Two-Dimensional Numerical Analysis on the Double Shear Specimens of Timber-Concrete Composite Structures: Effects of Screw Dimensions and Timber Density

Análisis Numérico Bidimensional de Especímenes de Doble Corte en Estructuras Compuestas de Madera y Concreto: Efectos de las Dimensiones del Tornillo y la Densidad de la Madera

Análise Numérica Bidimensional em Especificações de Cisalhamento Duplo de Estruturas Compostas de Madeira e Concreto: Efeitos das Dimensões dos Parafusos e da Densidade da Madeira

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Summary. - This study investigates the behaviour of screw connections in timber-concrete composite (TCC) structures using two-dimensional finite element modelling with LUSAS software. The research focuses on the shear force capacity and stiffness of screws arranged in a parallel 90-degree formation within a double shear test configuration. A comprehensive review of the literature provided the necessary data on embedment strengths of screws in timber and concrete. Finite element simulations of TCC structures were conducted and validated against previous experimental findings. The analysis examined how variations in screw diameter, depth, and timber density impact connection performance. Results indicate that a 10 mm diameter screw with a 100 mm embedment depth and timber density of 476 kg/m³ achieves a shear force capacity of 11.80 kN, a maximum displacement of 16.48 mm, and a stiffness of 701 N/mm. Reducing the screw diameter to 8 mm and 6 mm results in lower shear capacities of 9.45 kN and 7.07 kN, with corresponding stiffness of 574 N/mm and 438 N/mm. Similarly, decreasing the screw depth to 80 mm and 60 mm reduces shear capacities to 9.34 kN and 7.01 kN, with stiffness of 572 N/mm and 437 N/mm, respectively. Increasing the timber density to 600 kg/m³ improves the shear force capacity to 14.70 kN and the stiffness to 980 N/mm. The findings demonstrate that larger screw diameters, greater embedment depths, and higher timber densities significantly enhance the shear force capacity and stiffness of screw connections in TCC structures. The main finding of this research is the identification of the failure mode of screw connections, which is influenced by the properties of the timber, concrete, and screw. When the concrete strength surpasses the timber strength, failure occurs due to timber crushing, while screw deformation and timber crushing are expected when interaction stresses exceed the yield stress in the timber-screw interface. This study provides critical insights for optimizing screw connections in TCC designs and contributes to the development of more effective design codes for timber-concrete composites.

Keywords: Timber structures; Timber concrete composite; Screw connections; Embedment strength

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Resumen. - *Este estudio investiga el comportamiento de las conexiones por tornillos en estructuras compuestas de madera y concreto (TCC) utilizando modelado de elementos finitos bidimensionales con el software LUSAS. La investigación se centra en la capacidad de fuerza de corte y rigidez de los tornillos dispuestos en una formación paralela de 90 grados dentro de una configuración de prueba de corte doble. Una revisión exhaustiva de la literatura proporcionó los datos necesarios sobre las resistencias de incrustación de los tornillos en madera y concreto. Se realizaron simulaciones de elementos finitos de estructuras TCC, las cuales fueron validadas con base en hallazgos experimentales previos. El análisis examinó cómo las variaciones en el diámetro del tornillo, la profundidad y la densidad de la madera afectan el rendimiento de la conexión. Los resultados indican que un tornillo de 10 mm de diámetro con una profundidad de incrustación de 100 mm y densidad de madera de 476 kg/m³ alcanza una capacidad de fuerza de corte de 11,80 kN, un desplazamiento máximo de 16,48 mm y una rigidez de 701 N/mm. La reducción del diámetro del tornillo a 8 mm y 6 mm da lugar a capacidades de corte más bajas de 9,45 kN y 7,07 kN, con una rigidez correspondiente de 574 N/mm y 438 N/mm. De manera similar, la reducción de la profundidad del tornillo a 80 mm y 60 mm reduce las capacidades de corte a 9,34 kN y 7,01 kN, con rigidez de 572 N/mm y 437 N/mm, respectivamente. El aumento de la densidad de la madera a 600 kg/m³ mejora la capacidad de fuerza de corte a 14,70 kN y la rigidez a 980 N/mm. Los hallazgos demuestran que diámetros de tornillos más grandes, mayores profundidades de incrustación y mayores densidades de madera mejoran significativamente la capacidad de fuerza de corte y la rigidez de las conexiones por tornillos en estructuras TCC. El principal hallazgo de esta investigación es la identificación del modo de fallo de las conexiones por tornillos, que está influenciado por las propiedades de la madera, el concreto y el tornillo. Cuando la resistencia del concreto supera la resistencia de la madera, la falla ocurre debido al aplastamiento de la madera, mientras que se espera la deformación del tornillo y el aplastamiento de la madera cuando las tensiones de interacción superan la tensión de fluencia en la interfaz madera-tornillo. Este estudio proporciona información crucial para optimizar las conexiones por tornillos en el diseño de TCC y contribuye al desarrollo de códigos de diseño más efectivos para compuestos de madera y concreto.*

Palabras clave: *Estructuras de Madera, Compuestos de Madera y Concreto, Conexiones*

