WOOD RESEARCH
63 (2): 2018
227-238

EFFECT OF MACRO CHARACTERISTICS ON ROLLING SHEAR PROPERTIES OF FAST-GROWING POPLAR WOOD LAMINATIONS

Zhiqiang Wang, Weiqun Dong, Zhuanzhuan Wang
Nanjing Forestry University, College of Materials Science and Engineering
Nanjing, Jiangsu, China

Jianhui Zhou, Meng Gong
University of New Brunswick, Faculty of Forestry
and Environmental Management
New Brunswick, Canada

(Received August 2017)

ABSTRACT

Rolling shear modulus (G_R) and strength (f_R) of the cross layers are decisive mechanical properties in cross-laminated timber (CLT) plates. The influences of macro characteristics, such as annual ring orientation, distance to pith, and presence of pith on the rolling shear properties of fast-growing poplar boards were evaluated throughout this study. It were found the presence of pith had significant influence on the rolling shear properties of poplar board. Distance to pith and annual ring orientation both had effects on the rolling shear properties jointly. The rolling shear properties increase with the increase of distance to pith. The mean rolling shear modulus and characteristic rolling shear strength values of the poplar wood were determined to be 177 MPa and 2.24 MPa, respectively, which indicates a great potential of using poplar wood as the cross-layers in CLT.

KEYWORDS: Rolling shear properties, macro characteristics, fast-growing poplar, cross-laminated timber.

INTRODUCTION

In recent years, more and more cross-laminated timber (CLT) plates have been used in medium and high-rise wooden construction as roof, floor, and wall components. Due the existence of cross layers with radial-tangential cross sections, the transverse shear strength and stiffness of CLT are relative low compared to its in-plane bending strength and stiffness, leading to excessive deflection and rolling shear failure when subjected to out-of-plane load (Gagnon and Pirvu 2011). Rolling shear modulus (G_R) and strength (f_R) of the cross layers are decisive mechanical properties in CLT plates (Aicher et al. 2016). Comprehensive knowledge on rolling shear properties is therefore of utmost importance for an adequate design of CLT structures (Ehrhart et al. 2015).

Currently, CLT is word-wide almost exclusively manufactured from softwood boards, mainly spruce and fir. These softwood, such as spruce wood, has relative low rolling shear properties. The G_R of some normal softwood, e.g. spruce-pine-fire (SPF), D. Fir-L (Douglas fir-larch) and Hem-Fir lumber are assumed 50 MPa for design purpose in North American CLT handbook (Gagnon and Pirvu 2011), which is thought to be too low. The mean rolling shear strength and modulus values of No. 2 SPF were measured to be 1.4 MPa and 85 MPa, respectively (Wang et al. 2017). In recent years, hardwood, e.g. beech and yellow poplar, have gained increasing attentions for the development of homogeneous or hybrid CLT plates due to their relative high rolling shear properties (Aicher et al. 2016, Ehrhart et al. 2015, Gong et al. 2015). Aicher et al. (2016) investigated the rolling shear modulus and strength of beech wood (*Fagus sylvatica*). Their experimental results showed the $G_{R,mean}$ and $f_{R,05}$ of beech wood exceed the respective characteristic values for softwood by roughly factors 5 and 7 which indicating great potential for beech wood cross-layers in CLT. Ehrhart et al. (2015) measured the rolling shear properties of two kinds of softwoods, e.g. Norway spruce (*Picea abies* (L.) Karst.) and pine (*Pinus sylvestris* L.), and four kinds of hardwoods, e.g. birch (*Betula pendula* Roth), beech (*Fagus sylvatica* L.), poplar (*Populus* spp.) and ash (*Fraxinus excelsior* L.). They found Norway spruce had the relative low rolling shear properties, however, birch, beech and ash showed outstanding rolling shear properties with values about 2 to 3 times higher than those of spruce. The rolling shear modulus of poplar was found to be higher than that of spruce and lower than that of pine. However, poplar had a remarkable rolling shear strength which surpassed those of pine and spruce.

