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Performance of Notched Coach Screw Connection for Timber-Concrete Composite Floor System

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Summary

The notched connection for timber-concrete composite beams is obtained by cutting a notch from the timber beam and filling it with concrete during the pouring of the concrete slab. This type of connection has the advantage of high stiffness and strength compared to mechanical fasteners. The paper presents the outcomes of a parametric study of fourteen variations of notched connections which were loaded to failure under shear in push-out specimens. Laminated veneer lumber (LVL) was used for the timber part. Stiffness and strength values obtained from the different connection variations were compared to each other in order to identify the best types. Rectangular and triangular notches reinforced with a coach screw were found to perform satisfactorily. An alternative connection system with punched metal plates was also found to perform well, with the additional benefit of ease of construction. The experimental results were compared with numerical results carried out using a 3D finite element model implemented in ANSYS software package. Agreement was found between the predicted and the experimental failure mechanisms, however further work is needed to fully calibrate the software on the experimental results.

1. Introduction

The timber concrete composite (TCC) floor system is a construction technique where a concrete slab is mechanically connected to its supporting timber joists using either notches cut from the timber or mechanical fasteners. The concrete can be cast in-situ or alternatively the fasteners can be inserted into a prefabricated concrete slab to provide on-site connection to the timber. The shear connectors provide composite action which utilizes the advantages of both materials: tensile and bending resistance of timber, and compressive strength of concrete [1]. The performance of the TCC beam is significantly influenced by the behaviour of the connection system. Stiff and strong shear connectors are required to provide optimal structural efficiency. Some ductility is desirable since both timber and concrete exhibit quite brittle behaviour in tension and compression, respectively, and the plasticization of the connection is the only source of ductility for the TCC system [2-3]. However, the connection system needs to be inexpensive to manufacture and install in order to make TCC beams competitive with other construction systems such as steel and precast concrete floors.

At the University of Canterbury, New Zealand, a semi-prefabricated TCC floor system (see Fig. 1) is currently under investigation.. A timber panel made from laminated veneer lumber (LVL) joists and plywood sheets nailed on top of the joists will be prefabricated off-site. The panels will then be transported to the building site, lifted onto the supports, and propped at mid-span. They will form a permanent formwork for the concrete slab, which will be cast-in-situ. The connection system has notches cut from the LVL joist and reinforced with a coach screw to provide more ductile behaviour during failure and to increase the shear strength. The notched connection system was selected based on the outcomes of experimental tests performed on several types of connectors [4-6]. The notched connection was found to be far stiffer than mechanical fasteners, leading to higher composite efficiency and, therefore, to the possibility to use a limited number of connectors along the beam, resulting in a less expensive construction.

