



Flexural and shear performance of CLT panels made from salvaged beetle-killed white spruce

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ABSTRACT

This study aims to investigate the feasibility of CLT panels fabricated from salvaged dead standing trees after the beetle outbreak by evaluating the flexural and shear properties through mechanical tests and computational analysis. White spruce (*Picea glauca* (Moench) Voss) lumber salvaged from the dead and dying trees resulting from recent spruce budworm (*Choristoneura fumiferana* (Clem.)) activity were used to fabricate Cross-laminated timber (CLT) panels of three categories in terms of tree conditions: Category I—live; Category II—recently dead; and Category III—dead for some time. A total of 17 three-layer CLT panels measuring $107 \times 610 \times 2438$ mm were fabricated, 5 for Category I, 5 for Category II, and 7 for Category III. The CLT panels were tested with the third-point and mid-point bending tests following ASTM D198 for major-axis flexural and shear properties. The results indicated that the deterioration of dead, dying standing trees resulting from the budworm activity reduced the average bending strength and shear modulus of the CLT panels. The bending stiffness of the panels was not significantly affected. The CLT panels made from salvaged spruce lumber provided adequate flexural performance per current standard PRG 320–2019. The finite element model built with orthogonal constitutive law and progressive damage criteria simulated the flexural behaviors of the tested CLT panels. The model input modulus and strength were calibrated based on the tested MOE of laminations. The simulation results compared favorably with test data and provided reasonable estimates. The results of this study suggest that CLT panels fabricated from salvaged beetle-killed spruce satisfied the baseline performance requirement of the PRG 320 standard.

1. Introduction

Dead standing trees resulting from insect outbreaks increase the hazard of wildfire in our forest systems and pose a safety hazard to the public in urban areas. In the Upper Midwest, cyclic spruce budworm (*Choristoneura fumiferana* (Clem.)) outbreaks occur every 30 to 50 years, lasting approximately 10 years, causing significant forest defoliation and tree mortality [1]. Under the current climate projections, the frequency and severity of these insect outbreaks are likely to increase over time [2], so does the amount of tree mortality from these outbreaks. As a large number of affected trees become standing fuels in the forest, though it is found not influencing the probability of wildfire, it potentially enhances the fire intensity and widespread comparing with

younger stands [3]. To reduce hazardous fuels and improve forest health on our forest lands, forest managers are promoting the removal of many of these dead standing trees, particularly in areas with high recreation values and near the wildland-urban interface. Timber stands left in the wake of the current outbreak represent a significant economic resource. Timber salvage, as one response to the epidemic, could generate revenues for affected landowners to offset the cost of forestland restoration and mitigate the deleterious impacts of beetle-killed trees on the forest landscape. Depending on the residual wood quality, beetle-killed standing trees may be salvaged and utilized for structural lumber, engineered wood products, pulp and paper, and bioenergy, respectively [4]. However, because of the variable and unknown wood quality of dead and dying standing trees in insect-infested stands, salvaged trees

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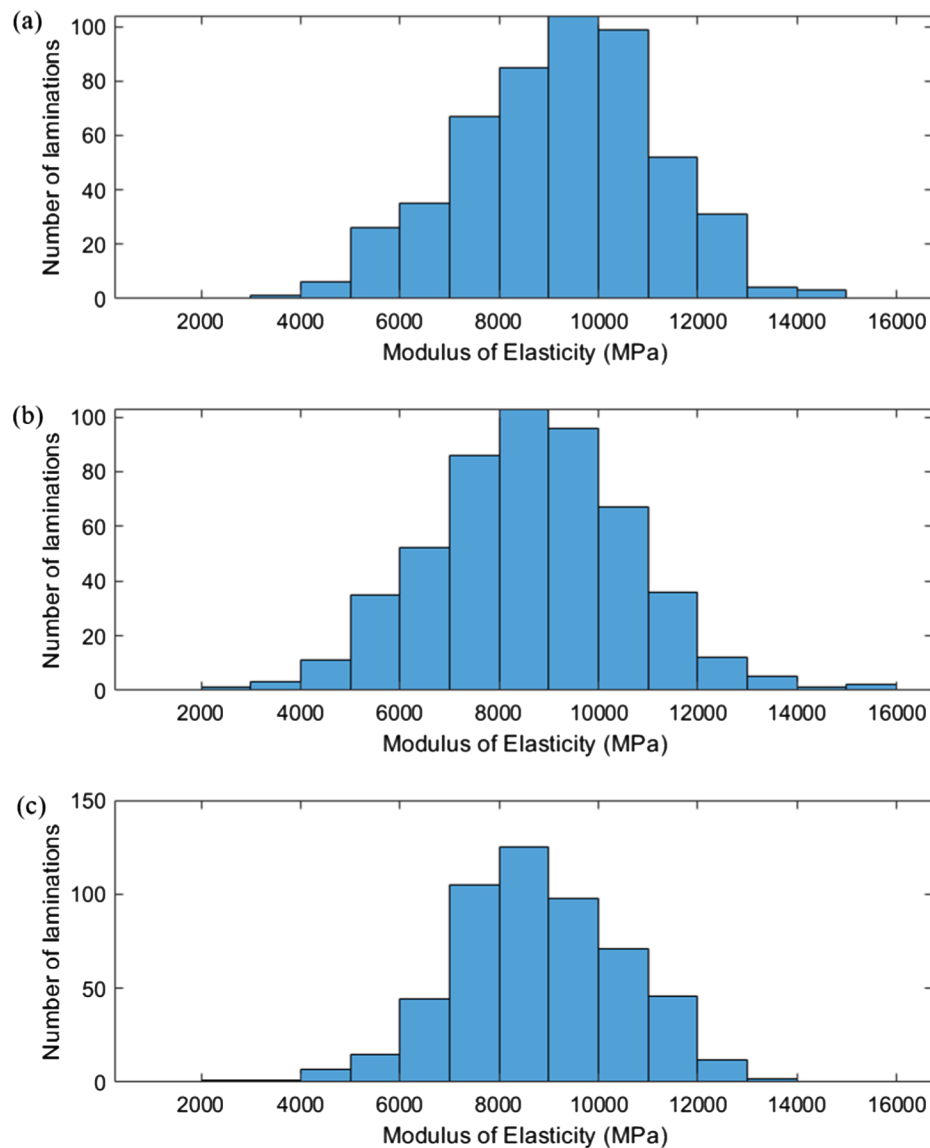


Fig. 1. Histogram of dynamic elastic modulus of the salvaged white spruce lumber. (a) Category I; (b) Category II; and (c) Category III.

tend to be utilized for low-value products that do not require strict wood quality standards, such as pulp and paper or bioenergy feedstocks. A new strategy is needed to maximize the value return by encouraging salvaged wood utilization for the highest and best uses. To achieve this goal, a project was conducted to nondestructively evaluate the wood quality of dead and dying standing trees prior to salvage operations, providing the opportunity to utilize them for the highest and best potential [5].

