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INVESTIGATING NOVEL STEEL-TIMBER CONNECTIONS AND THE EFFECTS OF KNURLING THROUGH EXPERIMENTAL DIRECT SHEAR TESTING

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ABSTRACT: Hybrid steel-timber floor systems, combining cross-laminated timber (CLT) panels and steel wide-flanged beams, are being constructed across the United States due to their sustainability and prefabrication benefits. However, despite their increasing adoption, knowledge gaps remain regarding their vibration behaviour and seismic performance. To address these gaps, six small-scale direct shear tests were conducted to evaluate the performance of steel-to-timber connections using novel steel-tapping screws. Two test series were investigated: one with a normal (smooth) steel top-flange surface and the other with a knurled steel top flange surface. Results demonstrated that knurling increased peak force by 22% and yield strength by 47%, though it reduced initial stiffness and ductility. Connections exhibited ductile failure mechanisms, characterized by CLT crushing, fastener yielding, and progressive failure. These findings highlight the potential for optimizing hybrid floor connections for both vibrational and seismic demands. Future work will explore alternative fastener systems and full-scale structural testing.

KEYWORDS: CLT, steel, hybrid, connection, experimental

1 – INTRODUCTION

Both steel and mass timber consist of prefabricated elements, which expedites the construction process, reduces on-site labour, and lowers cost of construction. In addition, structural steel is the most recycled material in the world [1] and mass timber is fabricated from renewable resources. These qualities enable steel-mass timber hybrid structures to be marketable as a building framing system that can reduce the cost of construction, increase the speed of construction, and meet sustainable construction performance objectives. Due to these apparent benefits, such structures are being built throughout the United States. However, even though these designs are being constructed, there are knowledge gaps as it pertains to (1) stiffness of the floors for serviceability limit states (e.g., vibration) and (2) diaphragm design for seismic or wind applications.

Much of these knowledge gaps fall in the range of limited understanding of the fundamental mechanisms of composite action between steel and mass timber, particularly cross laminated timber (CLT). Serviceability composite action examines the potential for slip at the connectors at low amplitude demands; whereas seismic demands on diaphragms will impose large shear force demands on the connectors. This paper will summarize an ongoing testing regime conducted at Oregon State University in collaboration with Virginia Tech to quantify and evaluate the performance of shear connectors for steel-CLT hybrid floors.

2 – BACKGROUND

Previous research on steel-timber hybrid floors has investigated steel-timber connectors such as large diameter screws (diameters greater than 6.35 mm) [2-6], large diameter screws with glue [2, 3], and bolts [2, 4]. This previous research concluded screwed connections have less initial stiffness than glued and bolted connections, however screwed connections have significantly greater ductility while bolted and glued

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connections demonstrate brittle failures [2, 3]. Across many investigations screws were observed to have large ductilities [3-7]. For screwed connections, the major determining factors for capacity and stiffness were embedment depth, spacing and diameter [4-8]. Increases to embedment depth increased the shear capacity of connections until a maximum effective embedment was reached, whereafter increases to embedment depth had no further effect on capacity [6, 7]. Increasing the screw diameter resulted in a decreased stiffness of the connection but increased ultimate capacity [4]. However, most screw connectors that have been tested were installed from below the beam. This installation method can be overly burdensome for construction workers adding substantial time to the construction project and compromising construction safety measures.

To address many of these construction challenges, screws have been developed that could be installed from the top of the CLT surface into the top flange of the wide-flanged beam. These screws were previously investigated by Nicholas [9]. These tests included direct shear and bending tests of the screws. the results of these tests demonstrated that the screws have a bending yield strength of 870 MPa, and a shear strength of a single fastener of 43.6 - 49.0 kN.

Yang et al. [10] also tested fasteners that thread into steel flanges and drive through wood. In this experimental program, no predrilling was performed on the 8 mm thick steel flange. The fasteners were observed to have a large post-peak displacement capacity, and after testing they were observed to have two plastic hinges indicating ductile behaviour from the fasteners. The fasteners were determined to be stiffer than the bolts that were also included in the testing program.

Adhesives and nail plates added to connections increase the friction between the two materials and often resulted in higher capacities and stiffnesses at the expense of producing brittle failure modes [3], [11], [12]. Adhesives unfortunately impede the fast construction that steel-timber hybrid floors provide due to the required curing time for the adhesives to set. However, mechanical additions such as nail plates allow for fast construction while still providing strength and stiffness bonuses at the cost of ductility.

