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Mechanical Performance of Yellow-Poplar Cross Laminated Timber

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ABSTRACT

Cross-laminated timber (CLT) is a structural wood composite material consisting of multi-layers of lumber orthogonal to each other creating massive wood panels. Development of CLT introduced a new concept of using wood in low to midrise buildings as an alternative for concrete and steel. Speed and ease of construction, seismic performance and carbon sequestration are advantages of CLT material. Softwood species have been traditionally used as wood structural materials while hardwood species have not. The purpose of this paper was to examine whether CLT made from fast growing hardwood species can provide sufficient mechanical performance need to be used in structural engineering applications. Yellow-poplar CLT was tested experimentally for stiffness and strength in five-point bending and four-point bending tests, respectively as well as resistance to shear by compression lading and resistance to delamination and the results were compared with *American National Standard Institute/APA-The Engineered Wood Association* (ANSI/APA) PRG 320-*Standard for Performance Rated Cross-Laminated Timber* and previous research. Bending stiffness, bending strength and resistance to delamination exceeded the required value in the standard, while wood failure in resistance to shear by compression loading was less than the required value. Shear strength of the yellow-poplar CLT was also greater than CLT produced from softwood species tested in previous research. Acceptable mechanical performance of yellow-poplar CLT confirmed in this research, could be a start point of using hardwood species in CLT structural design.

1. BACKGROUND

Cross-laminated timber (CLT) is a wood composite material consisting of at least three layers of lumber oriented orthogonally and glued together to form structural panels such as walls and floors and can be used in building and non-building structures. CLT is currently commercially manufacturing in Europe as well as Canada and Australia using spruce (*Picea spp.*), lodgepole pine (*Pinus contorta*) and Douglas fir (*Pseudotsuga menziesii*) (OpenEI 2010).

Among wood composites, strength-to-weight relationship of CLT seems to provide a solution for the long time problem of use of wood in mid to high rise buildings as an alternative to steel and concrete (Mohammad et al. 2012). CLT is generally compared to concrete construction due to the use of panels. Therefore, fast construction time, sustainable nature of wood, carbon sequestration, good seismic performance, appropriate insulation properties and lower embodied energy are among advantages of CLT in comparison to concrete construction (Robertson 2007).

In 2012, American National Standard Institute (ANSI) in collaboration with APA-The Engineered Wood Association released the first standard for performance-rated CLT, known as ANSI/APA PRG 320, *American National Standard Institute/APA-The Engineered Wood Association* (ANSI/APA 2012). In ANSI/APA PRG 320 different grades of CLT made of softwood species are tabulated and standard requirement for CLT panels from manufacturing level to quality assurance is provided. Testing of CLT adhesive properties is also specified in this standard. PRG 320 (ANSI/APA 2012) addresses ANSI/AITC A190.1-2007, *American National Standard Institute*/*American Institute of Timber Construction,* (ANSI/AITC 2007) for resistance to shear by compression loading test and resistance to delamination in bondlines of CLT layers.

According to the PRG 320 (ANSI/APA 2012), wood must have a minimum specific gravity of 0.35 and have moisture content of 12 ± 3% at the time of CLT manufacturing. Seven different grades of CLT are divided into two major groups labeled as E Grade (E1-E4) which contains machine stress rated (MSR) lumber and V Grade (V1-V3) which uses visually graded lumber. Allowable mechanical properties of these Grades of CLT including bending strength and stiffness as well as interlaminar shear capacity are also provided in PRG 320 (ANSI/APA 2012).

As recommended by PRG 320 (ANSI/APA 2012), the bending test to measure bending strength and stiffness of the CLT panels should be conducted flatwise (loads applied perpendicular to the face layer of

CLT) according to third point load testing method described in ASTM D 198 or ASTM D 4761 (ASTM 2013e). To obtain allowable design values and in order to be able to compare the bending strength values with values tabulated in PRG 320 (ANSI/APA 2012), data should be evaluated using procedure described in ASTM D 2915 (ASTM 2013e).

However following test requirements to obtain bending properties based on PRG 320 (ANSI/APA 2012) have some limitations including high span to depth ratio of 30:1. Achieving this span to depth ratio requires massive press or special manufacturing equipment as well as laboratory space for testing long beams. Another method such as connecting multiple CLT beams together to provide more length for testing requirement also was not found appropriate by Hindman and Bouldin (2014), who evaluated this connection method and reported failures in the lap joints connecting multiple CLT beams together (Hindman and Bouldin 2014). Therefore, short span five-point bending and four-point bending tests and simultaneous evaluation of the test data may be an appropriate solution to attain bending properties of wood composites (Bradtmueller et al. 1998, Harrison and Hindman, 2007).

Bradtmueller et al. (1998) showed that modulus of elasticity (MOE) and modulus of rapture (MOR) of wood composite can be simultaneously acquired based on load-deformation data from four-point and five-point bending tests. Moreover five-point bending test found to be an appropriate test method in determination of shear modulus and bending stiffness of the wood composites (Hunt et al. 1994, Bradtmueller et al. 1998). Harrison and Hindman (2007) compared the modulus of elasticity (E) and shear modulus (G) values using previously proposed simultaneous equations of five-point and four-point bending tests with values obtained from ASTM D 198 bending and torsion test. Consistent results were obtained for both calculated E and G compared to ASTM D 198, and the differences of 2.5 % and 17 % were found between values, respectively (Harrison and Hindman 2007). Despite this solution, still evaluation of mechanical performance of CLT beams were limited and more research is required. A few research investigated the mechanical properties of CLT based on requirements of PRG 320 (ANSI/APA 2012) and compared the bending properties with the values tabulated in the standard.

Hindman and Bouldin (2014) evaluated the mechanical properties of five layered southern pine (*Pinus spp.*) CLT panels. Mechanical properties included bending stiffness and strength, shear strength, resistance to shear by compression loading and resistance to delamination were tested. Results were compared to the Grade V3 provided in PRG 320 (ANSI/APA 2012). Bending strength and stiffness values met the requirement of the PRG 320 Grade V3 (ANSI/APA 2012). Wood failure in the resistance to shear by compression loading test was more than 80% which is established criterion in AITC A190.1, while PRG 320 does not tabulate required values of shear strength to be compared. Resistance to delamination was the only property was not greater than 5% required by AITC A 190.1 (AITC 2007a) (Hindman and Bouldin 2014).

Kramer et al. (2013) tested three layered hybrid poplar (*Pacific Albus*) hardwood with low specific gravity, CLT panels based on ANSI/APA PRG 320 test methods. Goal was to measure the characteristic bending strength and stiffness of the panels and to evaluate the usability of low specific gravity species in CLT production. Mechanical testing including nondestructive bending test, bending and shear tests both according to PRG 320, and block shear test according to ASTM D 905 (ASTM 2012b) were conducted. Obtained modulus of rapture (MOR) were greater than the tabulated values for Grade E3 CLT in PRG 320 (ANSI/APA 2012) while stiffness or modulus of elasticity (MOE) values were lower than the PRG 320 requirements. Result of hybrid poplar CLT shear test were considered appropriate since the experimental results were in good agreement with PRG 320 Grade E3 CLT values (ANSI/APA 2012). In order to have more efficient CLT panels, the mixed use of hybrid poplar and other high specific gravity species was recommended (Kramer et al. 2013).

Kim et al. (2013) investigated the shear performance of the polyurethane (PUR) adhesive in red pine (*Pinus densiflora*) CLT based on the Korean glulam standard. Resistance to shear by compression loading test was conducted which was similar to AITC T107 (AITC 2007b), however the requirement values differed. Shear strength of 508 psi and 90.3% wood failure was reported based on testing conducted. Rolling shear failure in wood was observed in 40% of the specimens and considered as common failure mode in CLT. No adhesive failure was reported, indicating good performance of polyurethane adhesive (Kim et al. 2013)

With use of CLT among designers and engineers and finding position in construction industry as a structural material, there is a need to research alternative species such as fast growing hardwoods for use in manufacturing CLT panels. Yellow-poplar (*Liriodendron tulipifera*) is a fast growing species grows in Eastern part of the United States from southern New England to north-central Florida (Elbert 1979). Because of the species versatility, yellow-poplar has good commercial value and being used as an alternative for softwood species in furniture and framing industry. Similar to other hardwoods, yellow-poplar traditionally was not considered as a structural material for lumber. Due to the specific gravity, strength and stiffness values of yellow-poplar in the *National Design Specification for Wood Construction*

(NDS) (AWC 2012), yellow-poplar should be an appropriate species to use in CLT panel production and further structural design purposes.

Currently, there is a need to evaluate the mechanical properties of CLT panels made of hardwood species to completely understand the structural performance of these panels and therefore be able to rely on hardwood CLT as a construction material. Comparison of experimental test results to the characteristic values listed in PRG 320 (ANSI/APA 2012) can be an appropriate method to ensure the structural performance of CLT panels. The purpose of this paper is to evaluate mechanical performance of yellow-poplar CLT as an alternative for standard CLT made of softwood species. The mechanical properties such as bending strength and stiffness as well as bondline shear strength and face delamination of three layered yellow-poplar CLT were investigated to determine the applicability of the hardwood CLT for structural engineering purposes. Results were compared to the CLT Grades V1 and V2 in the PRG 320 (ANSI/APA 2012) because specific gravity similarities of yellow-poplar to Douglas fir (specific gravity of 0.5) (Grade V1) and spruce-pine fir (specific gravity of 0.42) (Grade V2), respectively. Specified mechanical properties values of Grades V1 and V2 CLT are shown in Table 1 (ANSI/APA 2012).

Table 1. PRG 320 Specified Mechanical Properties Values for Three Layered CLT of Grades V1 and V2

CLT Grade	Bending Strength, F_bS (lb-ft/ft)	Bending Stiffness, EI (10^6 lb-in^2/ft)	Interlaminar shear capacity, GA (10^6 lb/ft)
V1[1]	2090	108	0.53
V2[2]	2030	95	0.46

[1] Grade V1 uses No 2 and No 3 Douglas fir-larch lumber with specific gravity of 0.5 in parallel and perpendicular layers, respectively.

[2]. Grade V2 uses No 2 and No 3 spruce-pine-fir lumber with specific gravity of 0.42 in parallel and perpendicular layers, respectively.

2. MATERIALS AND METHOD

Three layer yellow-poplar CLT panels were manufactured at the Research and Design Center for Advanced Manufacturing & Energy Efficiency (R&D CAMEE), a division of Southern Virginia Higher Education Center (SVHEC) in South Boston, Virginia. All CLT panels were constructed using Number 2 common yellow-poplar 6/4 lumber planed to 1.375 in thickness. Two sets of 12 specimen with high and low qualities characterization were constructed according to sample size recommended in PRG 320 (ANSI/APA 2012), to compare the effect of quality of lumber on CLT performance. In high quality specimens, defect free lumber were used while low quality CLT lumber may had defect such as sound knots.

