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Measurement of rolling shear modulus and strength of cross laminated timber fabricated with black spruce

Qinyi Zhou [a], Meng Gong [a,*], Ying Hei Chui [a], Mohammad Mohammad [b]

[a] Faculty of Forestry and Environmental Management, University of New Brunswick, Fredericton, NB E3B 5A3, Canada
[b] FPInnovations, Ottawa, ON, Canada

HIGHLIGHTS

- Two-plate shear test was proposed for measuring the rolling shear modulus of a cross layer in 3-layer CLT.
- Two-plate shear test could be used to determine the load capacity of 3-layer CLT at a relatively large span-to-depth ratio.
- The apparent modulus of elasticity and shear modulus of 3-layer CLT beam specimens were independent of the specimen width.
- An adjustment factor was proposed for predicting the deflection of a CLT beam specimen at a given range of span-to-depth ratios.
- Wooden cross layer specimens under the two-plate shear test failed in a ductile manner.

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ABSTRACT

The design and application of cross laminated timber (CLT) is strongly influenced by the rolling shear properties of cross layers. Hence, to predict the performance of CLT requires accurate information about its rolling shear properties. In this study, a wooden cross layer (WCL) specimen was made of 38 mm by 89 mm black spruce lumber of a grade of No. 3. The average rolling shear modulus of the WCL specimens measured by the two-plate shear test was 136 MPa. The rolling shear modulus measured was then used as input to predict, using the shear analogy method, the deflection (d_c) of a 3-layer CLT beam subjected to the centre-point bending load. Subsequently, the bending test was conducted to directly obtain the deflection (d_m) of a 3-layer CLT beam for validation. It was found that d_c could, with an adjustment factor (α), provide a good estimate of d_m at different span-to-depth ratios under the centre-point bending test. Additionally, the bending test results showed that the specimen width did not have a statistically significant effect on apparent modulus of elasticity (E_{app}) and apparent shear modulus (G_{app}) of 3-layer CLT beam specimens.

1. Introduction

Cross laminated timber (CLT) is a timber panel produced by gluing cross-wise oriented layers of laminates together. As a rule, the mid-layer in a symmetrical configuration made of an odd number of laminates is cross oriented. In order to obtain specific structural capacities, consecutive layers may be placed in the same direction, resulting in an even number of laminates. Compared to the raw material or other engineered wood products, the advantages of CLT are the homogenized mechanical and physical properties. Therefore, CLT is suitable for use as load bearing panels (floor or roof) that are subjected to out-of-plane bending and shear walls. However, as an innovative engineered wood product, research is still required to properly quantify some of the engineering design properties. The rolling shear properties in CLT were found to be critical design properties for out-of-plane bending applications [1], such as short-span bending and a concentrated load bending. The deflection of a CLT panel under bending can be significantly attributed to the shear deformation in the cross layer. This phenomenon can be attributed to the low rolling shear capacities of the cross layer in the radial–tangential (*rt*) plane. Wood can be deemed as an orthotropic material, Fig. 1, which illustrates three principal material directions. Rolling shear is defined as the shear stresses leading to shear strains in the *rt* plane [2]. Due to the structural configuration of commonly used CLT, the rolling shear properties of a cross layer (i.e. *rt* plane of wood) are very low.

* Corresponding author. Address: 1350 Regent Street, Fredericton, NB E3C 2G6, Canada. Tel.: +1 (506)458 7876; fax: +1 (506)453 3574.

E-mail addresses: qinyi.zhou@unb.ca (Q. Zhou), meng.gong@unb.ca (M. Gong), yhc@unb.ca (Y.H. Chui), Mohammad.Mohammad@fpinnovations.ca (M. Mohammad).

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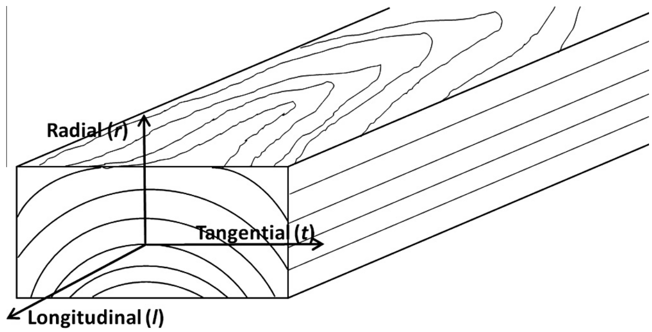

Fig. 1. Three principal axes of wood with respect to grain direction.

There is currently no suitable standardized test method for determining the rolling shear properties of full-size CLT specimens. Therefore, an in-depth study on the rolling shear properties and the development of a proper test method is required. It has been found that rolling shear properties of wood and wood-based products are mainly depended on species, growth ring orientation, lay-up, span-to-depth ratio, glued surface area, etc. Recently, European researchers explored some potential test methods for determining rolling shear properties. Aicher and Dill-Langer [3] predicted, using the finite element method, that the rolling shear modulus (G_{rt}) of 3-layer Norway spruce (*Picea abies*) boards was between 50 MPa and 200 MPa, depending on the growth ring orientation. They found that the maximum G_{rt} was 193 MPa when the mid-layer laminate had a growth ring angle of 45°. Joebstl et al. [4] tested orthogonally glued CLT laminates using three glued surface geometry by torsion. Their finding suggested that the smaller glued surface area with edge-grained laminates was recommended in order to achieve higher isotropic shear stresses. Additionally, FE calculation indicated that the maximum modulus of torsion occurs at an angle of approximately 50°. Fellmoser and Blaß [2] studied the rolling shear modulus of solid Norway spruce (*P. abies*) boards using a bending vibration test and the effect of span-to-depth ratio on the rolling shear properties of a 3-layer CLT panel via the shear analogy method. They found that the rolling shear modulus of 3-layer panels ranged from 40 MPa to 80 MPa, and shear deformation was strongly influenced by the span-to-depth ratio when it was below 20. They suggested that the shear deformation in the cross layer had to be taken into account when a small span-to-depth ratio appeared in CLT application. Steiger et al. [5] developed a fully automated procedure to determine two in-plane elastic moduli (E_r, E_t) and the three shear moduli (G_{lr}, G_{lt} and G_{rt}) of 3-layer Norway spruce (*P. abies*) CLT panels. They conducted an experimental modal analysis to determine the resonance frequencies and mode shapes of the panel, and then calculated the natural frequencies and mode shapes based on Reddy's high order plate theory [6]. These parameters were identified by minimizing the difference between measured and estimated resonance frequencies.

