Experimental Study on Notched Connectors for Glulam-lightweight Concrete Composite Beams

Yuchen Jiang,[a] Xiamin Hu,[b,]* Wan Hong,[b] Jun Zhang,[a] and Fangqian He [a]

A new type of structural element, the timber-concrete composite beam, exhibited excellent structural performance. The notched connector is widely used in timber-concrete composite systems as a result of its considerable shear capacity and stiffness. Six groups of push-out tests were performed to investigate the shear performance of the notched connectors for the timber-concrete composite beams, with consideration to the varying concrete types, the shear length of the timber, and whether the notch was reinforced. From the test results, the notched connectors that corresponded to the shear fracture of concrete or timber had a low shear capacity and poor ductility. Notched connectors that simultaneously failed at the concrete slab (*via* shear force), as well as at the lag screw reinforcement point during bending presented the greatest shear capacity. This was followed by the notched connectors that exhibited diagonal-compression failure at the concrete slab. Screw fasteners in the notch were shown to improve the strength, ductility, and post-peak behavior of the notched connectors. In addition, the concrete type, the shear length of the timber, and whether the notch was reinforced were found to have no major influence on the slip modulus of the notched connectors.

Keywords: Timber-concrete composite beam; Notched connectors; Push-out tests; Shear capacity; Slip modulus

Contact information: a: College of Civil Engineering, Taihu University of Wuxi, Wuxi 214064 China; and b: College of Civil Engineering, Nanjing Tech University, Nanjing 211816 China;
** Corresponding author: huxm_njtech@163.com*

INTRODUCTION

The characteristics of timber structures cater to the developmental concept of a low-carbon building. Timber structures are becoming more and more popular in construction engineering. The timber-concrete composite (TCC) beam is a newly developed structural element, in which a concrete slab is connected on the top of a timber beam *via* reliable connection systems. Compared to a pure timber floor, the TCC floor has a drastically higher bearing capacity and rigidity, as well as greater fire resistance, improved sound insulation, and vibrational performance (Lukaszewska *et al.* 2008; Yeoh *et al.* 2011; Jiang *et al.* 2017). During the construction process, timber beams can also play the role of a temporary support structure, which greatly enhances the efficiency of the construction process.

So far, quite a number of investigations have been performed on the mechanical behaviour of TCC beams (Brunner *et al.* 2007; Ceccotti *et al.* 2007; Khorsandnia *et al.* 2016). Ceccotti (2002) recommended the calculation method proposed in the Annex B of Eurocode 5 (CEN 2004a), known as γ- method, for linear-elastic analysis of TCC beams. Frangi and Fontana (2003) calculated the failure load of composite beams by assuming a rigid-perfectly plastic connection between timber and concrete. However, the linear-elastic method (γ- method) is the most widely used in the design of TCC beams.

The shear connector is a key component that transmits the longitudinal shear between the timber beam and the concrete slab to ensure effective composite action. The performance of the shear connectors has an important influence on the bearing capacity and rigidity of the TCC beams (Yeoh *et al.* 2011). In the past two to three decades, researchers have developed various types of shear connectors for the TCC system and have studied the shear performance of these connectors *via* experimentation (Kuhlmann and Schänzlin 2001; Steinberg *et al.* 2003; Fragiacomo *et al.* 2007; Clouston *et al.* 2008; Deam *et al.* 2008; Khorsandnia *et al.* 2012; Du *et al.* 2019). In terms of shear capacity and stiffness, notches that are cut into the timber and reinforced with mechanical fasteners, *e.g.*, screws, bolts, steel bars, *etc.*, are considered the best shear connectors (Deam *et al.* 2008; Yeoh *et al.* 2011). Mechanical fasteners in the notch contribute to the transmission of the shear force between the concrete and the timber. It was also demonstrated that the fasteners in the notch improve the ductility of the connection and help to prevent the separation of the concrete and the timber (Jiang and Crocetti 2019).

