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Elastic Response of Cross-Laminated Timber Panels using Finite Element and Analytical Techniques

Asad S. Albostami^{1*}, Zhangjian Wu², Lee S. Cunningham²

¹School of Civil Engineering, University of Petra, Amman-Jordan.

²School of Mechanical, Aerospace and Civil Engineering, The University of Manchester,
Manchester M13 9PL, UK

*Corresponding author:

Asad S. Albostami

00962791102786

E-mail address: asad.albostami@uop.edu.jo

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Abstract

Cross-Laminated Timber (CLT) is an engineered timber composite that is finding increasing structural application in construction today. Analysis of the structural behavior of CLT can be carried out by various analytical and numerical methods. Due to the complex behavior of CLT, use of numerical modelling such as the Finite Element Method (FEM) offers a convenient approach to analysis. In this paper, simulation of the elastic behavior of 1-way and 2-way spanning CLT panels using the FEM program ABAQUS is presented. Various modelling choices are explored numerically with the results being evaluated against those from either a 3D analytical method known as the State Space Approach (SSA) or existing experimental data. Among the case studies examined is a novel boundary condition for the SSA solution. In general, the optimum finite element model produced reasonable levels of accuracy with an average relative error equal to 3% in comparison to the SSA and a maximum of 10% in comparison to the experimental results.

Keywords

Cross-laminated timber, Finite element method, Analytical solution, State space approach.

1. Cross-Laminated Timber (CLT): Background and Characteristics

CLT is a laminated timber composite which can be used to form structural elements including walls, floor plates and roofs etc. It was first developed in Switzerland and Austria in the mid-1990s [1].

CLT panels are formed from at least three plies of wooden boards orthogonally cross-stacked and glued together on their faces, typically in a symmetric lay-up. Given that alternate plies are placed with the grain direction at 90° to that of the ply below, CLT can be considered as an orthotropic composite panel [2].

CLT panels can be produced in large sizes with comparable thickness to masonry or concrete walls. Consequently, CLT panels have significant strength and have allowed timber to compete with concrete and steel in multi-storey applications e.g. CLT buildings of 9 storeys or more have been constructed to date [3].

The use of CLT panels has increased in the construction sector over the last 10 years due to the significant advantages they offer [4], these include CLT's high strength to weight ratio, ease of handling, quick erection time and good thermal and sound insulation. Typical practical dimensions of a CLT panel [4] are shown in Fig. 1. In addition to the aforementioned, interest in the use of CLT has increased due to today's demand for more sustainable construction forms [5].

CLT panels can be subject to in-plane and out-plane forces. In the case of CLT floor panels, these typically span one-way due to practical constraints on panel widths (~3m max.) and floor spans. For transverse spans greater than 3m, 2-way action is theoretically possible with moment transfer connection details. Commonly in the case of CLT wall panels, where storey

heights are limited to 3m, 2-way action under horizontal loads is generated as the wall spans vertically between floor plates and return walls.

Due to the relatively low Young's modulus of timber in comparison to other construction materials, deflection of CLT panels often governs their design. Given the layered composite nature of the CLT panel, obtaining an accurate section stiffness can be challenging with various methods in common use. Shear deformation due to the flexible bond between timber plies influences the stress distribution and stiffness of the CLT panel. In CLT design, the phenomenon of rolling shear, whereby a longitudinal shear plane develops at the interface between plies, is often critical in determining panel strength [1]. The rolling shear strength and modulus depend on many factors such as the dimensions of the CLT boards and timber species etc. Different models have been developed to quantify the rolling shear modulus; however, no single specific method has been universally adopted. Typically, the rolling shear modulus is taken to be 1/10 of the shear modulus of the CLT board parallel to the grain [4].

1.1 Existing numerical modelling of CLT

For designers, a number of analytical approaches are commonly used for CLT including mechanically jointed beam theory (gamma method), composite theory (the k-method) and the shear analogy method as outlined in [4]. Crucially, the accuracy of each of these methods tends to reduce as the span to depth ratio of the CLT panel decreases beyond a threshold of 15 [6].

As an alternative to the aforementioned analytical models, researchers have studied the complex behavior of CLT by using numerical methods, primarily the Finite Element Method (FEM).

In 2015, Shahnewaz *et al.* [7] validated a numerical model using the experimental data from CLT beam and wall tests published in the Canadian CLT Handbook [4]. The FEM model was

developed using the software ANSYS. The bond between plies in the panel was modelled using contact elements and a high frictional coefficient based on the high stiffness of the glue. The FEM model gave results with ~10% difference to the experimental data in predicting elastic stiffness of the CLT. Using the validated model, a parametric study was conducted to explore the effect of thickness on the in-plane stiffness of CLT panels. [7] found that when the thickness of the panels is doubled, the stiffness is increased by up to 24%. Serrano and Enquist [8] simulated a series of experiments on a square three-ply CLT panel subject to uniform compressive stress on the top surface. For the FEM model, [8] recommended that the interaction between the individual boards be taken into account for more accurate results. [8] also found that at low load levels, large strains have already been developed at the interface between the plies of the CLT. Therefore, in order to fully capture the post-peak behavior observed in the test, an orthotropic plastic material model was suggested. However, it should be noted that from a design point of view, only the elastic behavior of a timber member is considered [4 & 9].