3 – RESEARCH OBJECTIVES

The objectives of this research are to: (1) Investigate the failure mechanisms, strength, and ductility of novel steel-tapping screws within steel-timber hybrid floors, (2) evaluate the effect of increasing friction between the steel beam and CLT on the behaviour of these connectors, and (3) compare the effectiveness of using top drilled screws compared with previous literature on steel-timber hybrid floor connectors.

4 - MATERIALS AND METHODOLOGY

To determine the strength and stiffness of novel timber connectors as well as how those characteristics are affected by knurling of the top flange, small-scale direct shear tests following the EN 26891 standard [13] modified to be displacement controlled were conducted on two test series. These small-scale test specimens consisted of a CLT deck fastened to the top flange of a W24x55 steel beam (Fig. 1). The CLT used was 5-ply V2 grade spruce-pine-fir (SPF) 175 mm thick, 1.22 m wide, and 0.61 m in length.

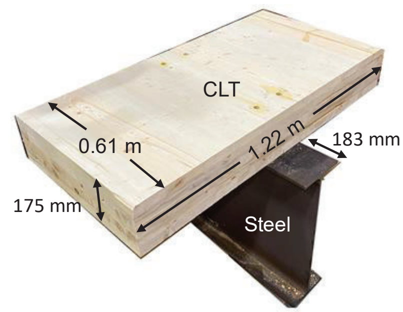

Figure 1. Fully built test specimen.

For all the test specimens, four steel-tapping screws connected the CLT to the steel beam. The screws were inserted from the top of the CLT through the CLT and the steel top flange. An image of the proprietary screws, MTC fasteners item number 360070133000808, is included in Fig. 2. The screws were 135 mm long, featuring a countersunk head with a head diameter of 17.5 mm, and a root diameter of 6.35 mm. Although the screws have a self-drilling tip, it is not adequate to drill through the 12.8 mm thick steel flange, therefore, each hole was predrilled through the entire thickness. Screws were installed with a spacing along the length of the beam of 457 mm, to avoid group effects. This distance was also chosen as it provides enough stiffness to restrain the top flange of the beam from buckling.

Figure 2. Proprietary fastener.

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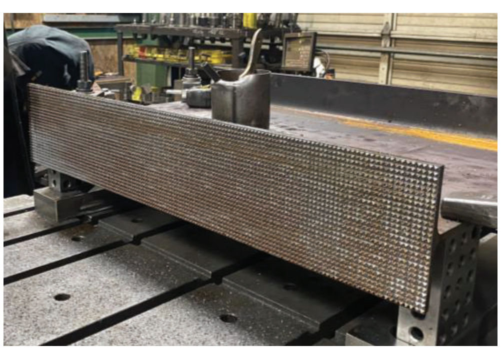
The length of the screw was shorter than the combined thickness of the CLT and beam top flange, therefore, holes for the screws were counterbored 70 mm deep in the screw locations to allow for the head of the screws to penetrate into the wood. The CLT and steel were predrilled together with a hole diameter equal to that of the root diameter of the screw (6.35 mm). Since the threaded length of the screw is present in both the steel and the wood, the screws were effectively fully threaded.

The first test series featured these screws inserted from above and an unmodified top flange surface and is referred to as series SA. The second test series featured screws from above in addition to a knurled top flange surface for increased friction at the interface between the CLT and the steel and is referred to as series SAK. This knurling effect was achieved through cutting 3.2 mm grooves into the top surface perpendicular and parallel to the direction of load creating a grid of pyramid-like protrusions on the surface. Pictures of the process and the resulting surface finish are included in Fig. 3.

The steel-CLT beam was loaded by an actuator attached to a strong wall. Each specimen was placed on two rollers to allow uninhibited translation in the longitudinal direction of the beam (also the direction of loading). The CLT panel was restrained from movement through a rigid steel frame bolted to the strong floor (Fig. 4b). This steel frame also prevented uplift on either side of the specimen. For all testing, the CLT panels were oriented such that the load direction was parallel to the outer lamella grain direction.

