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Effects of bonding pressure and lamina thickness on mechanical properties of CLT composed of southern yellow pine

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This study produced cross-laminated timber panels at a range of four lamina thickness (5/8, 1, 1 1/8, and 1 1/4 inch) and three bonding pressures (50, 125, 200 psi), producing a total of 12 panels for mechanical testing. The goal of this study is to observe how the thickness and pressure trends affect the mechanical properties of CLT. Tests include flatwise bending, flatwise shear, internal-bond, and delamination. Results showed that bending MOE decreases as the panel thickness increases while bonding pressure had no significance. Bending MOR was less significant for the thickness and more significant for pressure compared to the MOE. Shear tests showed strong inverse relationship between MOR and thickness while increasing pressure strongly increased MOR. Internal-bond testing showed no clear relationship between thickness or pressure. Delamination decreased as a result of higher pressures while thickness had no significant affect.

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CHAPTER I

EFFECTS OF BONDING PRESSURE AND LAMINA THICKNESS ON BENDING PROPERTIES OF CLT COMPOSED OF SOUTHERN YELLOW PINE

Introduction

Cross-laminated timber, or CLT, is a composite consisting of softwood dimension lumber glued into layers perpendicular to one another. CLT may be pressed at a variety of thicknesses, typically in odd-numbered layers, resulting in a quasi-rigid panel with high dimensional stability both in-plane and out-of-plane. Laminating softwood dimension lumber in this way is a relatively new technology that opens the door further for sustainable construction on a large scale [1].

Throughout the past two decades, research and development on CLT mass timber structures has made it a viable construction method, with fire and seismic resistance properties allowing it to comply with modern building codes while being competitive compared to traditional construction methods [2] [3] [4]. In the same way perceptions change about buildings' safety in fire and earthquake events, perceptions also change about the environmental impact of mass timber technologies. As societies trend toward being eco-friendlier and more conscious of carbon emissions, mass timber technologies emerge competitively as an alternative to steel and concrete in modern, tall building applications [5]. The research and development of CLT in Europe has allowed the material to prove its worth as a viable and competitive building material. Seeing this, other parts of the world, including North America, have followed suit in the adoption and continued development of mass timber technologies using native species, including southern yellow pine.

The biggest advantage of CLT (and mass timber) is that it can be used in many places where concrete, masonry, and steel are typically used. CLT and mass timber have been proven to be effective materials in construction of walls, floors, ceilings, stairways, elevator shafts, balcony elements, beams, etc. in buildings like schools, offices, multi-family apartments, and mixed-use buildings in excess of 17 stories. Mass timber buildings have an advantage as compared to traditional construction methods because mass timber elements are all prefabricated. Panel sections of CLT are cut to exact specification during manufacturing so that when they arrive to the construction site, they just need to be lifted and guided into place using a crane. Pouring concrete and constructing walls from raw materials on a job site requires more workers, time, space, and is quite noisy compared to modern prefabrication methods like mass timber. [6] [7]

Commercial Practice

In the US, CLT can be constructed using any softwood species recognized by the American Lumber Standards Committee. Different species may be used in different layers of a single panel, but any given layer must only contain a single species. Parallel layers (major axis) of CLT must be at least visual grade No.2, while perpendicular layers (minor axis) can be a minimum grade No. 3 [8].

Before gluing, it is required that the bonding faces be planed. Planing the bonding face of the lumber removes deviations from the face and gives a clean surface for the adhesive to bond with. This is one of the most important steps to ensure the glue joints form correctly. The planer used should feed at a rate that yields 20 to 30 knife marks per inch to produce a satisfactory bonding surface. Sanding-type planers are not recommended for glue preparation [9]. For best results, it is recommended that lumber be planed as close to the time of gluing as possible, 24-48 hours before gluing [10]. ANSI/APA PRG 320 Standard for Performance-Rated Cross-Laminated Timber requires that individual lamina be no thinner than 5/8 inch and no thicker than 2 inches. Depending on the number of layers and the thickness of the lumber used in the layup, a finished panel can be a wide range of thicknesses, depending on the final application.

The three main types of adhesive systems used with mass timber are PUR (polyurethane), MUF (melamine-urea formaldehyde), and PRF (phenol-resorcinol formaldehyde). PUR is a single-component polyurethane adhesive and is the most common adhesive system used in industry as well as academic papers focusing on CLT [11]. MUF is a two-component adhesive system commonly used in industry and academic studies with its system composed of a resin used with a hardener to set the adhesive. Some MUF resin systems have the ability to cure via a radio frequency treatment during pressing, in addition to being able to be used in hot-pressing operations [14]. PRF is another two-component adhesive system, using a resin and hardener to cure. PRF adhesives are able to be used in hot-press manufacturing operations as well as room temperature. It’s burgundy/brown color is favorable by researchers studying delamination as it keeps its dark color and can be seen, unlike PUR adhesives [11]. All adhesives used in CLT production must meet requirements specified in section 6.3 of PRG-320 for CLT production [8].

Though surface planing does remove thickness variation from the gluing surface, there will still be geometric variation among lumber pieces due to things like warp, density, and presence of knots that the planing process does not address. Because of this, an applied pressure is required to flatten the layers against one another to ensure a proper bond along each glue line. PRG-320 does not recommend a minimum bonding pressure, among other variables like assembly time, glue spread rate, or temperature of the surface. For these variables, PRG-320 says these should be dictated by the specific standards of the plant producing or by an “approved agency” [8]. In terms of bonding pressure and some other variables, the manufacturer of the adhesive being used often provides manufacturing guidance. Between different adhesive systems, bonding pressures, and pressing methods, there is room for debate about which combination of these produces the highest quality product. Because of this, pressing is the most important step of the process and its variables are often the subject of academic papers focusing on CLT production [13] [15] [16] [17].

Bonding pressure is described as the mechanism that brings the bonding surfaces into intimate contact so that, once the glue is cured, a satisfactory bond is achieved. Softer wood that deforms easily or wood that is true and free of imperfections requires a lower bonding pressure while harder, more dense woods or wood with the presence of imperfections like knots require a higher theoretical bonding pressure to achieve a satisfactory bond [9] [14]. For softwoods, a range of 100 to 200 psi is recommended by Freas and Selbo [10]. They wrote about GLULAM specifically, but these principles can be used in other mass timber elements like CLT. Vacuum bagging is a popular method of pressing for its lower cost compared to hydraulic or pneumatic pressing but it is only capable of reaching pressures of approximately 15 psi, or 1 atmosphere.