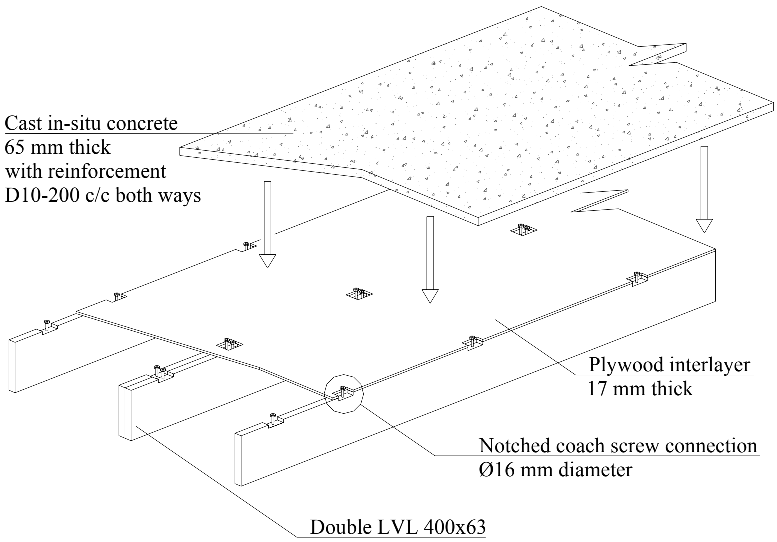


Fig. 1 Proposed semi-prefabricated TCC floor system

This paper reports the results of experimental tests recently performed on different notched connection systems. The purpose was to identify the parameters affecting the mechanical properties (shear stiffness and strength) and, ultimately, to optimize the connection detail. Geometrical variations included shape of the notch (rectangular, triangular and dove-tail), depth and length of the notch, use or not of a coach screw, diameter of the coach screw and the embedment length into the timber. In addition, toothed metal plate connections were also tested since this system is considerably easier to construct. The behaviour of all connections was characterized in terms of shear strength and stiffness at strength and serviceability limit state by testing small timber-concrete composite blocks with the connection loaded in shear (push-out specimens) to failure. Simplified analytical formulae based on the New Zealand Standard for the design of the notch under all possible failure mechanisms were developed and compared with the experimental results. A 3D finite element model of the connection detail was implemented into the ANSYS software package and compared with the experimental results.

2. Connection Push-Out Test

An experimental parametric study is essential for the optimization of the notch shape so that the best compromise between labour cost and structural efficiency is achieved. The performance of different connector shapes listed in Table 1 was evaluated through experimental push-out shear tests performed on small LVL-concrete composite blocks (see Fig. 2). Variations of the typical notched connection (see Fig. 3a) included the length, depth, and shape (dovetail, triangular and rectangular) of the notch. Coach screws of 12 mm and 16 mm diameters were also inserted in the centre of the notches in some cases, while in other cases no coach screw was used. The depth of penetration of the coach screw into the LVL, and the end distance of the notch from the LVL were also varied. Slightly modified toothed metal plate fasteners (see Fig. 3b) that are pressed in the lateral side of two adjacent 400 × 63 mm LVL joists were also investigated and compared with the notched connections. A total of 15 different types of connection were selected. Two push-out specimens were then constructed for each connection type, for a total of 30 specimens. The push-out tests were performed in accordance with EN 26891 [7] where the connections are loaded in shear and the load-slip relationship recorded using a load cell and potentiometers P1, P2, P5 and P6 (see Fig. 2).

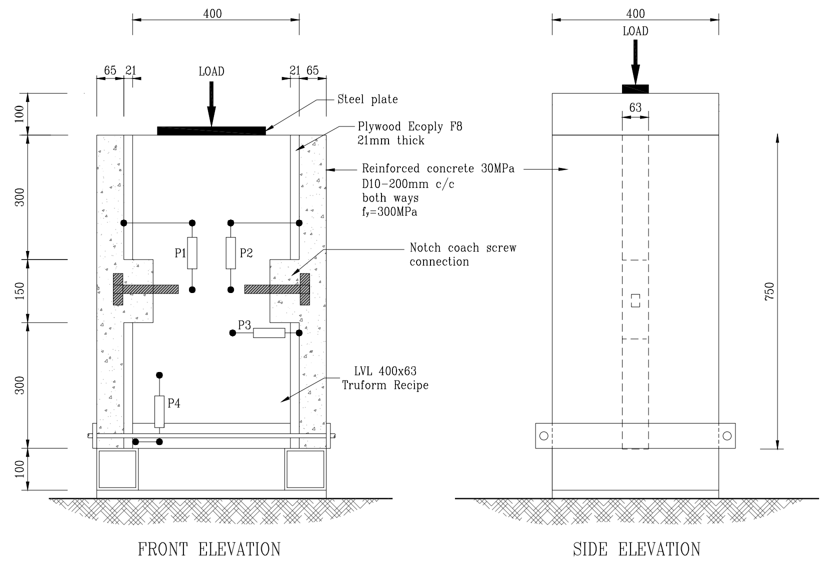
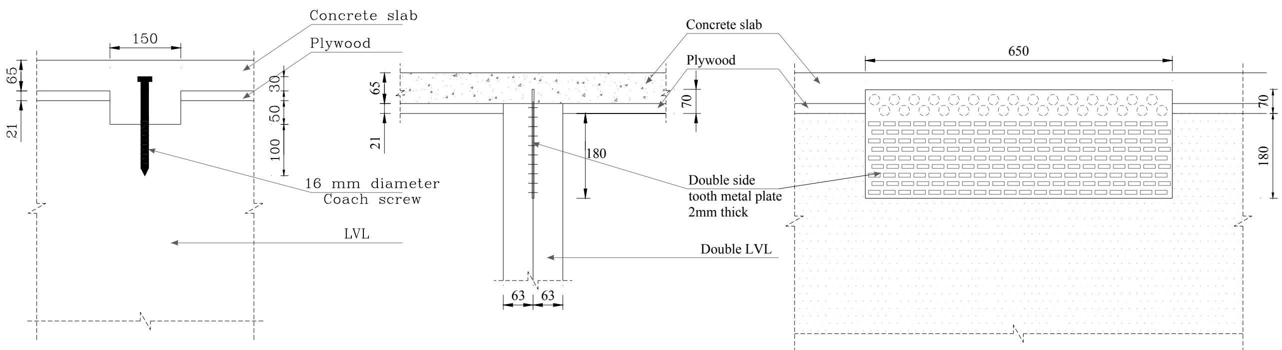


