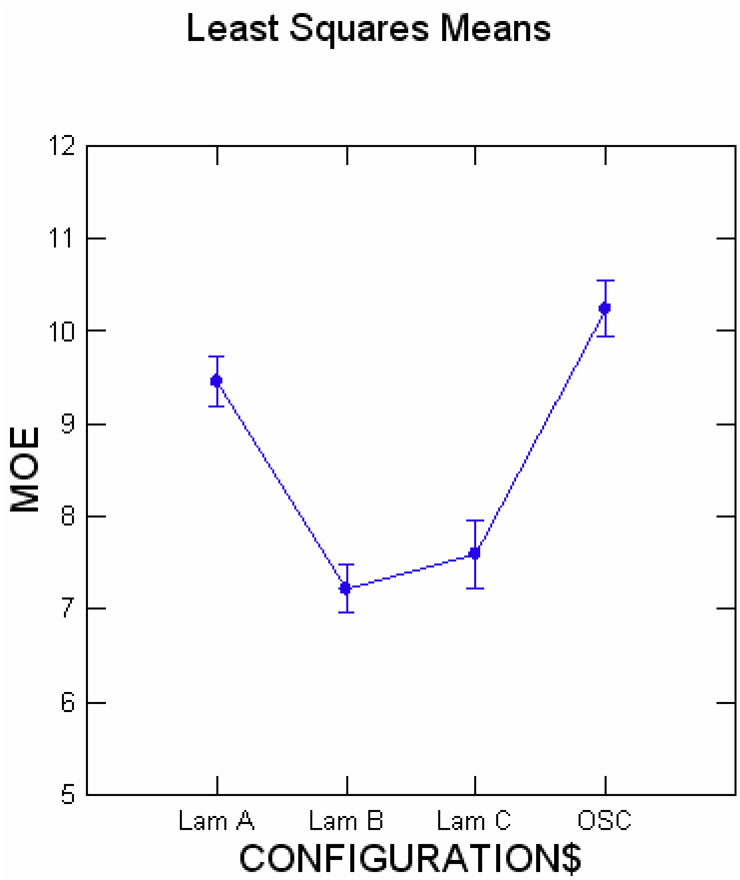
Factor	Level	MOE
CONSTANT		8.629
CONFIGURATION$	Lam A	0.831
CONFIGURATION$	Lam B	-1.411
CONFIGURATION$	Lam C	-1.035

Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	41.367	3	13.789	25.520	0.000
Error	11.887	22	0.540		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	9.459	0.260	8.000
CONFIGURATION$	Lam B	7.217	0.260	8.000
CONFIGURATION$	Lam C	7.594	0.368	4.000
CONFIGURATION$	OSC	10.244	0.300	6.000



Test for Normality		
	Test Statistic	p-value
Shapiro-Wilk Test	0.984	0.939

Durbin-Watson D Statistic	1.225
First Order Autocorrelation	0.344

Information Criteria	
AIC	63.436
AIC (Corrected)	66.436
Schwarz's BIC	69.726

▼Hypothesis Tests

Post Hoc Test of MOE
Using least squares means.
Using model MSE of 0.540 with 22 df.

Tukey's Honestly-Significant-Difference Test					
CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	2.242	0.000	1.221	3.263
Lam A	Lam C	1.865	0.002	0.615	3.115
Lam A	OSC	-0.785	0.227	-1.887	0.317
Lam B	Lam C	-0.377	0.836	-1.627	0.873
Lam B	OSC	-3.027	0.000	-4.129	-1.925
Lam C	OSC	-2.650	0.000	-3.968	-1.333

Scheffe Test					
CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	2.242	0.000	1.130	3.354
Lam A	Lam C	1.865	0.005	0.504	3.227
Lam A	OSC	-0.785	0.298	-1.986	0.416
Lam B	Lam C	-0.377	0.872	-1.738	0.985
Lam B	OSC	-3.027	0.000	-4.228	-1.826
Lam C	OSC	-2.650	0.000	-4.085	-1.215

Duncan Test			
SubGroup	CONFIGURATION$	Group Mean	Group Size
1	Lam B	7.217	8.000
	Lam C	7.594	8.000
2	Lam A	9.459	4.000
	OSC	10.244	6.000

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	MOE
N	26
Multiple R	0.885
Squared Multiple R	0.783

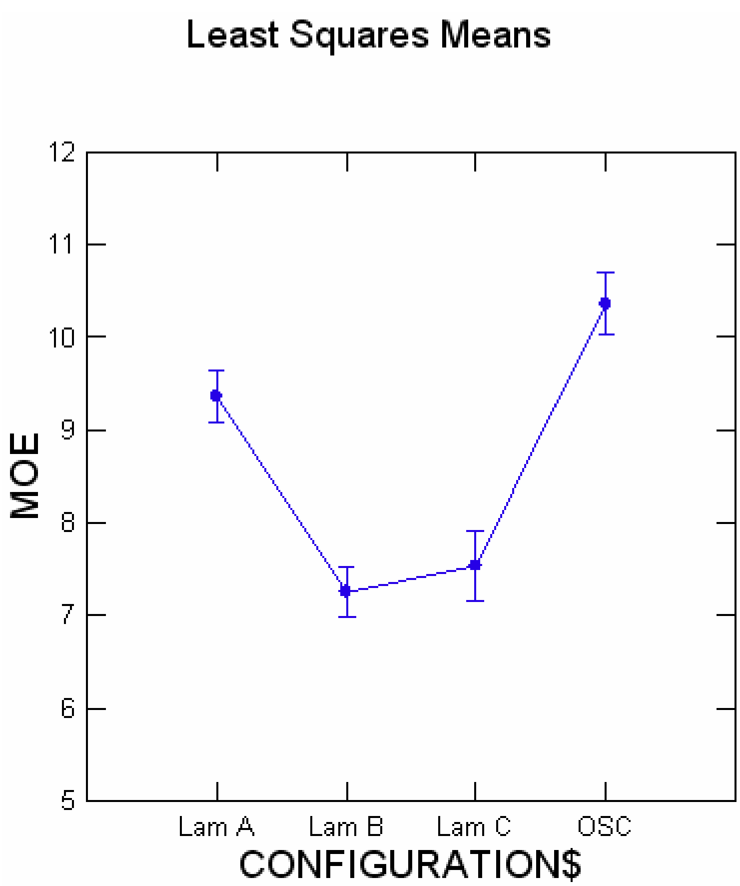
Estimates of Effects $B = (X'X)^{-1}X'Y$		
Factor	Level	MOE
CONSTANT		5.936
CONFIGURATION$	Lam A	0.735
CONFIGURATION$	Lam B	-1.374

Estimates of Effects B = (X'X)-1X'Y		
Factor	**Level**	**MOE**
CONFIGURATION$	Lam C	-1.092
DENSITY		0.004

Analysis of Variance					
Source	**Type III SS**	**df**	**Mean Squares**	**F-ratio**	**p-value**
CONFIGURATION$	41.695	3	13.898	25.254	0.000
DENSITY	0.330	1	0.330	0.599	0.448
Error	11.557	21	0.550		

Least Squares Means				
Factor	**Level**	**LS Mean**	**Standard Error**	**N**
CONFIGURATION$	Lam A	9.363	0.290	8.000
CONFIGURATION$	Lam B	7.254	0.267	8.000
CONFIGURATION$	Lam C	7.537	0.378	4.000
CONFIGURATION$	OSC	10.360	0.338	6.000

* Means are computed after adjusting covariate effect.