To observe the effects of bonding pressure, among other production variables, researchers selected bonding pressures similar to that of vacuum bagging (13 psi) and hydraulic pressing (174 psi). Through shear and delamination tests, no significant difference in performance was found between these two bonding pressures [15]. Another experiment was done using shear and delamination testing methods to observe the effects of bonding pressure, lamina thickness, and other production variables. The four bonding pressures ranged from 14.5 to 145 psi (0.1 to 1.0 MPa), pressing panels with lamina thicknesses of 0.59 and 1.38 inch (15 and 35 mm). Tests showed increasing bonding pressure lowered delamination percentage, while having no effect on shear strength. For the increased thickness, shear strength was unaffected while thicker specimens showed higher percentages of wood failure for both shear and delamination tests [13]. Another selected bonding pressure among other variables to study through bending and shear tests, but saw no significant influence of bonding pressures. Possibly this finding was due to the narrow range of the two bonding pressures used, 100 and 120 psi [16]. In a study selecting vacuum-bag and hydraulic-press-like pressures (11.6 and 116 psi), multiple lamina thicknesses (0.79 and 1.57 inch), in three- and seven-layer CLT specimens among other variables, a delamination test was conducted. The influence of bonding pressure and lamina thickness on delamination in this study are unclear [12]. In another experiment using shear and delamination test methods, CLT used was pressed at two bonding-pressures (14.5 and 101.5 psi), composed with lumber of different specific densities, and other production variables. Results showed that specimens produced at higher pressures showed greater resistance to delamination and shear strength. Also, the combination of high-density wood and low bonding pressure resulted in a low shear strength [17].

Objectives

Manufacturers have posed questions about bonding pressure required to achieve good bonding and alternatives to hydraulic pressing like pneumatic pressing or vacuum bagging. This study seeks to identify differences in mechanical properties associated with bonding pressure and lamina thickness trends.

Materials and Methods

Visually graded No. 2 southern yellow pine lumber was purchased and used for all of the panels produced in this study. Lumber was planed down from 2x6 lumber to get 1 1/4 inch, 1 1/8 inch, and 1 inch thick lamina, while 1x6 lumber was planed to get the 5/8 inch lamina. In this study, the time between planing the lumber faces and when the glue was applied did not exceed 24 hours. The adhesive used in CLT production was a two-component mixture supplied by Hexion Inc. CASOPHEN LT-75 is a liquid, phenol-resorcinol timber laminating resin and was used in conjunction with the dry, powdered hardener, CASOSET FM-260. The manufacturer's suggested ratio of 5.5:1 resin to hardener (by weight), with a spread rate of 0.1 lb of mixed adhesive per square foot of lumber was used [18]. This 0.1 lb/ft^2 applies to each face of the panel being glued, with a glue line resulting in two faces of lumber, both with the 0.1 lb/ft^2 spread, bonded together in the hydraulic press. The amount of adhesive applied to the faces was controlled and monitored by weighing before and after each spread of glue is applied. Adhesive was applied to the faces using 6 inch paint rollers. During the period of time where lumber was being planed, glued, and pressed, the lumber used had an equalized moisture content of 7.947%. (Figure 1)

Pressing

Adhesive curing tables exist for each glue type indicating press time at various glue line temperatures. Given the ambient temperature during panel production hot pressing was used to apply heat to the top and bottom faces of the panel accelerating the rate of glue line curing. When hot pressing, the platens of the press were measured at an approximate 240 degrees Fahrenheit. With the heat and pressure applied, the glue line reached a temperature of 200 degrees in about two hours allowing the production of two panels per day for thick panels and three per day for the thinner panels. At the point when a thermocouple, placed in a glue line, exceeded 200 degrees, the glue was considered cured, and the panel was removed from the press. Parent panels were pressed at three bonding pressures (50 psi, 125 psi, and 200 psi) and four thicknesses (1.875 inch, 3 inch, 3.375 inch, and 3.75 inch). This combination yielded a total of 12, 4x8 foot parent panels. From each of the 4x8 foot parent panels, four 1x8 foot child panels were cut. For each of the 12 parent panels, two of the child panels became the specimens for bending tests in this paper, yielding a total of 24 bending specimens.

Panel Evaluation

Following ASTM D198 sections 4 through 12 as recommended in PRG-320, static bending was performed on each child panel. The testing machine used for bending test was an Instron universal testing machine controlled by Instron Bluehill 3 software. The test frame was configured to conduct the test via 4-point bending consistent with the requirements of PRG 320, with the exception of depth-to-span ratios due to the dimensional limitations of the press used in panel production. With the panel length limited to 96 inches, the maximum test span that could safely sit on the bearing plates of the testing machine was 92 inches. Because of this, the two thicker panel thicknesses did not comply with the 30:1 depth-to-span ratio specified in PRG 320. The machine was programmed to take width, thickness, and span data, apply the force at the specified rate, and collect the stress-strain curve for each specimen. A reaction bearing plate supported the specimen at each end of the span and load bearing blocks were located at 1/3 and 2/3 the test span length, consistent with four-point loading. The face of the load bearing blocks were radiused to minimize stress-concentrations as a result of the load being applied through the blocks. Lateral support was not required as the specimens were tested flatwise. Deflection of each specimen was measured using an LVDT connected to the neutral axis mod-span of the specimens. Data for load and deflection were captured and saved in real time during testing.

Flexure Specimens

Flexure specimens were 1x8 foot child panels cut from the twelve 4x8 foot parent panels produced for this study. The parent panels measured 4x8 foot, once the uneven edges were trimmed, and flexure specimens then cut with an average width of 11.79 inches. PRG-320 section 8.5.3.1 states that the bending specimen width should be no less than 12 inches wide. The 11.79 inch width is 1.75% narrower than the recommended 12 inch and thus was considered negligible. During the testing procedure, the exact width and depth of the specimen was input into the testing apparatus and these true measurements were used in the calculation of MOR and MOE. The length of all the bending specimens was 8 foot. As the thickness of specimens increased, so did the required test span. PRG-320 section 8.5.3.1 states that the span between the supports must be approximately 30 times the specimen depth for flatwise specimens. The limitations of the pressing equipment used permitted that the maximum length of panel pressed was a maximum of 8 ft. With a specimen length of 8 foot or 96 inches, the maximum test span that could safely sit on the bearing plates of the testing machine was 92 inches. For the panels of approximate 1.875 and 3 inch thickness were long enough to comply with PRG-320 and had a span equal to 30 times that thickness. It must be noted that the two larger sizes, specimens of approximate 3.375 and 3.75 inches did not meet the span requirement for PRG-320. The ideal span for 3.375 and 3.75 inch specimens according to PRG-320 is 101.25 and 112.5 inches respectively and were shorter than the 92 inch span by 9.14% and 18.2% respectively. The recommend span of 30 times the thickness is to ensure that the bending specimens fail in bending, not shear. Of the larger specimens just described, it was noted if the specimens appear to fail in shear.

