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Article

Influence of Aspect Ratio on Rolling Shear Properties of Fast-Grown Small Diameter Eucalyptus Lumber

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Abstract: Eucalyptus is a major fast-grown species in South China, which has the potential for producing structural wood products such as cross-laminated timber (CLT). Aspect ratio (board width *vs.* board thickness) of eucalyptus lumbers is small due to the small diameter of fast-grown eucalyptus wood. To evaluate its rolling shear modulus and strength for potential CLT applications, three-layer hybrid CLT shear block specimens with different aspect ratios (2,4,6), were tested by planar shear test method. Digital image correlation (DIC) was employed to measure the rolling shear strain distribution and development during the planar shear tests. The mean values of rolling shear modulus and strength of eucalyptus lamination were 260.3% and 88.2% higher than those of SPF(*Spruce-pine-fir*) lamination with the same aspect ratio of 4, respectively. The rolling shear properties of eucalyptus laminations increased as the aspect ratio increased. Aspect ratio had a significant influence on rolling shear modulus compared to rolling shear strength. The high shear strain regions were primarily found around the gaps between segments of cross layer. The quantity of high shear strain regions increased as the aspect ratio of lamination decreased. Other high shear strain regions also occurred around the pith and along the glue line. The sudden failure of specimen occurred in the high strain region. In conclusion, the rolling shear strength and modulus of fast-grown eucalyptus laminations exceed the respective characteristic values for softwoods in the current standard by roughly factors of 3 and 8, indicating great potential for fast-grown eucalyptus wood cross-layers in CLT.

Keywords: Fast-grown eucalyptus; cross-laminated timber; rolling shear; aspect ratio; digital image correlation

1 Introduction

Due to its outstanding physical and mechanical properties such as dimension stability, stiffness, strength and fire resistance [1], cross-laminated timber (CLT) has been used increasingly as the load-bearing elements including roof, floor and wall in tall wood buildings. The global development of CLT is attracting more and more attentions from both industry and academia in China. CLT made with local wood species [2–5] would definitely promote its applications in timber construction around the world. The local fast-grown wood in

China, i.e., poplar, eucalyptus or Chinese fir, have been researched for its feasibility as raw materials for CLT production [6–8]. As a fast-grown plantation species, eucalyptus has been mainly used as a raw material for medium density fiberboard, finger-jointed furniture board and pulp production. However, eucalyptus has relatively high mechanical properties and short cultivation cycles, which is a potential alternative for structural application. Several attempts have been made to fabricate and evaluate CLT with eucalyptus lumber, which showed even better mechanical performance than commonly used softwood CLT [6,8].

Previous studies have focused on the use of hardwood or local wood species to produce CLT [2,3,5–7,9,10]. Aicher et al. [3,5] investigated a hybrid softwood-hardwood CLT with outer layers of European spruce and a cross-layer of European beech via out-of-plane bending. They found there was a great potential of mixed softwood-hardwood CLT build-ups for structural elements. Gong et al. [2] explored the planar shear properties of hybrid CLT, indicating that hardwoods (aspen and birches) presented a greater resistance to planar shear than softwood (spruce). Ehrhart et al. [9,10] carried out the experimental investigations on the rolling shear properties of six timber species. In comparison to Norway spruce, the rolling shear properties of European beech and ash were roughly three times higher. Liao et al. [6] studied the feasibility to manufacture CLT with small diameter eucalyptus lumbers, which indicated that the physical properties of CLT made of eucalyptus were equivalent to those of CLT sold in the market. Gong et al. [11] investigated the parameters of CLT made of Japanese larch including glue consumption, pressure and adhesive. Fortune et al. [12], Navaratnam et al. [13] performed four-point bending test to evaluate the performance of Radiata pine CLT, providing a basis of manufacturing CLT with Radiata pine. We explored the feasibility of fast-grown poplar using as cross layer in CLT. 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 [14]. And the mechanical properties of CLT panels containing poplar were similar to those made of non-poplar wood [7].

Additionally, several studies have found that the technical characteristics, such as aspect ratio (board width *vs.* board thickness), gaps and sawing pattern also have impact on the rolling shear properties of CLT. Ehrhart et al. found the aspect ratios and sawing patterns were identified as major parameters on the rolling shear modulus and strength [10]. Aicher et al. [3] evaluated the effect of the annual ring orientation and pith location on the rolling shear properties. The test results revealed the semi-quarter sawn boards had the highest rolling shear modulus and the values of pith specimens were generally lower. We measured the rolling shear strength and modulus of CLT, with cross layers being edge-glued and without, and with gaps of 2 mm, 4 mm, 6 mm. It was found that gap and edge-gluing had significant effect on rolling shear strength. However, it was not obvious when the gap width was more than 2 mm [15].