Kuhlmann and Schänzlin (2001) conducted shear tests on rectangular notches with and without the reinforcement of lag screws. The test results showed that shear fractures occurred in the timber of most of the test specimens, and the screws had no major influence on the shear capacity and the stiffness of the notch. A series of push-out tests were carried out at the University of Canterbury, to investigate the shear performance of different shaped notched connectors, with and without reinforcement in the notch (Deam *et al.* 2008; Yeoh *et al*. 2010). It was found that the rectangular notch reinforced with lag screws provided the greatest strength and stiffness, and the strength of the connectors increased drastically with the length of the notch. Contrary to the conclusion drawn by Kuhlmann and Schänzlin (2001), mechanical fasteners were found to improve the strength and post-peak behaviour of notched connectors. The difference in conclusions may be attributed to the varying failure modes of the two investigations. Bedon and Fragiacomo (2017) proposed a three-dimensional (3-D) FE model including cohesive elements for notched connectors. By use of the FE model, typical failure mechanisms of notched connectors can be captured with a good level of accuracy.

In this paper, six groups of push-out tests were performed to investigate the shear performance of the notched connectors for the TCC beam and to evaluate the influence of the concrete type, the shear length of the timber, and the notch reinforcement on the shear performance. On the basis of analyzing the possible failure modes of the notched connectors, designs and future research suggestions about notched connectors are presented.

EXPERIMENTAL

Materials

The timber members in the tests were made from Douglas fir. Based on five timber samples with the dimension of 20 mm × 20 mm × 20 mm. The average moisture content was 13.3%, and the average density was 0.54 g/cm^3. Mechanical properties of timber were tests according to GB/T 50329 (2012), and the mean compressive strength and the elastic modulus parallel to the grain of the Douglas fir were 43.5 and 10,680 MPa, respectively. The yield strength and the ultimate tensile strength of the lag screw provided by the manufacturer are 360 and 450 MPa, respectively. For each type of concrete, compression tests were conducted on three cubic samples. The average cubic compressive strength for the normal and lightweight concrete were 29.2 MPa and 28.7 MPa, respectively.

Push-out Tests

Test specimens

A total of eighteen push-out specimens, in six groups, were designed for the push-out tests, and the details of the dimensions and parameters of the test specimens are summarized in Table 1 and Fig. 1. Samples NC-N-1 and LC-N-1 were notched specimens without reinforcement, and used normal concrete and lightweight aggregate concrete, respectively. Samples LC-NS-1 through LC-NS-4 were notched specimens with lag screw reinforcement and used lightweight aggregate concrete. The shear lengths of timber for samples LC-NS-1 through LC-NS-4 were 150 mm, 200 mm, 275 mm, and 350 mm, respectively. All the connectors were rectangular notches with a length of 150 mm, a width of 150 mm, and a depth of 50 mm. The lag screws had a nominal diameter of 16 mm and were used in samples LC-NS-1 through LC-NS-4, with an embedded length of 90 mm in timber and 110 mm in concrete.

Table 1. Parameters of the Push-out Specimens

Test Series	Number	Concrete Type	Notch Dimension (mm)			Fastener	Shear Length of Timber (mm)
			Length	Width	Depth		
NC-N-1	3	C30	150	150	50	—	350
LC-N-1	3	LC30	150	150	50	—	350
LC-NS-1	3	LC30	150	150	50	S16	150
LC-NS-2	3	LC30	150	150	50	S16	200
LC-NS-3	3	LC30	150	150	50	S16	275
LC-NS-4	3	LC30	150	150	50	S16	350
Note: S16 represented a lag screw with a diameter of 16 mm and a length of 200 mm.							