The mechanical properties of hardwood CLT and hybrid CLT using hardwood as cross layers were studied in recent years (Kramer et al. 2013, Wang et al. 2014, Aicher et al. 2016, Liao et al. 2017). Kramer et al. (2013) developed low-density (hybrid poplar) CLT which met and exceeded the shear and bending strength requirement for ANSI/APA PRG-320 CLT Grade E3. However, the hybrid poplar CLT did not meet the bending stiffness requirements. Liao et al. (2017) reported the feasibility of manufacturing three-layer CLT using fast-grown small diameter eucalyptus wood (*Eucalyptus urophylla* × *Eucalyptus grandis*). Aicher et al. (2016) developed a hybrid, three-layered, softwood-hardwood CLT build-up with outer layer of European spruce (*Picea abies*) and a center cross-layer of European beech (*Fagus sylvatica*). They found that the high rolling shear properties of beech cross-layer rendered the shear lag implications of the softwood CLTs to a negligible quantity. Wang et al. (2014) studied the feasibility of using fast-growing poplar as cross layer to fabricate CLT plates.

Previous studies indicated that the macro and micro characteristics of wood such as growth ring, sawing pattern, thickness, and density, etc had significant influences on their rolling shear properties (Aicher and Dill-Langer 2000, Zhou 2013, Ehrhart et al. 2015, Aicher et al. 2016, Zhou et al. 2016). Zhou (2013) measured the rolling shear properties of Black spruce (*Picea mariana*) lumber with various annual ring orientation, e.g. flat sawn, in-between, and quarter sawn. It was found that growth ring had a significant effect on rolling shear modulus, while no effect on rolling shear strength was found. Aicher et al. (2016) theoretically analysed and experimentally investigated the influence of sawing pattern on rolling shear properties of beech wood. The semi-quarter-sawn board and the pith board had the highest and lowest rolling shear properties, respectively. Ehrhart et al. (2015) evaluated the rolling properties of two kinds of softwood timber species and four kinds of hardwoods with emphasis on the influence of sawing pattern and board geometry. The selected hardwood had different vessel characteristic, e.g. diffuse porous and ring porous timber species.

Fast-growing poplar is one of the most planted wood species in China and has been used mostly as non-structural plywood and solid wood for furniture and interior decoration materials.

A value-added use for fast-growing poplar is needed preferably as a sustainable building material. Many previous studies have been carried to develop fast-growing poplar for structural elements (Dong et al. 2016, He et al. 2016). Therefore, the aim of this paper is to gain a deeper insight into the rolling shear properties of fast-growing poplar lumber with emphasis on the influences of macro characteristics, such as pith, distance to pith, and annual ring orientation. Further, the great potentiality of using poplar as the cross layers in CLT would be revealed in this study.

MATERIAL AND METHODS

Sawing pattern of fast-growing poplar

The poplar wood specimens were cut from nine-years old fast-growing poplar trees (*P. deltoides* cv. I-69/55) originated from a forest in Pizhou, Jiangsu Province, China. The logs used to cut boards had bottom and top diameters of 300 mm and 320 mm, respectively. Two logs with length of 1.2 m were used in this study. Fig. 1 shows the investigated sawing patterns and board geometries. It is very difficult to investigate the effect of only one single factor on the rolling shear properties due to the irregular shape of logs and physical and mechanical variations of wood. As for the factor of annual ring orientation, the typical annual ring orientation of boards, such as quarter-sawn, semi-quarter-sawn and flat-sawn, were determined by setting the board locations without considering the change of the distance to pith, the group A, B, and C in Fig. 1 (a) and (c). When investigating the effect of distance to pith, the minor differences of annual ring orientation between the selected boards were also neglected, the group D, E, and F in Fig. 1 (b) and (d). Group G is the board with pith.