Manufacturing Cross-laminated timber (CLT) with non-destructive rated salvaged lumber could be a high value-added option for utilizing the salvaged lumber. The orthogonal layup of CLT can reduce the impact of mechanical property variance caused by local defects such as checks, knots and decay by redistributing the loads into other directions [6]. It is possible that limited defects in laminations caused by decay and beetle attacks could be tolerated acceptable when applied to CLT panels. The mechanical properties of salvaged beetle-killed lumber vary with the different attack stages (green-stage, red-and-dead-stage, and the gray-ghost stage) of the dead and dying trees. It was found that the Modulus of elasticity (MOE) is mostly not changed, and strength is reduced during the aging and decay of timber [7]. Traditional visual grading procedures developed for structural lumber do not incorporate estimates of any intrinsic wood properties, so that non-destructive tests

are required to evaluate the salvaged lumber.

In PRG 320 standard [8], the bending stiffness (MOE), bending capacity (MOR), shear modulus (G) and shear strength are used to evaluate the structural performance of CLT panels. The flexural properties are recommended to be evaluated by a third-point bending test following ASTM D198 [9]. The recommended span-to-depth ratio is 30 and the third-point load is applied to minimize the shear effect. The CLT made with Canadian hemlock has been tested in the points bending test with a span of 27.85 times depth [10]. According to PRG 320 [8], and the ASTM D198 [9], a span of four to six times the panel depth is recommended in three-point bending to test the shear properties. For instance, the shear of CLT panels was studied via experimental and simulated mid-point flexural tests for the understanding of the mechanism at the multiscale level [11]. In this study, the third-point bending test and the short-span mid-point bending test were both conducted to examine the flexural and shear performance of the CLT beams made with salvaged spruce.

The other technical challenge in manufacturing CLT panels with beetle-killed timber is to design the layups properly and accurately predict the mechanical performance of the designed panels. Finite element (FE) modeling could be used to simulate the mechanical performance to thoroughly investigate the impact of the beetle attack on the

Table 1

Area average layer elastic modulus of each panel based on the non-destructive rating of laminations.

CLT category	Layer position	Panel code and layer MOE (MPa)					
Category I		I-3	I-8	I-9	I-13	I-18	
	Top layer	9860	9101	8894	9791	9170	
	Mid layer	8894	8136	7998	9101	7377	
	Bottom layer	9722	10,825	8963	9308	9239	
Category II		II-5	II-7	II-11	II-15	II-19	
	Top layer	9721	7377	8618	11,170	8825	
	Mid layer	9721	7239	8894	8825	8067	
	Bottom layer	10,203	9238	9101	9997	9101	
Category III		III-2	III-6	III-10	III-12	III-14	III-16
	Top layer	9653	8550	8687	9239	9308	9446
	Mid layer	9032	8412	8963	8481	9377	8343
	Bottom layer	8618	10,480	8963	8894	7791	10,135

mechanical performance of the CLT panels. Integrated experimental and FE numerical analyses were applied to investigate the bending and compressive CLT properties made with Canadian hemlock [10]. The results approved the feasibility of using FE models to simulate the bending behavior of hemlock CLT panels. Similarly, the bending and shear stiffness of complex layups with different interlayer angles were successfully captured using integrated experimental and numerical investigation [12]. The elastic mechanical behavior of the CLT panels was captured with layer structure in that study. The flexural strength of CLT panels needs to be simulated with damage models such as Hashin damage criteria [13]. A constitutive law with the failure criteria based on the Hashin damage model was proved feasible in modeling the arbitrarily orientated behavior of timber [14]. The optimization procedure in designing intricate timber structures, such as ribbed CLT plates, can also be relying on the Hashin damage criteria [15]. Therefore, the Hashin damage criteria are applied in this study to capture the timber's orthogonal mechanical capacity.

This paper was aimed to evaluate the flexural and shear properties of CLT panels fabricated from salvaged dead standing white spruce (*Picea glauca* (Moench) Voss) resulting from the recent budworm activity in Upper Peninsula, Michigan, through mechanical tests and computational analysis to determine whether the CLT panels can reach the standards required by the PRG 320 standard [5]. The study was conducted through third-point bending tests and mid-point bending tests to determine the impact of different attack stages of the insect-infested trees on the stiffness and strength of the CLT panels. In the last section, the panel properties were further analyzed with the Finite Element model that was inputted with the lamination modulus rating test results and location record.

2. Lamination preparation and CLT fabrication

2.1. Lamination preparation and rating

The white spruce (*Picea glauca* (Moench) Voss) timber used for this study were salvaged from a defoliated forest stand affected by a recent spruce budworm outbreak near Iron River, Michigan. One hundred forty-nine mature white spruce trees were harvested in a salvage operation across a gradient of spruce budworm defoliation and decline present at the study site. The salvaged trees included three distinct categories defined using visual characteristics of decline and decay. Category I ($n = 50$) included live trees with any amount of visible green foliage and those with some sign of defoliation. Category II ($n = 49$) was in red-and-dead-stage, including dead-standing trees with reddish-brown foliage and most of the fine, needle-bearing branches intact. White spruce within Category II were assumed to have died relatively recently due to the presence of fine branches and attached brown foliage. Category III ($n = 50$) included dead-standing trees having no visible green foliage and needle bearing branches mostly absent. Category III represented dead standing trees with the poorest visual

appearance, assumably dead for some time.

A subset of the salvaged logs in each tree category was sawn into $51 \times 102 \times 2540$ mm lumber and kilned dried. All lumber was then machined to $36 \times 102 \times 2438$ mm and conditioned to 12% equilibrium moisture content (EMC). A total of 1550 pieces of lumber were obtained, including 513 pieces in Category I, 510 pieces in Category II, and 527 pieces in Category III. Each piece of lumber was then E-rated using the transverse vibration testing method according to ASTM D6874 [16]. The dynamic modulus of elasticity (MOE_{TV}) of each piece of lumber was calculated using the following Equation,

$$MOE_{TV} = \frac{f_r^2 w L^3}{K_d I g} \quad (1)$$

where f_r is the fundamental frequency (Hz), w is the weight of lumber (N), L is the span length (mm), I is the specimen moment of inertia; b is the lumber width (mm), h is the lumber height (mm), g is the acceleration due to gravity (9807 mm/s^2), and K_d is constant for free vibration of a simply supported beam, which equals to 2.47.

The lumber MOE distribution in each category is shown in Fig. 1. The average lumber MOE at 12% MC was 9,225, 8,613, and 8,808 MPa for categories I, II, and III, respectively. The average MOE of lumber in Category I was about the same as the MOE value of white spruce (9,200 MPa) given in the Wood Handbook (FPL 2010). Comparing with lumber of Category I, 6.6% and 4.5% reduction in MOE were observed in lumber of Category II and II, respectively. Statistical comparison analysis indicated that increased deterioration of dead standing trees in Category II and III resulted in a significant reduction in lumber MOE comparing the trees in Category I ($p = 3.16 \times 10^{-7}$ between I and II; $p = 5.79 \times 10^{-5}$ between I and III). However, no significant difference was found in average lumber MOE between Category II and III ($p = 0.139$).

2.2. CLT panel fabrication

The CLT fabrication process took place at the pilot plant (Sands Building) of the College of Forest Resources and Environmental Science, Michigan Technological University. E-rated lumber pieces used to construct 3-layer CLT panels were selected from each category with the following criteria: 1) MOE of 6,000–8,000 MPa for the middle perpendicular layer; 2) minimum MOE of 8,000 MPa for the outer parallel layers; and 3) lumber surfaces are satisfactory for gluing, containing no large holes or decay pockets that would prevent the glue from adhering in the boards.

