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STRUCTURAL PERFORMANCE, AND FAILURE MECHANISM, OF HARDWOOD CROSS LAMINATED TIMBER CONCRETE COMPOSITE UNDER SHEAR LOAD

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ABSTRACT: The performance of Timber Concrete Composite(s) (TCC) is primarily governed by the type of connection used in connecting the constituent members together. This paper investigates the performance of various commonly used connections in a TCC. The main goal of this research is to identify which type of connection provides the optimal structural performance while also identifying the effects parameters such as inclination angle and penetration/notch depth have on the performance of connections. Shear tests on 40 hardwood CLT Concrete Composite specimens comprising of 5 connection configurations, utilising notched and screw connections were undertaken in accordance to BS EN 26891. The results showed that notched connections provided the most satisfactory structural performance in relation to load carrying capacity and stiffness, with the depth of the notch having a significant impact on the behaviour of the composite under load. In terms of timber screw connections, screws inclined at 45° yielded the best structural performance in relation to load carrying capacity and stiffness.

KEYWORDS: Hardwood, Cross laminated timber, Push-out test, Shear connectors, Slip modulus, Failure modes

1 INTRODUCTION

To date the study of Engineered Wood Products (EWP) such as CLT and Glulam has been widely undertaken. Such materials offer a means of building larger timber structures, due in part to their improved structural properties compared to sawn timber, yet much like traditional timber construction there is a boundary to their structural capabilities. As a result of this, an old building technology has seen a recent increase in academic and industrial research. Timber Concrete Composites (TCCs) are a composite material originally used to renovate old timber structures due to a global lack of steel [1]. Yet TCCs are currently being utilised as a material which can overcome the structural limitations of timber and indeed EWP construction. The benefits of TCCs are well documented, with improved structural, thermal and seismic performance compared to timber only construction [2,3], while also being faster to construct, and have a significantly lower global warming potential compared to conventional concrete and steel construction [4,5]. In recent years, there has been an increase in interest on the use of a TCC which uses an EWP as the timber member. The results from recent studies show that such composites can overcome the limitations associated with traditional mass timber construction [6]. Previous TCC research has shown that the most important element in such a system is the connection used, as using an ineffective connection can result in a large reduction in structural performance [7]. The limited research on EWP TCC has mainly been focused on the effectiveness of connections used in the composite [3,8]. These studies reported that the orientation of dowel, notched and glued connections can greatly influence the overall performance of the composite. Despite the benefits of TCCs, limitations to their widespread adoption exist and can be attributed to a lack of design and practical knowledge on the behaviour of connections [2,6]. Furthermore, guidance on the slip modulus for inclined screws and the behaviour of notched connections with various notch depths and screw inclinations has not yet been fully investigated [3,8,10].

Additionally, there has been no research investigating the suitability and performance of a hardwood CLT Concrete Composite, leaving a notable gap in the current published literature on Timber Concrete Composites. Using hardwood CLT can further increase the scope of timber construction while making TCCs even more competitive compared to traditional materials as a result of its improved structural properties. Therefore, the main objective of this work is to examine the structural performance of various types of connections used in a hardwood CLT Concrete Composite.

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2. EXPERIMENTAL PROGRAMME

2.1 TESTING SUMMARY

A total of 40 specimens were tested, which comprised of two main connection categories, metal screw connections (S) and notched connections used in conjunction with screws (NS). Five different configurations of the (NS) and (S) connections commonly used in TCCs were adopted in this research. This included metal screw connections with various penetration depths (PD) and orientations (α) and notched connections cut to various PD coupled with screws at varying orientations. The PD for each of the (S) series specimens was based on the diameter of the screw, with d, being equal to the diameter (in this case d=5 mm). For the NS series the PD was measured as the depth from the top surface of the CLT as shown in Figure 1. Each (S) series specimen had a row of three (or six, if inclined screws were used) screws on each side of the CLT. Each (NS) series specimen had 2 notches and 2 screw (or 2 notches and 4 screws for the NS45 specimens) on either side of the CLT

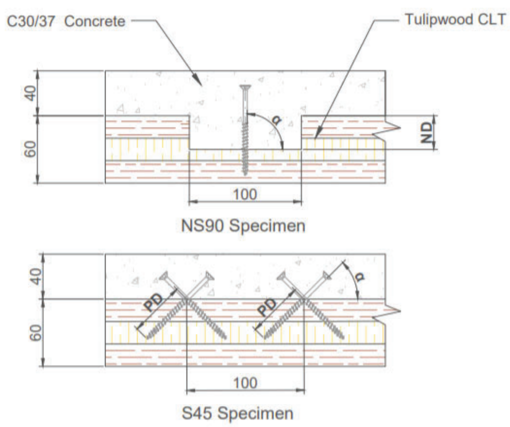

Figure 1*: Type (NS) and (S) connection schematic*

Table 1 provides further details on the number of specimens and connection configurations. Each specimen consisted of a 60×140 mm CLT member with a height of 430 mm, connected to two 40×140 mm concrete members of the same height.