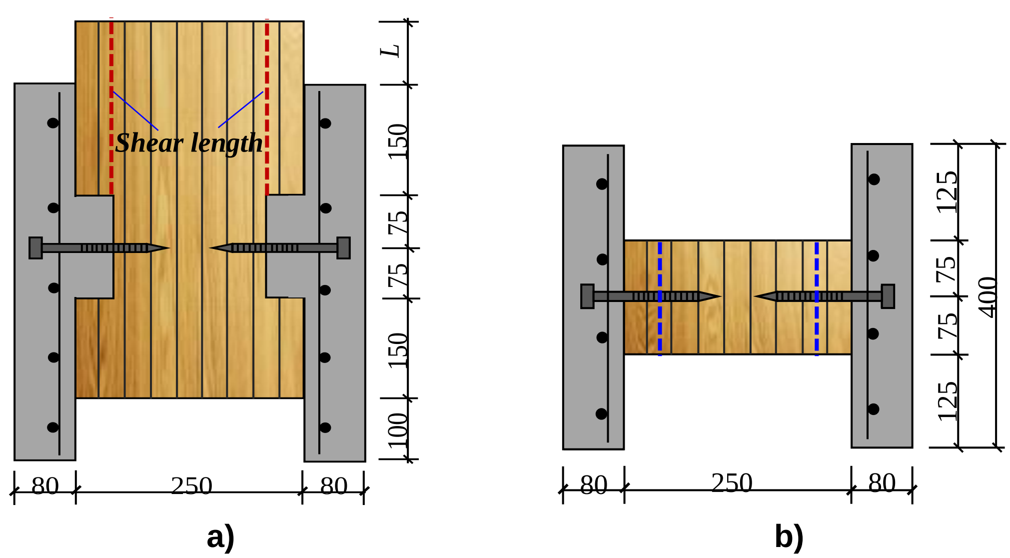

Fig. 1. Dimensions of push-out specimens (unit: mm): a) front view of specimens; b) top view of specimens. Note: In test series NC-N-1, LC-N-1, and LC-NS-4, *L* was 200 mm; in specimens LC-NS-1 through LC-NS-3, *L was* 0 mm, 50 mm, and 125 mm, respectively.

Test setups and loading procedure

For the push-out tests, the load was applied *via* a 300 kN universal testing machine (SHT4305, MTS Industry Systems (China) Co., Ltd, Shenzhen, China). As shown in Fig. 2, rubber pads were placed at the bottom of the concrete slabs to ensure that the concrete slabs had close contact with the table, and to avoid the stress concentration caused by the uneven bottom of the concrete slabs. During the tests, resistance-type displacement sensors with an accuracy of $\pm$0.1% F.S. were installed on both sides of the specimen to monitor the relative slip between the glulam and the concrete.

The push-out tests were carried out in accordance to the loading procedure specified in the European standard EN 26891 (1991). As illustrated in Fig. 3, F_{est} and F_{max} were the estimated shear capacity and the actual ultimate load of the connection, respectively. Based on the load-slip curves obtained from the tests, the shear capacity and stiffness (slip modulus) of the connections could be further determined.

Fig. 2. Test setup and measurements

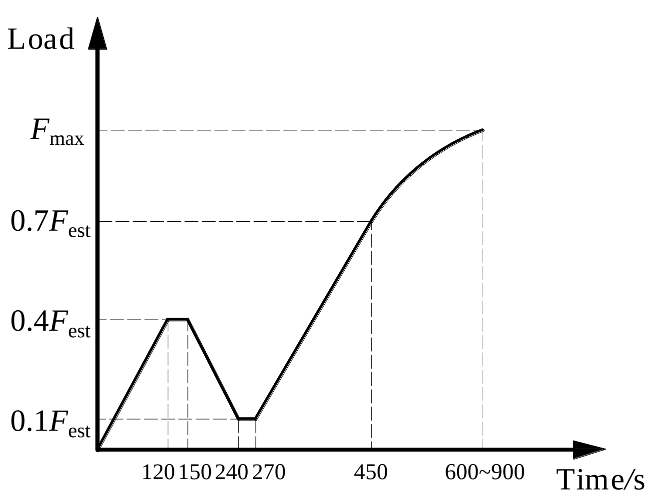

Fig. 3. Loading procedure according to EN 26891 (1991)

RESULTS AND DISCUSSION

Test Results

The primary results from the push-out tests are summarized in Table 2. Specimens in series NC-N-1 and LC-N-1 failed from shear force at the concrete slab portion of the sample, and the failure surface was located at the interface of the glulam and the concrete (as shown in Fig. 4a). The failure load of both the test series was relatively small, while the failure load of series NC-N-1 was slightly larger than series LC-N-1, which may be attributed to the fact that the shear strength of normal concrete is greater than lightweight aggregate concrete, with a similar compressive strength.

Specimens in series LC-NS-1 and LC-NS-2 (except sample LC-NS-1b) failed from shear force at the timber portion of the sample, as a result of insufficient shear length of the timber (a shown in Fig. 4b). For sample LC-NS-1b, the shear damage of the concrete at the notch occurred sooner, due to the poor casting quality, and thus the failure load was much lower than that of the other two specimens.