Digital image correlation (DIC) has been applied to evaluate the performance of CLT by measuring the strain distribution. The effect of strength class of wooden board on the properties of CLT had been investigated by DIC in [16]. It had shown that a qualitative and quantitative identification of plate failure mechanisms could be made by DIC. Niederwestberg et al. investigated the strain distributions of 5-layer composite laminated panels by both experimental and analytical methods in [17]. The DIC strain distribution was consistent with that calculated by shear analogy method. The performance of CLT subjected to torsion had been investigated in [18]. Numerical modeling by finite element method and optical measurement with DIC were used. Results of simulations showed that edge-bonding of layers had great influence on strain distributions and deflection of CLT panel. Pang et al. [19] measured swelling and shrinkage strains of CLT with DIC to evaluate the effect of moisture content. They reported that the difference of strain between the cross layer and the glue line increased as moisture content increased.

This study was aimed at investigating the influence of aspect ratio, which was decided according to the common size of the eucalyptus lumber available in the market in China, on the rolling shear properties of fast-grown eucalyptus laminations. For comparison, the rolling shear properties of SPF lumber was tested to explore the feasibility to manufacture CLT with eucalyptus lumber. Further, DIC was applied in the test for analyzing the shear strain distribution and failure mechanism.

2 Materials and Methods

2.1 Materials

Wood species used in this study were SPF dimension lumber (*Spruce-pine-fir*) from Canada and fast-grown eucalyptus (*Eucalyptus urophyllaS. T. Blak*) lumber grown in Guangdong Province, China. SPF dimension lumbers of J-Grade were 38 mm in depth, 89 mm in width and 2440 mm in length. Eucalyptus lumbers had three different widths, 40 mm, 80 mm and 120 mm, of which depth is 20 mm and length is 1000 mm. Average moisture content of SPF dimension lumbers and eucalyptus lumber were 12.98% and 12.41%, respectively. The average density of SPF and eucalyptus lumber were 0.45 g/m^3 and 0.59 g/cm^3, respectively. One-component polyurethane adhesive (Fule ICEMA R645/30) was used to bond the layers under pressure of 1.0 MPa without edge-gluing. The resin load is 250 g/m^2. Before testing, all specimens were placed at an environment of a temperature of 20°C and a relative humidity of 65% for equilibrium.

2.2 Modified Planar Shear Test

Four groups of 3-layer CLT specimens, having different wood species and aspect ratio of cross layer, were prepared in this study. The configurations of cross layer of each group is shown in Tab. 1. One small piece of wood lamination was placed at the end of the cross layer of each specimen due to the requirement of total length of specimen. The material used for outer layers, namely longitudinal layer, was 2 × 4 SPF dimension lumber for all specimens. Ten specimens were prepared for each group.

Table 1: Configurations of cross layers

Groups	Species	Aspect ratio (γ)	Thickness (mm)	Width (mm)
A	Eucalyptus	2	20	40
B	Eucalyptus	4	20	80
C	Eucalyptus	6	20	120
D	SPF	4	20	80

The modified planar shear tests were conducted using the method developed by Gong et al. [2] with the experimental setup shown in Fig. 1. The modified planar shear tests were conducted using a universal mechanical testing machine (SHIMADZU AG-X/AG-IC). The testing approach included three steps. First, one specimen of each group was loaded to failure to provide an estimate of the failure load of each group. Then other specimens were loaded until the load reached about 40% of the first failure load in step 1. The loading rate was 1.0 mm/min in this step. Two 25 mm linear variable differential transformers (LVDTs) (TDS-530) were used on both specimen sides to measure the displacements. The shear modulus (G_R) of the cross layer was calculated using Eq. (1). Finally, all the specimens were loaded to failure at a loading rate 3.0 mm/min. The shear strength (τ_R) of the cross layer was calculated using Eq. (2) [2].

$$G_R = \frac{P}{\Delta} \cdot \frac{t_{\text{cross}}}{L \cdot w} \cdot \cos(\alpha) \quad (1)$$

