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DEVELOPMENT OF CROSS-LAMINATED TIMBER (CLT) PRODUCTS FROM STRESS GRADED CANADIAN HEM-FIR

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ABSTRACT

To explore the feasibility of hem-fir for CLT products, this work addressed the exploratory and pilot plant studies of hem-fir cross-laminated timber (CLT) products through mechanical tests. The hem-fir lumber was procured and then stress-graded based on dynamic modulus of elasticity (MOE). The resulted 5-ply prototype CLT products were then tested non-destructively and 3-ply pilot plant hem-fir CLT was tested destructively. The results showed that bending performance of hem-fir CLT panel can be predicted. Considering cost-competitiveness and end applications of hem-fir CLT products, the panel structure can be optimized based on the stress-graded data of hem-fir lumber.

KEYWORDS: Hem-fir, cross-laminated timber (CLT), modulus of elasticity (MOE), modulus of rupture (MOR), stress-graded lumber.

INTRODUCTION

At present, forest resource is changing worldwide over time from old-growth to second growth with an increasing volume of shorter rotation plantations (Middleton and Munro 2001, Alteyrac et al. 2005, Liu and Zhang 2005, Beaulieu et al. 2006, Wei et al. 2013, Yang et al. 2018). To maximize the value return from the resource currently available, forest stands should be managed to produce trees with desired attributes for end products. For product development and market access, characteristics of the second growth plantations should be competitive not only to those of old-growth, but also to those of competing species (Wang et al. 2015, Gong et al. 2016, Liao et al. 2017).

Hem-fir is a combination of western hemlock (*Tsuga heterophylla* (Raf.) Sarg) and amabilis fir (*Abiesamabilis* (Dougl.) Forbes) and represents the largest component of forests in coastal forest region of British Columbia (BC), Canada (Chen et al. 2009). These two species are generally harvested and processed together and marketed as “hem-fir” (called coast hem-fir), which are generally used to produce both solid wood products and pulp and paper. Hem-fir solid wood is used primarily as structural lumber and plywood in home and commercial building construction. Products include framing lumber, joinery, windows, doors, staircases, cabinet doors, ladders, floors, roof decking, railway ties, boxes, interior woodworking and finishes, veneer/plywood, and laminating stock or glulam (Wang and Dai 2008).

Despite the widespread use, opportunities exist to recover more value from the short rotation hem-fir through increased utilization in engineered wood products (EWPs) because they present opportunities for potentially transformative product developments and process improvements. The key advantage of EWPs is that their performance is not necessarily limited by fiber quality. Potential EWPs include structural composite lumbers such as laminated veneer lumber (LVL), thick light-weight strand panels, and cross-laminated timber (CLT) that can replace concrete slabs in residential and non-residential constructions (Wang and Dai 2013). CLT is a solid wood-based composite product made by laminating and gluing multiple wood layers with adjacent layers normally oriented at 90º (Brandner et al. 2016). CLT is manufactured according to a wide range of specifications for such structural applications as floor, ceiling, wall and roof (Kanócz and Bajzecerová 2019).

While various proprietary processes are currently adopted, a typical manufacturing process of CLT products generally includes lumber selection, lumber grouping and planning, adhesive application, panel lay-up and pressing, product quality control, cutting and packaging, and so on (Liao et al. 2017). In North America, CLT product standard and plant qualification standard have been established to help fabricate products with desired grade and superior adhesive bond quality.

Unlike glulam with a column-beam structure (Glisovic et al. 2016), CLT panels were often used as floors, roofs and walls (Song and Hong 2018). For floor and roof applications, key characteristics of bending deflection must first be taken into account requiring higher modulus of elasticity (MOE) of CLT elements (Gagnon and Pirvu 2011). For wall applications, in-plane and out-of-plane shear performance of CLT elements needs to be emphasized with slightly lower MOE of CLT being used (Song and Hong 2018).

Based on the intended end uses of CLT, raw materials, specifically lumber and adhesive, and manufacturing technology can be adjusted. CLT panels can be designed with varying lumber grades and macro characteristics (Wang et al. 2018), thickness and lay-ups for desired engineering performance (Gagnon and Pirvu 2011).