For the specimens in series LC-NS-3 and LC-NS-4, the shear length of the timber was relatively longer, and there were two possible failure modes, namely, the shear failure of the concrete with screws, from bending (C+S) (as shown in Fig. 4c), and the diagonal-compression failure of the concrete (DC) (as shown in Fig. 4d). Which of the two failure modes was more likely to occur was dependent on the pouring quality of the concrete for the notch. However, the deformation of the screw, which corresponded to the DC failure mode, was much smaller than the C+S failure mode. For the C+S failure mode, only one plastic hinge appeared on the screw at the shear plane.

Table 2. Push-out Test Results of the Notched Connectors

Specimen No.	F_{max} (kN)			K_s(kN/mm)			S (mm)	Failure Mode
	Value	Average	COV	Value	Average	COV		
NC-N-1a	162.04	160.75	0.04	229.64	229.62	0.06	0.90	C
NC-N-1b	153.89			216.52			0.98	C
NC-N-1c	166.31			242.70			0.92	C
LC-N-1a	148.40	138.29	0.09	230.96	234.38	0.09	1.01	C
LC-N-1b	142.79			215.32			1.02	C
LC-N-1c	123.69			256.85			0.89	C
LC-NS-1a	154.04	149.43	0.10	213.88	231.84	0.10	1.11	T
LC-NS-1b	132.80			222.91			3.31	C
LC-NS-1c	161.46			258.72			1.99	T
LC-NS-2a	223.38	218.46	0.03	264.87	247.35	0.06	1.38	T
LC-NS-2b	210.28			236.55			1.40	T
LC-NS-2c	221.73			240.62			1.59	T
LC-NS-3a	230.32	235.22	0.04	228.99	239.05	0.07	2.63	C+S
LC-NS-3b	229.17			257.47			2.73	C+S
LC-NS-3c	246.17			230.68			4.53	C+S
LC-NS-4a	203.23	220.84	0.09	253.54	249.40	0.02	2.91	DC
LC-NS-4b	240.71			249.50			1.70	C+S
LC-NS-4c	218.58			245.16			2.80	DC

Note: F_{max} is the maximum load for the push-out tests; K_s is the serviceability stiffness of the connection, which was determined according to EN 26891 (1991); S is the slip between the glulam and concrete at the maximum load F_{max}; C, T, C+S, and DC represent the shear fracture of the concrete, the shear fracture of the timber, the shear failure of the concrete with screws from bending, and the diagonal-compression failure of the concrete, respectively.