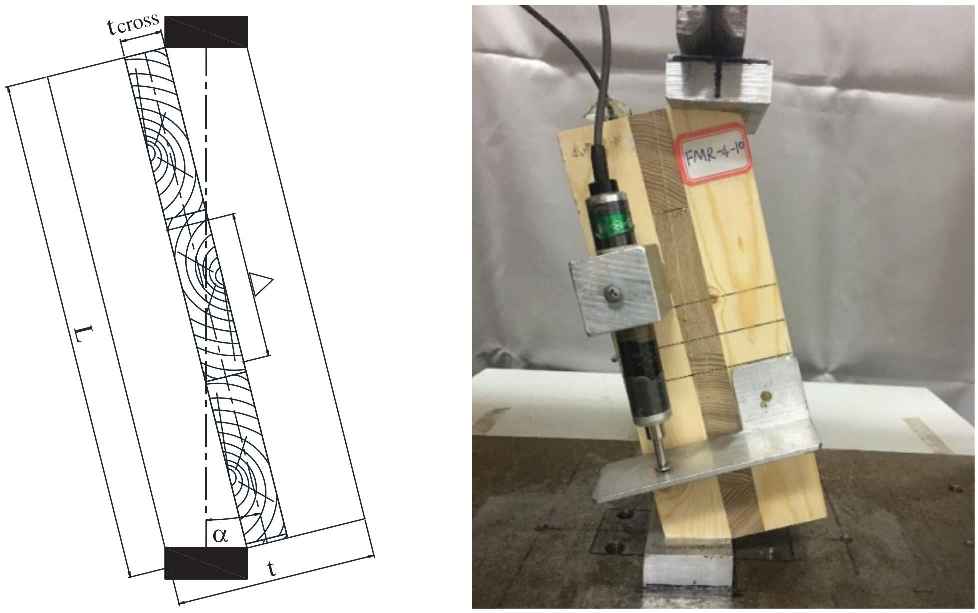

Figure 1: Experimental setup of modified planar shear test

$$\tau_R = \frac{P_{max} \cdot \cos(\alpha)}{L \cdot w} \tag{2}$$

where, t_{cross} is the cross layer thickness, the value of t_{cross} is 20 mm, L is the specimen length, the value of L is 242 mm, w is the specimen width, the value of w is 89 mm, P/Δ is the slope of the load-deformation curve below the proportional limit, α is the inclination angle, the value of α is 14°, and P_{max} is the peak load, N.

The characteristic rolling shear strength, i.e., the 5% quantile value at the confidence level of 75%, was calculated according to EN 14358 [20], Eqs. (3) and (4).

$$k_s(n) = \frac{6.5n + 6}{3.7n - 3} \tag{3}$$

$$\tau_k = \bar{y} - k_s(n)s_y \tag{4}$$

where τ_k is the characteristic rolling shear strength, $k_s(n)$ is the factor used to calculate characteristic properties for initial type testing, n is the number of test values, $\bar{y}$ is mean value, s_y is the standard deviation.

2.3 Three-Dimensional Digital Image Correlation Method

The DIC equipment in this study included a non-contact strain test system (DIC-3D) and two synchronous CCD cameras (focal length f is 25 mm, aperture F is 1.4), the shooting interval is 0.5 s, and the acquisition frequency was 5 Hz. The CCD camera was mounted directly on the front of the test specimens while ensuring that the optical axis was perpendicular to the surface of test specimens, Fig. 2. The angular deviation between the normal of the specimen surface and the optical axis of the camera was guaranteed to be within 5° to reduce the influence of the measurement results. During the test, the CCD camera was used to collect the speckle pattern on the surface of the test piece and saved to the computer system. At the end of the test, the speckle image was processed by DIC's analysis software (VID-3D 2010), and finally the deformation distribution of the entire surface of the specimen was obtained.

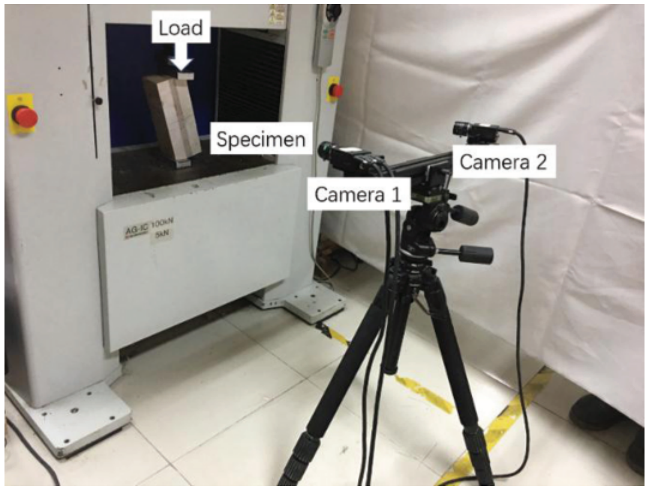

Figure 2: Experimental setup of modified planar shear test with DIC

3 Results and Discussion

The summary of rolling shear strength and modulus of all test groups is presented in Tab. 2. Overall, the mean rolling shear strength of eucalyptus laminations was 3.54 MPa with a coefficient of variation (COV) of 13.3%. Its mean rolling shear modulus was 429 MPa with a COV of 29.7% in this study. Detailed results and discussion are presented in the following sections.

Table 2: Rolling shear properties by groups: main statistics

Group	G_R (MPa)			τ_R (MPa)			
	Range	$G_{\mathrm{R,mean}}$	G_{R12}	Range	$\tau_{\mathrm{R,mean}}$	τ_{R12}	τ_k
A	273–573	375(24.9)	370	2.82–4.33	3.46(13.2)	3.38	2.68
B	229–586	418(32.5)	427	2.64–4.18	3.52(14.5)	3.63	2.60
C	312–681	495(25.8)	503	2.94–4.39	3.65(12.7)	3.74	2.81
D	73–180	116(28.8)	118	1.45–2.41	1.87(17.1)	1.92	1.24

Note: In parentheses is the coefficient of variation, %.