Resumo. ***-*** *Este estudo investiga o comportamento das conexões por parafusos em estruturas compostas de madeira e concreto (TCC) utilizando modelagem de elementos finitos bidimensionais com o software LUSAS. A pesquisa foca na capacidade de força de cisalhamento e rigidez dos parafusos dispostos em uma formação paralela de 90 graus dentro de uma configuração de teste de cisalhamento duplo. Uma revisão abrangente da literatura forneceu os dados necessários sobre as resistências de incrustação de parafusos em madeira e concreto. Simulações de elementos finitos de estruturas TCC foram conduzidas e validadas com base em resultados experimentais anteriores. A análise examinou como variações no diâmetro do parafuso, profundidade e densidade da madeira impactam o desempenho das conexões. Os resultados indicam que um parafuso de 10 mm de diâmetro com 100 mm de profundidade de incrustação e densidade de madeira de 476 kg/m³ atinge uma capacidade de força de cisalhamento de 11,80 kN, um deslocamento máximo de 16,48 mm e uma rigidez de 701 N/mm. A redução do diâmetro do parafuso para 8 mm e 6 mm resulta em capacidades de cisalhamento mais baixas de 9,45 kN e 7,07 kN, com rigidez correspondente de 574 N/mm e 438 N/mm. Da mesma forma, a diminuição da profundidade do parafuso para 80 mm e 60 mm reduz as capacidades de cisalhamento para 9,34 kN e 7,01 kN, com rigidez de 572 N/mm e 437 N/mm, respectivamente. Aumento da densidade da madeira para 600 kg/m³ melhora a capacidade de força de cisalhamento para 14,70 kN e a rigidez para 980 N/mm. Os resultados demonstram que diâmetros maiores de parafusos, maiores profundidades de incrustação e maiores densidades de madeira aumentam significativamente a capacidade de força de cisalhamento e a rigidez das conexões por parafusos em estruturas TCC. A principal conclusão desta pesquisa é a identificação do modo de falha das conexões por parafusos, que é influenciado pelas propriedades da madeira, do concreto e do parafuso. Quando a resistência do concreto supera a resistência da madeira, ocorre falha devido ao esmagamento da madeira, enquanto a deformação do parafuso e o esmagamento da madeira são esperados quando as tensões de interação excedem a tensão de escoamento na interface madeira-parafuso. Este estudo fornece informações críticas para otimizar as conexões por parafusos no design de TCC e contribui para o desenvolvimento de códigos de projeto mais eficazes para compostos de madeira e concreto.*

Palavras-chave: *Estruturas de madeira; Composto de madeira e concreto; Conexões por parafuso; Força de embutimento*

1. Introduction. - Timber-Concrete Composite (TCC) structural system integrates timber and concrete elements to enhance efficiency and durability, aiming to optimize the structural integrity and performance of composite beams. TCC systems are versatile and adaptable, capable of supporting substantial loads and stresses. The primary goal of TCC technology is to improve the overall strength and efficiency of structures through a robust structural connection between timber and concrete components [3, 8, 12, 14]. Various shear connectors, such as screws, bolts, nails, mesh plates, and steel plates, can be used to connect timber and concrete elements [4, 7, 18]. Screws are particularly prevalent as shear connectors in these systems. Design standards for timber-to-timber structures are available in many countries, offering guidelines for the effective use of these connectors, such as those provided by Eurocode 5 - Design of timber structures [6]. However, while Eurocode 5 provides design standards for timber-to-timber connections, it has certain limitations when applied to timber-concrete composite structures. Shear connections are essential for providing ductility in TCC systems, with design parameters such as strength, stiffness, deflection, and configuration being critical to their overall performance [1, 5, 15, 16]. Research has demonstrated that the shear force capacity $F_{V,R}$ and stiffness Ks of these systems are significantly affected by the material properties of timber, concrete, and fasteners [9, 17]. According to Eurocode 5, the strength of screw connections is influenced by both embedment strength and withdrawal strength [6, 13]. While Eurocode 5 provides guidelines for the embedment strength of vertical screw connections in TCC, it has limitations regarding the stiffness formula, as it depends on the types of timber, screw properties, and concrete properties used in TCC structures. In this context, the stiffness of screw connections in TCC structures is assumed to be twice that of screw connections in TTC structures. According to Eurocode 5, the failure of these connections is also influenced by the properties of the timber, concrete, and screw. Therefore, the failure modes of screw connections in TCC structures must be explored to determine whether the screw connection will fail due to screw snapping, withdrawal from the timber, or withdrawal from the concrete. To better understand how the failure of screw connections and embedment strength affect the strength and stiffness of these connections, this study conducted a numerical analysis of screw connections in TCC structures, utilizing a database of previous TCC structures that employed screw connections.

2. Aims of research. -This study aims to determine how the screw, timber, and concrete properties of TCC structures influence the shear force capacity and stiffness of the connection. It is expected that an increase in the diameter and length of the screw will enhance the shear force capacity and stiffness of the connection in TCC structures. Additionally, it is anticipated that higher timber density will improve the shear force capacity of the connections. Furthermore, the failure mode of the screw connections is dependent on the properties of the screw, timber, and concrete. Therefore, this study aims to achieve two main objectives:

- Validation of Double Shear Test Models: To validate finite element models used for double shear testing by comparing the results with established experimental data from previous studies.

- Analysis of Local Shear Connection Behaviour: To investigate the local behaviour of shear connections within TCC structures. This involves assessing the influence of varying timber densities and screw dimensions on connection performance and identifying associated failure mechanisms.

To fulfil these objectives, the study employs the finite element method using LUSAS software to construct a two-dimensional model grounded in prior experimental work as discussed in section of methodology. The model examines different timber densities and screw sizes to evaluate their effects on connection behaviour and to elucidate potential failure modes.

3. Methodology. - This research utilized the finite element method (FEM) with LUSAS software version 21 to model a double shear test involving screw connections [10]. The model was developed based on existing literature and previous research. To validate the model, the shear force capacity and stiffness obtained from the simulations were compared with data from earlier studies to assess the adequacy of the results. Subsequently, the study explored variations in material properties, including timber density, and screw dimensions, to examine their effects on the shear connections. This involved modifying these parameters and investigating their impact on the local behaviour of timber-concrete connections. Finally, the results were analysed and discussed to provide insights into the performance and behaviour of the connections under different conditions. Figure I shows the flowchart of this research.