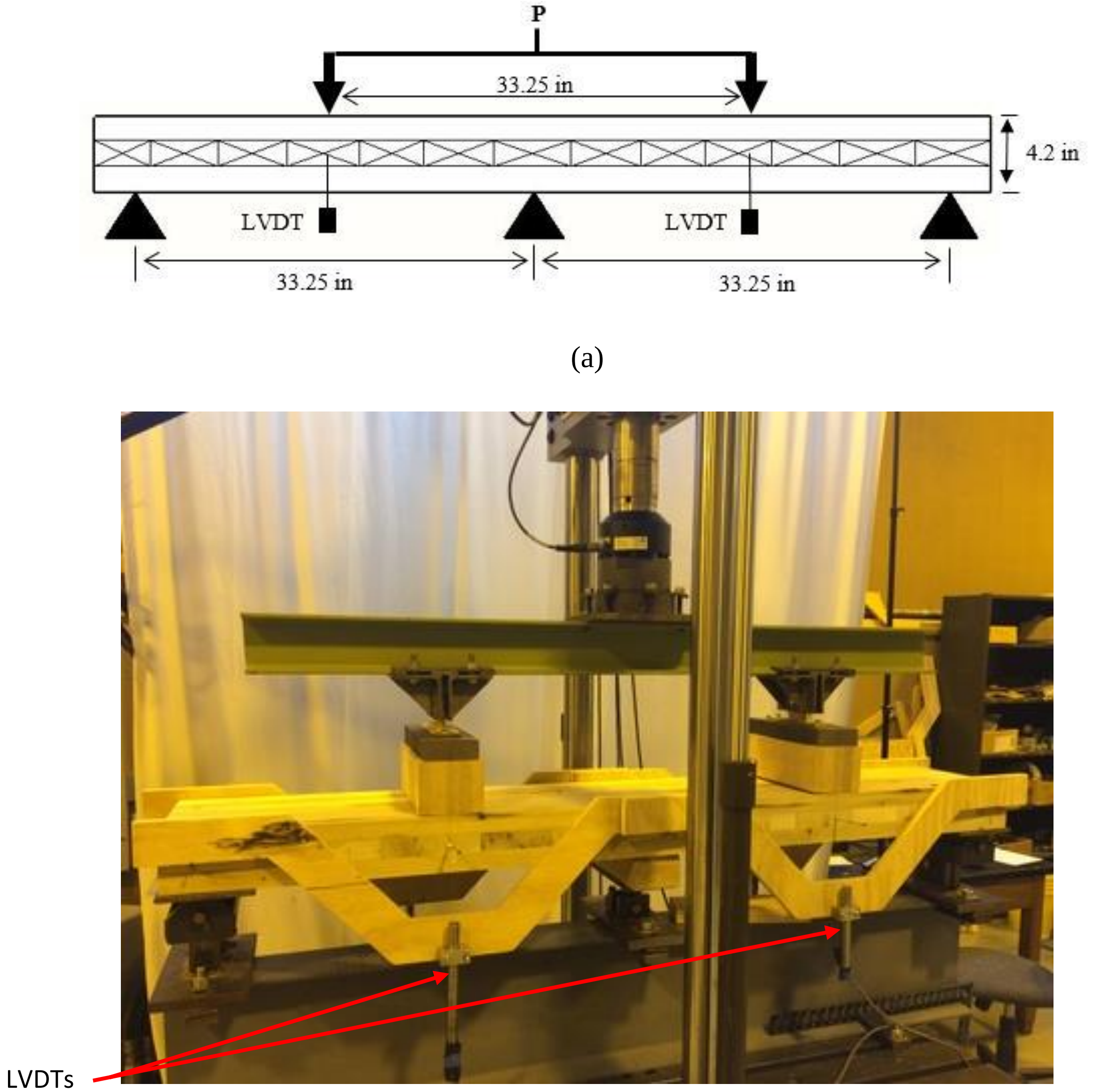
Panel layers were edge glued using phenol formaldehyde adhesive and a customized clamping fixture. A computer numerically controlled (CNC) machine with a flycutter bit was used to surface the layers to final thickness of 1.4 in. Cold press was used to assemble three-layer CLT panel using phenol formaldehyde adhesive. The final CLT panel thickness was 4.2 in and because of the limitation in the size of the press, the final dimension of each CLT panel was 11.8 in wide and 72 in long. The produced CLT panels were shipped to Wood Engineering Lab at Virginia Tech and stored in the lab for approximately 4 weeks before testing.

Bending tests including five-point and four-point bending were conducted on 72 in long specimens. After the bending tests, smaller samples were extracted from original CLT beams for moisture content, specific gravity, resistance to shear by compression loading and resistance to delamination tests. All testing were conducted according to ASTM (ASTM 2013) and AITC (AITC 2007) standard test methods except five point bending test which was followed based on recommendation in the previous research (Bradtmueller et al. 1998)

2.1. BENDING TESTS

Details of bending tests to evaluate the bending stiffness and strength of yellow-poplar CLT as well as interlaminar shear capacity of the panels are described in this section. CLT specimens were tested in a five-point bending test in other to use load-deformation data in evaluation of bending stiffness (*EI*) and interlaminar shear capacity (*GA*) of the specimens. The test was conducted based on recommendation proposed by Bradtmueller at al. (1998). Schematic diagram and photograph of the experimental set up are shown in Figure 1a and 1b. The clear span between middle and end supports was 33.25 in. Two point loads were applied to the middle of each span (16.62 in from the end) to the flatwise (perpendicular to the face layer) beam. An MTS universal testing machine with integrated load cell of 50,000 lbs. capacity was used attached with a data acquisition system for data collection of bending test. Testing speed was constant with the rate of 0.1 in/min and the test were stopped once loading reached the limit of 2000 lbs. This load was determined to be far less than yield limit of the CLT beams and was chosen for beam to remain elastic without having permanent deformation.

Four LVDTs (range of 2 in, sensitivity of ± 0.25%) connected to four wood yokes supported with screws attached to the midspans of the two spans test (Figure 1), both in front and back of the specimen, measured the deflection at the neutral axis (Bradtmueller et al. 1998). Load and displacement data were continuously monitored during the test. The inverse slope (Y_{FP}) obtained from relationship between load and average deflection recorded by four LVDTs was used for bending stiffness (EI) and interlaminar shear capacity (GA) calculations (Equation 1 and 2).

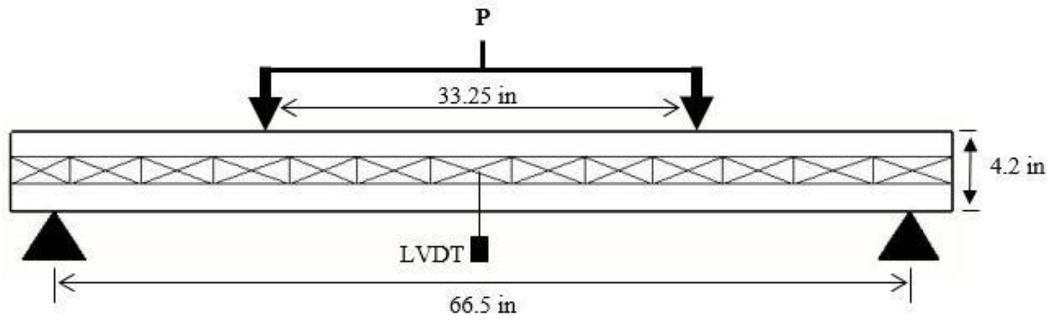


(a)

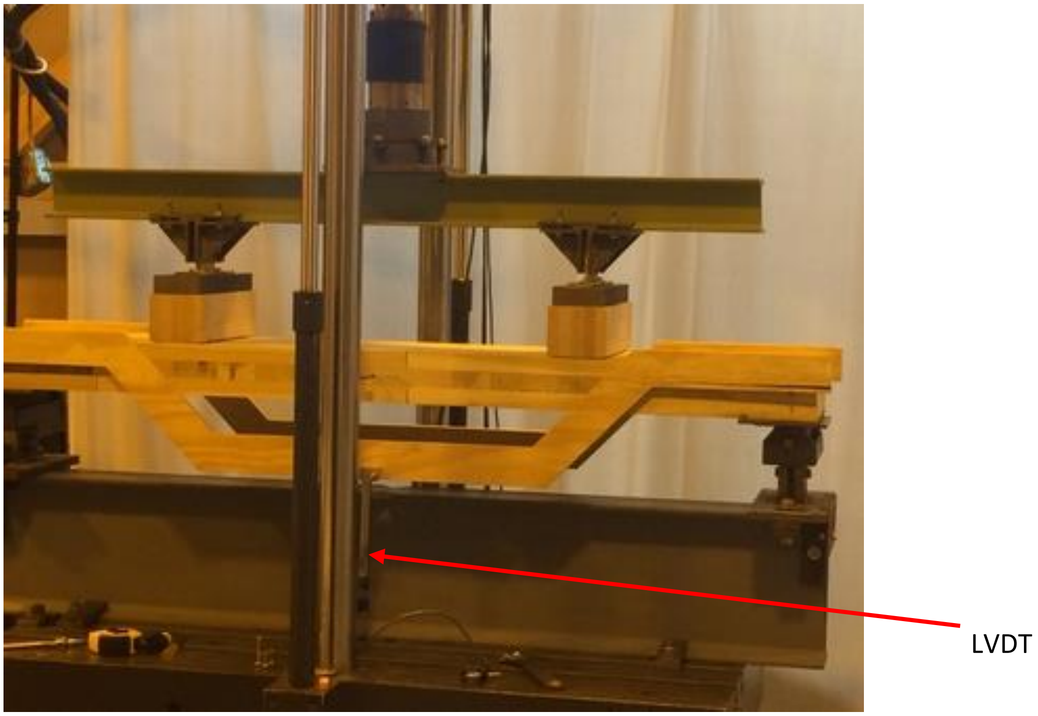
(b)

Figure 1. Five point bending test (a) Schematic diagram and (b) Experimental setup

In the four-point bending test, the middle support was removed and the specimens were tested in bending for ultimate bending strength (*F_bS*). The testing procedure was according to ASTM D 198 (ASTM 2013e) and as recommended by PRG 320 (ANSI/APA 2012). The clear span was 66.5 in between supports with a span-to-depth ratio of 16.1. At the third point (16.62 in from each support) two point loads were applied similar to previous bending test, to the flatwise (perpendicular of the face layer) beam. An MTS universal testing machine with integrated load cell of 50,000 lbs. capacity was used attached with a data acquisition system for data collection of bending test. Testing speed was constant with the rate of 0.1 in/min and the specimens were loaded to the failure. Figure 2 is a schematic diagram along with experimental setup of the four-point bending test.



(a)



(b)

Figure 2. Four-point bending test (a) Schematic diagram and (b) Experimental setup

Two LVDTs (range of 2 in, sensitivity of ± 0.25%) attached to two wood yokes supported with screws mounted to the midspans, both in front and back of the specimen, to measure deflection at the neutral axis. Load and displacement data were continuously monitored during the test. The ultimate load was used for bending strength (F_bS) calculations and the inverse slope (Y_{QP}) obtained from relationship between load and average deflection recorded by two LVDTs were used to evaluate bending stiffness (EI) and interlaminar shear capacity (GA) using Equations (1) and (2).

$$EI = \frac{249L^3}{\left\{4096\left[\frac{73}{128}Y_{QP} - Y_{FP}\right]\right\}} \quad (1) \qquad GA = \frac{747L}{\left\{5632K\left[Y_{FP} - \frac{7}{176}Y_{QP}\right]\right\}} \quad (2)$$

where G is the shear modulus, E is the modulus of elasticity, I is the moment of inertia, K is the shape factor (5/6 for rectangular section), A is the cross sectional area, L is the length of span in five-point test, Y_{FP} is the inverse slope of load-deformation in five-point bending test, and Y_{QP} is the inverse slope of load-deformation in four-point bending test.

After testing, moisture content and specific gravity specimens were chosen from one end of the bending specimen clear from cracks or damage. Moisture-content testing was conducted based on the oven-dry method specified in ASTM D 4442 (ASTM 2013b), and specific gravity test was conducted according to ASTM D 2395 (ASTM 2013d) which is based on volume by immersion method.

2.2. RESISTANCE TO SHEAR BY COMPRESSION LOADING

Shear specimens was extracted from previously tested bending specimens for the resistance to shear by compression loading test. In this test, conducted according to AITC T107 (AITC 2007b), a shear force must be applied to the bondline of CLT layers in the direction parallel to the grain of the specimen. Since AITC T107 was written for glued laminated timber without cross lamination, it still can be used for CLT with layers oriented perpendicular to each other. All resistance to shear by compression loading specimens were placed in the testing machine having parallel-to-grain layer upright in the fixture while the shear loading applied to the perpendicular-to-grain layer.