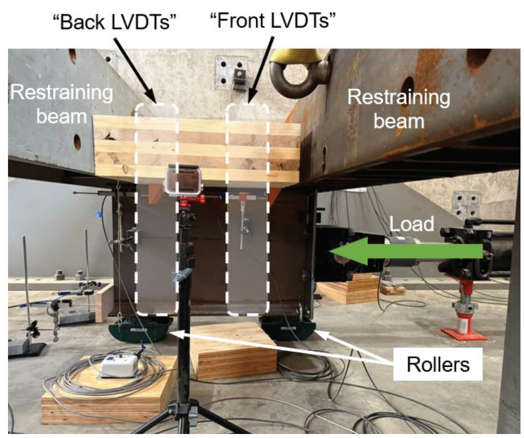
(a)



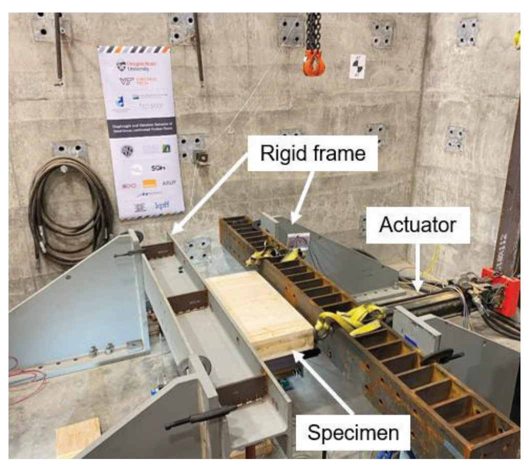
(b)

Figure 3. (a) knurling process (b) steel beam with knurled top flange.

The loading protocol per EN 26891 loaded the specimen to 40% of the estimated maximum load (F_{est}) which was followed by an unloading phase to 10% F_{est} before the specimen was loaded to failure [13]. For all testing, loading continued until absolute failure of the specimen occurred to document the entire force-slip behaviour. Failure was defined as fracture of all four screws in the specimen. An initial value for F_{est} was calculated referencing direct shear testing on the proprietary screws already performed [9]. A loading rate of 2.41 mm/min was selected for the first test in accordance with similar testing performed by Yang et al. [10]. In accordance with EN 26891, after the first test, F_{est} was updated to match the results and the loading rate was similarly updated [13]. The updated loading rate was 1.27 mm/min to 70% F_{est}, followed by 2.69 mm/min after 70% F_{est}. This loading rate remained for the rest of the SA and SAK testing series.



(a)



(b)

Figure 4. Small-scale direct shear (a) instrumentation and (b) test set-up.

Slip between the CLT and steel was measured by four linear variable differential transducers (LVDTs) located on either side of the steel beam at the location of the fasteners (see Fig. 4a). LVDTs on either side of the steel beam allowed for measuring out-of-plane movement during the test and LVDTs at each fastener along the length of the beam enabled measuring any shear lag during the test (Fig. 4a). Displacement of the steel beam was measured with two LVDTs attached to the steel beam on the side opposite the actuator. Out-of-plane movement was also monitored by two string potentiometers located at two opposite corners of the CLT panel. The moisture content of the CLT panel was measured in two panel locations with a moisture meter at the time of each test.

Yield load and slip was calculated in accordance with the EN 12512 standard methodology for force-slip data plots without a clear yield point [14], while stiffness was calculated in accordance with the implemented testing standard, EN 26891 [13]. The ultimate slip was taken as the post-peak slip at which the applied force dropped below 80% the peak load obtained during testing. Ductility was defined as the ratio of this ultimate slip to the yield slip.

(a)

(b)

Figure 5. Fakopp instruments for (a) withdrawal test for density and (b) microsecond timer for stiffness.

After testing, the density of all boards within the outer two lamella of the CLT was measured with a screw withdrawal test and the stiffness of every board within the CLT panel was measured with a time-of-flight recording. The screw withdrawal test was performed with a Fakopp Withdrawal Instrument fitted with a 5000 N Kaliber R 320 load cell (Fig. 5a). A screw 4 mm in diameter with an 18 mm thread length was installed in the surface of each board such that the threads were fully embedded in the wood. Then the screw was pulled out using the withdrawal instrument and the maximum force was measured with the load cell. The density of each board was calculated using the methods within The Wood Handbook [15]. For the stiffness measurement, two pins were inserted into either end of every board within the CLT panel, both connected to a microsecond timer, and the starting pin was excited by a steel hammer (Fig 5b). Then the microsecond timer measured the time of flight for the vibration to propagate to the end pin. Using the length of the board and the recorded time of flight, the velocity can be calculated. From the calculated values of density, ρ, and velocity, v, the modulus of elasticity, E, was determined from (1).

$$E = \rho * v^2 \tag{1}$$

4 – RESULTS AND DISCUSSION

The material measurements for all the specimens are included in Table 1. The data in this table shows the moisture content at the time of testing, denoted MC, the specific gravity, SG, and the modulus of elasticity, E, along with its coefficient of variance (CoV) for all panels tested.

