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MECHANICAL BEHAVIOUR OF TIMBER-STEEL COMPOSITE CONNECTION SYSTEMS

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ABSTRACT: Although timber is an ideal building material offering significant structural, environmental, and economic advantages, restrictions on the supply of high-quality timber is a limiting factor for the construction industry. To manage this problem, this study investigated an innovative approach to develop a sustainable and economical composite section with improved structural performance by combining low-grade timber and steel using advanced manufacturing technologies. In this paper, 20 specimens with 2 different configurations of this novel adhesive-free Timber-Steel Composite (TSC) connection system were designed, manufactured, and tested. By conducting standard pull-out tests on these new types of composite systems, the influences of factors such as type, pattern and spacing of the fasteners on the shear performance of these systems were evaluated and discussed. Test results demonstrated a significant difference between failure mode and nonlinear behaviour of nailed and screwed TSC connections. Screwed TSC connections showed on average 40% more shear capacity but 12% less stiffness compared to nailed TSC connections. A FE model of this composite system was developed and verified against test results. The FE model could accurately predict the nonlinear load-slip behaviour of this composite system. This model will be used in further work to develop an optimised full-scale TSC beam.

KEYWORDS: Timber-Steel Composite (TSC) connection system; Shear connectors; Static pull-out tests; Load-slip curves; Finite element modeling

1 INTRODUCTION

Timber is a strong, safe, and sustainable building material that offers significant structural, environmental, and economic advantages compared to other traditional building materials like concrete [1-3]. However, two significant reasons that are endangering the growing interest in timber construction are the high costs of manufacturing existing engineered mass timber products and limitations on the supply of high-quality timber [4]. One practical solution to address this problem is to combine low-grade timber with another building material like steel and manufacture a cost-efficient and sustainable composite section that would benefit from the structural advantages of both materials. Prior studies focused mostly on the potential for combining wood with other materials such as hot-rolled steel or concrete to create composite sections with better structural performance [5-8]. A literature review showed that even though the performance of some of these composite sections showed considerable improvement, the majority of them failed commercially because they used expensive materials or required a labour-intensive, and complex manufacturing methods [9, 10]. Therefore, the primary objective of this study is to develop a sustainable and economical composite connection system using low-grade timber and sheet steel and evaluate the performance of these novel adhesive-free components by conducting experimental studies and numerical modeling.

2 EXPERIMENTAL STUDY

2.1 MATERIALS AND METHODS

Timber material was provided from the Southern Queensland pine resource, which includes *pinus elliottii* var. *elliottii* (a.k.a. slash pine), *pinus caribaea* var. *hondurensis*, and a hybrid of the two species with F5 stress grade in accordance with AS 2858 [11]. F5 is the lowest grade of timber used in structural components with a nominal average modulus of elasticity of 6.9 GPa. All timber boards used for building TSC samples were cut with the same cross-section dimensions of (35 × 90) mm and length of 460 mm. Grade 250 structural steel plates with 1.6 mm thickness were utilised for manufacturing the composite specimens. All steel plates used for manufacturing specimens were cut with similar cross-

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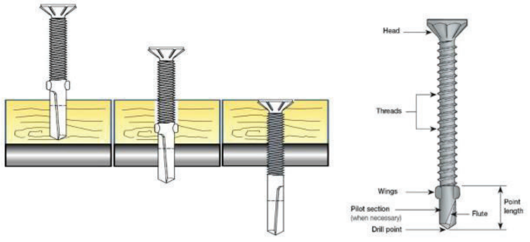
section dimensions of (1.6 × 90) mm and length of 340 mm. To fabricate each TSC specimen, a steel plate was placed in between two (2) F5 timber pieces in a symmetrical arrangement and all three layers were connected using mechanical fasteners. While smooth shank D-head nails with 2.87 mm diameter and 65 mm length were used for manufacturing of nailed TSC configurations, fully threaded self-drilling screws with 4.8 mm diameter and 70 mm length were used to fabricate screwed TSC configurations. The main advantage of using gun-driven D-head nails and self-drilling screws was increasing the speed of fabrication by elimination of pre-drilling timber and steel components.