Vilguts *et al.* [10] simulated via ANSYS an experiment of 1-way spanning CLT panels with a total thickness of 95 mm under distributed load. Vilguts *et al.* compared the numerical and experimental stresses acting on the edge of the panel and the maximum vertical displacement. The model and experimental results showed a relatively good match with deviations not exceeding $\pm 20\%$.

To gain an improved understanding of the behavior of CLT panels including shear failure, five-ply and seven-ply CLT panels under concentrated loads were studied by Bogensperger and Jöbstl [11]. Different parameters known to have an effect on the shear behavior such as the span to thickness ratio were investigated numerically. The non-linear analysis was carried out using FEM. For simplification in their model, all the stresses in the interactions between

the layers were neglected. It was found that the agreement between the experiment and the FEM results was good with approximate differences less than 20% in the linear elastic response, (with the FEM model predicting a stiffer response), but for the non-linear stage, the mechanical strength was overestimated by a greater margin. The results were improved after softening of the material was added in the model. In the same way, Saavedra Flores *et al.* [12] investigated the mechanical behavior of CLT panels by FEM within a multi-scale model. [12] validated their models against a series of experimental tests for bending, in-plane shear and axial stiffness properties. The numerical models gave good agreement compared with the experimental data; with a relative error of around 11%.

In the present paper, FEM will be used to investigate the elastic behavior of CLT panels and the results will be compared with a 3D analytical approach known as the State Space Approach (SSA) [13]. The SSA has been previously shown by the authors to be capable of capturing the elastic behavior of CLT to a good level of accuracy in comparison to experimental results [14]. The SSA originates from the linear control system where the principal concern is the relationship between inputs (or source) and outputs (or responses) [15]. The SSA provides theoretically accurate three-dimensional solutions that guarantee continuous transverse stress distributions across the thickness of the panels while the boundary conditions and the continuity at the interfaces are satisfied. Importantly, the SSA can give the full range of elastic structural behavior with theoretical accuracy for various plate thicknesses from thin to very thick panels [16], unlike the previously mentioned standard analytical approaches. The governing equations behind the SSA are briefly outlined section 1.2, further details can be found in reference [15].

For designers, accurate methods of capturing the elastic behavior of CLT is key to achieving structural efficiency. Due to the composite nature of a CLT panel and typical span to depth

ratios in practice, many standard analytical approaches are either not applicable or have reduced accuracy, hence the appeal of finite element techniques along with more sophisticated analytical techniques such as the SSA. The current paper is novel in its comparison of different finite element approaches to modelling CLT elastic behavior. Similarly, the analytical solution of a plate with three sides simply-supported and one free edge, has been hitherto unexplored using the SSA. The novel derivation of the SSA formulation for this boundary condition is the subject of a forthcoming publication by the authors.

1.2 Overview of the SSA formulation

Considering a rectangular plate with the boundary conditions of four sides simply-supported as shown in Fig. 2, this boundary condition can be satisfied by solving Eq. (1). To solve this equation, let $\zeta = m\pi/a$ and $\eta = n\pi/b$, where m and n are the numbers of Fourier series terms of the analytical solution in the x and y directions, respectively.

$$\frac{\partial}{\partial z} \{F_{mn}(z)\} = [D_{mn}] \{F_{mn}(z)\} \quad (1)$$

$\{F_{mn}(z)\} = [U_{mn}(z) \ V_{mn}(z) \ Z_{mn}(z) \ X_{mn}(z) \ Y_{mn}(z) \ W_{mn}(z)]^T$ is the state vector of the plate with the number of Fourier series terms m - n^{th} and the system matrix is

$$[D_{mn}] = \begin{bmatrix} 0 & 0 & 0 & C_8 & 0 & -\zeta \\ 0 & 0 & 0 & 0 & C_9 & -\eta \\ 0 & 0 & 0 & \zeta & \eta & 0 \\ C_2\zeta^2 + C_6\eta^2 & (C_3 + C_6)\zeta\eta & C_1\zeta & 0 & 0 & 0 \\ (C_3 + C_6)\zeta\eta & C_6\zeta^2 + C_4\eta^2 & C_5\eta & 0 & 0 & 0 \\ -C_1\zeta & -C_5\eta & C_7 & 0 & 0 & 0 \end{bmatrix} \quad (2)$$