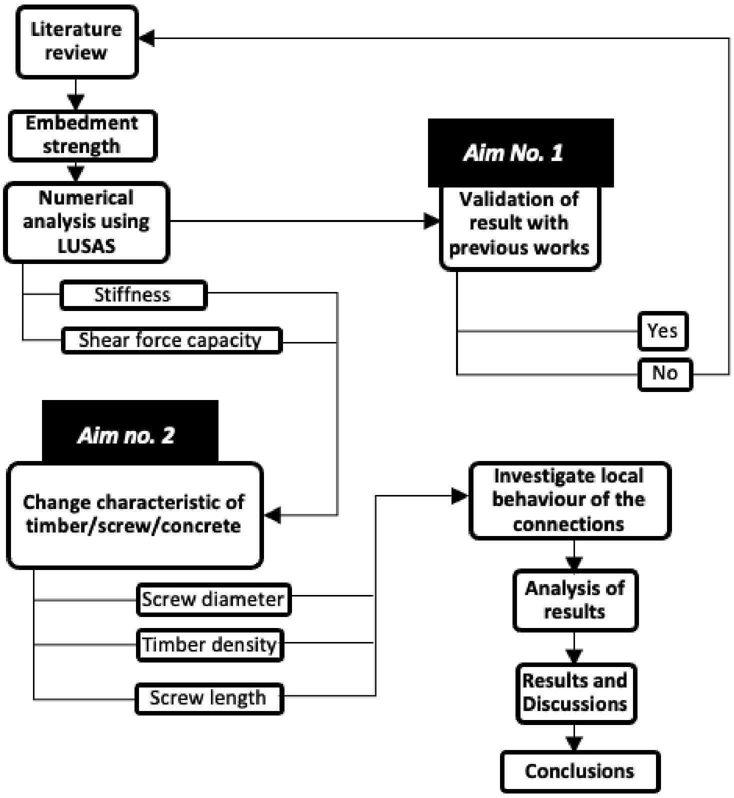
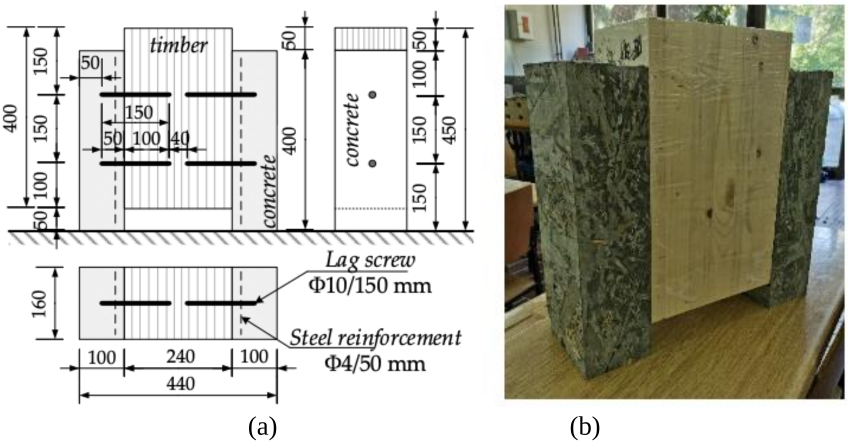


Figure I.- Flow chart of the research

3.1. Double shear test specimens physical and mechanical properties for finite element modelling. - This research utilized the data sample from the double shear test of screw connections in timber-concrete structures as reported by Manojlović et al. [11]. Figure II illustrates the dimensions of the screw and double shear specimen (2a) and the specimen prior to testing (2b). All material properties used in this research are detailed in Table 1. These physical and mechanical properties serve as the baseline for modelling of double shear specimen. Material properties for timber, concrete, and screws were defined using isotropic material models. For concrete, the material properties included a Young's modulus E_c of 30,000 N/mm², Poisson's ratio v_c of 0.2, mass density ρ_c of 2.4×10^{-6} t/mm² and compressive strength f_c of 55 MPa. Timber properties were set with a Young's modulus E_t of 13,000 N/mm², Poisson's ratio v_t of 0.2, mass density of 0.447×10^{-6} t/mm², and compressive strength f_t of 24 MPa. For the screws, the material was also defined isotopically with a Young's modulus E_s of 210,000 N/mm², Poisson's ratio v_s of 0.3, mass density ρ_s of 0.89×10^{-6} t/mm², and tensile strength of 695 MPa. The load was applied at the top of the timber member in the double shear test, simulating typical loading conditions for these connections.



(a) (b)

Figure II.- Sample used for FE Modelling (a) Details dimensions of screw connections in double shear specimen and (b) double shear specimen before tested [11]

Materials	Properties	Mean Value
Glulam GL24	Compressive strength, f_t	24 MPa
Concrete	Cubic compressive strength f_c	55 MPa
Screw	Tensile strength f_u	695 MPa

Table I.- Material properties of the specimens [11]

3.2 Tools and platform. - This study utilized the LUSAS Modeller software, available in the Computer Lab at the Universiti Sains Malaysia (USM), Engineering Campus. The modelling process involved several critical steps. Specifically, the double shear specimens were modelled on only one side due to symmetry considerations. For meshing, the timber surface was represented using plane strain elements with a quadrilateral shape and quadratic interpolation, employing a regular mesh approach to ensure accuracy. Concrete surfaces were similarly meshed with plane stress elements and quadratic interpolation, also utilizing a regular mesh. Screws were modelled as bar elements with quadratic interpolation and divided into four segments. Interface and delamination properties were defined by specifying line elements with plane strain characteristics for the interface and manually assigning the interaction between timber and concrete.

For the geometric properties, the model encompassed screw, timber, and concrete components. Screws were represented as geometric lines with bar properties, where the cross-sectional area was calculated using $A = 2\pi r^2$. For two screws, this resulted in a total cross-sectional area of 157.08 mm^2. The geometric surfaces for timber and concrete were defined with a thickness of approximately 160 mm (see Figure IIa). This setup ensured that the model accurately represented the spatial dimensions and properties of the materials involved in the timber-concrete composite structure.