Spruce-pine-fir (SPF) and Norway spruce are respectively the common species for CLT manufacturing in North America and Europe (Brandner et al. 2016). The North American standard of performance-rated CLT suggests softwood species with a minimum specific gravity (SG) of 0.35 for CLT manufacturing (ANSI/APA PRG 320 2018). Although hem-fir has a higher SG (≥ 0.35) than SPF and has tremendous strength properties, currently it is not included in the recommended species group for CLT by APA-The Engineered Wood Association because information is lacked regarding whether coast hem-fir is suitable for CLT manufacturing. Thus, research is urgently needed to explore the feasibility of hem-fir for CLT products through adhesive bond quality and mechanical tests.

The previous work demonstrated that CLT products manufactured from BC hem-fir lumber could achieve good bond quality and durability (Wang and Pirvu 2010). In the hem-fir CLT manufacturing, the adhesive type and applied pressure significantly affected percent wood failure (WF) and delamination. For PUR adhesive, a pressure higher than 0.83 MPa could be used to achieve good delamination resistance (Wang et al. 2018). The key objective of this work was to demonstrate the feasibility of manufacturing CLT products from BC coast hem-fir lumber through exploratory study in Canada and pilot plant mechanical tests in China. The study was intended to provide immediate guidance for the Canadian and Chinese CLT manufacturers to fabricate consistent products, increase CLT performance and reduce manufacturing costs.

MATERIALS AND METHODS

This work was carried out in FPInnovations (Canada) and in the pilot plant of Ningbo Sino-Canada Low-Carbon Technology Research Institute (China). The purpose of the exploratory study of hem-fir CLT in FPInnovations was to illustrate the influence of lumber MOE on the final product MOE to what extent. And then the pilot plant study was continued in China based on the initial results and gained experience of exploratory study.

Exploratory study

Material preparations

In FPInnovations, hem-fir lumber samples were directly purchased from a sawmill in BC with the following three categories: 4000 × 38 × 140 mm (Kiln-dried No. 1 grade), 4000 × 38 × 140 mm (Kiln-dried No.3 grade), and 2700 × 19 × 140 mm (Kiln-dried prior grade). At the time of purchase, the moisture content (MC) was maximum 23% for all hem-fir lumber.

Visual grading of hem-fir lumber stock was first performed in accordance with NLGA rule (2003). In FPInnovations, the E-rating of hem-fir lumber was done with a transverse vibration method over a 3600 mm span using E-computer equipment (Metriguard 239) (Fig. 1).

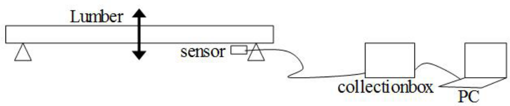

Fig. 1: Dynamic MOE testing by E-computer testing.

To help establish the relationship between CLT product MOE and lumber MOE, three hem-fir CLT construction grades (A, B and C) were distinguished based on the measured dynamic modulus of elasticity (MOE) of lumber within a certain range. The selected lumber was planed to 34 mm thick for 38 × 140 mm and 15 mm thick for 19 × 140 mm, and then grouped for different layers of CLT manufacturing. In the meantime, control western SPF and eastern SPF lumber pieces were grouped to make SPF CLT.

Prototype hem-fir CLT panel manufacturing

In FPInnovations, to reveal the relationship between CLT product MOE and lumber MOE, 5-ply prototype hem-fir CLT panels with a target size of 4000 × 1200 × 132 mm were designed with lay-up configurations shown in Tab. 1. Three hem-fir CLT construction grades (A, B and C) were considered with symmetrical lay-ups, with the outer main laminations (top and bottom faces) having higher MOE rating than the inner main laminations (center). The MOE boundaries indicated in Tab. 1 are based on the designations in the glulam standard for different glulam grades (AITC 2007), which were adapted to the actual MOE range obtained for the hem-fir sample and the number of pieces obtained for each MOE group. The resulted panel lay-up sequence was 34 - 15 - 34 - 15 - 34 (mm) in thickness laminated with adjacent layers oriented at 90° to each other, as shown in Fig. 2.

Tab. 1: The lay-up configurations of 5-ply prototype hem-fir CLT panels.