Figure 1 shows the function and details of the self-drilling screws used for fabrication of TSC specimens of this study. The twist shaped point of this type of screw acts as a drill and eliminates the necessity of pre-boring timber and steel elements. To prevent threads from engaging the upper timber piece, wings of this type of screw help by making a clearance hole through the timber that is wider than the threads. At final stage, the wings hit the steel and break off and threads then begin to engage. In this way, application of this type of self-drilling screw creates a solid connection between the steel and timber layers.

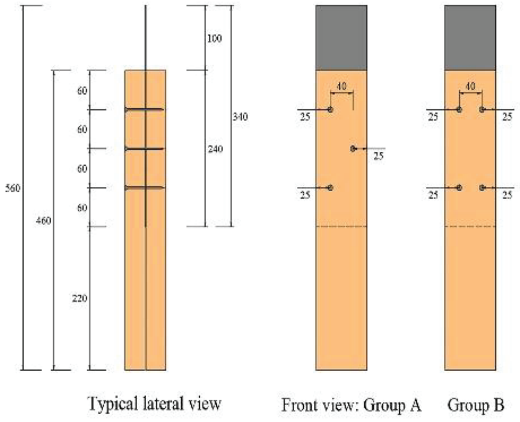


(a): Function *(b): Details*

Figure 1: *Self-drilling screws for developing TSC specimens*

Besides using simple, fast, and cost-effective fabrication method for developing these novel TSC connection systems, a unique testing setup and arrangement were fabricated to carry out the standard pull-out experiments of this study (Figure 2(a)). The pull-out tests were conducted on 20 TSC specimens with two (2) different configurations (Figure 2(b)) based on testing procedure provided by BS EN 26891 [12] standard to evaluate the effects of key parameters such as connector type, number, and patterns on the shear performance of these systems. The lower part of each specimen was held with three (3) bolts and the upper part was gripped in the jaws of the machine. As shown in Figure 2(b), specimens of group A were manufactured with three (3) fasteners with staggered pattern, while group B samples were built with four (4) fasteners with linear pattern. To evaluate the performance and effects of using different types of fasteners, all samples of each different group were fabricated using both D-head nails and self-drilling screws.

(a): Test setup



(b): Different TSC configurations

Figure 2: *Pull-out test on TSC connection systems*

2.2 CONFIGURATIONS, LOADING PATTERN AND INSTRUMENTATION

To make a direct comparison between different TSC configurations with various fasteners' pattern and spacing, the connectors end, and edge distances of all specimens were considered the same. Table 1 shows details of each TSC configuration of this study.

Table 1: *TSC configuration details and characteristic*

Group name	Config. ID	Type and size of connector	Spacing (mm)	Number of specimens
Group A	TSCA1	D-head Nail (∅ = 2.87, L= 65)	60	5
	TSCA2	Self-drilling Screw (∅ = 4.8, L= 70)	60	5
Group B	TSCB1	D-head Nail (∅ = 2.87, L= 65)	120	5
	TSCB2	Self-drilling Screw (∅ = 4.8, L= 70)	120	5

All specimens were loaded parallel to the grain direction until total failure. The pull-out loading protocol was based on a modified approach presented by the BS EN 26891 [12] standard with initial loading and unloading to remove any internal looseness between timber and steel elements. The load-slip curve of each specimen was obtained using two laser extensometers placed at both side of each sample.

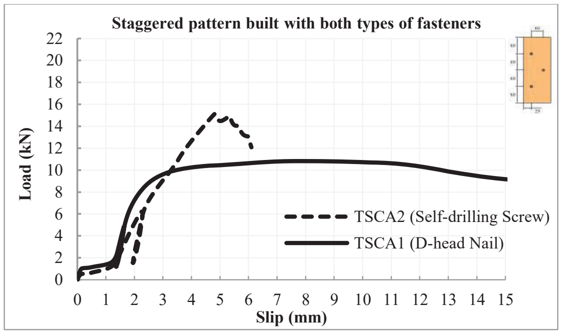
3 TEST RESULTS AND DISCUSSION

To compare the performance of various TSC configurations, the average nonlinear load-slip curves of all tested specimens of each configuration were plotted.