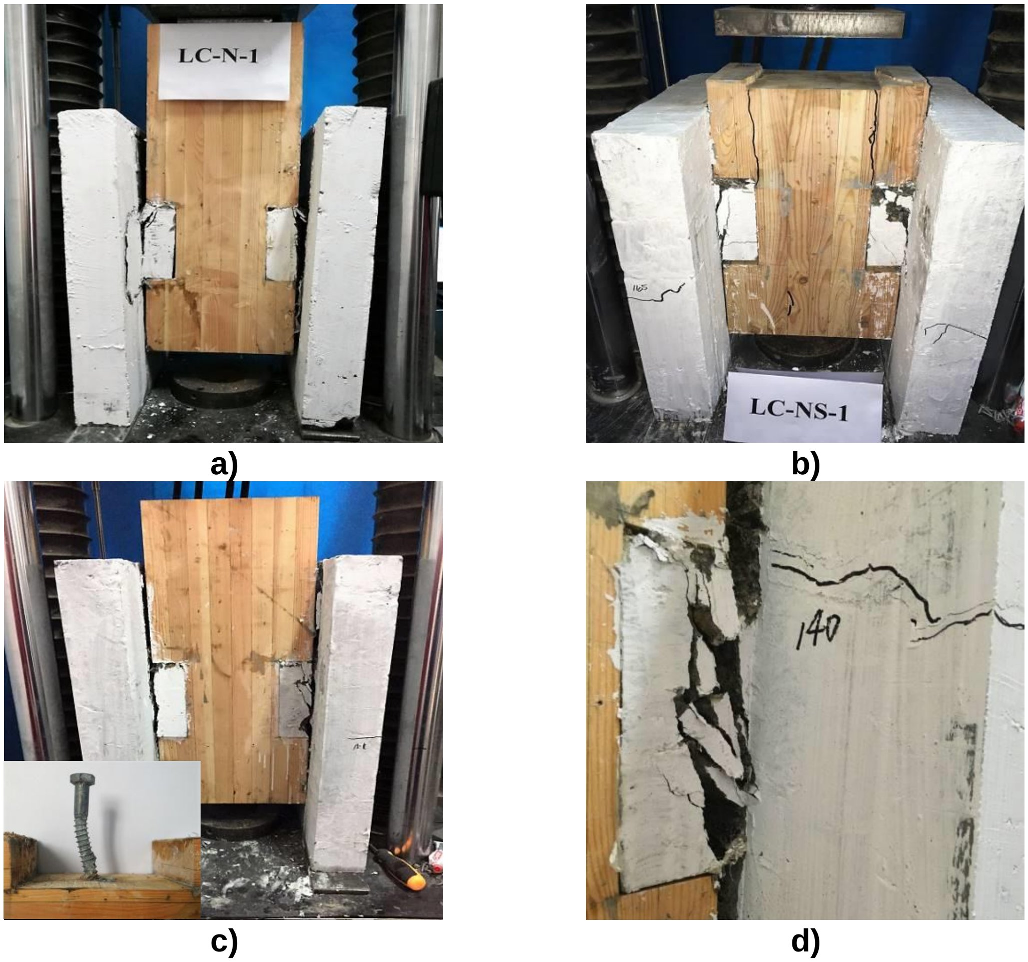

Fig. 4. Failure phenomena of the notched connectors: a) shear fracture of the concrete; b) shear fracture of the timber; c) shear fracture of the concrete with screw from bending; and d) diagonal-compression failure of the concrete.

It was noticeable, however, that all the investigated parameters, *i.e.*, concrete type, shear length of the timber, and whether the notch was reinforced, were found to have no major influence on the slip modulus of the notched connectors.

Load-slip Behavior

The load-slip curves could intuitively reflect the shear performance of the connectors. They provide an important basis for the analysis of the force mechanism of the TCC beams. The load-slip curves of the notched connectors from the push-out test are shown in Fig. 5.

For the notched connectors that failed from shear force at either the concrete or timber portion of the sample, the load-slip curves increased almost linearly until they reached the ultimate bearing capacity, and then the curves dropped sharply, which meant the connectors failed in a brittle way. However, for the notched connectors that corresponded to the C+S or DC failure modes, the post-peak behavior presented greater ductility. Therefore, it could be concluded that placing screw fasteners in the notch improved both the strength and the post-peak behavior of the connector.

By comparing the different failure modes, the notched connectors that corresponded to the shear fracture of concrete or timber had a low shear capacity and poor ductility. Notched connectors that simultaneously failed at the concrete slab (*via* shear force), as well as at the lag screw reinforcement point during bending presented the greatest shear capacity, followed by those occurred diagonal-compression failure of concrete. The last two failure modes had comparatively better ductility.

