A Performance Evaluation of Cross-Laminated Timber Manufactured With Aspen

By: Nicholas Vetsch

**Abstract**

CLT is an engineered wood product made from 3-7 layers of lumber assembled with alternating grains. Typically softwood lumber is used to manufacture CLT, but as Aspen (*Populus tremuloides*) lumber is highly available in Minnesota, this study was performed to investigate its feasibility for use in CLT panels. A CLT panel was manufactured using locally-acquired aspen lumber and tested for flatwise bending properties. A maximum load of 20.98 kN was found for the panel, which exceeds the standard [9]. However, the values found for MOE and MOR of 8,068 MPa and 13.26 MPa, respectively, were below those of the standard.

**Introduction**

Cross-laminated timber (CLT) is an engineered wood product which is a promising construction material and building system that has shown excellent environmental performance, seismic and fire behavior, and significant advantages in construction time [1]. A CLT panel is made from 3-7 layers of lumber, as seen in Image 1, assembled with alternating grains and joined together using adhesive and/or mechanical fasteners[1]. This application increases the strength properties of low-density wood species which are typically not rated as construction-grade materials for structural applications [2] and adds significant value to wood that would otherwise be used for much lower value-added applications [3]. CLT offers many benefits by greatly increasing the strength properties of the lumber used allowing for the prefabrication of long, wide flooring and wall slabs.  CLT is typically constructed using softwood species, but scarce information exists about CLT made using hardwood species. Aspen (*Populus tremuloides*), a hardwood, is the most abundant tree in the state of Minnesota with more than 3.4 billion cubic feet in standing trees as of 2011, more than double the second most abundant species as seen in Table 1 [4]. This low-density hardwood is not currently specified in American National Standards Institute (ANSI) standards, but is highly attractive for CLT applications due to its abundance and underutilization. The objective of this study was to demonstrate the viability of using Minnesota-grown aspen for manufacturing CLT panels.

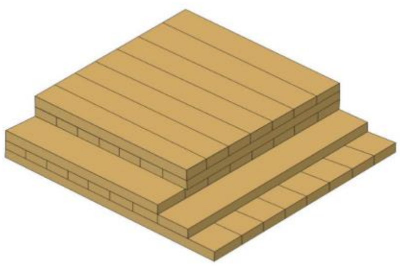

*Image 1:* Typical layout of a CLT panel.

| Rank | Species | Volume of live trees on forest land (1,000,000 $ft^3$) | Sampling error (%) | Change since 2006 (%) | Volume of sawtimber trees on timberland (1,000,000 bdft) | Sampling error (%) | Change since 2006 (%) |
|---|---|---|---|---|---|---|---|
| 1 | Quaking aspen | 3,454.9 | 2.6 | -3.6 | 6,244.1 | 4.0 | -14.5 |
| 2 | Paper birch | 1,169.1 | 3.4 | -9.5 | 1,220.3 | 5.9 | -19.7 |
| 3 | Red pine | 1,153.4 | 6.8 | 24.6 | 4,404.1 | 7.5 | 27.5 |
| 4 | Northern white-cedar | 1,133.8 | 6 | 7.9 | 2,874.3 | 7.4 | -2.2 |
| 5 | Bur oak | 1,031.9 | 4.6 | 10.6 | 2,066.9 | 6.7 | 1.7 |
| 6 | Black ash | 1,014.9 | 4.5 | 7 | 1,420.9 | 6.9 | 6.0 |
| 7 | American basswood | 973.6 | 4.9 | 7.4 | 2,576.0 | 6.3 | 18.7 |
| 8 | Northern red oak | 955.8 | 5.2 | 2.6 | 2,966.8 | 6.4 | 6.3 |
| 9 | Black spruce | 933.2 | 4.8 | 7 | 867.8 | 7.8 | 5.9 |
| 10 | Tamarack (native) | 704.0 | 3.4 | 5 | 1,158.3 | 5.5 | 0.2 |
| | Other softwood species | 2,153.4 | 3.7 | 6.3 | 5,610.5 | 4.7 | 0.1 |
| | Other hardwood species | 3,937.9 | 2.7 | 9.6 | 6,451.6 | 4.7 | 4.4 |
| | All species | 18,616.1 | 1.2 | 5.0 | 37,861.6 | 1.9 | 1.5 |

*Table 1:* Top 10 tree species by statewide volume estimates, Minnesota, 2006-2010 from the United States Department of Agriculture (USDA) publication *Minnesota's Forest Resources, 2011*[4].

