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Research Article

Hybrid Timber Concrete Composite Slab for Analysis of Lag Screw Embedment Connections

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Push-out-shear tests were used in this study to analyze lag screw connections in timber-concrete composite (TCC) slabs based on the embedment depth. The goal of this research is to look into the relationship between shear capacity and embedment depth in TCC, as well as to investigate the embedment strength of the wood. Experiments were carried out at different embedment depths (5.08 cm, 7.0 cm, and 8.9 cm). The prepared samples were examined in order to determine the failure modes and provide an accurate assessment of the influence of embedment depth on TCC slabs. The investigation on the embedment strength of the wood was performed then for the analysis of the crushing of wood fibers, lag screw yielding strength, and maximum load applied at embedment depths of 6.6 cm and 7.0 cm. The results indicate that between 5.08 cm and 7.0 cm, there was an apparent improvement in the relationship between embedment depth (ED) and shear capacity of TCC slabs in terms of the shear strength, while a significant difference was observed between 7.0 cm and 8.9 cm. The study suggests that the ED of the TCC slab should be maintained at around 7.33 times the diameter of the lag screw.

1. Introduction

1.1. Research Background. The development of the TCC system started in Europe after World Wars I and II. Due to the enormous loss in construction materials resulting from these two wars, a shortage in steel for reinforcement in concrete has been noticed. In 1922, Muller studied the system of nails and steel braces between timber and concrete. In 1939, Schaub analyzed steel Z-profile and I-profile connections [1, 2]. TCC was considered a refurbishment technique at that time, where it was used to restore old buildings rather than demolish them. The first report that was published which combines both theoretical and experimental refurbishment of historical buildings was reported by Godycki et al. in 1984 [3]. By using this method, several timber floors were refurbished in Lodz, Poland, at that time. Another study by Postulka between 1983 and 1997 mentioned that more than 10.000 m^2 of timber floors in the Czechoslovak Socialist Republic (CSSR) had been renovated with a timber-concrete structural system since 1960 [4]. In the last decade, several case studies have been investigating the practice of TCC in multistory buildings. Many TCC buildings have been constructed in Australia and Europe, followed by named Murray Grove building in London, the Forte building in Australia, and the Treet building in Norway [5–7]. TCC can offer numerous advantages. Timber, in terms of production, requires small amounts of nonrenewable energy, different steel, and concrete, as it is a natural, sustainable material [8, 9]. Furthermore, timber is a carbon store that can decrease the environmental impact of construction through its carbon sequestration mechanism, which is the process of restoration or removal of CO_2 from the atmosphere using a physical or biological process [10, 11]. Timber reduces the overall weight of a building while providing sufficient resistance, adding more aesthetic appeal, and enhancing environmental impact. Concrete, on the other side, is designed as a floor slab that reduces the floor vibrations and increases the amount of stiffness. Together, a combination of timber and concrete properties has developed a structural system known as TCC that can provide improved sound insulation, increased strength under gravity load, smaller self-weight, higher stiffness, which results in smaller deflection and vibration aspects, and lower cost compared with steel-concrete systems, especially since the cost of steel is increasing gradually [12].