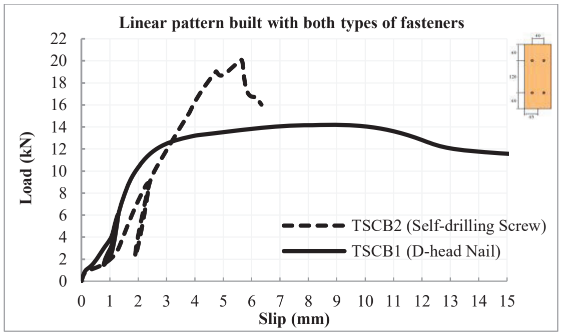
To evaluate the effects of different types of connectors on the shear performance of TSC connection systems, Figure 3 illustrates the average load-slip curves of TSC connections with staggered and linear connectors' patterns each of them built with both self-drilling screws and D-head nails.

As the load-slip curves clearly show, the major difference between nailed and screwed TSC connections is their failure modes and nonlinear behaviour of the connections after reaching their yield load. While nailed TSC connections experienced ductile behaviour with gradual failure, screwed TSC connections showed brittle behaviour with sudden failure. After reaching their ultimate load, nailed connections still had remarkable residual capacity left and this trend continued until total failure of the system, while the screwed connections suddenly failed with no residual capacity left in the system.

According to the test results and obtained nonlinear load-slip curves of all tested specimens, self-drilling screws showed greater load-carrying capacity in comparison to D-head nails used in TSC connections with both staggered and linear fasteners patterns. Using self-drilling screw instead of D-head nail for manufacturing TSC connections improved the yield, ultimate, and maximum load-carrying capacity of TSC configurations with staggered fasteners' pattern on average by 60%, 40%, and 40%, respectively. In contrast, due to this replacement the stiffness of the TSC connection reduced on average by 12%. Similarly, screwed TSC connections with linear connectors' pattern showed on average 40% more load-carrying capacity and 17% less stiffness compared to nailed ones with the same fasteners' pattern.

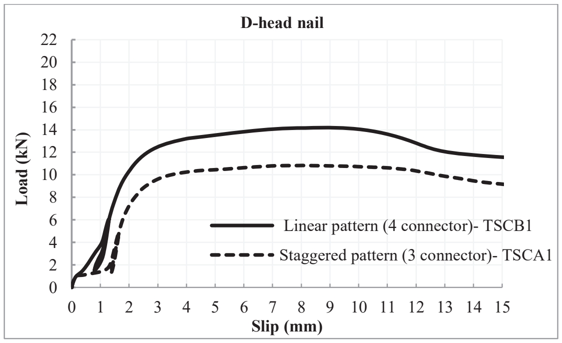


(a): Staggered pattern

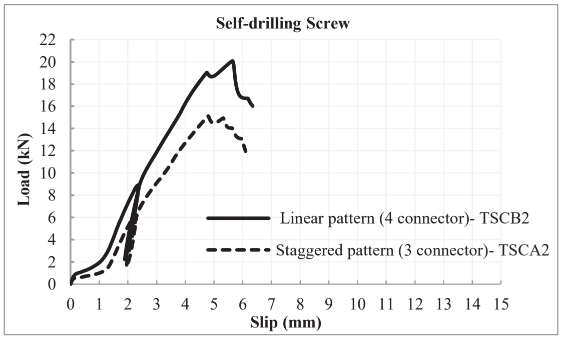


(b): Linear pattern

Figure 3: *Average load-slip curves of TSC connections with various connectors' patterns built with both types of fasteners*



(a): D-head nail



(b): Self-drilling Screw

Figure 4: *Average load-slip curves of nailed (top) and screwed (bottom) TSC connections with staggered and linear patterns*

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Figure 4 shows the influences of number and patterns of the fasteners on shear performance of the TSC connection systems.

According to the test results, the shear capacity and stiffness of both nailed and screwed TSC connections significantly improved by one fastener addition. We expect to see an improvement of 33% with the addition of an extra connector.

For nailed TSC connections, the shear capacity and stiffness of the specimens with linear pattern improved on average by 31% and 36%, respectively compared to nailed samples with staggered pattern. This aligns with expectations.