3.3 Embedment strength model as interface material. - The initial phase of this research involved a comprehensive literature review to gather the necessary properties of timber and concrete for use in numerical analysis. Key parameters required for modelling include embedment strength and maximum displacement. These parameters are essential for defining the interface material between the screw and timber/concrete. According to the LUSAS software guidelines, the interface material between two different materials can be characterized by a linear decrease in strength with increasing applied stress in the opening or tearing directions, reflecting a weakening connection, as illustrated in Figure III. The maximum value of the stress in Figure III also known as initiation stress, τ. Ben et al. [2] and Manojlović et al. [11] report that the embedment strength of the screw $f_{h,t}$ in glulam GL24 is 36.1 MPa, with a maximum displacement δ_{max} of approximately 15 mm. The value of initiation stress in the modelling were used to determine the fracture energy by calculating the area under the curve of embedment strength versus displacement, as shown in the graph provided by Manojlović et al. [11] in Figure IV. For the screw embedded in the concrete component, the embedment strength $f_{h,c}$ was calculated using the formula suggested by Mohd Snin and Kassem [13], as presented in Equation 1. The fracture energy was then determined from the area under this curve, with the initiation stress set at 46.75 MPa. In the modelling process, the interface material was assigned to line elements.

Consequently, the initiation stresses for both the timber and concrete interfaces with the screw needed to be multiplied by a correction factor, as well as by the circumference $C = 2\pi r$ of the screw's circular cross-section, to accurately represent the stress along the line as presented in Equation 2. Analysis revealed that applying a correction factor of 5 was necessary to align the results with experimental findings. This adjustment accounts for the use of line elements to represent the screw in the two-dimensional analysis. Table 2 shows the details of the data to calculate initiation stress and fracture energy for baseline model. Next, assign the master element for the timber and concrete where the screw will be located as presented in Figure Va. Set the slave element assignment for the screw by configuring the selection memory. After establishing the master and slave assignments, drag the interface element by selecting the slave assignment. Combine the timber and concrete components by first making them unmergeable (see Figure Vb). Position the screw within the timber and concrete. Finally, assign the material properties for the timber, concrete, and screw.

$$f_{h,c} = 0.85 f_c \ \ \mathbf{(N/mm^2)} \tag{1}$$

$$\tau = f_{h,c}\ or\ f_{h,t} \,.\, (2\pi r) . 5 \ \mathbf{(N/mm)} \tag{2}$$

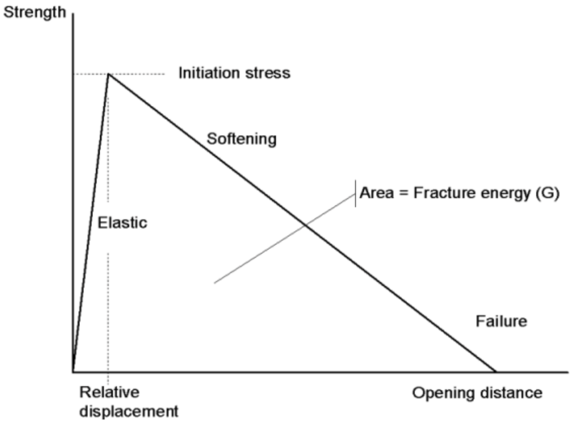


Figure III.- Material properties of interface element

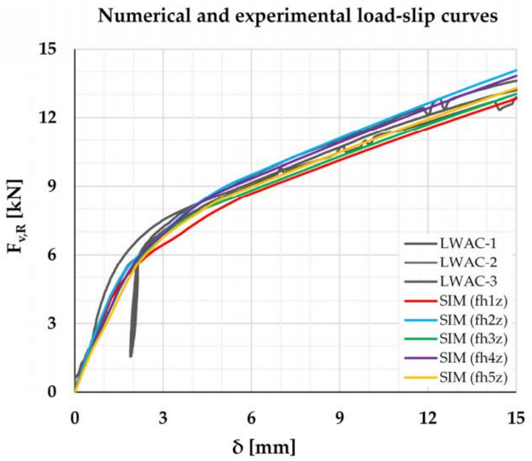
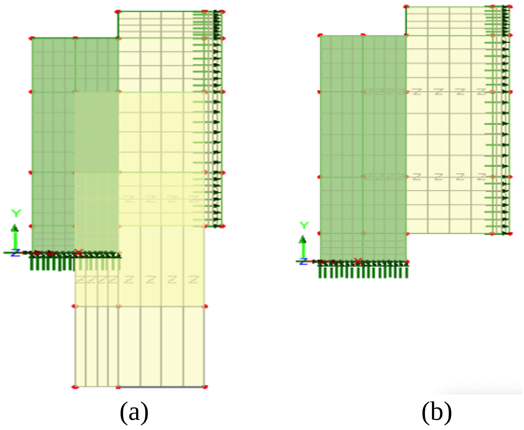


Figure IV.- Embedment strength against displacement used as the data for FE modelling from Manojlović et al. [11]

Part	Embedment strength (N/mm^2)	Initiation stress [Eq.2] (N/mm)	Fracture energy [Area under the graph] (J/mm^2)
Screw to timber	36.1	5667	84975
Screw to concrete	46.75	17150	17150

Table II.- Initiation stress and fracture energy for interface material



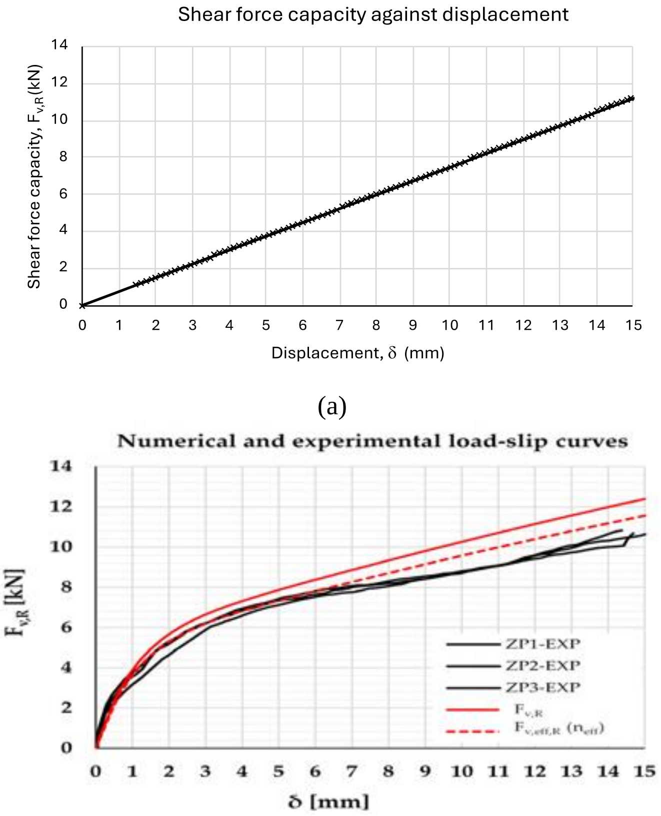
(a) (b)