1.2. Literature Review. It is believed that the structural performance of the TCC could be attributed to the relationship between the timber beams or slabs and other structural elements such as concrete, timber, and steel which is reflected in the stiffness and loading capacity [13, 14]. However, the classification of the connections could be based on how they were installed into the timber; they can be classified into discrete/continuous, prestressed/non-prestressed, glued/nonglued, and vertical/inclined [15]. Scholars at the Talbot Lab, University of Illinois, performed the Oregon test between 1938 and 1942 as the first TCC connection test in which a full-scale bending test was carried out on 32 composite systems by using various shear connectors. Richart and Williams [16] reported tests on vertical triangular steel plates, lag screws or spikes, triangular plates and spikes, and sloped notches with/without spikes. Most of the shear connectors showed adequate strength and stiffness, but beams with triangular plates and spikes showed more satisfactory results and were the best outcome group as they developed small slip and deflection and carried higher load-carrying capacity than other connections [16]. In 1995, Ceccotti classified the most common connections that have been used in joining timber to concrete into four different groups (Figure 1), where group *A* has the least stiffness while group *D* is the stiffest connector [17]. Group *A* connectors tend to have the least stiffness and rigidity as they are easy to install and inexpensive. Group *B* showed higher rigidity, ultimate strength, and ductility compared with group *A* [18, 19]. Group *C*, where notches were cut into the timber and reinforced with either lag screws or posttensioned bolts, showed better slip resistance and higher strength compared with group *B* [18]. Finally, group *D* is considered to be the stiffest, with higher rigidity compared with all other groups. The failure occurs in TCC mainly due to the connection between the timber-concrete interface layers. According to the Johansen yield theory [20], the possible failure modes for lag screws which is the type of connection that will be investigated in this study are double plastic hinges, single plastic hinges, and failure due to the rotation of the lag screw. A plastic hinge (single or double) occurs when the load applied causes bending stress, whereas the connection member would be in an elastic behavior. Once the load has increased, leading to larger bending stress causing the connections to yield, a plastic hinge occurs when the connections experience large deformations, but no rupture takes place. A double plastic hinge occurs when the screw rotates in both concrete and timber sections due to the embedment stress of the connection that has been distributed all over the length of the screw. A single plastic hinge forms at the interface where the screws would rotate as a stiff member in the timber section. This failure could occur only if the embedment length of the connection installed is enough to lead the connection to act in such a matter. Finally, failure due to rotation occurs when the lag screw installed in TCC rotates in the whole specimen. Several researchers have been investigating the feasibility of different connections among TCCs. Following these, a considerable body of work has been carried out to build high-performance shear connectors and quantify the load slip, load-bearing capacity, and stiffness of the connections, mostly via push-out-shear tests [21–26]. The connection in TCC was found to affect the load-bearing behavior of the composite beam, while the structural behavior of the slab was influenced by the stiffness, ductility, and shear resistance of the connection [27, 28]. Numerous studies on connection systems have focused on TCC performance [29].

1.3. Motivation of Research. The motivation of the study is to investigate timber-concrete composite structural design, which consists of a concrete slab, where concrete is designed to be in the compression zone, and the timber is attached below in the tension zone. These two materials are combined using different shear connectors, such as coach screw shear connectors (zinc-plated steel coach screw), stud connectors, dowels, and notches cut in the timber filled with concrete [20–30]. The shear connection between timber and concrete is essential as these connectors typically govern the strength and the structural behavior of the TCC structures. Therefore, it is crucial to use connectors that are strong and stiff enough to resist the shear force in the composite structure, as TCC typically fails if the connection fails [31].

1.4. Objective of Research. The aim of this work is to examine the failure modes with various EDs to improve knowledge on the influence of ED on TCC slabs, as well as to determine the relationship between connection failure loads and embedment strength. This was achieved by performing push-out-shear tests on the lag screw connections in TCC slabs at ED values of 5.08 cm, 7.0 cm, and 8.9 cm. The evaluation of the embedment strength, lag screw shear failure modes, and lag screw yielding was carried out by evaluating the embedment strength at ED values of 6.6 cm and 7.0 cm.