3.1 Influence of Aspect Ratio

Regarding to rolling shear strength, the cumulative distributions of all eucalyptus specimens is shown in Fig. 3. The rolling shear strength falls between 2.64 and 4.39 MPa. In addition, the characteristic rolling shear strength, i.e., the 5% quantile value, was 2.67 MPa regardless of aspect ratio according to Eqs. (3) and (4). Overall, there is slightly increase in rolling shear strength with increasing of aspect ratio, Fig. 4. In comparation with Group A (aspect ratio of 2), the mean value of rolling shear strength of Group B (aspect ratio of 4) and Group C (aspect ratio of 6) increase 1.69% and 5.67%, respectively. In the one-way ANOVA test of Groups A, B and C, a p value of 0.567 was obtained, so there is no significant difference of rolling shear strength between tested eucalyptus groups, Tab. 3.

Regarding to rolling shear modulus, there is obviously increase with increasing of aspect ratio, Fig. 4. The mean rolling shear modulus of Group B and C increase 11.31% and 31.86%, respectively, compared with Group A. Moreover, the results of one-way ANOVA test show there is significant effect of aspect ratio on rolling shear modulus, Tab. 4.

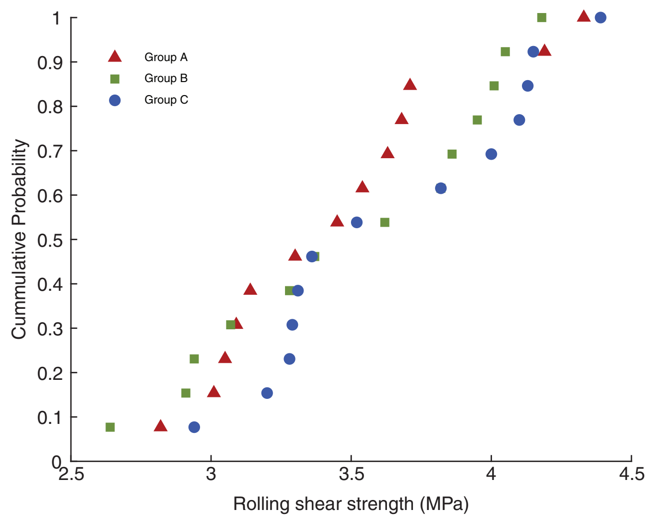

Figure 3: Cumulative distributions of rolling shear strength for different eucalyptus groups

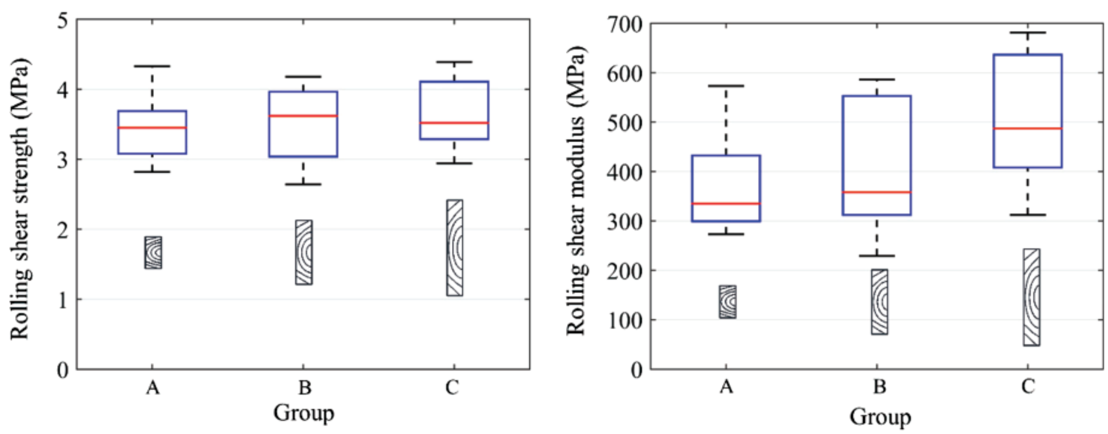

Figure 4: Rolling shear properties of different eucalyptus groups

Table 3: Variance analysis of rolling shear strength under different eucalyptus groups

Source of variation	Sum of squares	Degree of freedom	Mean square	F Value	p Value
Between groups	0.262	2	0.131	0.576	0.567
Within group	8.180	36	0.227		
Total	8.442	38			

Table 4: Variance analysis of rolling shear modulus under different eucalyptus groups

Source of variation	Sum of squares	Degree of freedom	Mean square	F Value	p Value
Between groups	95653.208	2	47826.604	3.302	0.048
Within group	521484.434	36	14485.679		
Total	617137.642	38			

Overall, the rolling shear properties of eucalyptus lamination increased with the increase of the aspect ratios, especially for rolling shear modulus. Other studies have obtained the same conclusion [10,21,22]. This can be explained by the boundary conditions: vanishing shear stresses at the free narrow faces of laminations caused stress concentrations and, thus, decreasing aspect ratios increased tensile stresses perpendicular to the grain [10].