A total of 17 CLT panels measuring $107 \times 610 \times 2,438$ mm were fabricated, including 5 in category I (lumber sawn from live trees), 5 in Category II (lumber sawn from trees of recently dead), and 7 in Category III (lumber sawn from trees dead for some time). The laminations meeting the MOE criterion were picked randomly from each category and assembled into layers. All the laminations in each panel were labeled and recorded for their locations. Due to the planner's maximum

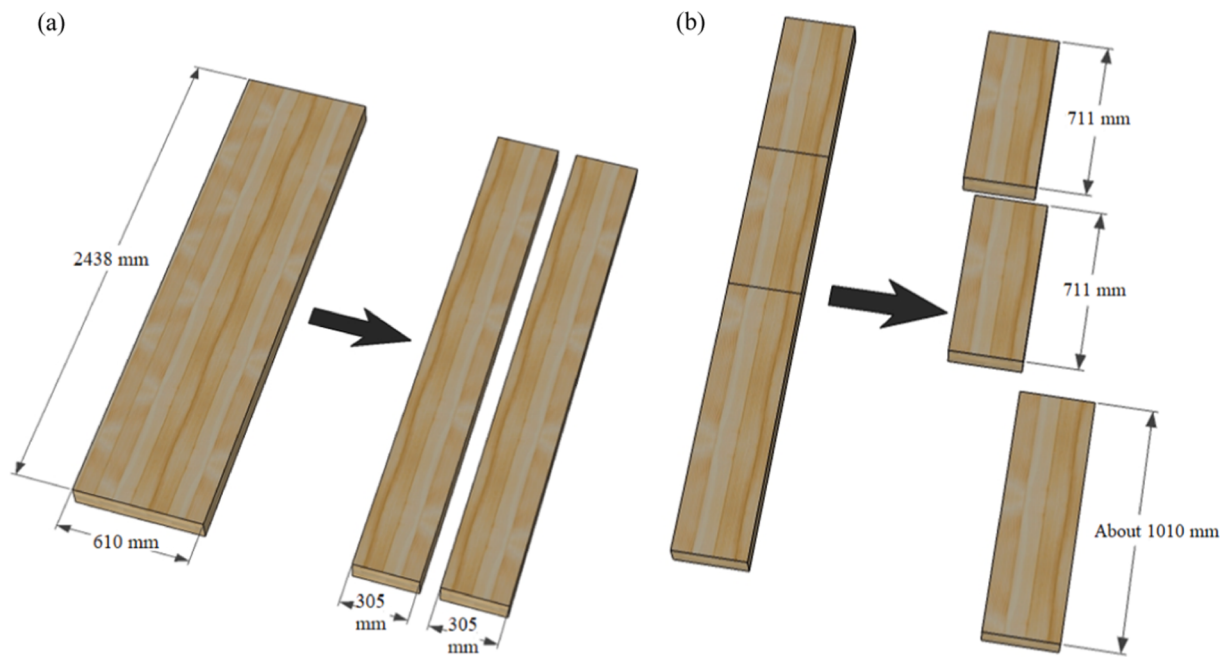


Fig. 2. Diagram of cutting CLT test samples (a) one long-span sample measuring $107 \times 305 \times 2438$ mm for bending test; (b) two short-span samples measuring $107 \times 305 \times 711$ mm for shear test.



Fig. 3. The test setup for conducting third point bending test with a third-point loading method.

width, the boards were first edge-glued into sub-sections with Titebond wood glue under clamp pressure for 24 h. Sub-sections were 3 to 4 boards each for outer parallel layers, and 4 to 5 boards each for the middle perpendicular layer. The subsections were then planed and edge-glued to form the full layer. The fast-cure formulation of Titebond wood glue was used for the edge bonding of the laminations primarily to meet the minimum width requirement, which is 3.5 times the thickness of the lamination in the perpendicular layers. The Titebond wood glue served that purpose with a much shorter curing time than the resorcinol-based adhesive. In addition, edge bonding the laminations with the wood glue makes material handling much easier in the CLT panel making process in the lab. Within 24 h after surface planing, the full layers were surface glued using phenol-resorcinol formaldehyde adhesive. The core layer was stored for 1–2 h in a chamber with a temperature of 27°C prior to gluing to ensure the temperature of the layers was not below the required for curing the adhesive. About 472.5 g of resorcinol adhesive was then applied to each bonding surface between layers. The layers were then stacked in the press for surface gluing. The panels were

pressed with $1.2\text{ MPa} \pm 0.5\text{ MPa}$ for 4 h. The press platen was warmed to 49°C to maintain sufficient temperature at the glue lines. Then the panel was removed from the press and trimmed to the final dimensions.

2.3. CLT panel sample types

The CLT panels were numbered in the order of fabrication with category code as a prefix, as shown in Table 1. Panels I–1 and II–4 were not proceeded for testing due to manufacturing failure and thus were not included in the test, resulting in a total of 17 CLT test panels. Each test panel was then cut into one long-span sample measuring $107 \times 305 \times 2438$ mm for the third point bending test and two short-span samples measuring $107 \times 305 \times 711$ mm for the shear test (Fig. 2). The long-span samples were labeled as A, while short-span samples were labeled as B. For instance, I-3B2 means the second short-span sample from panel 3, Category I.

As the laminations' cross-section area was identical, the average layer elastic modulus was calculated as the average elastic modulus of

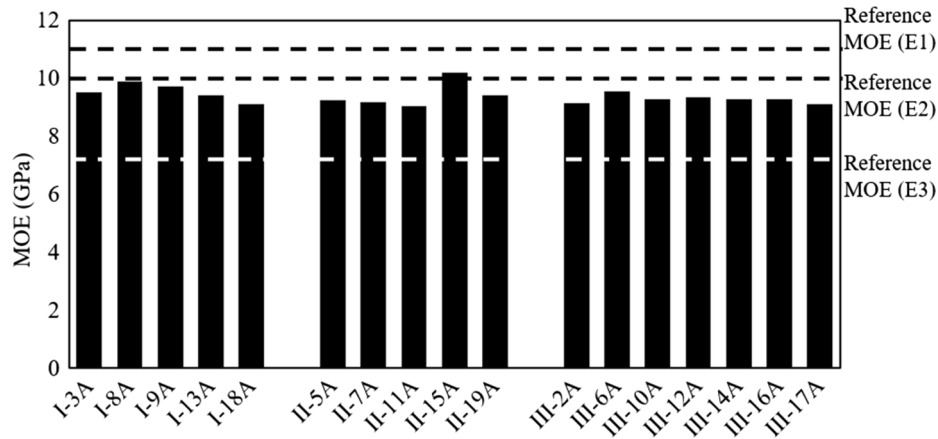


Fig. 4. MOE of the third-point bending samples and comparison with reference MOEs [8].

Table 2

Third-point bending test result.