By solving the differential Eq. (1) based on the classical solution method for a linear differential equation [17], the solution can be found as:

$$\{F_{mn}(z)\} = [G_{mn}(z)] \{F_{mn}(0)\} \quad (3)$$

$$\text{Where } [G_{mn}(z)] = \exp \{[D_{mn}] \cdot z\}, \text{ and when } z = h, \{F_{mn}(h)\} = [G_{mn}(h)] \{F_{mn}(0)\} \quad (4)$$

$$\begin{aligned}
C_1 &= -\frac{C_{13}}{C_{33}} & C_2 &= C_{11} - \frac{C_{13}^2}{C_{33}} & C_3 &= C_{12} - \frac{C_{13}C_{23}}{C_{33}} \\
C_4 &= C_{22} - \frac{C_{23}^2}{C_{33}} & C_5 &= -\frac{C_{23}}{C_{33}} & C_6 &= C_{66} \\
C_7 &= \frac{1}{C_{33}} & C_8 &= \frac{1}{C_{55}} & C_9 &= \frac{1}{C_{44}}
\end{aligned} \tag{5}$$

C_{ij} ($i, j=1, 2, \dots, 6$) is the elastic stiffness matrix of the orthotropic material of the plate. $\{F_{mn}(0)\}$ and $\{F_{mn}(h)\}$ are the values of the state variables on the top ($z=0$) and bottom ($z=h$) surfaces and can be determined uniquely on the basis of the load conditions on the top and bottom surfaces. For example, if the plate is subjected to an arbitrarily distributed external transverse pressure $q(x,y)$ on the top surface only, the state vectors on the top and bottom surfaces of the plate can be expanded into a Fourier series as shown in Eqs. (6) and (7),

$$\{F_{mn}(0)\} = \left\{ \begin{array}{c} U_{mn}(0) \\ V_{mn}(0) \\ \frac{4}{ab} \int_0^a \int_0^b q(x,y) \sin(m\pi x/a) \sin(n\pi y/b) dx dy \\ 0 \\ 0 \\ W_{mn}(0) \end{array} \right\} \tag{6}$$

and

$$\{F_{mn}(h)\}^T = [U_{mn}(h) \ V_{mn}(h) \ 0 \ 0 \ 0 \ W_{mn}(h)] \tag{7}$$

Substituting Eqs. (6) and (7) into (3), all displacement components on the top and the bottom surfaces of the plate can be obtained, that is, $U_{mn}(0), V_{mn}(0), W_{mn}(0)$ and $U_{mn}(h), V_{mn}(h), W_{mn}(h)$.

After finding all the displacements and the transverse stresses, the three in-plane stresses can be found by using the following equation:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} -C_2\zeta & -C_3\eta & -C_1 & 0 & 0 & 0 \\ -C_3\zeta & -C_4\eta & -C_5 & 0 & 0 & 0 \\ C_6\eta & C_6\zeta & 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} u \\ v \\ \sigma_z \\ \tau_{xz} \\ \tau_{yz} \\ w \end{Bmatrix} \quad (8)$$

Further simplification can be made if $q(x,y)=q$ is a constant.

1.3 Modelling of adhesive bonding

In CLT panels, adhesive is required to bond each successive ply, while the boards making up each ply may also have adhesive bonds along their edges.

In this paper, the adhesive between the plies will be simulated in the subsequent finite element models while the adhesive between the boards will be assumed as perfectly bonded for numerical expediency. The full bond assumption between the edges of the ply is a simplification, in practice, it is common for the edge of the boards to be left without adhesive. In the SSA, a full bond is assumed between successive plies and the boards making up the plies.

2. FEM model of CLT panels

In this section, five different case studies will be explored using ABAQUS. The first two studies are 3-ply CLT panels with simply-supported sides under sinusoidal (see Fig. 3) and uniformly distributed loading. The choice of mesh size and element type adopted for the FEM analysis is justified firstly. For the third and fourth case studies, the same types of loading are used but the boundary conditions have been changed to three simply-supported sides and a free edge. The numerical results for the four case studies are compared to those from the SSA. In the fifth case study, the developed FEM model will be used to simulate the behavior of a 5-ply CLT beam originally tested experimentally by O'Dowd *et al.* [18].

2.1 Case study 1: FEM model of 3-ply CLT panels with Simply-Supported sides under Sinusoidal Load

The focused panel has the same geometry as that examined analytically by Sturzenbecher and Hofstetter [19]. The panel is symmetrical with three plies of alternate grain orientation, i.e. $[0/90/0]^\circ$ as shown in Fig. 3.

Each board or ply has a thickness of 30 mm so that the total panel thickness is 90 mm. The in-plane dimensions of the panel are $a = b$ and $h/a = 0.25$. Here a is the length of the panel along the x -axis, b is the dimension of the panel along y -axis and h is the total thickness of the panel (z -axis) as shown in Fig. 3.

The set of elastic material parameters used for the timber plies are the same as per [19]; $E_1 = 11000$ MPa, $E_2 = E_3 = 370$ MPa, $G_{12} = G_{13} = 690$ MPa; $G_{23} = 50$ MPa, $\nu_{12} = \nu_{13} = 0.44$ and $\nu_{23} = 0.64$. All the calculations are based on C24-grade timber as the constituent of the CLT boards, in accordance with BS EN 338 [20], these were the same properties adopted in the analytical solution by [19].

The panel is simply-supported on all sides and subject to a sinusoidal load with a maximum magnitude of 1 MPa ($q(x,y) = q_0 \sin(\pi x/a) \sin(\pi y/b)$ where $q_0 = 1$ MPa) in the center of the top surface as shown in Fig. 3.

