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SHEAR CAPACITY PREDICTION OF *ACACIA MANGIUM* CROSS-LAMINATED TIMBER UNDER OUT-OF-PLANE BENDING

Kundari R[1,*], Achmad B[1], Halwan Alfisa S[1] & Buan A[2]

[1] *Universitas Sebelas Maret, Jl. Ir. Sutami No.36A Surakarta Indonesia*
[2] *University of Mataram, Jl. Pendidikan 37 Mataram Indonesia*

**kundari.rahmawati@staff.uns.ac.id*

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The popularity of cross-laminated timber (CLT) in construction has increased globally. In Indonesia, effort has been made to utilise local wood such as *Acacia mangium* in CLT production. The characteristics and properties of acacia CLT have not been studied in depth. Our study determined the shear capacity of short-span acacia CLT panels subjected to out-of-plane three-point bending tests and evaluated selected models (shear analogy method, gamma method, simplified composite beam method, and simple beam theory) in their ability to accurately estimate shear capacity. The simple beam theory (CSA086-14) gave predicted shear capacity values closest to the experimental results for three-layer acacia CLT samples (14.05 kN and 18.45 kN vs 13.7 kN and 18.06 kN for the 51 and 67 mm-thick panel samples respectively).

Keywords: short-span CLT, three-point bending test, planar shear block test, simple beam theory

INTRODUCTION

Cross-laminated timber (CLT) is an innovative, engineered composite wood comprising three or more layers of sawn timber boards each arranged perpendicular to the adjacent layer and bound orthogonally with glue. As CLT can bear substantial in- and out-of-plane loads, it has gained popularity particularly in mid- and high-rise structures (Schickhofer et al. 2016) for building floors, walls and roofs, which are subjected to out-of-plane loads (Ayanleye et al. 2022).

In CLT structures, out-of-plane loading configurations are common, resulting in shear stress on the longitudinal layers and rolling shear stress on the transverse layers. Rolling shear strength depends on timber species, sawing pattern (annual ring orientation) and width-to-thickness ratio (w_l/t_l) of a single lamina (Brandner et al. 2016). The rolling shear strength of the transverse layer and predicted shear capacity are important considerations in the design process of CLT members used in mass timber construction (Huang et al. 2023b). The shear failure mechanisms of the cross layers of CLT members subject to bending include rolling off between fibers, cracking intersecting annual rings, and debonding along the gluing interface (Huang et al. 2023a). Each of these mechanisms exhibit different shear properties thus whole-structure measurement of rolling shear properties should include all possible failure mechanisms.

Many models have been developed to predict shear capacity e.g., the shear analogy method, gamma method, composite beam theory and simple beam theory, but the many possible, complicated failure mechanisms make it difficult to accurately predict shear capacity. There is as yet no universally accepted model (Huang et al. 2023b)

In the past few decades, many studies have evaluated the shear properties of temperate, soft-wood timber species such as Norway spruce (*Picea abies*) (Das et al. 2023), Irish sitka spruce (*Picea sitchensis)* (Sikora et al. 2016a & 2016b), European beech (*Fagus sylvatica*, (Aicher et al. 2016) and spruce-pine-fir (Wu et al. 2021). In Indonesia, *Acacia mangium,* a widely-planted fast-growing tropical hardwood species has become increasingly utilised for CLT production (Srivaro et al. 2022, Purba et al. 2022). The focus on acacia as a raw material for CLT products is due

Table 1 Dimensions of the three-layer CLT samples used in the three-point short-span bending test

Sample ID	Lamination layups (mm)	Total thickness (mm)	Width (mm)	Span (mm)	Ratio of span to depth	N
CLT3/51A	17/17/17	51	140	306	6	3
CLT3/67A	25/17/25	67	140	402	6	3

to its economic viability, impressive strength and mechanical qualities of acacia CLT that exceed the minimal requirements for CLT raw material (Mohd Yusof et al. 2019).

The body of literature on acacia CLT and its properties is scarce, and no information on acacia CLT shear capacity was found. Therefore, the objectives of our research were to determine the shear capacity of acacia CLT subjected to out-of-plane bending loads using experimental tests and evaluate different models in their ability to predict shear capacity. Short-span CLT panels were subjected to the three-point bending test specified by ASTM D2718 (2018). This test was selected because it can be used to determine the shear performance of beams due to bending (Yusouf 2015). Analytical models used in this study were the shear analogy method, gamma method, simplified composite beam method and simple beam theory (CSA 086). Model parameters used to estimate the shear capacity of the CLT panels were rolling shear properties that were obtained using a modified planar shear test and mechanical properties of acacia measured in preliminary tensile and bending tests specified by ASTM D-143 (2014) for small clear specimens of timber.

