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Flexural Behaviour of Domestic Cross-Laminated Timber Considering Glued Edge Joint

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Abstract **-** Cross Laminated Timber (CLT) are panels made by arranging multiple layers of timber boards, with the fiber directions of the layers being generally orthogonal to each other. The glued edge joints in the same layer of the lamina usually doesn't apply during the mass production, however, it is a common method to apply glued edge joint due to the small scaled manufacturing locally in Taiwan. In this study, structural performance of domestic cross-laminated timber (CLT) considering edge joint with or without being glued was studied. The equivalent EI_{eff}, equivalent EI_{app} considering rolling shear, initial stiffness, and ultimate strength of domestic CLT were compared between experimental values and theoretical values. Four-point bending tests were carried out based on BS EN 408:2010 standards, and the deflection and the ultimate load of domestic CLT were obtained. Considering rolling shear, the results revealed that influence of MOE in weak layers was smaller even with edge joint glued, limiting its impact on flexural performance. Generally, the results in this study indicate that the Glued edge joint does not significantly affect the initial stiffness, however, the ultimate strength was improved.

Keywords**:** cross-laminated timber, bending strength, rolling shear, initial stiffness, ultimate strength

1. Introduction

The technology and construction methods of medium to large-scale timber buildings are becoming increasingly mature, and laws related to timber structures have been established in countries such as North America, Europe, and Japan. However, it faces several challenges in the development of timber structures in Taiwan. For example, under the current building regulations in Taiwan, timber structures of more than four stories are still not allowed to be constructed. Additionally, Taiwan's self-sufficiency rate of timber is approximately 1%, and the high cost of imported timber increases the cost of timber buildings. Moreover, due to fixed perceptions of timber among the public, the market share of timber structures in Taiwan is low, leading to slower development. To improve the utilization of local timber product, the application of domestic thinning wood was studied currently [1]. Furthermore, recent researches indicated that hybrid structure system which comprise reinforced concrete frame with timber wall and panel installed could be a potential solution to utilize engineered wood product despite the limitation of height of wooden buildings in Taiwan [2-4]. There are several manufacturers in Taiwan who are able to produce engineered wood products such as glued laminated timber (glulam or GLT) and cross-laminated timber (CLT), however, only small scaled manufacturing is allowed, and the manufacturing process is different from oversea. CLT are panels made by arranging multiple layers of timber boards, with the fiber directions of the layers being generally orthogonal to each other. It is a material suitable for large or high-rise timber construction. During the manufacturing, the glued edge joints in the same layer of the lamina usually doesn't being applied during the mass production, however, it is a common method to apply glued edge joint due to the small scaled manufacturing locally in Taiwan. Therefore, it aimed to manufacture CLT using local Japanese cedar (*Cryptomeria japonica*), which is a major species in Taiwan, to produce the domestic CLT, and structural performance of domestic cross-laminated timber (CLT) considering edge joint with or without being glued was studied. The equivalent EI_{eff}, equivalent EI_{app} considering rolling shear, initial stiffness, and ultimate strength of domestic CLT were compared between experimental values and theoretical values. By controlling variables such as laminate grade classification and lamination bonding, the quality of CLT specimens will be effectively managed.

2. Materials and methods

2.1. Specimen

In Taiwan, industrial standards for cross-laminated timber (CLT) are established by the Chinese National Standard (CNS) [5]. The specimens in this study were manufactured according to the machine stress rated grading (MSR) based on CNS16114 standard, using Japanese Cedar (*Cryptomeria japonica*) to produce 5-layer and 5-ply CLT panel. The MSR classification was grade M60B (with an average MOE of 6.0 GPa, upper limit of MOE with 9.0 GPa, and lower limit of MOE with 5.0 GPa). The dimensions of the laminas were 30 × 90 mm (T × W), and were bonded with phenol-resorcinol-formaldehyde (PRF) resin on the surface or width. The different configurations were prepared as shown in Table 1, with dimensions of 150 × 900 × 3000 mm (T × W × L) for CLT-1 and CLT-2, where CLT-1 has PRF adhesive applied to both the surface and edge of the laminas, while CLT-2 has PRF adhesive applied only to the surface of the laminas.

Table 1. Specification of Specimens

	Thickness (mm)	Width (mm)	Length (mm)	Edge Glued
CLT-1	150	900	3000	O
CLT-2	150	900	3000	X

2.2. Four-point bending test

The four-point bending tests were conducted according to the BS EN 408:2010 standard [6]. The load configuration for CLT-1 and CLT-2, as shown in Figure 1, had a span of 270 cm, a pure bending length of 90 cm, and a span-to-depth ratio (l/d) of 18. Displacement gauges were installed beneath the specimens to record deflection changes.

