Effect of Different Thickness of the Layers of Cross-laminated Timber Made from Chinese Fir on the Mechanical Performance

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Under the premise of an unchanging total thickness in cross-laminated timber (CLT) made from Chinese fir, research into the effect of different CLT laminate thicknesses on the mechanical performance (bending and shear performance) was performed using the existing CLT static analysis theory to calculate and compare the bending performance of CLT specimens. The results showed that at constant total thickness the bending performance increased, the shear performance worsened, and the destruction mode of the CLT structure became simpler with an increase in the CLT laminate thickness. Increasing the odd to even layer thickness ratio effectively improved the bending and shear performance of the CLT specimens for a certain percentage range.

Keywords: Chinese fir; Cross-laminated timber; Laminate thickness; Mechanical properties

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INTRODUCTION

The main forms of timber structures in China are light wood frame constructions, glued laminated timber structures, and sawn and round timber structures. Among these forms, the light wood frame construction, which is used in North America, occupies a major position in the modern timber structure system. However, GB 50005-2003 (2003) restricts the height of light wood frame constructions and stipulates that they should not exceed three floors, which greatly limits modern timber structural development in China. This situation has changed with the creation of cross-laminated timber (CLT), which is a new building structural material that adopts a lay-up method of stacking adjacent laminates with 90° cross-laminates to maintain a high dimensional stability and excellent mechanical performance. Foreign CLT buildings have been built with more than 18 floors, and China has developed the standard GB/T 51226-2017 (2017) in response (Yang 2017). Additionally, the design plan for the first six-story timber structure in China has been initially completed and will be implemented in Shandong Province. If CLT can be promoted in China, it will greatly promote the development of modern timber structures.

Much research on CLT has been conducted abroad (Park *et al.* 2003; Frangi *et al.* 2009; Zhou *et al.* 2014; Schneider *et al.* 2015; Cao *et al.* 2016; Knorz *et al.* 2017; Hashemi *et al.* 2018). However, in China, only Nanjing Forestry University, the Chinese Academy of Forestry, and other scientific research institutes have researched material performance, section design, node connection bearing, rolling shear, bending, and other mechanical performances of timber bridges and buildings with CLT.

The Chinese Academy of Forestry has discussed the influences of the laminate modulus, lay-up direction, and layers on the mechanical performance of CLT (Wang *et al.* 2014b; Que *et al.* 2015; Dong and Wang 2016; Gong 2017; Que *et al.* 2017). Cross-laminated timber is a multi-layer composite material, and laminates should not be too thick or too thin. For the overall thickness dimension, if the laminate is too thick, it will cause the overall structure of the component to not be uniform, which could cause a defect that is too concentrated. If the laminate is too thin, not only are there higher demands of the manufacturing process, but it also increases the amount of wood and gum (Guo 2007). When meeting the mechanical performance requirements, the thickness of the laminate should be fully considered. However, there is a lack of research on the thickness of CLT laminates in China.

Fir (*Cunninghamia lanceolata* (Lamb.) Hook) is an important tree species in Southern China that possesses characteristics of fast growth and high yields (Wang *et al.* 2014a). However, because fir is a fast-growing wood, it has a poor strength, moisture absorption, dimensional instability, and other defects that limit its applications. At present, Chinese fir is mainly used in decorations, furniture, and other minor uses. Therefore, actively broadening the scope of Chinese fir application not only can improve the utilization of Chinese fir, but also promote the development of the wood industry in China to a larger extent.

Chinese fir was chosen as the raw material for the lay-up laminates and cold press molding and to research the effect of the CLT laminate thickness on the mechanical performance with the condition of an unchanged overall thickness through the static testing of CLT laminates with different thicknesses. This will not only expand the application scope of Chinese fir, but also promote the development of CLT and accelerate the development of modern timber structures in China.

EXPERIMENTAL

Materials

The raw materials were market-purchased Chinese fir, which was made in Fujian Province. The average density was 0.394 g/cm^3 and the average moisture content was 13.5%. The relevant specifications of GB/T 50329-2002 (2002) were used for preparing specimens with a section size of 300 mm × 95 mm, and lengths of 2200 mm and 500 mm were used for the bending and shear tests, respectively. Three samples were tested for each of the properties.

The adhesive used was polyurethane, specifically HB S309, which is a one-component liquid polyurethane adhesive (Heinkel Adhesives, Düsseldorf, Germany). The maximum aging time was approximately 30 min, and the curing time was approximately 120 min.

The performance of the multi-layer composite materials is closely related to the performance of the constituent structural units, and so it was necessary to test various performance parameters of the Chinese fir boards before the CLT mechanical testing. The parameters were performed according to GB/T 1935-2009 (2009), GB/T 1936.1-2009 (2009), GB/T 1936.2-2009(2009) and GB/T 1937-2009(2009). Ten samples were tested for each of the performance. The test results are shown in Table 1.

Table 1. Results of the Mechanical Performance of the Chinese Fir Slats

Property		Value (MPa)	Standard Deviation (%)	Coefficient of Variation (%)
Compressive Strength of Parallel to Grain		28.3	2.8	14.9
Bending Strength		50.8	3.2	16.9
Elastic Modulus Parallel to Grain		7600	3.1	18.1
Elastic Modulus Perpendicular to Grain		262	2.1	12.5
Shear Strength Parallel to Grain	Radial Surface	4.9	3.4	14.7
	Chord Surface	5.4	2.7	15.6

There were two test programs employed in this study. The first was for studying the effect of the CLT laminate thickness on the mechanical performance with the condition of an unchanged total thickness (95 mm) (Test 1). The lay-up method parameters are shown in Table 2. The other test studied the effect of the CLT odd to even layer thickness ratios on the mechanical performance when the total thickness (95 mm) was not changed, with the five-layer CLT acting as an example (Test 2). The proportional relationship is shown in Table 3.

