Shear Performances of Shallow Notch-Screw Connections for Timber-Concrete Composite (TCC) Floors

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Shallow notch-screw connections, which showed potential superior slip moduli and load-carrying capacity compared with the traditional screwed connections and can be employed in the timber-concrete composite (TCC) floors were examined in this study. Eight groups of shallow notch-screw connections were designed to perform the push-out tests, in which the arrangement of screws, the heavy timber types, and the width of the shallow notch were considered. The depth of the notch was uniformly 15 mm. The vertical screws and the cross inclined screws were separately selected as the reinforcement for the shallow notch connections. The common heavy timber panels, including nail laminated timber (NLT), glulam, and cross laminated timber (CLT), were adopted. The width of the shallow notch tested included 100 and 200 mm. The experimental results showed that the shallow notch connections underwent ductile failure. The effects of testing factors on the shear strength, slip moduli, and ductility were discussed. The design proposals about the slip moduli of the shallow notches using each timber panel types were proposed, aiming to provide guidance for the application of the TCC floors with shallow notches.

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Keywords: Timber-concrete; Composite floor; Shallow notch; Slip modulus; Push-out test

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INTRODUCTION

Timber-concrete composite (TCC) structures are increasingly applied in the new-built residential and official buildings and short to medium span bridges (Dias *et al*. 2016). Compared with the pure timber floors, the TCC ones showed obvious improvement in bending stiffness, vibration resistance, and fire resistance performance as the result of the application of concrete slabs (Deresa *et al*. 2021).

The notch-screw connection is a type of hybrid connection that has excellent shear strength and slip modulus, in which the timber notch and the concrete tenon provide the dominant shear performance, while screws provide the necessary ductility and up-lifting resistance (Kudla 2017). Some studies have been done to evaluate the geometries and dimensions of the notch on the shear performances of the connection. Yeoh *et al.* (2009) investigated the shear performances of notch connections with various shapes. They found that the rectangular notch and the triangular notch with the 60° inclination showed relatively superior shear performances.

Xie *et al.* (2017) found the shear strength and slip modulus of the notch-stud connection improved as the notch width and depth increased (the depths of 20 and 40 mm were considered), and the diameter of the studs also showed obvious influences on the shear performances of the connection. This was because the width of the notch that was adopted was only 60 mm. Djoubissie *et al.* (2018) studied the shear performances of triangular notch connections reinforced with threaded bars and found that the shear strength doubled and the slip moduli increased by 1.5 times as the reinforcement function of the threaded bars while comparing with the pure triangular notch. Zhang *et al.* (2020) found that the timber length in front of the notch greatly influenced the shear strength of the connection, whereas the depth of the notch showed significant improvements on the slip moduli of the connection.

Dias *et al.* (2018a) provided design proposals for notch connections regarding the depth of the notch and the slip moduli. The suggested minimum depths for softwood and laminated veneer lumber (LVL) are 20 mm and 15 mm, respectively. Dias *et al.* (2018b) suggested that the minimum depths of the notches for the application in buildings and bridges are 20 and 50 mm, respectively. The deep and shallow notch connections have no obvious definition in the available investigations. Dias *et al.* (2018a) provided the design proposals of slip moduli based on the notch depth. The suggested slip modulus for the notches deeper than 30 mm was 1,500 kN/mm per meter width, while the suggested slip modulus for the notch of 20 mm width was 1,000 kN/mm per meter width. According to the experimental results of Zhang *et al.* (2020), the typical failure of notch-screw connection with the notch depth of 25 mm was timber shear failure, which was similar to the shear failure of deep notch (deeper than 30 mm) connection (Jiang *et al.* 2020; Shi *et al.* 2020a), while the specimens with a notch depth of 10 mm showed timber compression. For the connection with the notch depth of 20 mm, the timber shear failures were also the dominant failure type (Kuhlmann and Michelfelder 2004). However, the timber shear failure for the notch depth of 20 mm can be avoided by prolonging the length of the timber (15 times the notch depth) in front of the notch, and the failure mode turned to the timber fiber compression failure (Mönch and Kuhlmann 2018). Accordingly, the deep notch and shallow notch can be defined as the notch deeper than (or equal to) 30 mm and shallower than (or equal to) 20 mm, respectively, by distinguishing the failure modes analyzed above.