Table 1: *Detail of test specimens*

Test code	Connection	Connection orientation (°)	Penetration depth/ Notch depth (mm)	Number of specimens
S90	screw	90		
			10d	2
			11d	2
S45	screw	45	9d	3
			10d	3
			11d	3
S30	screw	30	9d	3
			10d	3
			11d	3
NS90	Notched & screw	90	25	3
			30	3
			35	3
NS45	Notched & screw	45	25	3
			30	3
			35	3

2.2 MATERIAL PROPERTIES

The Tulipwood (*Liriodendron tulipifera*) CLT used in this research was supplied by the American Hardwood Export Council (AHEC). This CLT was chosen as it offers increased structural performance compared to conventional European softwood CLT. Additionally, as mentioned previously, no published work has been undertaken investigating the effects of using a hardwood EWP in a TCC. The high strength to weight ratio of Tulipwood CLT makes it a very suitable choice for TCC fabrication, where weight plays a vital role in the effectiveness of the composite. Additionally, the increased density of this hardwood is expected to improve the load carrying capacity of the connections and thus the performance of the overall composite. The properties of the CLT used in this research has been previously determined in work undertaken by [11] and is shown in Table 2.

Two possible manufacturing options for concrete used in TCC construction exist. These are offsite concrete casting and in-situ casting. This research is focused on TCCs that are cast in-situ and as a result, in-situ concrete casting was used. The strength of concrete used in this research has been based on what is currently used as an industry standard in TCC design, which comprises of C30/37 concrete. The quantities of the constituents used in the concrete was calculated using a Building Research Establishment (BRE) concrete mix design. The properties of the concrete used can be seen in table 2.

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Table 2: *Mechanical properties of CLT, concrete and screws*

Material	Properties	Values	Units
CLT	Density (ρ)	485.79	kN/m^3
	Modulus of elasticity (E)	11010	N/mm^2
	Shear modulus (G)	196.57	N/mm^2
Concrete	Compressive strength ($f_{c,k}$)	36	N/mm^2
	Mean target strength ($f_{c,k}$)	43	N/mm^2
Screw	Tensile strength ($f_{tens,k}$)	7900	N
	Yield moment ($M_{y,k}$)	5909	N.mm
	Characteristic yield strength ($f_{y,k}$)	1000	N/mm^2
	Length (L)	80	mm
	Threaded length (B)	45	mm
	Diameter (D)	5	mm

5 x 80 mm *Spax* Windrox screws were used in this research. They have been chosen for their quality, availability and cost which according to [12] are important criteria to consider when choosing a suitable connection for a TCC. The screws are also corrosion resistant, which is a further benefit for use in this application [13]. The screws are partially threaded which offers high withdrawal strength, while the lack of threading near the head of the screw reduces the potential for concrete cracking to occur. The properties (provided by [14]) of the screws can be found in Table 2.

An important consideration in the design of a TCC is the spacing of the connectors. The spacing of the screw connections adopted in this work was calculated in accordance to EN 1995-1-1. The spacing for the notched connections is based upon the recommendations provided by [3] in addition to the size restraints of the specimens.

2.3 TESTING PROCEDURE

Each specimen was simply supported at their base. The supports elevated the specimens 50 mm above the ground providing sufficient space for the specimens to deform vertically. Horizontal movement was restrained by the self-weight of the specimens. The vertical slip between the timber and concrete members was measured and recorded using two Linear Variable Displacement Transducers (LVDT) each with a 50 mm maximum displacement. The LVDTs were fitted on the front and back of the specimens as shown in Figure 2. The specimens were tested in accordance to BS EN 26891. A F_{est} (maximum load) was established for each connection type, by testing a sacrificial specimen for each connection configuration. The test specimens were then loaded following the loading profile set out in BS EN 26891 as show in Figure 3. The specimens were tested in a Schenck Trebel Instron 5500 testing machine fitted with a 100 kN load cell.