Table 2. Lay-up Type of the CLT Specimens

Structure	Thickness of the Laminates (mm)
Three Layers	31.7
Five Layers	19
Seven Layers	13.6

Table 3. Thickness Variation of the Odd and Even Layers of the CLT Specimens

Odd Layer Thickness (mm)	Even Layer Thickness (mm)	Odd to Even Layer Thickness Ratio
19	19	1
21	14	1.5
23	12	1.9

The production of CLT uses a lay-up method of stacking adjacent laminates with 90° cross-laminates. The odd layers were the primary direction layers (parallel to the grain), and the even layers were the secondary direction layers (perpendicular to the grain). The main mechanical load-bearing direction was the direction parallel to the grain.

Production of the specimens

The production of CLT specimens mainly consists of three steps: planking, sizing, and cold pressing. After the materials were prepared, polyethylene film was first spread on the ground, and then the first laminate layer was placed on top of the film (after laying, all laminates need to be cleaned before lay-up and cannot be attached to wood chips to improve the glue quality), which was followed by sizing (Fig. 1a). Sizing was done as uniformly as possible, and the adhesive quantity was 120 g/m^2 to 160 g/m^2. The second laminate layer was laid immediately after sizing (Fig. 1b), and the second layer was glued. Then, the next layers were laid down until the desired number of test layers was reached. After the specimen was completely coated, it was fixed with a wooden block and the entire CLT specimen was wrapped tightly with a film (Fig. 1c). Cold pressing occurred after the specimen was produced (Fig. 1d). The pressure was set to approximately 1.5 MPa, and the holding time was approximately 2.5 h. This process is shown in Fig. 1.

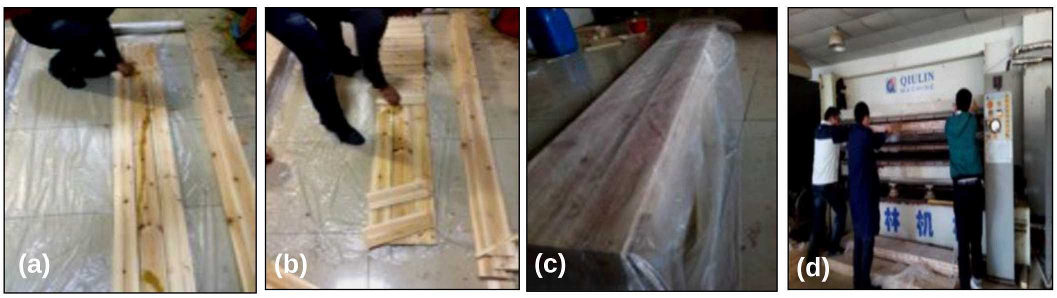


Fig. 1. Production of the CLT specimens: (a) sizing, (b) placement of the second layer, (c) film-wrapped specimen, and (d) cold pressing

Methodology

The device used was a UTM5105 microcomputer control material universal testing machine (Jinan Kesheng Test Equipment Co., Ltd., Jinan, China). The static tests were performed according to ASTM D198-05 (2005) and JIS 3079 (2013), which determined the bending stiffness, bending strength, and shear strength. Three valid specimens were tested for each configuration, and the average of the results was reported.

The test method for the binding performance was four-point bending, with a specimen length of 2000 mm. During testing, loading occurred at a uniform speed of 15 mm/min and the vertical deflection of the midpoint of the CLT specimens under a vertical load was measured with a displacement meter (YWC-100, Liyang Chaoyuan Instrument Factory, Liyang, China). A three-point test was conducted for the shear performance test with a specimen length of 240 mm, and the specimens were loaded at 5 mm/min.

To determine if the CLT model analysis theory has a realistic feasibility, the authors chose the model theories (γ-theory and κ-theory) (Gagnon and Pirvu 2012) of the bending performance (bending stiffness and strength) for calculation and analysis.

In the γ-theory, the bending performance was determined by calculating the equivalent bending stiffness of a specimen. The value of the equivalent bending stiffness was mainly related to the sectional performance of a beam and effective γ coefficient. The γ coefficient was related to the slip performance of the connector. When the wooden components were connected with adhesive, the γ value was generally between 0.85 and 0.99. The theoretical calculation used the five-layer CLT as an example, and the calculation of the five-layer CLT is shown in Fig. 2 and used Eqs. 1, 2, and 3.

$$EI_{eff} = \sum_{i=1}^{n} (E_i I_i + \gamma_i E_i A_i a_i^{\,2}) \tag{1}$$

$$\gamma_1 = \frac{1}{1 + (\pi^2 \cdot \frac{E_1 \cdot A_1}{l^2} \cdot \frac{\overline{h_1}}{G_R \cdot b})} \tag{2}$$

$$\gamma_3 = \frac{1}{1 + (\pi^2 \cdot \frac{E_3 \cdot A_3}{l^2} \cdot \frac{\overline{h_2}}{G_R \cdot b})} \tag{3}$$

where EI_{eff} is effective bending stiffness (Nmm^2); l is the span of simply supported beam (mm); G_R is rolling shear modulus (GPa), G_R is approximately $1/10$ $G_{\text{shearmod}\,ulus}$ and $G_{\text{shearmod}\,ulus}$ is $1/12$ - $1/20$ of the elastic modulus; b is width of CLT specimen (mm); A_i is the sectional area of the laminate (mm^2), γ_i is the equivalent slip coefficient ($\gamma_2 = 1$), I_i is the moment of inertia (mm^4), and h_1 and h_2 are the thicknesses of the primary and secondary direction laminates (mm), respectively. Here E_i is the elastic modulus of the laminate (GPa) ($E_1 = E_2 = E_3$), and a_i is the distance from the center of the laminate to the center of the specimen (mm).