CLT category	MOE _{CLT} Average (GPa)	MOE _{CLT} coefficient of variation	MOR _{CLT} Average (MPa)	MOR _{CLT} coefficient of variation
Category I	9.51	2.6%	35.62	2.9%
Category II	9.44	4.2%	35.43	6.1%
Category III	9.30	1.4%	34.97	2.1%

all laminations used in the layer. Combining the rating results of the laminations and the location records, the layer elastic modulus of each panel were calculated and listed in Table 1.

3. Long-span third-point bending test

3.1. Test setup and data processing

The long-span third-point bending test is designed to evaluate the flexural performance of CLT panels with minimized shear effects. Fig. 3 shows the setup of conducting a long-span third point test on bending specimens, with 152 mm (6 in. overhang on both ends, the total span is 2286 mm (90 in.), which provides a span-to-depth ratio of 21.4. The bending test was conducted in the Forest Product Lab following D198 [9]. The CLT specimen was supported with two rotatable roller pads to allow the rotation and horizontal displacement. The load was applied at the third points of the span length with two equal timber loading heads. The curvature of the contact surface ensures the contact and avoids the local compressive damage. The loads were applied with a vertical actuator and distributed with a steel beam. The loading rate was controlled as 6.4 mm/min to have an approximate test time of 10 min, as recommended by ASTM D198 [9]. The midspan displacement was measured with two Linear Variable Displacement Transducers (LVDTs) at the mid-span at both sides of the sample. The readings of two LVDTs were used to obtain an average mid-span displacement at the neutral axis. The horizontal sliding was eliminated with readings from LVDTs that measure the supports. The loading was recorded by the loading cell in the actuator. The average reading of the two LVDTs was recorded as the mid-span displacement.

The large span to depth ratio can reduce the portion of shear deflection during the test. Meanwhile, the section of the specimen between the two loading points was subject to pure bending. For the third point test, the modulus of elasticity of the CLT beam (MOE_{CLT}) can be calculated as in Equation (2):

$$MOE_{CLT} = \frac{Pa}{2\Delta_{max}I} \left(\frac{l^2}{8} - \frac{a^2}{6} \right) \quad (2)$$

where P is the recorded peak load; a is the distance between the support and loading point, which is one-third of the total span; Δ_{max} is the recorded maximum mid-span displacement; l is the total span of the sample; and I is the moment of inertia of the sample along the length.

The modulus of rupture of the CLT beam (MOR_{CLT}) was calculated as:

$$MOR_{CLT} = \frac{P \cdot a \cdot y}{2 \cdot I} \quad (3)$$

where y is half the total depth, which is the distance between the bottom and the neutral axis.

3.2. Test results and comparison with reference values

Based on the third point bending tests, the average MOE_{CLT} and the variance were as listed in Table 3. The average MOE_{CLT} of Category II panels was 0.72% smaller than Category I, while Category III was 2.17% smaller than Category I. In the meantime, the p-value was calculated as 0.64 between Category I and Category II and as 0.08 between Category I and Category III. It illustrated that the differences between Category I and II were not statistically significant. Therefore, the average MOE_{CLT} of Category I and II can be considered as basically equal, while that of Category III was slightly smaller.

The results were compared with the reference values provided in APA/PRG-320 [8]. For the E1 to E3 grade panel. Notice that E1 type CLT is the clear wood panel with the highest standard. The reference MOE of grade E1 CLT from APA PRG-320 is 11.28 GPa, 10.00 GPa for grade E2, and 7.05 GPa for grade E3 [8]. As shown in Fig. 4, though the tested panels of all the three categories were providing the average MOE 15.6%–17.55% less than the reference value of grade E1, all the samples have the MOE exceeding the reference value for grade E3. In literature, the average MOE of CLT made with Southern pine was 9.20 GPa [17], 12.24 GPa for Irish Sitka spruce [18], and 11.67 GPa for Canadian hemlock [10]. The relative difference between the Category I salvaged spruce CLT and the reference values are separately 3%, –22.3%, and –18.51%, which indicated that the stiffness is comparable with the CLT panels made with other softwood species.

The calculated MOR based on the test results were listed as shown in Table 2. The reduction of MOR in between the categories was also small. Comparing with the average MOR_{CLT} of samples in Category I, the reductions was 0.54% for Category II and 1.84% for Category III, separately. The p-value was calculated as 0.91 between Category I and Category II and 0.72 between Category I and Category III. The results show that the difference is minor and statistically insignificant.

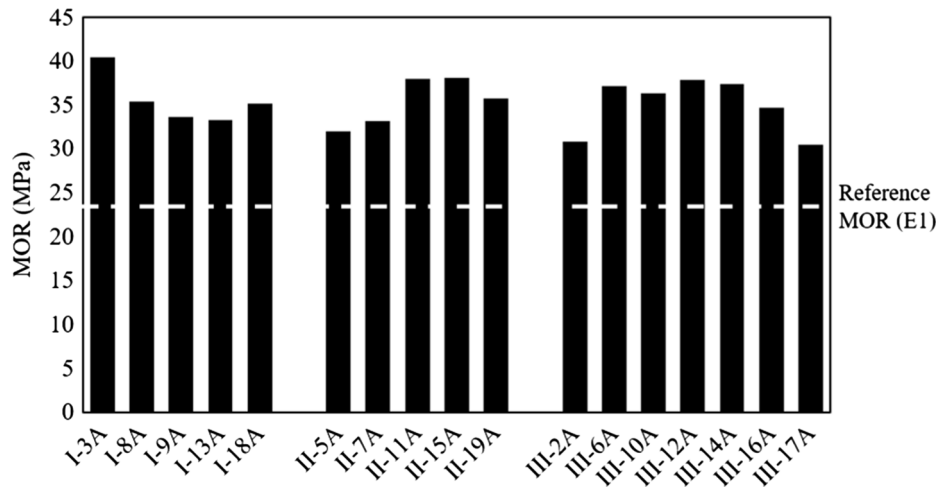


Fig. 5. MOR of the third-point bending samples comparison with reference MOR [8].



Fig. 6. Short-span three-point bending test setup.

Therefore, the three categories can be considered as providing the equal MOR. The results were reasonable, considering the most damaged boards of each category were manually disposed when checking for the surface quality. The panels provide an adequate bending capacity comparing with the reference value. The reference MOR for grade E1 CLT is 22.85 MPa [8], which is the highest among all provided reference

values. As shown in Fig. 5, the modulus of ruptures was at least 53% larger than the reference value for grade E1. Some reference MOR value of CLT panels made with other species was 19.98 MPa for Southern pine [17], 33.62 MPa for Irish Sitka spruce [18], and 22.40 MPa for Canadian hemlock [10]. The Category I salvaged spruce CLT provided an average MOR that was 78.3%, 5.6%, and 37.1% larger than the reference values.

