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ANALYSIS OF CROSS-LAMINATED TIMBER FLOORS WITH THE VIERENDEEL METHOD

Nicholas Boey[1], Hassan Karampour[2], Hong Guan[3], Ali Habibi[4]

ABSTRACT: A simply supported and continuous cross-laminated timber (CLT) floors with uniformly distributed loads and point loads were analysed using the Vierendeel Method (VM), in which each layer of the CLT is represented by an individual beam element and the connections between layers are idealised into vertical connecting beam elements. The VM models were created using different end release conditions and element formulations. Comparing the resulting deflections, flexural and shear stresses with those determined using the Gamma Method, Shear Analogy Method and a 2D FEM model, it was found that the VM models with rigid connections between the CLT layers and the Timoshenko beam formulation performed most similarly to Gamma Method and Shear Analogy Method for predicting axial and shear stresses, but tended to over-predict the deflections. Recommendations for future research are made for extending this method such that it can be used for analysing timber-concrete-composite floors that use CLT as the timber component.

KEYWORDS: cross-laminated timber, comparative analysis, Vierendeel method, shear analogy method, gamma method

1 – INTRODUCTION

The Gamma Method and Shear Analogy Method (SAM) are effective and commonly used techniques for analysing cross-laminated timber (CLT) floors in out-of-plane flexure. However, these methods have limitations due to underlying assumptions that make them unsuitable for certain situations such as the analysis of timber-concrete composite (TCC) floors with CLT substrates, continuous spans and arbitrary loads [1].

This paper applies the Vierendeel Method (VM) of analysis to a CLT floor with the purpose of comparing the results obtained with the VM against the Gamma Method and SAM as the first stage in an ongoing research project into a simplified general method of analysis for TCC floors. Although described in [1] as the "Strut-Tie" method, in this paper the name "Vierendeel" method is used to avoid conflict with the term "Strut and Tie" that is commonly associated with reinforced concrete design.

2 – BACKGROUND

Due to the very low shear stiffness of the perpendicular layers in CLT floor panels, when placed in out-of-plane flexure they do not typically obey the "plane sections remain plane" assumption required in Euler-Bernoulli beam models. Any deflections calculated ignoring this shear deformation and assuming standard Euler-Bernoulli beam behaviour will under-predict the deflection of the beam. A Timoshenko beam formulation cannot be readily used, as similar to Euler-Bernoulli models this requires the selection of a single value for the shear stiffness GA whereas CLT panels have different shear stiffnesses for each individual layer.

There are a number of analytical methods that allow the application of Euler-Bernoulli and Timoshenko beam analysis to the analysis of CLT floor panels [2]. The two most common methods used in practice are the Gamma Method as described in the Eurocode 5 for mechanically jointed beams [3] and the Shear Analogy Method [4]. These two methods were validated against a continuum model in [5].

By assuming a simply supported beam and a sinusoidally varying distributed load on the top of the beam, the Gamma Method simplifies the underlying differential equation of the beam into an equivalent Euler-Bernoulli formulation with an "effective" flexural stiffness EI_{eff}. This flexural stiffness is reduced from the gross elastic stiffness EI_{g} to account for the shear deformations of the layers that are perpendicular to the span direction. This method can be readily implemented using almost all standard structural analysis software or hand calculations, and as such is commonly used in practice despite the fact that the simply-supported and sinusoidally varying loading assumptions are almost never met.

Continuous spans are often used in practice to improve the efficiency of the spanning material. Although this is not strictly within the underlying assumptions of the Gamma Method, it has been recommended that an effective span

[1]School of Engineering and Built Environment, Griffith University, Gold Coast, QLD 4215, Australia, nick.boey@griffithuni.edu.au

[2]School of Engineering and Built Environment, Griffith University, Gold Coast, QLD 4215, Australia, h.karampour@griffith.edu.au

[3]School of Engineering and Built Environment, Griffith University, Gold Coast, QLD 4215, Australia, h.guan@griffith.edu.au

[4]Northrop Consulting Engineers, Sydney, NSW 2000, Australia, ahabibi@northrop.com.au

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length of 0.8L should be used for continuous spans and 2L should be used for cantilevers when the Gamma Method is used [2], [6]. The method as described in the Eurocode [3] is only applicable to 3 and 5-layer CLT panels, but has been extended to be applicable to panels with more than 5 layers as the Extended Gamma Method [6].