2. Materials and Methods

2.1. Material Properties

2.1.1. Timber. A sawn lumber section, specifically Douglas fir-larch (DF-L), No. 2 lumber, is analyzed for the timber

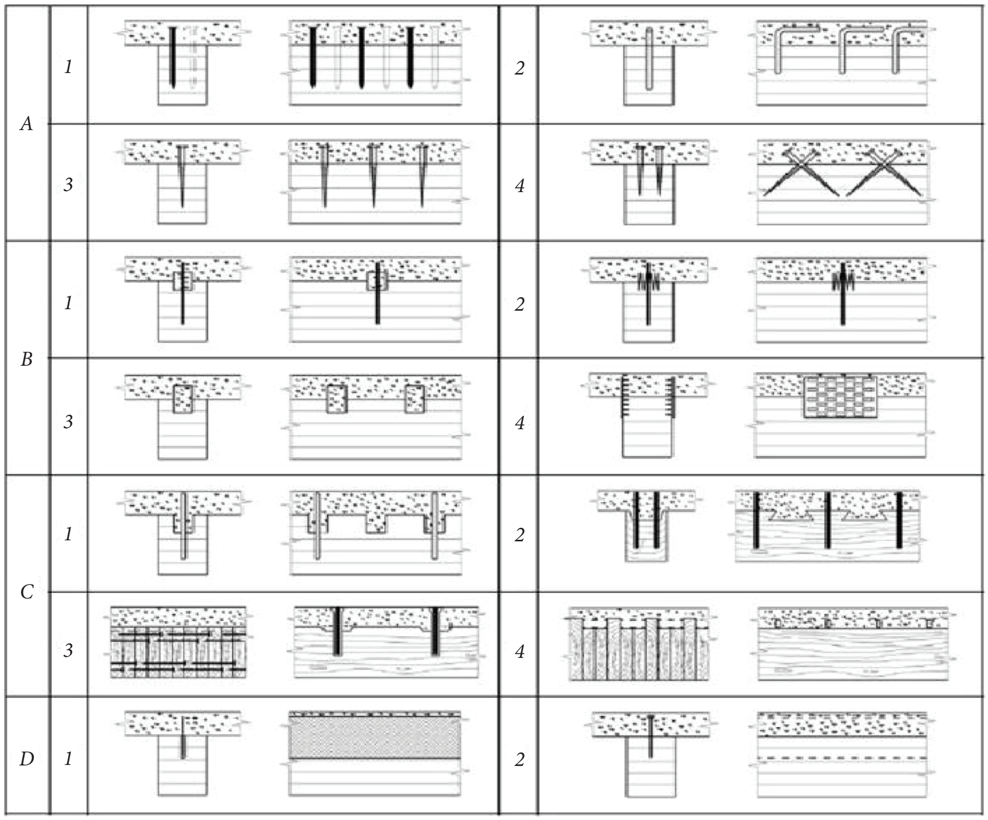


Figure 1: Connection classification and types (source: [16]).

section. Douglas Fir-Larch, No. 2 is known for its properties in strength, durability, and workability. Table 1 shows different characteristics of DF-L, No. 2.

Table 1: Properties of Douglas fir-larch (DF-L), No. 2 lumber.

Property	Value
Density	539.8 kg/m^3
Bending (F_b)	9307.7 KPa
Compression parallel to grain (F_c)	6377.7 KPa
Compression perpendicular to grain (F_c)	4309.2 KPa
Tension parallel to grain (F_t)	4654.0 KPa

2.1.2. Concrete. Concrete is prepared by using a QUIKRETE concrete mix. This is a mixture of Portland cement, sand, and gravel or stone. The mixture is poured and cured for 28 days in the structural lab to reach its specific compressive strength based on ASTM C39 [32], 27,579 KPa, with a slump range between 5.08 and 7.62 cm.

2.1.3. Connections. The connection used in this test is the steel lag screw shear connection (otherwise known as lag bolts or lag screws). The connections in the test have a fixed nominal diameter of 0.953 cm and a fixed length of 12.7 cm. This type of connection would be between timber and concrete to affix them together and then investigate the behavior and the modes of failure.

2.2. Design Parameters. The study parameters are shown in Table 2. These specimens are chosen due to the availability of the timber section in these dimensions. The first two embedment depths (5.08 cm and 7.0 cm) are illustrated in Figures 2(a) and 2(b), whereas Figure 2(c) illustrates an embedment depth of 8.9 cm, where due to the length of the timber section, lag screws have to be staggered.

Table 2: Dimensions of materials.

Timber section (width × thickness × height)	15.2 cm × 15.2 cm × 30.5 cm
Concrete section (width × thickness × height)	15.2 cm × 8.9 cm × 35.6 cm

2.3. Experimental Setup

2.3.1. Push-Out-Shear Test. Nine specimens are prepared by using three different embedment depths, which are 5.08 cm, 7.0 cm, and 8.9 cm. Each embedment depth has been analyzed by using three different specimens per ASTM minimum requirements. The push-out-shear test is conducted by using Tinius Olsen machine, and Tinius Olsen universal testing machine software (version 6.03.24) has been used to collect and extract the data (shear capacity and slip). The load applied has been increased until the maximum load where failure occurs in the connection, and the relative slip was accounted for at that maximum load. Push-out-shear