Fig. 2 Symmetrical push-out test setup (dimensions in mm)

2.1 Results and Discussion

The relationship between shear force and relative slip is presented in Fig. 4 for the 15 specimens most representative of the different connector shapes. The results in terms of shear strength (F_{max}), secant stiffness (also defined as slip modulus) at 40% ($K_{S,0.4}$), 60% ($K_{S,0.6}$) and 80% ($K_{S,0.8}$) of the strength [7] are summarized in Table 1. The strength F_{max} is defined as the largest value of shear force monitored during the test for slips not larger than 15 mm [7]. In order to provide some information on the post-peak behaviour and, therefore, on the ductility level, the ratio Δ2/Δ1 between the difference in strength at peak and at 10 mm slip, Δ2, and the peak strength, Δ1, is reported in Table 1. The lower the Δ2/Δ1 ratio, the better the post-peak behaviour and the higher the ductility.



(a) Typical Notched Coach Screw Connection

(b) Section and elevation of toothed metal plate specimen

Fig. 3 Typical notched coach screw and toothed metal plate connections (dimensions in mm)

The most important factors affecting the connection performance were found to be the length of the notch (compare F_{max} for specimens A1, 73kN and A2, 46kN) and the presence of a coach screw (compare F_{max} for specimens A1,=73kN, and B1, 48.3kN). Generally, all of the specimens failed by shear in the concrete (see photo in Fig. 4), hence a longer length of notch is necessary to improve the shear strength. The only source of ductility was provided by the coach screw, which also significantly increased the resistance. The presence of a coach screw and its depth of penetration into the timber (compare $K_{s,0.4}$ for specimens A1 with 100mm penetration,, 80kN/mm, and C2 with 140mm penetration, 211kN/mm,) significantly enhanced the stiffness of the connection.

The triangular shaped notch demonstrated close if not equal performance to that of a rectangular notch (compare F_{max} for specimens A1, 73kN, and E2, 83kN), thus making it one of the more viable options as it is much easier to manufacture. The metal plate connection (specimens H2, H3 and H4) exhibited a ductile plate tearing failure with high strength and stiffness. In addition, the strength of the latter connection can be easily determined from the plate's yield strength and length.