As analyzed above, the shallow notch connection also showed great application aspects due to the ductile behavior and acceptable shear strength, although the slip moduli declined to some extent with the decrease of the notch depth. Moreover, the disadvantages of the shallow notch in the aspect slip modulus can be avoided in the TCC floor systems by increasing the width of the notch width.

Regarding timber floors, many types of heavy timber are available on the market, such as the glulam, cross laminated timber (CLT), and nail laminated timber (NLT). The TCC floors constructed by glulam (Mönch and Kuhlmann 2018, Zhang *et al.* 2020), CLT (Jiang and Crocetti 2019; Thai *et al.* 2020), and NLT (Kuhlmann and Michelfelder 2016) were also investigated. However, the shear performances of the shallow notch connection using different heavy timber types were not evaluated. Additionally, due to the decline of the notch depth, the shear contribution of the screws may increase in the shallow notch connection compared to the screw connection, assuming that the notch depth in the pure screw connections was zero.

Therefore, the push-out tests for shallow notch-screw connections were performed to evaluate the shear performance using various timber types. The timber floors studied in this work included glulam, NLT, and CLT. The vertical screws and cross inclined screws were also comparatively researched in the NLT series specimens. In addition, the notch widths of 100 and 200 mm were also considered in push-out tests to supplement basic test data and to demonstrate the reliability of the test results. The experimental results of this study can provide guidance for the TCC floors in the application of timber bridges and civil buildings.

EXPERIMENTAL

Materials

The glulam, NLT, and CLT adopted in this experimental program were made of Douglas fir. All of the timber above were made of the same batch of the lumber. The main mechanical properties of the lumber parallel to grain based on the glulam are shown in Table 1. Twenty samples were prepared for each material test. The compressive and tensile properties were tested according to the EN standard 408 (2009). The shear strength of the timber was tested according to the ASTM standard D143-14 (2014), while the shear strength of the bond line was tested according to the ASTM standard D905-08 (2013). The density and moisture content of the lumber were 620 kg/m^3 and 10.0%, respectively which were tested according to the EN standard 13183-1 (2002).

Table 1. Mechanical Properties of the Glulam Parallel to Grain (MPa)

Lumber	Elastic Modulus	Compressive Strength	Tension Strength	Shear Strength of the Timber	Shear Strength of the Bond Line
Douglas fir	13,100	43.5	69.7	11.0	9.5

For the NLT, the lumbers were connected by three nails for each interface, as shown in Fig. 1. The nails adopted in the NLT were the smooth round nails with a diameter of 3.5 mm and a length of 90 mm. The nail was made of the type 304 stainless steel according to the Chinese standard GB/T 3280 (2015).

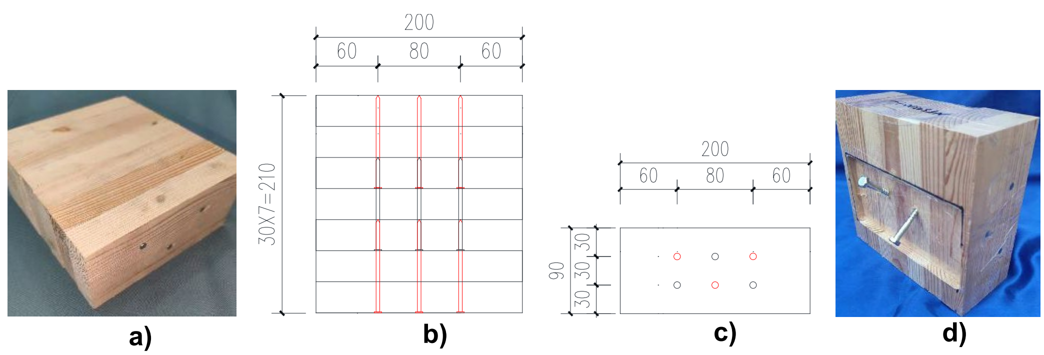

Fig. 1. The diagram of the NLT: a) a photograph of the NLT block; b) top view of the NLT; c) front view of the NLT; d) a NLT block with the shallow notch-screws (measurements are in mm)

The concrete that was employed in the push-out specimens was strength grade C40/50, in accordance with the EN 1992-1-1 standard (2004). The average compressive strengths of the standard cubic (150 mm) was tested as 40.8 MPa under the natural curing condition.