4. Short-span shear test

4.1. Test setup and data processing

The short-span bending test with the center-point loading was used to evaluate the CLT panels' shear modulus as per the standard of PRG320 (APA 2018). The setup of the short-span shear test is shown in Fig. 6. The specimen was supported on two rotatable roller pads with a span of 635 mm (25 in.) and an overhang of 38.1 mm (1.5 in.) on each end. The load was applied through the wooden loading head that has a radius of 203 mm. The actuator was in a displacement-controlled manner. The loading rate was set at 2.5 mm/min. The mid-span displacement at the neutral axis was measured through a pair of LVDTs attached to the yokes, which were attached on both sides of the

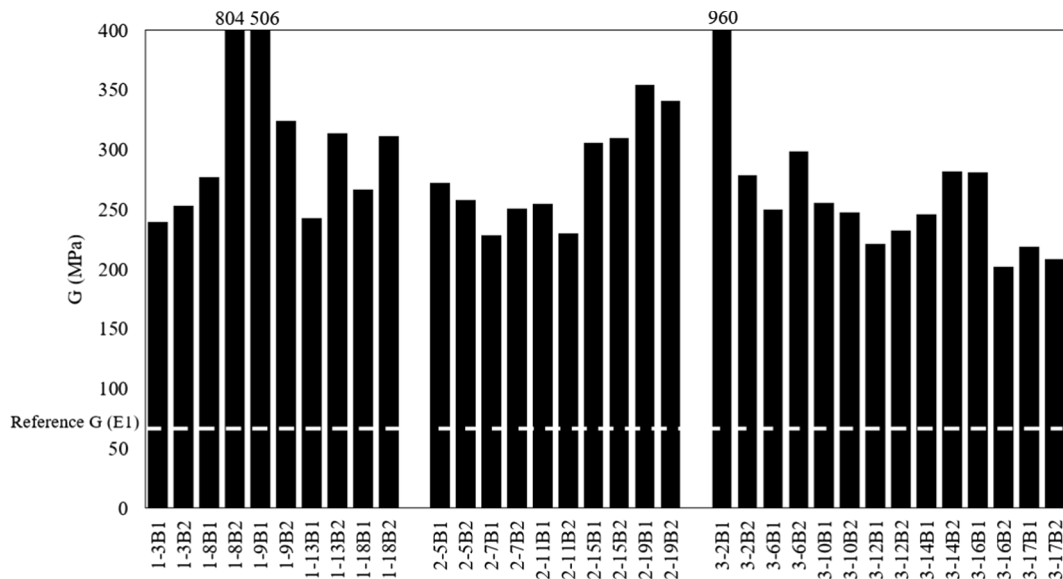


Fig. 7. Shear modulus (G) of the short-span mid-point bending samples and its comparison with reference G [8].

Table 3
Short-span mid-span bending test result.

CLT Category	Average Shear Modulus G (MPa)	Shear Modulus G Coefficient of variation
Category I	359.25	0.48
Category II	280.60	0.15
Category III	298.90	0.62

Table 4
Modulus parameters for lamination in each CLT panel (MPa).

Panel number	E _L	E _T	E _R	G _{LR}	G _{LT}	G _{RT}
I-3	9490	408	740	607	579	28
II-5	9881	425	771	632	603	30
I-9	8618	371	672	552	526	26
III-10	8870	381	692	568	541	27
II-15	9996	430	780	640	610	30
III-16	9307	400	726	596	568	28

specimen. The yolks were used to eliminate the influence of horizontal deformations. Same with the long-span third point bending test, the load was measured with the loading cell in the actuator. The displacement was measured as the average value of the two LVDTs in the mid-span. The load and displacement were recorded during the test to obtain the complete load–displacement curve.

The shear modulus was calculated according to the shear analogy method, which is the U.S. CLT handbook's primary design method [19]. The shear stiffness can be calculated as:

$$GA_{eff-test-S} = \frac{K_s E_{eff}}{\left(\frac{E_{eff}}{E_{app-test-S}} - 1\right) l^2} \quad (4)$$

where K_s is 14.4, which is the shear influence factor for pin supported three-point bending; $E_{app-test-S}$ is the apparent bending stiffness directly calculated based on the slope of the load–displacement curve in the elastic range from the test; E_{eff} is the effective bending stiffness as in Equation (5).

$$E_{eff} = \sum_{i=1}^n E_i b_i h_i^3 / 12 + \sum_{i=1}^n E_i A_i z_i^2 \quad (5)$$

where E_i is the elastic modulus of each layer in the panel longitudinal direction; h_i is the layer depth; z_i is the distance in between the panel neutral axis and the layer neutral axis; b_i is the panel width, and the area A_i is the layer area.

Then the shear modulus (G) of the short-span panels was calculated with the panel cross-section area A as:

$$G = GA_{eff-test-S} / A \quad (6)$$

4.2. Test results and comparison with reference values

The results of short-span mid-point bending tests for each sample were calculated with Eq. (4)–(6) and were shown in Fig. 7. The average and the coefficient of variation were calculated as listed in Table 3. The coefficient of variation shows that shear modulus has a higher variation

(8–19%) compared with the MOE and MOR tested with third-point bending test results for all three categories, indicating that the short-span test might require more replications for more stable results. It might be that the local defects had more impact on the mechanical performance with the reduction of sample dimensions. The p-value of Category I and II was calculated as 0.55, and then it was 0.22 for Category I and III. The results indicate that the correlation between categories is not statistically significant. However, similar to the MOE and MOR tested in the third-point bending test, the average shear modulus is decreased with the decay continues. The average shear modulus of Category II is 21.89% smaller than that of Category I. The reduction from Category I to Category III was found as 16.8%. Notice that the abnormal data from sample 3-2B1 influenced the average shear modulus of Category III. Despite that data, the average value would be 248 MPa, which is smaller than Category II.

As shown in Fig. 7, the manufactured panels provide a much higher shear modulus comparing with the reference value of grade E1, which indicated that the shear properties meet the requirement of PRG 320. The reference shear modulus from the PRG 320 for the CLT grade E1 panel is 69.52 MPa [8]. The shear modulus of the samples was 2.9 to 13.8 times the reference value.

From both tests, it was found that the MOE is slightly smaller than the reference value while the MOR and shear modulus were much higher than the reference value. The result illustrated that the salvaged spruce CLT provided sufficient bending and shear stiffness and strength under out-of-plane load. The high shear modulus indicated that the CLT plates would have better performance with a shorter span. All the MOE, MOR, and shear modulus G decreased with the progressing of decay condition from Category I to Category III, even if the boards with obvious surface damage were disposed.

5. Finite element modeling of CLT panels under bending

The Finite Element Method is used to simulate the third-point and mid-point bending test to check single panels' detailed mechanical behavior. Two lab-made CLT panels in each category were chosen randomly to demonstrate the simulation. Accordingly, two third-point bending samples and four short-span samples were simulated for each category.

5.1. Orthogonal timber model

Timber is an anisotropic material with different properties in longitudinal, tangential, and radial directions. The complexity of the flexural behavior of CLT is mainly controlled by the orthogonal material properties of timber as well as the direct assignment of the laminations in adjacent layers. Therefore, to estimate the overall performance appropriately, the direction and distribution of the layers, i.e., the CLT layout design, need to be explicitly considered. Due to timber's orthogonal material properties, the axial strength is significantly stronger along the grain direction of each lamination than in other directions. With the longest distance from parallel layers to the neutral axis, the CLT panels' bending resistance is maximized along the grain direction of the top and bottom layer, which is also defined as the major strength direction. The transverse direction is defined as a minor strength direction.

Table 5
Strength parameters for each panel (MPa).