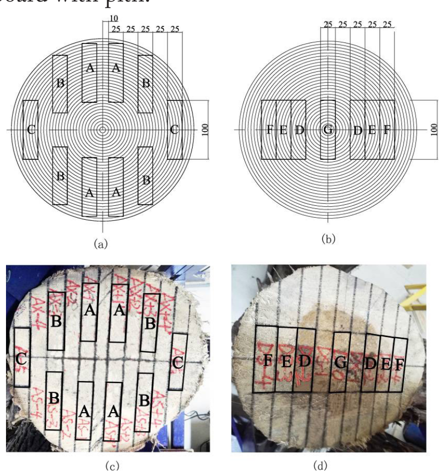


Fig. 1: Investigated sawing patterns and board geometries (a) and (b) the ideal sawing patterns, (c) and (d) the realized sawing patterns.

The logs were sawn flatwise as is usual in hardwood processing to planks of 25 mm thick, 100 mm wide and 600 mm long. The moisture content (MC) of the planks was about 99.3% at this moment. In order to minimize drying defects, the cross sections of poplar planks were sealed with sealant. The planks were then air-dried for one month prior to be dried in a climate chamber within a period of one week. The final mean MC of dried boards was 11.96% with a coefficient of variation (COV) of 0.32% via randomly measured the MC of 16 pieces of poplar boards. Most of the boards were almost defect free and had no cracks, except the group G. Further, all specimens were stacked indoor for two weeks prior to further process. All test specimens had a dimension of 20 mm (radial, thickness) × 90 mm (tangential, width) × 89 mm (longitudinal, length) in this study.

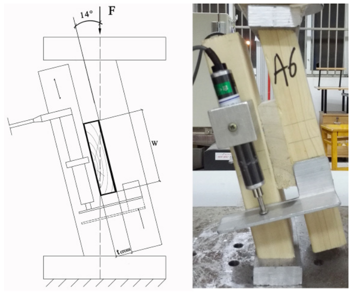
The typical annual ring orientations in the cross section of groups A, B, C and G are shown in Fig. 2. Aicher et al. (2016) developed the definition and calculation method of annual ring angle (φ_{mean}), and the range of φ_{mean} of quarter-sawn, semi-quarter-sawn and flat-sawn were condidered as from 60° to 90° , from 30° to 60°, and from 0° to 30°, respectively. Based on these definition and calculation, the average φ_{mean} of group A, B, and C were about 85°, 48°, and 14°, respectively, which verified that it was right to consider the groups A, B, and C were quarter-sawn, semi-quarter-sawn and flat-sawn in this study.

Fig. 2: Typical cross section annual ring orientations (a) group A, (b) group B, (c) group C, and (d) group G.

Test plan

The effect of annual ring orientation, termed sawing patterns, distance to pith and the presence of pith on rolling shear properties of poplar boards were invetigated in this study. Groups A, B and C, which were condiered as quarter-sawn board, semi-quarter-sawn board and flat-sawn board, respectively, cut from one poplar log and used to evaluat the effect of annual ring orientation on the rolling shear properties. Further, groups D, E, and F were considered to had the same annual ring orientation, i.e. quarter-sawn board, and different distance to pith cut from the another poplar log and used to investigat the effect of distance to pith on rolling shear properties. Group G is the board with pith used to assess the influence of pith on rolling shear properties. Ten specimens were tested for each group and a total of 70 specimens were used in this study.

To date, there is no universal test method for the determination of rolling shear properties of CLT cross-layers (Zhou 2013). In the well-established North American and European product standard on CLT (ANSI/ APA PRG 320: 2017, EN 16351: 2015), respectively, short-span bending test and planar shear test have been proposed for evaluating the rolling shear modulus and strength of CLT. In this study, the test method proposed in EN 408: 2012 standard and the modified planar shear test method reported by Gong and Chui (Gong et al. 2015) were adopted, which was thought to provide uniform shear stress in the cross layer and guarantee rolling shear failure. The angle between shear plane and force direction (α) was 14° for all tests according to EN 408: 2012 standard. The test configuration and a view of the realized test setup are shown in Fig. 3.



(a) (b)

Fig. 3: Experimental setup of modified planar shear test (a) test configuration, (b) view of the realized test setup with fixed LVDT slip measurement.