Procedure

As each specimen was loaded into the testing machine, its span, thickness, and width were recorded and input into the machine. These measurements are used by the machine software in calculating the stress in the specimen during testing. Each specimen was centered on the reaction supports with enough overhang past the reaction pivot point to ensure the specimen did not slip off the supports during testing. An LVDT was attached to the specimen to be tested at the midpoint of its span, at the neutral axis, allowing strain data to be calculated during testing. The average test time for each specimen was 5.7 minutes.

During each test, the testing apparatus and computer generated a stress-strain curve real time and saved this data for each specimen. The software used this graph to calculate MOE and MOR and to show the points in the test where slight breaks take place and the eventual failure at maximum load (Figure 2).

Results and discussion

Analysis of variance was used to analyze the bending test results of MOE and MOR. The first model was MOR based on thickness, pressure, and the interaction of thickness with pressure. The interaction of thickness and pressure was not significant so it was omitted from the analysis. The R^2 (0.6740) value is reasonable and pressure (0.0376) and thickness (0.0005) p-values are both significant (Figure 3). The boxplot for MOR and thickness shows a 1.875 inch specimens performed significantly higher for MOR. The three larger thicknesses were not found to be significant from one another (Figure 4). The pressure with the highest average MOR is 125 psi, and the lowest MOR was at 50 psi. The 200 psi specimens performed slightly worse than the 125 psi ones, this could be due to the excess of glue being “squeezed out” of the glue line while pressing at this higher pressure.

To further understand the MOR analysis after looking at the bar charts of MOR vs pressure, a new model was fit using the GLM procedure with LSMEANS and making thickness as a covariant to determine the influence of pressure. R^2 decreased slightly (0.5554) after changing thickness to a covariant in this model. Once again thickness and pressure were both significant in the explanation of MOR but the separation of pressure appears to reveal that MOR increases as the pressure moves from 50 to 125 psi but decreases at some point between 125 and 200 psi (Figure 5). This model follows conventional wisdom that applying pressure to get intimate contact between lamina layers is important. It is important to note that the beta value for thickness is negative. This is consistent with the size model in ASTM D1990 section 8.4.3, which describes a scaling of properties in a lumber specimen with its volume compared to reference design values [19]. It is also interesting to look at the magnitude of the beta values on pressure. During pressing it was observed that resin was forced out of each glue line of the panels, with the 200 psi panels exhibiting more “squeeze out” of the resin than the other 2 pressure values.

Analysis of variance using MOE as the dependent variable and thickness and pressure as independent variables, the ANOVA procedure was run. Thickness p-value (0.0082) is significant but pressure p-value (0.7045) and R^2 (0.4826) are not significant (Figure 6) (Figure 8). In the thickness vs MOE boxplot we can clearly see MOE decreases as the panel thickness increases. The pressure vs MOE boxplot reflects the insignificance of the pressure for MOE (Figure 7). Shear results also comply with the fracture mechanics theory which states that tensile strength is inversely proportional to the square root of the lamina thickness. [20]

Pressure was significant for MOR (p-value = 0.0376) and not significant for MOE (p-value = 0.7045), we can see that pressure has a much bigger impact on MOR than MOE (Figures 3 and 6). A possible explanation of this finding could be due to the nature of bending failure vs shear. Bending failure is usually associated with the tensile failure of the bottom layer of the specimen being tested. Testing continues past this point until rupture occurs, characterized by shear stress between lamina causing rupture of the test specimen. For this reason, MOR is a better value to test the bond between layers, as MOE is really more of a reflection of the tensile strength of the bottom layer of the test specimen, not of the quality of the bond between lamina. This speculation is reflected in the affect of pressure on MOR vs MOE discussed earlier.

Conclusions

MOE was clearly shown to decrease as panel thickness increased. When lumber is planed, the lamina become thinner and are thus better at stopping crack propagation. This makes the bottom layer more resistant to tensile failure, the failure mode most associated with the bending test. Bonding pressure was not significant for MOE because tensile failure in the bottom layer occurs before the bond between the lamina is tested. Box plots showed thinner panels performed significantly better in terms of MOR than the thicker panels, but there is no correlation between the three thicker panel thicknesses. For pressure, the lowest MOR was in the 50 psi panels and the highest performance was in the 125 psi panels, this pressure is within the 100-150 psi range recommended by the adhesive manufacturer. 200 psi panels performed slightly worse than the 150 psi ones, perhaps due to the amount of resin that is squeezed out of the panel when under excessive amounts of pressure. This “squeeze out” may be determined also by glue viscosity, temperature, wood species, wood surface, moisture content, and density, but these were beyond the scope of this study.

Figures

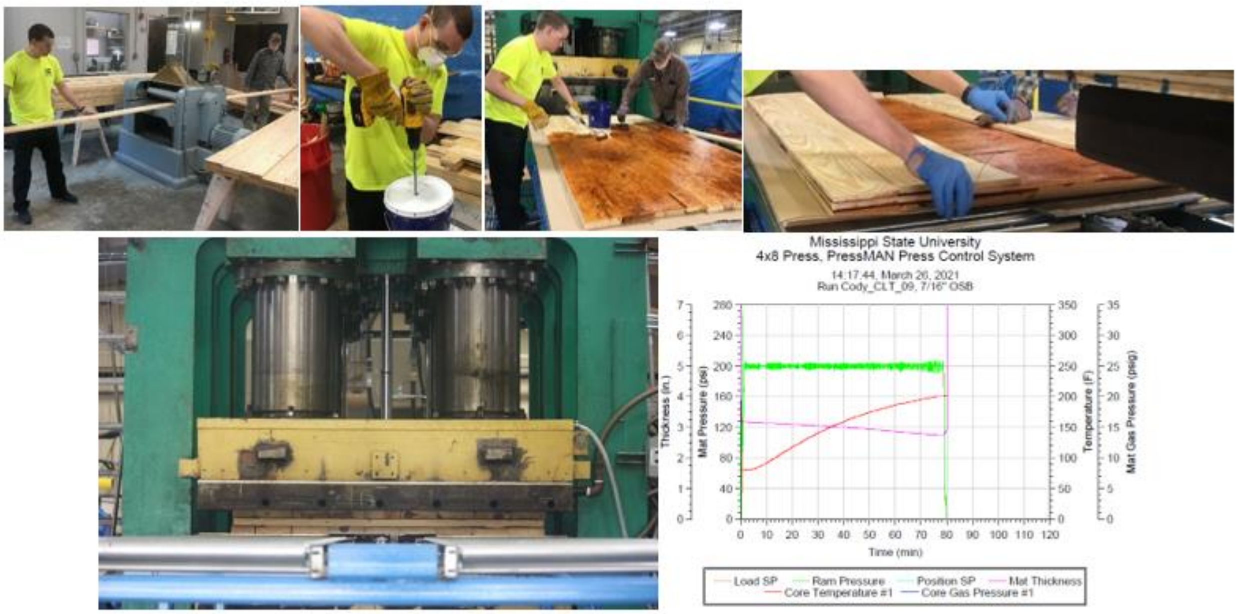

Figure 1 CLT production process

From L to R: planing, glue mixing, glue application, thermocouple inserting, pressing, press chart showing pressure, thermocouple temperature, and time.