For screwed TSC connections, the shear capacity and stiffness of the specimens with linear pattern increased on average by 33% and 28%, respectively compared to in comparison with screwed specimens with staggered pattern. This aligns with expectations.

4 NUMERICAL MODELING

A nonlinear 3D finite element (FE) model of nailed TSC connection with linear connectors' pattern was developed and analysed using CSI SAP [13] structural analysis software (Figure 5). The result of the nonlinear load-slip of the numerical FE model was compared and validated with experimental results.

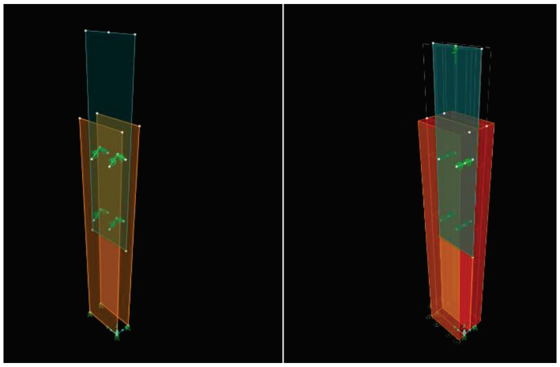

Figure 5: *FE model of nailed TSC connection in SAP program*

4.1 MATERIAL MODELLING

Timber was modelled as a nonlinear orthotropic material. To define the behaviour of F5 timber in the elastic zone, the material properties were obtained by conducting standard tests according to AS/NZS 4063.1:2010 [14] as presented in Table 2.

To define the nonlinear behaviour of timber under loading in plastic zone, the stress-strain curves of timber obtained by conducting standard compression and tension material tests on F5 timber specimens were used as shown in Figure 6.

Grade 250 structural steel was modelled as a nonlinear isotropic material with modulus of elasticity and Poisson's ratio equal to 200100 MPa and 0.3, respectively. Thanks to information obtained from the manufacturing company, the stress-strain curve of G250 steel plate was defined, as shown in Figure 7, to consider the actual behaviour of steel plate under loading.

Table 2: *Elastic Material properties and parameters for developing numerical models of F5 timber*

Description	Value
Longitudinal modulus of elasticity	6447 MPa
Tangential modulus of elasticity	290 MPa
Radial modulus of elasticity	477 MPa
Poisson's ratio for deformation along the tangential axis	0.444
Poisson's ratio for deformation along the radial axis	0.392
Poisson's ratio for deformation along the tangential axis	0.447
The modulus of rigidity based on shear strain in the LT plane	341.7 MPa
The modulus of rigidity based on shear strain in the LR plane	354.6 MPa
The modulus of rigidity based on shear strain in the RT plane	64.5 MPa

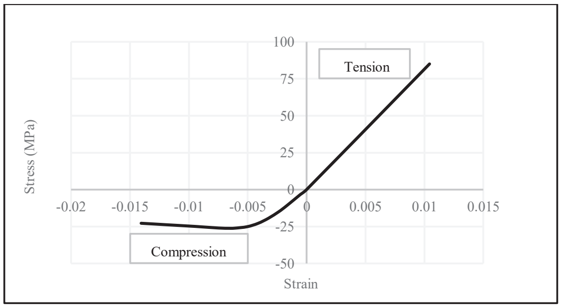

Figure 6: *Nonlinear stress-strain curve of F5 timber material in compression and tension zone*

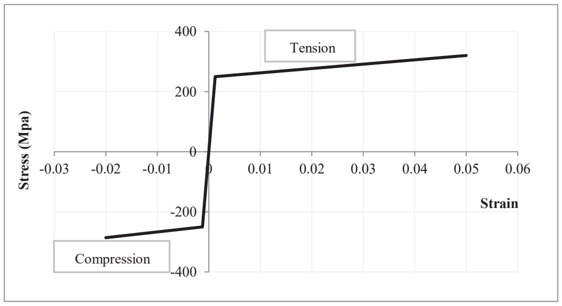

Figure 7: *Bilinear stress-strain curve of Grade 250 structural steel in compression and tension zone*

4.2 SHEAR CONNECTORS MODELLING

Fasteners can be modelled in CSI SAP software [13] using nonlinear two-joint link elements to connect timber and steel components as illustrated in Figure 8. This element has six controllable degrees of freedom (DOF) including three translational springs (U1, U2, and U3) and three rotational springs (R1, R2, and R3). U1 is an axial spring, U2 and U3 are shear springs, R1 is a torsional spring, and R2 and R3 are pure bending springs.