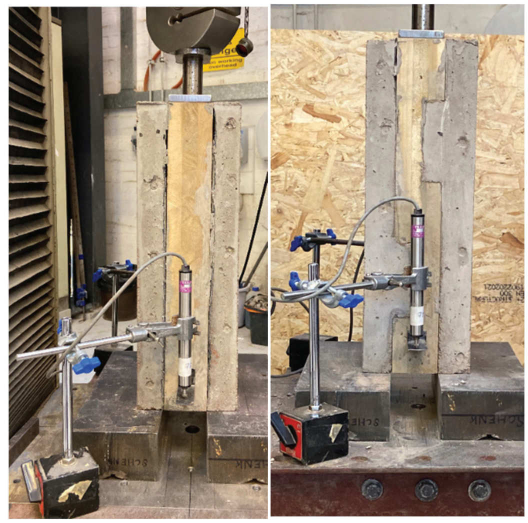

Figure 2: *S-Series specimen (left) and NS-Series Specimen (right) in testing apparatus*

3 RESULTS AND DISCUSSION

3.1 LOAD-SLIP RESPONSE

A simple and effective way of determining the structural behaviour of a TCC and the performance of the connections used, is by analysing the load-slip response of the specimens under shear load. This allows for the determination of the relative stiffness and slip modulus of connections and helps classify the type of failure that occurred. The load-slip response of the specimens was obtained by testing the specimens in accordance to BS EN 26891-1991. Figures 4 and 5 provide the load-slip response for the (S) series of specimens.

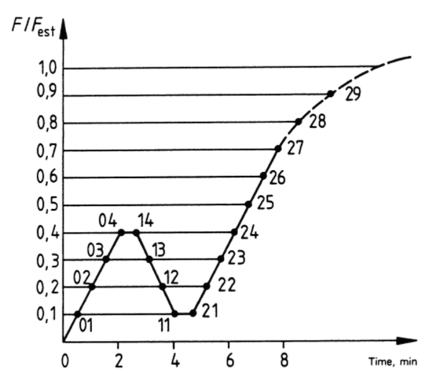

Figure 3*: Loading procedure for slip modulus and maximum load, accordance of BS EN 26891-1991.*

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3.1.1 Screw connections

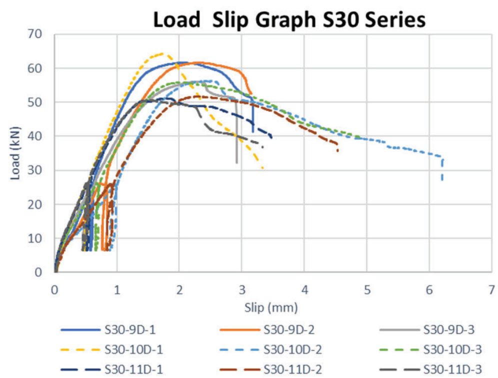

Figure 4: *Load-slip Graph 30° screw orientation*

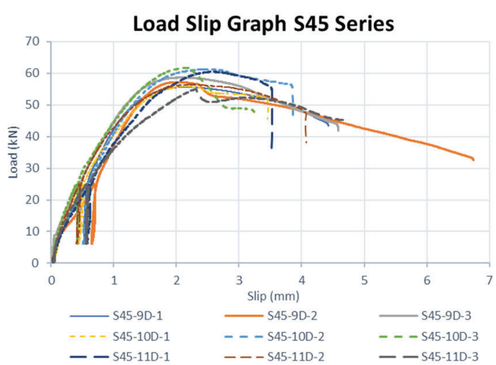

Figure 5: *Load-slip Graph 45° screw orientation*

It can be observed in Figure 4 & 5, that the S30 and S45 specimens failed in a similar manner regardless of the screw orientation and penetration depth, with a plateau of load carrying capacity followed by the failure of the screws and sudden drop in load. Such failure is typical for screw connections in TCC [17]. In terms of structural performance, the S45 specimens showed a higher average maximum load than the S30 series. However, the S30 series displayed a greater initial stiffness as illustrated in Figure 4. As for penetration depths, 11D specimens, specifically for the S30 series, yielded the lowest load carrying capacity. This is as a result of the shallow orientation angle of the S30 screws and the thickness of concrete used in this research. The level arm produced by screws inserted at 30° provided less resistance to load, due to a reduced resistive contact surface compared to the S45 series. This is most evident when looking at the S30 11D specimens, which produced the lowest load carrying capacity out of the three penetration depths tested. The S30 11D specimens also failed at a lower Fmax and in a more brittle manner, compared to S45 inserted at a lower penetration depth. The resulting shallow angle of the screw in combination with the penetration depth did not allow for favourable deformation/settlement of the screw and as a result an increase brittle failure of the specimen was observed.