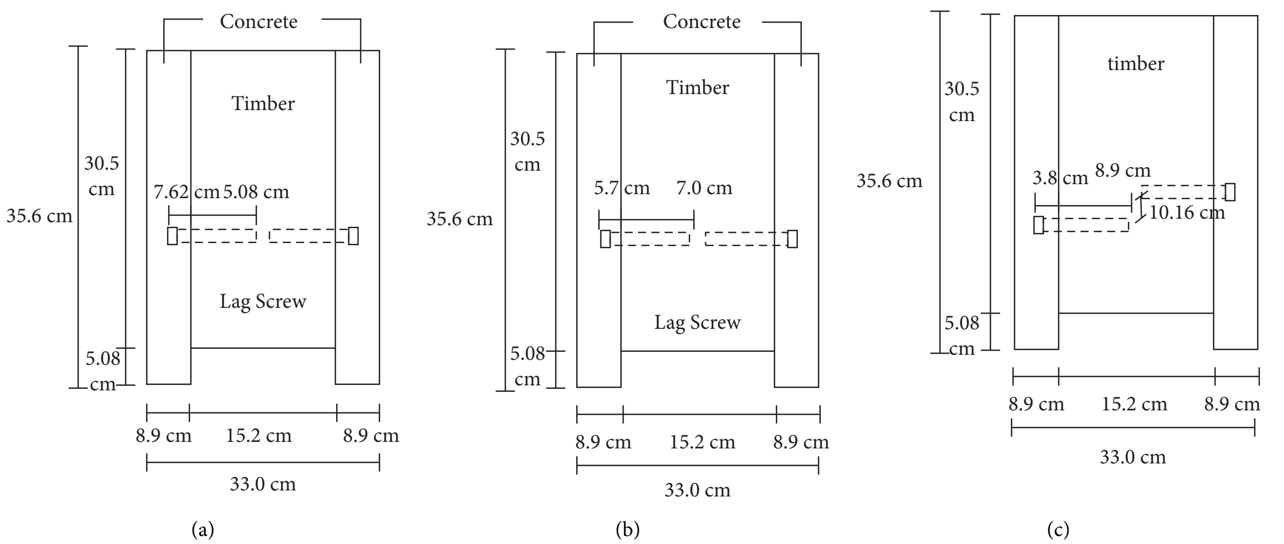


Figure 2: (a) Section view for 5.08 cm. (b) Section view for 7.0 cm. (c) Section view for 8.9 cm.

tests have been conducted in accordance with BS EN 26891 [33], as shown in Figure 3. The load has been increased linearly to $0.4F_{est}$ in the first 2 minutes and then held for 30 seconds at 0.4 F_{est}. Then, it was decreased to $0.1F_{est}$ and maintained for another 30 seconds. Later on, the applied load has been increased gradually up to the ultimate load, or slippage occurs at 15 mm, which is the maximum relative slip in accordance with EN 26891 [33]. Therefore, specimens with a slippage exceeding 15 mm were considered to have 15 mm as the maximum per the code. Theoretical equations that have been adopted to estimate the test specimen load capacities are shown in the following sections.

2.3.2. Embedment Strength Test. Embedment strength has been evaluated by using the Forney compression testing machine. Eight specimens have been prepared to understand the limitations per lag screw in two different embedment depths, which are 6.6 cm and 7.0 cm. Four trials have been conducted per embedment depth to analyze the yielding strength of the lag screws, the crushing of wood fibers, and the maximum loads that each specimen could resist. Figure 4 illustrates the dimensions used for both 6.6 and 7.0 cm embedment depths.

2.4. Theoretical Calculations and Predictions

2.4.1. Push-Out-Shear Test. Theoretical loads were estimated by using ACI 318-14 [34] and AISC 13th edition [35]. These codes were used to analyze the shear friction of the lag screw by using