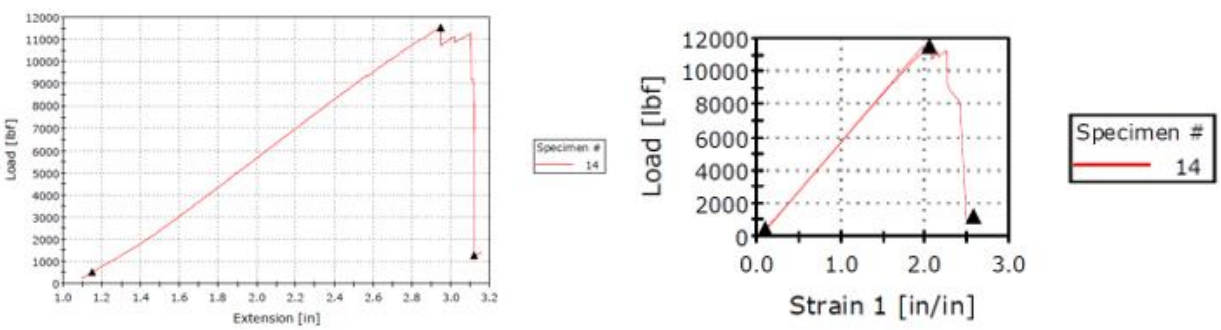

Figure 2 Instron output examples

Load vs load head extension (left) and load vs deflectometer displacement (right).

MOR ANOVA

The ANOVA Procedure

Class Level Information		
Class	Levels	Values
pressure	3	50 125 200
thickness	4	1.875 3 3.375 3.75

Number of Observations Read	24
Number of Observations Used	24

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	84994965.2	16998993.0	7.44	0.0006
Error	18	41111488.8	2283971.6		
Corrected Total	23	126106454.0			

R-Square	Coeff Var	Root MSE	mor Mean
0.673994	17.48266	1511.281	8644.458

Source	DF	Anova SS	Mean Square	F Value	Pr > F
pressure	2	18088490.08	9044245.04	3.96	0.0376
thickness	3	66906475.13	22302158.38	9.76	0.0005

Figure 3	Bending MOR ANOVA results.

Analysis of variance results showing R^2 and p-values for pressure and thickness.

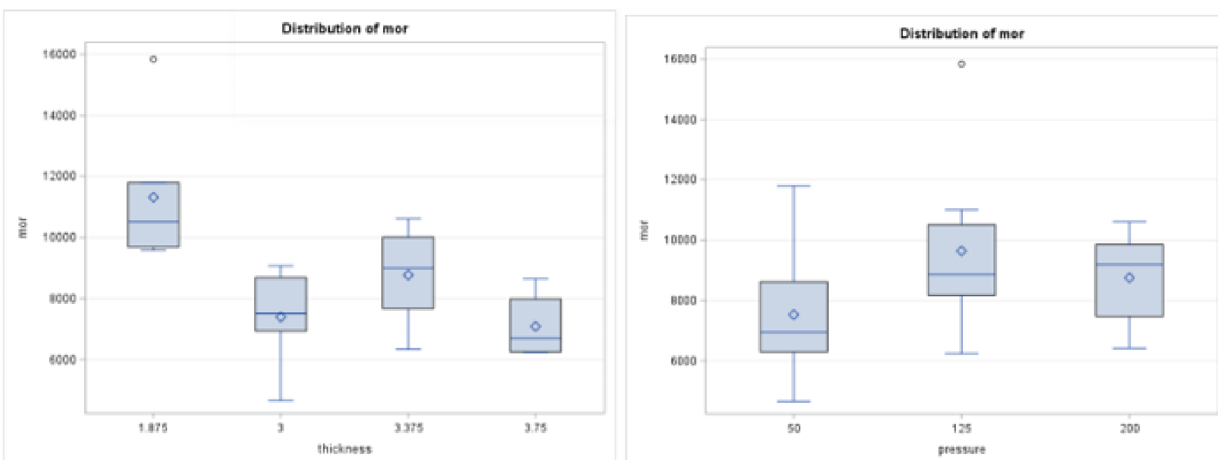

Figure 4	Bending MOR thickness and pressure box plots.

Box plots show means for thickness and pressure vs MOR.

The GLM Procedure

Dependent Variable: mor

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	1863479799	465869950	166.18	<.0001
Error	20	56066492	2803325		
Uncorrected Total	24	1919546291			

R-Square	Coeff Var	Root MSE	mor Mean
0.555403	19.36863	1674.313	8644.458

Source	DF	Type I SS	Mean Square	F Value	Pr > F
pressure	3	1811528327	603842776	215.40	<.0001
thickness	1	51951471	51951471	18.53	0.0003

Source	DF	Type III SS	Mean Square	F Value	Pr > F
pressure	3	295700049.8	98566683.3	35.16	<.0001
thickness	1	51951471.4	51951471.4	18.53	0.0003

Parameter	Estimate	Standard Error	t Value	Pr > |t|
pressure 50	13820.30357	1576.794837	8.76	<.0001
pressure 125	15937.67857	1576.794837	10.11	<.0001
pressure 200	15049.67857	1576.794837	9.54	<.0001
thickness	-2097.14286	487.153453	-4.30	0.0003

Figure 5 Bending MOR covariant model.

GLM process results showing covariance between pressures.

MOE ANOVA

The ANOVA Procedure

Class Level Information		
Class	Levels	Values
pressure	3	50 125 200
thickness	4	1.875 3 3.375 3.75

Number of Observations Read	24
Number of Observations Used	24

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	813143042703	162628608541	3.36	0.0257
Error	18	871823184408	48434621356		
Corrected Total	23	1.6849662E12			

R-Square	Coeff Var	Root MSE	moe Mean
0.482587	10.95989	220078.7	2008037

Source	DF	Anova SS	Mean Square	F Value	Pr > F
pressure	2	34593710011	17296855006	0.36	0.7045
thickness	3	778549332692	259516444231	5.36	0.0082

Figure 6 Bending MOE ANOVA test results.

Analysis of variance results showing R^2 and p-values for pressure and thickness.