Specimens with perpendicular screws (S90) exhibited a more ductile behaviour and as a result a significantly lower Fmax than S30 and S45 specimens. This is shown when comparing Figure 6 to Figure 4 and 5. This outcome was expected, as previous work by [18] carried out on perpendicular connections in CLT Concrete Composites and TCCs has concluded the same findings. Similarly to the previous research carried out by [6], a penetration depth of 11D for S90 specimens resulted in a connection with increased stiffness and on average a greater load carrying capacity, in comparison to the other penetration depths tested. However, for both penetration depths tested, the large slip yielded from the S90 specimens under load showed that they exhibit the lowest levels of composite action, highlighting the structural limitations of this orientation of metal screw connections in CLT Concrete Composites.

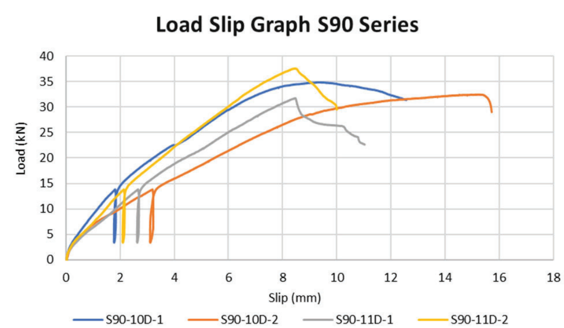

Figure 6: *Load-slip Graph 90° screw orientation*

3.1.2 Notch connections

Similarly to the theory regarding penetration depth and connection stiffness for screw connections, an increase in notch depth is directly related to an increase in maximum load carrying capacity [8,10]. The main parameters which govern the behaviour of notched connections according to [3] are the geometry of the notch (primarily the notch depth) and whether or not a metal fastener is used in combination with the notch. However, according to [8,10] to date there has been little research investigating the effective number and orientations of screws used in combination with notched connections.

The results from this research show the effects a change in notch depth and orientation of screws used in tandem with notches have on the performance of notched connections in CLT Concrete Composites. NS specimens exhibited the greatest load carrying capacity and stiffness of out all specimen configurations tested, as shown in Table 3. For the NS45 specimens, a linear relationship

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between Fmax and notch depth can be identified, with a clear increase in Fmax with an increase in notch depth. This ranges from a Fmax of 72.7 kN for a notch depth of 25 mm to a Fmax of 77.5 kN for a notch depth of 35 mm. Translating to an average increase of 3 percent in Fmax for every 5 mm increase in notch depth.

For the NS90 specimens, an increase in Fmax is noted between specimens NS90-25 and NS90-35 of 11.3 kN. However, unlike the NS45 specimens a further increase in notch depth to 35 mm does not result in an increase in maximum load. This difference in behaviour is likely a result of variance in the material used and not a result of the depth of the notch itself, as unlike screw connections, notched connections resist applied load through direct contact between the concrete and timber members. Thus, the performance of the composite is greatly dependant on the properties of said members. Additionally, the higher variance in results for the NS90, is also likely due to the manufacturing of the notch itself. As the notched specimens tested in this research were cut by hand, unlike the industry standard of using CNC machinery. Therefore, it is speculated that, despite the results shown in this research for the NS90 11D specimens, it is still believed that an increase of notch depth yields an increase in load carrying capacity. This interpretation is based on the results from the NS45 specimens and previous research by [3], [8] and [10] on notched connections in TCCs.

The depth of notched connections proved to have a significant influence on the performance of the connection, as an increase in notch depth provided greater ultimate load and lower slip modulus. This is shown in Figure 7 and 8. A similar relationship between notched depth and Fmax has also been recently reported by [10].

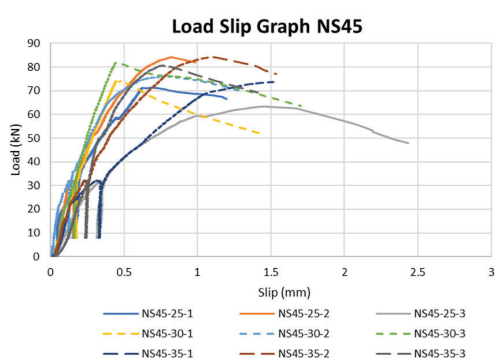

***Figure** 7: Load-slip graph NS45 specimens*

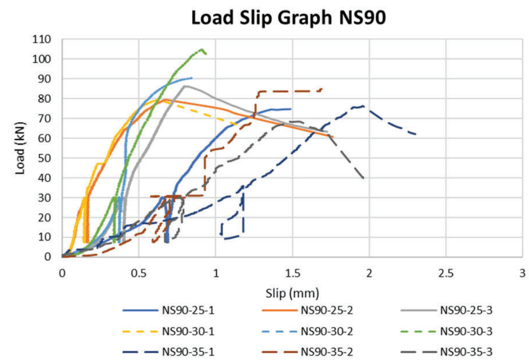

***Figure 8**: Load-slip graph NS90 specimens*

3.2 SLIP MODULUS

To calculate the slip modulus, displacements at 10, 40, 60 and 80 percent of the maximum load (F*est*) were obtained. Using these values, the initial slip modulus (Ki) and the Serviceability Slip modulus (Ks) were calculated according to BS EN 26891-1991.