The Shear Analogy Method (SAM) uses two parallel Timoshenko beams that are connected to ensure displacement compatibility. One beam (Beam A) is responsible for the flexural behaviour of each individual layer as though they were not connected, while the other beam (Beam B) is responsible for the flexural behaviour of the layers assuming that they are rigidly connected [2], [4].

The flexural and shear stiffness of each beam is independent of the span arrangement and loading conditions, and as such unlike the Gamma Method the SAM is applicable to all spans and loading arrangements. However, there is only a closed-form solution suitable for hand calculations for simply supported floors, and the computer application requires finite element software capable of analysing Timoshenko beams.

When applied to TCC floors, due to their underlying assumptions the Gamma Method can only be used reliably for simply-supported floors with a uniformly distributed arrangement of shear connectors and with a uniformly distributed load, and the SAM cannot directly account for shrinkage effects in the concrete or allow for widely spaced discrete shear connectors. An analytical comparison between the Gamma Method and direct solutions of the differential equations was conducted by Huber et al. [7] which found that the Gamma method significantly underpredicted the deflections and stresses in a TCC floor.

A uniaxial finite element analysis was used by Fragiacomo et al. [8] to investigate the effect of shrinkage and creep on a TCC beam with varying shear connector stiffnesses, spacings and temporary support conditions. This beam comprised a concrete topping slab and a supporting glulaminated timber beam. The proposed methodology is conceptually similar but aims to apply this methodology to multi-layered CLT.

The VM is recommended in [1] as a method suitable for use in analysing complex TCC floors as it overcomes these limitations while remaining simple enough to use in practice when compared to 3D nonlinear FEM. It is conceptually similar to the model used by Fragiacomo [8], however it uses a flexible link between the concrete and timber with the properties of the shear connector rather than rigid links with a horizontal spring whose stiffness is determined experimentally in a separate push-out test.

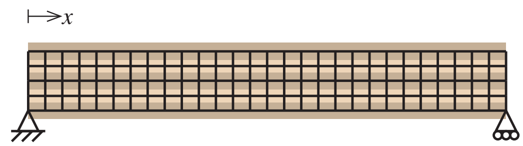

Figure 1: Simply supported Vierendeel model diagram

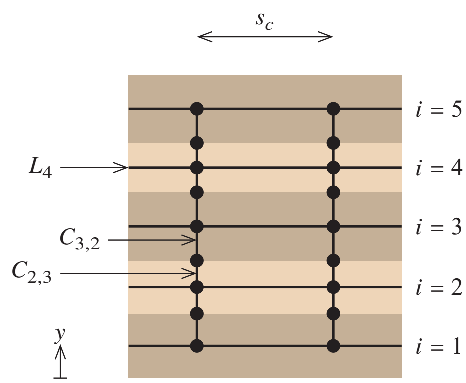

Figure 2: Internal structure of Vierendeel model

As opposed to the SAM, which uses two beams regardless of the number of layers in the TCC beam, the VM uses a separate beam for each layer in the TCC beam and flexible perpendicular beam elements at regular spacing that connect together the individual layers that model the incomplete composite connection between the layers. One benefit of the VM is that shrinkage and creep in both the timber and concrete layers can be modelled by directly inducing shrinkage strains and modifying the materials properties of the individual layers.

The proposed methodology here extends the VM to CLT panels that have multiple layers which are continuously connected together with no slip between the individual layers.

It is recommended in [1] that the connecting elements between layers have bending moment releases at the interface between the concrete and timber layers, however little advice is provided on the formulation of the connection elements between timber-to-timber layers in CLT panels or on the element formulations for the layer and connection elements. The shear stiffness of different connections between the concrete and timber layers may also need to be assessed differently for TCC floors with CLT. The concrete to timber connections typically penetrate through multiple layers in the timber whereas most experimental and numerical studies have been performed on glulam timber which is arranged in layers that are all parallel to the span direction [9].