The modified planar shear tests were performed on a universal mechanical testing machine (SHIMADZU, AG-X/AG-IC) with a loading rate of 1.0 mm·min^{-1}. Two 25 mm linear variable differential transformers (LVDTs, TDS-530) were used to measure the displacement on both sides of the specimen. The rolling shear modulus (G_R) and shear strength (f_R) can be calculated according to following formulas,

$$G_R = \frac{t_{cross}}{l \times w} \times \frac{p}{\Delta} \times \cos(\alpha) \tag{1}$$

$$f_R = \frac{p_{\max} \times \cos(\alpha)}{l \times w} \tag{2}$$

where: p_{max} - peak load,
l, w and t_{cross} - length, width and thickness of the cross layer,
$\frac{p}{\Delta}$ - the slope of the load-deformation curve between 20 and 50% of the proportional limit,
α - the angle of inclination.

RESULTS AND DISCUSSION

Density and rolling shear properties of poplar boards tested

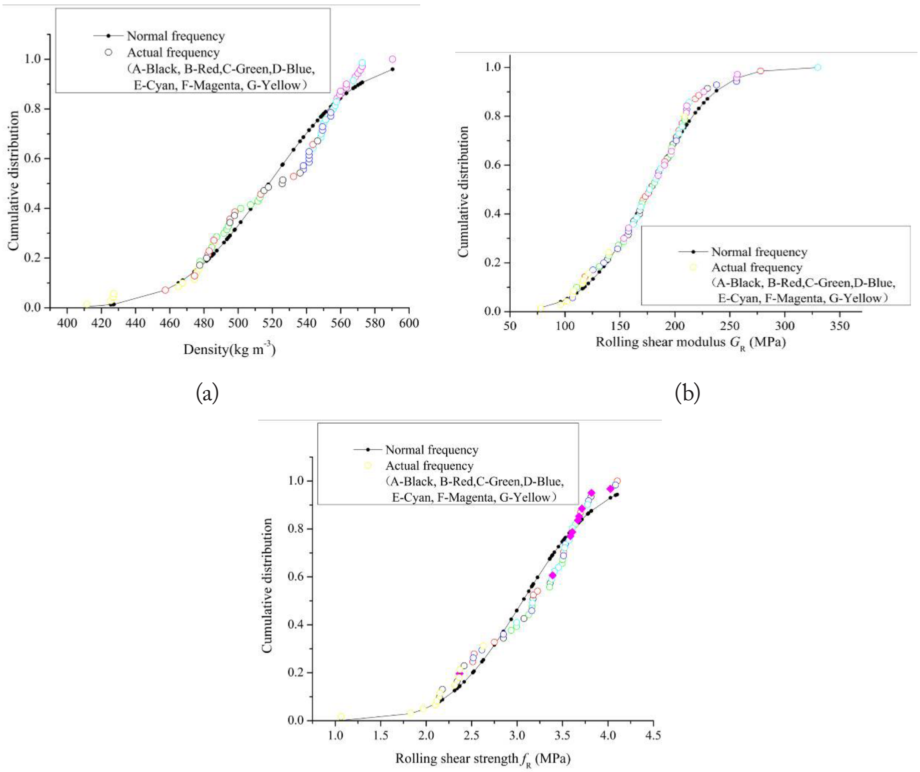
Tab. 1 gives a statistical evaluation of the density and rolling shear properties for all tested specimens. The mean densities of all tested specimens is 518 kg·m^{-3} ranged from 412 to 590 kg·m^{-3}. The group G, had the lowest mean density of 454 kg·m^{-3}, which is 19.64% lower than those of the boards without pith in the same log. Further, the scatter of the densities in each group was comparably small with COVs about 5%. The cumulative distribution of all tested specimens densities is shown in Fig. 4 a. There was no significant difference of density among the groups A, B, C, and among the groups D, E, and F. The reason might be that the fast-growing poplar grows fast and the poplar logs used in this study might be juvenile wood which leads to little variations in density between heartwood and sapwood.

Tab. 1: Statistical evaluation of densities and rolling shear properties of poplar specimens tested.