For the bond connection between different plies, there are a number of approaches to define layer contact, three of which are explored here. The first approach is the composite fully bonded model. The second approach is to define the contacted layers as a cohesive element and the third approach is to define the connection as an interaction contact layer. Before applying these approaches, mesh sensitivity, influence of element type and the boundary condition idealization options will be explored.

2.1.1 Mesh sensitivity study

A mesh sensitivity study was undertaken to define the most appropriate for analysis. Three mesh sizes with cohesive elements between the CLT plies were investigated comprising of equal-sided elements with dimensions of 3, 6, 12 and 24 mm. As shown in Fig. 4, when the mesh density increases, the values of the in-plane stress σ_x with respect to the theoretical solution (derived from the SSA) will be more accurate. Since the difference in results between the 3mm and 6mm mesh size is small, the 6mm mesh will be chosen for computational efficiency (the run time for the 3mm mesh was 11880s, ~10 times that of the 6mm mesh).

2.1.2 Choice of element types

As outlined in Table 1, two different solid elements have been studied (3D 8-node linear brick elements (C3D8) and 3D 20-node linear brick elements (C3D20)) [21] and the results from these have been compared with those from the SSA. Solid elements were used instead of shell elements because of their ability to map the displacements and stresses through the panel thickness. The most suitable solid element in terms of accuracy compared to the SSA is C3D20, hence this was adopted herein.

2.1.3 Boundary Condition (BC) sensitivity

Fig. 5 shows two different options to create simply-supported edges. The first BC1 is whereby U_3 is equal to zero along all the edges. The second, BC2 is whereby U_2 and U_3 are equal to zero along the y -axis, and U_1 and U_3 are equal to zero along the x -axis (note U is a translational restraint, 1, 2, and 3 are the global x , y and z directions). From Table 1, BC2 is closest to the theoretical solution [22].

Fig. 6 shows σ_x for BC1 and BC2 with the results of the SSA. From this figure, both give a good distribution through the thickness when compared to the SSA, with BC2 being closest.

Adopting the optimum mesh size, element type and the suitable boundary condition, three different options for interfacial connection to simulate the CLT panel are presented in the following subsections.

2.1.4 Model 1: 3-ply CLT panel using fully bonded model

The fully bonded model is shown in Fig. 7(a). The orientation of the layup and the fibers in each ply have important roles in determining the accuracy of the model. The fully bonded model the orientation of the fibers is defined from three parameters which are relative to each other; the layup orientation, the ply orientation and an additional rotation.

This method allows the definition of a reference orientation for the layup and a reference orientation for each ply in the layup. Furthermore, the direction of the fibers in a ply relative to the reference orientation of the ply can be specified [21].

2.1.5 Model 2: 3-ply CLT panel using Cohesive elements

Here, the CLT plies will be modelled as separate plies and bonded using cohesive elements to represent the glue or tie; this is defined as a mesh layer as shown in Fig. 7(b). The cohesive element is used to model adhesives between two components and to bind between different interfaces although they do not have any degree of freedom other than that for displacement [21]. In this model, the cohesive element used is an 8-node three-dimensional element (COH3D8). The material property for the cohesive element is set as linear elastic traction according to [23].

2.1.6 Model 3: 3-ply CLT panel using Contact interaction

In this model (Fig. 7(c)), contact interaction between the plies is directly applied and the material properties of the interaction can be defined, hence there is no need to create a section for the cohesive layer as in the previous case.

2.1.7 Case Study 1: Model 1, 2 and 3 Results

Table 2 presents the comparison between the three models and the SSA. From this table, it is clear that Models 2 and 3 are very similar except for the transverse normal shear stresses although even these are close to each other. Model 2 is more accurate than Model 1 in comparison with the SSA.

In terms of the displacements predicted by each model, the results show that for Model 1 (as the CLT plies are assumed as one block, i.e. layers perfectly bonded), the structure is stiffer and the displacement is less than the theoretical value. On the other hand, in Model 2 when the cohesive element is used, the predicted behavior of the CLT tends towards the theoretical solution derived from the SSA, especially for the transverse shear stresses τ_{xz} and τ_{yz} . For the reasons mentioned above, Model 2 with cohesive elements between the CLT plies will be adopted for the following case study.

After the sensitivity studies for the mesh size, element type and boundary condition are explored, the 3D solid element (C3D20) with the cohesive element (COH3D8) with 6mm mesh size is chosen. Fig. 8 shows the comparison between the distribution of the in- and out-of plane displacements along the x and y -axes for the SSA and FEM results at the top of the CLT panel. As can be observed from Table 3, very good agreements are obtained between the FEM and SSA, with relative errors 2.09%, 0.80% and 0.07% for the displacements u , v and w , respectively.

2.2 Case study 2: FEM model of 3-ply CLT panels with Simply-Supported sides under Uniformly Distributed Load

In this section, the same number of plies and material properties of Case study 1, with the Model 2 cohesive ply connection is used but with a 1MPa uniformly distributed load applied on the top of the panel.