MATERIALS AND METHODS

Test specimens

The CLT panels panels were manufactured from seven-year-old *Acacia mangium*. The average density of the panels was 662 kg m^{-3} with a coefficient of variation (COV) of 0.07 while mean moisture content was 12% (COV = 0.03). The diameter of the acacia lumber used in this study was small i.e. 30 cm. For the three-point bending test, three-layer CLT panels were fabricated from planks that were 2000 mm long, 100 mm wide, and 17 mm or 25 mm thick. Fabrication with 17/17/17 mm layups produced panels with a 51 mm total thickness while 25/17/25 layups produced panels that were 67 mm thick (Table 1). The planks were glued together with polyurethane sprayed at 160 g m^{-2} then cold-pressed for an hour in a hydraulic press at 1.60 N mm^{-2}. Panels were conditioned for four weeks at 65% relative humidity. For the planar shear test, blocks were cut from the 51 mm thick CLT panels to dimensions of 206 mm × 100 mm × 51 mm (length × width × thickness, or l × w × t).

Test methods

The three-point bending test was conducted to determine shear capacity of the short-span three-layer acacia CLT test specimens while the planar shear test and preliminary tensile and bending tests obtained parameter values used in the models estimating the shear capacity of the test specimens. The preliminary tensile and bending tests specified by ASTM D-143 (2014) for small clear specimens of timber had previously determined the modulus of elasticity for the tensile test as E_0 = 14832.16 (COV = 0.14, n = 15) and for the bending test as E_{90} = 7622.23 (COV = 0.13, n = 15).

Bending test

The three-point bending test was applied as specified by ASTM D2718 (2018) to the three-layer short-span CLT panel samples (span to depth ratio of 6) to determine shear capacity. The test setup on a 500 kN UTM is illustrated in Figure 1. The load was applied to the sample at mid-span at a rate of 2 mm min^{-1} to reach the maximum load in 5 min. The UTM recorded the load and deflection that occurred during loading. The data was used to determine the amount of load resisted and the capacity curve of the CLT panel under lateral loading.

Planar shear block test

The planar shear test method specified by prEN 16351 (CEN 2018) was conducted on the three-layer CLT test specimens to measure rolling

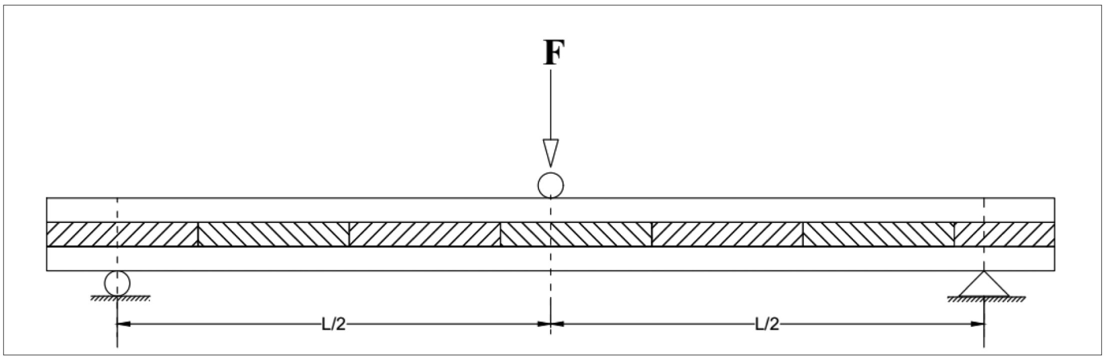

Figure 1 The three-point bending test setup for the three-layer short-span CLT samples