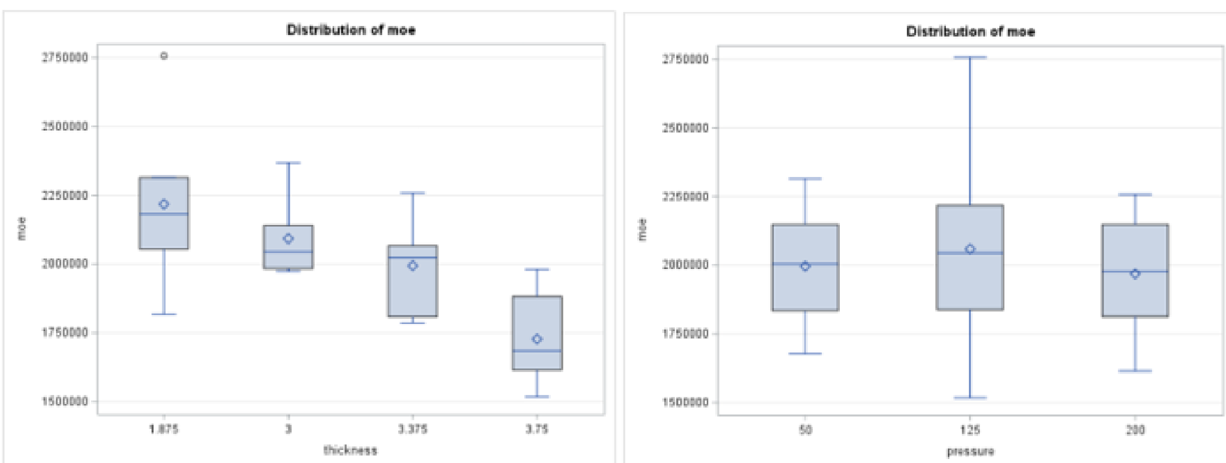

Figure 7 Bending MOE thickness and pressure box plots.

Box plots show means for thickness and pressure vs MOE.

The GLM Procedure

Dependent Variable: moe

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	9.7427849E13	2.4356962E13	472.83	<.0001
Error	20	1.0302557E12	51512787150		
Uncorrected Total	24	9.8458105E13			

R-Square	Coeff Var	Root MSE	moe Mean
0.388560	11.30279	226964.3	2008037

Source	DF	Type I SS	Mean Square	F Value	Pr > F
pressure	3	9.6807732E13	3.2269244E13	626.43	<.0001
thickness	1	620116774106	620116774106	12.04	0.0024

Source	DF	Type III SS	Mean Square	F Value	Pr > F
pressure	3	9.0757205E12	3.0252402E12	58.73	<.0001
thickness	1	620116774106	620116774106	12.04	0.0024

Parameter	Estimate	Standard Error	t Value	Pr > |t|
pressure 50	2683280.351	213745.0262	12.55	<.0001
pressure 125	2746760.601	213745.0262	12.85	<.0001
pressure 200	2656164.601	213745.0262	12.43	<.0001
thickness	-229121.492	66036.8902	-3.47	0.0024

Figure 8 Bending MOE covariant model.

GLM process showing covariance between pressures.

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CHAPTER II

EFFECTS OF BONDING PRESSURE AND LAMINA THICKNESS ON MECHANICAL PROPERTIES OF CLT COMPOSED OF SOUTHERN YELLOW PINE

Introduction

Cross-laminated timber, or CLT, is a composite timber product composed of dimensioned softwood lumber laminated in layers perpendicular to one another. With layers from 5/8 inch to 2.0 inches thick and a finished panel thickness of up to 20 inches, the end result is a panel with dimensional stability in-plane and out-of-plane [2]. Developed in central Europe in the late 1900s and early 2000s, CLT and other mass timber products are used as a sustainable alternative to steel and concrete materials used in various buildings, some in excess of 17 stories [1] [3] [4].

CLT Production

For CLT, a target thickness can be achieved by using a combination of different lamina thicknesses and number of layers. If someone can choose a three-ply panel with thicker layers, or use thinner layers in a five-ply configuration, what is the best option? PRG-320 states that the thickness of the lumber used be between 5/8 inch to 2 inches thick. It is known that planing dimension lumber to smaller thicknesses can be done to randomize strength reducing defects, which is speculated to increase the panel's resistance to rolling shear. This claim is speculated in a study examining the effect of two different thicknesses, 20 and 35 mm, on rolling-shear strength. This study showed that increasing the lamina thickness decreased rolling-shear strength

[6]. It is also known that due to their larger size, thicker lamina will deform more when exposed to moisture. The deformation of these layers contributes to delamination in CLT. Additionally, this delamination affect is thought to be greater in CLT than GLULAM due to the perpendicular layers that compose CLT compared to the parallel ones of GLULAM. The way wood shrinks at different rates depending on its orientation to the grain direction, 90 degree orientation of the layers of CLT cause more internal stresses in CLT than in GLULAM due to the opposing directions of shrinkage in CLT compared to the parallel structure of glulam [7]. After conducting an experiment to study bending strength and rolling shear strength concluded that these strengths decreased with panel thickness. They recommend further testing to confirm this trend [8]. A study focused on 3 and 5 layer CLT at two lamina thicknesses, among other variables, and found that lamina thickness had no influence on delamination test results [9]. Another study focused on lamina thickness among other things but was unable to find significant results after conducting both delamination and shear tests [10]. Another experiment evaluated CLT of 3 and 5 layers with bending and shear tests and found a slight decrease in bending strength and little to no effect on shear strength as the thickness of the panel increases [11].

The most common adhesive system in the CLT industry is a polyurethane adhesive known as PUR. This is a one-component adhesive, but it can be used in conjunction with a primer. In studies examining multiple adhesive types, PUR is almost always included as it represents what is most widely used in industry. Henkel PURBOND HB E452 is a specific PUR adhesive seen in literature [7]. Melamine-urea formaldehyde, or MUF/MF is another popular adhesive used. This resin is used in conjunction with a hardener to activate its adhesive properties. Cascomel MF resin from Hexion is a commonly used resin, used with a hardener component, in industry and the literature [12]. Cascomel MF resin also has the ability to cure via radio frequency and to be used in hot pressing if the press is capable. Phenol-resorcinol (PR), or phenol-resorcinol formaldehyde (PRF) is another resin used in conjunction with a hardener for use in softwoods. While this is not as common in industry as the first two adhesives mentioned, it is seen in studies, often compared to the previously mentioned adhesive systems. Cascophen LT-75 and Cascoset FM hardener, both from Hexion, can be seen in the literature representing the PRF adhesives [7]. All adhesives must follow PRG-320 section 6.3 that states the standardized performance requirements of adhesives used in CLT production [5].