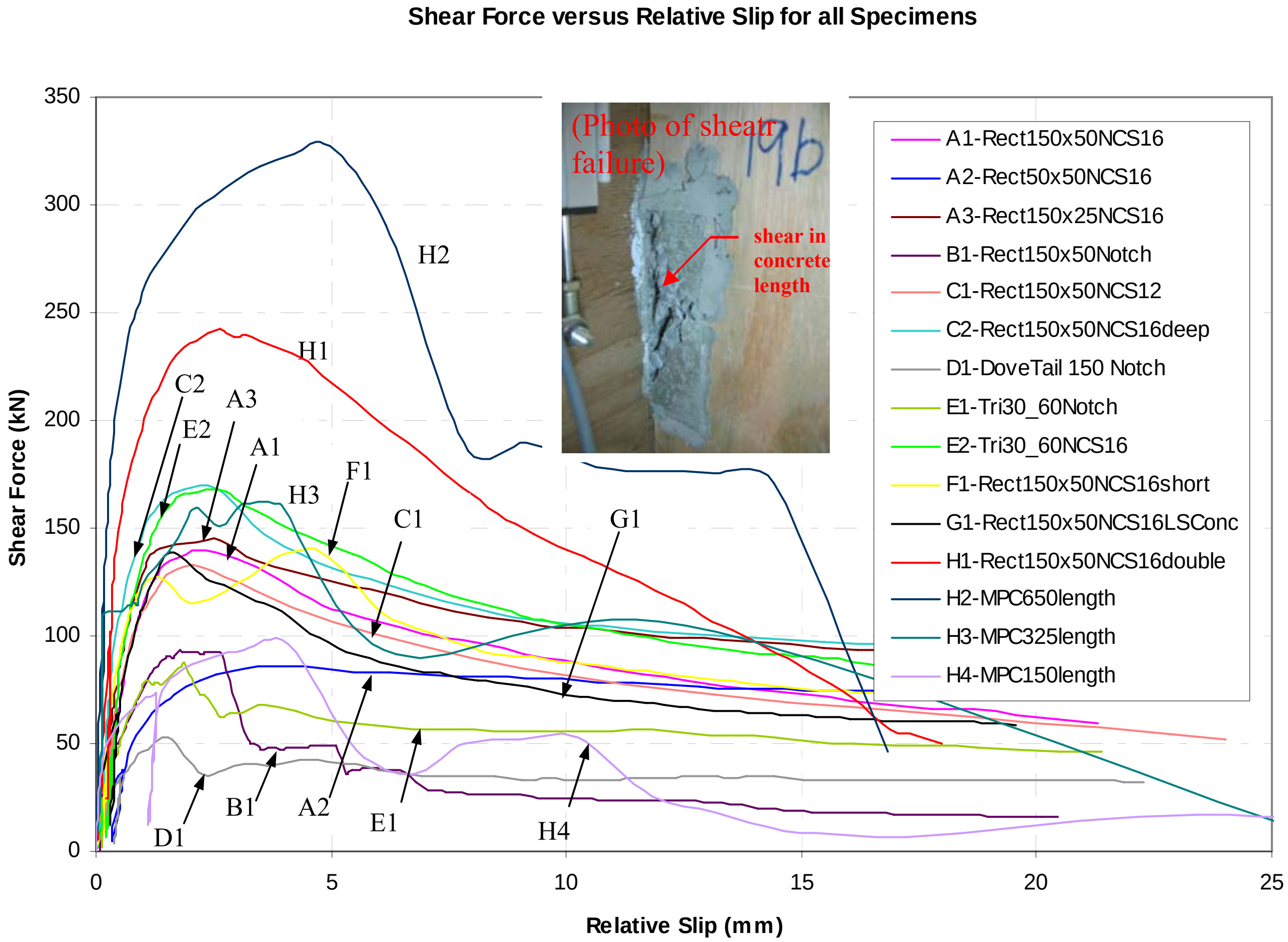


Fig. 4 Relationship between shear force and relative slip for 15 tested connection systems with photo of the shear failure in notched connection with coach screw

Based on the outcomes of these experimental tests to failure, and taking into account the ease of construction, the four most promising connection systems were selected: (1) 150 × 25 mm rectangular notch reinforced with 16 mm diameter coach screw; (2) 300 × 50 mm rectangular notch reinforced with 16 mm diameter coach screw; (3) 150 mm long triangular notch reinforced with 16 mm diameter coach screw; and (4) toothed metal plate connector. The 300 mm length of connection (2) was based on the length of notch being an important parameter in obtaining a strong connection. These systems are being used in the next phases of the experimental programme, the dynamic (vibrations) and static (collapse) test on full-scale strips of composite floor, which are currently in progress.