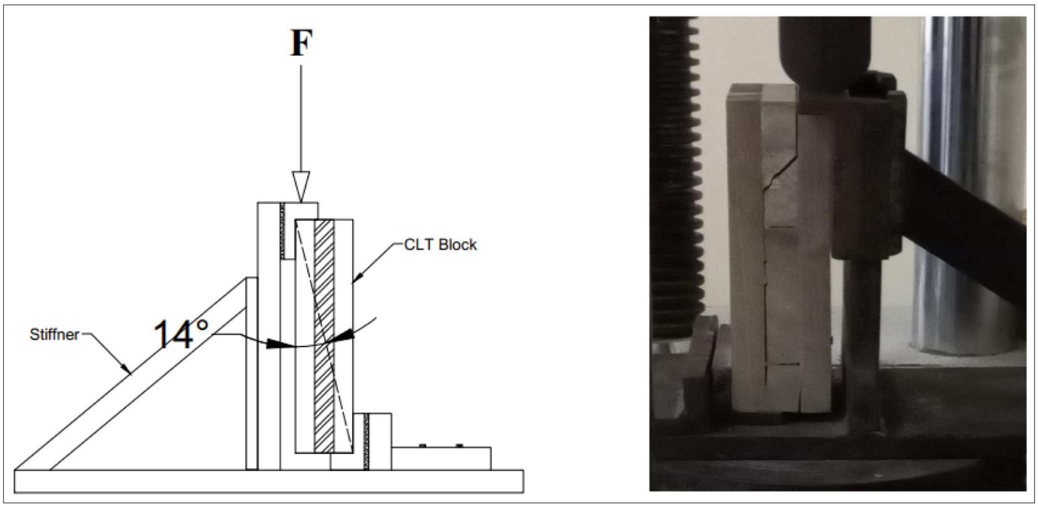

Figure 2 The planar shear test setup for three-panel CLT samples

shear strength and modulus that were used in the models to predict shear capacity of those samples. A loading configuration of 14° (Figure 2) was used to apply opposing pressures on the longitudinal layers. Following (Huang et al. 2023b), a bracket was affixed on the longitudinal layer of the sample block to apply the test load, with sufficient space to accommodate deformation. The sample was then loaded using a 500 kN universal testing machine (UTM) with a controlled displacement rate of 0.5 mm min^{-1} to the point of failure or maximum load. Data on loads and corresponding displacement was measured and recorded throughout the test.

Rolling shear stress (τ_r) and modulus (G_r)were calculated as follows (CEN 2004):

Rolling shear stress, $$\tau_r = \frac{F_u}{l.w}$$

Rolling shear modulus, $$G_r = \frac{(F_2 - F_1)}{(u_2 - u_1)} \frac{t}{l.w}$$

where F_u = maximum load, F_1 and F_2 = loads associated with $0.1F_u$ and $0.4F_u$ respectively, $u_1$and u_2 = displacements that correlate to F_1 and F_2 respectively.

Evaluation of models for estimating shear capacity

Referring to Huang et al. (2023b), the gamma method, shear analogy method, simplified composite beam method and simple beam theory are summarised below along with their formulas for calculating shear capacity.

Gamma method

The gamma method imagines the longitudinal layers as a beam and the cross layers as a continuously distributed connection. It is assumed that stiffness is only loaded on the transversal layer, which is identical to the rolling

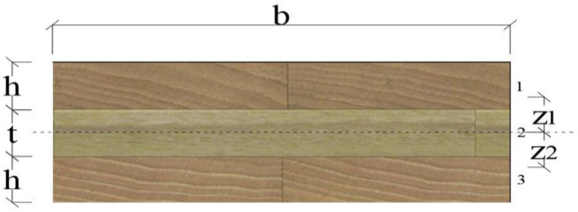

Figure 3 Geometric parameters of typical three-layer CLT

shear modulus (Huang et al. 2023b). Figure 3 illustrates the geometric parameters of a typical three-layer CLT.

The effective bending stiffness of the laminated beam was calculated following Ehrhart & Brandner (2018) as:

$$\mathrm{EI_{eff}} = \sum\nolimits_{i}^{n} (\mathrm{E_i.I_i} + \gamma_i.\mathrm{E_i.A_i.z_i^2})$$

where E_i = modulus of elasticity (MOE) for i-th longitudinal layer, I_i = moment of inertia of the i-th layer cross-section, A_i = area of the cross-section of the i-th layer, z_i = distance between the center of each layer and the entire cross-section, and γ_i = efficiency of layer-to-layer interactions given by:

$$\gamma_i = \left(1 + \frac{\pi^2.\mathrm{E_i.A_i}}{\mathrm{L_{reff}^2}}.\frac{\mathrm{h_i}}{\mathrm{G_{rj}}.b_j/h_j}\right)^{-1}$$

where L_{eff} is the effective length of the beam which equals to the length between two zero moment points; b*i* and hi are the width and depth of the ith longitudinal layer, respectively; G_{rj} is the modulus of rolling shear for the *j*th cross layer that connecting ith longitudinal layer; b_j and h_j are the width and depth of *j*th longitudinal layer, respectively.