	Group A	Group B	Group C	Group D	Group E	Group F	Group G
Density($kg \cdot m^{-3}$)							
Mean	512	497	496	545	555	568	454
COV (%)	4	5	2	1	2	2	6
Min	478	457	478	538	544	558	412
Max	546	544	512	554	573	590	485
Rolling shear modulus G_R (MPa)							
Mean	180	196	165	176	200	204	119
COV (%)	14	21	20	28	25	17	30
Min	139	118	111	107	162	154	78
Max	230	278	209	256	330	257	209
Rolling shear strength f_R (MPa)							
Mean	2.82	3.19	3.28	3.26	3.43	3.54	2.09
COV (%)	21	18	8	17	7	13	20
Min	2.15	2.51	2.94	2.52	3.00	2.37	1.06
Max	3.81	4.10	3.64	4.08	3.78	4.03	2.63

The cumulative distribution of G_R and f_R of all test results is shown in Fig. 4 b and c, respectively. The mean G_R of poplar boards tested was 177 MPa ranged from 78 to 330 MPa, and the f_R value was 3.06 MPa ranged from 1.06 to 4.08 MPa. These test results of rolling shear properties here are very close to those of some previous studies. Gong et al. (2015) reported the mean G_R and f_R of aspen (*Populus tremuloides*) to be 177 MPa and 2.88 MPa, respectively, and Ehrhart et al. (2015) also measured the mean G_R and f_R of poplar (*Populus* spp) to be 127 MPa and 2.88 MPa, respectively. The rolling shear modulus of softwood CLT is taken as 50 MPa or 1/10 of its shear modulus parallel to grain in current design practice in North American and European product standard on CLT (ANSI/ APA PRG 320: 2017, EN 16351:2015). Thus, the mean experimental rolling shear modulus of poplar (177 MPa) obtained in this study not only exceeds the design values (50 MPa) of softwood (ANSI/APA 2017) but also is about 1.6 times of the mean value (85 MPa) of NO. 2 spruce-pine-fir measured by Wang et al. (2017).

The characteristic rolling shear strength of all tested specimens and the specimens without pith, namely the 5% quantile value, were determined to be 1.89 MPa and 2.24 MPa, respectively, at the confidence level of 95% according to the nonparametric approach in ASTM D2915- 10 standard. In current CLT design guides and codes, the characteristic rolling shear strength is taken as 0.5 MPa for SPF CLT in Canada (ANSI/ APA PRG 320: 2017), while in Europe, the characteristic rolling shear strength is recommended to be 1.1 MPa for both edge glued softwood CLT and non-edge-glued CLT made of laminations with a minimum width-to-depth ratio of 4, otherwise 0.7 MPa should be used (EN 16351:2015). So the 5% quantile value $f_{R,05}$=2.24 MPa of poplar boards without pith again exceeds the specified values of softwood. It is about 2.5 times of the characteristic f_R of NO. 2 spruce-pine-fir (0.88 MPa) measured by Wang et al. (2017). These above results of rolling shear properties of the poplar boards indicate that fast-growing poplar wood has great potentiality to been used as cross-layer in CLT plates.

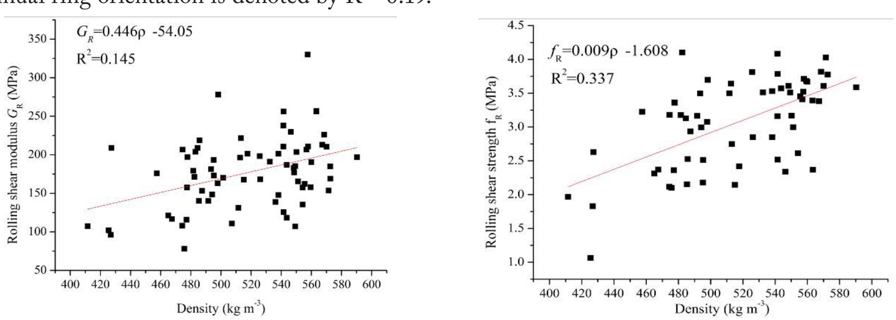


(a) (b)