Four samples were cut from each of the two bondlines of the 24 CLT specimens having a total of 96 resistance to shear by compression loading test specimens. Testing was conducted according to ASTM D

143 (ASTM 2013c) and the average shear area of the specimens measured to be 2.00 by 1.40 in. The loading speed was 0.024 in/min and specimens were loaded constantly up to total failure, then the maximum load was recorded.

2.3. RESISTANCE TO DELAMINATION

Resistance to delamination test was conducted according to AITC T110 (AITC 2007a). Similar to AITC T107 (AITC 2007b), AITC T110 is based on having all layers in parallel to grain direction and does not account for the perpendicular layers in CLT panels. Because of this issue, length measurement of each bondline were taken on all four faces of delamination specimen block rather than just two end grain faces as specified in AITC T110 (AITC 2007a). One sample of resistance to delamination test were cut from all 24 previously tested specimens in bending having full depth of CLT panels with dimensions 3 x 3 x 4.2 in. The specimens were weighted, submerged in water and then placed in the autoclave. Then a vacuum of 25 inches of mercury were drowned the specimens for 30 min followed by a pressure cycle of 75 psi for 2 hours. In the next step, specimens were placed in a drying oven with a temperature of 160 ^{o}F for at least 24 hours, then constantly weighted to be in the range within 7-15% of the original weight to be ready for final bondline measurements to take place.

Because of the Poisson's effect and radial and tangential swelling of lamina during vacuum and procedure in the autoclave, the length of bondlines increased and the bondlines lost the original straight shape and became a curve. After the specimens reached the desired weight percentage of difference, bondlines in each four faces of the delamination specimen block were inspected using a 0.03 in metal to determine separation in the face bondlines. The delamination length were measured using a flexible metal ruler. Delamination percentage was calculated based on the ratio of delamination length to total bondline length.

3. RESULTS AND DISCUSSION

3.1.BENDING TESTS

As described earlier, in the PRG 320 (ANSI/APA 2012) span to depth ration of 30:1 was recommended for evaluation of bending properties of CLT panels. However since this span to depth ratio is big and there was a limitation about length of CLT in press fixture to produce longer CLT, as well as having laboratory space limitation, simultaneous equations (Equations 1 and 2) proposed by Bradtmueller et al. (1998) and bending test procedure recommended by ASTM D 198 (ASTM 2013e) were followed for bending test (Bradtmueller et al. 1998).

The bending strength, bending stiffness, shear stiffness, moisture content, and specific gravity of the yellow-poplar CLT material are shown in Table 2. Both bending strength and stiffness of the high quality and low quality yellow-poplar CLT satisfied the requirements for Grade V1. Bending strength percent of differences between high and low qualities values and Grades V1 was 163 and 114%, respectively.

Table 2. CLT Testing Results and Comparison to Grades V1 in PRG 320 (ANSI/APA 2012)

Property[1]	High Quality (HQ)	Low Quality (LQ)	HQ % Difference with Grade V1[2]	LQ % Difference with Grade V1[3]
Bending Strength, F_bS (lb-ft/ft)	5490 (21%)[4]	4470 (23%)	163%	114%
Bending Stiffness, EI (10^6 lb-in^2/ft)	153 (13%)	137 (12%)	42%	27%
Interlaminar Shear Capacity, GA (10^6 lb/ft)	1.74 (16%)	1.86 (18%)	221%	239%
Moisture Content	10.30% (3%)	9.94% (14%)	N/A	N/A
Specific Gravity	0.47 (14%)	0.49 (11%)	6%	2%

[1] Bending strength and stiffness values for grades V1 and V2 are based on PRG 320 (ANSI/APA 2012), while specific gravity of grades V1 and V2 is according to values tabulated for No. 2 lumbers of Douglas-fir and spruce-pine-fir in national design specification for wood construction (NDS) respectively (AWC 2012).

[2] % Difference = [(HQ-V1) / V1] x100

[3] % Difference = [(LQ-V1) / V1] x100

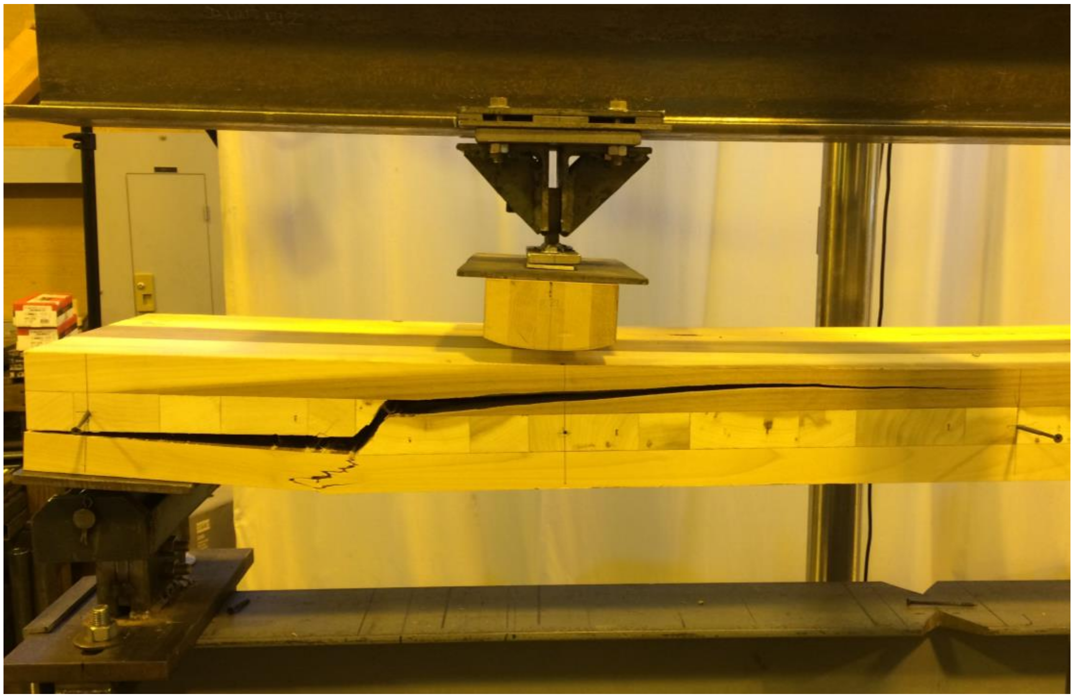
[4] Coefficient of variation (COV)

Bending stiffness percent of differences between high and low qualities yellow-poplar CLT with Grade V1 were 42 and 27%, respectively. This percentage of differences were the lowest among compared quantity and was expected because of low coefficient of variation obtained in the experiment indicating low variability in the samples. Obtained stiffness and strength results compared to allowable values listed in PRG 320 (ANSI/APA 2012) for Grade V1, are considered as good performance of yellow-poplar CLT in bending. Interlaminar shear capacity (*GA*) was also highly above the specified value for Grades V1 in PRG 320 (ANSI/APA 2012), which indicated 221 and 239% greater shear capacity. Therefore all bending properties including bending strength and stiffness as well as interlaminar shear capacity determined using four-point and five-point bending tests, well confirmed the appropriate performance of yellow-poplar CLT in bending in comparison to allowable values in the standard. The greater bending strength and stiffness values obtained for yellow-poplar CLT compared to Grade V1, could be a confirmation on enhanced mechanical performance of wood material when used as a cross laminated composite. Also span to depth ratio was half of the value required by PRG 320 (ANSI/APA 2012) for bending test, this may be another reason of having greater bending properties for yellow poplar CLT compared to Grade V1, however the effect of span-to-depth ratio could be small in comparison of the obtained high percentage of difference.

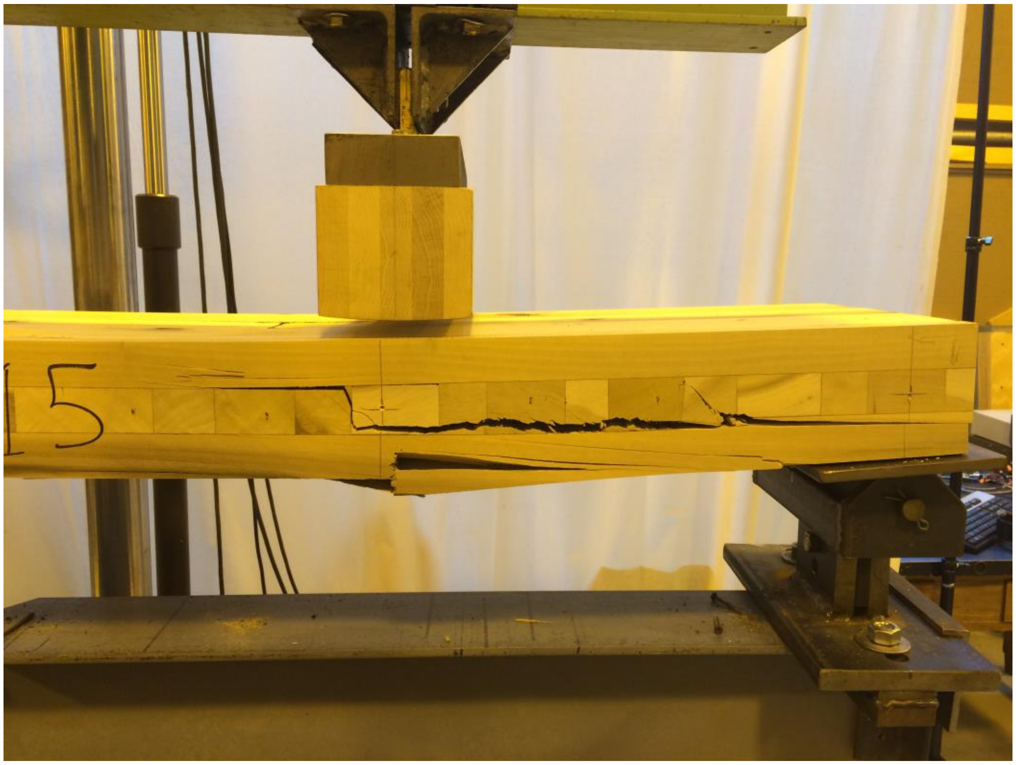
Average moisture content values of the specimens (10%) were greater than 8% as required by PRG 320 (ANSI/APA 2012) at the time of mechanical testing. The difference in average specific gravity of the high quality yellow-poplar was 6% and 2% for low quality compared to specific gravity of Grade V1 Douglas-fir-larch as tabulated in *National Design Specification for Wood Construction* (AWC 2012), which shows similarity between yellow-poplar and Douglas-fir-larch wood species.

Examples of observed failure modes in high quality and low quality yellow-poplar CLT in four-point bending test are shown in Figure 3 (a) and (b) respectively. In high quality CLT, 80% of specimens failed in tension face below one of the loading points. Bending failure was observed in the lowest parallel layer of the CLT and in the upper layers shear failure occurred that expanded horizontally toward support and middle of the beam (Figure 3a). Other specimens (20%) of high quality CLT specimens failed in the middle of the beam between two point loads having tension splitting failure. Bondline failure were also observed in specimens of high quality CLT bending test.

Low quality CLT specimens were also had similar failure patterns that were observed in high quality specimens. Shear failure was observed underneath one of the loading points in 70% of the specimens and extended to the support and middle of the beam while tension splitting failure in the bottom layer of the specimen also occurred (Figure 3b). Again these failure extension can be expected since the region between support and loading point possess the greatest shear load with lower bending moment in the beam. Other specimens (30%) of low quality CLT specimens failed in the middle of the beam between two point loads having shear failure in the middle layer along with bending failure in the lowest layer. Failure of the bondlines between layers in the location of the shear failures were also observed in specimens of low quality CLT bending test. In both high quality and low quality specimens, catastrophic fracture with sudden release of energy were occurred and no gradual crack or failure propagation were observed.



