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The effect of slip stiffness on the behavior of timber-concrete composite slabs

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Received: March 3, 2025 • Revised manuscript received: May 14, 2025 • Accepted: May 15, 2025
Published online: October 3, 2025

Pollack Periodica • An International Journal for Engineering and Information Sciences

21 (2026) 2, 7–13

DOI:
10.1556/606.2025.01353

ORIGINAL RESEARCH PAPER

ABSTRACT

Timber-concrete composite systems offer improved structural performance compared to bare cross-laminated timber slabs, but their effectiveness strongly depends on the stiffness of the shear connectors between both materials. This paper examines how varying the slip stiffness influences the mechanical response of the composite slabs. Three primary analytical models are compared against a two-layer finite element model. Parametric analyses reveal a critical range of connector stiffness, roughly between 10^4 and $10^6\,\mathrm{kN\,m^{-1}\,m^{-2}}$, in which deflections are sensitive to changes in slip stiffness. Beyond this range, either full or minimal composite action is effectively reached. The study proposes a practical approach to selecting upper and lower thresholds for connection stiffness (k_{max} and k_{min}).

KEYWORDS

cross-laminated timber, timber-concrete composite, slip stiffness, parametric

1. INTRODUCTION

Cross-Laminated Timber (CLT) is a structural composite made from solid sawn timber layers that are glued together with alternating grain orientations. Each successive layer is bonded perpendicularly to the previous one, while the outermost layers are aligned in the same direction, enhancing the panel's strength and stability [1, 2]. The use of CLT in construction has increased significantly in Europe over the last decade. Its application has not been limited to single-family houses; it has also extended to high-rise buildings [3]. CLT offers several advantages compared to traditional construction techniques like concrete, including faster construction, lower labor requirements, reduced carbon footprint, and lighter structural weight [4–8]. Although its lighter weight can be beneficial for foundation design and seismic load considerations, it can be disadvantageous since CLT buildings may be more sensitive to wind loads and uplift forces. A proposed solution is to add a concrete topping to the CLT to enhance the floor system's mechanical properties and increase its mass. Hamm et al. [9] found that CLT-concrete composite slabs also perform significantly better in vibration Serviceability Limit States (SLS) compared to standard CLT slabs. The connection between the two layers is typically achieved using elements like notches, screws, or epoxy adhesive [10]. Experimental testing developed by Balogh [11] indicates that adhesive connections provide higher load capacity compared to traditional notches because they avoid stress concentrations and wood weakening caused by notches.

Several research projects have investigated notched connections in CLT-concrete composites. Jiang and Crocetti [12] confirmed that CLT-concrete composite floors with notched connections exhibit high stiffness and composite action, with failure occurring primarily due to concrete shear fracture rather than connector failure. Their parametric analyses using finite element models revealed that while notch depth influences connection stiffness, it has minimal impact on the overall load-deflection response of the composite floor system.

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Similarly, Qingfeng Xu et al. [13] demonstrated that direct concrete shear failure was the primary failure mode in notched shear connections. Their experimental and theoretical analysis showed that incorporating screws or adhesives in the notches significantly improved slip stiffness and load-bearing capacity, with adhesive-enhanced connections achieving the highest performance. Minh Van Thai's [14] findings further indicated that connector performance is significantly influenced by notch depth and loaded edge length, although the relationship is not strictly linear. Deeper notches and shorter heels enhance stiffness and strength but also increase the likelihood of brittle failure. Juhász et al. [15] investigated the failure mechanisms of glulam-concrete composite beams through full-scale laboratory tests. Results indicate that adding shear reinforcement effectively shifts the failure from shear to tension modes, enhancing control over the structural response.