**Materials and Methods**

Panel Production

The CLT panel was constructed using 12 inch-wide prefabricated sections, made in turn of narrower boards already edge-glued together. These sections were cut to size and then arranged into five layers with the bottom, middle, and top layers having wood grain running the length of the panel and in-between layers having wood grain running perpendicular to the other layers. The sizing of each layer was determined based on a span-to-depth ratio of 30[9]. The span was chosen at 96 inches based on the length of lumber available, the corresponding depth for this span being 3.2 inches. The material used came at a thickness of 0.75 inches, so five layers resulted in a final depth of 3.75 inches. This arrangement, shown in Image 2, Image 3, and Image 4, was then glued using a Type I polyvinyl acetate (PVA) adhesive (Titebond III)[10] the selection of which was based on AITC 405-2005[11]. The glue was applied in an even layer using a paint roller.

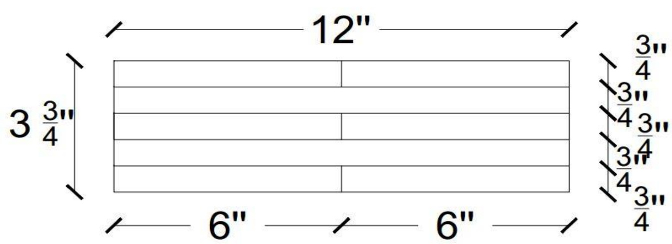


*Image 2:* Cross section of the constructed CLT panel.

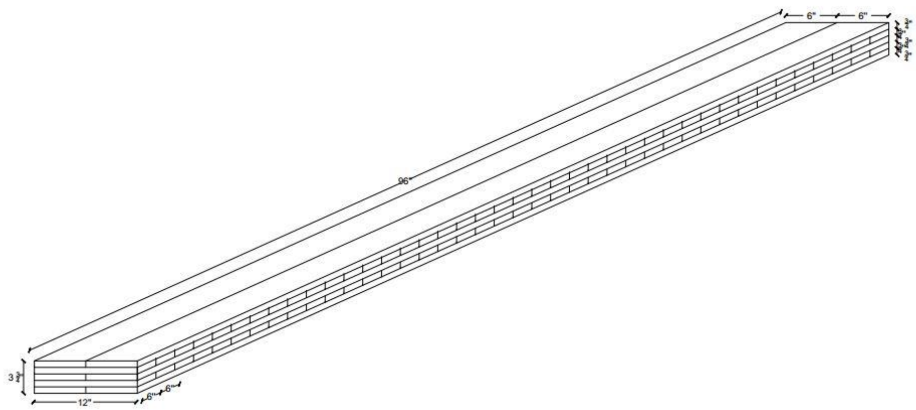


*Image 3:* Full view of the constructed CLT panel.

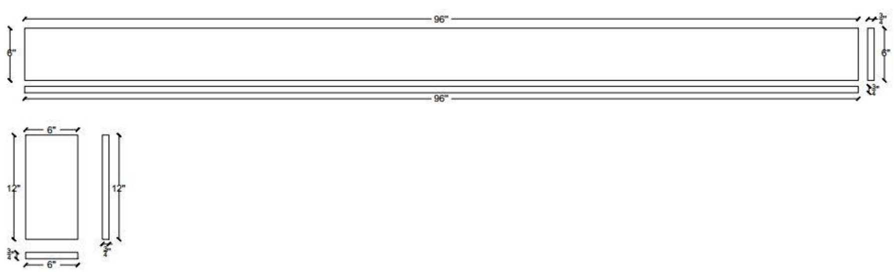


*Image 4:* Top view of the constructed CLT panel.

Clamping through the thickness of the material was done using bar clamps, which proved successful. Clamping along the length of the panel was more difficult and was attempted by using ratchet-strap clamps. Small gaps were left between some of the interior boards due to this.

<u>Mechanical Testing</u>

Mechanical testing was done based on standards of the American National Standard Institute (ANSI) and American Society for Testing and Materials (ASTM). The standards used were ANSI/APA PRG 320-2012 *Standard for Performance-Rated Cross-Laminated Timber* and ASTM D198-09 *Standard Test Methods of Static Tests of Lumber in Structural Sizes*. All mechanical testing was done on an Instron 4206 Universal Testing Machine using a two point loading setup as seen in Image 5 and Image 6. The testing setup was dictated by the ASTM International document which states that in a two point loading setup, supports on the bottom of the sample are placed a distance "L" apart. Each of the two loading points on the top of the sample are placed a distance "a" from the supports. One foot of sample was left over the end of each support, so the distance "L" used was six feet. The loading head used had a distance between loading points of 29 inches, so the distance "a" used was 21.5 inches.