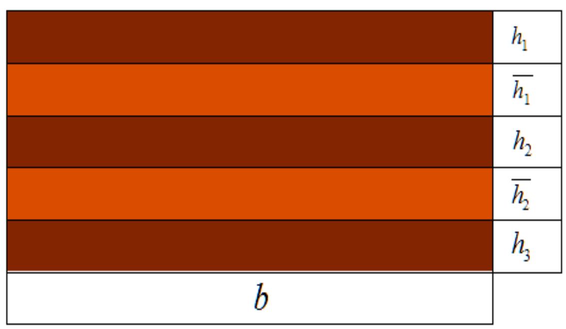


Fig. 2. Sectional analysis of the five-layer CLT structure

For the calculation of the equivalent bending stiffness of the seven-layer CLT, it was decomposed into five-layer and three-layer parts, as is shown in Fig. 3, and so,

$$(EI)_7 = (EI)_5 - (EI)_3' + (EI)_3 \tag{4}$$

where $(EI)_3'$ is the imaginary middle layer bending stiffness of the five-layer CLT and $(EI)_5$ is the bending stiffness of a hypothetical five-layer CLT.

Using the κ-theory to calculate the equivalent elastic modulus, the composite coefficient κ was calculated based on the loading direction of the vertical load. The κ coefficient was obtained using Eq. 5. The study used the κ coefficient to determine the bending strength, as is shown in Eq. 6,

$$k = 1 - (1 - \frac{E_{90}}{E_0}) \cdot \frac{a_{m-2}^3 - a_{m-4}^3 + \cdots \pm a_1^3}{a_m^3} \tag{5}$$

$$\sigma = \sigma_0 \cdot k \tag{6}$$

where a_m is the thickness of the specimen (mm), m is the number of layers of the laminate; "…" is to add and subtract in sequence. E_0 is the modulus parallel to the grain (7600 MPa), and E_{90} is the elastic modulus perpendicular to the grain (316 MPa); σ is bending strength (MPa); and σ_0 is bending strength parallel to the grain (MPa).

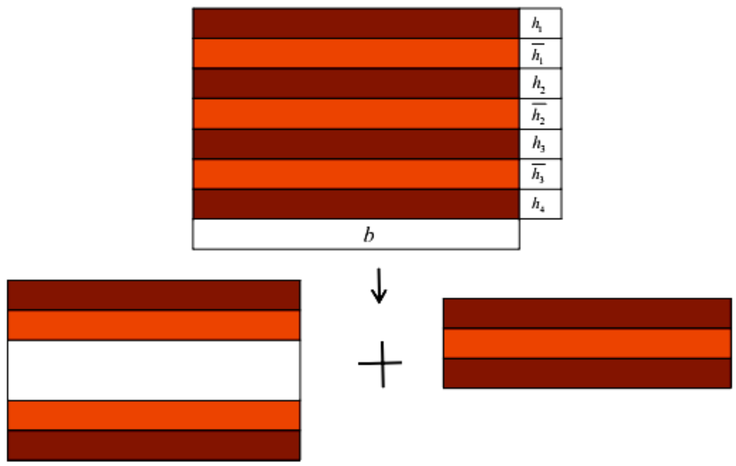


Fig. 3. Sectional analysis of the seven-layer CLT structure

RESULTS AND DISCUSSION

Effect of Different CLT Laminate Thicknesses on the Mechanical Performance: Test 1

The load-deflection curves at the midpoint of the effective CLT specimens (average) for different laminate thicknesses are shown in Fig. 4. Under loading, the overall change along the load-deflection curve of each CLT specimen was similar; the early load-deflection curve was basically a straight line. At the beginning of loading of the elastic phase, the curve was gentle. The main reason behind this phenomenon was the inevitable non-elastic deformation of the specimen at the stress bending stage. As loading continued, the midpoint deflection of the specimen changed rapidly, and then the deflection increased slowly. The load-deflection curve of the three-layer CLT specimen was more stable. The load-deflection curves of the five-layer and seven-layer specimens showed that as the number of layers increased, the stiffness of the CLT specimen gradually decreased, the ductility increased, and the failure modes were more complicated.

The detailed test results for the effect of different CLT laminate thicknesses on the mechanical performance are shown in Table 4. For the bending stiffness, the three-layer CLT specimen was the largest. When the bending stiffness of the three-layer CLT specimens was compared with that of the five-layer and seven-layer CLT specimens, there was a decrease of 11% and 18%, respectively. The structural performance of the three-layer specimen was relatively stable.