(a)



(b)

Figure 3. Four-point bending test results: (a) Failure of high quality CLT specimens, and (b) failure in low quality CLT specimens

3.2. RESISTANCE TO SHEAR BY COMPRESSION LOADING

Average yellow-poplar CLT bondline shear strength values are given in Table 3 and compared to values obtained in previous research for CLT made from southern pine and hybrid poplar. It should be noted that the same values of shear strength with same coefficient of variation were obtained for both high quality and low quality yellow-poplar CLT. Wood failure in the resistance to shear by compression loading test is also given in Table 4 for both high quality and low quality yellow-poplar CLT and compared to allowable values in the AITC A 190.1 standard.

Table 3. Comparison of Yellow-Poplar CLT Bondline Shear Strength to CLT Made from Different Species

CLT Species	Shear Strength	% Difference with Yellow-Poplar
Yellow-poplar[1]	785 psi (20%)	—
Southern pine[2]	635 psi (8.3%)	19%
Hybrid poplar[3]	444 psi (8.2%)	43%

[1] Same values of shear strength were obtained for both high and low quality yellow-poplar CLT.

[2] Hindman and Bouldin, 2014.

[3] Kramer et al. 2013.

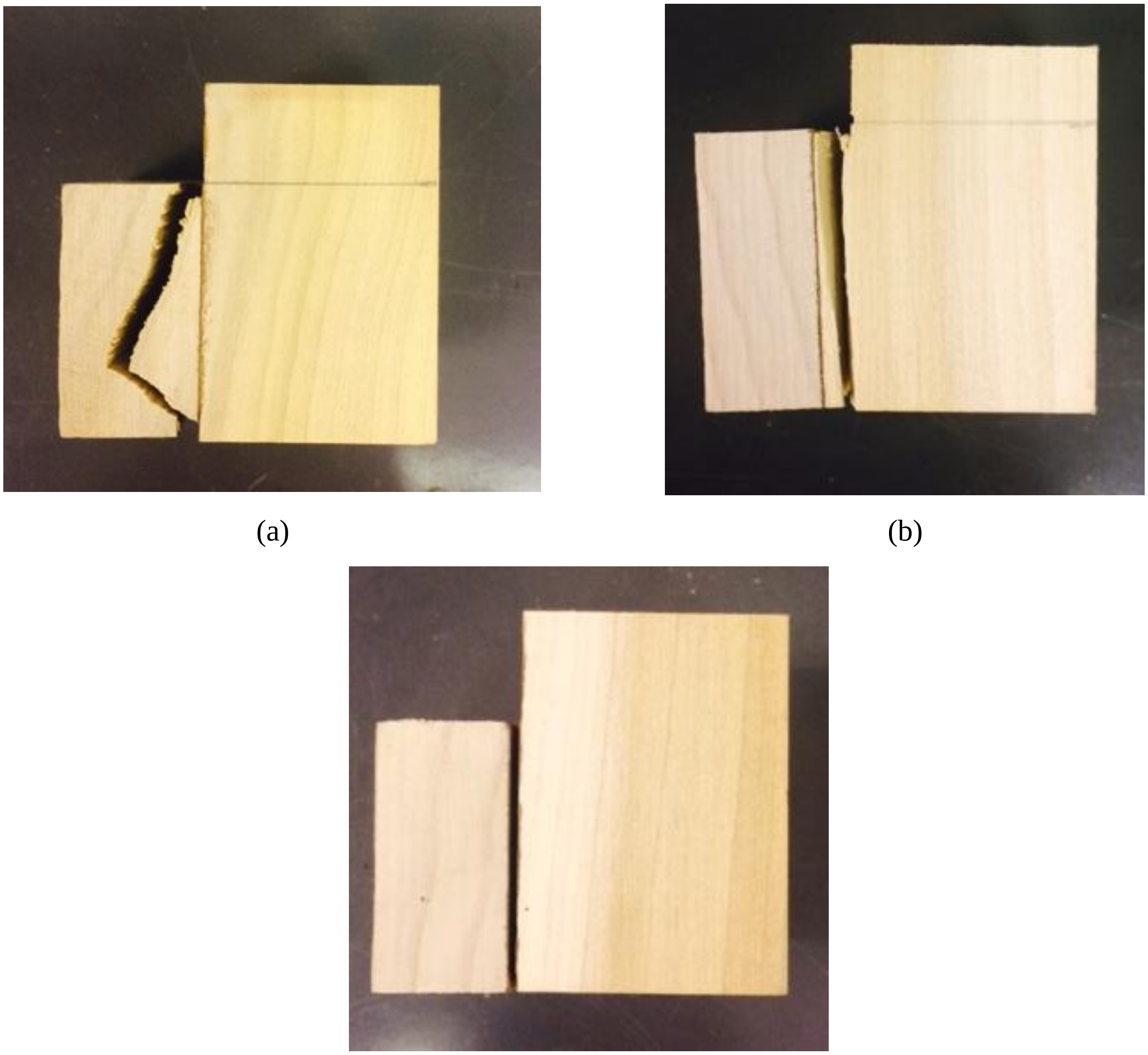
Yellow-poplar CLT has the greatest shear strength with the highest coefficient of variation compared to CLT made of southern pine and hybrid poplar species. Yellow-poplar had 19% and 43% greater shear strength than southern pine and hybrid poplar CLT, respectively. This amount of shear strength is considered suitable since adhesive and wood are both contributing to the measured shear strength in the bondline of the CLT layers. However, wood strength seems to have more contribution in the obtained shear strength since several adhesive failure was observed in the 4-point bending test between CLT layers. As shown in Table 4, wood failure in the resistance to shear by compression loading test was 72% and 61% in the high quality and low quality CLT, respectively. This amount of wood failure is less than 80% minimum wood failure required by AITC A 190.1 (AITC 2007b). However the amount of wood failure in high quality specimens was far better than low quality specimens; the difference was 15%. High strength of wood, confirmed by the results of the bending and shear strength tests, can be the reason of more adhesive failure observed, i.e. before shear load could break the wood, adhesive failure occurred. Although adhesive failure is not desired to occur in testing of wood composites, but the high amount of obtained shear strength compared to CLT made from other wood species (Table 3), could justify adhesive failure in yellow-poplar CLT meaning that adhesive failure only occurred after specimens could tolerate sufficient shear load in the testing. Type of the adhesive is also another reason that may affect the behavior of the bondline in the resistance to shear by compression loading test. Considering above discussion and shear strength values, performance of phenol formaldehyde adhesive in yellow-poplar CLT testing, can be considered appropriate.

Table 4. Comparison of Wood Failure and Face Delamination to AITC A 190.1 Values

Property[1]	High Quality	Low Quality	AITC A 190.1 Value
Wood Failure	72% (32%)	61% (49%)	> 80%
Face Delamination	3.8% (146%)	3.9 (141%)	<5%

[1] All specimens were extracted from previously tested bending specimens.

The three different failure modes that were observed in the resistance to shear by compression loading test are shown in Figure 4. These failure modes are including rolling shear (Figure 4a), shear parallel to grain (Figure 4b) and adhesive failure (Figure 4c). Combinations of these failure modes were observed in the majority of the specimens which combination of adhesive and shear failure were dominated in the obtained failure modes of the specimens. In the AITC T107 (AITC 2007b), which is written for evaluation of mechanical performance of structural glued laminated timber, rolling shear failure is not mentioned since rolling shear failure is not likely to occur in the glued laminated timber where all composite layers are oriented in parallel direction (AITC 2004). Rolling shear and shear parallel-to-grain failures are both categorized as wood failures which are considered appropriate failure modes in resistance to shear by compression loading test.



(a) (b)

(c)

Figure 4. Failure modes in resistance to shear by compression loading test (a) rolling shear, (b) shear parallel-to-grain, (c) adhesive failure

3.3. RESISTANCE TO DELAMINATION

The results of resistance to delamination test for yellow-poplar CLT specimens is shown in Table 4. According to AITC T110 (AITC 2007a) allowable bondline delamination should be less than 5%, therefore both high quality and low quality CLT specimens with 3.8% and 3.9% bondline delamination respectively, met the criteria. It should be noted that 12 specimens had zero delamination, so obtained high coefficient of variations (146% and 141%) are the results of this high variability in the resistance to delamination test. Hindman and Bouldin (2014), noted that the uncontrolled moisture content at the time of CLT manufacturing could be the main reason of the bondline delamination, therefore less than 5% delamination that is required by AITC T110 (AITC 2007a) and obtained in yellow-poplar CLT, can be the reason of controlled moisture content of the samples in manufacturing process.

3.4. NOTE ON DIFFERENCE BETWEEN BENDING PROPERTIES TESTING METHOD USED WITH PRG-320 REQUIREMENTS

Earlier described limitations, including long CLT beams manufacturing equipment and laboratory space to test long span beams, were the reasons that span to depth ratio of 30:1 as required by PRG 320 (ANSI/APA 320) were not followed in the bending test. However previous research suggested alternative methods such as combined five-point bending and four-point bending tests for mechanical performance evaluation of the wood composites (Bradtmueller et al. 1998, Harrison and Hindman, 2007). The obtained percentage of differences in bending strength (F_bS) and interlaminar shear capacity (GA) were sufficiently greater than required values for Grade V1 in PRG 320 (ANSI/APA 320) in order to consider the effect of different span to depth ratios and analysis methods used in this research negligible in comparison with PRG 320 (ANSI/APA 2012). However, bending stiffness values (EI) were relatively closer to the values tabulated in the standard, which caused concern about different span to depth ratios may affect the results, although still EI values were 42% and 27% greater than required values. It is worthwhile to mention that mechanical properties obtained from five-point and four-point bending has already validated with requirements in applicable standards for laminated veneer lumber (LVL) (Bradtmueller et al. 1998, Harrison and Hindman, 2007). However, based on bending stiffness (EI) results, authors recommend a long span testing of yellow-poplar CLT beam (30.1) to be conducted and results to be compared with the values obtained in this research in order to validate five-point and four-point bending results for CLT material and obtain certainty about similarity of the results.

4. CONCLUSIONS

Cross-laminated timber (CLT) made from yellow-poplar (*Liriodendron tulipifera*) was mechanically evaluated to investigate the use of CLT made of hardwood species in structural engineering applications. Because of the size of the CLT manufacturing press and laboratory space limitations alternative bending tests, four-point and five-point bending tests were conducted and data were analyzed using proposed simultaneous equations to obtain bending stiffness, strength and shear capacity of the specimens. Other mechanical tests such as resistance to shear by compression loading and resistance to delamination test were also conducted. The bending stiffness, bending strength and interlaminar shear capacity were significantly greater than specified values for Grades V1 and V2 in PRG 320 (ANSI/APA 2012). Yellow poplar CLT compared well with CLT Grades V1 and V2. Although results of bending strength and interlaminar shear capacity were considered appropriate based on obtained percentage of difference, but still long span beam testing for CLT material according to PRG 320 (ANSI/APA 2012) is recommended to ensure the validity of the results. Face delamination was also less than 5% required by AITC T110 (AITC 2007a). Bondline shear strength in resistance to shear by compression loading test was greater than CLT produced from other species while wood failure was less than 80% required by AITC T110 (AITC 2007b). Strong shear capacity of yellow poplar in the shear test can be the reason of relatively high percentage of adhesive failure obtained in this test. Therefore, yellow-poplar CLT is met most of the necessary requirements needed to be used in structural design and engineering applications.