3. Simplified Analytical Model for Strength Evaluation

A simplified analytical model for strength evaluation of the notched connection is presented in Equations (1) to (4). The formulae were verified with the experimental results and were found to predict the failure load within acceptable range in most cases (see Table 1). The model is based on the control of all possible failure mechanisms that may occur in the connection region. The notched connection is regarded as a concrete corbel protruding into the LVL joist subjected to shear and bending moment coming from the shear load applied on the connection. The coach screw acts as reinforcement for the concrete corbel, and contributes to the shear transfer from timber to the concrete. Fig. 5 illustrates the failure mechanism experimentally observed during most of the tests. In general, a shear plane begun to form at $0.6F_{max}$. Thereafter, the coach screw started to act in tension until two plastic hinges were developed. At that stage, the coach screw transfers most of the shear of the connection by rope effect.

Table 1 Shear strength and stiffness values for 15 different connection systems

Connection Type (***length*** **×** ***depth*** **×** ***width*****) mm**	$\mathbf{F_{max}}$ **Exp.**	**kN Anal.**	$\mathbf{K_{s,0.4}}$ **kN/mm**	$\mathbf{K_{s,0.6}}$ **kN/mm**	$\mathbf{K_{s,0.8}}$ **kN/mm**	**Δ2/Δ1 (%)**
A1: Rectangular notch 150×50×63 Coach Screw ϕ16	73.0	68.5	80.2	75.4	61.7	35.5
A2: Rectangular notch 50×50×63 Coach Screw ϕ16	46.0	49.1	38.2	34.5	27.5	13.3
A3: Rectangular notch 150×25×63 Coach Screw ϕ16	71.8		112.8	102.2	76.1	26.1
B1: Rectangular notch 150×50×63	48.3	56.7	104.7	59.3	41.3	73.9
C1: Rectangular notch 150×50×63 Coach Screw ϕ12	66.0	66.3	77.9	74.5	62.3	38.8
C2: Rectangular notch 150×50×63 Coach Screw ϕ16 depth 140mm	84.2	87.8	211.2	145.0	95.5	36.5
D1: Doves tail notch 150×50×63	20.5		51.1	28.1	33.5	37.0
E1: Triangular notch 30°_60° 137×60×63	40.2		100.8	57.3	37.9	34.1
E2: Triangular notch 30°_60° 137×60×63 Coach Screw ϕ16	82.6		122.8	104.0	75.4	36.5
F1: Rectangular notch short end 150×50×63 Coach Screw ϕ16	74.4		92.7	91.1	73.6	49.0
G1: Rectangular notch LSC 150×50×63 Coach Screw ϕ16	68.8		67.0	66.9	56.1	49.3
H1: Rectangular notch double LVL 150×50×126 Coach Screw ϕ16	128.2		217.9	183.1	119.1	42.1
H2: Double sided toothed metal plate 650 mm	163.9	163.4	377.6	275.9	127.4	44.0
H3: Double sided toothed metal plate 325 mm	81.1	81.7	480.0	508.4	53.4	33.3
H4: Double sided toothed metal plate 150 mm	47.9	37.7	54.3	38.7	31.2	37.5