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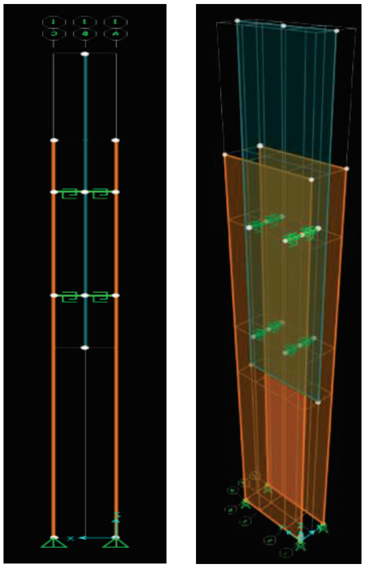
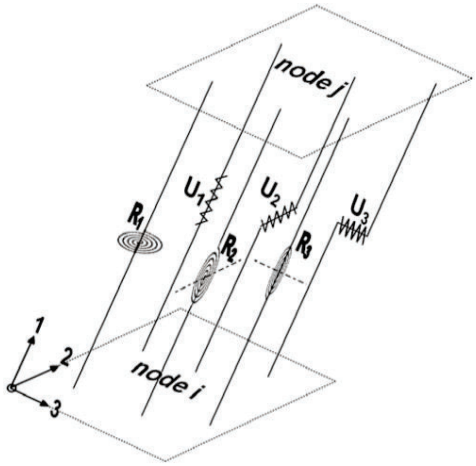


(a): Developed FE model in SAP



(b): Six DOF of link element

Figure 8: *Nonlinear two-joint link element used for modeling fasteners in CSI SAP software*

In actual testing condition, the compression of the fasteners is negligible. Therefore, to avoid the link elements being compressed or elongated during analysis, the U1 axial spring was fixed. The pure bending springs R2 and R3 were also fixed to avoid any relative rotation of the steel plates and timber boards during analysis. Torsional spring R1 represents the actual spinning of the nail inside the wood components. To consider this behaviour a stiffness of zero was assigned to this spring to enable the free torsional rotation of the link elements. The accurate nonlinear behaviour of the connectors was considered in the FE model by defining and assigning the nonlinear load-slip curve obtained by conducting pull-out tests on TSC connections to U2 and U3 shear spring as shown in Figure 9. Since the responses of the link elements in the U2 and U3 DOF are independent, they were defined uncoupled.

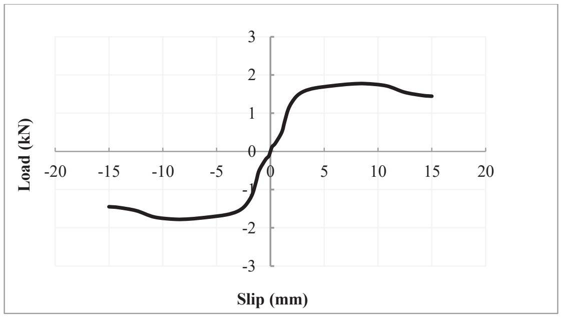


Figure 9: *Nonlinear load-slip response of each link element*

SAP software offers several options to define the nonlinear features of the link element among which the multi-linear Takeda plasticity property was chosen since it allowed the precise definition of the load-slip data even with this capability to consider stiffness degradation under cyclic loading condition.

Each connector was modelled by two link elements at each side of the steel plate so that the sum of the forces of two link elements were equal to the force of each fastener.

4.3 FE MODELLING PROCEDURE

Both timber boards as well as steel plate were modelled by Thick Shell Element. By assigning the nonlinear material properties that were defined in section 4.1 to these elements, the actual nonlinear behaviour of these elements was considered.