Table 4 shows the comparison between the SSA and the FEM results for all the displacements and the stress states for different locations. The FEM gives a generally good agreement with an average relative error equal to 1% with the SSA for the three-ply CLT. However, the results from the FEM models are inconsistent, with some parameters overestimated (such as; ν and τ_{yz}) and others underestimated. Fig. 9 shows the in-plane stress σ_x and the transverse shear stresses τ_{xz} and τ_{yz} obtained from the SSA and the FEM through the thickness of the panel. The FEM results show discontinuity of the transverse stresses τ_{xz} and τ_{yz} at the interfaces between the different plies (e.g. the bottom of the 1st ply for the SSA is equal to the top of the 2nd ply, but for the FEM, it is not the case). This is due to the fact that using solid elements in ABAQUS will lead to discontinuity of the transverse shear stresses at ply interfaces [21]. Accurate evaluation of the shear stresses at each layer is important given the propensity of the CLT section to fail in rolling shear. Furthermore, the values of τ_{xz} should be equal to zero at the top and the bottom of the panel, however, this is not the case with the FEM results.

The FEM model is able to capture the theoretical structural response of the CLT panel with a good level of accuracy in comparison to the theoretically exact solution from the SSA. In the following case studies, the boundary condition is changed to three simply-supported sides and a free edge, the plate geometry and material properties are unchanged.

2.3 Case study 3: FEM model of 3-ply CLT panels with three sides simply-supported and a free edge under Sinusoidal Load

The panel has three sides simply-supported at $x=0$, $y=0$ and b and a free edge at $x=a$, a sinusoidal load is applied to the top surface with a maximum magnitude of 1 MPa ($q(x,y) = q_0 \sin(\pi x/a) \sin(\pi y/b)$ where $q_0 = 1$ MPa).

Table 5 shows the comparison between the SSA and the FEM results for all the in- and out-of-plane displacements and stresses. In general, the SSA predicts higher values than the FEM for all the displacements and the stresses but the results remain. The FEM shows discontinuity in the transverse shear stresses τ_{xz} and τ_{yz} between the plies while the SSA shows continuity.

2.4 Case study 4: FEM model of 3-ply CLT panels with three sides simply- supported and a free edge under Uniformly Distributed Load (UDL)

This case study comprises the same panel and boundary conditions as the previous, however, the load is now a uniformly distributed pressure load with a magnitude of 1 MPa. The resulting in-plane and out-of-plane stresses and displacements through the thickness of the three plies of CLT are shown in Table 6.

As per the previous case, the SSA results are higher than the FEM results, while still in relative agreement with an average relative error equal to 3%. Additionally, the values of the displacements and the stresses for the uniformly distributed load are approximately twice the values of the sinusoidal load from Table 5. As mentioned in section 2.3, the same trends as the previous case study are observed with FEM displaying discontinuity in the transverse shear stresses in between the plies. Fig. 9(a) shows the in-plane stress σ_x distribution through the thickness of the CLT by using the SSA and the FEM, both show good agreement with an average relative error equal to 2.5%.

2.5 Case study 5: 5-ply CLT beam examined by O'Dowd *et al.* [18]

O'Dowd *et al.* examined the bending stiffness of a number of CLT panels experimentally. The focused panel examined here consisted of five laminae, with samples from each lamina being removed and subject to testing to obtain their modulus of elasticity parallel to the grain. Table 7 presents the modulus of elasticity parallel to the grain (E_1) reported by [18], all other

moduli given are based on the characteristic values for the respective timber grades given in EN 338 [20].

The focused panel was 1700mm long (1600mm clear span) $\times$ 150mm wide $\times$ 99mm thick (each ply was 19mm thick, each glue layer was 1mm thick). Polyurethane glue was used to bond the laminae together, this had a longitudinal shear strength of 10 MPa and a tensile strength perpendicular to the bond line of 5 MPa [23].

The test set-up was based on that described in BS EN 408 [24] as shown in Fig. 10. In the experiment, the sample exhibited approximately linear behavior with the total out-of-plane maximum loading and the corresponding deflection recorded being 35.30kN and 25.83mm respectively [18].

For the FEM model in this study, 3D 20 node element types with a cohesive element layer between the CLT plies and an element mesh size of 10.75mm is used. Since the specimen thickness and span is larger than the panels previously investigated, a slightly larger element size was adopted in order to maintain computational efficiency.

As can be seen from Fig. 11, the FEM model gives a fairly good agreement with the experimental work, however, the response is slightly stiffer with a maximum of 10% error with the experimental result. The FEM curve shows more pronounced non-linearity due to the involvement of the shear effect with bending as a result of the beam thickness, some slight non-linearity was observed in the experimental results. There are a number of possible sources of error in the model including inaccuracies in the bond assumptions. As mentioned in section 1.1, the FEM models in this paper assume full bond along the short edges of the CLT boards. This will result in a stiffer response compared to the physical specimen where edge adhesive may not have been applied (no confirmation of edge gluing of the boards was given in the original experimental paper).