Shear stress was then calculated as:

$$V_{max} = \frac{\tau.EI_{eff}.w}{(\mathrm{EQ})}$$

where EQ = effective moment of area was calculated as:

$$\mathrm{EQ} = \frac{1}{2}.\gamma_i.\mathrm{E_0.b.h\,(h+t)} + \frac{1}{8}\,\mathrm{E_{90}.b.t^2}$$

where E_0 = MOE parallel to the grain (or transverse MOE), E_{90} = MOE of grain h and t, which are the thicknesses of longitudinal and transversal layers respectively, with E0 and E90 being MOE values previously determined by the preliminary tensile and bending tests.

Shear analogy method

This method imagines the panel as made up of beams A and B (Christovasilis et al. 2016). The total inherent flexural stiffness of the layers is applied to beam A along its neutral axis while beam B receives the joint flexural stiffness of all layers and connections along its neutral axis plus the total shear stiffness of all layers. The effective bending stiffness of the samples were calculated following (Ehrhart & Brandner 2018) as:

$$\mathrm{EI_{eff}} = (\mathrm{EI})_A + (\mathrm{EI})_B$$

$$(\mathrm{EI})_A = \sum\nolimits_{i}^{n} \mathrm{E_i.I_i}$$

$$(\mathrm{EI})_B = \sum\nolimits_{i}^{n} \mathrm{E_i.A_i.I_i.z_i^2}$$

where E_i = MOE parallel to the longitudinal grain, I_i = moment of inertia of the i-th layer cross-section, A_i = area of cross-section of the i-th layer, z_i = distance between the neutral axis of global bending and the i-th layer center.

The shear capacity of the CLT beam was calculated as:

$$V_{max} = \mathrm{V_B}\left[1 + \frac{(\mathrm{EI})_A}{(\mathrm{EI})_B}\right]$$

where V_B = shear force carried by beam B and calculated as:

$$\mathrm{V_B} = \frac{(\mathrm{EI})_B.\tau}{\sum_{i+1}^{n}(\mathrm{E_j.A_j.z_j})}$$

Simplified composite beam method

This method provides the most straightforward formula for determining shear capacity because the layered cross-section is considered homogeneous

The stresses in the transverse layer do not contribute significantly to overall bending because the transverse MOE of the cross-layer is only around 1/30 of the MOE parallel with the grain of the longitudinal layer. The shear stress, static moment of area and moment of inertia for three-layer CLT samples were calculated as:

$$\tau = \frac{V.S}{b.I}$$

$$S = \frac{1}{2} b.h(h+t)$$

$$I = 2\left[\frac{1}{12} b.h^3 + \frac{1}{4} b.h(h+t)^2\right]$$

Maximum shear capacity for the three-layer CLT was then calculated as:

$$V_{max} = \frac{b\,[h^2 + 3(h+t)^2]\tau_r}{3(h+t)}$$

Simple beam theory

Under this theory, specified by Canadian design code CSA086-14 (Barrett et al. 2014) the factored shear resistance (Vr) of the CLT samples assumes the shear strength of the material and rolling shear strengths are equal, and is calculated as:

$$V = \varphi F_s \frac{2A_g}{3}$$

where $\varphi = 0.9$, F_s = rolling shear stress, A_g = gross cross-sectional area of the panel for the major stress axis.

RESULTS AND DISCUSSION

Bending test

The V_{max} of CLT3/67 at 18.06 kN (COV = 0.11) was 24.16% higher than that of CLT3/51 (Table 2). This result was in line with a report from Li et al. (2021) on radiata pine CLT that shear capacity was positively correlated with thickness of the CLT. Lamina thickness significantly influenced maximum shear capacity in three-point bending experiments conducted by previous researchers (e.g. Li 2017, Li et al. 2021, Glasner et al. 2023, Huang et al. 2023b) who reported that thicker lamina layers in CLT panels increased maximum shear capacity.