Different methods have been applied to model this composite system and estimate its mechanical properties. Among these, Timoshenko beam theory is the most general and computationally intensive, the gamma method is the most widely used, and the shear analogy method (also known as Kreuzinger's method) is renowned for its accuracy [16, 17]. Huang et al. [18] conducted a thorough study on the appropriateness of these analytical models through experimental testing and analytical calculations. Their three-point bending tests on 3-layer and 5-layer CLT panels showed that composite beam theory, the shear analogy method, and a newly proposed simplified method produced similar results, making the simplified method a viable alternative. The gamma method, however, was more suitable when using shear strength values obtained from planar shear tests. Christovasilis et al. [19] concluded that the shear analogy method provides the most reliable estimates for elastic and strength properties. Meanwhile, Silva et al. [20] proposed a correction factor for the gamma method to improve the estimation of CLT panel bending stiffness through a finite element parametric study. More advanced plate theories were also assessed under different loading conditions and laminate configurations by Stürzenbecher et al. [21] including Murakami and Ren plate theories. Their results indicated that shear deformations significantly affect mechanical behavior, particularly in thick laminates and under concentrated loads, where simpler plate theories like Kirchhoff's fail to provide reliable predictions.

The gamma factor in the gamma method measures the connection efficiency based on the slip stiffness of the shear connection between the two materials. A more rigid connection results in a higher gamma factor, leading to greater effective bending stiffness and reduced deflections. This paper examines the effect of slip stiffness on the deflection of CLT-concrete composite structures and evaluates the suitability of various analytical methods for modeling their behavior. Both analytical and numerical approaches are considered, with models validated against analytical results. Additionally, threshold values for minimum and maximum slip stiffness are proposed to ensure composite behavior.

2. METHODS

2.1. Shear analogy method

This method is highly accurate and precise, with no limitations on the number of CLT layers. It can be applied to systems of multiple spans and to cases where loads are non-uniformly distributed. However, it can be computationally demanding [22].

The shear analogy method models the composite floor system as two imaginary beams, referred to as Beam A and Beam B. Beam A accounts for the flexural stiffness of the individual layers, while Beam B represents the combined flexural and shear stiffness of the layers and connections. An effective bending stiffness and effective shear stiffness are calculated, shown in Eqs (1) and (2), respectively. Then the total deflection is obtained by summing the bending and shears deflections, as it is indicated in Eq. (3),

$$EI_{eff} = \sum_i E_i I_i + \sum_i E_i A_i a_i^2, \tag{1}$$

$$GA_{eff} = \frac{e^2}{\left(\frac{h_1}{2G_1 b_1}\right) + \left(\sum_{i=2}^{n-1} \frac{h_i}{G_i b_i}\right) + \left(\frac{h_n}{2G_n b_n}\right)}, \tag{2}$$

where EI_{eff} is the effective bending stiffness, E_i is Young's modulus of elasticity for layer i, I_i is the moment of inertia for layer i, A_i is the cross-section area of layer i, a_i is the distance between the composite neutral axis and that of layer i. GA_{eff} is the effective shear stiffness, e is the distance between the centroids of the lower and upper layers, G_i is the shear modulus for layer i, h_i is the thickness of layer i, and b_i is the width of layer i,

$$w = w_m + w_v = \frac{5}{384}\frac{qL^4}{EI_{eff}} + \frac{1}{8}\frac{qL^2}{\frac{GA_{eff}}{\kappa}}, \tag{3}$$

where w is the total deflection of a simply supported beam with a uniformly distributed load, w_m is the deflection coming from the bending term, w_v is the deflection coming from the shear term, q is the uniformly distributed load, L is the span, and κ is the shear coefficient (often assumed to be 1.2).

Figure 1 explains all the distances in the cross-section.

The basic formulation of the shear analogy method does not fully account for the composite action between CLT and concrete. A proposed solution, like the approach used by P. Grönquist et al. [23] for adhesively bonded timber-concrete composites, has been generalized to accommodate various

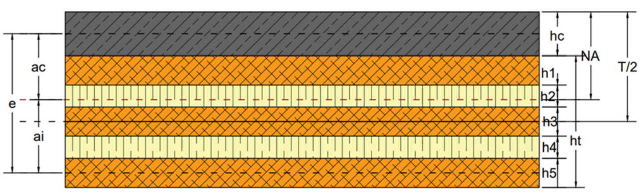

Fig. 1. Shear analogy method cross-section

connection types, like notches or screws, as expressed in Eq. (4). This approach, referred to as the "extended shear analogy method", will be evaluated in this paper,

$$GA_{eff} = \frac{e^2}{\left(\frac{1}{K}\right) + \left(\frac{h_1}{2G_1 b_1}\right) + \left(\sum_{i=2}^{n-1} \frac{h_i}{G_i b_i}\right) + \left(\frac{h_n}{2G_n b_n}\right)}, \quad (4)$$

where K is the stiffness of the shear connectors smeared over the surface of the interface between the concrete and CLT.