Munthe and Ethington [7] evaluated the shear properties of kiln-dried Sitka spruce (*Picea sitchensis*) plank with different growth ring curvature and orientations by the two-plate shear method. They found that rolling shear strength in the *rt* plane was 1.77 MPa, which is only 19.5% of that in longitudinal–tangential (*lt*) plane. Yawalata and Lam [8] investigated the impact of manufacturing process variables on the rolling shear strength of 3-layer spruce-pine-fir (SPF) and hem-fir CLT panels with the dimensions of $50 \times 102 \times 686$ mm. They discovered that the rolling shear strength of 3-layer SPF panels made under a pressure of 0.4 MPa was 2.22 MPa, which was higher than 1.85 MPa under a pressure of 0.1 MPa. This result suggested that higher manufacturing pressure produced stronger panels, which subsequently led to higher shear strength. They also found that the species had an impact on the rolling shear strength. The 5-layer CLT panel made of spruce-pine-fir (SPF) group had mean rolling shear strength of 1.89 MPa, which was 13% higher than those made of hem-fir group. Pirvu [9] conducted two-plate shear tests on lodgepole pine (*Pinus contorta*) specimens composed of edge-glued wood laminates or no edge-glued laminates with a 2 mm gaps between them. Three cross sectional sizes were included: 38 mm by 38 mm, 38 mm by 89 mm and 38 mm by 140 mm. He discovered that mean rolling shear modulus increased with increasing cross sectional dimensions for those specimens with 2-mm gaps between wood laminates, while it slightly decreased with increasing sectional size for the edge-glued specimens. The maximum rolling shear modulus was 210 MPa for edge-glued specimens made of the 38 mm by 38 mm lumber, and it remained almost the same, around 170 MPa, for those made of 38 mm by 89 mm and 38 mm by 140 mm. These results suggest that specimen width has almost no effect on the rolling shear modulus when the width exceeds a certain value. ANSI/APA PRG320 [10] proposes the flatwise centre-point loading method, in accordance with ASTM D198, for measuring the shear properties of CLT beams. Zhou et al. [11] compared two methods, variable span bending tests and two-plate shear test, of measuring the rolling shear modulus and strength of the cross layer in CLT made of black spruce. They found that the results from the two-plate shear test could, in comparison to those from the variable span bending test, be used as input to accurately predict deflection of CLT beam specimen at common span-to-depth ratios, which is more practical and useful in CLT application. Therefore, two-plate shear test was chosen as the full-size testing method in this study.

The shear analogy method developed by Kreuzinger [12] is widely used to calculate the deflection of a CLT beam under the concentrated bending, which is reported to be a suitable approach for analyzing the stress distribution in and the deformation behavior of solid wood panels with cross layers. The shear analogy method is also recommended in the CLT Handbook published by FPInnovations [13], which is also adopted in ANSI/APA PRG 320 standard [10]. This method is based on the assumption that a multi-layer laminated panel can be modeled using two virtual beams. The different modulus of elasticity and shear modulus of each beam were considered. The stress distribution of a entire cross-section can be, therefore, obtained by overlaying the bending moment and shear stresses of two beams.

This study was aimed at assessing the applicability of the two-plate shear tests for measuring the rolling shear properties of 'full size' edge-glued wooden cross layer (WCL) specimens made of 38 mm by 89 mm black spruce lumber. Results were verified by comparing the deflections of 3-layer CLT beam specimens predicted by the shear analogy method and the deflections directly measured by the centre-point bending tests.

2. Materials and method

2.1. Materials and specimen preparation

Black spruce (*Picea mariana*) lumber was obtained from a local supplier in New Brunswick, Canada, which included structural light framing No. 3 grade [14] 38 mm by 89 mm and No. 2 grade 38 mm by 140 mm lumber. The characteristics of lumber were given in Table 1. All lumber pieces were placed in a conditioning chamber set at a temperature of 20 °C and relative humidity of 65%, with a target equilibrium moisture content of about 12%. Three-layer CLT beams were manufactured at the Wood Science and Technology Centre, University of New Brunswick, Fredericton, New Brunswick, Canada.

According to ANSI/APA PRG 320 [10], the lumber used in the perpendicular layer and the parallel layer of CLT shall be visual grade No. 3 and No. 2, respectively. The No. 3 grade 38 mm by 89 mm lumber pieces were used for the cross layer, whereas No. 2 grade 38 mm by 140 mm lumber pieces were used for the outer layers. First, No. 3 grade 38 mm by 89 mm was cut into laminates with the length of 800 mm. The modulus of elasticity (MOE) value of each laminate was determined