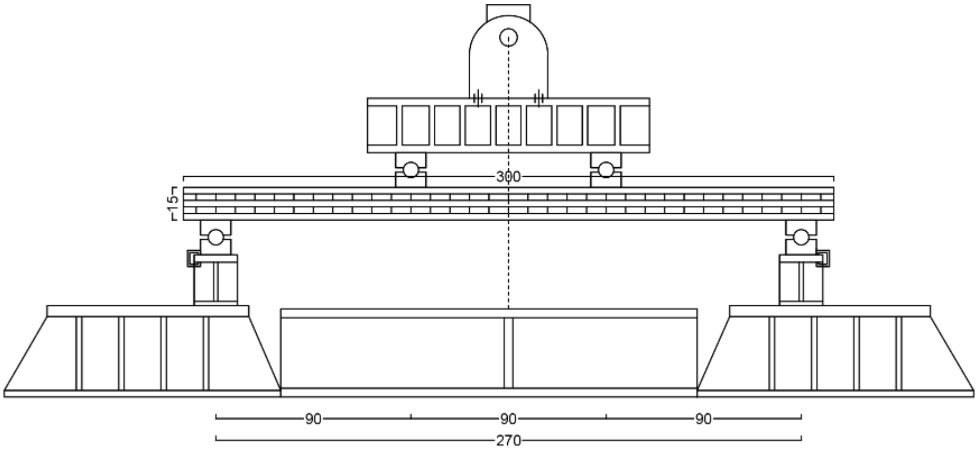

Fig. 1: CLT-1 and CLT-2 setting in four-point bending test.

2.3. Estimation of bending strength

The calculation method for the equivalent EI_{eff} of CLT was adopted based on the CLT Handbook [7]. The bending strength of CLT was calculated based on the cross-sectional dimensions of the specimens, span, and the MOE of the laminas. The MOE in the direction perpendicular to the wood fibers (E_{90}) is typically 1/30 of the MOE in the fiber direction (E_0). The equivalent EI_{eff} was represented by the following equation.

$$\mathrm{EI}_{eff} = \sum_{i=1}^{n} E_i \times b_y \times \frac{{t_i}^3}{12} + \sum_{n=1}^{n} E_i \times b_y \times t_i \times {z_i}^2 \qquad (1)$$

where:

EI_{eff} : Effective bending stiffness (N)
E_i : Modulus of elasticity of an individual layer (MPa)
b_y : Width of an individual layer (mm)
t_i : Thickness of an individual layer (mm)
z_i : Distance from the centroid of the layer to the neutral axis, except for the middle layer, where it is to the centroid of the top half of that layer (mm)

Due to the low values of the elastic tangential modulus or the rolling shear modulus (GR) perpendicular to the wood fibers, significant shear deformation occurs in the transverse layers, resulting in increased deflection and vibration of CLT and affecting the stress distribution inside [8]. The magnitude of GR is related to wood density, ring width, pith location, CLT cross-sectional dimensions, and width-to-thickness ratio [9], and reducing the width-to-thickness ratio of CLT disproportionately decreases rolling shear, especially when GR is high [10]. In this study, shear stiffness (GA) was considered, and the equivalent EI_{app} considering rolling shear was investigated to determine the theoretical initial stiffness and ultimate strength of CLT. Shear stiffness (GA), equivalent EI_{app} considering rolling shear, theoretical initial stiffness (k), and ultimate strength (P) are represented by the following equations, respectively.

$$\mathrm{GA} = \frac{(h-\frac{t_1}{2}-\frac{t_n}{2})^2}{[\left(\frac{t_1}{2\times G_1\times b_y}\right)+(\sum_{i=2}^{n-1}\frac{t_i}{G_i\times b_y})+\left(\frac{t_n}{2\times G_n\times b_y}\right)]} \tag{2}$$

$$EI_{app} = \frac{EI_{eff}}{1+\frac{11.5\times EI_{app}}{GA\times L^2}} \tag{3}$$

$$\mathrm{k} = \frac{2\times 1296\times EI_{app}\times 10000}{23\times L^3} \tag{4}$$

$$\mathrm{P} = \frac{\sigma_x\times\frac{b\times h^3}{12}}{\frac{h}{2}\times L}\times\frac{b\times h}{2}\times 9.8 \tag{5}$$

where:

GA : Shear stiffness (N/mm)
EI_{app} : Bending stiffness considering rolling shear (MPa)
k : Initial stiffness (N/mm)
P : Initial ultimate strength (N)
G_i : Rolling shear modulus (MPa)
b : Width of CLT (mm)
h : Thickness of CLT (mm)
L : Span (mm)

Furthermore, based on the load-displacement curves obtained from the four-point bending tests of CLT, the values of deflection corresponding to 0.1 and 0.4 times the ultimate load were taken, and the slope of the line constructed from these values was calculated to derive the stiffness of CLT. The stiffness (k) is represented by the following equation.

$$k = \frac{0.4P_{max} - 0.1P_{max}}{\delta_{0.4P_{max}} - \delta_{0.1P_{max}}} \tag{6}$$

where:

k : Stiffness (N/mm)
P_{max} : Ultimate strength (N)
δ : Deflection (mm)

3. Results and discussion

3.1. Four-point bending test

The results of the four-point bending tests, as shown in Figure 4, and Figure 5, along with Table 2, indicated that for CLT-1, the ultimate load reached 217414N when the bending test machine was compressed by 31.52 mm, resulting in a stiffness of 6974 N/mm, which is 1.15 times higher comparing with the theoretical initial stiffness. Generally, the test results were consistent with the theoretical values. For CLT-2, the ultimate load reached 102994 N when the bending test machine was compressed by 15.47 mm, resulting in a stiffness of 6113 N/mm, which was nearly the same as the theoretical initial stiffness. The test results were consistent with the theoretical values.

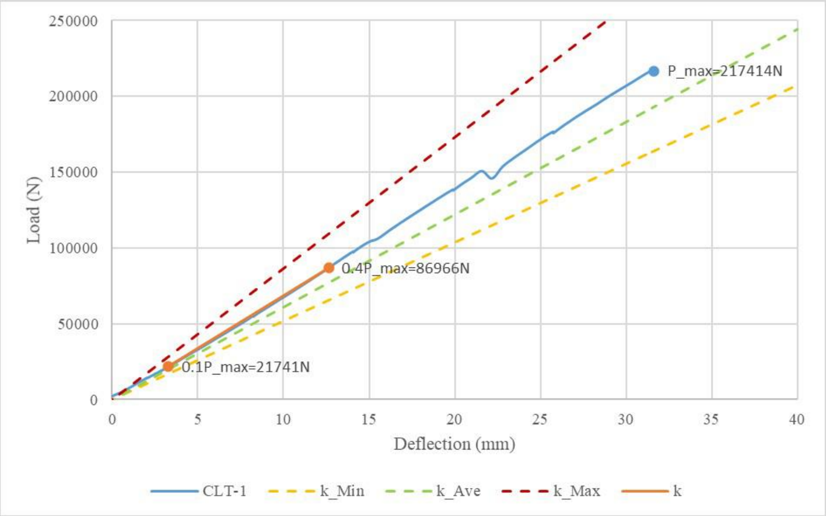

Fig. 4: The load-deflection curve of CLT-1.

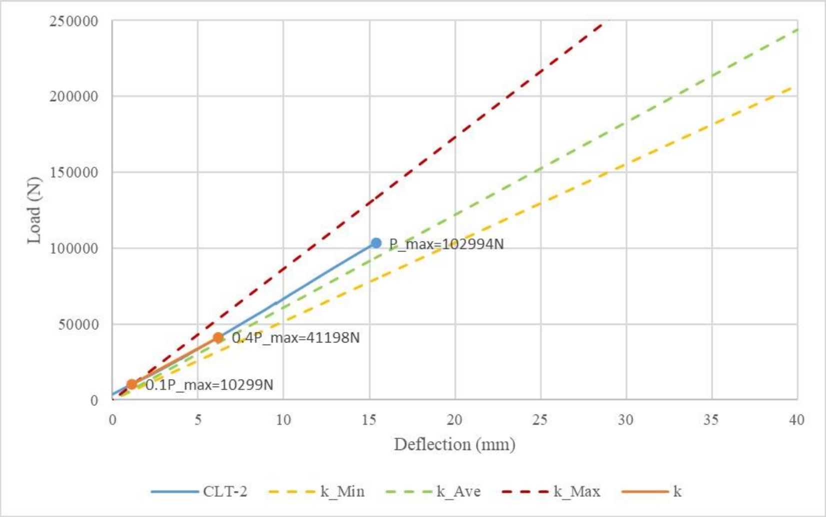

Fig. 5: The load-deflection curve of CLT-2.