5. ACKNOWLEDGMENTS

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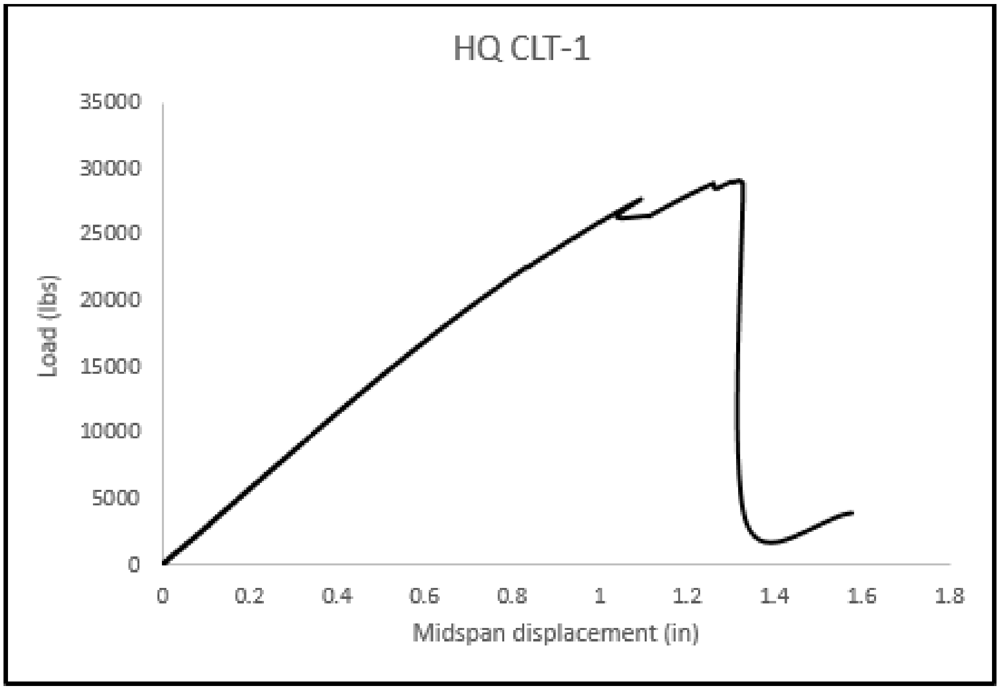
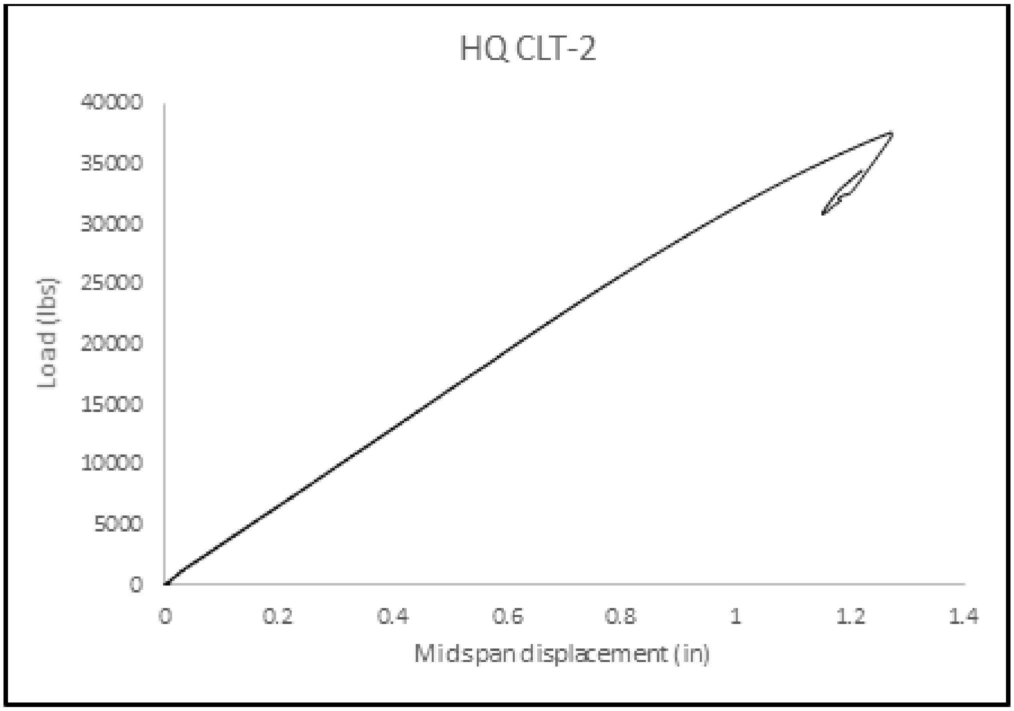
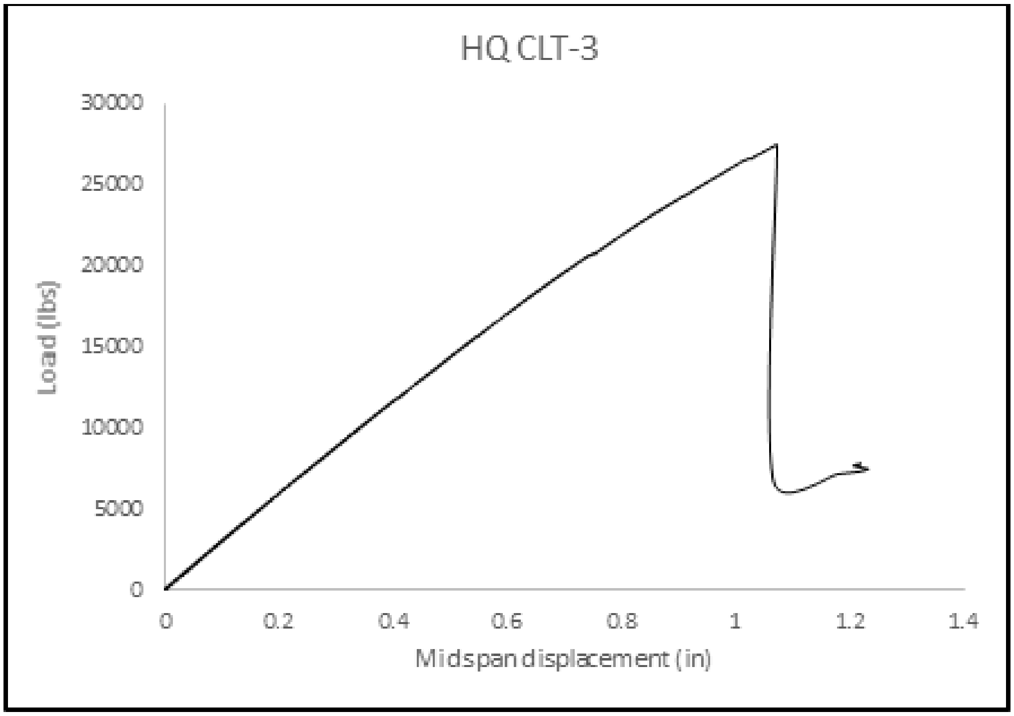
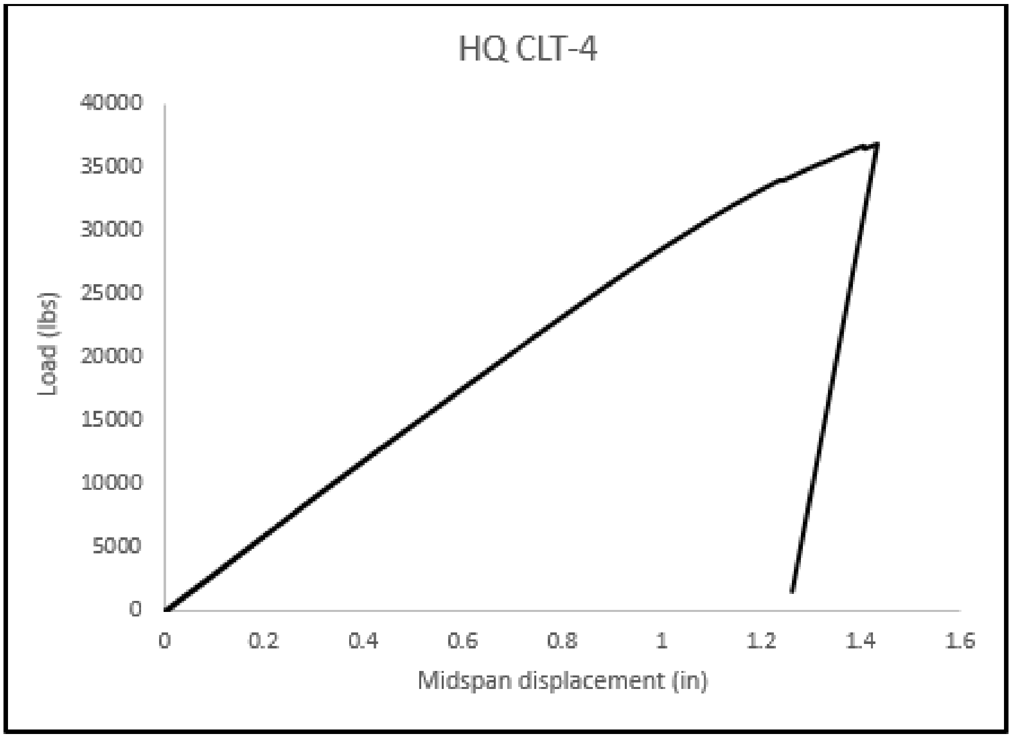
APPENDIX

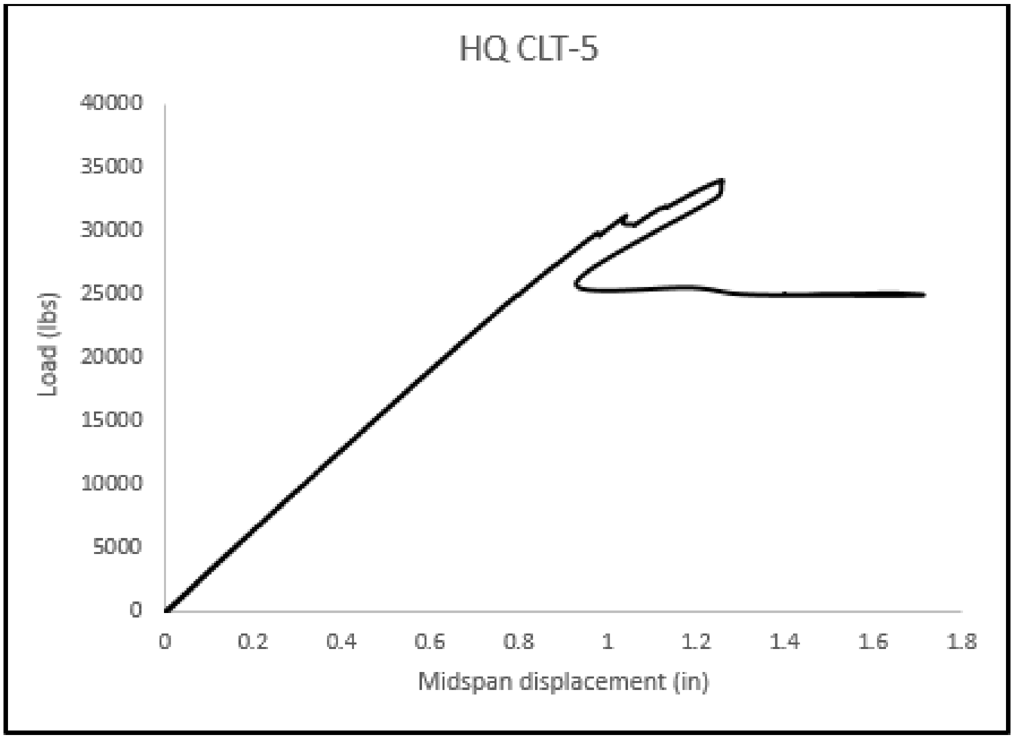
1- Load-deformation curves of high quality yellow-poplar CLT in 4-point bending test.