$$A = \frac{\pi d^2}{4}, \tag{1}$$

$$S = \frac{\pi d^3}{32} \text{ (Ffor Elastic)}, \tag{2}$$

$$Z = \frac{d^3}{6} \text{ (Ffor plastic)}, \tag{3}$$

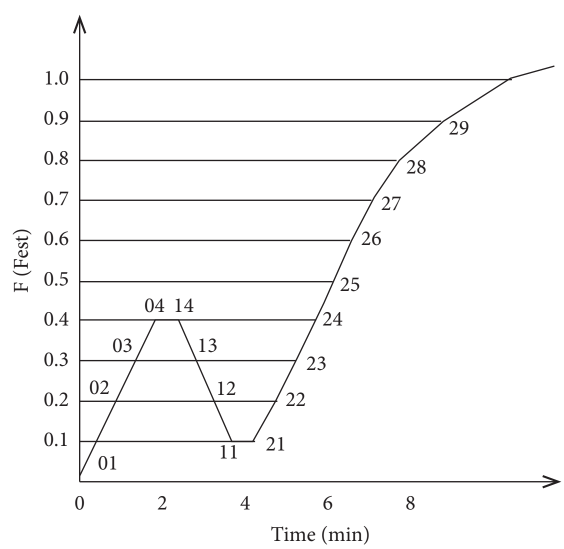


Figure 3: Testing criteria according to EN 26891 (source: [20]).

$$I = \frac{\pi d^4}{64}, \tag{4}$$

$$M_{\max} = \frac{Pl}{2} = 0.6F_y S \text{ (Ffor Elastic)}, \tag{5}$$

$$M_{\max} = \frac{Pl}{2} = 0.9F_y Z \text{ (Ffor plastic)}, \tag{6}$$

$$\Delta_{\max} = \frac{Pl^3}{12EI}, \tag{7}$$

$$\text{SF} = 0.85 * A_{LS} * F_y * \text{COF}, \tag{8}$$

where A_{LS} is the area of the lag screw, F_y is the yield strength of the lag screw, and COF is the coefficient of friction which

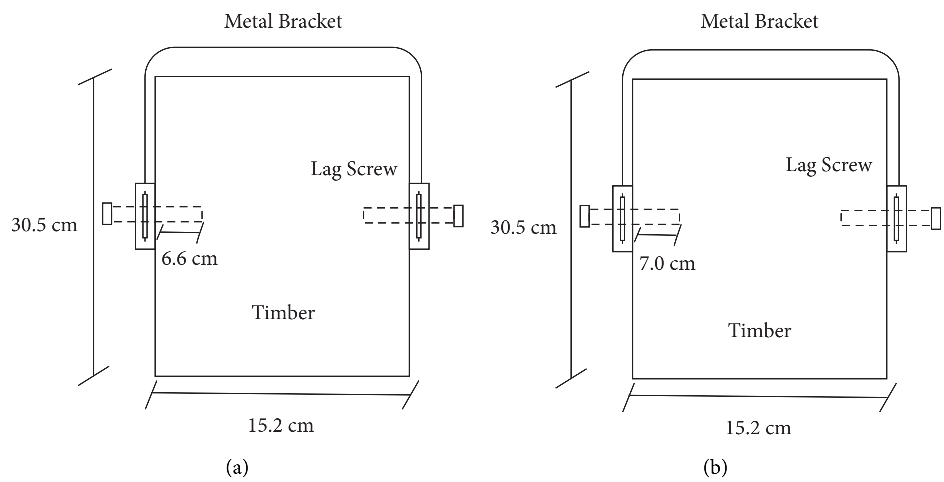


Figure 4: (a) Section view for 6.6 cm . (b) Section view for 7.0 cm.

was estimated as 0.62 [36]. Bearing strength of concrete on lag screw was analyzed by using

$$F_B = \varnothing\left(0.85\, t f_c' n A_{1,\min} q\right), \tag{9}$$

where $\varnothing$ is the reduction factor (0.65), f_c' is the compressive strength of concrete, and $A_{1,\min}$ can be found by using

$$A_{1,\min} = \left(\frac{1}{4}\right)\left(\frac{9}{16}\right) + \left(L - \frac{1}{4}\right)(d), \tag{10}$$

where d is the diameter of the lag screw, and L is the length of the lag screw in the concrete section. The nominal strength of one shear connector was found by using

$$Q_n = 0.5 A_{sc}\sqrt{f_c' E_c} < A_{sc} F_u, \tag{11}$$

where E_c is the modulus of elasticity of concrete, A_{sc} is the area of steel lag screw, and F_u is the tensile strength of lag screw. For the single plastic hinge and based on the single curvature bending (beam diagram 22) in AISC 9$^{\text{th}}$ edition, the following approach was analyzed by using

$$M_{\max} = PL = 0.9 F_y Z, \tag{12}$$

$$\text{Shear Friction of lag screw} = 0.85 * A * F_y * \text{Coefficient of friction}, \tag{13}$$

$$\text{Total Force to resist} = \left(P + \left[SF \text{ or } F_B\right]\right)(2), \tag{14}$$

where P is the load applied for plastic bending in addition to the load that was found based on the controlling limit per each embedment depth. Estimated values (F_{est}) are presented in Table 3 for all of the different penetration depths analyzed.