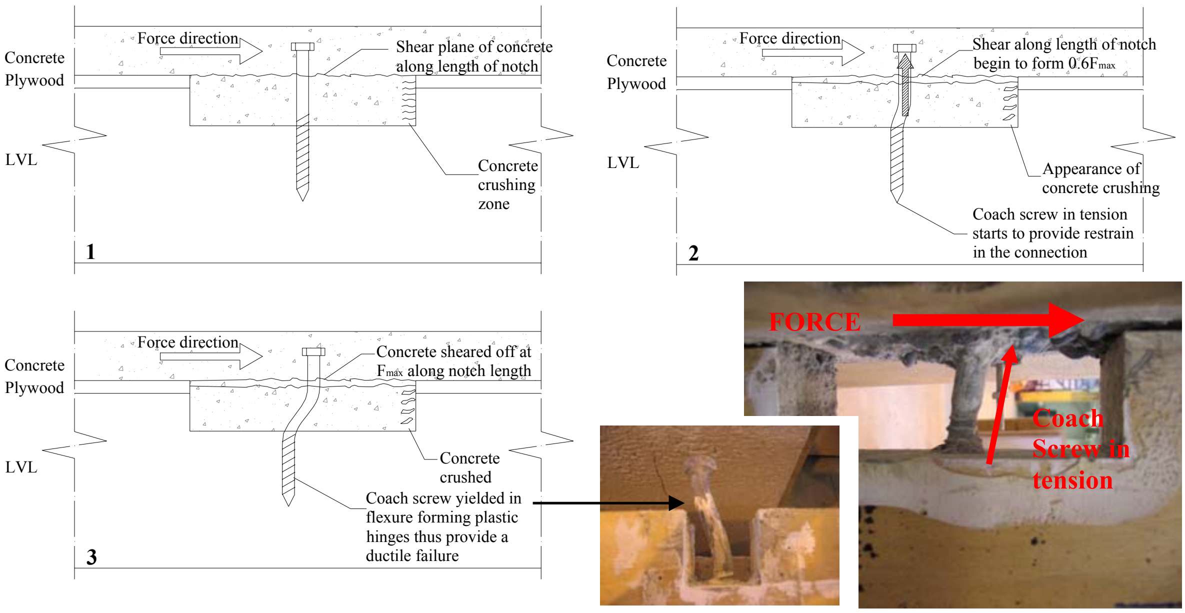


Fig. 5 Experimental failure mechanism of notched connection with coach screw

The design formulas are used to calculate the failure load associated with all the possible failure mechanisms of the connection, which are: (1) failure of concrete in shear in the notch; (2) failure of concrete in compression in the notch; (3) failure of LVL in longitudinal shear, between two consecutive notches or between the last notch and the end of the beam; and (4) failure of LVL in crushing parallel to the grain at the interface with the concrete corbel. The corresponding design strengths are calculated in accordance with provisions of the New Zealand Standards for both timber and concrete structures [8-9]. The formulas are reported in the following:

1) Nominal shear strength of concrete for a notched connection reinforced with a coach screw:

$$F_{conc,shear} = 0.2f'_c bd + nkpQ_k \quad (1)$$

where f'_c is the compressive strength of concrete, b and d are the breath and depth of notch, respectively, n is the number of coach screws, k is the modification factor for duration of loading for timber, p is the depth of penetration and Q_k is the characteristic withdrawal strength of the coach screw.

2) Nominal compressive strength of concrete in the crushing zone:

$$F_{conc,crush} = f'_c A_c \quad (2)$$

where A_c is the crushing zone effective area, i.e. $b \times d$.

3) Nominal longitudinal shear strength of LVL between two consecutive notches or between the last notch and the end of the timber beam:

$$F_{LVL,shear} = k_1 k_4 k_5 f_s Lb \quad (3)$$

where k_1 is the modification factor for duration of load, k_4 and k_5 are the modification factors for load sharing, f_s is the LVL characteristic shear stress, L is the shear effective length and b is the breadth of the LVL beam.

4) Compressive strength of LVL at crushing zone,

$$F_{LVL,crush} = k_1 f_c hb \quad (4)$$

where f_c is the LVL characteristic compressive stress, and h is the depth of the notch.

The design values of the shear strength is then obtained by multiplying the minimum among the four values reported above by the strength reduction factor ϕ.

4. Numerical Modelling of Notched Connections

A numerical analysis of the connection type A1 (see Table 1) was carried out using the finite element program ANSYS [10]. The planes of symmetry of the push-out specimen were used in order to reduce the number of degrees of freedom: only a quarter of the real geometry was modelled. The solid model and the mesh are represented in Fig. 6. A three-dimensional eight-node element with quadratic shape functions was selected to model the solid parts of the specimen (concrete, timber, and coach screw).