3.2 Correlation between Rolling Shear Properties and Aspect Ratio

Several studies have discussed the regression analysis of rolling shear properties and aspect ratios. Ehrhart et al. [10] established a linear relationship between rolling shear parameters and aspect ratios for Norway spruce CLT, Eqs. (5) and (6). But the equation does not acknowledge the benefit effects of high aspect ratios. The strength limit of 1.4 MPa and modulus limit of 100 MPa were set for spruce with aspect ratios $\gamma \geq 4$.

$$\tau_k = min\{\begin{matrix} 0.2 + 0.3\gamma \\ 1.4 \end{matrix} \tag{5}$$

$$G_{R,\,\mathrm{mean}} = min\{\begin{matrix} 30 + 17.5\gamma \\ 100 \end{matrix} \tag{6}$$

Li et al. [21] proposed Eqs. (7) and (8) for characteristic strength values of Radiata pine (RP) and Douglas fir (DF), which defined aspect ratios γ in the range from 4 to 10.

$$\tau_{k,\mathrm{RP}} = 0.6 + 0.12\gamma \qquad 4 \leq \gamma \leq 10 \tag{7}$$

$$\tau_{k,\mathrm{DF}} = 0.3 + 0.15\gamma \qquad 4 \leq \gamma \leq 10 \tag{8}$$

Fig. 5 shows the regression analysis between rolling shear properties and aspect ratios in this study. Similarly, the linear relationships between rolling shear properties and aspect ratios were established, Eqs. (9)–(11).

$$\tau_k = 2.57 + 0.03\gamma \tag{9}$$

$$\tau_{R12} = 3.22 + 0.09\gamma \tag{10}$$

$$G_{R12} = 300.33 + 33.25\gamma \tag{11}$$

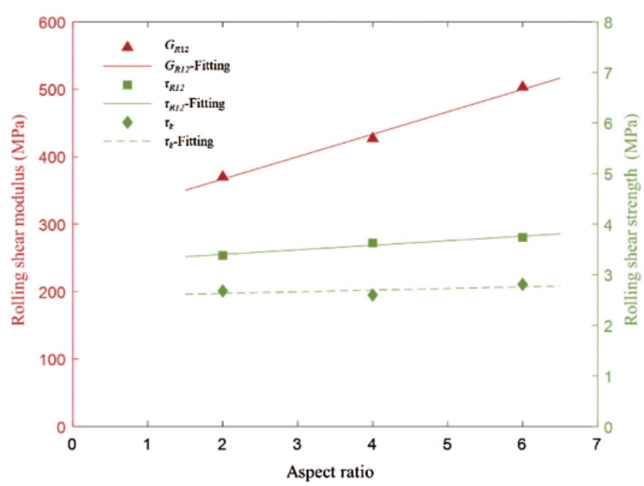

Figure 5: Aspect ratio *vs.* rolling shear modulus and strength

Tab. 5 summarizes the calculation results of rolling shear properties of eucalyptus lamination, using the Eqs. (5)–(11). There are relative higher relative errors between experimental and calculation results using Eqs. (5)–(8), compared with those using Eqs. (9)–(11), which basing on here obtained experimental data. These differences are because there are other important effect factors on rolling shear properties, such as density, resulting in the boundedness of each fitted equation.

Table 5: Comparison of properties evaluated by proposed equations and experimental results

Group	Properties	Eq. (5)	Eq. (6)	Eq. (7)	Eq. (8)	Eq. (9)	Eq. (11)
A	G_R	–	65(82.4)	–	–	–	367(0.9)
B		–	100(76.6)	–	–	–	433(1.5)
C		–	100(80.1)	–	–	–	500(0.6)
A	τ_R	0.8(70.1)	–	–	–	2.63(1.9)	–
B		1.4(46.2)	–	1.08(58.5)	0.9(65.4)	2.70(3.8)	–
C		1.4(50.2)	–	1.32(53.0)	1.2(53.0)	2.76(1.8)	–

Note: In parentheses is the relative errors between calculation and experimental value, %.

3.3 Correlation between G_R and τ_R

The regression analysis on rolling shear strength *vs.* modulus shows the linear relationship between these two properties, Fig. 6. Previous studies had also found there was low correlation between rolling shear modulus and strength especially for softwood. Due to their homogeneous density profile over the entire thickness of annual rings, hardwood had higher correlation between rolling shear modulus and strength than softwood. Ehrhart et al. [9] found the correlation of R^2 = 0.03, R^2 = 0.14 for softwood Norway spruce and pine, respectively. However, high correlation of R^2 = 0.37, R^2 = 0.63, and R^2 = 0.55 were found for hardwood beech, ash, and birch. Aicher et al. [3] reported the correlation of R^2 = 0.39 for European beech.