Figure V.- Process to assign the interface element between screw to timber/concrete. (a) Master (on timber/concrete) and slave (on screw) assignment and (b) Completed assignment of interface element

After modelling the double shear test for timber-concrete composite structures, the resulting graph of shear force capacity versus displacement can be generated. Compare this graph with those from Manojlović et al. [11]. If the results from the modelling significantly differ from those in the reviewed articles, recheck the properties and materials entered into the LUSAS software to ensure they match those reported by Manojlović et al. [11]. Additionally, examine the local behaviour of the screw within the timber and concrete surfaces. Displacement and deformation should be clearly observable from the results. Next, modify the characteristics of the timber, concrete, or screw, such as timber density or screw diameter, and observe any changes in the behaviour of deformation within the TCC structures. Finally, analyse all the results from the modelling, and provide a discussion and recommendations based on these results.

4. Result and Discussion. -

4.1 Validation of the results. - After completing the modeling process, a graph comparing shear force capacity versus displacement was simulated, as shown in Figure VI. This figure illustrates a comparison between the results of this study and the previous findings of Manojlović et al. [11]. The details of the comparison between the experiment are provided in Table III, and these results are also compared with the theoretical values from Eurocode 5. Specifically, the shear force capacity of the TCC structure (per screw) in this study is 11.80 kN, and the stiffness is approximately 701 N/mm (calculated based on the slope of the graph). In comparison, Manojlović et al. [11] reported a shear force capacity of 10.65 kN and a stiffness of approximately 2889 N/mm. The percentage difference in shear force capacity is approximately 10.79%, while the percentage difference in stiffness is about -74%. The significant deviation in stiffness between the numerical value from this study and the experimental value from Manojlović et al. [11] is attributed to the bond strength model used in this study, which assumes linear properties, as shown in Figure III. This model results in a linear behavior of the bond between the screw and timber/concrete in the numerical analysis. However, validation of the failure mode of the screw connection has been conducted to support the results of this numerical study.



(a)

(b)

Figure VI.- Graph of shear force capacity against displacement (a) Numerical analysis in this study and (b) Experimental and Numerical works from Manojlović et al. [11]

Parameter	Method	Mean	Deviations [%]
Shear force capacity (N)	Experiment	10,650	-
	Theoretical (Eurocode 5)	10,491	-2.44
	Numerical from this study	11,800	10.79
Stiffness (N/mm)	Experiment	2889	-
	Theoretical (Eurocode 5)	6975	141.43
	Numerical from this study	750	-74

Table III.- Comparison of shear force capacity and stiffness between these numerical results to experimental work and theoretical formula from Eurocode 5.

Moreover, the results can be further validated by comparing the screw failure observed in the modelling with failure images from previous studies. Specifically, Figure VII illustrates screws being pushed out from the timber, which is consistent with the failure patterns shown in Figure VIII a) from prior research. This comparison reveals similar crushing deformation of the timber and bending deformation of the lag screw. Additionally, the push-out failure mechanism observed in this study aligns with the mechanisms described in previous works. Hammad et al. (2024) stated that the failure mode of the screw inside the timber involves two plastic hinges, as shown in Figure VIII b), which appear before the screw breaks. In the current study, the model also showed the formation of double hinges on the screw, as shown in Figure VII.

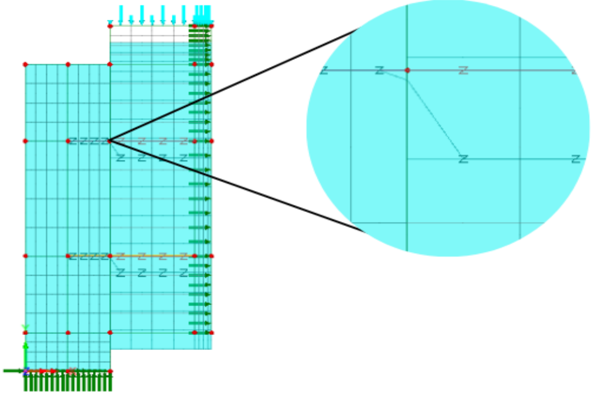
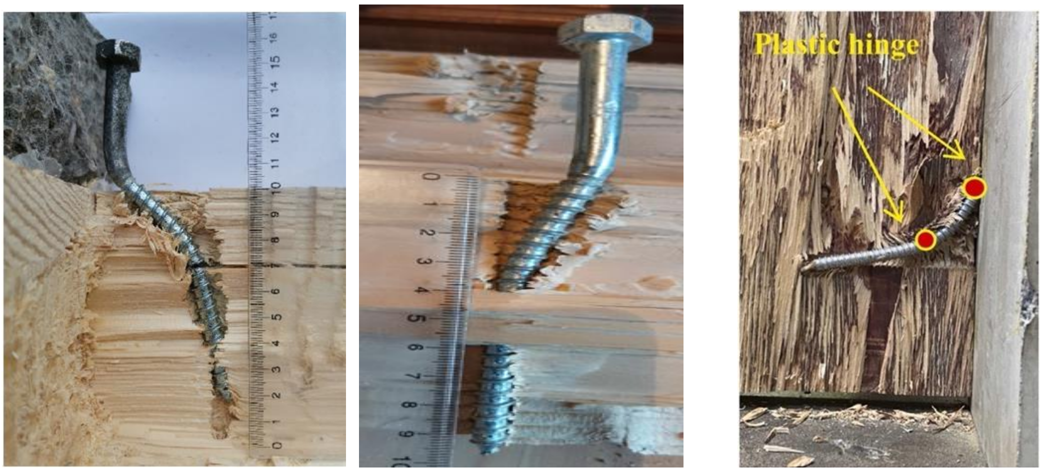