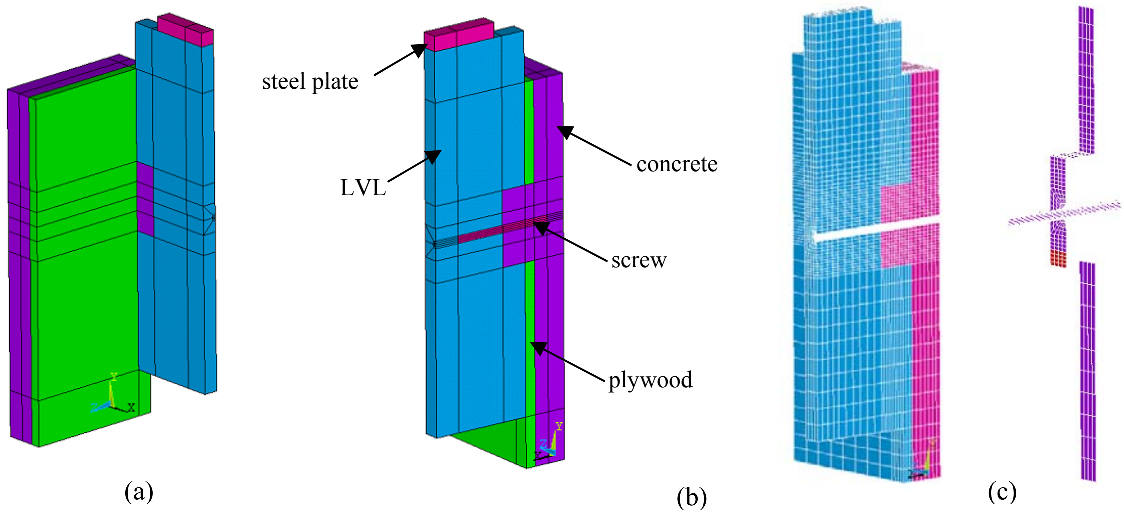


Fig. 6 Implemented geometry(a-b) and utilized mesh (c) for the numerical simulation

Non-linear material models with different strength values in tension and compression were used for concrete and timber. The anisotropic behaviour of timber was also included. The available "Aniso" material model, based on the generalised Hill potential theory [11], was chosen to simulate the timber behaviour. The "concrete" material option was used to model the concrete part of the model. The steel of the coach screw was modelled with a bilinear material law with kinematic hardening. For the interface between the concrete and the LVL and for the screw/concrete and timber/concrete surfaces, 3D contact elements were used to simulate the friction among these materials.

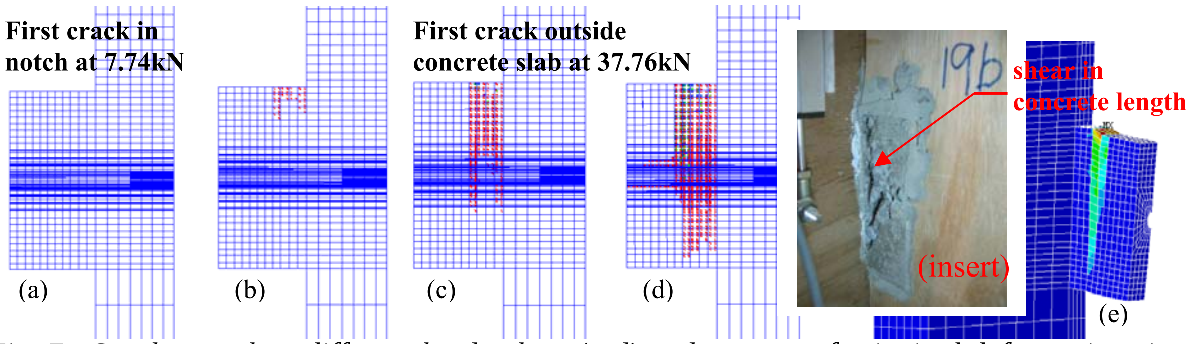


Fig. 7 Crack growth at different load values (a-d) and contour of principal deformations in the concrete part of the model (e). Insert photo shows the experimental comparison.

A non-linear numerical analysis was carried out by increasing the displacement on the steel plate on the top of specimen to failure. The progressive development of a crack path in the concrete is illustrated in Fig. 7 for different load steps, together with the contour of the principal deformations. By comparing Fig. 7(d–e) with Fig. 5, general agreement between the predicted and the actual failure mechanism can be noted. A visualisation of the principal concrete deformations in the notch is demonstrated in Fig. 7(e) which is found to be compatible with the experimental failure.