***Table 3**: Maximum load and slip modulus results*

Connection type	Fmax	Slip at Fmax	Initial	Serviceability limit state
	(kN)	(mm)	Ki (kN/mm)	Ks Slip Modulus (kN/mm)
NS 45 25	72.9	0.99	151.0	161.5
NS 45 30	77.2	0.56	213.0	227.9
NS45 35	79.5	1.13	124.3	125.1
Average	76.6	0.9	162.7	171.5
NS 90 25	80.2	0.98	103.8	176.0
NS 90 30	91.5	0.79	127.2	200.5
NS 90 35	76.5	1.71	39.0	57.0
Average	82.7	1.2	90.0	144.5
S90 10D	33.7	12.33	6.0	5.1
S90 11D	34.7	8.47	5.9	5.1
Average	34.2	10.4	5.9	5.1
S45 9D	57.2	2.07	39.6	40.2
S45 10D	59.6	2.29	52.5	48.1
S45 11D	57.3	2.37	47.0	43.7
Average	58.0	2.2	46.4	44.0
S30 9D	59.0	2.20	42.3	39.3
S30 10D	58.7	2.07	38.7	34.9
S30 11D	51.1	1.89	43.1	34.3
Average	56.3	2.1	41.3	36.2

As shown in Table 3, the notched connections exhibited the greatest slip modulus compared to the other specimen configurations. This was expected as it was previously stated that notched connections offer the highest load resistance and lowest slip. In terms of comparing the slip modulus of the NS90 and NS45 connections, the slip modulus for NS45 specimens was 26.9 kN/mm higher on average than the NS90 specimens. This difference can be attributed to several factors ranging from material density, screw orientation and concrete properties. Therefore, in terms of notch connections, the NS45 specimen outperformed the NS90 specimens in terms of slip modulus, but further testing is required to validate this finding and establish which notch connection configuration yields the greatest structural performance.

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For the S series connections both S30 and S45 specimens obtained a far greater slip modulus with up to 8 times the S90 values, ranging between 34.3 and 48.1 kN/mm respectively (as shown in Table 3). The low slip modulus of the S90 specimens shows good agreement with previous research on CLT Concrete Composites, as it was found that screws connected at 90° behave in a more ductile manner under load [2,5]. Furthermore, the slip modulus obtained for the S30 and S45 specimens also shows good agreement with the values obtained in previous research on CLT Glulam Concrete Composites which also tested the performance of inclined connections [2,5,18]. Additionally, similar results were found when correlating a relationship between the slip modulus and inclination of the connector. In the case of this research, S45 specimens showed a slightly higher slip moduli compared to S30 specimens, which is the opposite to what was found by [2]. However, it must be noted that [2] conducted tests on Glulam Concrete Composites and not CLT, which due to timber grain direction can potentially partially explain the discrepancies in results. Despite this, [5] tested screws with various inclinations inserted in CLT Concrete Composites and found that 30° specimens for any given penetration depth yields higher values of slip modulus than 45° specimens. Given the difference in slip modulus for inclined screws obtained in this research is low, the difference in findings between this paper and previous research can be associated with a large variance in the properties of the timber and connectors used. In spite of this, the results obtained from the BS EN 26891 testing shows good general agreement with previous research, whilst also highlighting key differences in slip modulus based on the type of connection, inclination and timber used.

3.2 FAILURE MODES

3.2.1 Johansen's failure modes

One way in which the load carrying capacity and failure of connections in timber structures can be predicted, is through a numerical approach known as the European Yield method or the Johansen's equations. This method is very effective for timber to timber connections, however, there has been no formal adaptation provided for connections in TCCs. Therefore, to classify the failure modes of TCCs, experimental work needs to be carried out. Previous research by [9, 6] has shown that only a handful of failure modes can occur in TCCs, this is due to the low possibility of connection embedment in the concrete member. The failure modes most likely to occur in TCCs are modes E and F.