Figure VII.- The failure mode of the screw for TCC-structure from modelling



(a) (b)

Figure VIII.- The failure mode of pushing out specimen and crushing deformation of timber
a) Minoljovic et al. [11] b)Hammad et al. [20]

4.2 Local behaviour of the screws. - Since the strength of the connection in TCC structures depends on the interaction between the timber and the screw, as well as the concrete and the screw, the discussion focuses on these types of interactions. After modelling with LUSAS software, the local behaviour of the screw can be assessed from the contour patterns of stresses on the screw and the interaction between the screw to timber and concrete. Prior to failure, a screw progresses through several stages: elastic deformation, yielding, strain hardening, reaching ultimate strength, and eventual failure. Initially, the screw deforms elastically under applied load, returning to its original shape once the load is removed, as described by Hooke's Law. When the load increases and the screw reaches its yield point, plastic deformation begins, resulting in permanent changes. Subsequently, strain hardening may occur, enhancing the material's strength and resistance to further deformation, thus allowing it to support greater loads. The ultimate strength represents the maximum load the structure can withstand before failure mechanisms take over and this stage often includes necking, a localized reduction in cross-sectional area. Failure may occur in the interaction due to either a snapped screw or the withdrawal of the screw, which can happen in the timber or the concrete. The withdrawal of the screw is related to the stress at the interface between the screw and the timber, as well as between the screw and the concrete. As shown in Figure IX, the interfaces between the screw and timber, and the screw and concrete, are modeled to fail in a debonding manner. Failure occurs when the structure can no longer support the load, leading to breakage or collapse. Ductile materials undergo significant plastic deformation before failure, while brittle materials fail abruptly with minimal plastic deformation. This discussion refers to the initiation stress at the interfaces between the screw and timber/concrete, which are 5667 N/mm² and 11328 N/mm², respectively, with the screw strength being 250 N/mm², as presented in Figure IX.

At a load factor of 10 kN (per side), the stresses on the interface between screw and timber are approximately 2400 N/mm², and between screw and the concrete, they are about 4800 N/mm². No deformation or failure is observed in the screw, concrete, or timber at this load. When the load factor increases to 18 kN (per side), stresses rise to about 8640 N/mm² between screw and timber interface, while in the concrete, they reach approximately 4320 N/mm². These interface stresses remain below the yield stresses, indicating that the structure can still withstand additional force. At a load factor of 23.6 kN (per side), as presented in Figure VII, which corresponds to the shear force capacity of the model, the stresses at the screw-timber interface are approximately 5664 N/mm², while at the screw-concrete interface, they are about 11328 N/mm².The initial embedment strength of the screw in timber, considered its yield stress, is around 5665 N/mm². Thus, as the stresses exceed this yield stress, deformation of the screw and timber crushing are expected. However, the initial embedment strength of the screw in concrete is about 17175 N/mm². The stresses between screw and concrete the interface remain below this yield stress, so no deformation occurs in the concrete. This mechanism is similar to that observed by Mohd Snin et al. [13], where the failure of the screw involved it being withdrawn from the timber but remaining in the concrete. Very little deformation occurred in the part of the screw embedded in the concrete. From the model in this study, it was found that the initiation stress applied to the interface between the concrete and screw was 2 times higher compared to the timber-to-screw interface. This makes the bond between the concrete and the screw very strong.

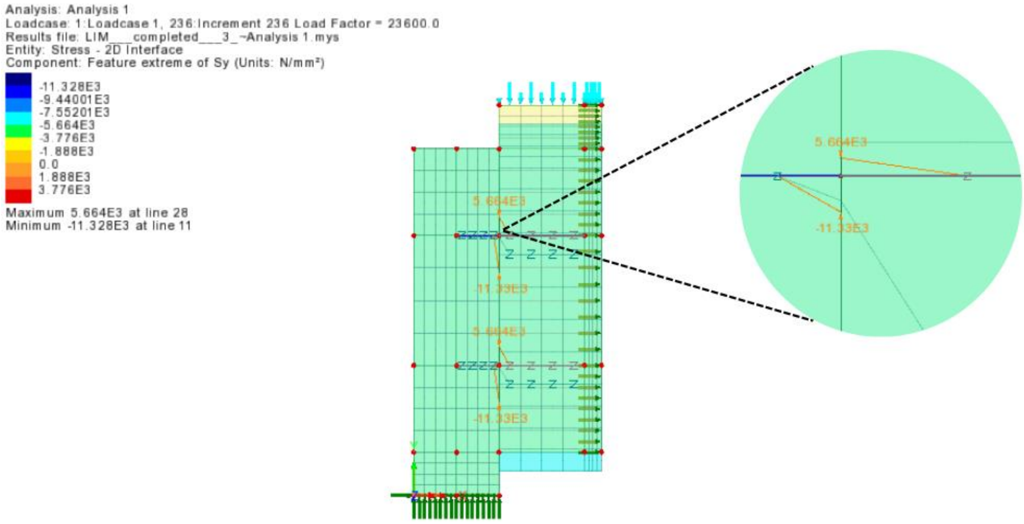


Figure IX.-Interface stresses of the screw at maximum load factor of 23.6 kN (per side)