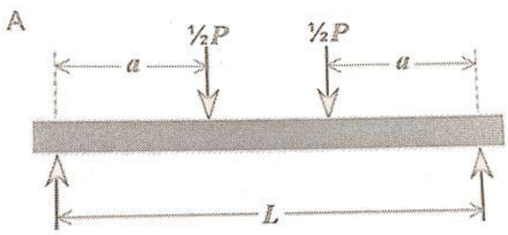


*Image 5 (left) and Image 6 (right):* Image 2: Mechanical properties testing setup. Image 3: Standard two point loading diagram [8].

Initial tests were performed bending the panel only slightly to ensure proper setup of the testing rig and practice calculations without destroying the panel. The final test of the panel was done to full failure. These tests followed ANSI/APA PRG-320-2012: *Standard for Performance-Rated Cross-Laminated Timber* [5] bending test guidelines.

Calculations

The results of mechanical testing were evaluated and compared based on the calculated modulus of rupture (MOR) and modulus of elasticity (MOE), which are calculated using equations (1) and (2). Due to the use of $P_{max}$, MOR could only be evaluated for the breakage test while MOE was evaluated for both tests. Equations used were from the ASTM International document *Standard Test Methods of Static Tests of Lumber in Structural Sizes.*

Modulus of Rupture [8]

$$MOR = \frac{3aP_{max}}{bh^2} \quad (1)$$

where
MOR = modulus of rupture
$P_{max}$ = maximum applied load (N)
a= distance between end of panel and nearest loading point (mm)
b = width (mm)
h= depth (mm).

Modulus of Elasticity [8]

$$MOE = \frac{aP(3L^2-4a^2)}{4bh^3d} \quad (2)$$

where
MOE = modulus of elasticity
P = applied load (N)
a = distance between end of panel and nearest loading point (mm)
L = span (mm)
b = width (mm)
h = depth (mm)
d = center span deflection (mm).

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Moisture Content and Specific Gravity

Standards of the American Society for Testing and Materials (ASTM) were utilized in this study to determine moisture content [6] and specific gravity [7]. Moisture content was found by weighing a sample of lumber, oven drying it for 24 hours, then weighing it again. Specific gravity was found using a sample of known mass and finding the volume of water the sample displaces.

Limitations

Some difficulty was found in the clamping of the panel during the drying of the glue as proper equipment for the task was not available. Clamping of the panel in thickness was successful, but clamping the panel along its length proved more difficult. An attempted was made to use a ratchet strap to clamp along the length; but this was not fully successful.

## Results and Discussion

Non-destructive Bending

Results of the non-destructive testing can be seen in Figure 1. From this data, MOE was found to be 7240.45 MPa.

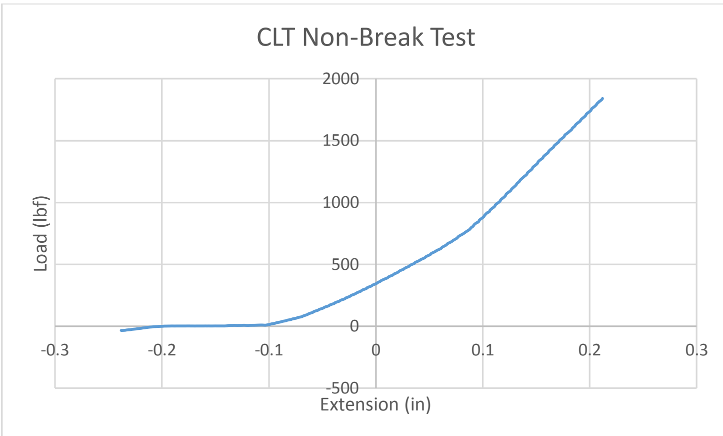


*Figure 1:* Plot of non-breakage test data.

<u>Full Breakage Results</u>

Figure 2 shows the applied load versus the extension of the loading head. Breakage occurred at a maximum load of 20,977.19 N and a maximum extension of 12.598 mm. From these values an MOR of 13.26 MPa and an MOE of 8068.54 MPa were calculated. This is a similar result to the MOE calculated for the non-breakage test of 7240.45 MPa.