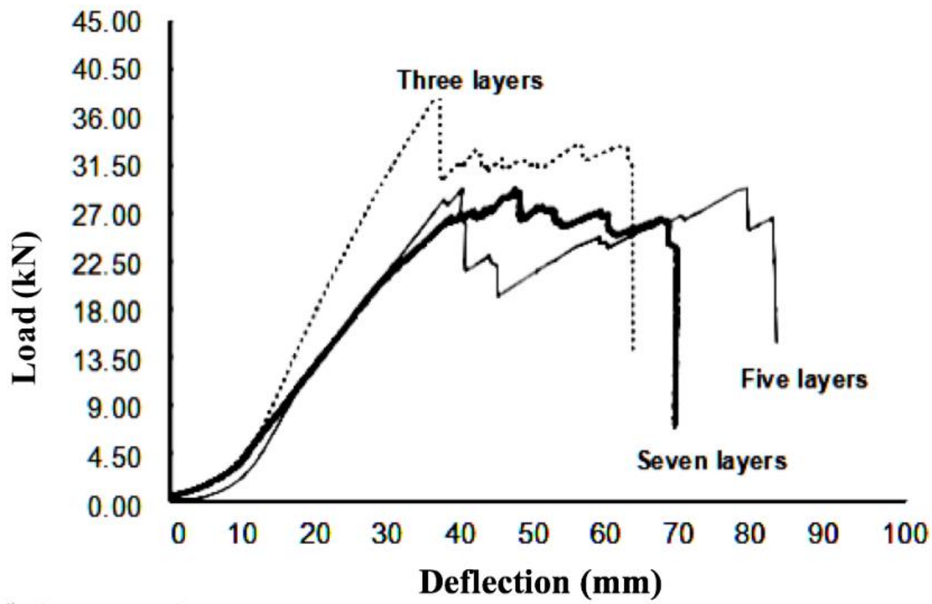


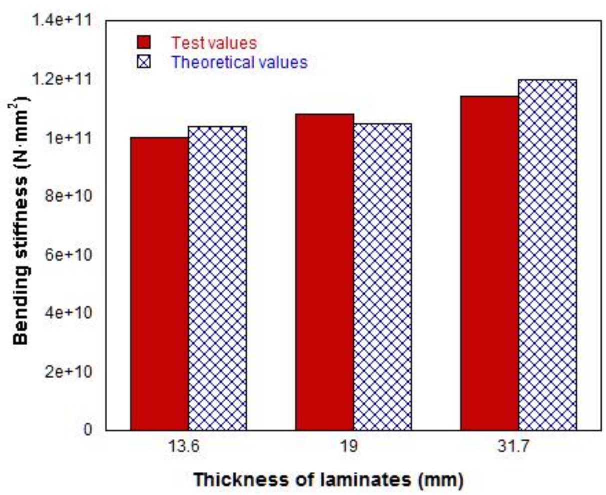
Fig. 4. Load-deflection response curves for the specimens

The bending strength of the five-layer CLT specimen was 18% higher compared with that of the three-layer CLT specimen and 36% higher compared with that of the seven-layer CLT specimen. The bending strength of the three-layer CLT specimen was higher than that of the seven-layer CLT specimen by approximately 16%. The shear strength of the five-layer and seven-layer CLT specimens were 2.6% and 16% higher compared with that of the three-layer CLT specimen, respectively. The test results showed that under the premise of the same overall thickness, the bending stiffness of the specimen improved as the laminate thickness increased. The bending strength was the largest in the five-layer structure, followed by the three-layer and seven-layer structures. Additionally, the shear strength decreased as the laminate thickness increased.

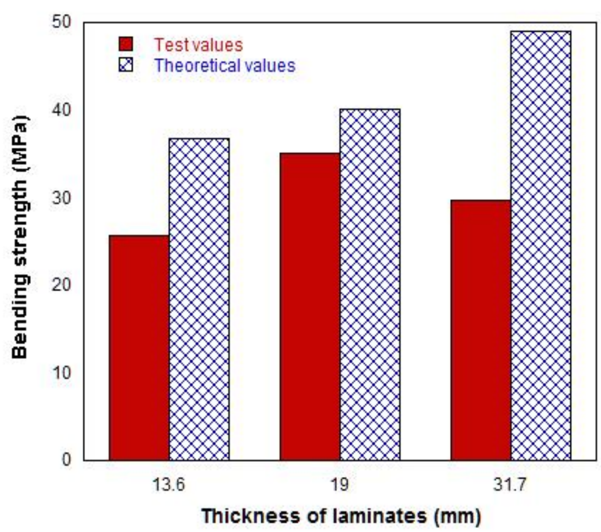
Table 4. Results of the Effect of Different CLT Laminate Thicknesses on the Mechanical Performance

Number	Laminate Thickness (mm)	Bending Stiffness x 10^{11} (Nmm^2)	Avg x 10^{11} (Nmm^2)	Bending Strength (MPa)	Avg (MPa)	Shear Strength (MPa)	Avg (MPa)
A-3-1	31.7	1.10	1.14 (1.20)	33	29.7 (48.96)	5.10	5.48
A-3-2		1.14		29		5.24	
A-3-3		1.19		27		6.11	
A-5-1	19	1.17	1.08 (1.05)	35	35 (40.03)	5.51	5.62
A-5-2		1.05		33		5.24	
A-5-3		1.02		37		6.11	
A-7-1	13.6	0.94	1.00 (1.04)	29	25.7 (36.73)	6.71	6.39
A-7-2		0.96		26		6.34	
A-7-3		1.10		22		6.11	
Note: Theoretical values are given in parentheses; and Avg represents average							

The results from the tests were compared with the values calculated from the theoretical models, which are shown in Table 4. Comparison diagrams are shown in Fig. 5. In general, the theoretically calculated values were higher than the results of the mechanical tests. The reason behind this phenomenon was that the deformation of the specimen was affected by many factors in the test (such as the defect distribution on the laminate, randomness of the mechanical strength on the laminate, glue line failure and external environment), which could not be considered in the theoretical calculations. However, the overall trend of the effect of the laminate thickness on the bending stiffness was consistent between the test results and theoretical calculations.