4.3 Effects of diameter of screws on shear force capacity. - This section examines the impact of screw diameter on the shear force capacity and stiffness of connections. A plot of shear force capacity versus displacement, categorized by screw diameters of 6 mm, 8 mm, and 10 mm, is presented in Figure X. The data indicate that the 10 mm screw exhibited the highest shear force capacity at 11.8 kN, followed by the 8 mm and 6 mm screws with capacities of 9.47

kN and 7.07 kN, respectively. *Table IV* details the shear force capacity and stiffness for each screw diameter and their correlation with initiation stress and fracture energy. This is supported by the research conducted by Long et al. (2022), which found that a larger diameter size increased the embedment strength of the screw connection by 30%. The increased shear force capacity with larger screw diameters is attributed to the greater cross-sectional area, which enhances the screw's ability to withstand shear stresses. This improvement facilitates more effective shear load transfer across concrete and timber layers. Larger diameter screws generally support heavier loads and exhibit increased stress endurance, thereby enhancing the composite structure's shear capacity. Additionally, the stiffness of the joint between concrete and timber is improved with larger screws, resulting in reduced relative displacements and better composite action. This improved mechanical coupling between concrete and timber leads to enhanced frictional resistance at the interface and more even distribution of shear forces, reducing the likelihood of local failures. In summary, larger screw diameters correlate with higher initiation stress, increased fracture energy, and improved shear force capacity. This, in turn, results in a higher stiffness and greater rigidity of the TCC structure, strengthening the overall connection.

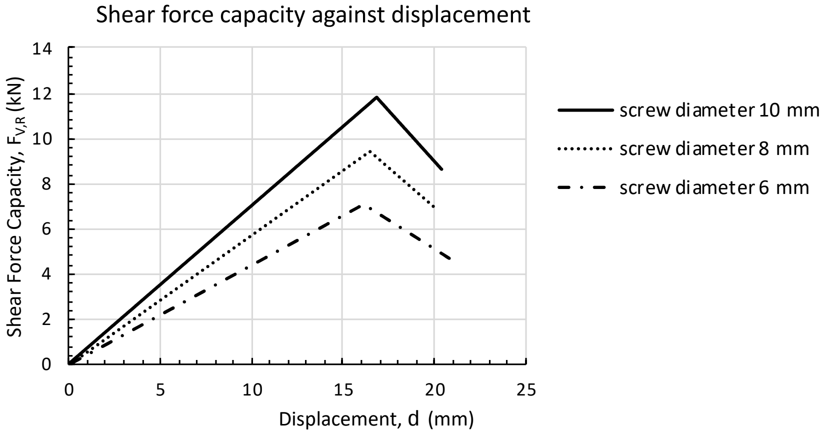


Figure X.- Shear force capacity against displacement with different screw diameter (per screw)

Diameter of screw (mm)	Initiation stress (N/mm)	Fracture energy (J/mm^2)	Shear force capacity (kN)	Stiffness (slope of the graph) (N/mm)
6	3402	51035	7.07	438
8	4536	68040	9.45	574
10	5665	84975	11.80	701

Table IV.- Summary of comparison of the results based on different screw diameter (per screw)

4.4 Effects of depth of screws in timber on shear force capacity. - This section investigates the effect of screw length on the shear force capacity and stiffness of connections using an 8 mm diameter screw. Shear force capacity versus displacement for screw embedded in timber lengths of 60 mm, 80 mm, and 100 mm is illustrated in Figure XI. The data reveal that the 100 mm screw embedded in timber length achieved the highest shear force capacity at 11.8 kN, followed by the 80 mm and 60 mm screws, with capacities of 9.43 kN and 7.01 kN, respectively. Table 4 presents the shear force capacity and stiffness associated with each screw embedded in timber length. This matches the study performed by Ribeiro et al. (2018), which found that increasing the screw depth can enhance the withdrawal strength of the screw due to the larger contact area between the timber and the screw. Similar to this study, increased embedment depth improves the screw's resistance to shear forces by providing a larger surface area in contact with the timber. This deeper engagement reduces the likelihood of localized failures by distributing the load over a broader area. Consequently, a deeper screw results in a stronger connection between concrete and timber, facilitating more efficient shear force transfer and enhancing the composite structure's overall shear capacity. The rigidity of the joint, measured by the stiffness, improves with greater screw length. A longer screw, being more deeply embedded, creates a stiffer bond, reducing relative movement (displacement) between the concrete and timber layers under load. This increased resistance to deformation results in a lower slip and a higher stiffness, indicating a more robust connection. In summary, increased screw length enhances shear force capacity and stiffness, leading to greater rigidity and a stronger connection in the TCC structure. The deeper the screw is embedded in the timber, the more effective the load distribution and connection strength, resulting in improved structural performance.

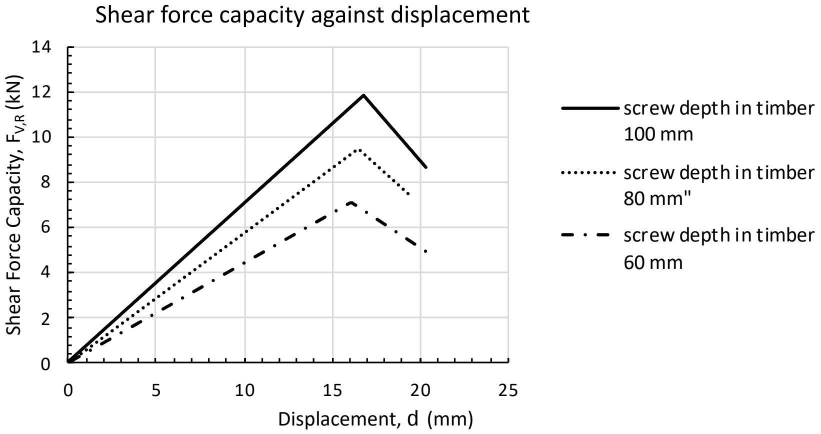


Figure XI.- Shear force capacity against displacement with different screw depth in timber (per screw)

Depth of screw in timber (mm)	Shear force capacity (kN)	Stiffness (Slope of the graph) (N/mm)
60	7.01	437
80	9.43	572
100	11.80	701