Eight points were defined on the middle steel plate and four points were defined on each timber board at the exact location of the fasteners to assign the nonlinear two-joint link element at these places for connecting timber and steel plates. All points on each shell element were constraints as a full body to move and rotate as a uniform element. To model restraint effects of steel brackets in actual testing condition, the end of each timber board was restrained as a pinned support to prevent translation in three (3) directions.

Unit loads at locations of loading points were assigned to the steel plate. This load was incrementally increased and pulled the steel plate upward until the control point at the top of the steel plate reach the target displacement. Nonlinear displacement controlled static pull-out analysis were then performed by considering P-Delta effects to fully monitor large displacement due to nonlinear behaviour of the connectors.

4.4 ANALYSIS RESULTS

Figure 10 shows the comparison between the average experimental load-slip curve obtained by conducting pull-out tests on nailed TSC connections (grey line) with linear connectors' pattern and the simulated load-slip curve obtained from the developed FE model of this TSC configuration in CSI SAP software (black line). Clearly, the FE model closely simulates the load-slip response of the connection system. The model could precisely predict the behaviour and stiffness of the connection in the elastic zone and closely determine the yield point and maximum load-carrying capacity of the system (Table 3). More importantly, the developed FE model could accurately reflect the real nonlinear behaviour of the connection system by simulating the strength reduction and stiffness degradation after reaching its peak shear capacity. It should be noted that since the FE model was analysed under uniform loading condition, it did not reflect the initial slip of the system that was monitored in the actual tests due to applying ISO loading pattern with initial loading and unloading steps.

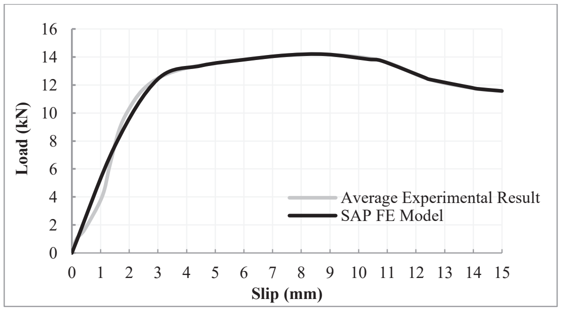


Figure 10: *Comparison between experimental and numerical load-slip curves of nailed TSC connection*

Table 3: *Comparison of experimental and FE results*

Config. ID	F_{Exp} (kN)	F_{FE} (kN)	V_{Exp} (mm)	V_{FE} (mm)	$\frac{F_{Exp}}{F_{FE}}$	$\frac{V_{Exp}}{V_{FE}}$
TSCB1	14.19	14.18	8.85	8.86	1.0007	0.9988
Standard Deviation	1.17	-	1.21	-	-	-

Note: *F* denotes maximum load and *V* is the joint slip corresponding to the maximum load.

5 CONCLUSION

Several pull-out tests on different configurations of a novel TSC connection system were conducted to monitor the shear performance and capacity of the specimens and evaluate the impacts of key variables such as various type, pattern and spacing of the fasteners. In addition, FE model of this composite system was developed in CSI SAP software and the analysis result of the model was compared and verified against experimental load-slip curve.

The test results showed critical difference between failure mode and nonlinear behaviour of nailed and screwed TSC connections under loading condition. While nailed TSC connections showed ductile behaviour with gradual failure, screwed TSC connections experienced brittle behaviour with sudden failure. Self-drilling screws showed 40% more shear capacity compared to D-head nails used in TSC connections. However, screwed TSC connections had on average 12% less stiffness compared to nailed ones. TSC connections with linear pattern of fasteners showed on average 30% more load-carrying capacity compared to the TSC configurations with staggered pattern.

The developed FE model could simulate the nonlinear load-slip response of the nailed TSC connection with great accuracy. This modeling approach offers a simple means to investigate the influences of key variables such as a greater number of fasteners or different thickness of steel and timber elements on shear capacity of the TSC connection system. The calibrated FE model will be refined with additional test results of various configurations and used to develop optimised full-scale TSC beams. Furthermore, to further investigate the effects of various variables, a comprehensive parametric study will be conducted in future research.

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