WARNING

Case 26 is an Outlier (Studentized Residual : -5.623)

Test for Normality		
	Test Statistic	p-value
Shapiro-Wilk Test	0.962	0.430

Durbin-Watson D Statistic	1.143
First Order Autocorrelation	0.339

Information Criteria	
AIC	64.705
AIC (Corrected)	69.126
Schwarz's BIC	72.253

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

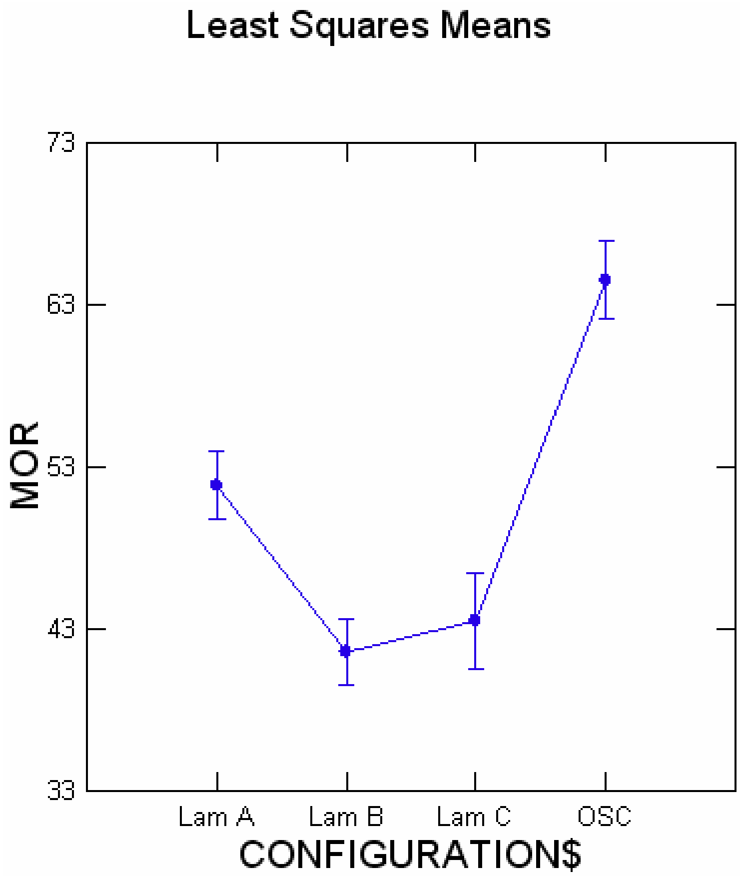
Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	MOR
N	26
Multiple R	0.852
Squared Multiple R	0.725

Estimates of Effects B = (X'X)$^{-1}$X'Y		
Factor	Level	MOR
CONSTANT		50.353
CONFIGURATION$	Lam A	1.494
CONFIGURATION$	Lam B	-8.787
CONFIGURATION$	Lam C	-6.840

Analysis of Variance					
Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	2020.852	3	673.617	19.366	0.000
Error	765.238	22	34.784		

Least Squares Means				
Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	51.847	2.085	8.000
CONFIGURATION$	Lam B	41.566	2.085	8.000
CONFIGURATION$	Lam C	43.513	2.949	4.000
CONFIGURATION$	OSC	64.484	2.408	6.000



Test for Normality		
	Test Statistic	p-value
Shapiro-Wilk Test	0.970	0.615

Durbin-Watson D Statistic	1.530
First Order Autocorrelation	0.212

Information Criteria	
AIC	171.719
AIC (Corrected)	174.719
Schwarz's BIC	178.010

▼Hypothesis Tests

Post Hoc Test of MOR
Using least squares means.
Using model MSE of 34.784 with 22 df.

Tukey's Honestly-Significant-Difference Test					
CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	10.281	0.010	2.092	18.470
Lam A	Lam C	8.334	0.127	-1.695	18.363
Lam A	OSC	-12.638	0.003	-21.482	-3.793
Lam B	Lam C	-1.947	0.948	-11.976	8.082
Lam B	OSC	-22.918	0.000	-31.763	-14.074
Lam C	OSC	-20.972	0.000	-31.543	-10.400

Scheffe Test					
CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	10.281	0.020	1.362	19.200
Lam A	Lam C	8.334	0.181	-2.589	19.257
Lam A	OSC	-12.638	0.007	-22.271	-3.004
Lam B	Lam C	-1.947	0.961	-12.870	8.976
Lam B	OSC	-22.918	0.000	-32.552	-13.285
Lam C	OSC	-20.972	0.000	-32.486	-9.457

▼Descriptive Statistics

Results for CONFIGURATION$ = Lam A

	DENSITY	MOE	MOR
N of Cases	8	8	8
Minimum	695.414	0.980	7.040
Maximum	723.191	1.340	11.505
Median	707.581	1.165	10.127
Arithmetic Mean	708.053	1.158	9.967
Standard Deviation	11.197	0.127	1.304
Shapiro-Wilk Statistic	0.890	0.947	0.803
Shapiro-Wilk p-value	0.232	0.684	0.031

Results for CONFIGURATION$ = Lam B

	DENSITY	MOE	MOR
N of Cases	8	8	8
Minimum	687.770	1.580	14.766
Maximum	725.960	1.898	20.048
Median	700.416	1.711	16.930
Arithmetic Mean	702.914	1.718	17.446
Standard Deviation	11.545	0.111	1.913
Shapiro-Wilk Statistic	0.904	0.961	0.925
Shapiro-Wilk p-value	0.312	0.817	0.468

Results for CONFIGURATION$ = Lam C

	DENSITY	MOE	MOR
N of Cases	4	4	4
Minimum	697.064	4.326	29.783
Maximum	707.612	5.225	36.773
Median	702.010	5.141	36.001
Arithmetic Mean	702.174	4.958	34.639
Standard Deviation	4.616	0.424	3.295
Shapiro-Wilk Statistic	0.982	0.728	0.769
Shapiro-Wilk p-value	0.913	0.023	0.057

Results for CONFIGURATION$ = OSC

	DENSITY	MOE	MOR
N of Cases	6	6	6
Minimum	608.478	1.151	9.043
Maximum	752.816	1.670	14.357
Median	694.804	1.555	13.545
Arithmetic Mean	689.430	1.465	12.703
Standard Deviation	54.607	0.209	2.040

	DENSITY	MOE	MOR
Shapiro-Wilk Statistic	0.958	0.863	0.832
Shapiro-Wilk p-value	0.803	0.201	0.113

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	MOE
N	26
Multiple R	0.989
Squared Multiple R	0.978

Estimates of Effects B = (X'X)$^{-1}$X'Y

Factor	Level	MOE
CONSTANT		2.807
CONFIGURATION$	Lam A	-1.162
CONFIGURATION$	Lam B	-0.605
CONFIGURATION$	Lam C	2.635
DENSITY		-0.001

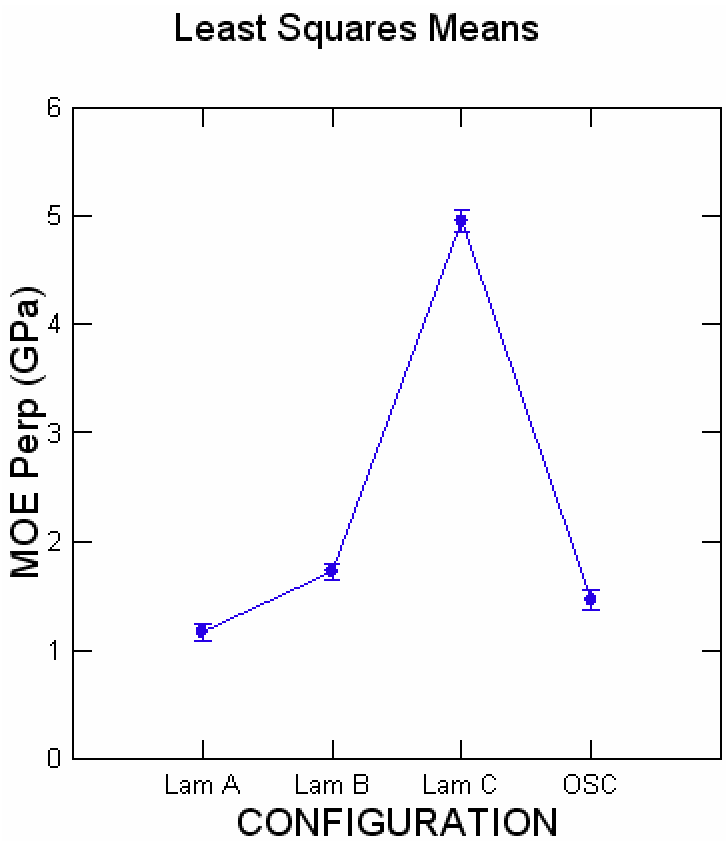
Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	43.029	3	14.343	317.789	0.000
DENSITY	0.008	1	0.008	0.176	0.679
Error	0.948	21	0.045		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	1.163	0.076	8.000
CONFIGURATION$	Lam B	1.719	0.075	8.000
CONFIGURATION$	Lam C	4.959	0.106	4.000
CONFIGURATION$	OSC	1.456	0.089	6.000

* Means are computed after adjusting covariate effect.