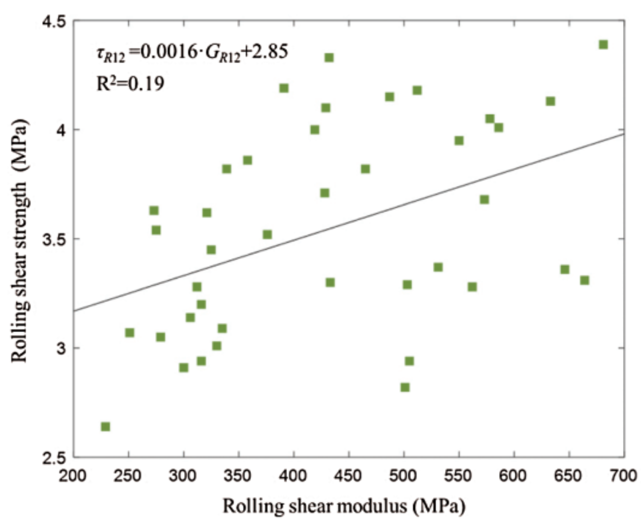

Figure 6: Rolling shear modulus *vs.* strength

3.4 Comparison of Rolling Shear Properties between Eucalyptus and SPF Laminations

Fig. 7 presents the difference of rolling shear properties between fast-grown eucalyptus and SPF laminations, which having the same aspect ratio of 4. The rolling shear modulus and strength of eucalyptus lamination were 260.3% and 88.2% higher than those of SPF lamination with the same aspect ratio of 4, respectively. Regardless of aspect ratio, the differences were 271.3% and 90.0%, respectively. Other studies found hardwood had higher rolling shear properties than those of softwood [2,3,5]. Aicher et al. [3] experimentally investigated the rolling shear strength and modulus of European beech wood, which exceed the respective characteristic values for softwoods by roughly factors of 5 and 7.

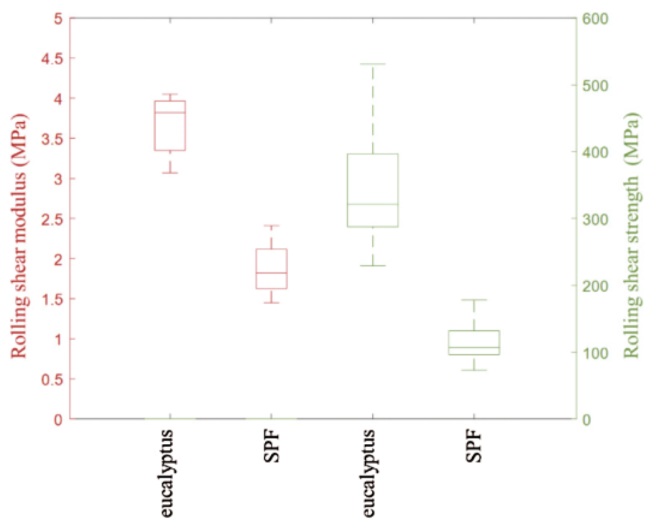

Figure 7: Comparison of rolling shear properties between eucalyptus and SPF

In current CLT design guides and codes, the characteristic rolling shear strength is 0.5 MPa for SPF CLT in Canada [23], while in Europe, the characteristic rolling shear strength is recommended 1.1 MPa for both edge-glued softwood CLT and non-edge-glued CLT made of laminations with a minimum aspect ratio of 4, otherwise 0.7 MPa should be used [24]. Thus, the characteristic rolling shear strength of eucalyptus lumber was 2.67 MPa, which exceeds the design value by a roughly factor of 3. At present, a mean G_R of 50 MPa for spruce and fir laminations is in general assumed for design purposes [25]. Thus, the here obtained experimental value of G_R 429 MPa exceeds the specified value by a factor of 8. Apparently, eucalyptus lamination, which using as the cross layer, will lead to an enhanced out-of-plane strength and stiffness behavior of CLT.

3.5 Rolling Shear Failure Modes Evaluated by DIC

The shear strain distribution and development evaluated by DIC at different stress levels of one typical eucalyptus specimen with aspect ratio of 2 is shown in Fig. 8. The development of shear strain can be described as following: (1) In the initial stage, high shear strain zones appeared around the gaps near the loading head, especially for the specimens with aspect ratio of 2; (2) With the increase of load, the strain distribution of the whole section changed. High shear strain zones developed from specimen ends to center along the length of specimens and the following high shear strain zones appeared in several gaps between segments; (3) In the loading later period, the strain around the gaps became higher, and the shape of high shear strain zones changed along the horizontal direction, vertical direction or other fold line. In some cases, double high strain zones would combine and form a new big high strain zones; (4) Finally, a sudden failure of the specimens occurred in the high strain zones. In general, gaps between