Hexagonal head wood screws were adopted to reinforce the shallow notch connections. The diameter and length of the screw were 8 mm and 100 mm, respectively, as shown in Fig. 2. The average ultimate bending strength of the screw was determined to be 284.9 MPa, in accordance with the ASTM standard F1575-17 (2017).

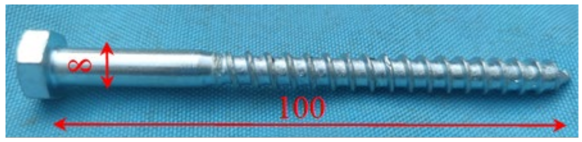

Fig. 2. The dimensions of the screw (measurements are in mm)

Design for Specimens

The grouping for the push-out specimens of the shallow notch-screw connections is shown in Table 2. The timber types, the notch width, and the inclination angles of the screws were all considered. The timber types considered included NLT, glulam, and CTL, which are common structural timber types in TCC floors. The width of the shallow notch considered included 100 and 200 mm. The inclination cases for the screw included 90° and cross 45°.

Table 2. Grouping of the Push-out Specimens

Designation	Timber Types	Notch Dimensions (mm)	Notch Depth (mm)	Screw Dimensions (mm)	Screw Inclination	Screw Number	No.
NPS90N	NLT	100 × 100	15	8 × 100	90°	4	3
NPS45N	NLT	100 × 100	15	8 × 100	Cross 45°	4	3
NPS45G	Glulam	100 × 100	15	8 × 100	Cross 45°	4	3
NPS45C	CLT	100 × 100	15	8 × 100	Cross 45°	4	3
NFS90N	NLT	200 × 100	15	8 × 100	90°	4	3
NFS45N	NLT	200 × 100	15	8 × 100	Cross 45°	4	3
NFS45G	Glulam	200 × 100	15	8 × 100	Cross 45°	4	3
NFS45C	CLT	200 × 100	15	8 × 100	Cross 45°	4	3

Note: NP and NF in the designation denotes partly notch and fully notch, respectively; S45 and S90 denote the inclination angles of the screws; N, G, and C denotes the NLT, glulam and CLT, respectively; Notch dimensions are described in the form of width × length.

Figure 3 shows the schematics of the push-out specimens, taking the groups NFS90N and NPS45C as examples. The thickness of the concrete slabs was 40 mm, while the depth of the timber was 90 mm. The width of the specimens was 200 mm, which was equal to the width of the full notch. The length of the notch was uniformly 100 mm. For the specimens in groups NPS90N and NFS90N, the center distance between the opposite screws was 15 mm as shown in Fig. 3a. In addition, for other specimens made of the NLT, screws should be installed into the lumber away from the nails, as shown in Fig. 1d.

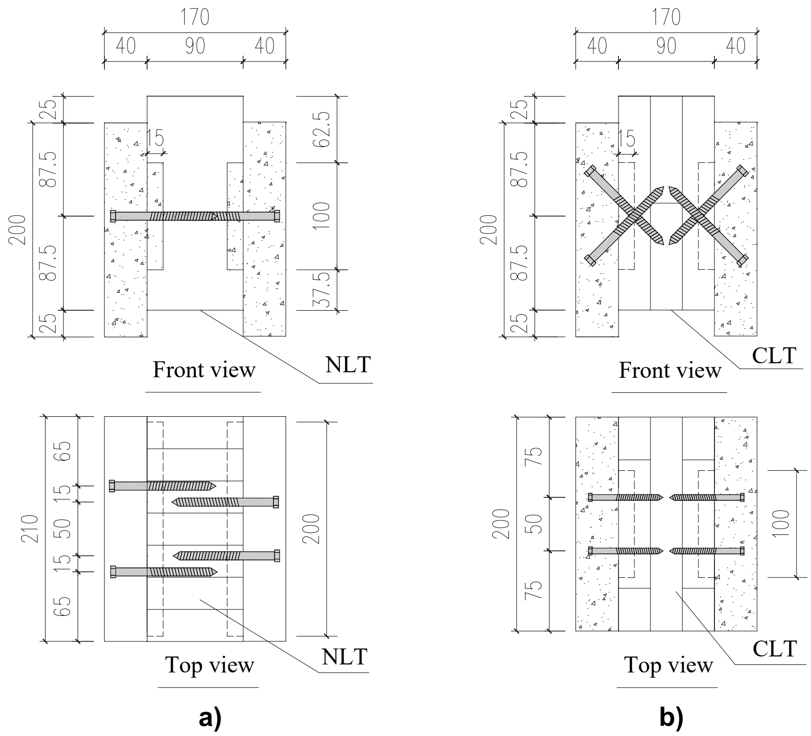

Fig. 3. The schematics of the push-out specimens using the a) NLT with fully shallow notches (NFS90N) and b) CLT with partly shallow notches (NPS45C). (measurements are in mm)