WARNING

Case 20 is an Outlier (Studentized Residual : -5.018)

Durbin-Watson D Statistic	2.164
First Order Autocorrelation	-0.111

Information Criteria	
AIC	-0.319
AIC (Corrected)	4.102
Schwarz's BIC	7.229

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	MOE
N	26
Multiple R	0.989

Dependent Variable	MOE
Squared Multiple R	0.978

Estimates of Effects B = (X'X)$^{-1}$X'Y

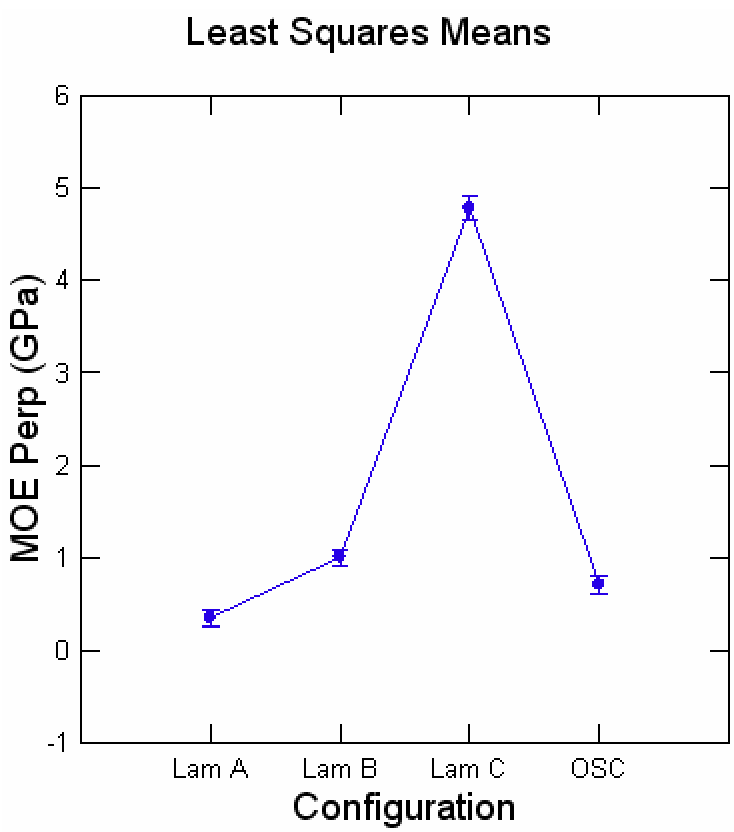
Factor	Level	MOE
CONSTANT		2.325
CONFIGURATION$	Lam A	-1.167
CONFIGURATION$	Lam B	-0.607
CONFIGURATION$	Lam C	2.634

Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	43.030	3	14.343	330.151	0.000
Error	0.956	22	0.043		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	1.158	0.074	8.000
CONFIGURATION$	Lam B	1.718	0.074	8.000
CONFIGURATION$	Lam C	4.958	0.104	4.000
CONFIGURATION$	OSC	1.465	0.085	6.000



WARNING

Case 20 is an Outlier (Studentized Residual : -5.149)

Durbin-Watson D Statistic	2.175
First Order Autocorrelation	-0.112

Information Criteria	
AIC	-2.102
AIC (Corrected)	0.898
Schwarz's BIC	4.189

▼Hypothesis Tests

Post Hoc Test of MOE
Using least squares means.
Using model MSE of 0.043 with 22 df.

Tukey's Honestly-Significant-Difference Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.560	0.000	-0.849	-0.271
Lam A	Lam C	-3.800	0.000	-4.155	-3.446
Lam A	OSC	-0.306	0.056	-0.619	0.006
Lam B	Lam C	-3.240	0.000	-3.595	-2.886
Lam B	OSC	0.254	0.140	-0.059	0.566
Lam C	OSC	3.494	0.000	3.120	3.867

Scheffe Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.560	0.000	-0.875	-0.245
Lam A	Lam C	-3.800	0.000	-4.186	-3.414
Lam A	OSC	-0.306	0.089	-0.647	0.034
Lam B	Lam C	-3.240	0.000	-3.626	-2.854
Lam B	OSC	0.254	0.198	-0.087	0.594
Lam C	OSC	3.494	0.000	3.087	3.901

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	MOR
N	26
Multiple R	0.975
Squared Multiple R	0.951

Estimates of Effects $B = (X'X)^{-1}X'Y$

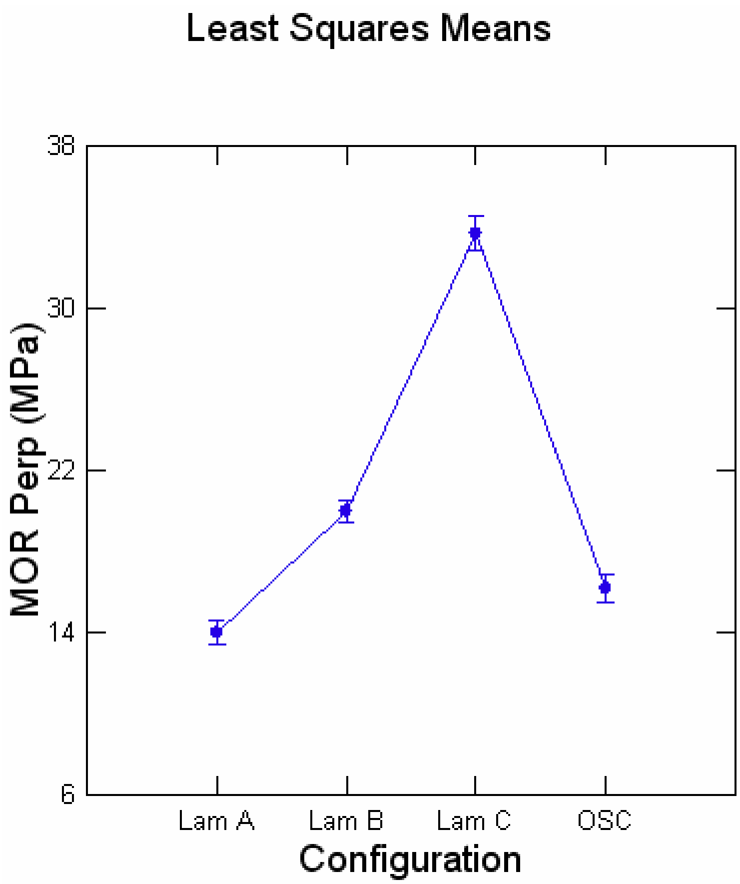
Factor	Level	MOR
CONSTANT		18.689
CONFIGURATION$	Lam A	-8.722
CONFIGURATION$	Lam B	-1.243
CONFIGURATION$	Lam C	15.951

Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	1750.223	3	583.408	141.206	0.000
Error	90.895	22	4.132		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	9.967	0.719	8.000
CONFIGURATION$	Lam B	17.446	0.719	8.000
CONFIGURATION$	Lam C	34.639	1.016	4.000
CONFIGURATION$	OSC	12.703	0.830	6.000



WARNING

Case 20 is an Outlier (Studentized Residual : -3.333)

Durbin-Watson D Statistic	2.541
First Order Autocorrelation	-0.272

Information Criteria	
AIC	116.327
AIC (Corrected)	119.327
Schwarz's BIC	122.617

▼Hypothesis Tests

Post Hoc Test of MOR
Using least squares means.
Using model MSE of 4.132 with 22 df.

Tukey's Honestly-Significant-Difference Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-7.478	0.000	-10.301	-4.656
Lam A	Lam C	-24.672	0.000	-28.129	-21.216
Lam A	OSC	-2.736	0.089	-5.784	0.312
Lam B	Lam C	-17.194	0.000	-20.650	-13.737
Lam B	OSC	4.742	0.001	1.694	7.791
Lam C	OSC	21.936	0.000	18.293	25.579

Scheffe Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-7.478	0.000	-10.552	-4.405
Lam A	Lam C	-24.672	0.000	-28.437	-20.908
Lam A	OSC	-2.736	0.133	-6.056	0.584
Lam B	Lam C	-17.194	0.000	-20.958	-13.429
Lam B	OSC	4.742	0.003	1.422	8.062
Lam C	OSC	21.936	0.000	17.968	25.904

▼Descriptive Statistics

Results for CONFIGURATION$ = Lam A

	TEN_MOD	MAX_STRESS
N of Cases	12	12
Minimum	7.769	25.979
Maximum	11.497	34.716
Median	9.678	26.912
Arithmetic Mean	9.515	28.414
Standard Deviation	0.933	2.742
Shapiro-Wilk Statistic	0.956	0.836
Shapiro-Wilk p-value	0.723	0.025

Results for CONFIGURATION$ = Lam B

	TEN_MOD	MAX_STRESS
N of Cases	12	12
Minimum	3.088	18.125
Maximum	6.711	25.560
Median	5.264	19.968
Arithmetic Mean	5.315	20.208
Standard Deviation	1.011	2.007
Shapiro-Wilk Statistic	0.949	0.825
Shapiro-Wilk p-value	0.617	0.018

Results for CONFIGURATION$ = Lam C

	TEN_MOD	MAX_STRESS
N of Cases	8	8
Minimum	3.579	19.273
Maximum	7.284	25.857
Median	6.193	22.703
Arithmetic Mean	5.636	22.485
Standard Deviation	1.297	1.997
Shapiro-Wilk Statistic	0.905	0.971
Shapiro-Wilk p-value	0.322	0.905