Ideally, the required minimum bonding pressure for laminating CLT is very low. In this case, the lumber used is all the uniform thickness, square, and free of knots. This is not the case in the real world. After planing lumber to the desired thickness, there will still be slight variation in the thickness of the boards, some with more wane, bow, crook, and nots than others. Because of this, the objective press pressure applied during lamination is to flatten all the boards with their faces against those in other layers. The face contact due to the pressure as the applied glue cures results in a satisfactory bond between lamina.

Delamination tests have shown in some cases that an increase in bonding pressure can increase resistance to delamination in some articles [10] [15] while other scientists were unable to make a correlation with bonding pressure [13] [9]. For the influence of bonding pressure on shear strength, studies show bonding pressures' affect to be minimal. Most authors report little correlation between the two [13] [10] [14], while some have observed an increase in shear strength with increased bonding pressure [15].

Objectives

The rationale for this study is to give manufacturers and fellow research more knowledge about the effects of bonding pressure and lamina thickness in CLT. Pressing systems can vary between hydraulic and vacuum bagging systems in terms of the bonding pressure, so the study utilizes a wide range of bonding pressures (50, 125, 200 psi) and lamina thicknesses (0.625, 1, 1.125, 1.25 inch). This paper aims to determine how bonding pressure and lamina thickness affect southern yellow pine CLT through evaluation of the glue line using internal-bond and delamination tests.

Materials and Methods

Lumber Selection and Preparation

CLT parent panels were constructed in this study using No. 2 visually graded southern yellow pine lumber. The study included four panel different panel constructions and thickness. Three larger thickness of parent panels used, 2x6 lumber, commercially purchased, and planed down to 1.25 inch, 1.125 inch, and 1 inch. For the fourth, thinner panel thickness, 1x6 lumber was purchased and planed to 0.625 inch thickness. Surface irregularities were removed from the bonding face of the lumber through this process, leaving a clean and flat surface to promote adhesive bonding. Planing also assured that all of the lumber was uniformly thick. Planing the lumber down to these thicknesses yields four different thicknesses with the goal of understanding the influence of lamina thickness on CLT through evaluation with standardized test methods. Lumber was planed for the parent panel no more than 24 hours before gluing, assembly and pressing took place. During the period of time where lumber was being planed, glued, and pressed, the lumber used had an equalized moisture content of 7.947%.

CLT Gluing and Layup

The adhesive used for CLT production was a two-component mixture supplied by Hexion Inc. CASOPHEN LT-75 is the liquid, phenol-resorcinol timber laminating resin and was used in conjunction with the dry, powdered hardener, CASOSET FM-260. The combination of these two at the correct ratio provides a proper adhesive for laminating untreated softwoods for both wet and dry-use applications, meeting both ASTM D-2559-84 and ANSI/AITC 190.1-83 (PS 56-73) [16]. The recommended mixing ratio was 18 lb of hardener per 100 lb of adhesive used, or a ratio of approximately 5.5:1 resin to hardener. When mixing, all weights were measured in grams. The recommends application rate in the glue line was a spread rate of 0.1 lb of mixed adhesive per square foot of glue line, with two glue lines holding the three layers together. Adhesive was applied to each face of each glue making 4 glue faces. For each of the four glue faces, 1.6 lb (725 g) of mixed adhesive was the target spread for each faces. The glue was applied to the faces by at least two people with 6 inch long paint rollers. After adhesive application, the mixing container was weighed to determine the amount of adhesive applied to the face. Glue usage was calculated after each face layer was glued and the usage per glue line was determined [16].

Pressing

A thermocouple was inserted during CLT panel construction to monitor the temperature of the coolest glue line during pressing. A glue line temperature chart supplied by the resin manufacturer was used to determine the time and/or glue line temperature required for successful panel pressing. The process for producing the parent panels for this study utilized a hydraulic hot press. Using the hot press, panels remained under the target pressure until the thermocouple read a temperature of 200 degrees Fahrenheit and were then removed. Using hot-pressing, most parent panels were cured and removed from the press in about two hours. The thinner panels took less time for the glue line to reach the target temperature than the thicker panels. Thinner panels insulate the glue line less than thicker ones so they take less time to press.

After the 12 parent panels were pressed, 3 pressures and 4 thickness, each panel was cut into four approximate 1x8 foot child panels. Two of the child panels from each parent panel were selected to yield specimens for shear, internal bond, and delamination tests. From each child panel, 2 shear specimens, 8 internal-bond specimens, and 8 delamination samples were rendered, resulting in 48 shear, 96 internal-bond, and 96 delamination specimens.

Shear Test

Flatwise shear specimens were cut, two each, from strips 2 and 4 of each CLT panel. PRG-320 section 8.5.3.1 states that the flatwise shear specimen width should be no less than 12 inches wide. The 11.79 inch width is 1.75% narrower than the recommended 12 inch. This variation, however, was considered negligible. The length of all the shear specimens were calculated and cut according to the panel thickness and were panel calculated as thickness times six and then 1 inch was added for overhang on the test span supports.

The testing machine used for flatwise shear was a Satek universal testing machine utilizing Bluehill 3 software and was configured to conform to sections 45-52 “SHEAR MODULUS” of ASTM D198. [17]. The shear modulus testing was performed using center point loading as prescribed by the standard.

The weight of each sample was recorded before testing, and each specimen was measured for span, width, and thickness and input into the testing machine software. An LVDT was placed at the midpoint of the span, allowing strain data to be calculated during testing. The load for the test specimen was applied so that the average time for the specimens to reach their maximum load was 6.8 minutes per specimen.

Internal Bond Test

Internal bond testing is a tension test perpendicular to the gluing surface to determine the strength of the bond between wood and glue for a composite being tested. The methodology and specifics for this test are specified in ASTM D1037-12 section 11 "Tension Perpendicular to Surface (IB)." Test specimens for IB were 2 x 2 inch squares cut from child panels of the CLT panels produced for this study. The thickness of each IB sample was the full thickness of the CLT panel from which it was cut. Four IB specimens were cut from each child panel yielding a total of 96 specimens for testing. [18] The testing machine used for this test was an Instron 2N tabletop machine configured to conform to the ASTM D1037. The machine utilized Bluehill 3 software to control the testing, collect the data and calculate the IB for each specimen.

Before testing, loading blocks were bonded on the top and bottom side of each specimen using a hot melt adhesive and is intended to provide a bond that exceeds the internal bond of the material. During testing, the specimens are loaded and fixed into the machine using the load blocks on either side of the specimen. During the test, the machine applies a load to the sample at the specified rate prescribed by the testing standard until failure occurs and the IB is calculated. Specimens that did not fail within the wooden specimen/glue line, but instead failed due to the adhesive bond of the loading block were noted, and those results were discarded from the test as per the standard.