In the experiment, the specimen failed in rolling shear. Typically, the characteristic rolling shear strength for CLT constructed using C24 softwood timber of this type is $\sim 0.75 \text{ N/mm}^2$ to 1.5 N/mm^2 [25 & 26]. Fig. 12 shows the FEM derived horizontal shear stresses through the thickness of the panel at the peak load, this clearly indicates a rolling shear failure is predicted.

Another possible source of error in the model is the uncertainty in the material properties of each board making up the CLT panel. Despite tests being undertaken on each timber layer of the CLT panel, these were at discrete points and given that timber is a natural material, there remains uncertainty of the material properties throughout the panel, hence upper and lower 95th percentiles of the modulus of elasticity are simulated in ABAQUS, as shown in Fig. 13. It can be observed that at a decrease in elastic modulus of 5% results in a much closer prediction.

3. Conclusions

FEM models were developed for a 3-ply CLT panel and a 5-ply CLT beam under out-of-plane loads. The modelling is able to predict all the in- and out- of plane displacements and stresses to a reasonable degree of accuracy. For cases 1-4, the FEM models were compared with the SSA, and with existing experimental data for case 5. From the comparison the following conclusions can be drawn:

- Among different element types, the 3D 20-node linear brick element gives more accurate results.
- The cohesive element mesh layer and the interaction contact models give almost the same results. Both are more accurate than the fully bonded method when taking the SSA results as the benchmark.
- The FEM results show discontinuity of the transverse stresses τ_{xz} and τ_{yz} at the interaction between the different plies, this problem is avoided with the SSA method.

- For the specific cases studied, the developed FEM model can give a reasonable prediction of the maximum deflection of a CLT panel and is also able to predict the rolling shear failure mode observed experimentally.
- The FEM model for the case study of 3-ply CLT panels with three sides simply-supported and one free edge gave good agreement with the SSA results, although the FEM underestimated the in- and out-of-plane stresses and displacement. Also, the FEM showed discontinuity of the transverse stresses across the interfaces between different plies.

The conclusions above need to be viewed within the context of limitations of the models employed. As previously mentioned, for the FEM models, edge gluing of the boards making up each ply was not modelled, a full bond was assumed, hence the model would be expected to be stiffer. In the case of the SSA models, a full bond is assumed between plies on both the face and the edges.

In both the FE and SSA models, only elastic material behavior was considered. The models could be further extended to include appropriate failure criteria. Addressing these limitations forms part of the authors' ongoing work.

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list of symbols

a	Length
b	Width
$E_{1,2,3}$	Young's Moduli
G	Shear Moduli
h	Thickness of plate
h_{board}	Thickness of each CLT panel board
h_{panel}	Thickness of CLT panel
h/a	Thickness-to-width ratio
l_{panel}	Length of CLT panel
q_o	Unit load
u, v, w	Displacement components in the x, y and z directions respectively
$U_{1,2,3}$	Translational restraint, 1, 2, and 3 are the global x, y and z directions
W_{board}	Width of each CLT panel board
W_{panel}	Width of CLT panel
γ	Shear strain
ε	Strain vector
ν	Poisson's ratio
σ	Stress vector
τ	Shear stress

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Table 1 Effect of element type and BC sensitivity on the displacements (mm) and stresses (MPa) of 3-ply CLT panel ($h/a = 0.25$).

	(x,y)	z	SSA	FEM		
				BC 1 (C3D20)	BC 2 (C3D20)	BC 2 (C3D8)
u	$(\frac{a}{2}, 0)$	*T	0.1246	0.1251	0.1272	0.1283
		*B	-0.1240	-0.1607	-0.1272	-0.1283
v	$(0, \frac{b}{2})$	*T	0.1870	0.2801	0.2121	0.2148
		*B	-0.2138	-0.2520	-0.2121	-0.2148
w	$(\frac{a}{2}, \frac{b}{2})$	*T	0.9943	1.0753	0.9936	0.9988
		*B	0.9168	0.9935	0.9143	0.9200
σ_x	$(\frac{a}{2}, \frac{b}{2})$	*T	-13.0319	-14.3495	-13.0035	-11.2076
		*B	12.2872	13.7223	12.2756	10.6314
σ_y	$(\frac{a}{2}, \frac{b}{2})$	*T	-10.1361	-10.9284	-10.0436	-9.8312
		*B	10.6190	11.7134	10.6640	10.5847
τ_{xy}	$(0, 0)$	*T	1.8764	1.1808	2.0314	2.0499
		*B	-2.0339	-1.1809	-2.0314	-2.0499
τ_{xz}	$(\frac{a}{2}, 0)$	$h/2$	0.7242	0.8756	0.7127	0.7553
τ_{yz}	$(0, \frac{b}{2})$	$h/2$	1.0865	1.2238	0.9827	1.0294

* Where T and B are the top and bottom of the panel through the thickness respectively.

