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Bending and compressive properties of cross-laminated timber (CLT) panels made from Canadian hemlock

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HIGHLIGHTS

- Cross-laminated timber (CLT) panels made from Canadian hemlock were tested.
- Numerical models that can predict the bending properties of CLT panels were developed.
- Theoretical bending properties of the CLT panels were analyzed and evaluated.

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ABSTRACT

Cross-laminated timber (CLT) is an innovative engineering wood panel product made from gluing layers of solid-sawn lumber at perpendicular angles. Owing to the excellent structural rigidity in both orthogonal directions, CLT becomes a preferred construction material for shear walls, floor diaphragms, and roof assemblies. CLT is normally made of Spruce-pine-fir (SPF) lumber or Douglas fir-Larch lumber. Recently, attempts have been made to manufacture CLT with Canadian hemlock. This paper investigates the out-of-plane bending properties and compressive properties of CLT panels made from Canadian hemlock. The mechanical properties of the CLT panels in the major/minor strength directions were obtained through experimental tests, and numerical models were developed to predict bending stiffness and ultimate load resisting capacity of the CLT panels. Moreover, theoretical bending stiffness of the CLT panels was calculated according to the equations provided in different code provisions, and the calculated values were compared with the experimental data. Results show that CLT panels made from Canadian hemlock perform as well as those made from other common used lumber species (i.e. SPF or Douglas fir), and the bending stiffness and ultimate load resisting capacity of the CLT panels can be predicted by the developed numerical models. In addition, in the major strength direction, the global bending stiffness of the panels can be predicted using the theoretical bending stiffness. In the minor strength direction, the local bending stiffness of the panels can be predicted using the theoretical bending stiffness calculated according to the Shear Analogy theory. The results presented in this paper can provide fundamental basis for supporting the potential engineering application of CLT panel products made from Canadian hemlock.

1. Introduction

Cross-laminated timber (CLT) is a massive engineering wood product made by gluing cross-wise layers of sawn lumber to form large-scale timber panels. The cross section of a CLT panel usually consists of three to seven glued layers of dimension lumbers placed in orthogonally alternating orientation to the neighboring layers. CLT has advantages of similar mechanical properties in orthogonal directions, large in-plane strength and stiffness, good acoustic and thermal performance, and high level of prefabrication, etc. These advantages make CLT a suitable and competitive construction material for residential or mixed occupancy mid- and high-rise buildings.

In Europe and Canada, CLT panels are mainly manufactured with Spruce-pine-fir (SPF) lumber. As of now, several CLT manufacturing facilities operate in the United States, and Douglas fir-Larch lumber is planned to be used for the CLT manufacturing. However, the demand for CLT products from construction industry has been increasing many fold times in recent years, and many other wood species have been investigated to evaluate their applicability for CLT manufacturing. Fortune and Quenneville [1] studied the feasibility to manufacture CLT with New Zealand Radiata pine.

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Nomenclature

K_e	initial elastic bending stiffness
F_{max}	ultimate load resisting capacity
$f_{c,0}$	compressive strength in the major strength direction
$f_{c,90}$	compressive strength in the minor strength direction
$E_{l,0}$	modulus of elasticity of the lumber in the major strength direction
$E_{l,90}$	modulus of elasticity of the lumber in the minor strength direction
$E_{c,0}$	in-plane modulus of elasticity of the CLT panels in the major strength direction
$E_{c,90}$	in-plane modulus of elasticity of the CLT panels in the minor strength direction
$f_{c,0}$	compressive strength of the CLT panels in the major strength direction
$f_{c,90}$	compressive strength of the CLT panels in the minor strength direction
$f_{l,0}$	compressive strength of the lumber in the parallel-to-the-grain direction
$f_{l,90}$	compressive strength of the lumber in the perpendicular-to-the-grain direction
$EI_{m,l}$	local stiffness of the CLT panels
$EI_{m,g}$	global stiffness of the CLT panels
G_0	shear modulus of the CLT panels
G_{90}	rolling shear modulus for transverse layers of the CLT panels
GA_{eff}	effective shear stiffness of the CLT panels
K	shear correction factor
EI_{eff}	effective bending stiffness of the CLT panels
$f_{b,0}$	characteristic bending strength in the major strength direction
$f_{b,90}$	characteristic bending strength in the minor strength direction
M_{max}	the maximum bending moment
h_i	thickness of the CLT panels
S_{eff}	effective section modulus of the CLT panels
E_1	modulus of elasticity of the outer layer of the CLT panels
$E_{local,0}$	modulus of elasticity in bending parallel to the major strength direction
$E_{local,90}$	modulus of elasticity in bending parallel to the minor strength direction
G_c	in-plane shear stiffness of the CLT panels

Hindman and Bouldin [2] tested the bending and shear performance of CLT panels made from Southern pine to establish design values of bending strength, bending stiffness and shear strength. Park et al. [3] investigated the bending creep performance of thirty types of CLT panels made from five timber species (i.e. Kiri, Katsura, Sugi, Hinoki, and Buna).