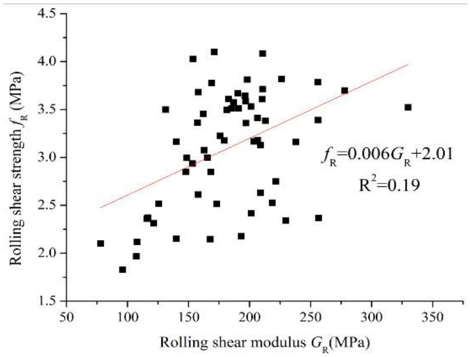
(c)

Fig. 4: Cumulative frequencies and fitted lognormal distribution of (a) density, (b) rolling shear modulus, and (c) rolling shear strength.

The relationships between ρ and G_R, ρ and f_R, as well as f_R and G_R for all test specimens are characterized by a slightly positive correlated trend as shown in Fig. 5, which agree with the results of other previous researches (Aicher et al. 2016, Ehrhart et al. 2015). Density shows low influence on the G_R and f_R data, and the correlation of f_R and G_R is independent from the specific annual ring orientation is denoted by R^2=0.19.



(a) (b)



(c)

Fig. 5: The corrections between (a) density and rolling shear modulus, (b) density and rolling shear strength, and (c) rolling shear modulus and rolling shear strength.

Influences of the presence of pith and distance to pith on rolling shear properties

From Tab. 1, it can be obviously seen that group G, i.e. boards with pith, had the lowest value of rolling shear properties. Compared with group G, the mean G_R and f_R values of three groups of D, E and F were 62.46% and 63.16% higher than those of group G, respectively. The low rolling shear properties of boards with pith are inherently due to the low density and cracks of pith. The one-way ANOVA test of groups D, E, F and G showed that there was significant difference among the four poplar groups obtained for rolling shear modulus and strength, respectively.

Groups D, E, and F were considered to have the same annual ring orientation but different distance to pith. From Tab. 1, it could be concluded that the rolling shear properties increase with the increase of distance to pith. The mean G_R and f_R of group F was 2% and 16%, and 3.2% and 8.6% higher than those of group E and D, respectively. The reason for this phenomenon is that groups D and E are close to the pith with lower density, Tab. 1, and thin cell wall which resulting in the relative low rolling shear properties. However, the one-way ANOVA test of groups D, E, and F showed that there was no significant difference among the three poplar groups with a p value of 0.351 and 0.798 obtained for rolling shear modulus and strength, respectively.

Influence of the annual ring orientation on rolling shear properties

The influence of annual ring orientation on rolling shear properties could be analyzed by comparing the rolling shear properties of groups A, B, and C. From Tab. 1, it was found that the annual ring orientation had different influences on rolling shear modulus and strength, respectively. For instance, the semi-quarter-sawn boards, i. e. group B, had the highest rolling shear modulus, and the flat-sawn boards, i.e. group C, had the lowest rolling shear modulus. Regarding to rolling shear strength, however, the flat-sawn boards, i.e. group C, had the highest test value, and the quarter-sawn board, i.e. group A, had the lowest test value. From Tab. 1, it is also obvious that the semi-quarter-sawn board has relative high rolling shear properties in this study. In some previous studies done by Zhou (2013) and Aicher et al. (2016), the semi-quarter-sawn boards had the highest test value of rolling shear properties. The reasons for this difference may be that in this study, the groups A, B, and C cut from the same log, but each group had both different sawing patterns and distance to pith. As a result, affected by the two factors, the semi-quarter-sawn boards didn't have the highest test value of rolling shear modulus and strength. The one-way ANOVA test of groups A, B, and C showed that there was no significant difference among the three poplar groups with a p value of 0.139 and 0.264 obtained for rolling shear modulus and strength, respectively. Zhou (2013) found that the annual ring orientation of the laminates had a statistically significant effect on the rolling shear modulus of cross layer, but did not have a significant effect on the rolling shear strength. Aicher et al. (2016) also verified that the effect of sawing patterns on rolling shear properties varied. For instance, there was a statistically significant effect on the rolling shear properties between flat-sawn and quarter-sawn, however not a statistically significant effect on the rolling shear properties between flat-sawn and semi-quarter-sawn.