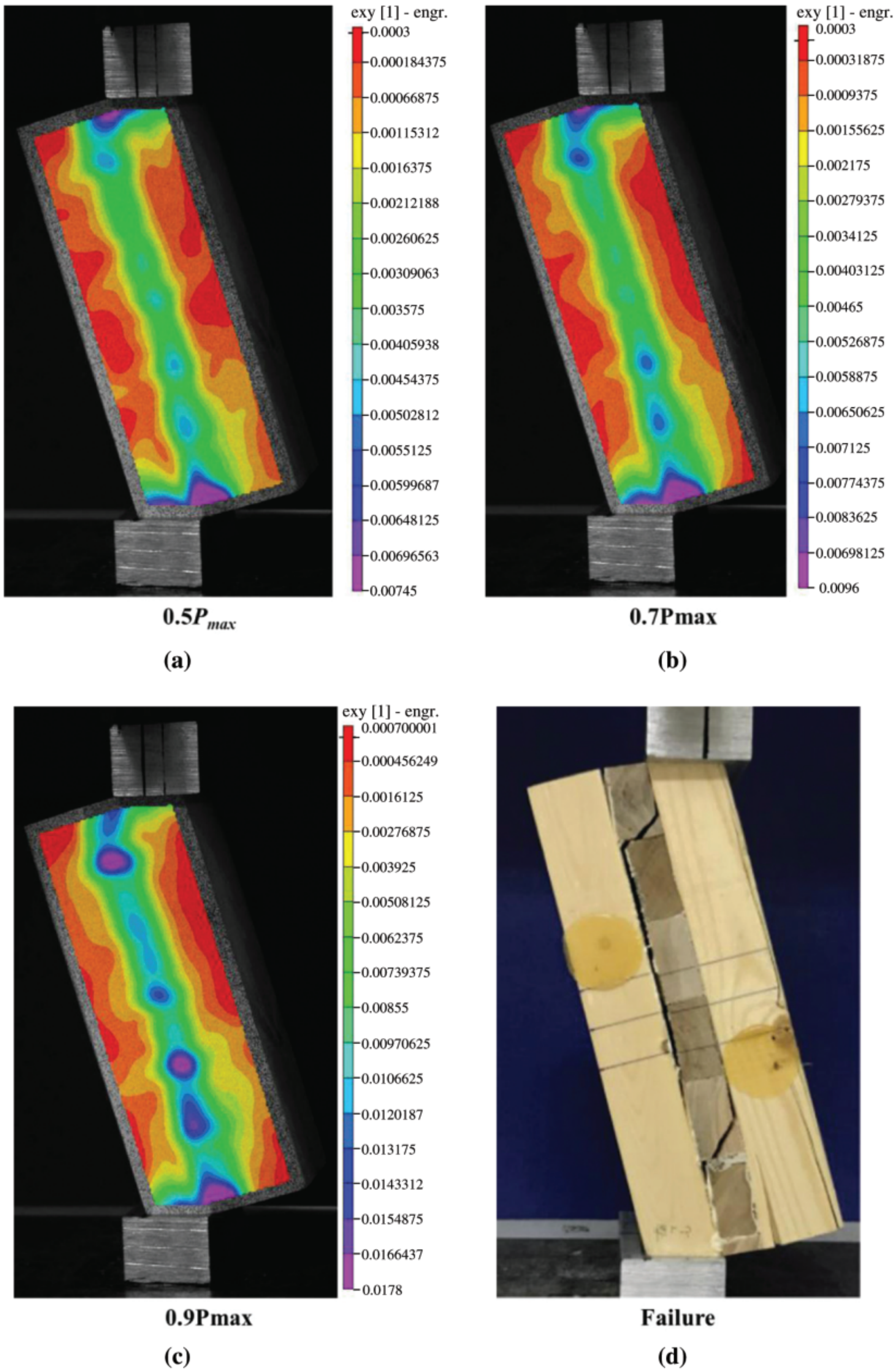

Figure 8: Strain distribution of eucalyptus specimens (A-3) at different stress levels