CLT layer	Lumber visual grade	Lumber thickness (mm)	CLT panel grade			
			A	B	C	
			Required lumber MOE (MPa)			
1	Top face	No.2 & better	34	11721 ≤ MOE < 13792	9652 ≤ MOE < 11721	6896 ≤ MOE < 9652
2	Top cross	No.2 &better	15	MOE ≥ 6896	MOE ≥ 6896	MOE ≥ 6896
3	Centre	No.2 & better	34	9652 ≤ MOE < 11721	6895 ≤ MOE < 9652	MOE < 8274
4	Bottom cross	No.2 & better	15	MOE ≥ 6896	MOE ≥ 6896	MOE ≥ 6896
5	Bottom face	No.2 & better	34	11721 ≤ MOE < 13792	9652 ≤ MOE < 11721	6896 ≤ MOE < 9652

The grade A CLT was made from lumber with the highest possible MOE with potentially lowest recovery of lumber stock. The grade C CLT was made from lumber with the lowest possible MOE with potentially highest recovery of lumber stock. The grade B CLT was made as a medium grade CLT with relatively high utilization of lumber stock. For each CLT panel, each of the three longitudinal layers (top face layer #1, centre layer #3 and bottom face layer #5) was formed by 9 pieces of 4000 mm long 34 × 140 mm whereas each of the two cross-layers (top cross layer #2 and bottom cross layer #4) was formed by 29 pieces of 1200 m long 15 × 140 mm. Each grade of CLT panel was repeated three times.

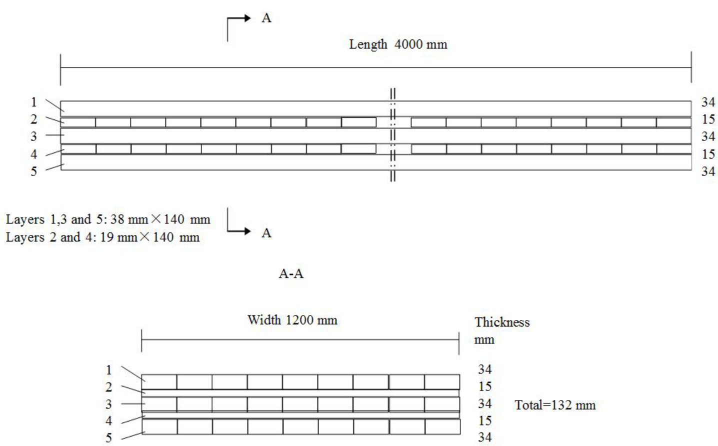

Fig. 2: The lay-up structure of prototype hem-fir CLT panel.

Based on the visual requirements in combination with MOE values of lumber as set out in Tab.1, lumber were selected and placed in MOE groups from where they were randomly selected for various layers of the three CLT panels. For use as cross laminations, each 2700 mm long 15 × 140 mm hem-fir piece was trimmed into two 1200 mm short pieces. At the manufacturing site where an industrial press (4000 × 1200 mm) was used, all pieces were further face- and edge-planed to the target sizes within 24 h of glue application and pressing.

A commercial polyurethane (PUR) resin was acquired from an adhesive supplier. The CLT panel's lay-up arrangement and sequence, such as the number and location of each lumber piece per layer, was recorded for each CLT panel. During CLT manufacturing, the ambient temperature was about 7-8°C and the average glue application rate was about 200 $g{\cdot}m^{-2}$. The panel assembly time was about 15 min without edge-gluing lumber pieces within each layer. However, to minimize the potential gaps between lumber pieces in the top face, center and bottom face layers, a maximum allowable side pressure of 0.35 MPa was applied during pressing. The vertical pressure applied was 0.38 MPa (maximum value offered by the press) with a pressing time of 150 min. After unloading, all CLT panels were stored at ambient temperature and relative mosture content for about two months before flexure testing.

Flexure test of prototype hem-fir CLT panel

The effective bending stiffness of CLT (EI_{eff}) for the major strength axis with alternating orthogonal layers shall be calculated as follows (Gagnon and Popovski 2011):

$$EI_{eff} = \sum_{i=1}^{n} E_i b_i \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i b_i t_i z_i^2 \quad (1)$$

where: b_i- width of the panel for the major strength axis, (mm)
E_i- modulus of elasticity of laminations in the i-th ply, (MPa)
$E_{\parallel}$ - for laminations in the longitudinal layers, (MPa)
$E_{\perp}$ - for laminations in the transverse layers, which is 1/30 of MOE of lumber in the direction parallel to grain $E_{\parallel}$, (MPa)
n- number of layers in the panel
t_i- thickness of laminations in the i-th layer, (mm)
z_i- distance between the center point of the i-th layer and the neutral axis, (mm).