Fig. 1 shows a diagrammatic representation of the model used in the VM for a simply supported 5-layer panel, where each layer of the CLT panel is represented by a

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Table 1: Layer properties of the 200mm XLAM CLT panel

Layer i	Material type	Direction	Thickness h_i (mm)	Elastic modulus $E_{i,0}$ (MPa)	Elastic modulus $E_{i,90}$ (MPa)	Shear modulus G_i (MPa)
1	XLG1	Parallel	42.5	10,000	400	670
2	XLG2	Perpendicular	35	6000	240	29
3	XLG2	Parallel	45	6,000	240	400
4	XLG2	Perpendicular	35	6000	240	29
5	XLG1	Parallel	42.5	10,000	400	670

horizontal beam element. These horizontal beam elements are interconnected with vertical beam elements that form a Vierendeel truss. Fig. 2 is a close-up view that shows the internal structure of the model, where nodes are inserted at a spacing s_c at the centroid of each layer and at each layer interface. The horizontal lines L_i represent the primary layer elements with index i and the vertical lines $C_{i,j}$ represent the connection elements between layers i and j.

3 – METHODOLOGY

A numerical analysis of simply supported and continuous CLT floors with distributed and point loads was undertaken using the VM and compared against the results of analyses using the Gamma Method (denoted GM), the Shear Analogy Method (denoted SAM) and a 2 dimensional plane-strain continuum FEM model (denoted CONT). The VM, GM and SAM models were analysed using the author's own linear elastic Finite Element Method solver, and the continuum model was analysed using the FEM package ABAQUS [10].

The floors analysed were 1m wide strips of a simply supported and two-span continuous floor with 6m spans and the properties of the 5-layer, 200mm thick CLT panel produced by XLAM [11]. The perpendicular-to-grain elastic modulus E_{90} was taken as $E_0/25$ as has been reported for CLT manufactured using Australian Radiata Pine [12]. The properties of the panels are reproduced below in Table 1.

Two load cases were analysed for the simply supported beam and three load cases were analysed for the continuous beam. For the simply supported beam (see Fig. 3), a 10kN point load was applied at midspan (PL) and a distributed load of 6.3kN/m was applied to the entire span (UDL). The UDL selected is based on the ultimate load for a typical commercial floor with (G = 1.5kPa and Q = 3 kPa). For the continuous beam in Fig. 4, a 10kN point load (PL) was applied at midspan of the first span and a 6.3kN/m distributed load was applied to the first span as a pattern load (PAT) and to both spans as a uniformly distributed load (UDL).

The deflection at midspan (Δ), shear stresses (τ) at $x = 0.6$ metres from the end support and the bending stresses (σ) adjacent to the midspan at x = 2.7 metres were calculated using the methods in [2] and compared. The shear stress and axial stress were calculated just adjacent to the support and point load application point to avoid peak localised stresses at these application points from interfering with the comparison, as these are present only in the CONT and VM models. A linear elastic analysis was undertaken as the stresses are all within the elastic range.

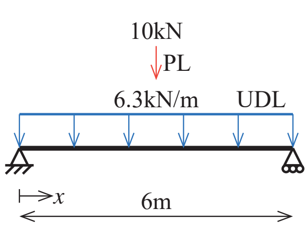

Figure 3: Simply supported beam arrangement

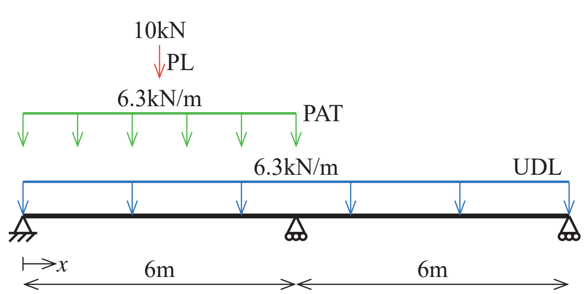

Figure 4: Continuous beam arrangement

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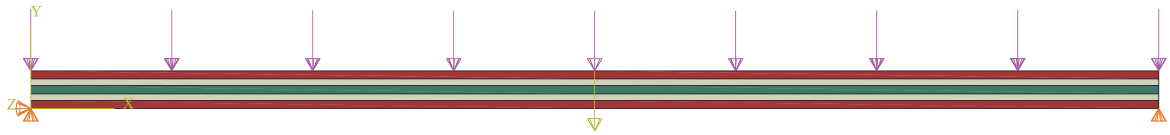