Testing Methods

The testing set-up is shown in Fig. 4a. The interface relative slip between the concrete slabs and the timber floor was measured by four linear voltage displacement transducers (LVDT). Since the shear length of the timber in front of the shallow notch was 62.5 mm, as shown in Fig. 4a, the timber block was completely covered by the steel basement in the push-out tests, as shown in Fig. 4a. This was done because the shear performance of the shallow notch with different types of timber floors was the main research focus. The shear strength of the timber in front of the notch was considered sufficient. As shown in Fig. 4b, the push-out test for the TCC connections was performed according to the EN standard 26891 (1991).

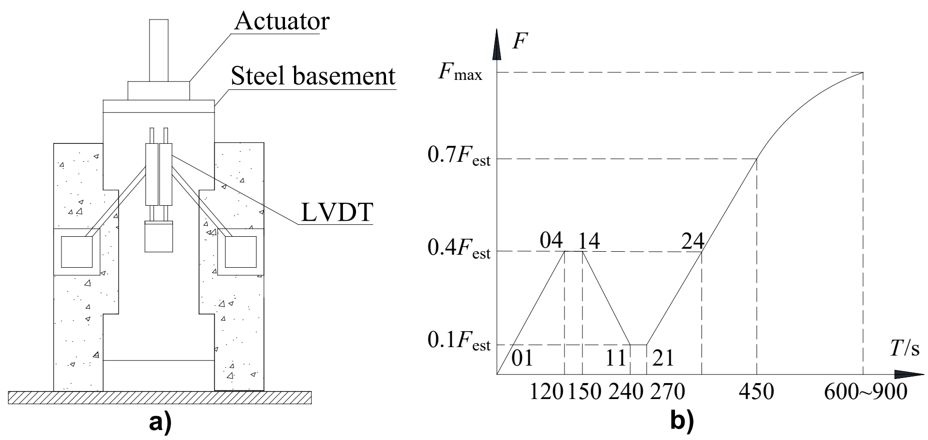

Fig. 4. The test methods for the a) test set-up and b) loading procedure

RESULTS AND DISCUSSIONS

Failure Modes

The failure modes of the push-out specimens are displayed in Fig. 5. As shown in Figs. 5a and 5b, the specimens with partly shallow notches mainly showed concrete cracking or expulsion failure. This was caused by the uplifting force of the shear-compression loaded screws (Tao *et al.* 2021), which also led to the opening gap between the timber and concrete, as shown in Fig. 5c. This failure mode was also observed in the crossed inclined screw type timber-concrete connections in many studies (Derikvand and Fink 2021; Tao *et al.* 2021).

For the fully shallow notch connection, the main failure was the concrete shear failure from the top of the notch to the upper surface of the concrete slab, which are consistent with the failure characteristics of notch type timber-concrete connections (Mönch and Kuhlmann 2018).