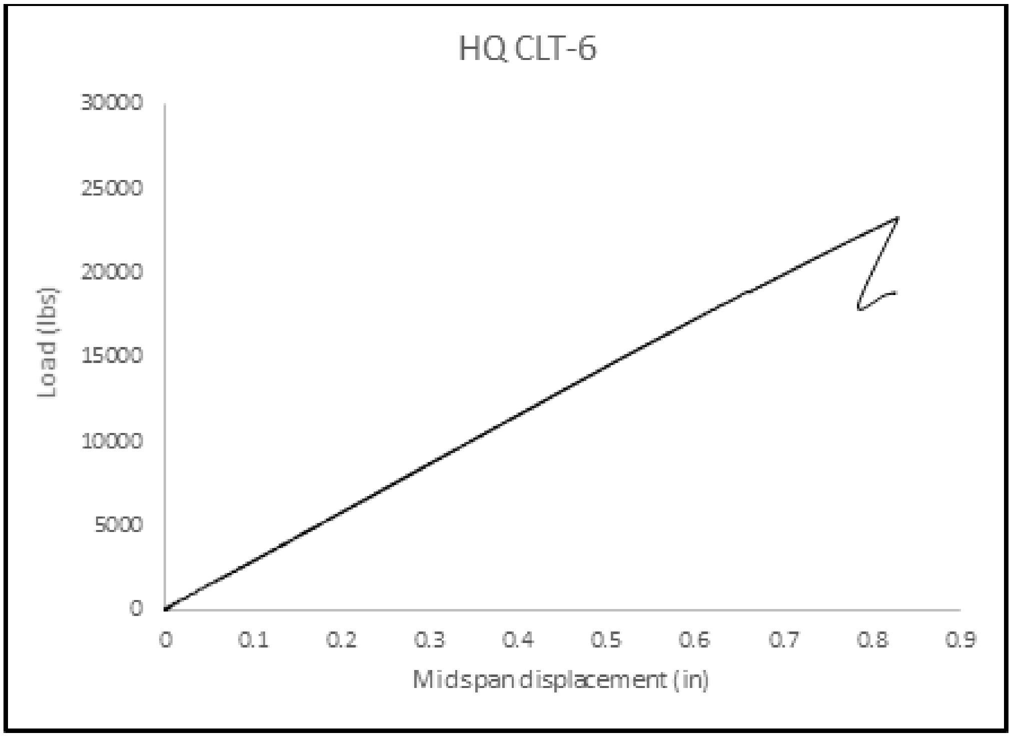




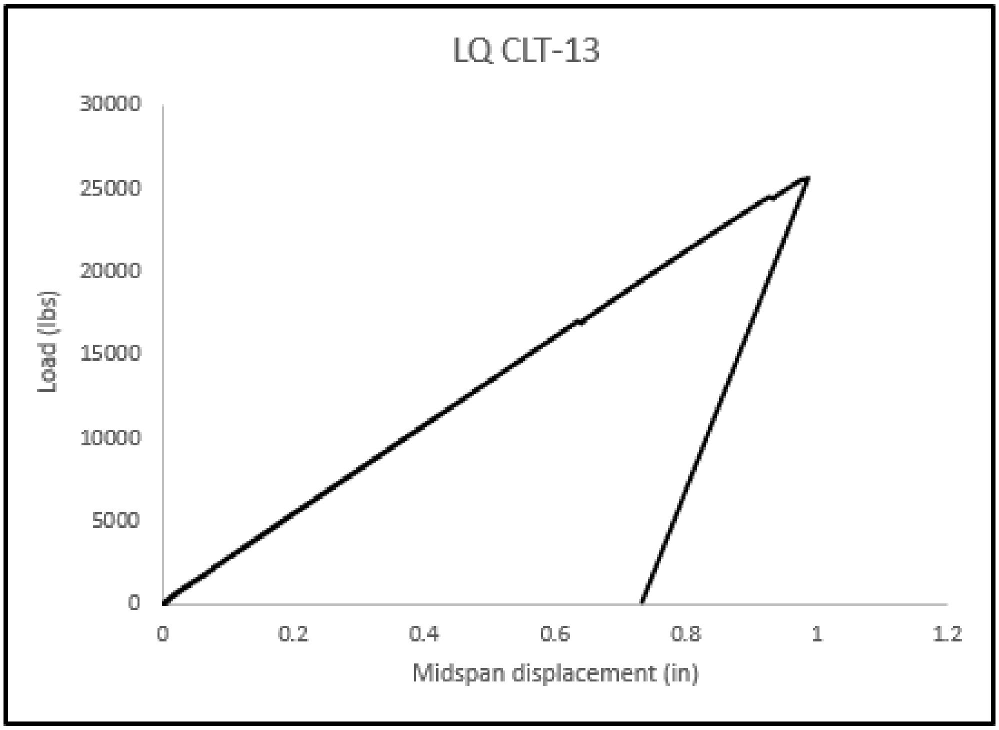

HQ CLT-3
Load (lbs)
30000
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Midspan displacement (in)

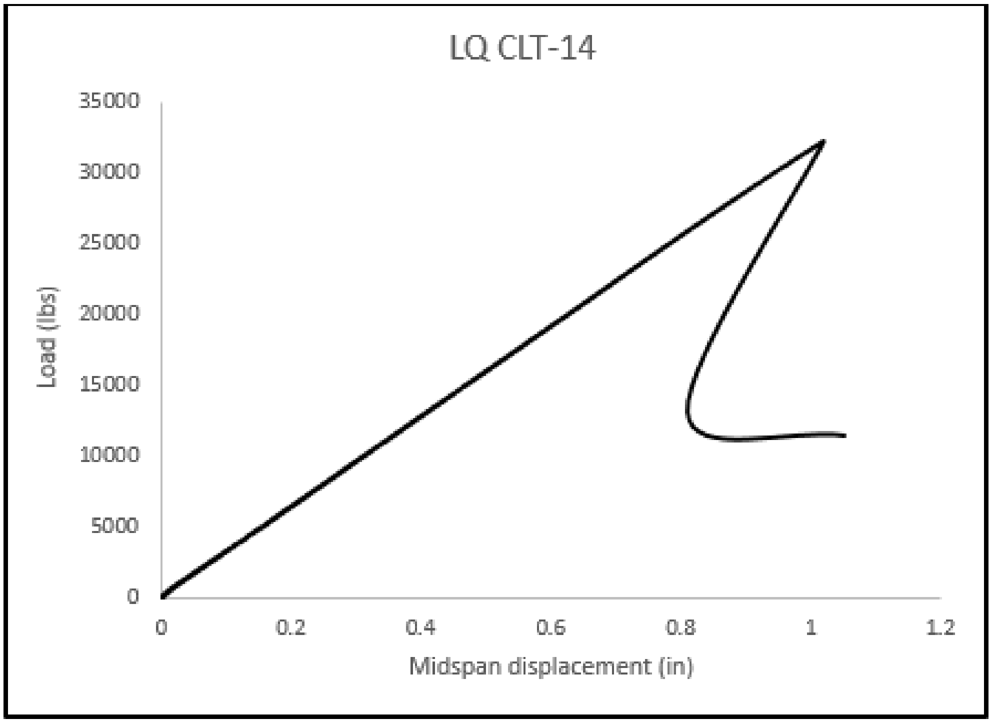

HQ CLT-4
Load (lbs)
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Midspan displacement (in)

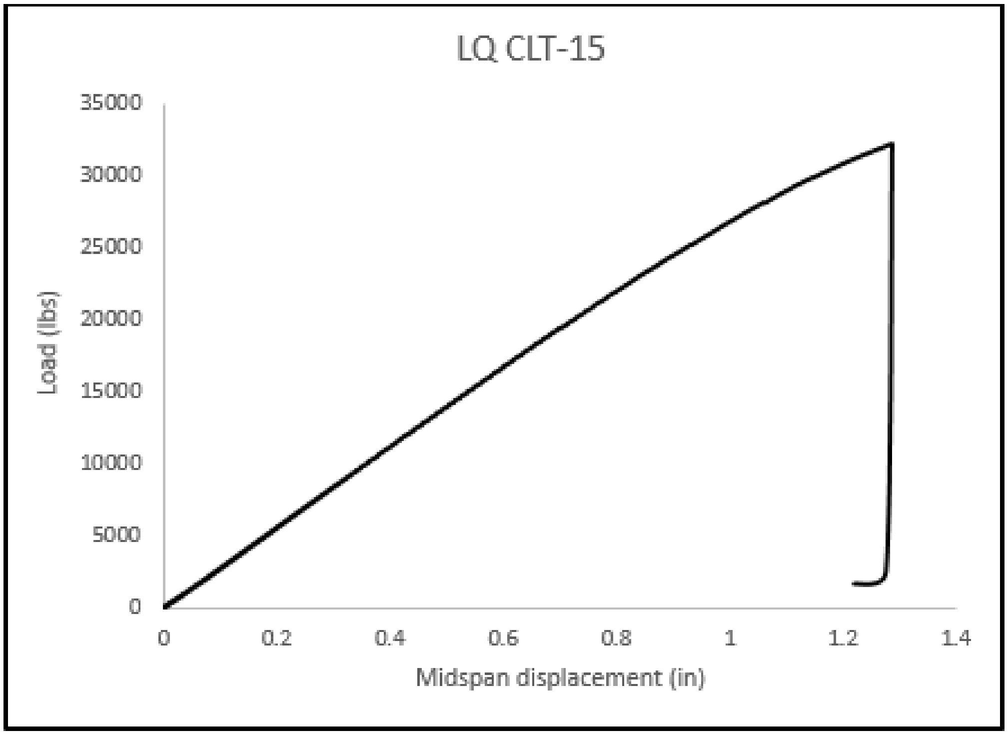

HQ CLT-5
Load (lbs)
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Midspan displacement (in)

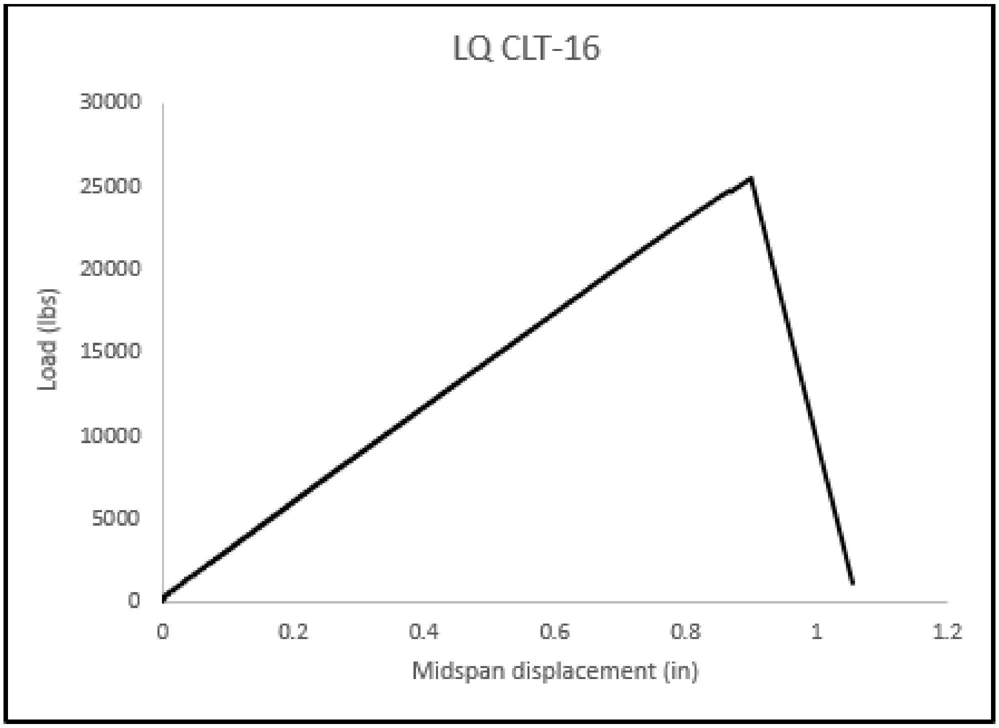

HQ CLT-6
Load (lbs)
30000
25000
20000
15000
10000
5000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Midspan displacement (in)