Delamination Test

AITC Test T110-2007 describes a cyclic delamination test for measuring the effect of vacuum-pressure-soak/rapid drying in mass timber products. PRG 320 states that the evaluation of bond line openings through moisture cycles as per AITC Test T110-2007. The test required the specimens endure two soaking cycles, one in a vacuum and another under pressure, and finally a fast-drying oven cycle. Once the specimens dried enough to where they were within a certain percentage of the original dry weight, they were removed from the oven and delamination was measured on the glue lines and a total percent of delamination was determined for each specimen. Whether or not the specimen passed or failed the test determined whether or not it goes through a second cycle for further testing [19].

The apparatus for this test was a vessel capable of drawing a vacuum for the first part of the cycle and applying a pressure for the second part of the cycle. The test required a vacuum of at least 25 inches of mercury (12.3 psi) then a pressure of at least 75 psi. Additionally, a drying oven was required for the rapid drying portion of the procedure. The oven was able to maintain a temperature of approximately 160 degrees F, a relative humidity from 8% to 10%, and circulated air at approximately 500 ft/minute along the end grain of the specimens being dried [19].

During CLT production, glue was applied only on the face joints between members composing each panel. Accordingly, delamination specimens were cut from T110.4.1. The standard calls for the sample to have a length and width of 3 inches, with the thickness being that of the finished panel. Delamination specimens were cut from child panels with four delamination samples coming from each panel. This yielded a sample of 96 delamination specimens for testing using this method.

Before testing each specimen was weighed and recorded to the nearest gram. This weight was used to determine the end of the drying cycle. Next, the specimens were placed on a wire screen so that all end grain surfaces were exposed to the water once submerged in the pressure vessel. Once the specimens were lowered into the vessel, sufficient water (65-85 deg. F) was added to completely submerge the specimens. Once submerged, the specimens were subjected to a vacuum soak at 30 psi for 30 minutes, followed by a pressure cycle of 75 psi for 120 minutes.

The rapid drying portion of the cycle took place immediately after the specimens were removed from the pressure vessel and placed into the oven. The oven was preheated to 160 deg F while the soak cycle was taking place and maintained 160 deg F throughout the drying process. The specimens were placed in the oven with at least two-inch spacing with the face of the end grain of the top and bottom layers oriented parallel to the air flow through the oven. The specimen weights were periodically checked and were removed when the weight returned to within 12-15% of the original mass of the specimens before the soak cycle began.

Once a specimen has dried to 12-15% of its original dry mass, delamination was measured immediately and recorded. AITC Test T110 states the delamination must be measured along the bond line and reported as a percentage of the total length of the bond line. Delamination was measured along the bond line using a feeler gauge of 0.06 mm thickness. The delamination was measured only on the glue line where the lamina separated. Cracks and failure were often observed within the lamina themselves, often close to the glue line, but only the separations on the glue line between lamina were measured. After one delamination cycle, specimens that delaminated less than 5% passed the test. If the delamination measured exceeded 5% but did not exceed 10%, that specimen was subjected to a second soak/drying cycle. After the second cycle, if the specimen did not exceed 10%, the specimen has passed the test. Specimens that went through the second cycle but exceed 10% delamination failed the test.

Results and Discussion

Shear Results

An ANOVA procedure was run using MOR as the dependent variable with pressure and thickness as independents to understand their interaction (Figure 9). This gave a good R^2

(0.8170) and significant p-values for both pressure (0.0002) and thickness (<0.0001). The thickness box plot shows a strong inverse relationship between panel thickness and MOR, with the highest means being the 1.875 inch specimens. The pressure box plot from the ANOVA showed a direct relationship between pressure and MOR (Figure 10). Though not as significant as the thickness result, a clear increase in MOR can be seen as the bonding pressure increases. Perhaps this is due to the increased pressure bringing the lamina in more intimate contact with one another, resulting in a stronger bond.

Internal Bond Results

ANOVA results for the internal bond test yielded significant p-values for thickness (0.0023) and pressure (0.0171), but a low R^2 (0.211287) (Figure 11). The thickness boxplot reflects the poor R^2 value, with no real correlation between thickness and internal bond. The pressure box plot is similar, with no clear correlation between bonding pressure and internal bond (Figure 12). Though the p-values indicate statistical significance, the box plots show no correlation with internal bond performance, for both pressure and thickness.

Delamination Results

The ANOVA procedure for the delamination after the first cycle yielded significant for the pressure (0.0007) while thickness (0.2348) and R^2 (0.181567) were both insignificant (Figure 13). The box plot for pressure shows the highest percentage of delamination taking place in the 50 psi specimens and the lowest delamination percentages being in the 200 psi specimens (Figure 14). This higher bonding pressure brings the lamina to closer contact while the glue cures, allowing it to penetrate deeper into the surface of the wood, resulting in a better bond, more capable of resisting delamination. This affect can be seen on the boxplot of delamination vs pressure.

Conclusions

Shear test results showed a clear inverse relationship between MOR and lamina thickness. Perhaps this is due to the thinner lamina requiring less pressure to be brought into intimate contact with one another, as the thinner boards are easier to “flatten” and conform to the shapes of the other boards during pressing. Testing showed that an increase in bonding pressure resulted in higher MOR values, perhaps due to the higher pressures creating more intimate contact between the lamina as the adhesive cured.

Delamination results showed lamina thickness to have no effect on delamination while an increase in the bonding pressure showed a decrease in percentage of delamination. It is speculated that this is again due to the contact between lamina provided by the higher bonding pressures as the adhesive cures. Another effect of the thinner lamina is that they make the material more homogeneous, randomizing and minimizing the defects present in a panel.

Internal bond testing and analysis showed no clear relationship between the lamina thickness or bonding pressure.

Figures

MOR ANOVA

The ANOVA Procedure

Dependent Variable: mor

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	53776325.37	10755265.07	37.50	<.0001
Error	42	12046468.86	286820.69		
Corrected Total	47	65822794.23			

R-Square	Coeff Var	Root MSE	mor Mean
0.816986	11.08598	535.5564	4830.934

Source	DF	Anova SS	Mean Square	F Value	Pr > F
pressure	2	6045314.63	3022657.31	10.54	0.0002
thickness	3	47731010.74	15910336.91	55.47	<.0001

Figure 9 Shear MOR ANOVA results.

Analysis of variance results showing R^2 and p-values for pressure and thickness.