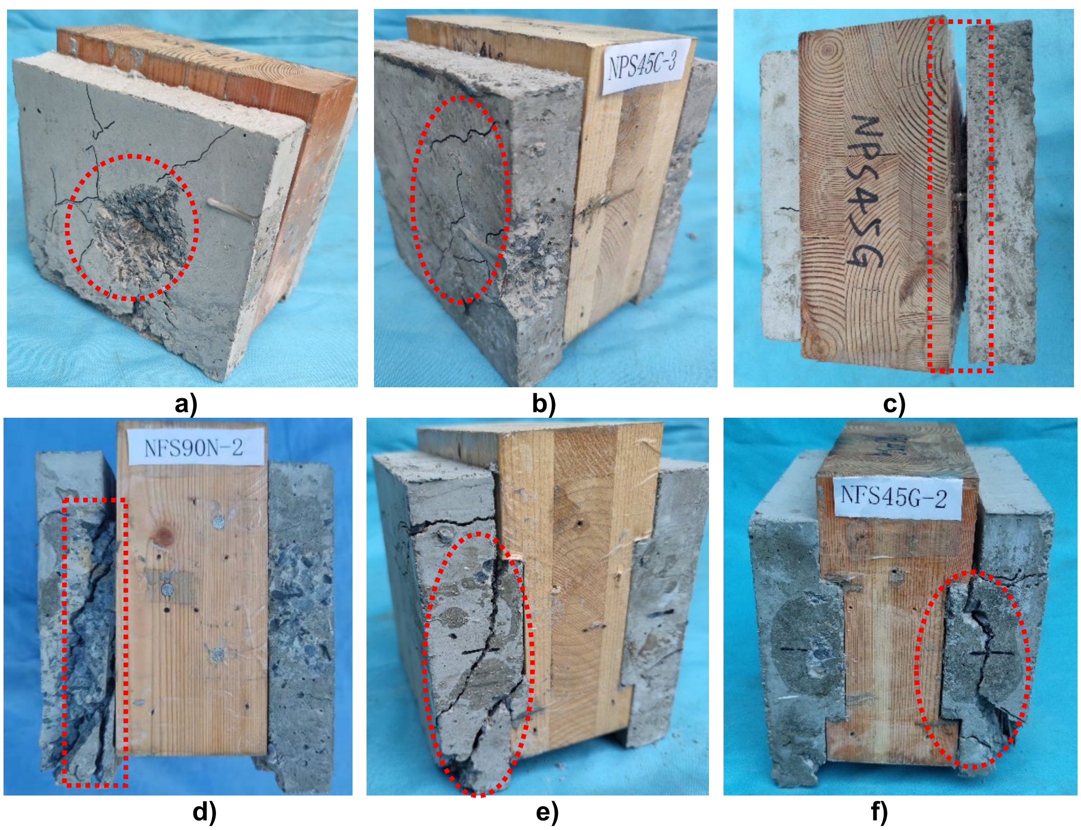

Fig. 5. The failure modes of the push-out specimens: a) expulsion failure of the concrete in NPS45N; b) concrete cracking of NPS45C; c) opening gap of NPS45G; d) notch shear failure for NFS90N; e) notch shear failure for NFS45C; f) notch shear failure for NFS45G

The disassembly photographs of the push-out specimens are shown in Fig. 6. As shown in Fig. 6a, the shallow notch connection reinforced by the vertical screws revealed the single-plastic hinge yielding of the screw, which was similar to the screw connection and was commonly not observed in the deep notch connection. For the shallow notch connection reinforced with crass inclined screws, the tension-shear loaded screws indicated no obvious deformation, as shown in Fig. 6b, while the compression-shear loaded screws indicated the screw yielding and embedment failure in the timber member as shown in Fig. 6c and Fig. 6d. The deformation of the screws in the shallow notches are similar but slight in the pure cross inclined screw connections (Mirdad and Chui 2020).

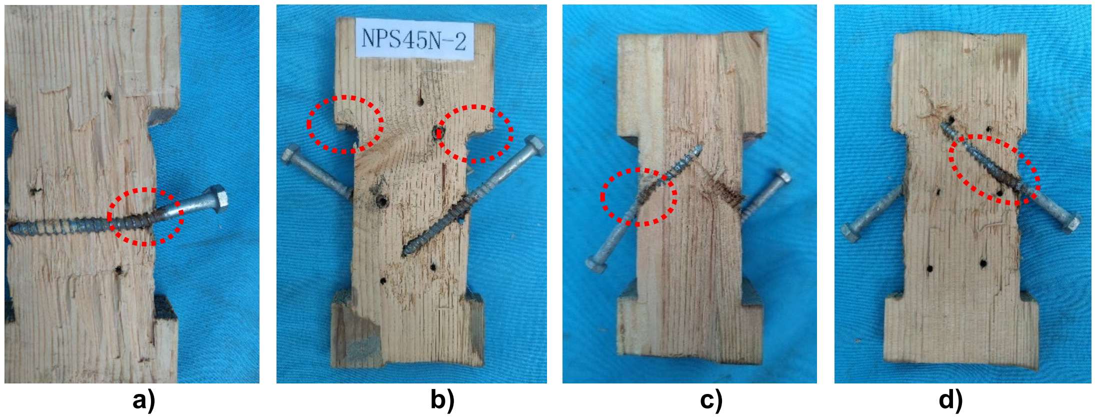

Fig. 6. The disassembly photographs of the push-out specimens: a) screw yield with one single plastic hinge in NPS90N; b) timber compression deformation at the front of the notch for NPS45N; c) screw yield in the compression-shear condition for NFS45N; d) embedment failure in the timber member for NPS45N

Effects of the Screw Inclined Angles

The load-slip curves of the push-out specimens are illustrated in Fig. 7. Based on the load-slip curves, the testing results are summarized in Table 3. The testing loads in Fig. 7 and the strengths and slip moduli in Table 3 denote the shear behaviors of two shear planes.