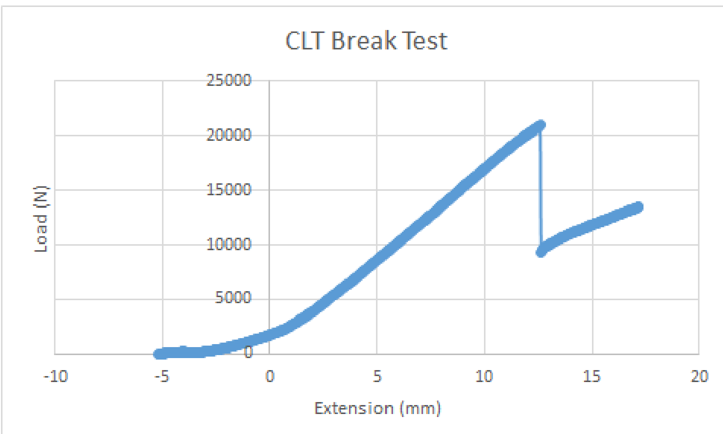


*Figure 2:* Plot of breakage test data.

The values obtained were compared to the standard values found in the *Standard for Performance-Rated Cross-Laminated Timber* [9]. This standard provides minimal strength properties for differing grades of CLT manufactured using softwood lumber and was used because a published standard for hardwood CLT does not exist. Average values were found from this standard to allow for a comparison between the softwood and hardwood. It was found that the panel manufactured using hardwood exceed the standard maximum load, but fell short on modulus of elasticity. Values for modulus of rupture and maximal extension were not provided by the standard so these values were compared to those in the publication titled "*Viability of Hybrid Poplar in ANSI Approved Cross-Laminated Timber Applications,"* [2] which reports results from tests of CLT manufactured with Poplar, a hardwood. A greater deflection at failure was found for this study's panel, but a lower modulus of rupture. Comparisons of all three data sets are shown in Table 2 and the tables from which values were taken for the comparison hardwood paper and the standard are shown in Table 3 and Table 4, respectively.

| Property | Result of this Study | Result of *Viability of Hybrid Poplar in ANSI Approved Cross-Laminated Timber Applications*[2] | Average value from *Standard for Performance-Rated Cross-Laminated Timber*[9] |
|---|---|---|---|
| Modulus of Rupture (MPa) | 13.26 | 23.0 | - |
| Modulus of Elasticity (MPa) | 8,068.54 | - | 10,160 |
| Max Load (kN) | 20.98 | 111 | 18.26 |
| Failure Deflection (mm) | 12.6 | 12.1 | - |

*Table 2:* Results of this study compared to those of *Viability of Hybrid Poplar in ANSI Approved Cross-Laminated Timber Applications* [2].

**Table 2: Results from short span bending and block shear tests along with their standard deviations (STDEV) and coefficient of variations (COV)**

| Short Span Bending Tests | | | | | Block Shear Tests | | |
|---|---|---|---|---|---|---|---|
| Test | Modulus of Rupture | Max Shear Stress | Max Load | Failure Deflection | Test | Max Load | Shear Strength |
| Units | MPa | MPa | kN | mm | Units | kN | MPa |
| 04 - 01 | 24.0 | 2.08 | 115 | 15.3 | 01 - B2 | 6.67 | 3.50 |
| 04 - 02 | 20.1 | 1.76 | 98.0 | 13.0 | 01 - B3 | 5.75 | 2.85 |
| 04 - 03 | 17.2 | 1.50 | 83.0 | 8.70 | 02 - B1 | 5.82 | 2.93 |
| 04 - 04 | 26.0 | 2.27 | 125 | 13.9 | 02 - B2 | 5.56 | 2.81 |
| 05 - 01 | 28.2 | 2.45 | 134 | 13.5 | 02 - B3 | 6.26 | 3.16 |
| 05 - 02 | 22.9 | 1.99 | 110 | 13.2 | 03 - B1 | 6.33 | 3.14 |
| 05 - 03 | 21.2 | 1.84 | 102 | 8.40 | 03 - B2 | 6.53 | 3.28 |
| 05 - 04 | 24.6 | 2.14 | 118 | 11.2 | 03 - B3 | 5.57 | 2.80 |
| Mean | 23.0 | 2.00 | 111 | 12.1 | Mean | 6.06 | 3.06 |
| STDEV | 3.00 | 3.02 | 16.0 | 2.50 | STDEV | 0.44 | 0.25 |
| COV | 15.1% | 15.1% | 14.7% | 20.4% | COV | 7.20% | 8.20% |

*Table 3:* Table 2 from *Viability of Hybrid Poplar in ANSI Approved Cross-Laminated Timber Applications* [2].