Results for CONFIGURATION$ = OSC

	TEN_MOD	MAX_STRESS
N of Cases	12	12
Minimum	6.624	21.347
Maximum	12.362	35.132
Median	9.620	29.929
Arithmetic Mean	9.658	29.371
Standard Deviation	1.454	4.056

	TEN_MOD	MAX_STRESS
Shapiro-Wilk Statistic	0.963	0.961
Shapiro-Wilk p-value	0.827	0.792

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	TEN_MOD
N	44
Multiple R	0.878
Squared Multiple R	0.771

Estimates of Effects B = $(X'X)^{-1}X'Y$

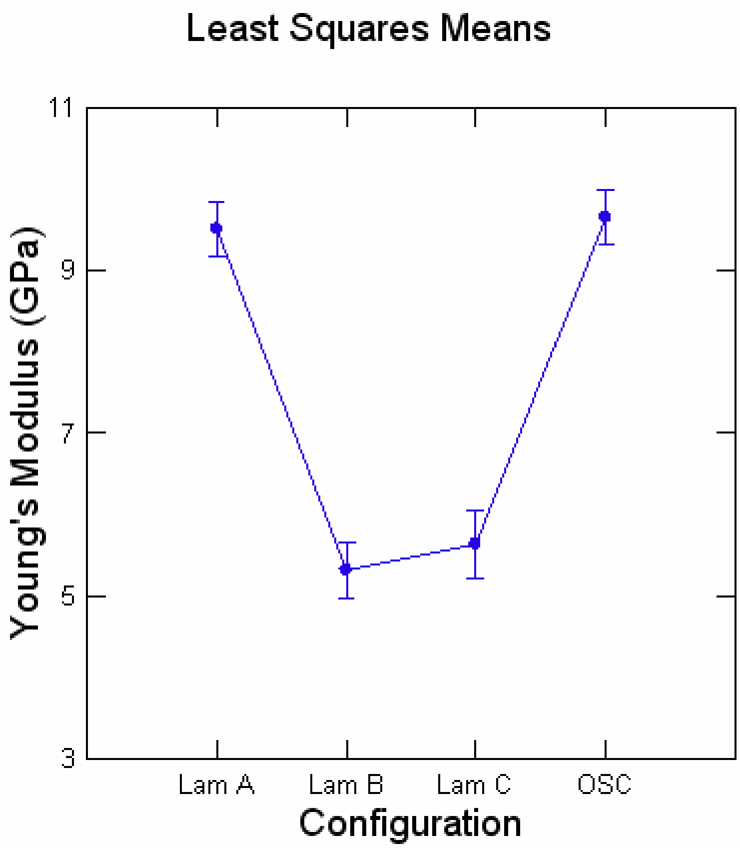
Factor	Level	TEN_MOD
CONSTANT		7.531
CONFIGURATION$	Lam A	1.984
CONFIGURATION$	Lam B	-2.216
CONFIGURATION$	Lam C	-1.896

Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	187.898	3	62.633	44.862	0.000
Error	55.845	40	1.396		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	9.515	0.341	12.000
CONFIGURATION$	Lam B	5.315	0.341	12.000
CONFIGURATION$	Lam C	5.636	0.418	8.000
CONFIGURATION$	OSC	9.658	0.341	12.000



Durbin-Watson D Statistic	2.137
First Order Autocorrelation	-0.093

Information Criteria	
AIC	145.356
AIC (Corrected)	146.935
Schwarz's BIC	154.277

▼Hypothesis Tests

Post Hoc Test of TEN_MOD
Using least squares means.
Using model MSE of 1.396 with 40 df.

Tukey's Honestly-Significant-Difference Test					
CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	4.200	0.000	2.907	5.493
Lam A	Lam C	3.880	0.000	2.434	5.325
Lam A	OSC	-0.143	0.991	-1.436	1.150
Lam B	Lam C	-0.320	0.933	-1.766	1.125
Lam B	OSC	-4.343	0.000	-5.636	-3.050

Tukey's Honestly-Significant-Difference Test					
CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam C	OSC	-4.023	0.000	-5.468	-2.577

Scheffe Test					
CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	4.200	0.000	2.792	5.608
Lam A	Lam C	3.880	0.000	2.306	5.454
Lam A	OSC	-0.143	0.993	-1.550	1.265
Lam B	Lam C	-0.320	0.949	-1.894	1.254
Lam B	OSC	-4.343	0.000	-5.751	-2.935
Lam C	OSC	-4.023	0.000	-5.597	-2.449

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

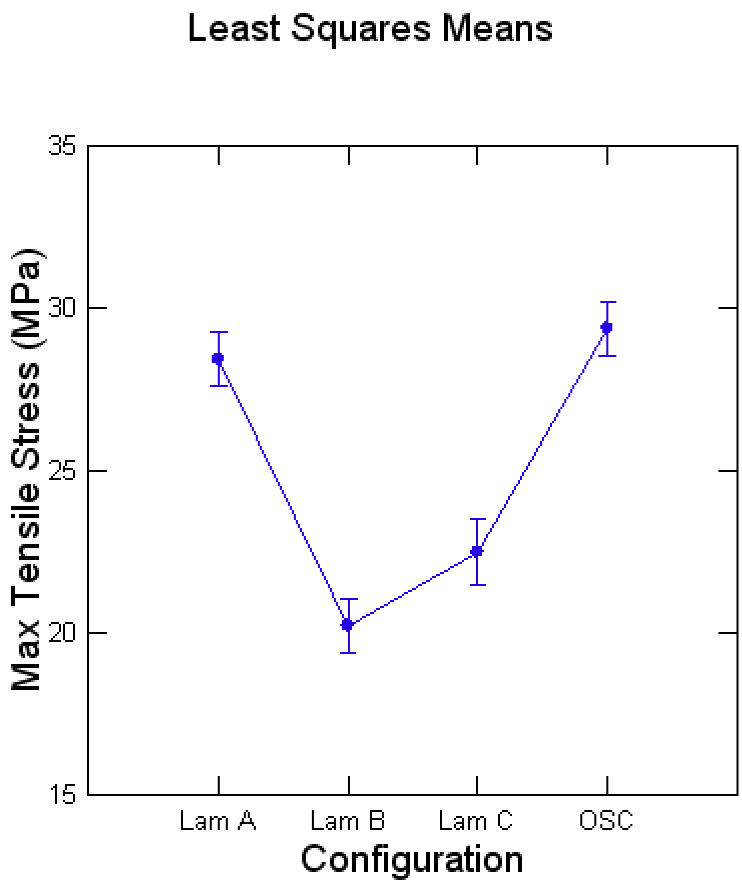
Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	MAX_STRESS
N	44
Multiple R	0.820
Squared Multiple R	0.672

Estimates of Effects $B = (X'X)^{-1}X'Y$		
Factor	Level	MAX_STRESS
CONSTANT		25.120
CONFIGURATION$	Lam A	3.295
CONFIGURATION$	Lam B	-4.912
CONFIGURATION$	Lam C	-2.635

Analysis of Variance					
Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	689.672	3	229.891	27.373	0.000
Error	335.939	40	8.398		

Least Squares Means				
Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	28.414	0.837	12.000
CONFIGURATION$	Lam B	20.208	0.837	12.000
CONFIGURATION$	Lam C	22.485	1.025	8.000
CONFIGURATION$	OSC	29.371	0.837	12.000



WARNING

Case 33 is an Outlier (Studentized Residual : -3.211)

Durbin-Watson D Statistic	2.165
First Order Autocorrelation	-0.129

Information Criteria	
AIC	224.307
AIC (Corrected)	225.886
Schwarz's BIC	233.228

▼Hypothesis Tests

Post Hoc Test of MAX_STRESS
Using least squares means.
Using model MSE of 8.398 with 40 df.