As to the effects of the inclined angles of the screw on the shear performances of the shallow notch-screw connections, three main conclusions can be drawn. Firstly, the shallow notch connections with cross inclined screws showed an improvement of approximately 15% to 20% in the ultimate strength, compared to those with the vertical ones. The improvement range in the yield strength was also approximately 15% to 20%. Secondly, the slip moduli of the connections with the cross inclined screws improved slightly. Basically, they were smaller than 10% at both serviceability limit and ultimate states, compared to those with the vertical screws. As the notch width increased, the effect of the screw on slip moduli seemed to decline, which needs to be verified further. Finally, the ductility of the shallow connection also improved as the result of the adoption of the cross inclined screws. The ductile factor of the NPS45N sample reached 3.8.

In summary, the effects of the inclined angles of the screws in shallow notch-screw connections on the shear performances of the connection were similar to those of the pure screwed connection. Du *et al.* (2019) found that the slip moduli of the cross inclined screw connection were 1.7 times those of the vertical screw connection, while their shear strength values were basically same. Apparently, the contribution of the screw on the shear performances (strength and slip moduli) cannot be ignored in the shallow notch connections. Increasing the penetration depth of the screw and the embedment foundations of the timber are effective to improve the shear strength of the shallow notch-screw connections.

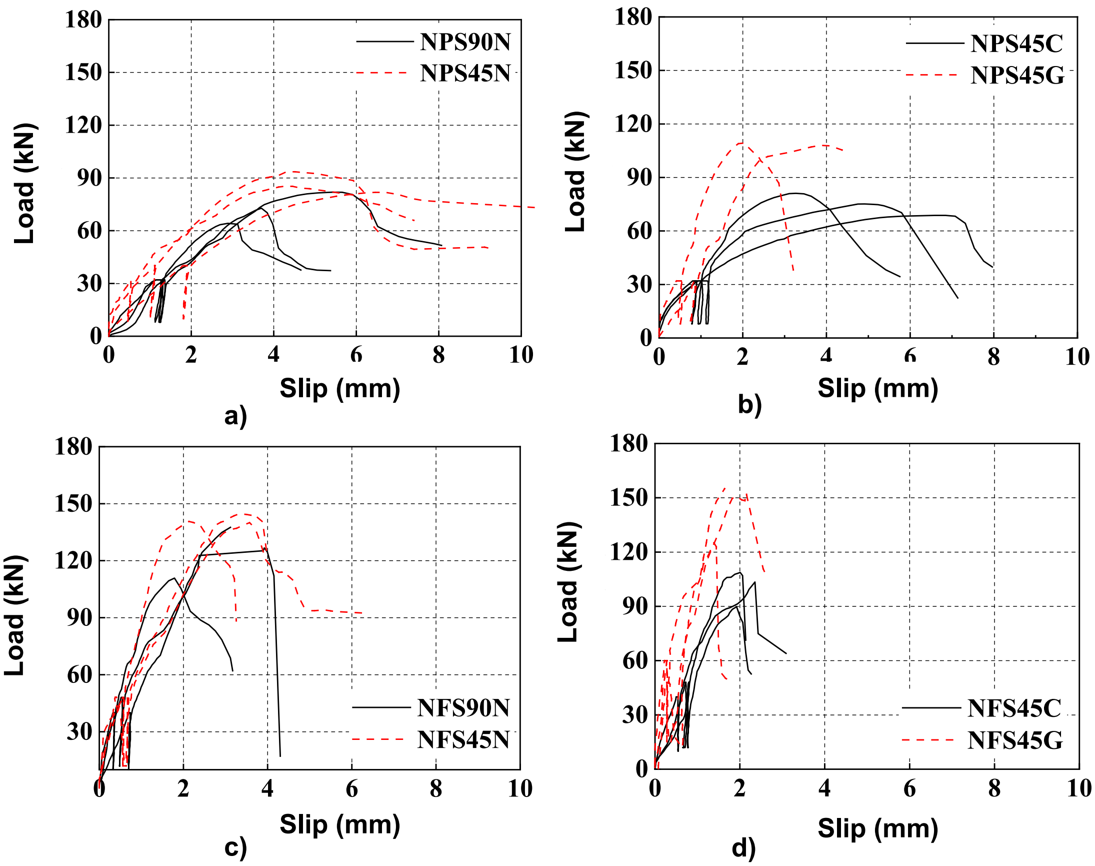

Fig. 7. The load-slip curves: a) NPS90N and NPS45N; b) NPS45C and NPS45G; c) NFS90N and NFS45N; d) NFS45C and NFS45G

Effects of the Floor Types

Considering that the embedment and withdrawal properties of timber parallel to the grain are higher than those perpendicular to the grain, the shear strength and slip stiffness of the screws loaded parallel to the grain in the specimens made of GLT or NLT were higher than those of the screws in the specimens made of CLT, causing the higher shear capacity and slip moduli of the GLT or NLT composite specimens than that of the CLT composite specimens. Moreover, the relatively weak interfacial slip restraints between the laminates of NLT could be the reason for the lower connection shear properties of the NLT composite specimens, when compared with the specimens made of GLT.