Figure 5: ABAQUS model of single span floor

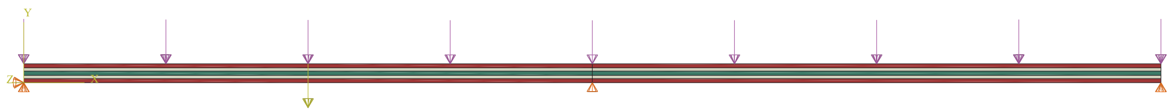

Figure 6: ABAQUS model of two span floor

3.1 Continuum model

The continuum model was created as a 2D plane strain model using the software package ABAQUS [10]. The 8 node plane stress quadrilateral element with 8 integration points (CPS8) was used with 8 integration points. The material properties of each layer are noted in Table 1. An approximate element size of 6mm x 6mm was used.

The flexural and shear stresses were extracted directly from the model as the S11 and S13 stresses without averaging.

3.2 Gamma Method models

As the CLT panel has 5 layers, the normal Gamma Method is applicable and the Extended Gamma Method was not required.

The flexural stiffnesses were calculated in accordance with [2] and are shown in Table 2. For the continuous beam scenario, the stiffness was calculated assuming that the effective length L_{eff} is $0.8L$ (4.8 m), approximating the length between points of contraflexure in the beam [6].

The flexural and shear stresses were recovered from the analysis results as follows using the procedures in [2].

3.3 Shear Analogy Method model

The SAM model (shown diagramatically in Fig. 7) is comprised of two parallel Timoshenko beams, connected together with pinned links at 300mm spacing that maintain deflection compatibility between the beams but do not transfer bending moment between them. Beam A represents the bending stiffness of the individual layers and Beam B represents the "Steiner" component of the stiffness and includes the shear flexibility of the beam.

The flexural stiffnesses $(EI)_A$ and $(EI)_B$ and shear stiffnesses $(GA)_A$ and $(GA)_B$ of each beam are calculated as follows:

$$\begin{aligned}(EI)_A &= \sum_{i=1}^{n} E_{i,0} I_i \\ (GA)_A &= 0 \\ (EI)_B &= \sum_{i=1}^{n} E_{i,0} A_i z_i^2 \\ (GA)_B &= \frac{1}{a^2}\left[\sum_{i=1}^{n-1} \frac{h_1}{2G_1 b} + \sum_{i=2}^{n-1} \frac{h_i}{G_i b} + \frac{h_n}{2G_n b}\right]\end{aligned} \tag{1}$$

Where $E_{i,0}$ and G_i is the elastic modulus of layer i (see Table 1); I_i is the second moment of inertia of layer i; A_i is the cross sectional area of layer i; z_i is the distance from the section's neutral axis to the centroid of layer i; a is the distance between the centroids of the top and bottom layers; b is the total width of the panel; and h_i is the thickness of layer i. The calculated bending and shear stiffnesses are shown in Table 3.

The flexural and shear stresses of the overall cross-section are recovered by calculating for each beam the proportion of bending moment and shear force that is distributed to each layer within the section. This is based on the proportion of the stiffness of each layer to the overall stiffness of the beam. The proportioned bending moment and shear forces for each layer are then converted into flexural and shear stresses using an ordinary Euler-Bernoulli stress distribution and shear-flow methods [2].