For both the 51 mm- and 67 mm-thick CLT samples (CLT3/51 and CLT3/67 respectively) the dominant failure mode was rolling shear failure (Table 2, Figure 3). Cracks started in the transverse layer and spread along the annual ring then at failure would disperse suddenly in z- or multiple z-shaped pattern(s). Similar rolling shear failure modes were reported by Li (2017) and Li et al. (2021) for CLT made of radiata pine. Mohd Yusof et al. (2019) also reported failure resulting from rolling shear starting close to the bond line in acacia CLT. This failure was manifested as transverse shear stress against the grain typical of the rolling shear behaviour in CLT. The span to depth ratio (L= 6h) specified by ASTM D 2718 for the rolling shear test was confirmed valid for acacia CLT panels in our study.

The load-displacement curves for all the samples showed a similar linear response up

Table 2 Shear properties of three-layer short-span acacia CLT samples under three-point bending tests

Sample ID	Load at first crack F_u(kN)	Shear capacity V_{max} (kN)	Mean V_{max} (kN)	COV	Failure mode
CLT3/51-1	25.10	12.55	13.70	0.09	Rolling shear
CLT3/51-2	26.89	13.44			Rolling shear
CLT3/51-3	30.21	15.10			Rolling shear
CLT3/67-1	40.25	20.12	18.06	0.11	Rolling shear
CLT3/67-2	36.00	18.00			Rolling shear
CLT3/67-3	32.14	16.07			Rolling shear

Figure 4 Failure modes of three-layer short-span acacia CLT samples under three-point bending tests

until the maximum load then an abrupt drop upon fracture (Figure 5). Samples exhibited elastic behavior until the first crack appeared. The greater bending stiffness of the CLT3/67 panel than the CLT 3/51 panel is reflected in the slope of their load-displacement curves. The increase in thickness of 16 mm resulted in a 54% increase in stiffness and a 4% decrease in deformation at maximum load.

Planar shear block test

The CLT block samples in this test exhibited rolling shear failure (Figure 6) similar to the short-span panels in the bending test. Some shears cracked in a z-shaped pattern along the annual ring in the middle layer and spread outwards along both sides of the glue line. The samples showed no failure in adhesion although there was a crack close to the glue line. The measured mean ultimate load (F_u) of 64.79 kN (COV = 0.13) gave a calculated rolling shear stress (τ_r) of 3.28 MPa (COV = 0.13, n = 10) and shear modulus (G_r) of 68.24 MPa (COV = 0.14, n = 10).

Evaluation of models predicting shear capacity

Predicted V_{max} using the simplified composite beam and shear analogy methods was the same (Table 3), supporting the use of the simplified composite beam method in place of the shear analogy method. It implies a negligible effect of the transversal layer on shear capacity. However, the difference between the test and predicted results using this method was relatively big i.e. 23% for CLT3/51 and 19% for CLT3/67.

Table 3 Shear capacity (V_{max}) of short-span

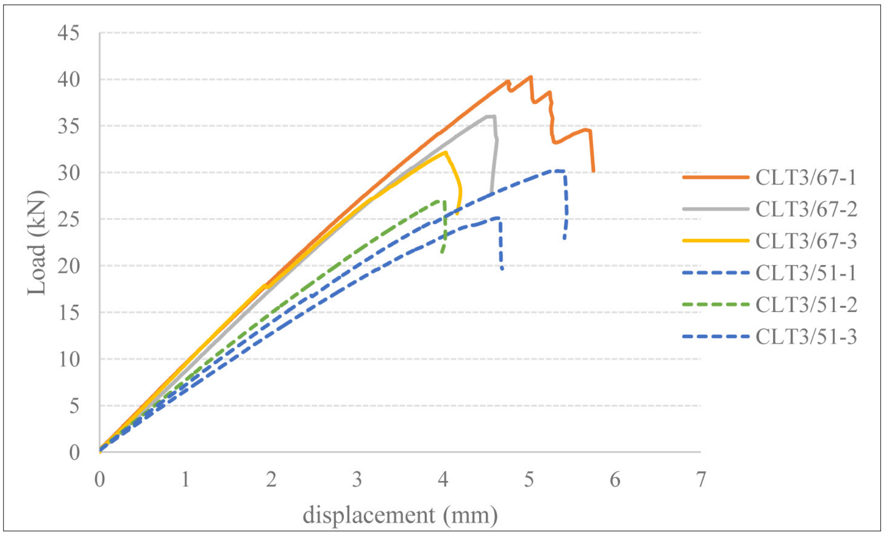

Figure 5 Load–displacement response for the short-span acacia CLT samples under three-point bending