For 5-ply hem-fir CLT in this work, n = 5, b_i = 1200 mm, t_i = 34 mm (i = 1, 3, 5) or 15 mm (i = 2, 4), z_i= 49 mm (i = 1, 5) or 24.5 mm (i = 2, 4) or 0 mm (i = 3) and $I = b_i (t_1 + t_2 + t_3 + t_4 + t_5)^3/12$ = 229996800 mm^4. Thus, the Eq. 1 can be further derived as follows:

$$E_{eff} = 0.44(E_1 + E_5) + 0.048(E_2 + E_4) + 0.017\,E_3 \quad (2)$$

Based on the coefficient of lumber MOE in the Eq. 2, it can be derived that lumber MOE of face and back layers largely determined the final CLT product MOE.

Each 4000 × 1200 mm CLT panel was tested three times non-destructively under four-point loading in bending over a span of 3600 mm to determine stiffness and MOE.

Pilot plant study

Material preparations

In China, hem-fir lumber samples were directly imported from a sawmill in BC of Canada with a size of 38 ×140 mm (5490 mm). All hem-fir lumber was dried in a kiln to reach a measured MC of 12% before using.

Considering the grade outturn and practical applications, all the hem-fir lumber with a sample number of 557 in this work was classified into three grades (E_1, E_2, E_3) based on the dynamic MOE values which were determined by another transverse vibration method using FFT spectrum analyzer (AZ CRAS, Nanjing, China) (Fig. 3). And then lumbers prepared for manufacturing CLT were planed to 35 mm thick.

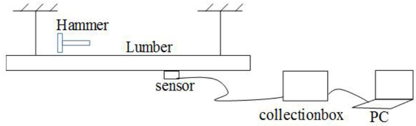

Fig. 3: Dynamic MOE testing by FFT spectrum analyzer.

Pilot plant hem-fir CLT panel manufacturing

In China, the panel lay-up sequence was 35 - 35 - 35 (mm) in thickness laminated with adjacent layers oriented at 90° to each other. And two configurations of hem-fir CLT were designed for different applications (floor and wall) based on the lumber E grade, as shown in Tab. 2. For each CLT panel, each of the two longitudinal layers (top face layer #1 and bottom face layer #3) was formed by 9 pieces of 5490 mm long 35 × 140 mm whereas the cross-layer (Centre layer #2) was formed by 39 pieces of 1280 mm long 35 × 140 mm. Two hem-fir CLT replicates were manufactured for each configuration with the same processing parameters as the above description for exploratory study.

Tab. 2: The lay-up configurations of 3-ply pilot plant hem-fir CLT panels.

CLT layer			Lumber visual grade	Lumber thicakness (mm)	Required lumber grade	Required lumber grade
Floor panel	1	Top face	No.2 & better	35	E1
	2	Centre	No.2 & better	35	E3
	3	Bottom face	No.2 & better	35	E1
Wall panel	1	Top face	No.2 & better	35	E2
	2	Centre	No.2 & better	35	E3
	3	Bottom face	No.2 & better	35	E2

Bending test of pilot plant hem-fir CLT panel

For each 5490 × 1280 mm 3-ply CLT panel, two pieces of CLT bending specimens were cut from both symmetrical sides along with the fiber direction of the top face. Six CLT specimens of wall panel with a size of 3150 × 298 × 105 mm were obtained. Similarly, another six CLT specimens of floor panel with a size of 3150 × 298 × 105 mm were also obtained. Bending tests were conducted flatwise (loads were applied perpendicular to the face layer of CLT) in accordance with the four-point load method. The load continued to increase at a speed of 2 mm·min^{-1} until the CLT failure occurred (Fig. 5). The deflection of the specimen at the center of the span was measured via linear variable differential transformers (LVDTs). Both the MOE and MOR of CLT in the major strength direction were evaluated at a span-to-depth ratio of 30 according to ASTM D198 (2015).

RESULTS AND DISCUSSION

Exploratory study

Fig. 4 shows the frequency distributions of dynamic MOE for both 38 × 140 mm and 19 × 140 mm hem-fir dimension lumber pieces in FPInnovations. Based on the target MOE range (6896 MPa -13792 MPa), hem-fir seemed to have a low reject rate and high grade outturn. The average MOE of 38 × 140 mm hem-fir lumber was 11170 MPa with a standard deviation of

2413 MPa. Based on a parallel study (Wang and Pirvu 2010), the average MOE of 38 × 140 mm western SPF lumber was 10135 MPa with a standard deviation of 2137 MPa. For this study with limited number of hem-fir samples, it was estimated that: *1)* only about 1% of total hem-fir lumber has a MOE value below 6896 MPa; and *2)* about 29% of total hem-fir lumber (24% for 38 × 140 mm and 33% for 19 × 140 mm) has a MOE value equal or greater than 13792 MPa. The hem-fir grade outturn was about 70%. These high MOE lumber pieces can be used to make higher grade CLT. Amabilis fir only accounted for a small proportion (average 7.1%) of the total hem-fir lumber stock.