TABLE A3.
**SPECIFIED STRENGTH AND MODULUS OF ELASTICITY[a,b,c] FOR PRG 320 CLT (for use in Canada)**

| | Major Strength Direction | | | | | | Minor Strength Direction | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CLT Grades | $f_{b,0}$ (MPa) | $E_0$ (MPa) | $f_{t,0}$ (MPa) | $f_{c,0}$ (MPa) | $f_{v,0}$ (MPa) | $f_{s,0}$ (MPa) | $f_{b,90}$ (MPa) | $E_{90}$ (MPa) | $f_{t,90}$ (MPa) | $f_{c,90}$ (MPa) | $f_{v,90}$ (MPa) | $f_{s,90}$ (MPa) |
| E1 | 28.2 | 11,700 | 15.4 | 19.3 | 1.5 | 0.50 | 7.0 | 9,000 | 3.2 | 9.0 | 1.5 | 0.50 |
| E2 | 23.9 | 10,300 | 11.4 | 18.1 | 1.9 | 0.63 | 4.6 | 10,000 | 2.1 | 7.3 | 1.9 | 0.63 |
| E3 | 17.4 | 8,300 | 6.7 | 15.1 | 1.3 | 0.43 | 4.5 | 6,500 | 2.0 | 5.2 | 1.3 | 0.43 |
| V1 | 10.0 | 11,000 | 5.8 | 14.0 | 1.9 | 0.63 | 4.6 | 10,000 | 2.1 | 7.3 | 1.9 | 0.63 |
| V2 | 11.8 | 9,500 | 5.5 | 11.5 | 1.5 | 0.50 | 7.0 | 9,000 | 3.2 | 9.0 | 1.5 | 0.50 |

For SI: 1 MPa = 145 psi

(a) See Section 4 for symbols.

(b) Tabulated values are Limit States design values and not permitted to be increased for the lumber size adjustment factor in accordance with CSA O86. The design values shall be used in conjunction with the section properties provided by the CLT manufacturer based on the actual layup used in manufacturing the CLT panel (see Table A4).

(c) Custom CLT grades that are not listed in this table shall be permitted in accordance with Section 7.2.1.

*Table 4:* Table A3 from the ANSI/APA document *Standard for Performance-Rated Cross-Laminated Timber* [9].

Failure Analysis

In the full breakage test the panel experienced a delamination failure as evidenced in Image 7, which shows the loss of bondage between the top and second layer of lumber. Image 8 was also a result of the delamination failure as after removing a sample from the center of the panel for moisture content determination the top layer was able to be fully removed on half of the panel.

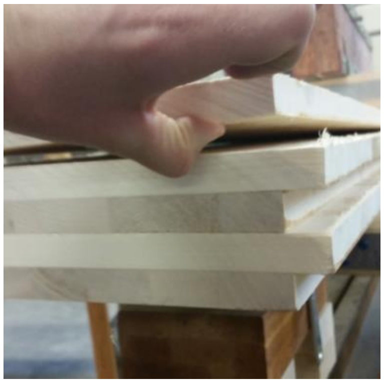

*Image 7:* Delamination failure of CLT panel.

*Image 8:* Delaminated CLT panel after breakage testing.

Specific Gravity and Moisture Content

Table 5 shows the results of specific gravity and moisture testing. The CLT Handbook [1] states that a minimum specific gravity of 0.35 and a moisture content of 8±3 percent are required for lumber used for CLT. The specific gravity of the specimen used in these tests was 0.50 both at construction and after testing which is well above the required value. Moisture content found through both the resistance meter and oven-drying procedure were within the specified range.

| Specific Gravity at Construction (g/g) | Specific Gravity After Testing (g/g) | Resistance Meter Moisture Content (%) | Oven Dry Moisture Content (%) |
|---|---|---|---|
| 0.50 | 0.50 | 7.6 | 6.86 |

*Table 5:* Specific gravity and moisture content values.

**Conclusions**

Due to the failure type of delamination, it is theorized that better bonding of the adhesive and lumber will result in a CLT panel that meets the standard. The prefabricated sections of lumber used were finely sanded which likely resulted in poor adhesive penetration, so in future testing a coarse sanding of the lumber would likely be helpful. The sample tested was close to meeting the standard, but being that only one sample was tested no definitive conclusions can be made. A better clamping setup, coarsely sanded lumber, and, most of all, a larger number of samples would likely yield better results in future studies. However, results are not statistically significant as only one sample was tested. These preliminary results suggest that Aspen wood might be an appropriate raw material for CLT; however further testing is required.

**References**


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