In the absence of composite action between the CLT and concrete, the slip stiffness K is zero, causing the extended shear analogy method to fail numerically. In these cases, the standard shear analogy method is applied. The effective bending stiffness is computed using only the first term of Eq. (1), disregarding the Steiner term for the concrete. The shear stiffness is determined based on Eq. (2), with a conservative assumption that only the shear stiffness of the CLT is considered. As it will be demonstrated later, this approach provides reasonable estimates for deflection values at the two extremes - either zero stiffness or stiffness values approaching full composite behavior - but proves inaccurate for intermediate stiffness values.

2.2. Gamma method

The gamma method is proposed in EN 1995–1-1:2004, Annex B of Eurocode 5 [24]. It relies on a reduction factor, the γ factor, which accounts for the connection efficiency between the connected members of a built-up section i.e., the layers with parallel grain direction in a CLT panel. The factor can take a value between 0 and 1, where 0 means no composite action between the cross-layers, and 1 means a fully rigid connection. In practical application, this number is somewhere in between.

This approach is straightforward and provides reasonably accurate results for simply supported spans. However, it is limited to three layers of CLT and was initially developed only for uniformly distributed loads [22]. Compared to the shear analogy method, the gamma method is simpler to use. However, its applicability is constrained by several underlying assumptions, including uniform loading, simply supported boundary conditions, and the number of layers. These simplifications, while useful for analytical convenience, limit the generalizability of the method to more complex structural configurations, such as multi-span systems, variable loading scenarios, or composite sections with more than three layers.

In CLT-concrete composite slabs, an extended gamma method can be applied, in which the formulas are adapted to account for more than three layers. Alternatively, an equivalent gamma method can be used: first apply the gamma method to determine the effective stiffness of the CLT alone, and then treat the CLT as a single equivalent layer when analyzing the CLT-concrete system. In this case, the measured gamma factor reflects the efficiency of the connector between the two materials, as it is proposed by A. Forsberg and F. Farbäck [25].

The composite factor γ_c and the effective bending stiffness are calculated as shown in Eqs (5) and (6), respectively. The deflection is calculated in a similar manner to the shear analogy method only from the bending stiffness term. The gamma method comes up with an equivalent beam, where only the bending deflection needs to be evaluated, the shear not, which is another limitation as the equivalent bending stiffness is different for different spans,

$$\gamma_c = \frac{1}{1 + \frac{\pi^2 E_c A_c}{K L^2}}, \quad (5)$$

$$EI_{eff} = EI_c + \gamma_c E_c A_c a_c^2 + EI_t + \gamma_t E_t A_t a_t^2, \quad (6)$$

where E_c is concrete's Young's modulus, A_c is the cross-sectional area of the concrete layer, K is the stiffness of the shear connectors smeared over the surface of the interface between the concrete and CLT, and L is the span length of the composite system. EI_c is the effective bending stiffness of the concrete layer, EI_t is the effective bending stiffness of the timber layer, γ_t is the timber gamma factor to reduce the Steiner addition to the moment of inertia, A_t is the cross-sectional area of the timber layer, a_c and a_t are the distances between the centers of the concrete/timber layer and the neutral axis of the composite. Figure 2 shows all the dimensions corresponding to the cross-section distances for the gamma method.