Tukey's Honestly-Significant-Difference Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	8.206	0.000	5.035	11.377
Lam A	Lam C	5.929	0.000	2.384	9.475
Lam A	OSC	-0.957	0.850	-4.128	2.214
Lam B	Lam C	-2.277	0.326	-5.822	1.269
Lam B	OSC	-9.163	0.000	-12.335	-5.992
Lam C	OSC	-6.886	0.000	-10.432	-3.341

Scheffe Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	8.206	0.000	4.754	11.659
Lam A	Lam C	5.929	0.001	2.069	9.789
Lam A	OSC	-0.957	0.883	-4.410	2.495
Lam B	Lam C	-2.277	0.408	-6.137	1.583
Lam B	OSC	-9.163	0.000	-12.616	-5.711
Lam C	OSC	-6.886	0.000	-10.747	-3.026

▼Descriptive Statistics

Results for CONFIGURATION$ = Lam A

	TEN_MOD	MAX_STRESS
N of Cases	12	12
Minimum	0.877	4.646
Maximum	1.772	7.664
Median	1.316	6.187
Arithmetic Mean	1.298	6.068
Standard Deviation	0.339	0.936
Shapiro-Wilk Statistic	0.900	0.954
Shapiro-Wilk p-value	0.159	0.691

Results for CONFIGURATION$ = Lam B

	TEN_MOD	MAX_STRESS
N of Cases	12	12
Minimum	1.811	10.553
Maximum	2.719	13.781
Median	2.311	12.487
Arithmetic Mean	2.242	12.263
Standard Deviation	0.332	0.975
Shapiro-Wilk Statistic	0.900	0.959
Shapiro-Wilk p-value	0.158	0.766

Results for CONFIGURATION$ = Lam C

	TEN_MOD	MAX_STRESS
N of Cases	8	8
Minimum	3.480	16.279
Maximum	5.075	26.919
Median	4.549	20.065
Arithmetic Mean	4.368	20.560
Standard Deviation	0.664	3.785
Shapiro-Wilk Statistic	0.859	0.940
Shapiro-Wilk p-value	0.116	0.611

Results for CONFIGURATION$ = OSC

	TEN_MOD	MAX_STRESS
N of Cases	13	13
Minimum	0.742	4.617
Maximum	1.280	6.382
Median	1.077	5.757
Arithmetic Mean	1.021	5.628
Standard Deviation	0.168	0.569
Shapiro-Wilk Statistic	0.924	0.854
Shapiro-Wilk p-value	0.284	0.032

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	TEN_MOD
N	45
Multiple R	0.957
Squared Multiple R	0.915

Estimates of Effects B = $(X'X)^{-1}X'Y$

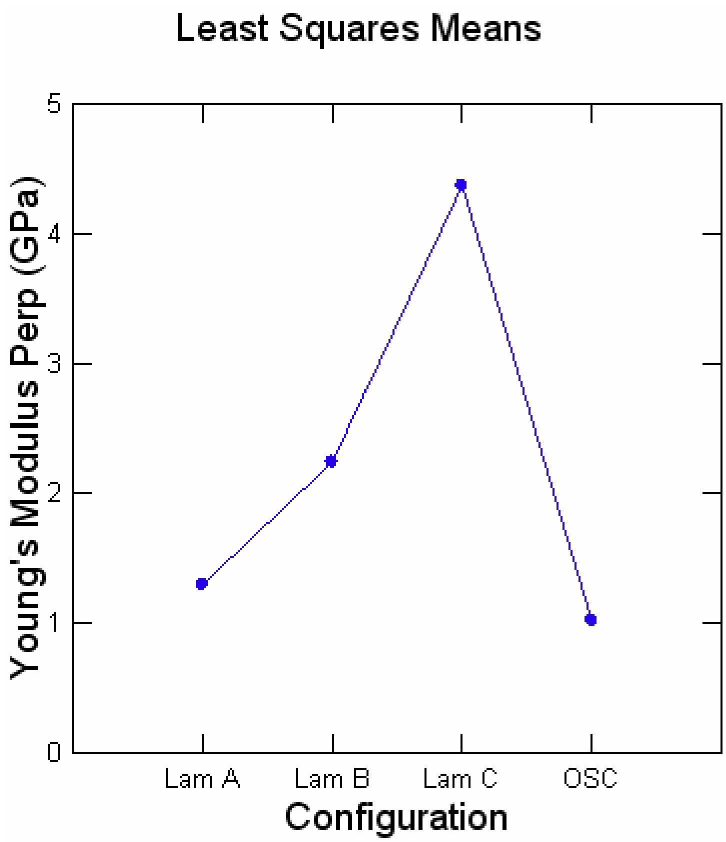
Factor	Level	TEN_MOD
CONSTANT		2.232
CONFIGURATION$	Lam A	-0.934
CONFIGURATION$	Lam B	0.010
CONFIGURATION$	Lam C	2.136

Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	63.944	3	21.315	147.919	0.000
Error	5.908	41	0.144		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	1.298	0.110	12.000
CONFIGURATION$	Lam B	2.242	0.110	12.000
CONFIGURATION$	Lam C	4.368	0.134	8.000
CONFIGURATION$	OSC	1.021	0.105	13.000



Durbin-Watson D Statistic	2.032
First Order Autocorrelation	-0.036

Information Criteria	
AIC	46.338
AIC (Corrected)	47.877
Schwarz's BIC	55.371

▼Hypothesis Tests

Post Hoc Test of TEN_MOD
Using least squares means.
Using model MSE of 0.144 with 41 df.

Tukey's Honestly-Significant-Difference Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.944	0.000	-1.359	-0.529
Lam A	Lam C	-3.071	0.000	-3.535	-2.607
Lam A	OSC	0.277	0.278	-0.130	0.684
Lam B	Lam C	-2.127	0.000	-2.590	-1.663
Lam B	OSC	1.221	0.000	0.814	1.628
Lam C	OSC	3.347	0.000	2.891	3.804

Scheffe Test

CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.944	0.000	-1.396	-0.492
Lam A	Lam C	-3.071	0.000	-3.576	-2.565
Lam A	OSC	0.277	0.357	-0.166	0.720
Lam B	Lam C	-2.127	0.000	-2.632	-1.621
Lam B	OSC	1.221	0.000	0.778	1.664
Lam C	OSC	3.347	0.000	2.850	3.845

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	MAX_STRESS
N	45
Multiple R	0.958
Squared Multiple R	0.918

Estimates of Effects $B = (X'X)^{-1}X'Y$

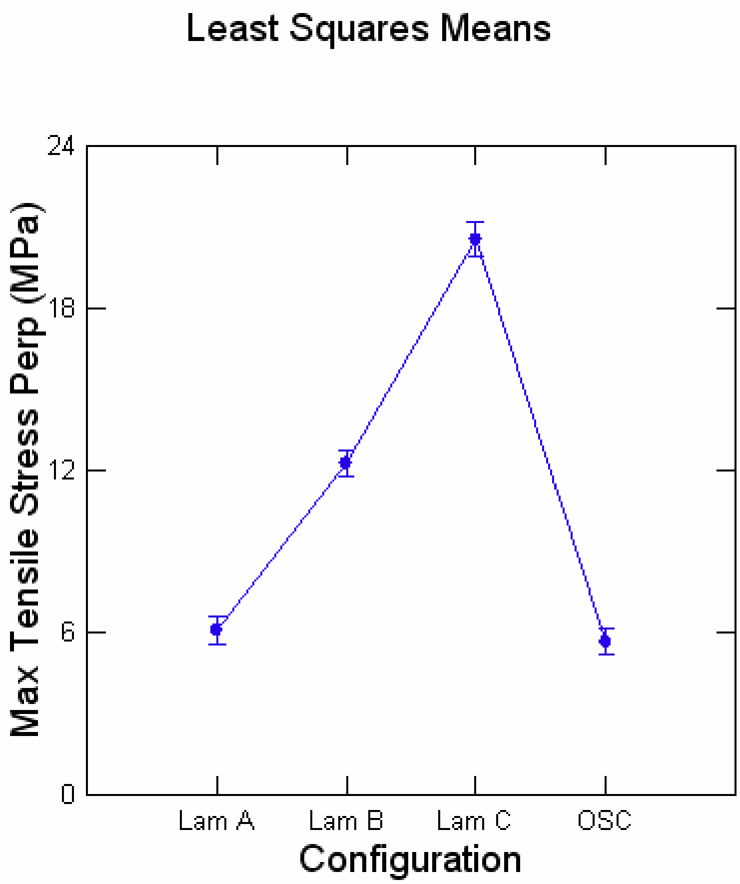
Factor	Level	MAX_STRESS
CONSTANT		11.130
CONFIGURATION$	Lam A	-5.061
CONFIGURATION$	Lam B	1.133
CONFIGURATION$	Lam C	9.430

Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	1386.239	3	462.080	152.452	0.000
Error	124.271	41	3.031		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	6.068	0.503	12.000
CONFIGURATION$	Lam B	12.263	0.503	12.000
CONFIGURATION$	Lam C	20.560	0.616	8.000
CONFIGURATION$	OSC	5.628	0.483	13.000



WARNING

Case 31 is an Outlier (Studentized Residual : 4.866)

Durbin-Watson D Statistic	2.360
First Order Autocorrelation	-0.184

Information Criteria	
AIC	183.415
AIC (Corrected)	184.954
Schwarz's BIC	192.449

▼Hypothesis Tests

Post Hoc Test of MAX_STRESS
Using least squares means.
Using model MSE of 3.031 with 41 df.