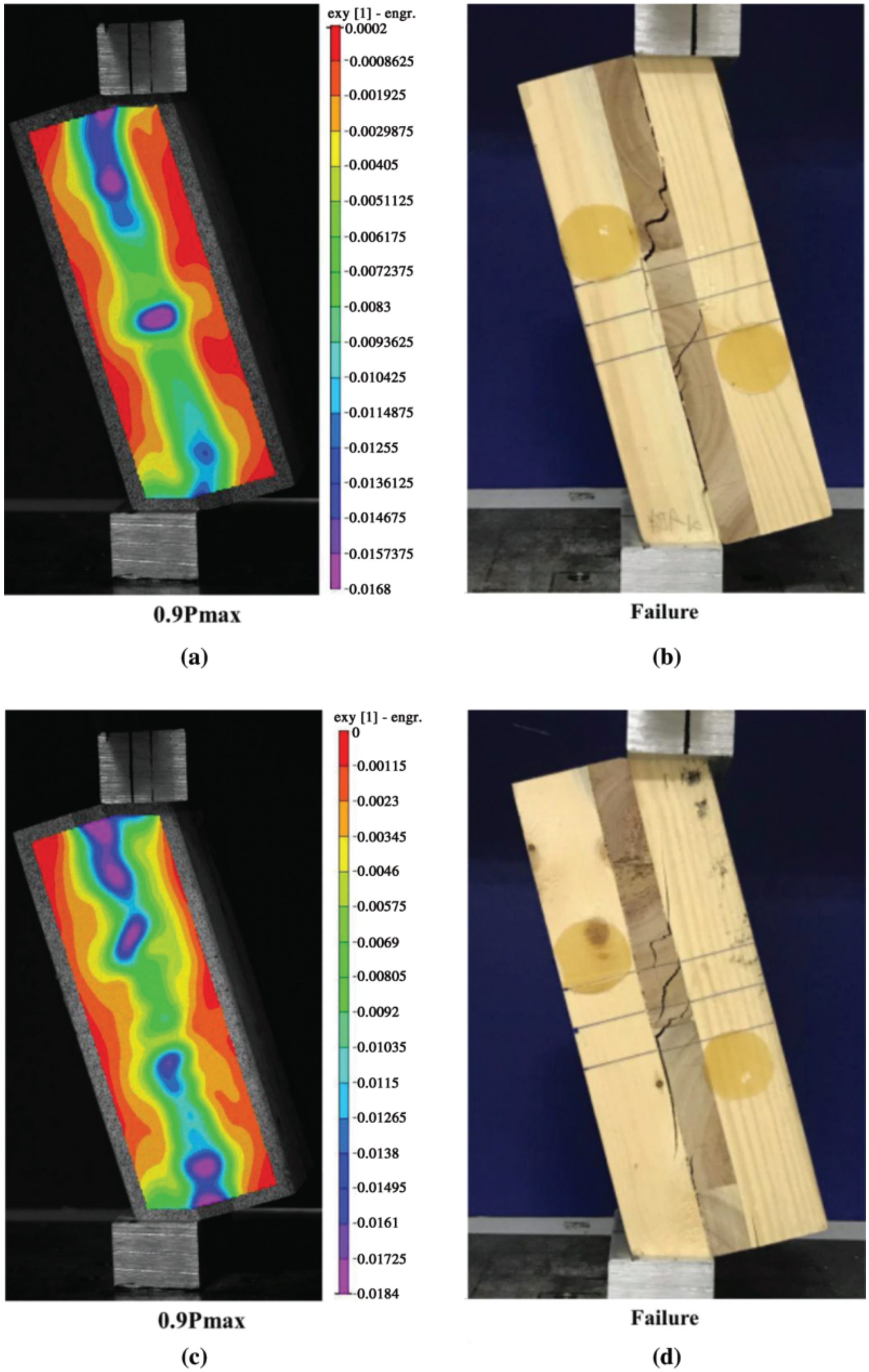

Figure 9: Strain distribution and failure of eucalyptus specimens: (a) and (b) $\gamma = 4$, and (c) and (d) $\gamma = 6$

segments were the primary high shear strain zone, so the failure of the specimens often occurred near the gaps. Furthermore, the high shear strain zones also were found around pith and alone glue lines, where were the failure locations. The failure mechanism of rolling shear, observed by DIC in this study, is in agreement with the results in other studies [5,10,26].

Specimens with different aspect ratios had similar rolling shear strain development. The specimens with high aspect ratios had less gaps between segments as well as high shear strain zones in the process of failure, which could improve the rolling shear properties (Fig. 9).

4 Conclusions

In this study, rolling shear properties of eucalyptus laminations with aspect ratios of 2, 4, and 6 were evaluated by modified planar shear tests. The rolling shear strain distribution and failure process were analyzed by DIC. Simultaneously, the rolling shear properties of SPF specimens were compared to evaluate the potential of using fast-grown eucalyptus in CLT manufacturing. The main conclusions are summarized below:

1. The characteristic rolling shear strength and mean value of rolling shear modulus of all tested eucalyptus specimen were 2.67 MPa and 429 MPa, respectively. Rolling shear modulus of eucalyptus with aspect ratio of 2, 4, 6 were 375, 418, 495 MPa, respectively. And rolling shear strength of eucalyptus with aspect ratio of 2, 4, 6 were 3.46, 3.52, 3.65 MPa, respectively. The rolling shear properties of eucalyptus laminations increased as the aspect ratio increased. Aspect ratio had a significant influence on measuring rolling shear modulus rather than rolling shear strength. Linear equations, with low R^2 of 0.19, of rolling shear strength and modulus were founded for eucalyptus specimen.
2. Fast-grown eucalyptus wood had great potential to use as cross layer in CLT. Experimental rolling shear modulus and strength of eucalyptus with the same aspect ratio of 4 were 260.3% and 88.2% higher than those of SPF, respectively. And the rolling shear strength and modulus of fast-grown eucalyptus laminations exceed the respective characteristic values for softwoods in the current standard by roughly factors of 3 and 8.
3. The rolling shear strain distribution and failure process of cross layer could be well analyzed by DIC. The initial high shear strain zones usually occurred around the gaps between the segments of cross layer. The high shear strain zones would redistribution during the loading process. Except gaps, the high shear strain zones also occurred around the pith and alone the glue lines. Finally, sudden failure occurred in the high shear strain zones, and the specimen broke. Compared with the specimen with high aspect ratio, more high shear strain zones occurred around the gaps between the segments of cross layer in the specimens with low aspect ratio.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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