(a)



(b)

Fig. 5. Comparison of the results for the bending stiffness (a) and strength (b) of Test 1 and the theoretical calculation

Under the premise of an unchanged overall thickness, the bending stiffness gradually increased as the thickness of the laminate increased. However, the test and theoretical results for the relationship between the bending strength and laminate thickness were different. The mechanical test results showed that the bending strength of the five-layer CLT specimen was the highest, followed by the three-layer and seven-layer structures. The theoretical analysis and calculations showed that as the thickness of the laminate increased, the bending strength increased. The three-layer CLT specimen had the highest bending strength, followed by the five-layer and seven-layer structures. This showed that the application of CLT should be based on practical results and should not be applied using only theoretical analysis and calculation.

The deformation of the specimen was generally larger during bending. There were three main failure modes, namely breakage of the bottom plate (Fig. 6a), failure of the adhesive layer in the tensile zone (Fig. 6b), and failure of the rolling shear (Fig. 6c). However, a specimen was more likely to be destroyed where a defect was concentrated (decay, wood section, *etc.*) (Fig. 6d). There was also the phenomenon of adhesive layer peeling and slippage between the laminate in the tensile zone of the specimen.

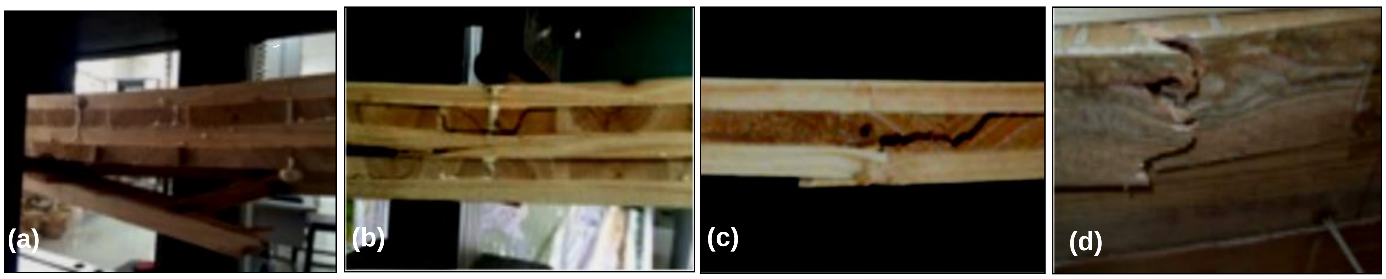


Fig. 6. Main failure modes of the CLT specimens in the bending test: (a) bottom plate, (b) adhesive layer in the tensile zone, (c) rolling shear, and (d) defect section

The overall performance of the three-layer specimen was stable during the bending failure process. The main failure mode was breakage of the bottom plate (Fig. 6a), with a small amount of rolling shear failure of the inner plates (Fig. 6c), and no cracking of the adhesive layer and slipping of the end laminar plate occurred. The rolling shear began to increase during bending of the five-layer CLT specimens. Because of the thinness of the laminate, the shear strength of the laminate was lower. The final failure modes included breakage of the bottom plate, slipping of the end laminar plate, and cracking of a few adhesive layers. The degree of breakage of the bottom plate was less severe. Additionally, the rolling shear and cracking of the adhesive layer occurred more during bending of the seven-layer CLT specimens because the thickness of the laminate was too thin and the adhesive layer stability and shear resistance of the laminate decreased remarkably. Furthermore, there were as many as six adhesive layers in the seven-layer CLT structures, which were prone to failure by adhesive layer peeling (Fig. 6b). The main failure modes of the seven-layer CLT specimens included breakage of the bottom plate, slipping of the end laminar plate, rolling shear, and adhesive layer peeling, among which the main modes were adhesive layer peeling and rolling shear damage.

As the failure modes of the specimens showed, breakage of the bottom plate in the tensile zone of the three-layer CLT specimens was more obvious than in the five-layer and seven-layer structures. However, adhesive layer peeling and tensile failure of the bottom plate were more serious for the five-layer and seven-layer CLT specimens during bending. For instance, in the five-layer CLT specimen, the tensile area consisted of two layers, namely the primary and secondary direction layers. In the tension process, the laminar plates in the primary and secondary directions were mutually restrained, which resulted in rolling shear failure of the secondary direction laminates and fracture of the primary direction laminates. Under the same circumstances, the three-layer CLT specimen had only one main direction layer in the tension zone, which was relatively easy to break. In contrast, the seven-layer laminates were thinner, and the bottom laminate plate was easier to break than that of the five-layer laminate. This was the reason why the bending strength of the five-layer CLT specimen was the highest. Finally, it was concluded that under the premise of an unchanged overall thickness and as the number of layers increased, the laminate became thinner and was more likely to break and deform, which to a large extent was also the reason why the seven-layer CLT specimen had the lowest bending stiffness and strength values, while the performances of the three-layer and five-layer CLT specimens were excellent.