The specimens that were made of NLT had initial slip moduli and shear strength values that were approximately 15% and 17% to 40% larger than the specimens that were made from CLT. This result denotes that the NLT panel may have superior structural behavior in the unidirectional loaded member, so it can be applied in TCC bridges and TCC floors under unidirectional loads. The shear strength values of the specimens made of glulam were approximately 1.5 times larger than the specimens that were made of CLT. For the notches with 100 mm width, the initial slip moduli values of the NPS45G specimens were 1.7 times greater than those of the NPS45C specimens. For the notches with 200 mm width, the initial slip moduli values of the NFS45G specimens were 3.8 times greater than those of the NFS45C specimens. At the ultimate state, the slip moduli values of the specimens comprised of the NLT and the CLT were approximately 50% those of the specimens that were made of glulam. According to the experimental results, the preliminary conclusion can be made about the slip modulus of the connections made of different timber types, as seen in Eq. 1,

$$K_C = K_N = 0.5K_G \quad (1)$$

where K_c, K_N, and K_G denote the slip moduli values for the CLT, NLT, and glulam specimens, respectively.

The ratios of K_u/K_s were close to 1 for all cases of the floor types. This conclusion was also suggested in the investigation of Dias *et al.* (2018a). The testing results demonstrated that the design proposal in Eq. 2 is suitable for all timber type cases.

$$K_s = K_u \quad (2)$$

Table 3. The Testing Results Considering Two Shear Planes

Designation	F_u (kN)	F_y (kN)	s_u (mm)	s_y (mm)	K_s (kN/mm)	K_u (kN/mm)	μ
NPS90N	73.0 (10%)	64.8 (4%)	4.6 (27%)	2.4 (6%)	31.7 (14%)	26.0 (11%)	1.9 (24%)
NPS45N	86.9 (6%)	73.6 (23%)	9.4 (42%)	2.4 (34%)	33.5 (26%)	28.7 (20%)	3.8 (12%)
NPS45G	108.7 (1%)	103.2 (3%)	3.6 (21%)	2.0 (20%)	50.5 (21%)	59.9 (26%)	1.8 (2%)
NPS45C	75.0 (7%)	64.3 (18%)	5.9 (22%)	2.1 (15%)	29.0 (8%)	30.3 (12%)	3.0 (39%)
NFS90N	124.8 (9%)	100.7 (23%)	2.7 (14%)	1.4 (50%)	81.8 (26%)	70.8 (20%)	2.2 (28%)
NFS45N	141.7 (1%)	120.9 (9%)	3.8 (12%)	1.5 (15%)	82.6 (18%)	70.0 (13%)	2.5 (21%)
NFS45G	148.3 (12%)	94.3 (6%)	1.7 (18%)	0.7 (22%)	266.4 (20%)	159.3 (13%)	2.7 (27%)
NFS45C	100.7 (8%)	88.7 (11%)	2.2 (8%)	1.4 (9%)	70.5 (4%)	73.5 (7%)	1.6 (18%)

Note: Percentage values in brackets denote the coefficients of variation (COV); F_u is the maximum testing loads of the push-out specimens; F_y is the yield load determined in accordance with the EN standard 12512 (2001); s_u and s_y are the ultimate slip and yield slip, respectively, which were determined according to the EN standard 12512 (2001); K_s and K_u denote the slip moduli of the shallow notch connection in the serviceability limit state and ultimate state, respectively, which were calculated according to the EN standard 26891 (1991); μ is the ductility factor determined by the ratio of s_u/s_y.