2.3. Two-layer finite element model

Several Finite Element (FE) software packages offer solutions for designing CLT elements, but very few provide dedicated tools for CLT-concrete composite structures. AXIS VM, for instance, includes a CLT module that works based on Mindlin plate theory, which is a two-dimensional generalization of Timoshenko beam theory [26]. While the software provides accurate results for CLT slabs, it lacks built-in support for CLT-concrete composites. To address this limitation, each layer - CLT and concrete - is modeled separately. Layers were modeled using shell elements, the mesh consisted of six nodded serendipity elements with an average size of 0.25 m, and connected to each other using spring elements, where the stiffness of the spring elements is assigned based on the stiffness of the mechanical connectors. The material model for concrete was defined as linear elastic and isotropic, while the CLT as linear elastic and orthotropic to account for its directional stiffness properties. A linear static analysis was performed. Töpler et al. [27] discuss the use of FE analysis in the design of timber structures,

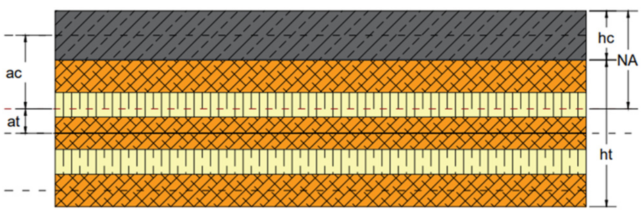

Fig. 2. Gamma method cross-section

focusing on its integration into structural design processes and standards, particularly within the framework of the Eurocode 5. They highlight the challenges associated with FE modeling in timber engineering, such as material anisotropy, connection stiffness, and validation of numerical models.

3. RESULTS AND DISCUSSION

3.1. Validation of the design models

To validate the proposed models, deflection values were calculated for various layer configurations and span lengths under two extreme conditions: no composite action and a fully rigid connection. The panels were simply supported, modeled with a hinge at one end and a roller at the other, and had a width of 1.0 m. A uniform surface load of 5.0 kN m^{-2} was applied. Examined spans (L) were 3.0 m, 5.0 m, and 8.0 m. Concrete quality is C20/25-X0-16-F2, and timber is C24.

Tables 1 and 2 present the configuration of the examined cases and the calculated deflection results for the extended shear analogy method, the two-layer numerical model, and the Timoshenko beam theory, in which the deflections were calculated using a commercial CLT design calculator. The commercially available calculator is not built to analyze the case of zero slip stiffness. This is why only the values of deflections for the extended shear analogy method and the two-layer model are shown. Error is calculated in relation to the results obtained from the Timoshenko model.

Table 1. Deflections for the case of full composite action

Span	Thickness			Extended Shear analogy		Two-layer		*Timoshenko*
L	C_t	CLT_t	h	w	error	w	error	w
m	mm	mm	mm	mm	%	mm	%	mm
3	50	40–40–40	170	**1.105**	0.45	**1.110**	0.90	**1.1**
3	40	30–40–30	140	**1.830**	3.68	**1.980**	4.21	**1.9**
3	60	40–20–20–20–40	200	**0.740**	5.71	**0.733**	4.71	**0.7**
3	80	40–30–40–30–40	260	**0.438**	9.50	**0.396**	1.00	**0.4**
3	80	30–35–30–30–30–35–30	300	**0.388**	29.33	**0.298**	0.66	**0.3**
5	50	40–40–40	170	**6.880**	4.44	**7.200**	0	**7.2**
5	40	30–40–30	140	**12.280**	7.60	**13.370**	0.52	**13.3**
5	60	40–20–20–20–40	200	**4.600**	4.54	**4.548**	3.36	**4.4**
5	80	40–30–40–30–40	260	**2.430**	5.65	**2.300**	0	**2.3**
5	80	30–35–30–30–30–35–30	300	**1.980**	16.47	**1.773**	4.29	**1.7**
8	50	40–40–40	170	**40.000**	10.31	**44.470**	0.27	**44.6**
8	40	30–40–30	140	**76.280**	8.31	**82.610**	0.69	**83.2**
8	60	40–20–20–20–40	200	**27.600**	1.84	**27.310**	0.80	**27.1**
8	80	40–30–40–30–40	260	**13.830**	3.20	**13.400**	0	**13.4**
8	80	30–35–30–30–30–35–30	300	**10.640**	15.65	**9.875**	7.33	**9.2**
Total					**8.44**		**1.92**	