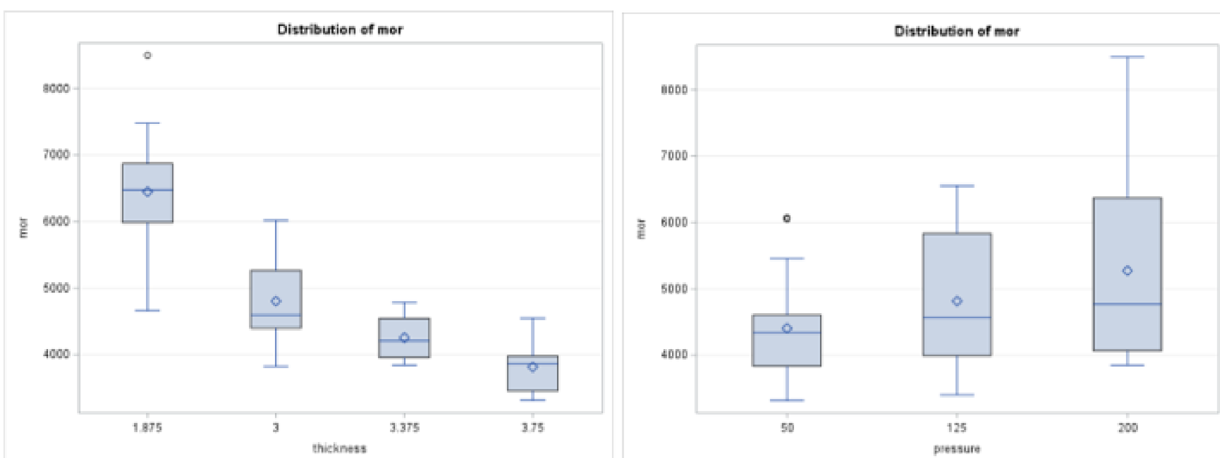

Figure 10 Shear MOR thickness and pressure box plots.

Box plots show means for thickness and pressure vs MOR.

Internal Bond ANOVA

The ANOVA Procedure

Dependent Variable: internalbond

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	185006.5579	37001.3116	4.82	0.0006
Error	90	690610.9268	7673.4547		
Corrected Total	95	875617.4847			

R-Square	Coeff Var	Root MSE	internalbond Mean
0.211287	27.02248	87.59826	324.1681

Source	DF	Anova SS	Mean Square	F Value	Pr > F
pressure	2	65391.8629	32695.9314	4.26	0.0171
thickness	3	119614.6950	39871.5650	5.20	0.0023

Figure 11 Internal bond ANOVA results.

Analysis of variance results showing R^2 and p-values for pressure and thickness.

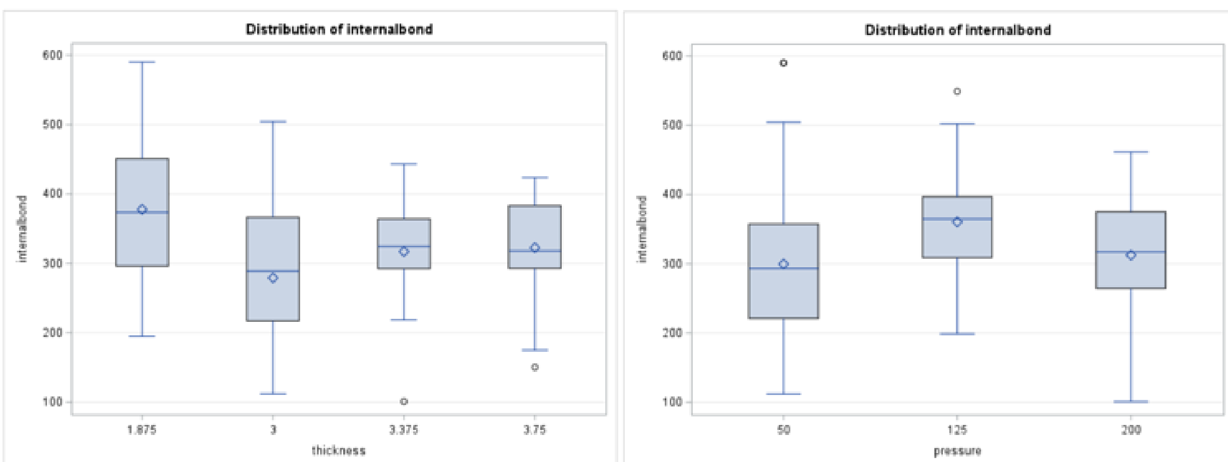

Figure 12 Internal bond thickness and pressure box plots.

Box plots show means for thickness and pressure vs IB.

Delam 1 ANOVA

The ANOVA Procedure

Dependent Variable: delam1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	2828.84107	565.76821	3.99	0.0026
Error	90	12751.32328	141.68137		
Corrected Total	95	15580.16435			

R-Square	Coeff Var	Root MSE	delam1 Mean
0.181567	131.6082	11.90300	9.044271

Source	DF	Anova SS	Mean Square	F Value	Pr > F
pressure	2	2214.306615	1107.153307	7.81	0.0007
thickness	3	614.534453	204.844818	1.45	0.2348

Figure 13 Delamination ANOVA results.

Analysis of variance results showing R^2 and p-values for pressure and thickness.

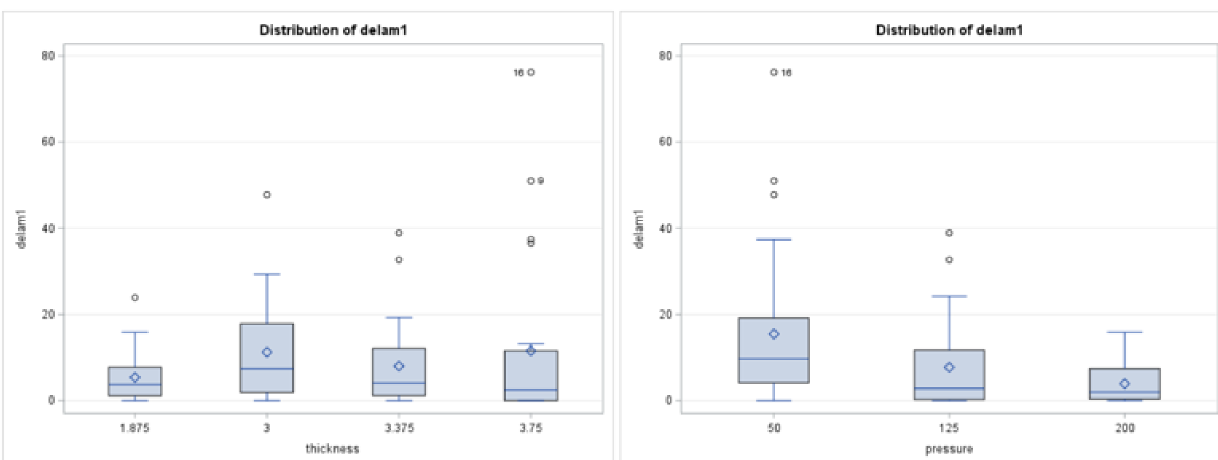

Figure 14 Delamination thickness and pressure box plots

Box plots show means for thickness and pressure vs delamination.

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