Table 2: The stiffness of CLT-1, CLT-2.

	$0.1P_{max}$ (N)	$0.4P_{max}$ (N)	$\delta_{0.1}P_{max}$ (mm)	$\delta_{0.4}P_{max}$ (mm)	K (N/mm)
CLT-1	21741	86966	3.28	12.63	6974
CLT-2	10229	41198	1.12	6.17	6113

3.2. Influence of glued edge joint

The results of the four-point bending test showed that the initial stiffness value of CLT-2 is 88% of the value of CLT-1. The initial stiffness was very close for CLT-1and CLT-2, however, the initial stiffness of CLT-1 was slightly higher than CLT-2, indicating that the edge joint glued lamination conduct slightly reinforcement for the initial stiffness. The ultimate strength revealed the great difference between CLT-1 and CLT-2, as shown in Figure 4 and Figure 5. The ultimate strength for CLT-1, which was the specimen with edge joint glued, was approximately 2 times higher than CLT-2 without edge joint glued. It was also clarified that the failure modes of CLT-1 were combined by rolling shear and crack of glued layer, and the major failure occurred during the crack of the bottom layer of CLT, as shown in Figure 6. The failure modes for CLT-2 were caused by rolling shear, and the major failure was the crack of the bottom layer of CLT, as shown in Figure 7. Because of the edge joint glued, CLT-1 exhibited various crack path, providing better load resisting ability. Generally, the results in this study indicate that the Glued edge joint does not significantly affect the initial stiffness, however, the ultimate strength was improved.

Fig. 6: Typical failure mode of CLT-1: combined failure form rolling shear and glued layer

Fig. 7: Typical failure mode of CLT-2: failure form rolling shear

3.3. Influence of transversal layers strength

The bending strength of CLT based on CLT Handbook [7] showed the MOE in the direction perpendicular to the wood fibers (E_{90}) is typically 1/30 of the MOE in the fiber direction (E_0). However, in reality, the value of E_0 is very small, and its impact on the overall bending strength of CLT is limited. If it was assumed that the modulus of elasticity (E) and shear modulus (G) of the orthogonal layers in CLT are both 0 ($E_{90} = G_{90} = 0$), the results of the equivalent EI_{eff}, the equivalent h EI_{app} considering rolling shear, and theoretical initial stiffness calculated for CLT-1 and CLT-2 showed that the equivalent EI_{eff} decreases by only 0.9%. Similarly, the equivalent EI_{app} considering rolling shear and theoretical initial stiffness decrease by only 0.7% - 0.8%. This indicated that the value of the MOE of the transversal layers (E_0) has a limited impact on the flexural performance of CLT.

4. Conclusion

This study was aimed to investigate the flexural performance of CLT manufactured using domestic Japanese cedar, considering equivalent EI_{eff}, equivalent EI_{app} considering rolling shear with and without edge joint glued, the conclusions drawn from the study were as follows:

(1) Using domestic Japanese cedar with the same grade classification and manufacturing CLT with identical cross-sectional dimension, with or without glued edge joint resulted in 12% difference in initial stiffness. However, the ultimate strength of CLT-1 with edge joint glued, was approximately 2 times higher than that of CLT-2 without edge joint glued.

(2) It was clarified that the failure modes of CLT-1 were combined by rolling shear and crack of glued layer, and the major failure was the crack of the bottom layer of CLT, while the failure modes of CLT-2 were caused by rolling shear, and the major failure was the crack of the bottom layer of CLT. Because of the edge joint glued, CLT-1 exhibited various crack path, providing better load resisting ability. Generally, the results in this study indicate that the Glued edge joint does not significantly affect the initial stiffness, however, the strength capacity was improved.

(3) Incorporating shear stiffness (GA) into the calculations enabled effective evaluation of the bending strength and initial stiffness of CLT. While the numerical value of E_0 compared to E_{90} was very small, its impact on the flexural performance of CLT was limited.

(4) The initial stiffness of CLT was determined by the slope of the line constructed from the $0.1P_{max}$ and $0.4P_{max}$ obtained from the four-point bending test, along with their corresponding deflections. Comparative analysis results indicated that the experimental stiffness of CLT is approximately 1.01 times comparing with the theoretical stiffness. This demonstrated that the method was effective in evaluating the bending strength and initial stiffness of CLT with or without glued edge joints.

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