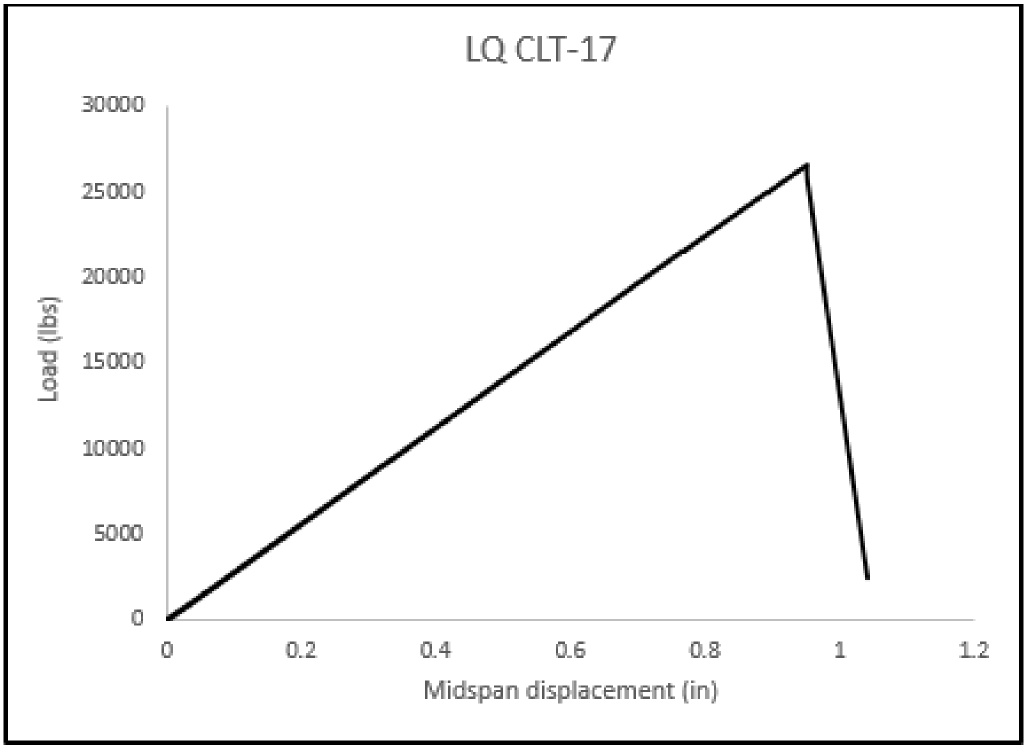
2- Load-deformation curves of low quality yellow-poplar CLT in 4-point bending test.

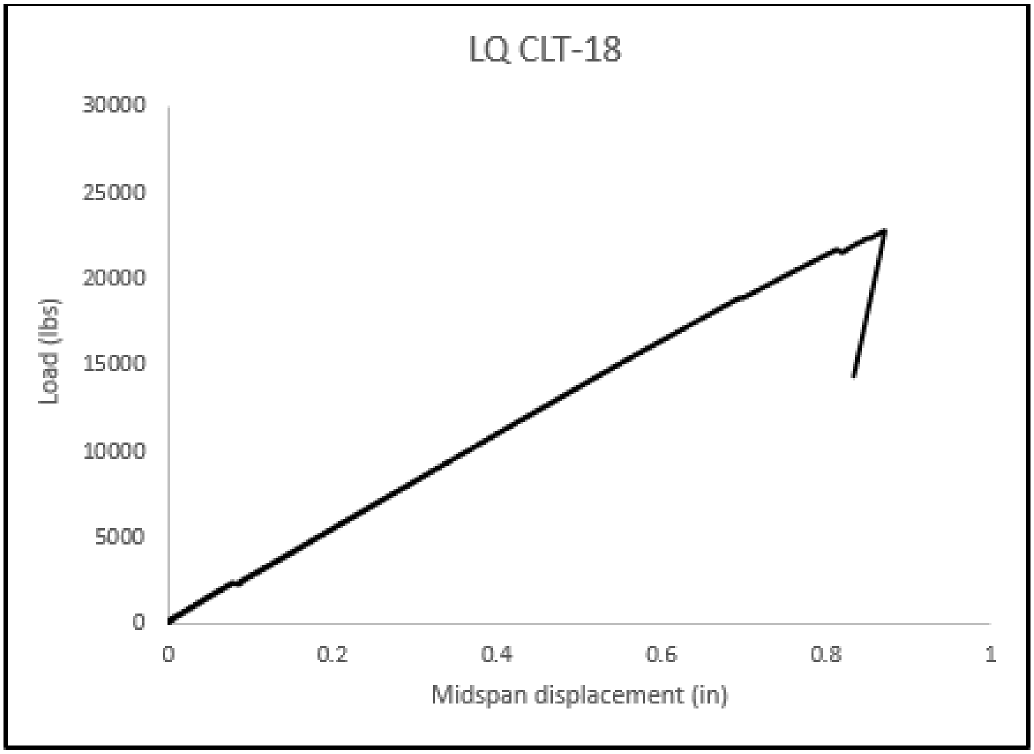




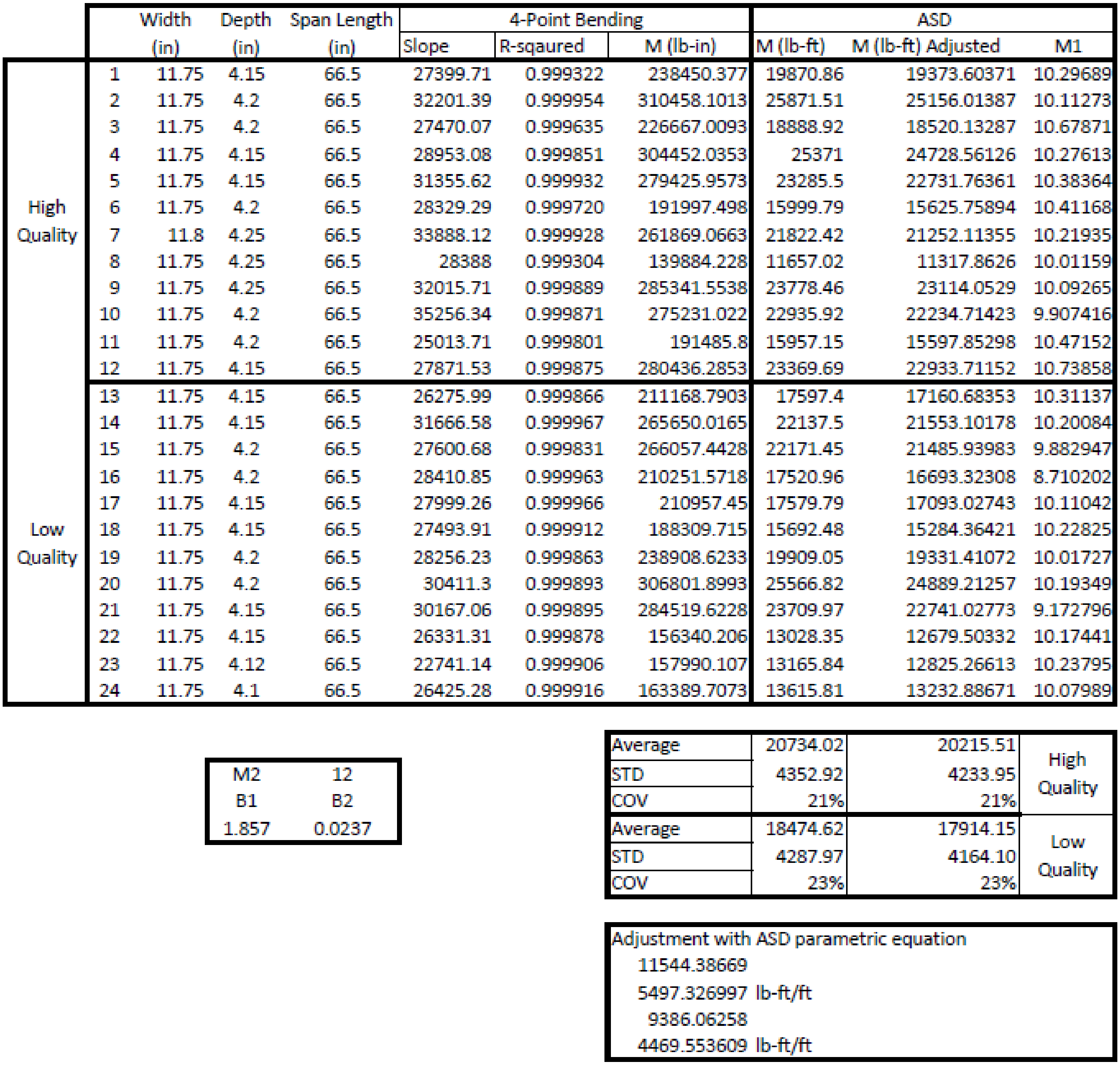

LQ CLT-15
Load (lbs)
35000
30000
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Midspan displacement (in)


LQ CLT-16
Load (lbs)
30000
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
1
1.2
Midspan displacement (in)


LQ CLT-17
Load (lbs)
30000
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
1
1.2
Midspan displacement (in)


LQ CLT-18
Load (lbs)
30000
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
1
Midspan displacement (in)

3- Bending strength (F_bS) calculation. Data adjusted according to ASTM D 2915 (ASTM 2013e).