Figure 6 Failure mode of acacia CLT blocks under the planar shear test

acacia CLT as predicted by models and measured in the bending test

The maximum shear capacity calculated using simple beam theory was closest to the test results, differing by only about 2% while shear capacity predicted by the gamma method was between 5% to 9% higher than that of the experimental results. Conversely, Huang et al. (2023a) reported that the gamma method was better than the simple beam theory in predicting shear capacity of three-layer CLT made from Canadian spruce, pine and fir (SPF) and European spruce (EUS). Karacabeyli & Gagnon (2019) recommended the gamma method to analyse (asymmetrical) CLT panels made up of assorted timber species layers. The better results predicted by the simple beam theory as compared with the gamma method may be explained by the more homogenous three-layer CLT made from acacia alone, where the direction of constituent fibers in predicting shear capacity was not considered.

Currently, the use of acacia raw materials in CLT fabrication in Indonesia is still in the research and development phase. The planar test based on prEN 16351:2018 could be used to determine the rolling shear stress of CLT made from local timber and compare several timber species' CLT rolling shear stress and rolling shear stress determined by Eurocode 5. Three-layer acacia CLT showed a rolling shear capacity exceeding the CLT24 rolling shear

Table 3 Shear capacity (V_{max}) of short-span acacia CLT as predicted by models and measured in the bending test

	CLT3/51		CLT3/67	
	V_{max} (kN)	Diff (%)	V_{max} (kN)	Diff (%)
Gamma method	14.45	5.55	19.62	8.64
Shear analogy method	16.91	23.47	21.56	19.38
Simplified composite beam theory	16.91	23.47	21.56	19.38
Simple beam theory CSA	14.05	2.57	18.45	2.20
Bending test	13.70		18.06	

stress required by Eurocode 5. At 662 kg/m3, the density of acacia timber used in our study was close to that of European birch (*Betula pendula,* 612 kg/m^3). Ehrhart & Brandner (2018) explained that European birch CLT 3 layer with dimensions of 190 mm × 100 mm × 105 mm (length × width × thickness) tested using the planar shear test method has a rolling shear stress of 2.91 Mpa, which is lower than the rolling shear stress of acacia CLT. Another European hardwood species, CLT made from European beech (*Fagus sylvatica* L.) with a density of 720 kg/m^3 tested in the same way had a rolling shear stress of 4.67 Mpa, indicating that timber density has an important role in rolling shear performance.

Further research could investigate acacia CLT with more layers, e.g., 5, 7, 9, under loading. A comprehensive test program determining the mechanical properties of acacia CLT is needed to ensure that it can be safely applied to mass timber construction.

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REFERENCES

Aicher S, Christian Z & Hirsch M. 2016. Rolling shear modulus and strength of beech wood laminations. *Holzforschung* 70: 773–781. https://doi.org/10.1515/hf-2015-0229

Ayanleye S, Udele K, Nasir V, Zhang X & Militz H. 2022. Durability and protection of mass timber structures: A review. *Journal of Building Engineering* 46: 103731 https://doi.org/10.1016/j.jobe.2021.103731

ASTM D-143. 2014. *Standard test methods for small clear specimens of timber.* ASTM International, Pennsylvania.

ASTM D2718. 2018. Standard Test Methods for Structural Panels in Planar Shear (Rolling Shear). ASTM International, Pennsylvania.

Brandner R, Flatscher G, Ringhofer A, Schickhofer G & Thiel A. 2016. Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products* 74: 331–351. https://doi.org/10.1007/s00107-015-0999-5

CEN. 2004. *Europan Committe for Standardization. Eurocode 5: Design of Timber Structures Part 1-1; General-Common rules and rules for buildings. EN 1995-1-1:2004* (Vol. 1, Issue 2004). British Standars Institution (BSI), London.

CEN. 2018. *European Committee For Standardization: prEN 16351. 2018. Timber structures - Cross laminated timber – Requirements.* GlobalSpec, New Yorkk.