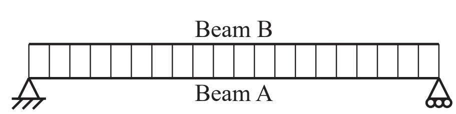

Figure 7: Diagram of simply supported SAM model

Table 2: Gamma Method calculated stiffnesses

Span type	I_{eff} (mm⁴/m)
Simply supported ($L_{\text{eff}} = L$)	479,495
Continuous ($L_{\text{eff}} = 0.8L$)	449,525

Table 3: Shear Analogy Method calculated stiffnesses

Beam	EI_{eff} (N mm^2/m)	GA_{eff} (N/m)
A	174.93×10^6	0
B	5293.73×10^6	9581

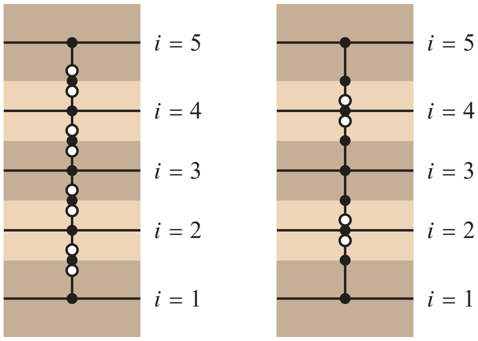

Figure 8: Location of moment releases for VM.PIE and VM.PIT (left) and for VM.PPE and VM.PPT (right)

3.4 Vierendeel Method model

Six different VM models were analysed to investigate the difference that element formulations and member end releases would have on the results. Table 4 describes the variations between the models that were analysed. Either Euler-Bernoulli or Timoshenko formulations were used for both the layer elements and connection elements in each model.

The different end release configurations are shown in Fig. 8. Where the models were released at the interlayers (the PI models), moment releases were applied at the ends of the connection elements where they connect to the nodes positioned between two layers. Where the models were pinned at the perpendicular layers (the PP models), moment release were applied at the ends of the connection elements where they connect to the layers that are perpendicular to the span (i.e. the even-numbered layers). The members were otherwise all connected rigidly at the nodes.

The spacing of the connection elements s_c was selected at 50mm for all models. The connecting elements between the individual CLT layers were spaced at 50mm, with the formulation of these elements matching the formulation of the main layer beam elements. This thickness of the vertical connecting beams was modelled at 50mm throughout with the exception of the ends of the beams, where they were modelled at 25mm thick. This required a very large number of elements, and as such a parametric study to determine the error from increasing the spacing is recommended for future research.

Table 4: Vierendeel Method model types

Model name	Element formulation	End releases
VM.PIE	Euler-Bernoulli	Pinned at interlayers
VM.PIT	Timoshenko	Pinned at interlayers
VM.PPE	Euler-Bernoulli	Pinned at perpendicular layers
VM.PPT	Timoshenko	Pinned at perpendicular layers
VM.RE	Euler-Bernoulli	Rigid
VM.RT	Timoshenko	Rigid

The model provides layer-by-layer centroidal axial forces, bending moments and shear forces denoted here as N_i, M_i and V_i. Design checks of the cross-sectional stresses require the distribution of internal flexural and shear forces within the section to be calculated. A method for doing this is not clearly described within [1].

The peak flexural stresses in each layer are calculated as the normal Euler-Bernoulli flexural stresses within the layer element, and the interlayer shear stresses are extracted from the shear forces in the connecting elements.

$$\sigma_i = \frac{N_i}{A_i} \pm \frac{M_i}{Z_i} \tag{2}$$

$$\tau_{i,i\pm1} = \frac{V_{c,i,i\pm1}}{bs_c} \tag{3}$$

Where σ_i is the peak flexural stresses in each layer; $\tau_{i,i\pm1}$ is the interlayer shear stresses at the junction between the layers i and $i \pm 1$; $V_{c,i,i\pm1}$ is the shear force in the connection element between layers i and $i \pm 1$.

The discretisation of the connecting elements results in the introduction of peak bending moments in the layer elements at the nodes. The continuously bonded CLT layers should result in a continuous bending moment distribution along the length of each layer element but with the VM instead has a sawtooth pattern of bending moments where there are peaks at each introduction of moment from the vertical connecting elements. Flexural stresses calculated using this peak moment are therefore higher than the actual peak flexural stresses. To mitigate this, the average of the bending moment values on each side of the connecting element was used to determine the flexural stress in each layer.

The shear stress calculated above is at the interlayer boundary. The shear stresses between these boundaries should have a parabolic distribution, however due to the shear forces being also carried by the layers the recovery of the full shear stress profile of the section has not been developed. As such, in the present study only the interlayer boundary shear stresses have been compared and the creation of a method to recover the full shear stress distribution is left to future research.