2.4.2. Embedment Strength Test. In order to estimate the embedment strength in the timber section, an equation adopted from IBC-2012 [37] was used to estimate the amount of load (P) that could be resisted per each lag screw by using

$$P = \frac{\left(A\, x\, S_1\, x\, b\right)}{2.34}, \tag{15}$$

$$\text{Total Load} = 2P, \tag{16}$$

where A is the embedment depth into timber, S_1 is the compression parallel to the grain, and b is the diameter of the lag screw. This equation is initially used to determine the nonconstrained embedment depth required to resist the lateral loads for drilled foundations. The estimated maximum loads that each lag screw could resist are provided in Table 4.

3. Results and Discussion

3.1. Push-Out-Shear Test. The results from the push-out-shear test of the nine specimens were analyzed to understand the behavior of each TCC specimen. All the data collected for each embedment depth are displayed in Tables 5–7.

In 5.08 cm embedment, two specimens failed due to double plastic hinge (Figure 5(a)), while one of the trials failed due to the rotation of the lag screw (Figure 5(b)) as the specimen experienced yielding between 19.2 kN and 24.2 kN due to the slippage that occurred between timber and concrete sections which exceeded 15.0 mm, but it was set to 15 mm as per the maximum relative slip based on EN 26891. Moreover, some connections failed as single plastic hinges due to the compression of the internal timber fibers (Figure 5(c)). Specimen number 3 at 5.08 cm embedment depth had the lowest experimental load compared with the other trails, as the concrete section got cracked when the specimen was being lifted to the push-out-shear testing machine. Concrete crack repair epoxy was used to close the cracks and kept curing for another 24 hours as it is required. All the specimens experienced a slippage between timber and concrete within the maximum limit set by EN 26891, while 2 specimens experienced higher slippage than 15 mm.

The test results showed that the shorter the embedment depth is, the more the specimen is prone to double plastic hinge failure, as it only occurred in TCC specimens of

Table 3: Estimated failure load in different embedment depths.

Embedment depth in timber (cm)	Failure mode and estimated failure load		
	Single plastic hinge mode (kN)	Rotation mode (kN)	Double plastic hinge mode (kN)
5.08	19.5 (equation (14))	17.8 (equation (8))	20.3 (equations (6) and (8))
7.0	18.6 (equation (14))	17.8 (equation (8))	19.8 (equations (6) and (9))
8.9	13.7 (equation (14))	17.8 (equation (8))	15.4 (equations (6) and (9))

Table 4: Theoretical loads of lag screw strength.

Embedment depth (cm)	The load applied per lag screw (kN) (equation (15))	The total load applied on timber (kN) (equation (16))
6.6	1.72	3.43
7.0	1.81	3.63

Table 5: Results for 5.08 cm embedment specimens.

Specimen	Experimental load (kN)	Failure mode	Maximum slip (mm)
1	31.2	Double plastic hinge	11.7
2	24.2	Rotation	15.0
3	20.4	Double plastic hinge	12.2

Table 6: Results for 7.0 cm embedment specimens.

Specimen	Experimental load (kN)	Failure mode	Maximum slip (mm)
1	47.3	Single plastic hinge	14.0
2	51.8	Single plastic hinge	11.9
3	49.0	Single plastic hinge + rotation	2.29