Table 2. Deflections for the case of no composite action

	Thickness			Extended Shear analogy			Two-layer	
L	C_t	CLT_t	h	EI_{eff}	GA_{eff}	w	w	Var.
m	mm	mm	mm	kN·m^2	kN	mm	mm	%
3	50	40–40–40	170	1,976	6,900	**3.480**	**2.969**	14.68
3	40	30–40–30	140	1,096	5,453	**5.670**	**5.174**	8.74
3	60	40–20–20–20–40	200	3,076	11,129	**2.220**	**1.918**	13.60
3	80	40–30–40–30–40	260	6,176	14,700	**1.236**	**1.004**	18.70
3	80	30–35–30–30–30–35–30	300	8,534	16,717	**0.954**	**0.774**	18.90
5	50	40–40–40	170	1,976	6,900	**22.850**	**20.840**	8.79
5	40	30–40–30	140	1,096	5,453	**39.500**	**36.845**	6.72
5	60	40–20–20–20–40	200	3,076	11,129	**14.630**	**13.436**	8.16
5	80	40–30–40–30–40	260	6,176	14,700	**7.650**	**6.841**	10.57
5	80	30–35–30–30–30–35–30	300	8,534	16,717	**5.700**	**5.063**	11.17
8	50	40–40–40	170	1,976	6,900	**139.000**	**130.000**	6.47
8	40	30–40–30	140	1,096	5,453	**249.400**	**230.516**	7.57
8	60	40–20–20–20–40	200	3,076	11,129	**90.280**	**83.870**	7.10
8	80	40–30–40–30–40	260	6,176	14,700	**45.900**	**42.287**	7.87
8	80	30–35–30–30–30–35–30	300	8,534	16,717	**33.640**	**30.782**	8.49

In the case of full composite behavior, the results of the two-layer finite element model and the Timoshenko beam model are nearly identical. However, the extended shear analogy method deviates from these results. Nonetheless, this deviation remains within an acceptable range, as confirmed by previous research.

When no composite action is present, there is some difference between the calculated deflection from the extended shear analogy method and the two-layer model. The extended shear analogy method seems to be conservative in general and overestimates the deflections. This is reasonable considering that in our approach, the shear stiffness of the concrete was not considered.

3.2. Parametric study of a variable slip stiffness

As previously stated, varying slip stiffness affects the overall stiffness of the composite system and, consequently, its deflections. This relationship is examined through a parametric study, which will be demonstrated in the following sections. The study evaluates the extended shear analogy method, the gamma method, and the two-layer model, considering two simply supported slab configurations, as it is shown in Table 3.

The primary variable in this study is the slip stiffness of the connection between the CLT and concrete, ranging from no composite action to full composite behavior. Since the effective stiffness values derived from different methods are not directly comparable, deflections are used as the primary basis for comparison. Calculated deflections are normalized to the minimum deflection obtained from the numerical model to ensure a consistent comparison framework.

The connector stiffness is expressed in $\mathrm{kN\,m^{-1}\,m^{-2}}$, meaning the stiffness is smeared over the slab area. To better visualize the variation in deflection across different stiffness values, the stiffness is plotted on a logarithmic scale.

Figures 3 and 4 illustrate the normalized deflection as a function of slip stiffness for configurations A and B, respectively. These graphs show that the analytical formulas establish both upper and lower limits for deflections. The gamma method and the two-layer model yield similar results in capturing the effect of slip stiffness on effective stiffness, expressed in terms of deflection. In configuration B, the overall trend remains similar; however, there are slight discrepancies between the deflection values obtained from the numerical model and those from the gamma method.