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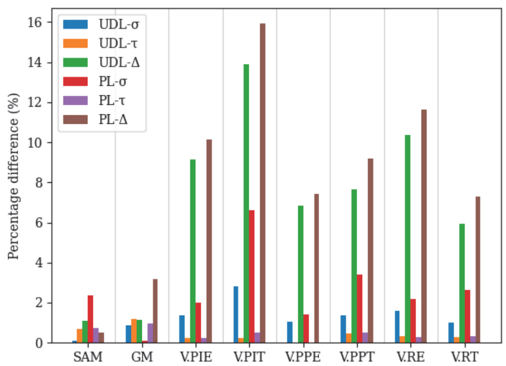

Figure 9: Simply supported beam result comparison

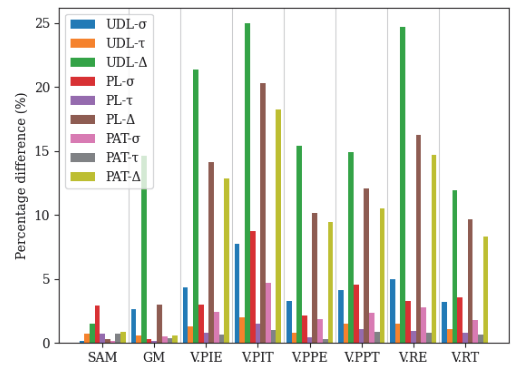

Figure 10: Continuous beam result comparison

4 – RESULTS

4.1 Comparison between models

Fig. 9 and Fig. 10 compare the results of the VM, GM and SAM models with the CONT model results for flexural stress (σ), shear stress (τ) and mid-span deflection (Δ) in the simply-supported and continuous span arrangements respectively. The V.RT and V.PPE models performed the best of all of the VM models. Both models showed stresses within 5% of the CONT model and deflections within 10% of the CONT model.

The GM models performed similar to or better than the VM models in their prediction of the flexural and shear stresses, and the SAM was generally the most similar to the CONT model for the prediction of flexural stress, shear stress and deflection for both span arrangements.

With the exception of the V.PIT models which showed more deviation from the CONT model, the Vierendeel models all performed similarly to one another for the simply supported case for the prediction of flexural and shear stresses. There was no clear pattern as to whether the Timoshenko beam formulations were more accurate than the Euler-Bernoulli formulations. If Timoshenko beam behaviour is supported in the analysis software used by practitioners, it is recommended that greater accuracy is achieved by using rigid connections throughout. Given the ease in modelling the rigidly-connected models compared to the released models it is expected that these will be preferred in practice.

If only Euler-Bernoulli beam behaviour is supported, it is recommended that moment releases are applied to the connection elements where they connect to the perpendicular layers, as this reduction in stiffness appeared to balance the increased stiffness of the Euler-Bernoulli beam formulation. It is noted that should this be used, the deflections predicted are likely to be unconservative by up to 15%. The below detailed inspection of the deflection and stress results look specifically at the V.PPE and V.RT models as it is expected that these would be favoured in practice.

4.2 Deflection

Fig. 11 and Fig. 12 plot the vertical deflections of the single span and two span configurations under uniformly distributed loads respectively. The VM.RT models tended to predict a greater (more conservative) deflection when compared to the CONT and SAM models, while the V.PPE models tended to predict a lower (less conservative) deflection. The GM models were well correlated in the simply supported scenario but varied from the CONT and SAM models in the two span scenario.

Fig. 13 and Fig. 14 show similar results when the first span is loaded with a point load. The backspan of the Gamma Method deviates substantially from the other models in the two-span configuration, where the simply-supported and sinusoidally loaded assumptions underlying the method are most significantly violated.

4.3 Flexural stress

The calculated cross-sectional flexural stresses agreed well between all models in the simply supported case (Fig. 15), with the GM tending to diverge again where the simply-supported assumption was not upheld as shown in Fig. 16. The VM.RT model predicted higher flexural stresses while the VM.PPE model predicted lower flexural stresses.