Rolling shear failure modes

The typical failure modes of all tested specimens were shown in Fig. 6, which were all observed to be brittle failure mode regardless of sawing patterns and distance to pith. Generally, no obvious differences in failure modes were found among the tested specimens without pith. Two typical failure mechanisms were observed in the poplar boards without pith during the modified planar shear tests. The first and most common failure mode was the so-called rolling shear failure shown in Fig. 6 a, c and e.

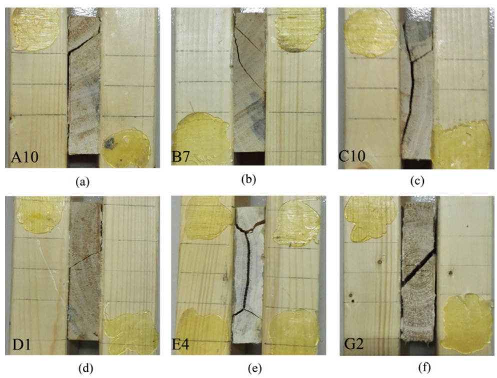


Fig. 6 Rolling shear failure modes of poplar boards tested.

The cracks were found to initiate suddenly and propagated along the growth ring. With the shear stress induced perpendicular to the longitudinal direction of poplar board, a friction surface was created along the transition from earlywood to latewood within a growth ring. Due to the different resistance to shear stresses of earlywood and latewood, the increasing shear stress caused the rolling of wood fiber in a single growth ring and finally progressed to adjacent layers. The crack(s) stopped at the bonding surface between the outer layers and cross layer, resulting in the final brittle fracture (Blass and Fellmoser 2004). The second failure mode was the shear failure found along wood ray as shown in Fig. 6 b and d. Wood rays always consisted of one or two rows of parenchyma cells, which can be a weak zone that cracks were caused by the tension stress perpendicular to grain and propagated along the wood ray direction. As for the poplar boards having pith, with the load approaching peak load, a crack or cracks would suddenly initiated around the pith and then propagated along the growth ring or wood ray direction. This was the primary failure mode for such poplar board specimens as shown in Fig. 6 f. It is known that wood pith mainly consists of parenchyma cells and has relative low mechanical properties. During the actual tests, the initial failure may be caused by one of the above described mechanisms, however, with the increase of either load or displacement, the combination of three different failure modes can be observed in the cross layers of a specimen due to very complicated stress redistributions. The findings here agree well with the failure mechanisms reported other previous study (Nie 2015, Wang et al. 2017). Nie (2015) recorded the detailed failure process of CLT cross layers with high speed camera and categorized the initial failure modes into three types, tension perpendicular to grain type, rolling shear type and marginal type.

CONCLUSIONS

The influences of macro characteristics such as annual ring orientation, presence of pith, and distance to pith on the rolling shear properties of fast-growing poplar were evaluated throughout this study. The board with pith had the lowest rolling shear properties and the influence of presence of pith was found to be significant on the rolling shear properties of poplar board. Distance to pith and annual ring orientation both had effects on the rolling shear properties jointly. The rolling shear properties increase with the increase of distance to pith. Generally, no obvious differences in failure mode were found among the poplar boards without pith, which mainly including rolling shear failure along the growth ring and tension failure along the wood ray. However, the failure around the pith was the main failure mode of the boards with pith tested.