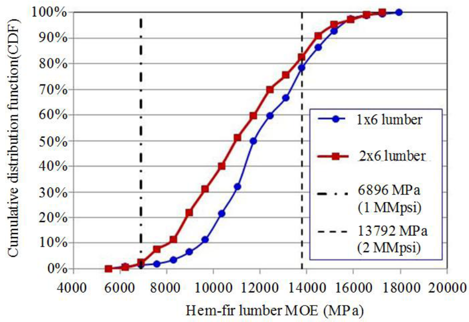

Fig. 4: Frequency distributions of hem-fir lumber dynamic MOE for exploratory study.

As shown in Fig. 5, the CLT bending performance is mainly governed by the lumber MOE in the tension/compression layers (i.e. outer face and back layers), which agrees well with the theoretical derivation.

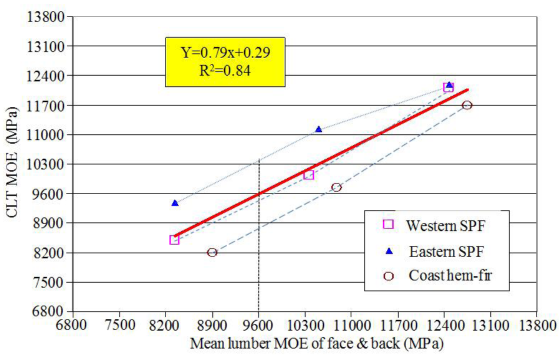

Fig. 5: The relationship between lumber MOE and final hem-fir CLT MOE.

There was a good correlation between the hem-fir CLT panel MOE and average MOE of dimension lumber used for the face and back layers (R2 = 0.84). The higher the lumber MOE in the outer layers, the higher the CLT MOE. Similarly, for spruce-pine-fir (SPF) commonly used for CLT manufacturing in North America, CLT bending performance was also determined by the lumber MOE of outer layers. In addition, according to the trend lines when lumber with the same MOE was used for the outer layers, the eastern SPF-CLT had the greatest bending modulus, western SPF-CLT followed and hem-fir CLT was the last. This difference to a great extent can be attributed to wood texture feature that affected the mechanical properties of wood along the grain. Development of different CLT grades based on the MOE rating of dimension lumber is beneficial for structural applications as floor and roof components. For wall components, the bending MOE may not be as critical as other properties, such as shear and compression. Thus, selection of the hem-fir dimension lumber for use in CLT should be based on the end application of CLT panels. The use of hem-fir lumber for CLT panels provided promising results. However, given the limited sample size, further studies are needed to confirm appropriateness of hem-fir as a species for CLT manufacturing and acceptance in the Canadian CLT standard.

It was found that the CLT bending performance was basically governed by the lumber MOE of outer layers (R^2 = 0.84), namely the lumber closer to the core layer influenced less on the final CLT bending performance. The shear stiffness of core-layers, which can be viewed as another main factor, affected the deformation of CLT owing to its lower stiffness of lumber in the cross-section (Gagnon and Pirvu 2011). Thus, the number of layers can be reduced under the premise of end application and the species which has higher shear stiffness in the cross-section can be selected as the core-layers to make hybrid CLT.

Pilot plant study

The frequency distributions of dynamic MOE for both 38 × 140 mm hem-fir dimension lumber pieces in Ningbo Sino-Canada Low-Carbon Research Institute are shown in Fig. 6. About 30% of total hem-fir lumber has a MOE value below 9120 MPa and about 35% of total hem-fir lumber has a MOE value equal or greater than 11600 MPa. The two MOE boundaries were selected to achieve a mean lumber MOE of 13800 MPa for E1 grade and a mean lumber MOE of 10340 MPa for E2 grade. Thus, the hem-fir lumbers were classified into three grades, namely, E_1 (MOE ≥11600 MPa), E_2 (9120 MPa ≤ MOE ≤ 11600 MPa), and E_3 (MOE < 9120 MPa).