Tukey's Honestly-Significant-Difference Test					
CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-6.195	0.000	-8.098	-4.292
Lam A	Lam C	-14.491	0.000	-16.619	-12.364
Lam A	OSC	0.441	0.921	-1.426	2.307
Lam B	Lam C	-8.297	0.000	-10.424	-6.169
Lam B	OSC	6.635	0.000	4.769	8.502
Lam C	OSC	14.932	0.000	12.837	17.027

Scheffe Test					
CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-6.195	0.000	-8.267	-4.123
Lam A	Lam C	-14.491	0.000	-16.808	-12.175
Lam A	OSC	0.441	0.940	-1.591	2.472
Lam B	Lam C	-8.297	0.000	-10.613	-5.980
Lam B	OSC	6.635	0.000	4.604	8.667
Lam C	OSC	14.932	0.000	12.651	17.213

▼Descriptive Statistics

Results for CONFIGURATION$ = Lam A

	DENSITY	IB_STRESS
N of Cases	20	20
Minimum	623.693	229.825
Maximum	789.244	529.838
Median	702.346	358.910
Arithmetic Mean	707.742	369.770
Standard Deviation	44.179	84.452
Shapiro-Wilk Statistic	0.969	0.961
Shapiro-Wilk p-value	0.742	0.565

Results for CONFIGURATION$ = Lam B

	DENSITY	IB_STRESS
N of Cases	20	20
Minimum	653.739	159.438
Maximum	787.257	447.746
Median	694.138	290.019
Arithmetic Mean	705.876	297.707
Standard Deviation	36.920	81.854
Shapiro-Wilk Statistic	0.951	0.957
Shapiro-Wilk p-value	0.378	0.477

Results for CONFIGURATION$ = Lam C

	DENSITY	IB_STRESS
N of Cases	10	10
Minimum	592.649	152.806
Maximum	773.771	470.796
Median	720.314	257.973
Arithmetic Mean	705.577	292.697
Standard Deviation	54.309	113.467
Shapiro-Wilk Statistic	0.880	0.924
Shapiro-Wilk p-value	0.132	0.395

Results for CONFIGURATION$ = OSC

	DENSITY	IB_STRESS
N of Cases	15	15
Minimum	555.930	196.106
Maximum	808.822	675.763
Median	652.680	460.098
Arithmetic Mean	660.657	476.890
Standard Deviation	71.050	138.949
Shapiro-Wilk Statistic	0.958	0.964
Shapiro-Wilk p-value	0.658	0.754

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	IB_STRESS
N	65
Multiple R	0.651
Squared Multiple R	0.424

Estimates of Effects $B = (X'X)^{-1}X'Y$

Factor	Level	IB_STRESS
CONSTANT		-148.414
CONFIGURATION$	Lam A	1.169
CONFIGURATION$	Lam B	-69.532
CONFIGURATION$	Lam C	-74.323
DENSITY		0.731

Analysis of Variance

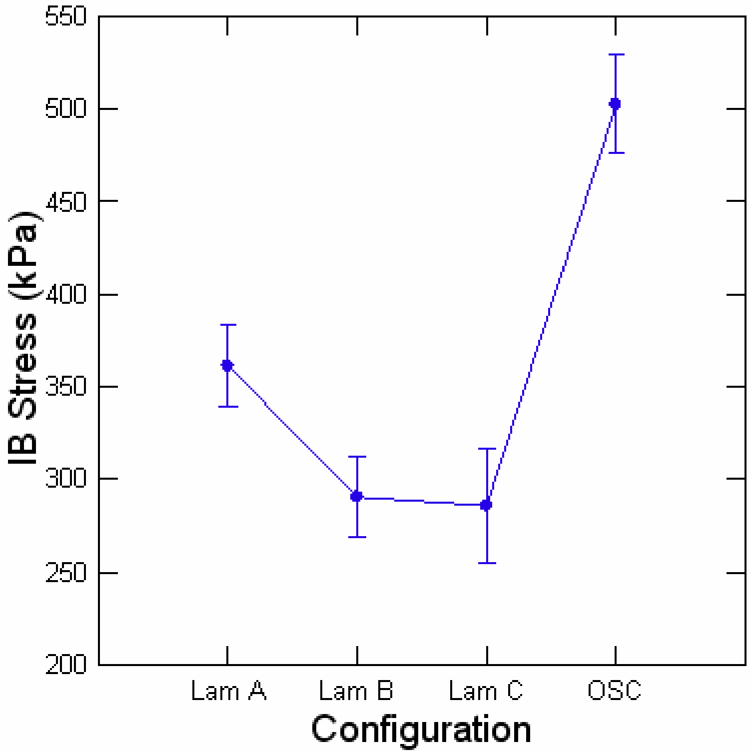
Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	407169.575	3	135723.192	14.452	0.000
DENSITY	85492.038	1	85492.038	9.103	0.004
Error	563484.948	60	9391.416		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	361.170	21.856	20.000
CONFIGURATION$	Lam B	290.469	21.802	20.000
CONFIGURATION$	Lam C	285.678	30.734	10.000
CONFIGURATION$	OSC	502.687	26.442	15.000

* Means are computed after adjusting covariate effect.

Least Squares Means



Durbin-Watson D Statistic	2.172
First Order Autocorrelation	-0.129

Information Criteria	
AIC	785.850
AIC (Corrected)	787.298
Schwarz's BIC	798.896

▼Hypothesis Tests

Post Hoc Test of IB_STRESS
Using least squares means.
Using model MSE of 9391.416 with 60 df.

Tukey's Honestly-Significant-Difference Test					
CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	70.701	0.108	-10.281	151.683
Lam A	Lam C	75.492	0.195	-23.690	174.674
Lam A	OSC	-141.517	0.001	-228.987	-54.046
Lam B	Lam C	4.791	0.999	-94.391	103.973
Lam B	OSC	-212.217	0.000	-299.688	-124.747
Lam C	OSC	-217.008	0.000	-321.556	-112.461

Scheffe Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	70.701	0.162	-17.451	158.852
Lam A	Lam C	75.492	0.267	-32.471	183.455
Lam A	OSC	-141.517	0.002	-236.731	-46.302
Lam B	Lam C	4.791	0.999	-103.172	112.754
Lam B	OSC	-212.217	0.000	-307.432	-117.003
Lam C	OSC	-217.008	0.000	-330.811	-103.205

▼Descriptive Statistics

Results for CONFIGURATION$ = Lam A

	DENSITY	MC	WATER_ABS	TS
N of Cases	4	4	4	4
Minimum	576.561	71.802	52.218	13.357
Maximum	642.423	81.882	60.393	20.252
Median	630.786	76.602	55.875	18.771
Arithmetic Mean	620.139	76.722	56.090	17.787
Standard Deviation	29.576	4.179	3.416	3.058
Shapiro-Wilk Statistic	0.792	0.995	0.993	0.852
Shapiro-Wilk p-value	0.089	0.979	0.975	0.234

Results for CONFIGURATION$ = Lam B

	DENSITY	MC	WATER_ABS	TS
N of Cases	4	4	4	4
Minimum	604.135	73.300	53.876	17.678
Maximum	644.267	80.426	58.048	19.661
Median	624.592	77.937	56.619	19.155
Arithmetic Mean	624.397	77.400	56.290	18.912
Standard Deviation	19.887	3.590	1.984	0.866
Shapiro-Wilk Statistic	0.872	0.845	0.896	0.888
Shapiro-Wilk p-value	0.307	0.211	0.410	0.374

Results for CONFIGURATION$ = Lam C

WARNING Shapiro-Wilk test is valid only when number of cases is between [3, 5000].

	DENSITY	MC	WATER_ABS	TS
N of Cases	2	2	2	2
Minimum	597.230	81.402	60.041	18.578
Maximum	599.258	84.042	61.424	19.932
Median	598.244	82.722	60.733	19.255
Arithmetic Mean	598.244	82.722	60.733	19.255
Standard Deviation	1.434	1.866	0.978	0.958
Shapiro-Wilk Statistic	.	.	.	.
Shapiro-Wilk p-value	.		.	