** The values of σ_y are the top and bottom of the 2nd layer ($\theta=90^\circ$).

Table 2 Case Study 1: FEM and SSA results for displacements (mm) and stresses (MPa)

	(x,y)	z	SSA	*** FEM		
				Model 1	Model 2	Model 3
u	$(\frac{a}{2}, 0)$	*T	0.1246	0.0871	0.1272	0.1272
		*B	-0.1240	-0.0871	-0.1272	-0.1272
v	$(0, \frac{b}{2})$	*T	0.1870	0.0848	0.2121	0.2120
		*B	-0.2138	-0.0848	-0.2121	-0.2121
w	$(\frac{a}{2}, \frac{b}{2})$	*T	0.9943	0.4523	0.9936	0.9936
		*B	0.9168	0.3772	0.9143	0.9143
σ_x	$(\frac{a}{2}, \frac{b}{2})$	*T	-13.0319	-9.2528	-13.0035	-13.0035
		*B	12.2872	8.5113	12.2756	12.2756
** σ_y	$(\frac{a}{2}, \frac{b}{2})$	*T	-10.1361	-8.3951	-10.0436	-10.0436
		*B	10.6190	8.3277	10.6640	10.6640
τ_{xy}	$(0, 0)$	*T	1.8764	1.0335	2.0314	2.0312
		*B	-2.0339	-1.0335	-2.0314	-2.0311
τ_{xz}	$(\frac{a}{2}, 0)$	$h/2$	0.7242	0.1208	0.7127	0.7223
τ_{yz}	$(0, \frac{b}{2})$	$h/2$	1.0865	1.7858	0.9827	1.1138

* Where T and B are the top and bottom of the panel through the thickness respectively.

** The values of σ_y are the top and bottom of the 2nd layer ($\theta=90^\circ$).

*** The FEM model is 3D 20-node linear brick element (C3D20) with mesh element size 6 mm.

Table 3 Case Study 1: FEM and SSA results for displacements (mm) at $z = 0.0$.

	(x,y)	SSA	** FEM	Relative errors
u	$(\frac{a}{2}, 0)$	0.1246	0.1272	2.09
v	$(0, \frac{b}{2})$	0.2138	0.2121	-0.80
w	$(\frac{a}{2}, \frac{b}{2})$	0.9943	0.9936	-0.07

* Where T and B are the top and bottom of the panel through the thickness respectively.

** The FEM model is 3D 20-node linear brick element (C3D20) with mesh element size 6 mm.

Table 4 Case Study 2: In- and out-of-plane displacements (mm) and stress states (MPa) predicted by SSA and FEM.

(x,y)	Number of the ply	z	SSA	**FEM		SSA	**FEM
u	1 st Ply	*T	0.2512	0.2167	v	0.2954	0.3089
		*B	-0.1862	-0.2167		0.1811	0.1851
	2 nd Ply	*T	-0.1862	-0.1543		0.1811	0.1851
		*B	0.1479	0.1543		-0.2025	-0.1851
	3 rd Ply	*T	0.1479	0.1952		-0.2025	-0.1849
		*B	-0.2131	-0.1952		-0.3674	-0.3572
w	1 st Ply	*T	1.9931	1.5113	σ_x	-18.2685	-18.0570
		*B	1.7317	1.5057		12.0051	12.0933
	2 nd Ply	*T	1.7317	1.5065		-0.2387	-0.2352
		*B	1.6328	1.4721		-0.3774	-0.3708
	3 rd Ply	*T	1.6328	1.4720		-11.8776	-11.6885
		*B	1.5621	1.4248		18.2443	18.1924
σ_y	1 st Ply	*T	-1.8828	-1.8396	τ_{xy}	4.1017	4.3203
		*B	-0.7354	-0.7281		-0.2632	-0.2424
	2 nd Ply	*T	-13.9692	-13.7273		-0.2632	-0.2424
		*B	14.7099	14.8148		-0.3209	-0.2919
	3 rd Ply	*T	0.1310	0.1403		-0.3209	-0.2919
		*B	1.2603	1.2746		-3.6199	-3.6184
τ_{xz}	1 st Ply	*T	0.0000	-0.0604	τ_{yz}	0.0000	0.0000
		*B	1.1439	1.2216		1.1590	1.1890
	2 nd Ply	*T	1.1439	1.1490		1.1590	1.5002
		*B	1.2696	1.3339		0.6757	0.7091
	3 rd Ply	*T	1.2696	1.3494		0.6757	0.6565
		*B	0.0000	0.0812		0.0000	0.0151

* Where T and B are the top and bottom of the plies through the thickness respectively.

** All the FEM models use 3D 20-node linear brick elements (C3D20) with mesh size 6 mm.

Table 5 Case Study 3: In- and out-of-plane displacements (mm) and stress states (MPa) predicted by SSA and FEM.