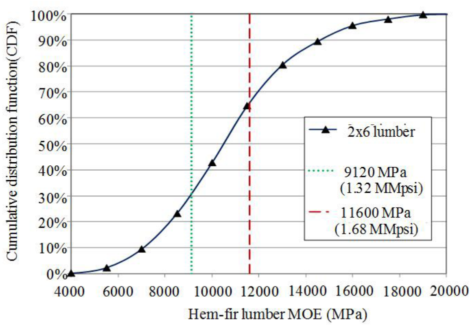

Fig. 6: Frequency distributions of hem-fir lumber dynamic MOE for pilot plant study.

The MOE and MOR of 3-ply pilot plant hem-fir CLT are listed in Tab. 3. Although there was not a good correlation between the hem-fir CLT panel MOE and average MOE of dimension lumber used for the face and back layers owing to the limitations of specimen's number, it was no doubt that the higher the lumber MOE in the outer layers, the higher the CLT MOE and MOR. According to the publication (Liao et al. 2017), at least the 3-ply pilot plant hem-fir floor CLT panel in this study can meet the requirements of CLT grade E1 in the major strength direction and the 3-ply pilot plant hem-fir wall CLT panel can meet the requirements of CLT grade E2, which provided a strong evidence that hem-fir had a feasibility of manufacturing CLT, so called value-added EWP.

Tab. 3: Bending properties of 3-ply hem-fir CLT.

<table>
<tr><td rowspan="2">CLT configuration</td><td colspan="4">MOE (MPa)</td><td colspan="3">MOR (MPa)</td></tr>
<tr><td>Mean lumber MOE of face & back</td><td>Measured CLT MOE</td><td>CLT grade E_1*</td><td>CLT grade E_2*</td><td>Measured CLT MOR</td><td>CLT grade E_1*</td><td>CLT grade E_2*</td></tr>
<tr><td>Floor panel</td><td>14993.30
(703.99)**</td><td>12044.34
(1373.19)**</td><td rowspan="2">11721.5</td><td rowspan="2">10342.5</td><td>39.91
(5.33)**</td><td rowspan="2">28.24</td><td rowspan="2">23.89</td></tr>
<tr><td>Wall panel</td><td>10312.25
(329.02)**</td><td>10833.24
(899.60)**</td><td>34.78
(2.47)**</td></tr>
</table>

Note: * The data indicate required characteristic test value for PRG 320 CLT in the major strength direction.
**The data in the brackets indicate the standard deviations.

As indicated by Fig. 6 and Tab. 3, the grade outturn of hem-fir lumber was estimated at 35% each for E_1 and E_2 grades, which can be successfully used to make E_1 and E_2 grade CLT respectively in accordance with ANSI/APA PRG 320 standard (2018).

CONCLUSIONS

Based on the exploratory and pilot plant studies, it can be concluded that it was feasible to manufacture CLT using BC coast hem-fir lumber. The main findings were summarized as following:

(1) BC coast hem-fir lumber stock could be used to manufacture CLT products with distinct product MOE classes (grades). The high MOE hem-fir lumber pieces can be used for higher grade CLT. The grade outturn of hem-fir lumber was estimated at 35% each for E_1 and E_2 grades, which can be successfully used to make E_1 and E_2 grade CLT respectively in accordance with ANSI APA PRG 320-2018 standard.

(2) According to the trend lines when lumber with the same MOE was used for the outer layers, the eastern SPF-CLT had the greatest bending MOE, western SPF-CLT followed and hem-fir CLT was the last. This difference to a great extent can be attributed to wood texture feature that affected the mechanical properties of wood along the grain.

(3) The final hem-fir CLT product can be designed for cost-effectiveness and predictable bending performance. A good correlation was found between the hem-fir CLT product MOE and MOR and average MOE of hem-fir lumber used for the outer layers.

(4) The final hem-fir CLT product can be designed based on the end applications such as floor or wall panels. The 3-ply pilot plant hem-fir floor CLT panel in this study can meet the requirements of CLT grade E_1 in the major strength direction and the 3-ply pilot plant hem-fir wall CLT panel can meet the requirements of CLT grade E_2 in accordance with the current ANSI APA PRG 320-2018 CLT standard, which provided a strong evidence that hem-fir had a feasibility of manufacturing CLT.

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