3.2.2 S90 series

The S90 specimens deformed predictably, with the development of a plastic hinge associated with a mode E failure. The hinge occurred on the section of the screw located at the concrete-timber interface. Such deformation was also noted in previous research by [9] who tested screws oriented at 90° in CLT Concrete Composites. As clearly indicated from the slip modulus, Fmax and slip at Fmax, S90 series had the largest deformation out of all specimens tested. This resulted in large hinge development of the connector and embedment in the timber member. Differences in the magnitude of hinge development and timber embedment was noted for S90 specimens connected with varying penetration depths (as shown in Figure 9a). For S90-10D specimens a timber embedment of 13-15 mm was observed, compared to only 10–13 mm for S90-11D specimens. The difference in magnitude of failure is due to the connection performance in correlation to the connection's penetration depth, as shown in Table 3. The failure of the concrete members for all the S90 specimens showed typical and uniform failure. As recorded during testing, hairline fractures propagated at approximately 20 kN. These fractures occurred along the row of screws on the CLT member, which eventually fully developed and failed. This is shown below in Figure 9b. Such failure can be attributed to the deformation of the connector inside the concrete. It was found that penetration depth had little impact on whether cracking of the concrete member occurred. Rather the failure in the concrete member was related to the concrete thickness/cover adopted in the specimens.

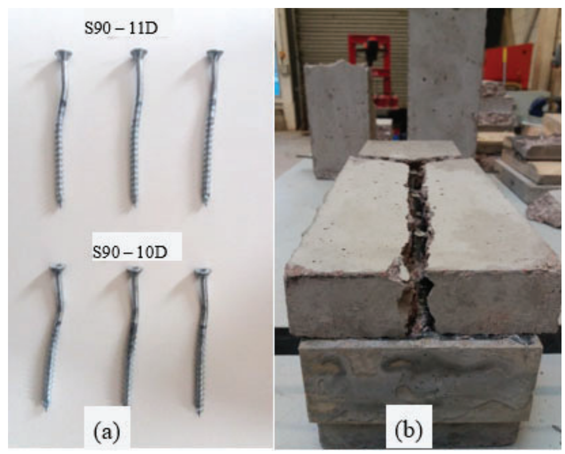

Figure 9*: (a) S90 screw deformation (b) concrete failure S90 specimens*

3.2.3 S30 & S45 series

The deformation of screws for the S30 and S45 specimens differ to the deformation of the S90 specimens. This is due to their orientation, as when inclined, one screw is loaded in tension while the other is loaded in compression. As a result of the distribution of tensile and compressive forces, different yields can be identified, with the screws in tension showing very little deformation, while the screws in compression showing the development of a plastic hinge, as shown in Figures 10 and 11. According to [2] three failure modes of inclined screws should be examined in TCCs. These correspond to Johansen's failure modes A, E and F. From the examination of the inclined screws post testing, failure modes E and F were identified with two hinges being visible. It is important to note that the hinge development for the S30 specimens was not as visible compared to the S45 specimens at all

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penetration depths. Evidently this provides insight into a reason for the lower S30 specimen loads, which was that the screws did not fully yield underload, thus loosing additional potential load bearing resistance.

A further area of interest with the failure of inclined screws is the concrete failure that occurred as a result of the applied load. For both S45 and S30 specimens the concrete members failed as a result of concrete punching failure (shown in Figure 10). This occurred just prior to and in most cases after the Fmax being reached. This type of failure was evident with almost all of the S45 specimens, regardless of their penetration depth. However, this concrete failure only occurred in S30 specimens with a penetration depth of 9D and 10D. It is believed that the lower inclination of the S30 specimens meant that they had increased concrete cover, thus requiring a far greater load to achieve the concrete punching failure. [2] Also noted a similar concrete failure in their research on inclined screws in Glulam Concrete Composites. [2] found that the failure is due to the displacement of screws inside the concrete member under load. It was found that the screws acting in tension, were responsible for this type of failure, as a result of the withdrawal of the screw while under load. Despite concrete punching failure only occurring at a force greater than Fmax, it would be recommended that either a minimum concrete thickness or a minimum penetration depth be adopted to mitigate this type of failure. In order to determine these values further testing on CLT Concrete Composites connected with inclined screws is advised.