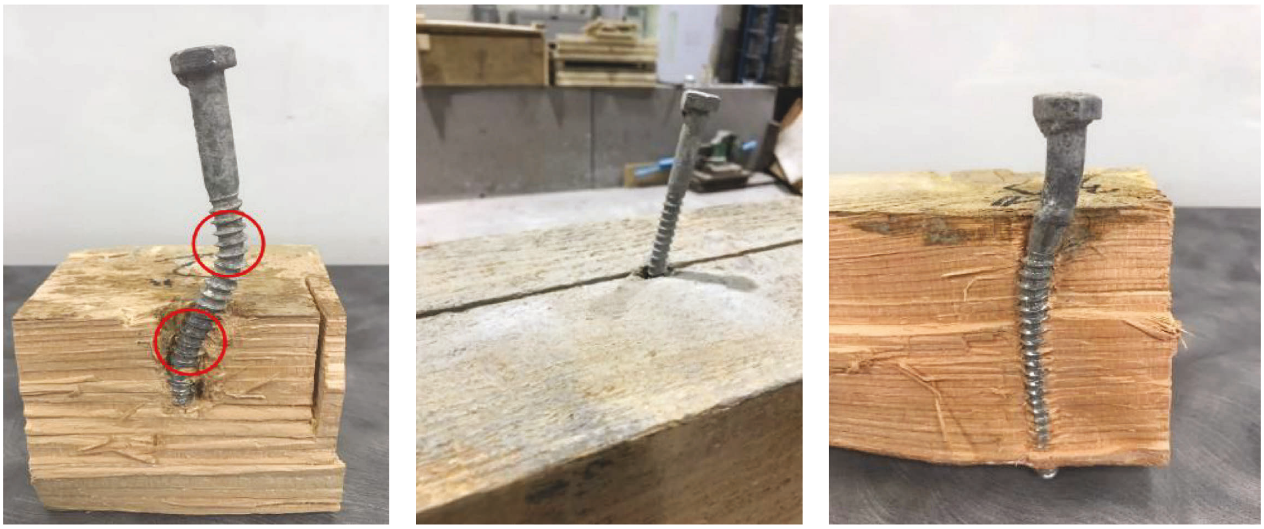
Table 7: Results for 8.9 cm embedment specimens.

Specimen	Experimental load (kN)	Failure mode	Maximum slip (mm)
1	50.0	Single plastic hinge	12.4
2	52.8		15.0
3	53.5		13.2

5.08 cm embedment. The results also showed that changing embedment depth from 5.08 cm to 7.0 cm could increase the shear capacity from 16.1 kN to 31.4 kN. The analysis of all variations of the embedment depths concluded that there is a clear increase of shear capacity between 5.08 cm and 7.0 cm, but no significant changes between 7.0 cm and 8.9 cm. A statistical test, one-way analysis of variance (ANOVA), was used to find the effect of the shear strength between the three different embedment depths. Embedment depth was treated as an independent variable and shear capacity as the dependent variable. ANOVA showed that there is a statistically significant difference in response to the shear capacity (F (2.6) = 50.7, $P < 0.05$). Post hoc analysis was carried out using Tukey's test ($HSD_{\propto} = 0.05 = 9007.6$) and then had been verified. Based on the comparisons between all the trials, it was found that there is a statistically significant difference between 5.08 cm and 7.0 cm and between 5.08 cm and 8.9 cm, while there was not any statistically significant difference in the shear strength between 7.0 cm and 8.9 cm. Effect size analysis ($\eta^2 = 0.94$) showed that there is a large effect between the lowest embedment depth and the other two embedment depths. 5.08 cm is not recommended due to the excessive bending of the lag screws. Another factor that renders 5.08 cm embedment feasible is the excessive compression of the internal wood fibers, which would affect the overall TCC behavior. The factor of safety (based on the ratio of experimental and analytical results) is calculated to be 1.3, which is low when compared with the factor of safety of 2.16 for shear in the NDS-2015 [38], making the system more vulnerable to failure. 8.9 cm embedment depth is not recommended, on the other hand, as there is a large discrepancy between the theoretical and experimental values, with a factor of 3.81, making it more conservative to account for. Therefore, 7.0 cm is the most suitable embedment depth among those tested as it resulted in a factor of safety of 2.65, which is reasonable compared with 2.50 based on TMS 402/602-16 [39]. The theoretical load accounted at 7.0 cm (18.6 kN) had a higher shear capacity load compared with 8.9 cm embedment (13.7 kN) even when the connections failed due to the same mode of failure. Moreover, the mean of the slip resistance accounted for the different trails at 7.0 cm embedment depth showed a smaller slip compared with the other two embedments, which nominates it to be found as the best outcome group where connections are stiffer at 7.0 cm.