Table IV.- Summary of comparison of the results based on different screw depth in timber (per screw)

4.5 Effects of timber density on the shear force capacity. -This section examines the influence of timber density on the shear force capacity and stiffness of connections using an 8 mm diameter and 150 mm length screw. Figure XII presents the relationship between shear force capacity and displacement for timber densities of 476 kg/m³ (typically softwood) and 600 kg/m³ (typically hardwood). The data indicate that the timber with a density of 600 kg/m³ achieved the highest shear force capacity of 14.7 kN, compared to 11.8 kN for the 476 kg/m³ density. This was also found by Ribeiro et al. (2018), who reported that a higher density of timber increased the bond strength between the screw and the timber. Cabrera et al. (2022) also found that the higher density of Beech species increased the embedment strength of the screw when compared to Poplar species, which has a lower density. Higher-density timber, being more rigid and strong, enhances the shear force capacity of the TCC structure as it better withstands the forces imparted by screws or connectors (see Table V for details of strength and stiffness). In contrast, lower-density timber is less rigid and weaker, reducing its capacity to resist shear stresses. Connectors such as screws or dowels perform more effectively in higher-density timber due to the material's increased resistance to pull-out and embedment forces, thereby improving overall shear capacity. Lower-density timber, with its tendency for easier embedment and pull-out, may not support connections as effectively, diminishing shear force capability. Higher-density timber also leads to stronger connections that deform less under load. This reduced deformation results in less relative movement or displacement between the concrete and timber layers, thereby increasing the stiffness. The improved performance of connectors in higher-density timber further enhances load transmission and composite action, resulting in an increased stiffness. In summary, higher timber density correlates with greater shear force capacity and stiffness, leading to increased rigidity and stronger connections in TCC structures.

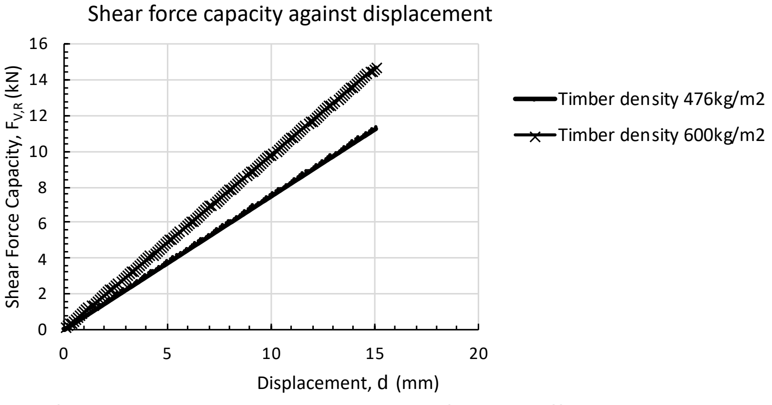


Figure XII.- Shear force capacity against displacement for two different timber density (per screw)

Timber density (kg/m^3)	Shear force capacity (kN)	Stiffness (Slope of the graph) (N/mm)
476	11.80	701
600	14.70	980

Table V.- Summary of the comparison of the results based on different timber density (per screw)

5. Limitations and Future Work. - This research is limited to a two-dimensional analysis, with a focus on the failure mode of the screw connection influenced by the material and geometric properties of the screw, timber, and concrete. The discussion also emphasizes global behavior, such as shear force capacity and stiffness, which are affected by the material properties of the screw, timber, and concrete. Future work should address local characteristics, such as the plastic hinges that may form due to shear forces, influencing the embedment and withdrawal strength of the screw. However, this would require experimental work to observe the actual shape of the screw after failure. By examining the details of the plastic hinge formation on the screw, it would be possible to measure and correlate this with the shear strength of the screw connection.

6. Conclusions.- This study successfully met its objectives of validating double shear test models and analyzing local shear connection behaviour in timber-concrete composite (TCC) structure. The finite element models used for simulating double shear tests demonstrated quite similar results when compared to experimental data. The simulation results for shear force capacity was within 10% of the experimental values reported by Manojlović et al. [11]. The study also found that increasing the screw diameter to 10 mm significantly improved shear force capacity and stiffness, thereby enhancing the structural performance of the connections. Greater embedment depths (100 mm) resulted in higher shear force capacity and improved stiffness, indicating better load distribution and reduced localized failures. A higher timber density (600 kg/m³) increased both shear force capacity and stiffness compared to lower-density timber (476 kg/m³), highlighting the benefit of using denser timber for stronger connections. The most significant finding of this research is the identification of the failure mode of the screw connections. The study revealed that the failure of screw connections depends on the properties of the timber, concrete, and screw. When the concrete strength exceeds the timber strength, failure occurs due to timber crushing. In the interaction between timber and screw, when the interaction stresses exceed the yield stress, screw deformation and timber crushing are expected. These results underscore the critical role of screw dimensions and timber density in optimizing the performance of shear connections in TCC structures. The insights gained offer valuable guidance for both practical engineering applications and future research in the field. Lastly, Table VI shows the summary of the findings for this research

Parameter	**Key Finding**		
	Details	Shear force capacity	Stiffness
Screw diameter	6 mm	low	low
	8 mm	medium	medium
	10 mm	high	high
Screw length	60 mm	low	low
	80 mm	medium	medium
	100 mm	high	high
Timber density	476 kg/m^3	low	low
	600 kg/m^3	high	high

Table VI.- Summary of findings according to different variable in screw and timber properties

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Author contribution:
1. Conception and design of the study
2. Data acquisition
3. Data analysis
4. Discussion of the results
5. Writing of the manuscript
6. Approval of the last version of the manuscript

LJE has contributed to: 1, 2, 3, 4, 5 and 6.
MAMS has contributed to: 1, 2, 3, 4, 5 and 6.
SNFG has contributed to: 1, 2, 3, 4, 5 and 6.
NAFM has contributed to: 1, 2, 3, 4, 5 and 6.
MIZ has contributed to: 1, 2, 3, 4, 5 and 6.
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