Results for CONFIGURATION$ = OSC

	DENSITY	MC	WATER_ABS	TS
N of Cases	3	3	3	3
Minimum	604.357	80.574	64.324	21.512
Maximum	646.546	94.780	77.014	28.103
Median	630.313	86.927	70.320	23.691
Arithmetic Mean	627.072	87.427	70.553	24.435
Standard Deviation	21.281	7.116	6.348	3.358

	DENSITY	MC	WATER_ABS	TS
Shapiro-Wilk Statistic	0.983	0.996	0.999	0.963
Shapiro-Wilk p-value	0.747	0.884	0.939	0.631

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	MC
N	13
Multiple R	0.871
Squared Multiple R	0.759

Estimates of Effects B = (X'X)$^{-1}$X'Y

Factor	Level	MC
CONSTANT		165.685
CONFIGURATION$	Lam A	-3.979
CONFIGURATION$	Lam B	-2.718
CONFIGURATION$	Lam C	-0.979
DENSITY		-0.137

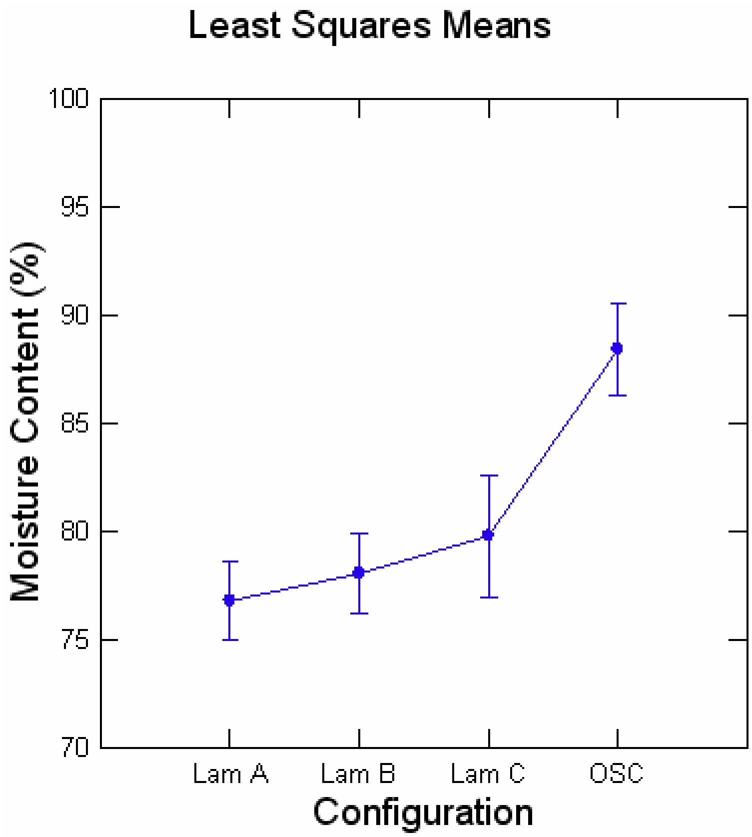
Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	265.044	3	88.348	6.593	0.015
DENSITY	88.614	1	88.614	6.613	0.033
Error	107.201	8	13.400		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	76.785	1.830	4.000
CONFIGURATION$	Lam B	78.046	1.847	4.000
CONFIGURATION$	Lam C	79.784	2.829	2.000
CONFIGURATION$	OSC	88.440	2.150	3.000

* Means are computed after adjusting covariate effect.



WARNING

Case 12 is an Outlier (Studentized Residual : 6.387)

Durbin-Watson D Statistic	3.164
First Order Autocorrelation	-0.669

Information Criteria	
AIC	76.319
AIC (Corrected)	90.319
Schwarz's BIC	79.709

▼Hypothesis Tests

Post Hoc Test of MC
Using least squares means.
Using model MSE of 13.400 with 8 df.

Tukey's Honestly-Significant-Difference Test					
CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-1.261	0.960	-9.550	7.028
Lam A	Lam C	-3.000	0.811	-13.152	7.153

Tukey's Honestly-Significant-Difference Test					
CONFIGURATION$(i)	**CONFIGURATION$(j)**	**Difference**	**p-value**	**95.0% Confidence Interval**	
				Lower	**Upper**
Lam A	OSC	-11.655	0.014	-20.609	-2.702
Lam B	Lam C	-1.738	0.956	-11.891	8.414
Lam B	OSC	-10.394	0.025	-19.347	-1.441
Lam C	OSC	-8.656	0.165	-19.357	2.046

Scheffe Test					
CONFIGURATION$(i)	**CONFIGURATION$(j)**	**Difference**	**p-value**	**95.0% Confidence Interval**	
				Lower	**Upper**
Lam A	Lam B	-1.261	0.970	-10.302	7.779
Lam A	Lam C	-3.000	0.850	-14.072	8.073
Lam A	OSC	-11.655	0.022	-21.420	-1.890
Lam B	Lam C	-1.738	0.967	-12.811	9.334
Lam B	OSC	-10.394	0.038	-20.159	-0.629
Lam C	OSC	-8.656	0.217	-20.327	3.016

Successfully saved file J:\SYSTAT\Lam TS.syz
Processed 6 Variables and 13 Cases.

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	**Levels**			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

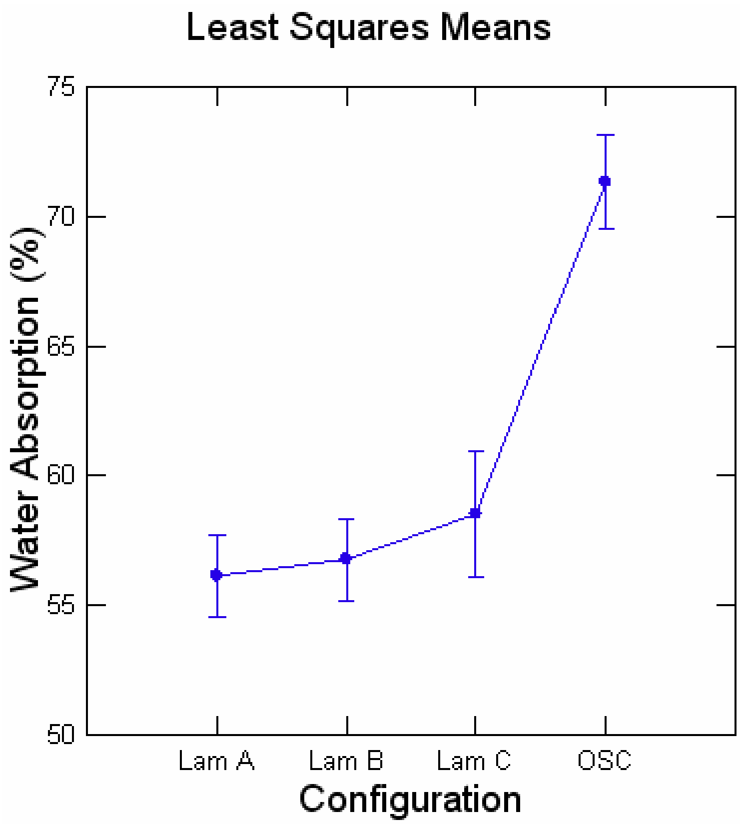
Dependent Variable	WATER_ABS
N	13
Multiple R	0.930
Squared Multiple R	0.865

Estimates of Effects $B = (X'X)^{-1}X'Y$		
Factor	**Level**	**WATER_ABS**
CONSTANT		124.609
CONFIGURATION$	Lam A	-4.550
CONFIGURATION$	Lam B	-3.911
CONFIGURATION$	Lam C	-2.166
DENSITY		-0.103

Analysis of Variance					
Source	**Type III SS**	**df**	**Mean Squares**	**F-ratio**	**p-value**
CONFIGURATION$	478.857	3	159.619	16.338	0.001
DENSITY	50.207	1	50.207	5.139	0.053
Error	78.156	8	9.770		

Least Squares Means				
Factor	**Level**	**LS Mean**	**Standard Error**	**N**
CONFIGURATION$	Lam A	56.138	1.563	4.000
CONFIGURATION$	Lam B	56.777	1.577	4.000
CONFIGURATION$	Lam C	58.522	2.416	2.000
CONFIGURATION$	OSC	71.315	1.836	3.000

* Means are computed after adjusting covariate effect.



WARNING

Case 12 is an Outlier (Studentized Residual : 7.497)

Durbin-Watson D Statistic	3.204
First Order Autocorrelation	-0.666

Information Criteria	
AIC	72.211
AIC (Corrected)	86.211
Schwarz's BIC	75.601

▼Hypothesis Tests

Post Hoc Test of WATER_ABS
Using least squares means.
Using model MSE of 9.770 with 8 df.