Panel number	$f_{t \text{ longitudinal}}(F_{1t})$	$f_{c \text{ longitudinal}}(F_{1c})$	$f_{t \text{ transverse}}(F_{2t})$	$f_{c \text{ transverse}}(F_{2c})$	$f_{s \text{ longitudinal}}(F_6)$	$f_{s \text{ transverse}}(F_4)$
I-3	62.39	34.38	2.39	2.85	6.44	1.48
II-5	64.95	35.79	2.49	2.97	6.70	1.54
I-9	56.65	31.22	2.17	2.59	5.85	1.34
III-10	58.31	32.13	2.23	2.67	6.02	1.38
II-15	65.71	36.21	2.52	3.01	6.78	1.56
III-16	61.18	33.71	2.34	2.80	6.31	1.45

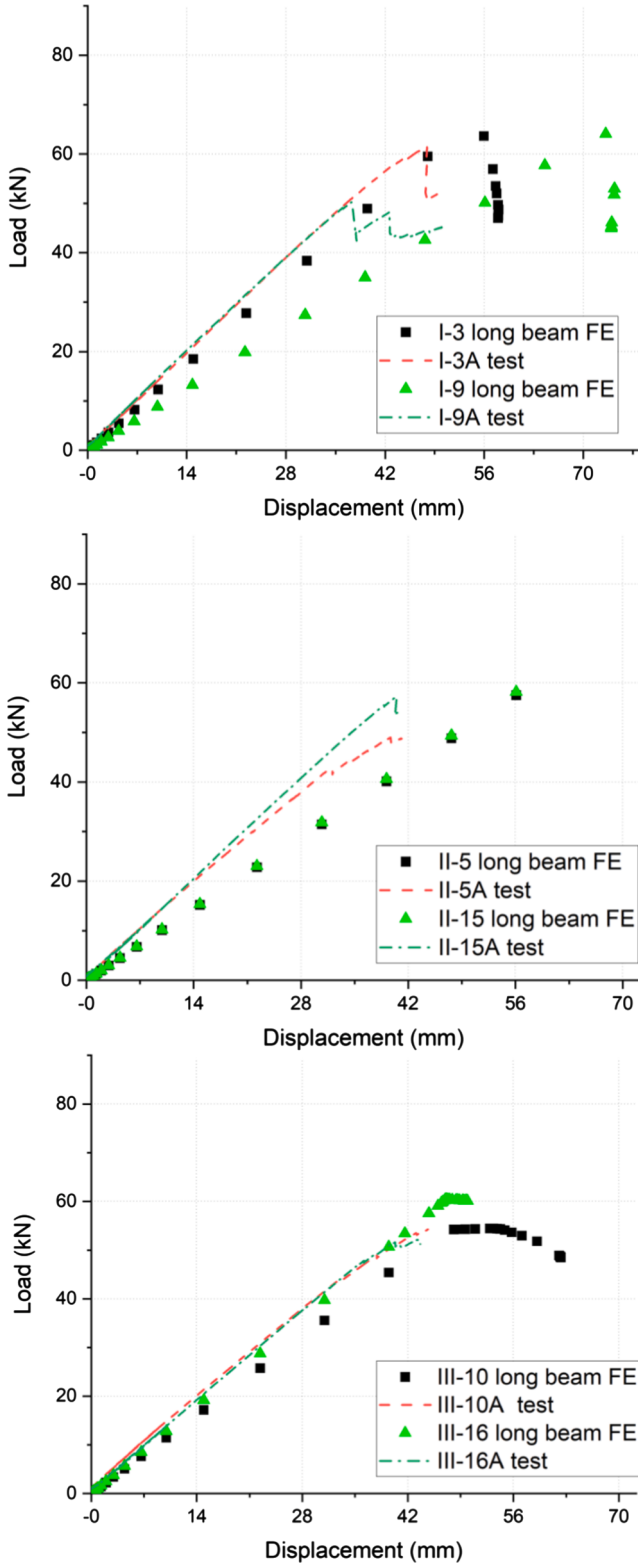


Fig. 8. Third-point bending load–displacement curves from test and simulation for (a) Category I; (b) Category II; (c) Category III.

The timber material is homogenized with the average properties to avoid the requirement of detailed modeling with grain, growth ring, and knots. Numerous parameters and uncertainties such as the grain direction, knots, and checks, as well as the current moisture content distribution, growing environment, and time of the tree lead to the high variance of timber material properties. By grading the lumbers

technically, the variance can be reduced to an acceptable level for design and construction purposes. The simplification may neglect some critical features that cause local fragility and fracture development. However, it can significantly reduce the computational cost while providing reasonable estimation for design and construction purposes.

The timber orthotropic behavior is modeled with an orthotropic elastic material model in the finite element analysis platform ABAQUS [20]. Three principal radial axes L (longitudinal direction), R (radial direction), and T (tangential direction) of timber were transformed into a Cartesian coordinate system for simplifications. The elastic compliance of the material was demonstrated as Eq. (7).

$$\begin{bmatrix} 1/E_L & -\nu_{RL}/E_R & -\nu_{TL}/E_T & 0 & 0 & 0 \\ -\nu_{LR}/E_L & 1/E_R & -\nu_{TR}/E_T & 0 & 0 & 0 \\ -\nu_{LT}/E_L & -\nu_{RT}/E_R & 1/E_T & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{LR} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{LT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{RT} \end{bmatrix} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{xz} \\ \sigma_{yz} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} \quad (7)$$

where, E_i , G_{ij} and ν_{ij} separately represent the elastic modulus, shear modulus, and Poisson's ratio; ε_{ii} , γ_{ij} are the axial and shear strains; and σ_{ij} are the stress in the corresponding direction. Elastic modulus in the three directions (E_L , E_R , and E_T), shear modulus in the three directions (G_{LR} , G_{LT} , and G_{RT}) and three Poisson's ratios ν_{LR} , ν_{LT} , and ν_{RT} were needed to be inputted into the material model.

The input parameters were determined based on the MOE rating of the lamination included in the panel and reference values of white spruce and Englemann spruce from the Wood handbook [21]. In the simulations, the timber samples' moisture content was assumed to be constant at 12%, which is the standardized, average moisture level for timber structures.

In the Wood Handbook [21], there are convert ratios for estimating the elastic modulus and shear modulus in all directions based on the longitudinal MOE. Notice that the modulus converting ratio of white spruce is not included in the Wood Handbook [21]. Since Englemann spruce is considered very close to the white spruce [22], the convert ratios data of Englemann spruce are used to calculate the modulus in this study. The elastic modulus in tangential and radius directions are 0.059 and 0.128 of the longitudinal elastic modulus. The shear modulus in Longitudinal-Radius (LR), Longitudinal-Tangential (LT), and Tangential-Radius (TR) directions are determined as 0.124, 0.12, and 0.01 of the tested longitudinal MOE_{ND} [21]. The modulus inputs for laminations of each panel were calculated as listed in Table 4 based on the average lamination MOE_{ND} from Table 2 and the convert ratios. To capture the layer direction, the correlation between the local axis system LTR and the global axis XYZ depends on the direction of the layer. For the outer layers, which have the longitudinal direction along the X axis, the L, T and R separately corresponding to the X, Y and Z direction. For mid layer lied in the orthogonal direction, the L, T and R were separately fit in Y, X and Z directions.