3.2. Embedment Strength Test. During the testing for the embedment strength, the loads were increased manually until the lag screw would yield in each specimen or a crack noise of the wood fibers could be noticed. The loads were then incremented manually until the timber specimen could not resist any higher loads. Tables 8 and 9 illustrate data collected at both embedment depths of 6.6 cm and 7.0 cm in terms of the crushing of the wood timber, yielding of lag screws, and maximum load applied on each specimen.

In all of these trials, the wood fibers started to crush and crack before the lag screw started to yield, concluding that the lag screw would act as an efficient bond between timber and concrete, which would secure the composite action in TCC. Another remark was found that this type of connection is stiff enough to resist the load as timber fibers started to crack before lag screws get yielded. After the wood fibers cracked, the load was increased manually until the lag screw would yield (Figure 6). Once the lag screw yielded and had a noticed bent, the load was increased until the specimen



(a) (b) (c)

Figure 5: (a) Double plastic hinge. (b) Rotation of lag screw. (c) Single plastic hinge.

Table 8: Results for 6.6 cm embedment specimens.

Trial number	Crushing of wood timber (kN)	Yielding of the lag screw (kN)	Maximum load (kN)
#1	7.56	10.7	10.9
#2	8.45	9.96	10.6
#3	8.63	9.35	9.70
#4	9.35	9.61	9.79
Mean	8.49	9.90	10.2

Table 9: Results for 7.0 cm embedment specimens.

Trial number	Crushing of wood timber (kN)	Yielding of the lag screw (kN)	Maximum load (kN)
#1	8.45	10.5	10.6
#2	7.12	10.6	11.3
#3	8.45	10.9	11.4
#4	9.35	10.2	10.5
Mean	8.34	10.6	10.9

could not resist any further loads. In most of these trials, the lag screw almost behaved in elastic deformation, but it did not return to its original position (zero deflection), which means that with lag screws, the elastic limit cannot take place within this type of connection, as proved by Newlin and Martin Gahagan in 1938 too [40].

After the test, the specimens were investigated regarding the failure of the lag screws. The specimens were cut to extract a clear section of one specimen per each embedment. Figure 7 shows that the lag screws deformed and that the lag screw had a single plastic hinge near the surface of the timber specimen, but it did not fail in the timber section. The results showed that the experimental results were twice the theoretical wood fiber crushing strength calculated. Using the equation adopted from IBC-2012 [37] for the ultimate load for the embedment strength, a factor of 1.5 is calculated, which is lower than the 2.34 as provided. However, after a more in-depth study, a reduction in the coefficient from 2.34 to 1.5 may be considered. The two embedment depths that have been analyzed for this testing showed no significant difference in the embedment strength or terms of the failure modes (crushing of wood fibers and yielding of lag screws). However, it was noticed that the lag screws at 7.0 cm had lower displacement values, and lower wood fiber crushing occurred around the lag screws.

Figure 6: Lag screw yielding at 6.6 cm.

The TCC behavior might be limited by three constraint limitations based on the findings of this study which are the bearing strength of concrete on the lag screw, double bending of lag screws, and embedment strength. As the connection progresses through these stages, each lag screw with an ED value of 7.0 cm can safely support stresses of 12.7 kN, as illustrated in Table 10.

Figure 7: Lag screw section at 6.6 cm embedment.

Table 10: Total load/lag screw at 7.0 cm.

Load criteria	Loads (kN)
Plastic bending load (P_p)	1.13
Bearing strength of concrete on lag screw (F_B)	8.75
Embedment strength (P)	2.82
Total loads (design of lag screw)	12.7

4. Conclusions

The ED shear capacity relationship of TCC slabs was also investigated, and a considerable improvement in shear strength was found between ED values of 5.08 cm and 7.0 cm, but not at ED values of 7.0 cm and 8.9 cm. Hence, an ED value of 7.0 cm is expected to be the closest to an ideal ED among the analyzed values. The findings also suggest that the lag screws must maintain the least penetration depth of 7.33 d (d = diameter of the lag screw) into the timber specimen; this is because the multiplication of the lag screw diameter by this factor would offer the required ED to withstand the applied loads with lower lag screw displacement and deflection. Furthermore, the lag screws at 7.0 cm showed lower displacement values, as well as less wood fiber crushing surrounding the lag screws, which is deemed noteworthy for the majority of the samples in this investigation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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