A mean rolling shear modulus (G_R) of about 177 MPa and a 5% quantile of shear strength (f_R) of 2.24 MPa were obtained for the poplar boards without pith. These values are about 1.6 and 2.5 times of the corresponding reported values of spruce-pine-fir, respectively. These results substantiate the potential of poplar wood to be used in cross-layers of advanced hybrid CLT.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the National Natural Science Foundation of China (Grant No. 31570559) and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

REFERENCES

1. Aicher, S., Christian, Z., Hirsch, M., 2016: Rolling shear modulus and strength of beech wood laminations, Holzforschung 70(8): 773-781.
2. Aicher, S., Dill-Langer, G., 2000: Basic considerations to rolling shear modulus in wooden boards, Otto-Graf-J 11:157-165.
3. ANSI/APA PRG 320, 2017: Standard for performance-rated cross-laminated timber.
4. ASTM D2915, 2010: Practice for sampling and data-analysis for structural wood and wood-based products.
5. Blass, H.J., Fellmoser, P., 2004: Influence of rolling shear modulus on strength and stiffness of structural bonded timber elements, CIB-W18 Meet.
6. Dong, Y., Wang, K., Yan, Y., Zhang, S., Li, J., 2016: Grafting polyethylene glycol dicrylate (PEGDA) to cell walls of poplar wood in two steps for improving dimensional stability and durability of the wood polymer composite, Holzforschung 70(10): 919-926.

7. Ehrhart, T., Brandner, R., Schickhofer, G., Frangi, A., 2015: Rolling shear properties of some European timber species with focus on cross laminated timber (CLT): Test configuration and parameter study, In: Görlacher R (ed) Proc. 2nd Int. Netw. Timber Eng. Res. Timber Scientific Publishing, Sibenik, Pp 61–75.
8. EN 408, 2012: Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties.
9. EN 16351, 2015: Timber structures - Cross laminated timber - Requirements.
10. Gagnon, S., Pirvu, C., 2011: CLT handbook : cross-laminated timber (ed. Gagnon, S. and Ciprian P). Pp 114-185, FPInnovations. Vancouver.
11. Gong, M., Tu, D., Li, L., Chui, Y.H., 2015: Planar shear properties of hardwood cross layer in hybrid cross laminated timber, In: ISCHP 2015 5th Int. Sci. Conf. Hardwood Process. Pp 85–90.
12. He, X., Xiao, Z., Feng, X., Sui, S., Wang, Q., Xie, Y., 2016: Modification of poplar wood with glucose crosslinked with citric acid and 1,3-dimethylol-4,5-dihydroxy ethyleneurea. Holzforschung 70(1): 47-53.
13. Kramer, A., Barbosa, A.R., Sinha, A., 2013: Viability of hybrid poplar in ANSI approved cross-laminated timber applications, Journal of Materials in Civil Engineering 26(7): 615-621.
14. Liao, Y., Tu, D., Zhou, J., Zhou, H., Yun, H., Gu, J., Hu, C., 2017: Feasibility of manufacturing cross-laminated timber using fast-grown small diameter eucalyptus lumbers. Construction and Building Materials 132: 508-515.
15. Nie, X., 2015: Failure mechanism of rolling shear failure in cross-laminated timber, University of British Columbia, Canada, 111 pp.
16. Wang, Z., Fu, H., Chui, Y.H., Gong, M., 2014: Feasibility of using poplar as cross layer to fabricate cross-laminated timber, In: World Conference on Timber Engineering, Quebec city, paper 220.
17. Wang, Z., Fu, H., Gong, M., Luo, J., Dong, W., Wang, T., Chui, Y.H., 2017: Planar shear and bending properties of hybrid CLT fabricated with lumber and LVL, Construction and Building Materials 151: 172-177.
18. Zhou, J., Ying, H.C., Gong, M., Hu, L., 2016: Elastic properties of full-size mass timber panels: Characterization using modal testing and comparison with model predictions, Composites Part B Engineering 112: 203-212.
19. Zhou, Q., 2013: Development of evaluation methodology for rolling shear properties in cross laminated timber (CLT), University of New Brunswick, Canada, 168 pp.

Zhiqiang Wang*, Weiqun Dong, Zhuanzhuan Wang
Nanjing Forestry University
College of Materials Science and Engineering
Nanjing 210037
Jiangsu, China
Phone: +86 13913927164
Corresponding author: wangzhiqiang@njfu.edu.cn

Jianhui Zhou, Meng Gong
University of New Brunswick
Faculty of Forestry and Environmental Management
New Brunswick E3b 5A3
Canada