(x,y)	Number of the ply	z	SSA	** FEM		SSA	** FEM
u	1 st Ply	*T	0.2458	0.2432	v	0.5786	0.5732
		*B	-0.0970	-0.0791		-0.2452	-0.2450
	2 nd Ply	*T	-0.0970	-0.0791		0.2452	0.2450
		*B	0.0830	0.0719		-0.2294	-0.2262
	3 rd Ply	*T	0.0830	0.0719		-0.2294	-0.2262
		*B	-0.2398	-0.2373		-0.5525	-0.5489
w	1 st Ply	*T	2.1364	2.1174	σ_x	-9.4205	-9.2012
		*B	2.0978	2.0614		6.8563	6.6015
	2 nd Ply	*T	2.0978	2.0614		-0.5742	-0.5730
		*B	2.0902	2.0562		0.4647	0.4734
	3 rd Ply	*T	2.0902	2.0562		-6.1605	-5.9002
		*B	2.0617	2.0517		8.6928	8.5826
σ_y	1 st Ply	*T	-2.3705	-2.3310	τ_{xy}	3.4633	3.4270
		*B	-1.0488	-1.0314		0.42820	0.4000
	2 nd Ply	*T	-21.9300	-22.7521		-0.4820	-0.4000
		*B	24.3113	23.6217		0.5483	0.5392
	3 rd Ply	*T	0.7333	0.7316		-0.5483	-0.5392
		*B	1.9334	1.8996		-3.7150	-3.5900
τ_{xz}	1 st Ply	*T	0.0000	0.0237	τ_{yz}	0.0000	0.0177
		*B	0.8334	0.8086		0.4640	0.4114
	2 nd Ply	*T	0.8334	0.7745		0.4640	0.5258
		*B	0.8921	0.8613		0.3695	0.3750
	3 rd Ply	*T	0.8921	0.8774		0.3695	0.3642
		*B	0.0000	0.0364		0.0000	0.0032

* Where T and B are the top and bottom of the plies through the thickness respectively.

** All the FEM models use 3D 20-node linear brick elements (C3D20) with mesh size 6 mm.

Table 6 Case Study 4: In- and out-of-plane displacements (mm) and stress states (MPa) predicted by SSA and FEM.

(x,y)	Number of the ply	z	SSA	**FEM		SSA	**FEM
u	1 st Ply	*T	0.4651	0.4618	v	1.1404	1.1259
		*B	-0.1602	-0.1203		0.5581	0.5567
	2 nd Ply	*T	-0.1602	-0.1203		0.5581	0.5567
		*B	0.1125	0.1010		-0.4589	-0.4568
	3 rd Ply	*T	0.1125	0.1010		-0.4589	-0.4568
		*B	-0.4492	-0.4492		-1.0868	-1.0713
w	1 st Ply	*T	4.5258	4.4845	σ_x	-10.8941	-10.8707
		*B	4.4804	4.4283		5.0770	4.4411
	2 nd Ply	*T	4.4804	4.4283		-1.0180	-0.9961
		*B	4.3894	4.4141		0.4485	0.4267
	3 rd Ply	*T	4.3894	4.4141		-5.3133	-4.4411
		*B	4.3890	4.3400		10.5695	10.8675
σ_y	1 st Ply	*T	-4.2652	-4.2241	τ_{xy}	7.6243	7.5607
		*B	-1.9857	-1.9811		0.5445	0.5410
	2 nd Ply	*T	-46.2344	-46.0482		-0.5445	-0.5410
		*B	47.5175	47.5051		1.1608	1.1466
	3 rd Ply	*T	1.3747	1.3369		-1.1608	-1.1466
		*B	3.7774	3.6138		-7.0645	-6.9494
τ_{xz}	1 st Ply	*T	0.0000	-0.0825	τ_{yz}	0.0000	0.0000
		*B	1.4299	1.3969		1.1590	1.1890
	2 nd Ply	*T	1.4299	1.2766		1.1590	1.5002
		*B	1.5870	1.4984		0.6757	0.7091
	3 rd Ply	*T	1.5870	1.5286		0.6757	0.6565
		*B	0.0000	0.0836		0.0000	0.0151

* Where T and B are the top and bottom of the plies through the thickness respectively.

** All the FEM models use 3D 20-node linear brick elements (C3D20) with mesh size 6 mm.

Table 7 Case Study 5: Material Properties [18].

Lamina (1) = Lamina (5) C24	Lamina (3) C16	Lamina (2) = Lamina (4) C24
$E_1 = 11880$ MPa	$E_1 = 8980$ MPa	$E_1 = 14480$ MPa
$E_2 = 370$ MPa	$E_2 = 270$ MPa	$E_2 = 370$ MPa
$E_3 = 370$ MPa	$E_3 = 270$ MPa	$E_3 = 370$ MPa
$G_{12} = 690$ MPa	$G_{12} = 500$ MPa	$G_{12} = 690$ MPa
$G_{13} = 690$ MPa	$G_{13} = 500$ MPa	$G_{13} = 690$ MPa
$G_{23} = 50$ MPa	$G_{23} = 36$ MPa	$G_{23} = 50$ MPa
$\nu_{12} = 0.44; \nu_{13} = 0.44; \nu_{23} = 0.64$ (For all the laminas)

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(a)

(b)

(c)

(d)

(e)

(f)

Fig. 8. Distribution of the in- and out- of plane displacements along x and y at $z=0$. (a), (c) and (e) are the SSA values and (b), (d) and (f) are the corresponding FEM results for u , v and w (mm), respectively.

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