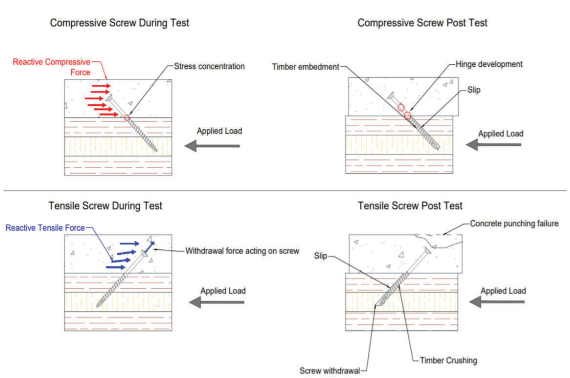

***Figure 10**: Failure process of S30/45 specimens*

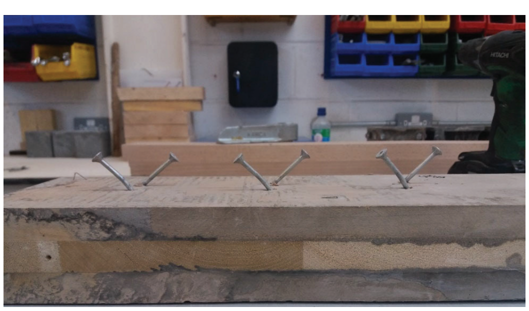

***Figure 11**: Deformation of screws with 45° orientation*

3.2.4 NS45 & NS90 series

Unlike screw connections, the failure of notched connections cannot be classified using Johansen's equations. The failure mechanisms for notch connections are dependent on the strength of both the concrete and timber members, as the load is directly transferred from one material to another. It is therefore of critical importance that both members are sufficiently strong to ensure that premature failure of the section does not occur [19]. According to [8] and [16], the failure of notch connections can be caused by the following; (1) Failure of concrete in shear, (2) Crushing of concrete in compression in the notch, (3) Failure of the timber member in shear between two consecutive notches, (4) Failure of the timber member in crushing. From observations during the loading of the specimens both NS90 and NS45 specimens failed as a result of crack propagations originating at the concrete notches. After the development of the hairline cracks (1) at ≈ 40 kN (shown in Figure 12a), a loss of composite action was realised at ≈ 60 kN. After the failure of the concrete members, the load was then distributed to the CLT where the failure of the timber member between two notches (3) occurred (shown in Figure 12b) resulting in the sudden and brittle failure of the specimen. There were no obvious signs of timber crushing (4) on any of the specimens tested. This can be attributed to the high strength and density of the Tulipwood CLT and, additionally, to the grain direction of the CLT, as it varies, notches cut in CLT Concrete Composites can almost certainly be cut in the optimum grain orientation. According to [8] TCCs with notch connections made from Glulam exhibited large amounts of timber crushing and shearing (4) and (5) when they are cut in the transverse direction of the grain.

The difference in screw inclination proved to have little effect on the global failure, however, varying levels of uplift between the two types of notched connections was observed, with the NS45 specimens providing more restraint between the concrete and CLT members. Furthermore, the difference in screw deformation for the NS45 and NS90 specimens was negligible, with both specimens showing no sign of a plastic hinge. Therefore, it can be said that the effects of using inclined screws in tandem with notch connections has been seen to reduce the uplift between the concrete and timber members. To conclude the failure of the notched specimens tested in this research shows very good agreement with [8], [10] and [17]. This research also found that increasing the notch depth had no influence on the type of failure. Although it must be noted that in the case that hardwood CLT is used, and where a small timber section is adopted, a large notch depth > 35 mm could result in a significant loss of cross section, and thus in a reduction in overall strength. Therefore, further testing should be undertaken on inclined screws in TCC notched connections to determine the optimum notch depth.

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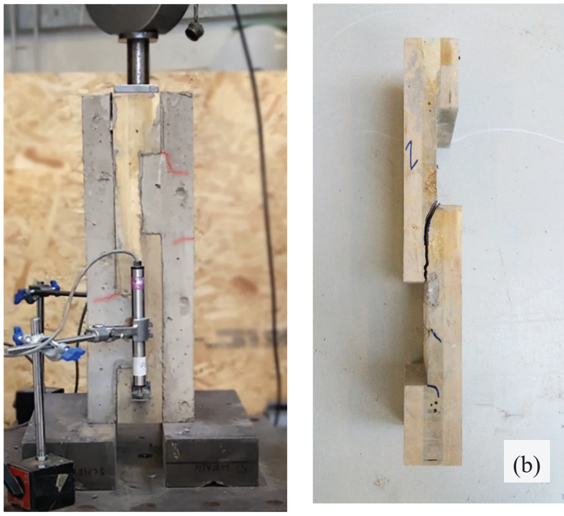

***Figure 12**: (a) Typical fracture in concrete (1), (b) failure in CLT for notched specimens (3)*

4 CONCLUSION

4.1 INFLUENCE OF PARAMETERS

4.1.1 Penetration depth

For the S90 series, a penetration depth of 11D was found to provide the greatest maximum load at 34.6 kN. From the post testing examination of the screws, it was found that screws inserted at 11D showed less deformation compared to the 10D specimens. Furthermore, the 11D specimens exhibited a lower slip on average at all stages of loading. These results concur with previous research on CLT Concrete Composite connections by [6] and [9].