In the literature, the mean longitudinal MOE of white spruce were tested as 6214 MPa [23], 7954 MPa [24], 9642 MPa [25], and 9852 MPa [26]. In this study, the CLT panels' input data were ranging from 8617 MPa to 9996 MPa, which matches the range of reference values cited above. The ν_{12} , ν_{13} , and ν_{23} of white spruce were set as the reference value provided in the Wood Handbook [21], which are separately 0.467, 0.372, and 0.245.

5.2. Progressive damage model

The Hashin damage criteria were assigned to determine the failure based on timber's orthotropic mechanical capacity in the numerical simulation [27]. Tensile along the Fiber direction (F_f^t), the compressive along the Fiber direction (F_f^c), the transverse tensile (F_m^t), and transverse compressive (F_m^c) are the four damage indexes that are considered in the

Table 6

Third-point simulation result and comparison to the test results.

Sample code	Peak load (kN)	Displacement with peak load (mm)	MOE _{CLT}	MOE _{CLT} relative difference	MOR _{CLT}	MOR _{CLT} relative difference
I-3A	59.51	48.8	8386	11.90%	39.22	3.10%
I-9A	64.09	74.4	5927	38.93%	42.24	−25.61%
II-5A	57.50	57.0	6935	24.97%	37.89	−18.25%
II-15A	58.16	57.0	7016	31.10%	38.33	−0.66%
III-10A	54.45	54.1	6921	25.49%	35.88	1.33%
III-16A	60.35	47.7	8693	6.36%	39.78	−14.63%

damage criteria. Based on the four considered damage patterns, the failure criteria were defined with six parameters. The parameters include tensile strength in the longitudinal direction (F_{1t}) and transverse direction (F_{2t}), the compressive strengths in the longitudinal direction (F_{1c}) and transverse direction (F_{2c}), and the longitudinal shear strength (F_6) and transverse shear strength (F_4). The four damage indexes are calculated by Eqs. (8)–(11). When any of these indexes exceeds 1.0, the damage is considered to occur.

(1) Longitudinal tension: (When $\sigma_{11} \geq 0$)

$$F_f^t = \left(\frac{\sigma_{11}}{F_{1t}} \right)^2 + \alpha \left(\frac{\sigma_{12}}{F_6} \right)^2 \quad (8)$$

(2) Longitudinal compression: (When $\sigma_{11} \leq 0$)

$$F_f^c = \left(\frac{\sigma_{11}}{F_{1c}} \right)^2 \quad (9)$$

(3) Transverse tension and/or shear: (When $\sigma_{22} \geq 0$)

$$F_m^t = \left(\frac{\sigma_{22}}{F_{2t}} \right)^2 + \left(\frac{\sigma_{12}}{F_6} \right)^2 \quad (10)$$

(4) Transverse compression: (When $\sigma_{22} < 0$)

$$F_m^c = \left(\frac{\sigma_{22}}{2F_4} \right)^2 + \left[\left(\frac{F_{2c}}{2F_4} \right)^2 - 1 \right] \frac{\sigma_{22}}{F_{2c}} + \left(\frac{\sigma_{12}}{F_6} \right)^2 \quad (11)$$

where σ_{ij} are the stress tensor components, with 1 as the longitudinal direction and 2 as the transverse direction; α is a preset parameter defining the shear stress proportion in longitudinal tensile criteria.

Similar to the modulus input data, the strength parameters were determined based on the laminations' non-destructive dynamic flexural test and the reference value. It was found that timber strength and MOE are approximately proportional for single species lumber [28,29]. Accordingly, the strengths of laminations in each panel were assumed to be proportional to the corresponding reference strength values. The ratio for each sample was obtained with the average MOE from Table 1, and the reference MOE in the Wood Handbook [21]. The input strength parameters were then calculated by multiplying the reference strengths with the ratio. The strength parameters for each simulated panel are listed in Table 5.

5.3. Third-point CLT bending simulations

The long-span third point bending test was firstly simulated with the material and damage model. Since the variation of sample geometry is considered minor, the geometry of the model was set according to the design of the specimen, as mentioned in section 2.2. The model was meshed to around 5 mm size 3D shell elements to capture the bending and shear behavior under out of plane loads. The left supports were fixed in all three directions, while the right support was only fixed for the vertical direction, which provides an ideal simply supported condition for the model. The load was applied with vertical nodal displacement to provide displacement-controlled simulation. The value of load was recorded by reading the sum of the reaction of the controlled loading nodes. The mid-span nodes were monitored for displacement. The average displacement in the vertical direction was recorded as the mid-

span displacement. The simulated load–displacement curves are as shown in Fig. 8. According to the sample label and layer direction, the material model was inputted with the parameters from Table 4, and the damage model was inputted as parameters in Table 5.

As shown in Fig. 8, the simulation provides a close trend as the test. However, for some of the samples, the result is not very close. As shown in Table 6, the simulated MOE and MOR were calculated according to Eq. (2) and (3). The simulated MOE contains an underestimation of 6.4% to 38.9%. On the contrary, for the MOR_{CLT}, most of the model was providing an overestimation compared with the test data. The model of I-3A, II-15A, and III-10A had a very close estimation of the MOR, which generated a relative difference of 0.66% to 3.15%. The models' estimations can be an adequate reference to these CLT panel types considering the high variance of the testing result.

5.4. Short-span mid-point bending simulation

For short-span mid-point bending tests, the simulation was conducted following the sample geometry as in Section 2.2 and test setup as in Section 4.1. The boundary condition and the loading were applied similarly to the third-point bending model, which was ideal simply supported with displacement controlled nodal loads. The material and damage models were input with the parameters same with the correlated long-span third point bending model to simulate the two short-span samples made from the same CLT panel. The load–displacement curves from the model and the tests are shown in Fig. 9 by category. The detailed results of shear modulus and the comparison between the simulation and the test results were calculated following Eqs. (4)–(6) and listed in Table 7. The difference is calculated as the relative difference between the simulated result and the average value of the two correlated test results.

As shown in Figure 10, some of the simulated load–displacement curves fitted the curves well. As shown in Table 7, the relative difference between the shear modulus of the I-3B model and the test results was 21.46%. For I-9B and the samples in Category II, the differences were relatively large. For Category III, the simulated shear modulus relative difference to test results were −8.89% and −12.25% separately for III-10B and III-16B. The results illustrate that the simulation cannot account for the considerable variation in some specific samples. The simulated results provided a conservative and reasonable estimation for the three-point bending behaviors of different sample types, considering the samples' high variance. The sample-to-sample simulation results have some difference with the test data, which may be caused by the variance of the lumber's material properties that cannot be captured by the parameters determined by the proportional estimation. Meanwhile, the decay conditions affect more in the lamination strength than the modulus. As a result, the model can provide a conservative prediction for the CLT panels based on the non-destructive elastic modulus test results and the laminations' calibrated strength values.