The failure modes of the specimens were similar during the shear strength test, and each of the damaged specimens underwent a large number of phenomena, such as rolling shear, splitting of the laminates, and slipping of the end laminar plate. Therefore, these failure modes meant that performance differences could not be assumed from appearance alone. Furthermore, this paper did not describe the failure mode of the shear strength based on the effect of the CLT odd to even layer thickness ratio on the mechanical performance (Test 2).

Effect of the CLT Odd to Even Layer Thickness Ratio on the Mechanical Performance: Test 2

The results of Test 2 are shown in Table 5. It was observed that the mechanical performances of the CLT specimens improved (the bending stiffness, bending strength, and shear strength increased by appreciable percentages) as the odd layer laminate thickness increased and the even layer laminate thickness decreased. For the CLT specimens that were simply supported from both sides, the direction of the main force on the specimen when subjected to the vertical load was parallel to the grain (odd layer laminates).

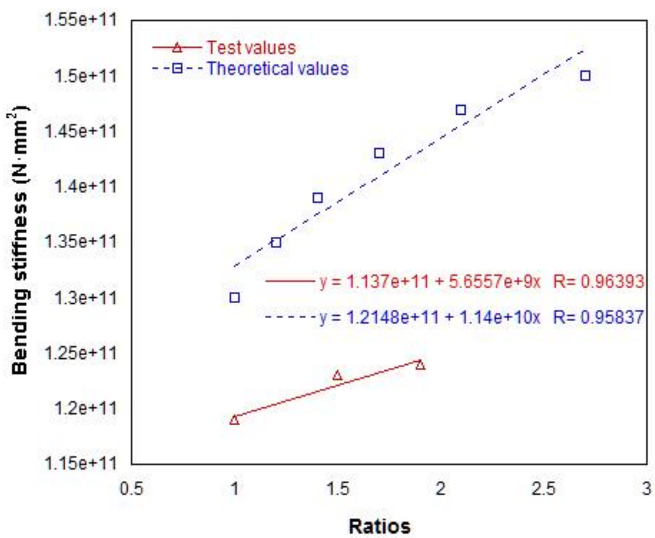
Table 5. Effect of the CLT Odd to Even Layer Thickness Ratio on the Mechanical Performance

Number	Ratio		Bending Stiffness x 10^{11} (N·mm^2)	Avg x 10^{11} (N·mm^2)		Bending Strength (MPa)	Avg (MPa)		Shear Strength (MPa)	Avg (MPa)
B-1-1	1	(1)	1.16	1.19	(1.30)	35	32	(40.7)	5.31	5.30
B-1-2			1.22			33			5.28	
B-1-3		(1.2)	1.19		(1.35)	29		(42)	5.32	
B-2-1	1.5	(1.4)	1.25	1.23	(1.39)	35	35	(43.4)	5.53	5.62
B-2-2			1.22			34			5.75	
B-2-3		(1.7)	1.23		(1.43)	37		(44.6)	5.57	
B-3-1	1.9	(2.1)	1.27	1.24	(1.47)	33	36	(45.7)	5.91	5.94
B-3-2			1.22			38			5.78	
B-3-3		(2.7)	1.24		(1.50)	37		(46.7)	6.12	

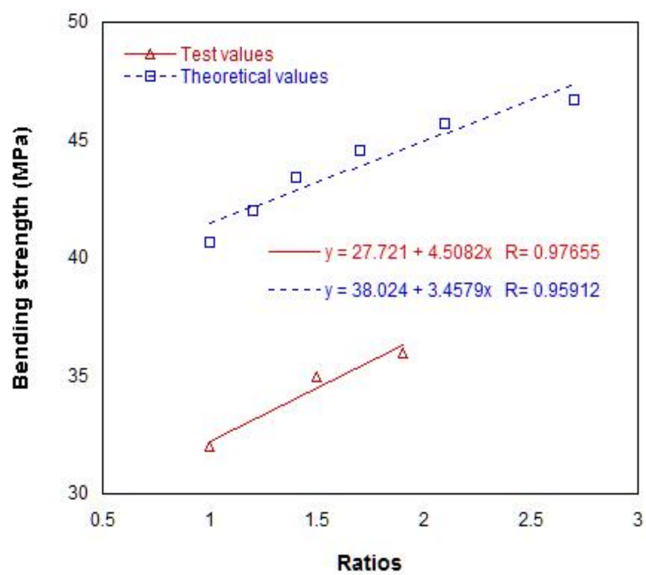
Note: Theoretical values given are in parentheses; Avg is average

The even layer laminates had a relatively small role in the bearing capacity. Additionally, the bending stiffness, bending strength, and shear strength of the wood parallel to the grain were greater than those for the wood perpendicular to the grain. This provided a theoretical basis for the test results that as the odd to even layer thickness ratio increased, the bending stiffness, bending strength, and shear strength also increased continuously.

For the results obtained by specimen testing, the odd to even layer thickness ratios were 1, 1.5, and 1.9. From the results of the theoretical analysis and calculation, the odd to even layer thickness ratios were 1, 1.2, 1.4, 1.7, 2.1, and 2.7 (multiple values were similar to the test ratios). The comparison results are shown in Table 5, and the relationship between the two is shown in Fig. 7.