Christovasilis IP, Brunetti M, Follesa M, Nocetti M & Vassallo D. 2016. Evaluation of the mechanical properties of cross laminated timber with elementary beam theories. *Construction and Building Materials* 122: 202–213. https://doi.org/10.1016/j.conbuildmat.2016.06.082

CSA O86–14. 2014. *Engineering design in wood.* Canadian Standards Association, CSA Group, Toronto.

Das S, Gašparík M, Sethy AK, Kytka T, Kamboj G & Rezaei F. 2023. Bonding performance of mixed species cross laminated timber from poplar (*Populus nigra* L.) and maple (*Acer platanoides* L.) glued with melamine and PUR adhesive. *Journal of Building Engineering* 68. https://doi.org/10.1016/j.jobe.2023.106159

Ehrhart T & Brandner R. 2018. Rolling shear: Test configurations and properties of some European soft- and hardwood species. *Engineering Structures* 172: 554–572. https://doi.org/10.1016/j.engstruct.2018.05.118

Glasner D, Ringhofer A, Brandner R & Schickhofer G. 2023. Rolling Shear Strength of Cross Laminated

Timber (CLT)—Testing, Evaluation, and Design. *Buildings* 13: 2831. https://doi.org/10.3390/buildings13112831

Huang Z, Huang D, Chui YH & Chen Z. 2023a. A layered beam-based model for analyzing the stress of rolling shear for the cross-laminated timber panels under out-of-plane bending. *Engineering Structures* 289: 116290. https://doi.org/10.1016/j.engstruct.2023.116290

Huang Z, Jiang L, Ni C & Chen Z. 2023b. The appropriacy of the analytical models for calculating the shear capacity of cross-laminated timber (CLT) under out-of-plane bending. *Journal of Wood Science* 69: 14. https://doi.org/10.1186/s10086-023-02089-y

Li M. 2017. Evaluating rolling shear strength properties of cross-laminated timber by short-span bending tests and modified planar shear tests. *Journal of Wood Science* 63: 331–337. https://doi.org/10.1007/s10086-017-1631-6

Li X, Ashraf M, Subhani M, Kremer P, Li H & Anwar-Us-Saadat M. 2021. Rolling shear properties of cross-laminated timber (CLT) made from Australian Radiata Pine – An experimental study. *Structures* 33: 423–432. https://doi.org/10.1016/j.istruc.2021.04.067

Mohd Yusof N, Md Tahir P, Lee SH, Khan MA & Mohammad Suffian James R. 2019. Mechanical and physical properties of Cross-Laminated Timber made from Acacia mangium wood as function of adhesive types. *Journal of Wood Science* 65: 20 https://doi.org/10.1186/s10086-019-1799-z

Purba CYC, Pot G, Collet R, Chaplain M & Coureau JL. 2022. Assessment of bonding durability of CLT and glulam made from oak and mixed poplar-oak according to bonding pressure and glue type. *Construction and Building Materials* 335: 127345 https://doi.org/10.1016/j.conbuildmat.2022.127345

Schickhofer G, Brandner R & Bauer H. 2016. Introduction to CLT, Product Properties, Strength Classes In *Joint Conference of COST Actions FP1402 and* FP1404. 10–11 March 2016, Stockholm..

Sikora KS, McPolin DO & Harte AM. 2016a. Effects of the thickness of cross-laminated timber (CLT) panels made from Irish Sitka spruce on mechanical performance in bending and shear. *Construction and Building Materials* 116: 141–150. https://doi.org/10.1016/j.conbuildmat.2016.04.145

Sikora KS, McPolin DO & Harte AM. 2016b. Shear strength and durability testing of adhesive bonds in cross-laminated timber. *Journal of Adhesion* 92: 758–777. https://doi.org/10.1080/00218464.2015.1094391

Srivaro S, Lim H, Li M & Pasztory Z. 2022. Properties of mixed species/density cross laminated timber made of rubberwood and coconut wood. *Structures* 40: 237–246. https://doi.org/10.1016/j.istruc.2022.04.016

Wu G, Zhong Y & Ren H. 2021. Effects of Grain Pattern on the Rolling Shear Properties of Wood in Cross-Laminated Timber. *Forests* 12: 668. https://doi.org/10.3390/f12060668

Mohd Yusouf AL, Suffian M, Hashim WS & Rafaedah E. 2015. Optimum Slope of Load-Deflection Curve for Bending Young's Modulus Derivation. *Journal of Tropical Forest Science* 27: 527–534