Effects of the Notch Width

As to the effects of the notch width on the shear performances of the shallow notch-screw connections, two valuable conclusions can be made. Firstly, when the notch width was doubled, the ultimate strength of the shear connections increased by about 30% to 70% for each comparative series. This is because the failure modes of the specimens with the 100 mm notch width experienced concrete expulsion failure and an opening gap between the timber and the concrete, while the specimens with the 200 mm notch width mainly showed the concrete shear failure. Secondly, the slip moduli increased obviously, depending on the width of the notch. The slip moduli of the shallow notch connections per millimeter width are displayed in Fig. 8. Thus, for the TCC shallow notch connection made of CLT and NLT, the proposal slip modulus per millimeter width was 150 N/mm on the basis of the experimental results. The proposal slip modulus per millimeter width for the shallow notch connection with glulam was 300 N/mm. Considering the relatively large coefficient of vibration in groups the NPS45G and NFS45G, it was acceptable that the proposal slip moduli per millimeter for shallow notch-screw are slightly bigger than those of NPS45G specimens and obviously smaller than those of NFS45G. In addition, the suggestion values in Fig. 8 are relatively conservative compared with the available design suggestions introduced by Shi *et al.* (2022).

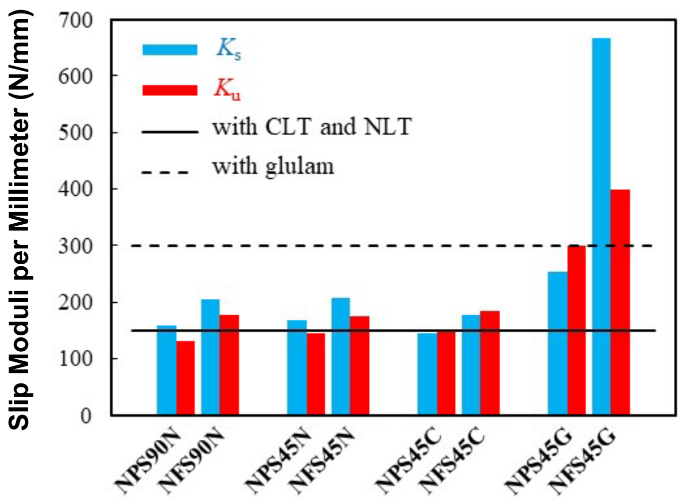

Fig. 8. The slip moduli per millimeter width and design proposals

Further Investigations

Further investigations will focus on the effects of the screws on the shear performances of the shallow notch-screw connections. In the deep notch connection, the effects of the screws can be ignored. However, by comparing the NPS90N and NPS45N specimens (or NFS90N and NFS45N), the effect of the arrangement of the screws cannot be ignored for the shallow notch connection. With and without the screws, the penetration and the diameter of the screws will be evaluated in a subsequent research program.

Additionally, the long-term behaviors of the shallow notch-screw connections should also be investigated considering the design and application requirements. Although the long-term performances of the deep notch, screw, and adhesive connections have been studied (Shi *et al*. 2020a,b, 2021), the long-term slip of the shallow notch-screw connection needs further research due to the changes in the stress mechanisms of the timber, screws, and concrete.

CONCLUSIONS

1. The shallow notch connection combined with the cross inclined screws showed an approximate 15% to 20% improvement in the strength moduli and a slight improvement in the slip moduli than when it was combined with the vertical screws.
2. The shallow notch-screw connection made by the glulam showed the best shear performances compared to those made by the CLT and NLT. The shear strength and slip moduli of the connections made by the glulam were 1.5 times and 2.0 times greater than those of the connections made by the CLT or NLT, respectively. Considering the coefficient of the variation, more samples need to be tested to improve the reliability

further.

3. When the notch width was doubled, the shear strength increased by approximately 30% to 70%, and the slip moduli increased by approximately 100%. Based on the experimental results, the slip moduli per millimeter width for the shallow notch-screw connection using the NLT/CLT and glulam were 150 and 300 N/mm, respectively.

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