(a)



(b)

Fig. 7. Comparison of the results for the bending stiffness (a) and strength (b) of Test 2 and the theoretical calculation

From Table 5 and Fig. 7, it was observed that the results of the overall theoretical calculation were higher than the results of the mechanical testing, and the parameters of the relationship between the bending stiffness, bending strength, and laminate thickness had the same regularity of variation. The correlation coefficient (*R*) was close to 1, which indicated that there was a linear correlation and the correlation between the two was very high. With an unchanged total thickness and within a certain percentage range, the bending stiffness and strength of the specimens increased as the odd layer thickness increased and the even layer thickness decreased.

For the failure modes of the different odd to even layer thickness ratios, an abnormal sound began 90 s into the bending test. No change in the appearance occurred during this time, but the specimen became slightly curved. After the bending process proceeded for 2 min, the abnormal sound frequency increased, which was mainly the sound of the adhesive layer cracking and breakage of the wood fiber. At the same time, slight slippage of the end laminar began to occur. After approximately 3 min, the destruction of the specimen began, and included failure of the rolling shear and breakage of the bottom plate. After an increase in the load, second and third damages appeared. Additionally, damage appeared earlier in defect areas of the specimen, such as decay and wood nodes. The failure modes of the specimens with an odd to even layer thickness ratio of 1 were mainly rolling shear in the two secondary direction layers, accompanied by breakage of the bottom plate and adhesive layer peeling (Fig. 8a). The failure modes of the specimens with an odd to even layer thickness ratio of 1.5 were mainly the destruction of the bottom two layers in the tension zone, which involved breakage of the bottom plate, rolling shear in the secondary direction layer, and adhesive layer peeling (Fig. 8b). The ultimate failure modes of the specimens with an odd to even layer thickness ratio of 1.9 were slight rolling shear and cracking of the adhesive layer in the secondary direction layer (Fig. 8c). Through the analysis of the failure modes, it was observed that as the odd to even layer thickness ratio increased within a certain range, the bending performance increased and the range of damage modes and destruction strength decreased.

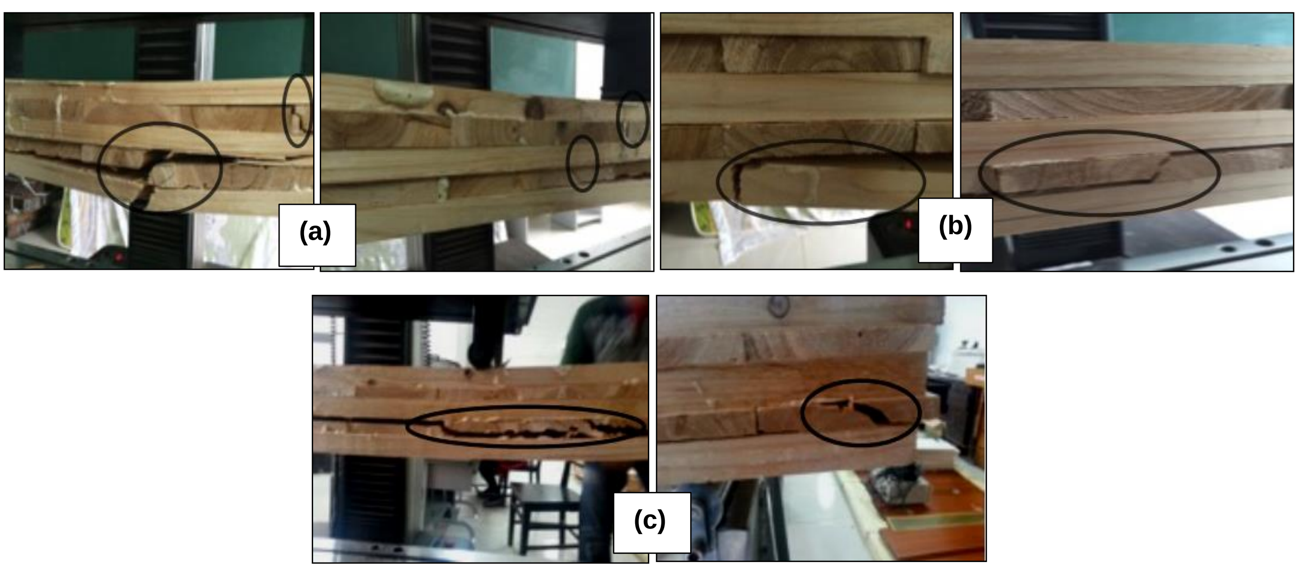


Fig. 8. Failure modes of the different odd to even layer thickness ratios of (a) 1, (b) 1.5, and (c) 1.9

CONCLUSIONS

1. Rolling shear, breakage of the laminates, adhesive layer peeling, and slipping of the laminar were the main failure modes of the CLT structures under vertical loading. The failure modes of the specimens were related to the laminate thickness.
2. When the specimen was damaged in the bending tests, the three-layer CLT specimen was prone to cracking of the bottom plate, and the five-layer and seven-layer structures were prone to adhesive layer cracking and slipping of the end plate.
3. Under the premise of an unchanged overall thickness and as the CLT laminate thickness increased, the bending stiffness increased, the shear performance worsened, and the destruction mode of the CLT structure became simpler. The bending strength of the five-layer CLT specimen was the highest.
4. Within a certain percentage range, the odd to even layer thickness ratio should be increased as much as possible. Thus, increasing the thickness of the odd layers while reducing the thickness of the even layers could effectively improve the bending and shear of CLT specimens without increasing the amount of wood used.