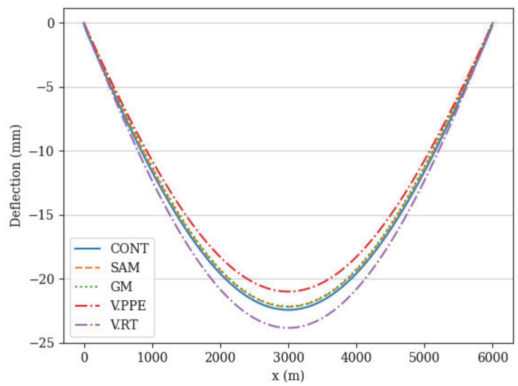

Figure 11: Deflection of single span with UDL

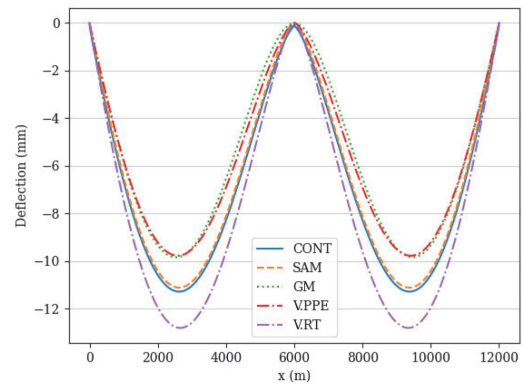

Figure 12: Deflection of continuous span with UDL

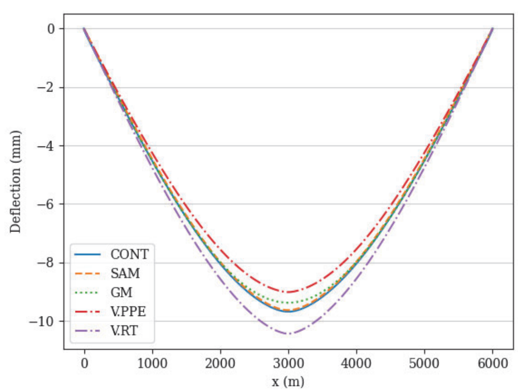

Figure 13: Deflection of single span with point load

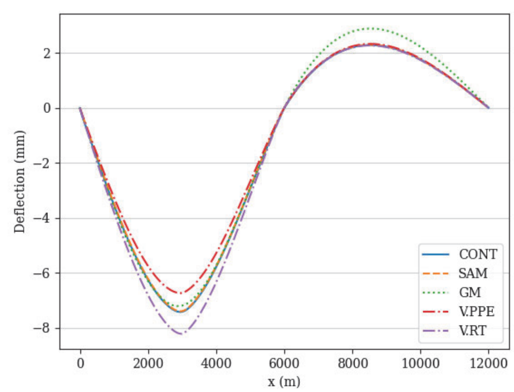

Figure 14: Deflection of continuous span with point load

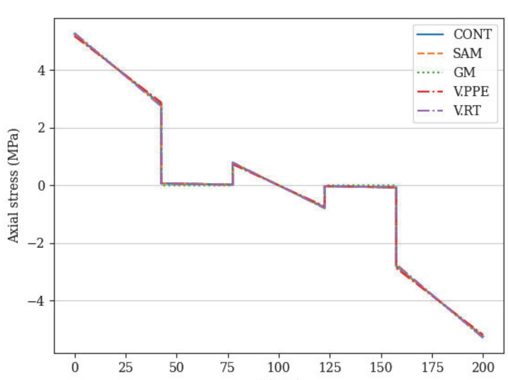

Figure 15: Midspan flexural stress in single span with UDL

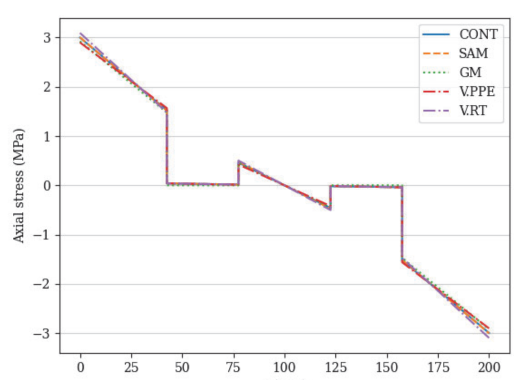

Figure 16: Midspan flexural stress in continuous span with UDL

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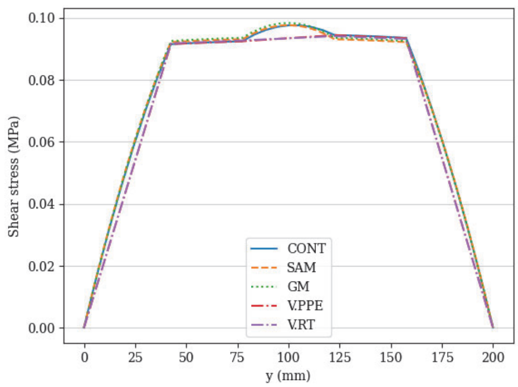

Figure 17: Shear stress in single span with UDL

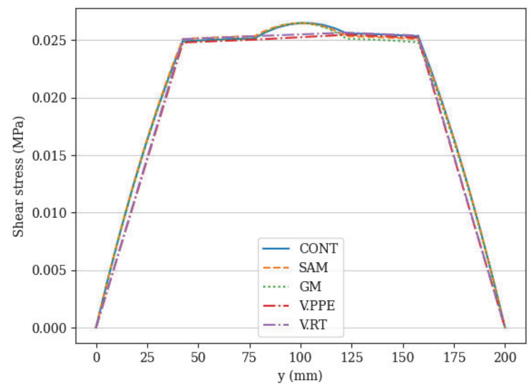

Figure 18: Shear stress in single span with point load

4.4 Shear stress

The cross-sectional shear stresses at the interlayer boundaries were closely aligned for all of the model types (Fig. 17 and Fig. 18). As noted above the shear stresses were not calculated within each layer due to limitations of the VM, and thus the interlayer shear at y = 42.5 millimetres was compared. Similar to the CONT models, the VM models show an asymmetric shear stress distribution due to the asymmetric application of support to the bottom layer of the CLT. This is as opposed to the GM and SAM models, where the supports and forces are applied to the model as a whole rather than to any individual layer.

5 – CONCLUSIONS AND RECOMMENDATIONS

The numerical analysis undertaken demonstrates that the Vierendeel Method is a valid analytical method for CLT floors in out-of-plane flexure, and performs similarly to the well-established Gamma Method and Shear Analogy Method for predicting the peak axial stresses and interlayer shear stresses while over-predicting the deflections.