The bending stiffness, bending strength, and shear strength of CLT panels are quite important properties since they have significant influence on the structural design of CLT floor or roof assemblies. The influence of panel thickness on the bending performance of CLT was investigated by Sikora et al. [4]. The bending performance of CLT panels made from spruce boards was assessed by Christovasilis et al. [5] based on four-point bending tests, and elementary beam theories were implemented to estimate the stiffness and strength properties perpendicular and parallel to the principle plane of the CLT panels. Chen and Lam [6] studied the bending performance of CLT panels made from SPF lumber and then took a further research on the bending properties of a kind of box-based CLT floor system. Currently, however, few studies have concentrated on the bending performance of CLT panels made from Canadian hemlock.

When the width-to-length ratio of a CLT panel is close to 1.0, the CLT panel becomes a two-way bending element which means force- and moment-transfer occurs in both directions. Although most current studies focus on the bending performance of CLT panels in the major strength direction, few studies concentrate on the bending performance of CLT panels in the minor strength direction. In this paper, 20 5-meter long CLT specimens were tested to study the bending performance of CLT panels made from Canadian hemlock in both the major strength direction and the minor strength direction. In addition, the in-plane compressive properties of the CLT panels in the major strength direction and the minor strength direction were tested. The initial elastic bending stiffness (K_e), out-of-plane ultimate load resisting capacity (F_{max}), compressive strength in the major strength direction ($f_{c,0}$), and that in the minor strength direction ($f_{c,90}$) were obtained. The bending properties of the tested CLT panels were compared with those of CLT panels made from SPF or Douglas fir-Larch. Finally, a numerical model that can predict the bending stiffness and strength of the CLT panels was developed, and the theoretical bending properties of the CLT panels were analyzed and evaluated.

2. Materials and methods

2.1. Materials and specimens

NO. 2 Canadian hemlock lumber was used for the CLT panels in this study. The nominal cross-section dimension of the lumber was 140 mm × 35 mm. The length of the lumber used in the longitudinal laminations was 5200 mm and that of the lumber used in the perpendicular laminations was 1240 mm. No end joints of the lumber existed in the CLT panels. The CLT panels were assembled in cold press using polyurethane adhesive. Each panel was made up of five orthogonally crossed layers while edge gluing was not performed, and the thickness of each CLT panel was 175 mm. The estimated value of the pressure applied on individual CLT panel was around 800 kPa. The CLT panels were pressed with the dimension of 5.2 m long by 1.24 m wide and then were cut into specimens with required dimensions. Average moisture content of the lumber was about 13.2%, which was between the recommended range of 9%–15% as in ANSI/APA PRG 320-2012 [7].

2.2. Material properties

Modulus of elasticity (MOE) of each piece of lumber was measured directly with non-destructive method using the Transverse Vibration E-Computer. The average MOE of the lumber in the parallel-to-grain direction ($E_{l,0}$) and that in the perpendicular-to-grain direction ($E_{l,90}$) were 10766.5 MPa and 978.8 MPa, respectively. Standard deviations for the $E_{l,0}$ and $E_{l,90}$ were 1123.5 MPa and 103.7 MPa, respectively. The stiffness properties of the CLT panels were calculated based on the equivalent stiffness of multi-layer orthotropic materials following *CLT handbook* [8]. The in-plane MOE of the CLT panels in the major strength direction ($E_{c,0}$) and that in the minor strength direction ($E_{c,90}$) were 6851.4 MPa and 4893.9 MPa, respectively. Standard deviations for the $E_{c,0}$ and $E_{c,90}$ were 715.6 MPa and 511.6 MPa, respectively. The in-plane compressive strength of the CLT panels was estimated from tests on 20 compressive rectangular specimens extracted from the CLT panels. These rectangular specimens, which included 10 rectangular specimens for the compressive strength in the major strength direction and the other 10 rectangular specimens for the compressive strength in the minor strength direction, were extracted from the CLT panels. The sampling area of each rectangular specimen was 80 mm to 80 mm square according to PRG 320 [7]. The thickness of the rectangular specimens was equal to the thickness of the CLT panels, thus, the dimension of these rectangular specimens (Fig. 1) was 80 mm in width, 80 mm in height, and 175 mm in thickness. The compressive strength of the rectangular CLT specimens in the major strength direction ($f_{c,0}$) and that in the minor strength direction ($f_{c,90}$) were obtained as 18.3 MPa and 14.4 MPa, as shown in Fig. 2. Standard deviations for the $f_{c,0}$ and $f_{c,90}$ were 2.1 MPa and 1.6 MPa, respectively. In addition, according to the test results from the CLT manufacturer, the compressive strength of the Canadian hemlock lumber in the parallel-to-the-grain direction ($f_{l,0}$) and that in the perpendicular-to-the-grain direction ($f_{l,90}$) were 26.1 MPa and 6.6 MPa, respectively. Standard deviations for the $f_{l,0}$ and $f_{l,90}$ were 2.6 MPa and 0.67 MPa. The compressive properties (i.e. stiffness and strength) of the Canadian hemlock lumber and those of the CLT panels are listed in Table 1. The strain-stress relationships for the CLT panels are shown in Fig. 2.