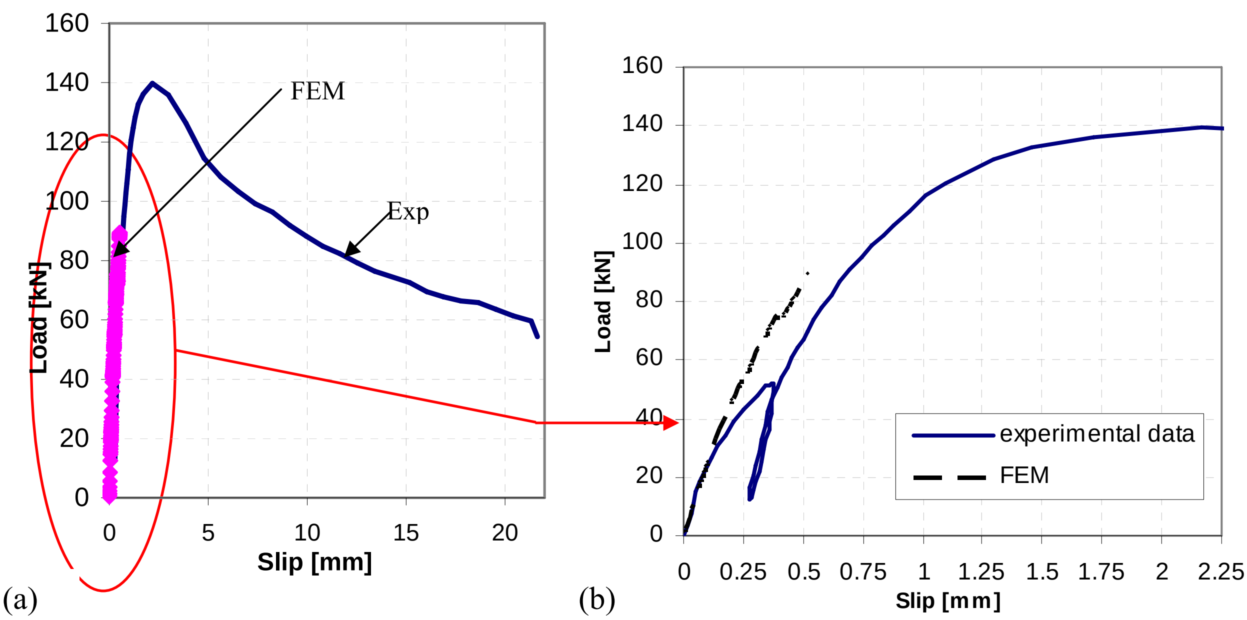


Fig. 8 Experimental and numerical load-slip comparison

The development of the numerical model is not yet concluded. At the moment the numerical results are not fully satisfying, due to the difference between predicted and experimental stiffness: the numerical value of 96.6 kN/mm represents about 120 % of the experimental secant value at 40% of the shear strength. Fig. 8 displays the experimental and numerical load-slip comparisons where the numerical relationship began to diverge from the experimental above the 30 kN load step. The numerical analysis could be run up to a load of 44.07 kN, when converge problems occurred. Such a value is lower than the experimental one (73 kN). Possible reasons for the convergence problems could be a mesh not adequate or the utilised material models. Some refinement and further investigation is therefore needed for the calibration of the 3D model on the experimental results.

5. Conclusion

Based on the results of the shear push-out tests performed on several connection systems, it can be concluded that rectangular and triangular notches cut from of the timber beam and reinforced with coach screws are an excellent connection system. High shear strength and stiffness can be achieved, along with acceptable post-peak behaviour characterized by gradual decrease in strength. The most important factors affecting the connection performance were found to be the length of the notch and the presence of a coach screw. Another promising system is the use of toothed metal plates pressed into the lateral surface of the LVL joists. This system avoids cutting the timber joist, providing a simpler and more cost effective construction detail with excellent mechanical performance.

Design formulas for the shear strength of the notched connection were derived, based on the control of all possible failure mechanisms. Those formulas were found to predict the experimental failure load within acceptable range in most cases. Lastly, the experimental results were compared with numerical results carried out using a 3D finite element model implemented in ANSYS software package. Predicted and experimental failure mechanisms agreed reasonably well, although some refinement and further investigation are needed to fully calibrate the model on the experimental results in terms of both strength and stiffness.

6. Acknowledgements

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