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REFERENCES CITED

ASTM D198-05 (2005). "Standard test methods of static tests of lumber in structural sizes," ASTM International, West Conshohocken, PA.
Cao, Y., Wang, Y.-L., Wang, Z., and Wang, J.-H. (2016). "Application and research progress of overseas cross-laminated timber (CLT) construction," *China Forest Prod. Ind.* 43(12), 3-7. DOI: 10.3969/j.issn.1001-5299.2016.12.001
Dong, W., and Wang, Z. (2016). "Development and research of cross-laminated timber and rolling shear properties," *J. Shandong Forestry Sci. Technol.* 46(4), 93, 99-103. DOI: 10.3969/j.issn.1002-2724.2016.04.028
Frangi, A., Fontana, M., Hugi, E., and Jübstl, R. (2009). "Experimental analysis of cross-laminated timber panels in fire," *Fire Safety J.* 44(8), 1078-1087. DOI: 10.1016/j.firesaf.2009.07.007
GB 50005-2003 (2003). "Code for design of timber structures," Standardization Administration of China, Beijing, China.
GB/T 1935-2009 (2009). "Method of testing in compressive strength parallel to grain of wood," Standardization Administration of China, Beijing, China.
GB/T 1936.1-2009(2009). "Method of testing in bending strength of wood," Standardization Administration of China, Beijing, China.
GB/T 1936.2-2009(2009). "Method for determination of the modulus of elasticity in static bending of wood," Standardization Administration of China, Beijing, China.

GB/T 1937-2009(2009). "Method of testing in shearing strength parallel to grain of wood," Standardization Administration of China, Beijing, China.

GB/T 50329-2002 (2002). "Standard for test method of timber structure," Standardization Administration of China, Beijing, China.

GB/T 51226-2017 (2017). "Technical standard for multi-story and high rise timber buildings," Standardization Administration of China, Beijing, China.

Gagnon, S., and Pirvu, C. (2012). "CLT Handbook: cross-laminated timber," FPlnnovation, Québec, QC, Canada.

Gong, Y. C. (2017). *Preparation and Mechanical Performance of Cross-laminated Timber Made from Larix kaempferi Domestically*, Chinese Academy of Forestry, Beijing, China.

Guo, F. Y. (2007). *Modification of Fast-growing Chinese Fir and Design and Fabrication of Structural Plywood*, Master's Thesis, Nanjing Forestry University, Nanjing, China.

Hashemi, A., Zarnani, P., Masoudnia, R., and Quenneville, P. (2018). "Experimental testing of rocking cross-laminated timber walls with resilient slip friction joints," *J. Struct. Eng*. 144(1). DOI: 10.1061/(ASCE)ST.1943-541X.0001931

JIS 3079 (2013). "Japan agriculture standards on Cartesian boards," Japanese Standards Association, Tokyo, Japan.

Knorz, M., Torno, S., and van de Kuilen, J.-W. (2017). "Bonding quality of industrially produced cross-laminated timber (CLT) as determined in delamination tests," *Constr. Build. Mater.* 133, 219-225. DOI: 10.1016/j.conbuildmat.2016.12.057

Park, H.-M., Fushitani, M., Sato, K., Kubo, T., and Byeon, H.-S. (2003). "Static bending strength performances of cross-laminated woods made with five species," *J. Wood Sci.* 49(5), 411-417. DOI: 10.1007/s10086-002-0502-x

Que, Z.-l., Li, Z.-r., Jiang, G.-c., Zeng, Q.-h., and Ji, N. (2015). "Review of research and development of cross-laminated timber," *China Wood Ind.* 29(6), 22-26. DOI: 10.3969/j.issn.1001-8654.2015.06.005

Que, Z.-l., Li, Z.-r., Wang, F.-b., Hou, T.-y., and Shang, P. (2017). "Review of research and development status of cross-laminated timber used by medium high-rise structure in Europe," *Building Structure* 47(2), 75-80.

Schneider, J., Shen, Y., Stiemer, S. F., and Tesfamariam, S. (2015). "Assessment and comparison of experimental and numerical model studies of cross-laminated timber mechanical connections under cyclic loading," *Constr. Build. Mater.* 77, 197-212. DOI: 10.1016/j.conbuildmat.2014.12.029

Wang, J., Wu, P., Zhou, L., and Ma, X. (2014a). "Research progress on biomass and productivity of Chinese fir plantation," *J. Hebei North Univ. (Natural Science Edition)* 30(3), 36-40. DOI: 10.3969/j.issn.1673-1492.2014.03.009

Wang, Z.-q., Fu, H.-m., Dai, X.-h., Na, B., and Lu, X.-n. (2014b). "Experimental study on mechanical properties of cross-laminated timber with different tree species wood," *J. Central South Univ. Forestry Technol.* 34(12), 141-145. DOI: 10.3969/j.issn.1673-923X.2014.12.026

Yang, X.-B. (2017). "Status and standards of multi-story and high-rise timber structures," *China Wood Ind.* 31(4), 24-27. DOI: 10.19455/j.mcgy.20170405

Zhou, Q., Gong, M., Chui, Y. H., and Mohammad, M. (2014). "Measurement of rolling shear modulus and strength of cross laminated timber fabricated with black spruce," *Constr. Build. Mater.* 64, 379-386. DOI: 10.1016/j.conbuildmat.2014.04.039

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