In terms of the inclined screws, S45 specimen showed a linear increase in Fmax for penetrations 9D and 10D. 11D penetration depths for S45 specimens, resulted in a Fmax marginally lower than the 10D specimens. Additionally, the S30 specimens exhibited a decrease in Fmax with an increase in penetration depth, with a drop of 13.28 percent from 9D to 11D. This contradicts findings by [2] and [5] who have found that for both inclinations of 30° and 45° an increase in penetration depth results in an increase in both Fmax and slip modulus. However, the penetration depths studied by [5] was increased in increments of 20 mm for each penetration depth, while the penetration depth studied in this research increased in increments of 5 mm. Furthermore, [2] investigated TCCs which used Glulam Concrete Composites as opposed to CLT. These differences in scale of penetration increase and materials used, could be the result of the variation between findings. Therefore, further testing should be undertaken to support the current findings.

4.1.2 Notch depth

It was found that a linear increase in notch depth provides an increase in structural performance for both NS45 and NS90 specimens. These results show good agreement with research conducted by [10], who also investigated the influence of notch depth on CLT Concrete Composites. It was also found that the governing parameters of notched connections was the strength of the concrete and timber members, with hardwood CLT offering potential increases in structural performance for notched connections opposed to softwood CLT. Additionally, it was found that almost no timber embedment was evident in any of the specimens. This differs to what was found by [8], where timber embedment was clearly identifiable. The reason for the difference in specimen condition is that, CLT is orthogonally bound. [8] stated that notches cut in the longitudinal grain orientation are superior to notches cut in the transverse direction. Thus, notches cut in Hardwood CLT, due to the orthogonal nature of CLT and increased density of the hardwood, may be more suitable than notches cut in alternative softwood timber members. To validate this claim further testing should be undertaken.

4.1.3 Screw inclination

Out of the three screw orientations tested, an orientation of 45° proved to be the most effective, in both load carrying capacity and slip modulus. This result contradicts current findings, which state that decreasing the inclination angle of screw connections will increase their structural performance [5,21]. The reason for the difference in findings can be attributed to several factors ranging from the types of screws used, concrete thickness and spacing adopted. However, in the case of this research, and as mentioned previously the S30 provided a lower Fmax due to premature failure in the concrete member, and as a result of the connections reduced load resisting lever arm due to its shallow insertion angle.

The inclination of screws in notched connections, proved to have a minor influence on the load carrying capacity of the connection. The NS90 specimens showed increased values for Fmax, however, they also exhibited a greater slip at Fmax and a reduced slip modulus compared to the NS45 specimens. The orientation of the screws used in NS specimens did, however, have an impact on the failure of the specimen, with the NS45 specimens showing less signs of uplift between the concrete and timber members of the composite compared to the NS90 specimens. A reduction in uplift between the members shows that the timber and concrete members are achieving a greater level of composite action, which is evident as the NS45 yielded a greater slip modulus than the NS90 specimens. This provides an insight into which screw orientations provides the greatest structural performance in a notch connection. However, further research into the inclination of screws used in notched connections in TCCs should be carried out to verify these findings and expand on current research.

4.1.4 Failure modes

After examining the screws taken from the specimen's post testing, two clear failure modes were identified. Mode E and F failures from Johansen failure modes were exhibited. This shows good agreement with previous research and highlights that only certain Johansen failure modes can occur in TCCs. It was also noted that the failure modes were governed by the penetration depth of the connection, with 11D specimens exhibiting less deformation compared to the 9D specimens for inclinations of 30° and 90°. It was also found that the failure of the concrete member was greatly governed by the penetration depth and inclination of the screws with failures such as concrete punching being observed for the inclined screw, which was also noted in research by [2]. The concrete failure for notched specimens identified in this testing showed good agreement with [8] and [10]. However, it must be noted that the failure mode of connections in CLT Concrete Composites cannot be calculated and can only be accurately obtained via laboratory testing. This is a result of a lack of guidance in the design standards. Therefore, the development of a new or even a modified equation based on the existing Johansen's equation is recommended.

4.1.5 Recommendations for future research

From the lack of guidance in the current design standards, there is a noticeable gap not only for an accurate equation to calculate the slip modulus, but for improved guidance on obtaining the load carrying capacity and failure modes of TCCs. Therefore, work addressing these issues is encouraged. Additionally, as the knowledge of connections under conventional loading is being increasingly covered, it is recommended that connections in TCCs be tested under dynamic loading, to gain a better understanding of the behaviour of various connections under such types of loads and how this will affect the overall structural performance of the composite

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