It is recommended that for future studies on the use of the Vierendeel Method for Timber Concrete Composites (TCC) that Timoshenko beam elements rigidly connected at all nodes are used, as this is the simplest method to implement and provides the most accurate results. Many simpler Finite Element Analysis packages used in practice only implement beams with the Euler-Bernoulli formulation. If only Euler-Bernoulli elements may be used, it is recommended that the connecting elements have moment releases applied at the perpendicular layers to improve the accuracy of the results. It is noted that the Shear Analogy Method is more simple and has superior performance to the Vierendeel Method, and it is thus not recommended that the Vierendeel method is used in lieu of the Shear Analogy Method for plain CLT floors.

For the application of the Vierendeel Method to the analysis of CLT floors, we identified two remaining points that require further study. The first point is in the averaging of the bending moments used to calculate the peak flexural stresses in each layer. This study found adequate accuracy where the mean value of the bending moments on each side of the connection was taken, however a more sound justification of this method is warranted. The second point is in the calculation of the shear distribution across the entire cross section between the interlayer boundaries. These peak stresses do not typically govern the design of a CLT slab, as this generally occurs in the parallel layers where the shear strength is significantly higher than the perpendicular layers which are controlled by a lower rolling shear strength, but is nonetheless necessary for completeness of the analysis methodology.

For the application of the Vierendeel Method to TCC floors, the next steps will be to develop shear connector stiffness that are compatible with the Vierendeel Method, and to assess the accuracy of the Vierendeel Method in analysing the deflections resulting from differential shrinkage of the timber and concrete layers in a TCC floor with CLT layers.

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