6. Conclusions

CLT panels made from salvaged white spruce were manufactured and evaluated for the mechanical properties to promote the salvaged spruce's utilization. The panels were made from salvaged beetle-killed

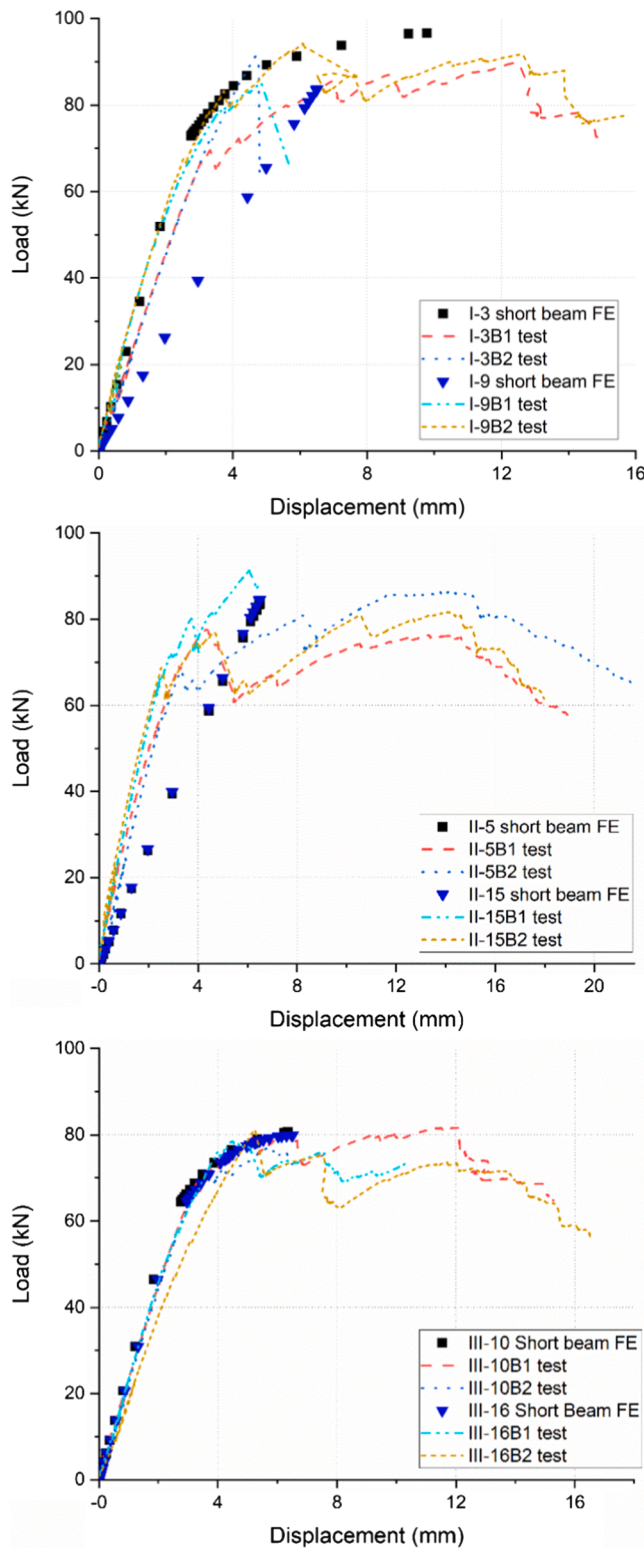


Fig. 9. Short-span bending load-displacement curves from test and simulation (a) for Category I; (a) for Category II; (a) for Category III.

white spruce resulting from a recent spruce budworm outbreak in Upper Peninsula, Michigan. The salvaged timber used for CLT panel fabrication was obtained from dead and dying trees of three distinctly different conditions: category I—live; category II—recently dead; and category III—dead for some time. The elastic Modulus (MOE), Modulus of rupture (MOR), and shear modulus (G) of the CLT plate samples were

Table 7

Short-span simulation result and comparison to the test results.

Sample code	Peak load (kN)	Peak displacement (mm)	G (MPa)	G relative difference to test result
I-3B	72.85	2.80	299.5	21.46%
I-9B	58.70	4.50	99.9	-77.37%
II-5B	83.65	6.61	100.5	-62.11%
II-15B	59.38	4.50	105.2	-65.83%
III-10B	64.49	2.80	229.3	-8.89%
III-16B	64.04	3.00	212.0	-12.25%

investigated based on the ASTM D198. The mechanical properties of CLT panels were tested with long span third-point bending test and short span mid-point shear test. The finite element simulation was correspondingly conducted with orthogonal constitutive law and damage models based on the layer properties to predict the mechanical performance in both tests. The following conclusions can be drawn from the study:

- The average MOE of sawn lumber from the live trees of Category I was equivalent to the MOE value of white spruce given in the Wood Handbook. The average MOE of sawn lumber from dead standing trees of Category II and III decreased 6.6% and 4.5%, respectively comparing with Category I. No significant difference was found in average MOE between category II and III.
- The deterioration of dead and dying white spruce trees have limited effects on mechanical property reduction of the fabricated CLT panels. The average MOE reductions of Category II and III were not significant by comparing with Category I. Similar results was also found for the MOR reductions of Category II and Category III. However, the average shear modulus of Category II and Category III decreased by 21.9% and 16.8% comparing with Category I.
- The modulus of elasticity of the Category I salvaged spruce CLT panels was 15.6% lower than the reference value for grade E1 CLT in PRG 320. However, all the stiffness and strength data exceeded the reference value for grade E3 in PRG320. The bending MOR of the CLT panels were at least 53% higher than the reference values. The shear modulus was 2.9 to 13.8 times the reference value of the grade E1 panel. Comparing with reference values of CLT made with other softwood species from literature, the Category I salvaged spruce CLT panels provided comparable MOE (-22.3% to +3% differences) and superior MOR (5.6%-78.3% higher than reference values).
- Finite element models for both long-span bending test and short-span shear tests can provide a conservative prediction of the modulus of elasticity, modulus of rupture, and shear modulus of the salvaged spruce CLT panels. The predicted MOE had 6.4–38.9% over-estimation comparing with the average test results. The simulated MOR had a different range from -3.1% to +25.6%. The shear modulus of the model had larger differences, which varies from 8.9% to 77.4%.

In summary, the results of this study suggest that CLT panels fabricated from salvaged beetle-killed white spruce can meet the baseline performance requirement of the PRG 320 standard and provide adequate stiffness and strength for uses as structural components, especially for components under bending with short spans. The FE modeling of the CLT panels according to the orthogonal constitutive law and progressive damage model can be used to estimate the flexural and shear properties of CLT panels based on the lamination E-rating results. A comprehensive qualification testing program is recommended to further validate the use of salvaged beetle-killed white spruce lumber in manufacturing CLT panels.

CRedit authorship contribution statement

Yunxiang Ma: Methodology, Data curation, Software, Formal

analysis, Writing - original draft, Writing - review & editing. **Xiping Wang:** Conceptualization, Writing - review & editing, Supervision, Project administration. **Marshall Begel:** Methodology, Investigation, Data curation, Formal analysis. **Qingli Dai:** Writing - original draft, Writing - review & editing, Supervision. **Yvette Dickinson:** Conceptualization, Resources, Funding acquisition. **Xinfeng Xie:** Writing - review & editing, Supervision. **Robert J. Ross:** Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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