Tukey's Honestly-Significant-Difference Test

CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.639	0.991	-7.717	6.439
Lam A	Lam C	-2.384	0.841	-11.052	6.285
Lam A	OSC	-15.178	0.001	-22.822	-7.533
Lam B	Lam C	-1.745	0.932	-10.413	6.924
Lam B	OSC	-14.538	0.001	-22.183	-6.894
Lam C	OSC	-12.794	0.015	-21.931	-3.656

Scheffe Test

CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.639	0.993	-8.358	7.080
Lam A	Lam C	-2.384	0.875	-11.838	7.070
Lam A	OSC	-15.178	0.002	-23.515	-6.840
Lam B	Lam C	-1.745	0.948	-11.199	7.709
Lam B	OSC	-14.538	0.002	-22.876	-6.201
Lam C	OSC	-12.794	0.024	-22.759	-2.828

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

Dependent Variable	WATER_ABS
N	13
Multiple R	0.882
Squared Multiple R	0.778

Estimates of Effects B = $(X'X)^{-1}X'Y$

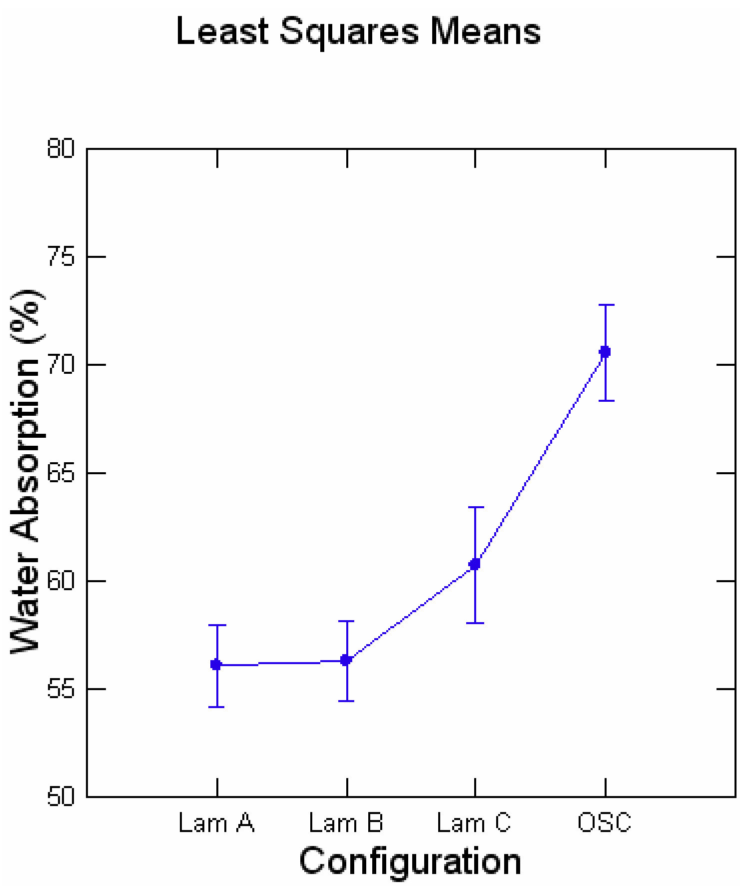
Factor	Level	WATER_ABS
CONSTANT		60.917
CONFIGURATION$	Lam A	-4.826
CONFIGURATION$	Lam B	-4.626
CONFIGURATION$	Lam C	-0.184

Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	450.808	3	150.269	10.536	0.003
Error	128.363	9	14.263		

Least Squares Means

Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	56.090	1.888	4.000
CONFIGURATION$	Lam B	56.290	1.888	4.000
CONFIGURATION$	Lam C	60.733	2.670	2.000
CONFIGURATION$	OSC	70.553	2.180	3.000



WARNING

Case 11 is an Outlier (Studentized Residual : -2.576)
Case 12 is an Outlier (Studentized Residual : 2.760)

Durbin-Watson D Statistic	3.079
First Order Autocorrelation	-0.541

Information Criteria

AIC	76.661

Information Criteria	
AIC	76.661
AIC (Corrected)	85.233
Schwarz's BIC	79.486

▼Hypothesis Tests

Post Hoc Test of WATER_ABS
Using least squares means.
Using model MSE of 14.263 with 9 df.

Tukey's Honestly-Significant-Difference Test					
CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.200	1.000	-8.537	8.137
Lam A	Lam C	-4.643	0.519	-14.853	5.568
Lam A	OSC	-14.462	0.003	-23.467	-5.458
Lam B	Lam C	-4.442	0.553	-14.653	5.768
Lam B	OSC	-14.262	0.004	-23.267	-5.258
Lam C	OSC	-9.820	0.075	-20.583	0.943

Scheffe Test					
CONFIGURATION$(i)	CONFIGURATION$(j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.200	1.000	-9.290	8.890
Lam A	Lam C	-4.643	0.591	-15.776	6.491
Lam A	OSC	-14.462	0.006	-24.281	-4.644
Lam B	Lam C	-4.442	0.622	-15.576	6.691
Lam B	OSC	-14.262	0.006	-24.081	-4.444
Lam C	OSC	-9.820	0.108	-21.556	1.916

▼General Linear Model

Effects coding used for categorical variables in model.
The categorical values encountered during processing are

Variables	Levels			
CONFIGURATION$ (4 levels)	Lam A	Lam B	Lam C	OSC

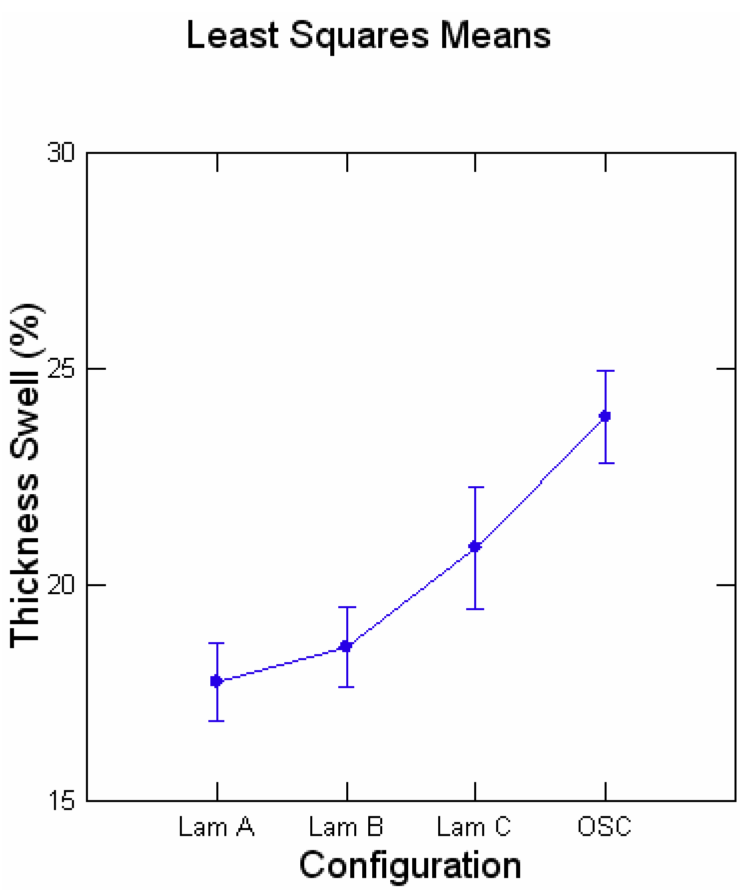
Dependent Variable	TS
N	13
Multiple R	0.896
Squared Multiple R	0.803

Estimates of Effects B = (X'X)[-1]X'Y		
Factor	Level	TS
CONSTANT		-26.293
CONFIGURATION$	Lam A	-2.511
CONFIGURATION$	Lam B	-1.706
CONFIGURATION$	Lam C	0.601
DENSITY		0.075

Analysis of Variance					
Source	Type III SS	df	Mean Squares	F-ratio	p-value
CONFIGURATION$	74.973	3	24.991	7.370	0.011
DENSITY	26.634	1	26.634	7.854	0.023
Error	27.129	8	3.391		

Least Squares Means				
Factor	Level	LS Mean	Standard Error	N
CONFIGURATION$	Lam A	17.753	0.921	4.000
CONFIGURATION$	Lam B	18.558	0.929	4.000
CONFIGURATION$	Lam C	20.865	1.423	2.000
CONFIGURATION$	OSC	23.880	1.081	3.000

* Means are computed after adjusting covariate effect.



WARNING

Case 12 is an Outlier (Studentized Residual : 3.608)

Durbin-Watson D Statistic	2.987
First Order Autocorrelation	-0.568

Information Criteria	
AIC	58.456
AIC (Corrected)	72.456
Schwarz's BIC	61.846

▼Hypothesis Tests

Post Hoc Test of TS
Using least squares means.
Using model MSE of 3.391 with 8 df.

Tukey's Honestly-Significant-Difference Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.805	0.924	-4.975	3.365
Lam A	Lam C	-3.112	0.327	-8.220	1.995
Lam A	OSC	-6.127	0.011	-10.631	-1.623
Lam B	Lam C	-2.307	0.574	-7.415	2.800
Lam B	OSC	-5.322	0.022	-9.826	-0.818
Lam C	OSC	-3.015	0.416	-8.398	2.369

Scheffe Test

CONFIGURATION$(-i)	CONFIGURATION$(-j)	Difference	p-value	95.0% Confidence Interval	
				Lower	Upper
Lam A	Lam B	-0.805	0.942	-5.353	3.743
Lam A	Lam C	-3.112	0.397	-8.682	2.458
Lam A	OSC	-6.127	0.017	-11.039	-1.215
Lam B	Lam C	-2.307	0.642	-7.877	3.263
Lam B	OSC	-5.322	0.035	-10.234	-0.410
Lam C	OSC	-3.015	0.489	-8.886	2.857