The extended shear analogy method accurately estimates deflections when the connector stiffness approaches full composite action. However, at low stiffness values (below approximately 100,000 $\mathrm{kN\,m^{-1}\,m^{-2}}$), it diverges toward

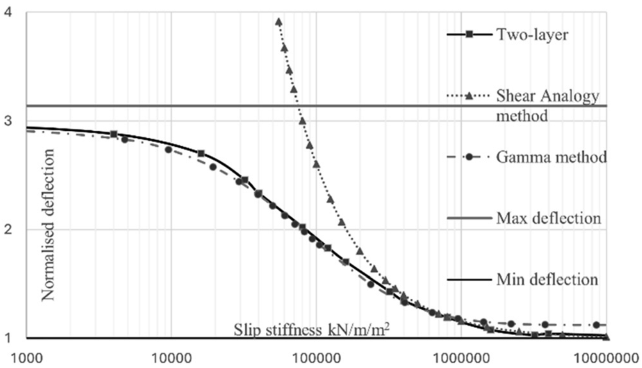

Fig. 3. Normalized deflection vs. slip stiffness, configuration A

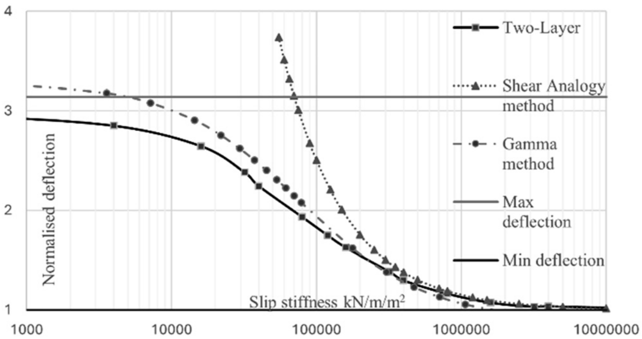

Fig. 4. Normalized deflection vs. slip stiffness, configuration B

infinite deflection as it was previously discussed in the introduction to the extended shear analogy method. Notably, there is a critical point where the shear analogy method curve intersects the deflection level where no composite action is assumed, marking the threshold beyond which the shear analogy method is no longer giving meaningful results.

There is an effective range between 10^4 and 10^6 $\mathrm{kN\,m^{-1}\,m^{-2}}$, where deflections are highly sensitive to changes in slip stiffness. It shall be possible therefore to determine two slip stiffness k_{min} corresponding to the level under which no composite action can be expected and k_{max} beyond which full composite behavior can be assumed.

3.3. Upper and lower thresholds for connection stiffness (k_{max} and k_{min})

Since the gamma method has proven to be a reliable approach for estimating the effect of slip stiffness on deflection, it will serve as the basis for determining k_{max} and k_{min}.

Table 3. Parametric study configuration

Configuration	Span m	Concrete thickness mm	CLT-Layers mm	Total height mm	Loads $\mathrm{kN\,m^{-2}}$	Concrete material	CLT material
A	5	80	40–30–40–30–40	260	5	C20/25	C24
B	5	60	40–20–20–20–40	200	5	C20/25	C24

To calculate $k_{\max}$, starting with the condition for full composite behavior, where $\gamma_c = 1$. From Eq. (6) the corresponding effective bending stiffness is given by

$$EI_{eff,\max} = EI_c + E_c A_c a_{c,\max}^2 + EI_t + \gamma_t E_t A_t a_{t,\max}^2, \quad (7)$$

where $a_{c,\max}$ and $a_{t,\max}$ are the distances between the centers of the concrete/timber layer and the neutral axis of the composite in the case of full composite action.

The minimum deflection in that case is

$$w_{\min} = \frac{5}{384} \frac{qL^4}{EI_{eff,\max}}. \quad (8)$$

To quantify the effect of slip stiffness on deflection, we introduce a deflection reduction factor, ε, where if $\varepsilon = 5$, implies that the calculated deflection is 5% lower than the minimum deflection. This is represented as

$$(1+\varepsilon) w_{\min} = (1+\varepsilon) \frac{5}{384} \frac{qL^4}{EI_{eff,\max}} = w = \frac{5}{384} \frac{qL^4}{EI_{eff}}, \quad (9)$$

Substituting Eqs (6) and (7) into Eq. (9) and isolating $\gamma_{c,\max}$ the following is obtained

$$\gamma_{c,\max} = \frac{EI_c + EI_t + E_c A_c a_{c,\max}^2 + \gamma_t E_t A_t a_{t,\max}^2 - (1+\varepsilon)\left(EI_c + EI_t + \gamma_t E_t A_t a_t^2\right)}{(1+\varepsilon) E_c A_c a_c^2} \quad (10)$$

This equation provides the gamma factor that results in deflections reduced by ε relative to the maximum deflections.