		Width	Depth	Span Length	4-Point Bending			ASD		
		(in)	(in)	(in)	Slope	R-sqaured	M (lb-in)	M (lb-ft)	M (lb-ft) Adjusted	M1
High Quality	1	11.75	4.15	66.5	27399.71	0.999322	238450.377	19870.86	19373.60371	10.29689
	2	11.75	4.2	66.5	32201.39	0.999954	310458.1013	25871.51	25156.01387	10.11273
	3	11.75	4.2	66.5	27470.07	0.999635	226667.0093	18888.92	18520.13287	10.67871
	4	11.75	4.15	66.5	28953.08	0.999851	304452.0353	25371	24728.56126	10.27613
	5	11.75	4.15	66.5	31355.62	0.999932	279425.9573	23285.5	22731.76361	10.38364
	6	11.75	4.2	66.5	28329.29	0.999720	191997.498	15999.79	15625.75894	10.41168
	7	11.8	4.25	66.5	33888.12	0.999928	261869.0663	21822.42	21252.11355	10.21935
	8	11.75	4.25	66.5	28388	0.999304	139884.228	11657.02	11317.8626	10.01159
	9	11.75	4.25	66.5	32015.71	0.999889	285341.5538	23778.46	23114.0529	10.09265
	10	11.75	4.2	66.5	35256.34	0.999871	275231.022	22935.92	22234.71423	9.907416
	11	11.75	4.2	66.5	25013.71	0.999801	191485.8	15957.15	15597.85298	10.47152
	12	11.75	4.15	66.5	27871.53	0.999875	280436.2853	23369.69	22933.71152	10.73858
Low Quality	13	11.75	4.15	66.5	26275.99	0.999866	211168.7903	17597.4	17160.68353	10.31137
	14	11.75	4.15	66.5	31666.58	0.999967	265650.0165	22137.5	21553.10178	10.20084
	15	11.75	4.2	66.5	27600.68	0.999831	266057.4428	22171.45	21485.93983	9.882947
	16	11.75	4.2	66.5	28410.85	0.999963	210251.5718	17520.96	16693.32308	8.710202
	17	11.75	4.15	66.5	27999.26	0.999966	210957.45	17579.79	17093.02743	10.11042
	18	11.75	4.15	66.5	27493.91	0.999912	188309.715	15692.48	15284.36421	10.22825
	19	11.75	4.2	66.5	28256.23	0.999863	238908.6233	19909.05	19331.41072	10.01727
	20	11.75	4.2	66.5	30411.3	0.999893	306801.8993	25566.82	24889.21257	10.19349
	21	11.75	4.15	66.5	30167.06	0.999895	284519.6228	23709.97	22741.02773	9.172796
	22	11.75	4.15	66.5	26331.31	0.999878	156340.206	13028.35	12679.50332	10.17441
	23	11.75	4.12	66.5	22741.14	0.999906	157990.107	13165.84	12825.26613	10.23795
	24	11.75	4.1	66.5	26425.28	0.999916	163389.7073	13615.81	13232.88671	10.07989

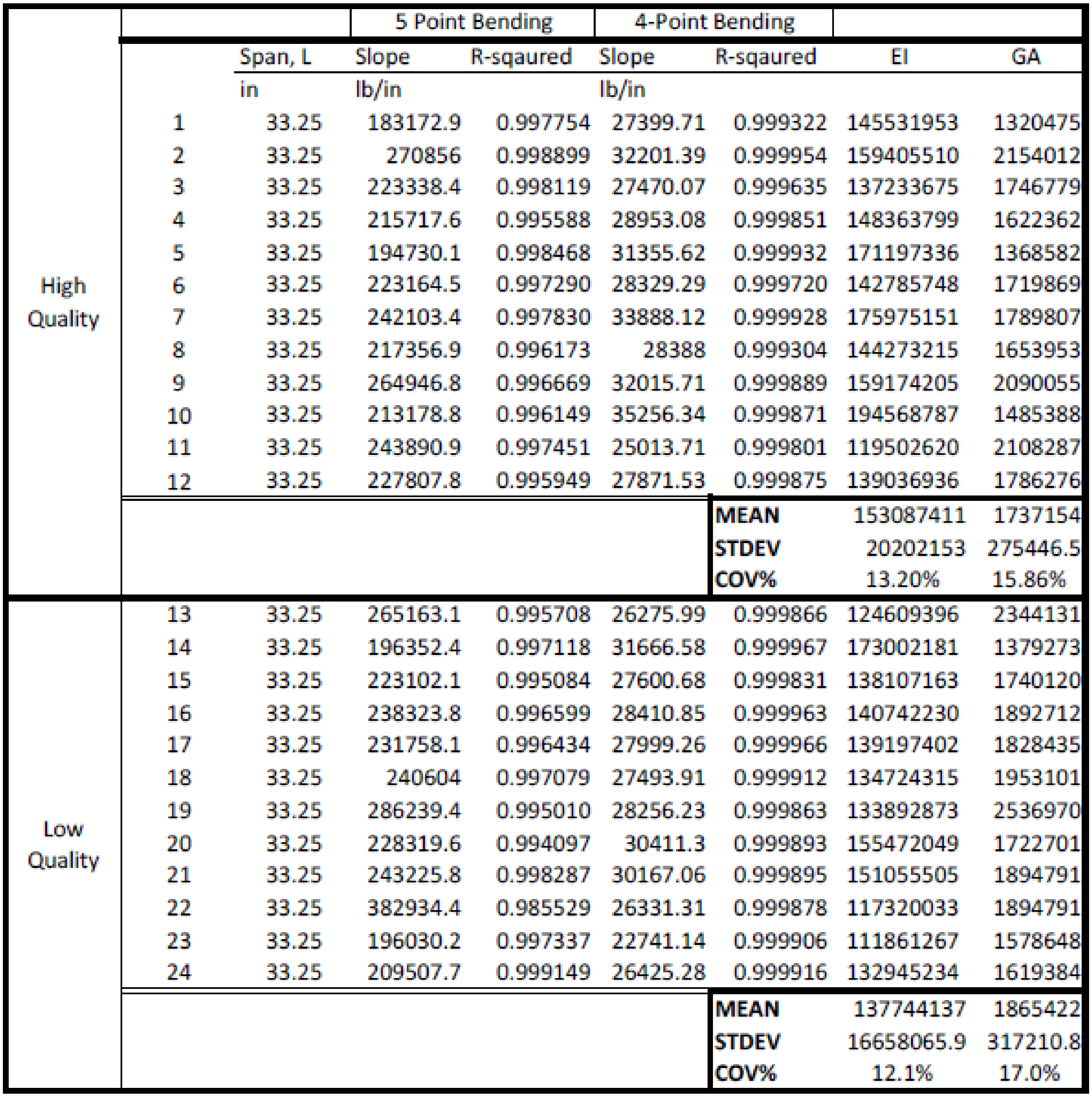
M2	12
B1	B2
1.857	0.0237

Average	20734.02	20215.51	High Quality
STD	4352.92	4233.95	
COV	21%	21%	
Average	18474.62	17914.15	Low Quality
STD	4287.97	4164.10	
COV	23%	23%	

Adjustment with ASD parametric equation

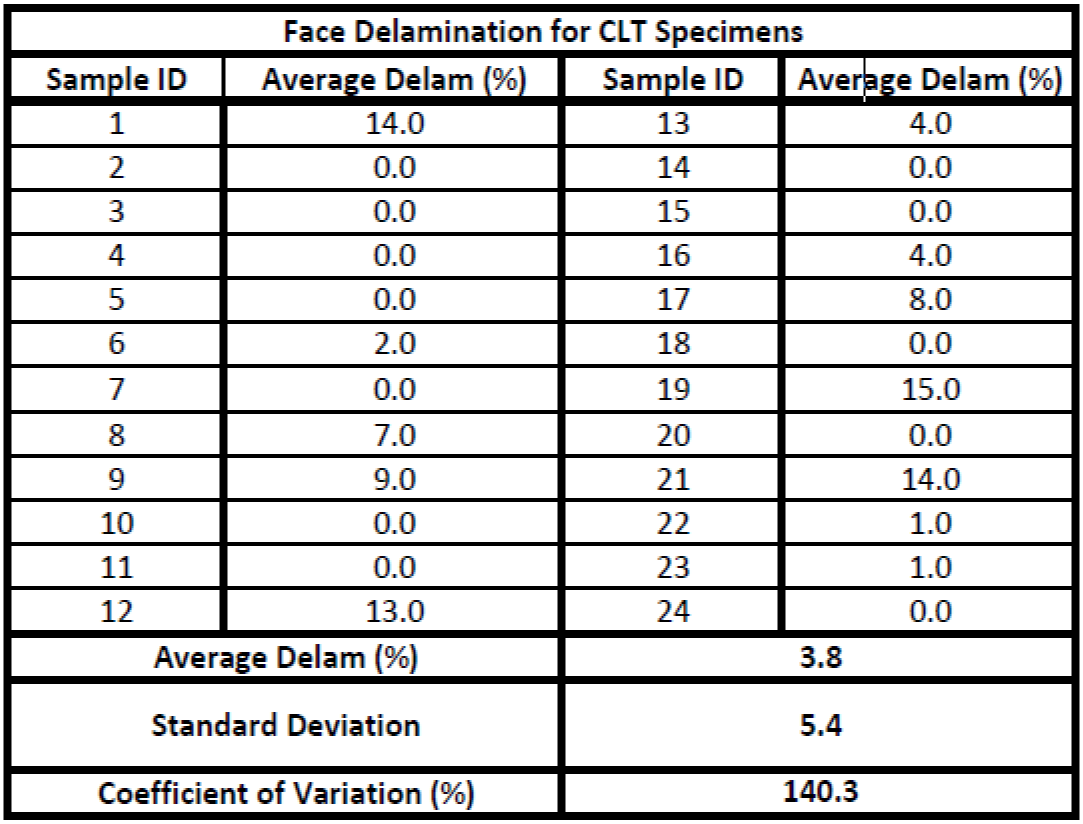
11544.38669	
5497.326997	lb-ft/ft
9386.06258	
4469.553609	lb-ft/ft

4. Bending stiffness (*EI*) and interlaminar shear capacity (*GA*) calculation using 5-point and 4-point bending tests data.



			5 Point Bending		4-Point Bending			
		Span, L	Slope	R-sqaured	Slope	R-sqaured	EI	GA
		in	lb/in		lb/in			
High Quality	1	33.25	183172.9	0.997754	27399.71	0.999322	145531953	1320475
	2	33.25	270856	0.998899	32201.39	0.999954	159405510	2154012
	3	33.25	223338.4	0.998119	27470.07	0.999635	137233675	1746779
	4	33.25	215717.6	0.995588	28953.08	0.999851	148363799	1622362
	5	33.25	194730.1	0.998468	31355.62	0.999932	171197336	1368582
	6	33.25	223164.5	0.997290	28329.29	0.999720	142785748	1719869
	7	33.25	242103.4	0.997830	33888.12	0.999928	175975151	1789807
	8	33.25	217356.9	0.996173	28388	0.999304	144273215	1653953
	9	33.25	264946.8	0.996669	32015.71	0.999889	159174205	2090055
	10	33.25	213178.8	0.996149	35256.34	0.999871	194568787	1485388
	11	33.25	243890.9	0.997451	25013.71	0.999801	119502620	2108287
	12	33.25	227807.8	0.995949	27871.53	0.999875	139036936	1786276
						MEAN	153087411	1737154
						STDEV	20202153	275446.5
						COV%	13.20%	15.86%
Low Quality	13	33.25	265163.1	0.995708	26275.99	0.999866	124609396	2344131
	14	33.25	196352.4	0.997118	31666.58	0.999967	173002181	1379273
	15	33.25	223102.1	0.995084	27600.68	0.999831	138107163	1740120
	16	33.25	238323.8	0.996599	28410.85	0.999963	140742230	1892712
	17	33.25	231758.1	0.996434	27999.26	0.999966	139197402	1828435
	18	33.25	240604	0.997079	27493.91	0.999912	134724315	1953101
	19	33.25	286239.4	0.995010	28256.23	0.999863	133892873	2536970
	20	33.25	228319.6	0.994097	30411.3	0.999893	155472049	1722701
	21	33.25	243225.8	0.998287	30167.06	0.999895	151055505	1894791
	22	33.25	382934.4	0.985529	26331.31	0.999878	117320033	1894791
	23	33.25	196030.2	0.997337	22741.14	0.999906	111861267	1578648
	24	33.25	209507.7	0.999149	26425.28	0.999916	132945234	1619384
						MEAN	137744137	1865422
						STDEV	16658065.9	317210.8
						COV%	12.1%	17.0%

5. Cyclic delamination test results.



Face Delamination for CLT Specimens			
Sample ID	Average Delam (%)	Sample ID	Average Delam (%)
1	14.0	13	4.0
2	0.0	14	0.0
3	0.0	15	0.0
4	0.0	16	4.0
5	0.0	17	8.0
6	2.0	18	0.0
7	0.0	19	15.0
8	7.0	20	0.0
9	9.0	21	14.0
10	0.0	22	1.0
11	0.0	23	1.0
12	13.0	24	0.0
Average Delam (%)		**3.8**	
Standard Deviation		**5.4**	
Coefficient of Variation (%)		**140.3**	