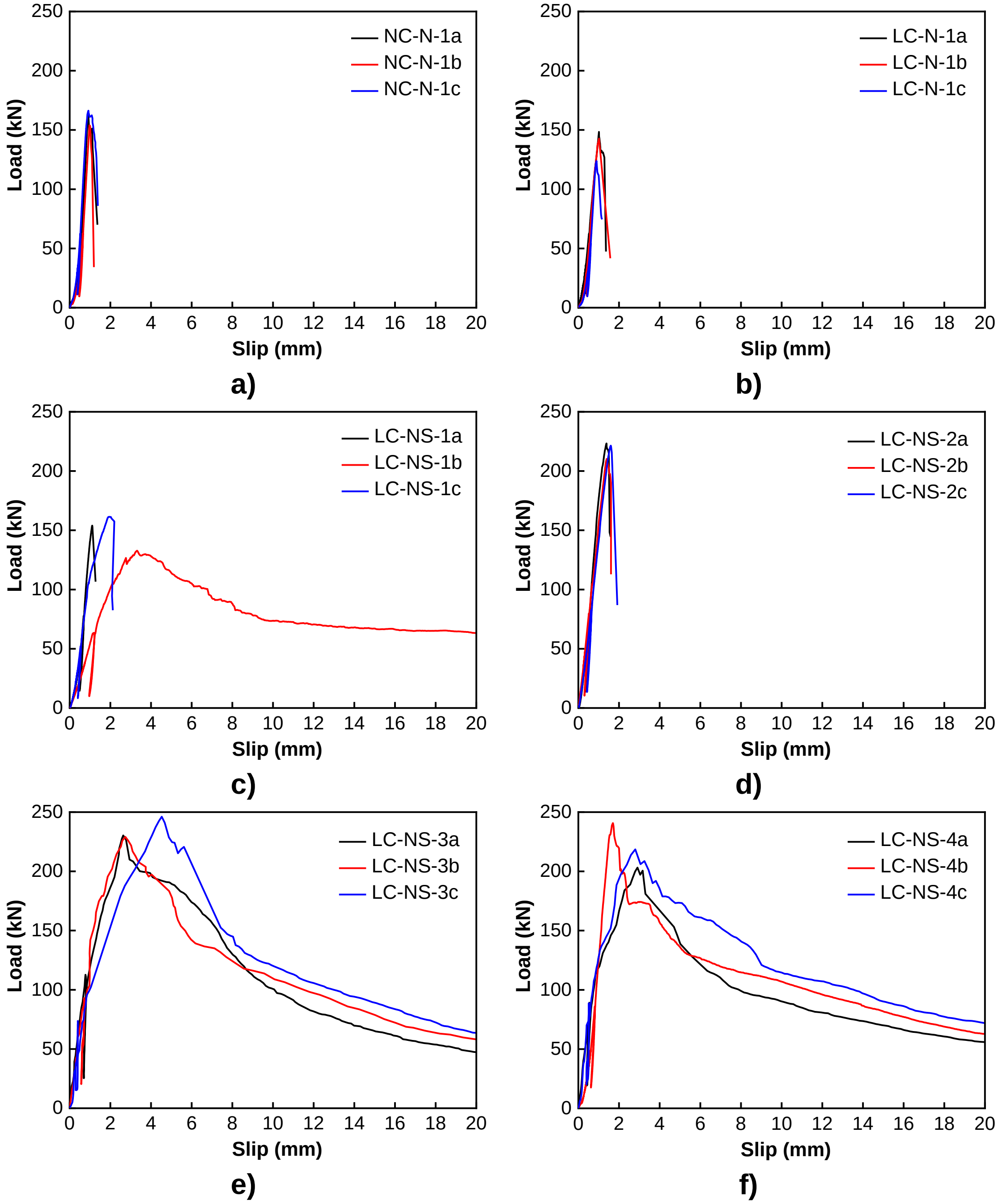

Fig. 5. Load-slip curves for the notched connectors: a) Test series NC-N-1; b) Test series LC-N-1; c) Test series LC-NS-1; d) Test series LC-NS-2; e) Test series LC-NS-3; and f) Test series LC-NS-4

Suggestions and Outlook

For the notched connectors, the shear fracturing of the concrete or timber portion of the structure should be avoided by utilizing proper design, in consideration of the low shear capacity and poor ductility. It is also necessary to set mechanical fasteners in the notch, to improve the ductility and post-peak behavior of the connection.

To establish a complete calculation method for the notched connector, additional parameters need to be studied. For example, the local bending moment that exists at the notch corner had an adverse effect on the shear strength of the concrete or timber and was positively correlated to the notch depth. In addition, the deformation mode and strength contribution of the screw fastener was very likely affected by its diameter and embedded depth in the timber. Therefore, parameters such as the notch depth, the screw diameter, and the embedded depth of the screw in timber, *etc.*, should be investigated in the future.

CONCLUSIONS

In this work, six groups of push-out tests were performed to investigate the shear performance of notched connectors for the timber-concrete composite beams. Based on the test results, the following conclusions can be drawn:

1. The notched connectors that corresponded to the shear fracturing of the concrete or timber portion of the sample had a low shear capacity and poor ductility. Notched connectors that simultaneously failed at the concrete slab (*via* shear force), as well as at the lag screw reinforcement point during bending presented the greatest shear capacity, followed by those occurred diagonal-compression failure of concrete.
2. The addition of screw fasteners in the notch was demonstrated to improve the strength, ductility, and post-peak behavior of the notched connectors.
3. All the investigated parameters, *i.e.*, concrete type, shear length of the timber, and whether the notch was reinforced, had no major influence on the slip modulus of the notched connectors.

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