Finally, rearranging Eq. (5), the expression for $k_{\max}$ is derived,

$$k_{\max} = \frac{\pi^2 E_c A_c}{\left(\frac{1}{\gamma_{c,\max}} - 1\right) L^2}. \quad (11)$$

Following the same methodology to calculate $k_{\min}$

$$w_{\max} = \frac{5}{384} \frac{qL^4}{EI_{eff,\min}}, \quad (12)$$

$$EI_{eff,\min} = EI_c + \gamma_{c,0} E_c A_c a_{c,\min}^2 + EI_t + \gamma_t E_t A_t a_{t,\min}^2, \quad (13)$$

$$(1-\varepsilon) w_{\max} = (1-\varepsilon) \frac{5}{384} \frac{qL^4}{EI_{eff,\min}} = w = \frac{5}{384} \frac{qL^4}{EI_{eff}}, \quad (14)$$

$$\gamma_{c,\min} = \frac{EI_c + EI_t + \gamma_{c,0} E_c A_c a_{c,\min}^2 + \gamma_t E_t A_t a_{t,\min}^2 - (1-\varepsilon)\left(EI_c + EI_t + \gamma_t E_t A_t a_t^2\right)}{(1-\varepsilon) E_c A_c a_c^2}, \quad (15)$$

where $a_{c,\min}$ and $a_{t,\min}$ are the distances between the centers of the concrete/timber layer and the neutral axis of the composite in the case of no composite action. $\gamma_{c,0}$ is equal to zero theoretically but numerically should be a small number.

Finally, the expression for $k_{\min}$ is derived,

$$k_{\min} = \frac{\pi^2 E_c A_c}{\left(\frac{1}{\gamma_{c,\min}} - 1\right) L^2}. \quad (16)$$

3.4. Practical application of $k_{\max}$ and $k_{\min}$ in engineering design

The defined stiffness thresholds support the selection of appropriate connectors in CLT-concrete composite systems. When the layer thicknesses and SLS deflection limits are defined Eqs. (11) and (16) can be used to calculate the required connector stiffness. This enables designers to select connectors that meet performance criteria without unnecessary overdesign, accounting for material efficiency.

4. CONCLUSIONS

This paper investigated the impact of slip stiffness on the bending and shear stiffness represented as deflections of timber-concrete composite (TCC) slabs. Both analytical methods (extended shear analogy and gamma method) and numerical simulations (a two-layer finite element model) were employed to determine how varying connection stiffness influences overall performance. The Timoshenko beam theory served as an additional benchmark for validation.

The gamma method generally tracked the finite element results closely for intermediate slip stiffness values, offering a practical tool for predicting effective stiffness and deflection where partial composite action dominates. The extended shear analogy method provides accurate deflection estimates at the two extreme conditions of zero and full composite action; however, it becomes numerically unstable at low but nonzero slip stiffness values. Under full composite action, the finite element results match well with Timoshenko beam theory calculations. Slight deviations arise in the extended shear analogy when full composite action is assumed, but they remain within an acceptable range, consistent with earlier research.

A parametric study demonstrated that deflections become highly sensitive to changes in connector stiffness between approximately 10^4 and $10^6\,\mathrm{kN\,m^{-1}\,m^{-2}}$. Beyond this range, further increases or decreases in stiffness have diminishing effects on deflection, effectively corresponding to full or minimal composite action. Formulas derived from the gamma method were proposed to define practical upper and lower stiffness thresholds, $k_{\max}$ and $k_{\min}$. Connection stiffness above $k_{\max}$ yields negligible additional deflection reductions, while values below $k_{\min}$ provide minimal improvements over non composite behavior.

ACKNOWLEDGEMENTS

KDP-IKT-2023-900-I1-00000957/0000003 has been implemented with the support provided by the Ministry of Culture Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the C2316739 and OTKA K138615.

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