Table 1. CLT material properties

Sample	MC	SG	E (GPa)	[CoV]
S-SA-1	9.5%	0.48	15.22	[21%]
S-SA-2	9.5%	0.48	16.07	[20%]
S-SA-3	9.4%	0.49	16.01	[21%]
S-SAK-1	9.4%	0.48	17.60	[19%]
S-SAK-2	9.2%	0.48	17.06	[19%]
S-SAK-3	9.6%	0.49	17.06	[19%]

The force displacement plots for all six tests are included in Fig. 6, and the results for each test, as well as the mean and coefficient of variation for each test series are included in table 2. The recorded strength per fastener for these connections were nearly twice that of the similar steel threading screws tested by Yang et al. [10].

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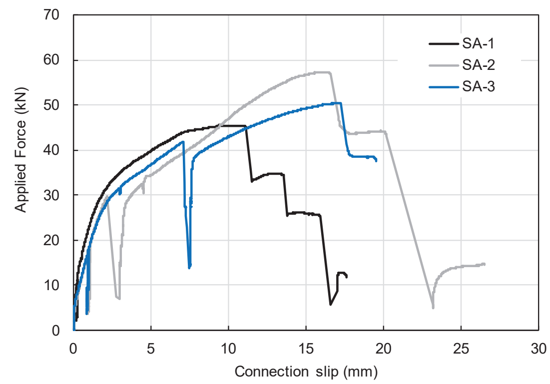
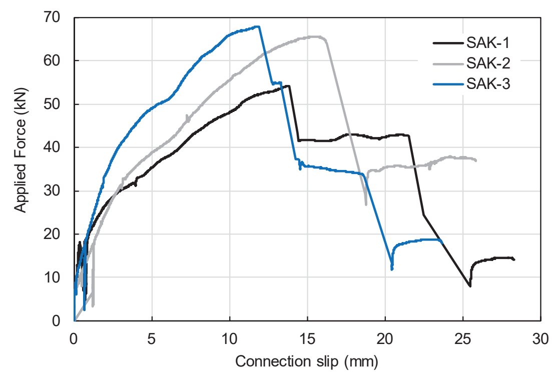
The force-displacement data, shown in Fig. 6, shows drops in load that correspond to the time when each screw sequentially fractured. Larger drops in load indicate two screws fracturing at the same time. Most specimens failed in four equivalent drops in load. Some had only three drops in load, with one of the load drops being twice as large as the others, suggesting that in these cases, two screws in the connection failed simultaneously.

Series SAK, the samples featuring a knurled top flange surface, had an average 22% increase in peak force compared to samples without this surface roughening (series SA). The slip at this maximum force was approximately the same for both test series. However, the knurling dramatically changed the calculated yield point. Series SAK yielded at an average 47% higher applied force correlating to a 105% larger yield slip. This higher yield force and yield slip resulted in series SAK having lower calculated ductilities despite having similar ultimate displacements and displacements at maximum force.

The addition of knurling reduced the initial stiffness of the connection. A possible explanation for this would be the screws in this connection were acting as fully threaded fasteners with threads present in both the wood and the steel. Fully threaded fasteners hold materials in place rather than providing a clamping force as with partially threaded screws. This means the points of the knurls were not forced to embed into the CLT. At the beginning of loading, the screws would be in bending and the knurling would begin to embed into the CLT. Once the CLT adequately engages with the knurling, the connection would see an increased stiffness. This behaviour was evident in the force-displacement plots which show an initial stiffness softening before



(a)



(b)

Figure 6. plots of applied force versus connection slip for (a) test series SA and (b) test series SAK.

hardening (when the CLT is fully engaged with the knurls).

Large amounts of CLT crushing were observed in the specimens before the screws fractured. Fig. 7 displays this crushing around the fastener observed after testing SAK-2. For series SAK, the failure mechanism also included significant scratching of the bottom of the CLT

Table 2. Experimental results.

Specimen ID	Peak force (kN)	Displacement at peak force (mm)	Yield force (kN)	Yield displacement (mm)	Ultimate displacement (mm)	Initial stiffness (kN/mm)	Ductility
SA-1	45.6	9.39	27.6	1.03	11.4	29.3	11.1
SA-2	57.4	16.2	28.3	1.75	17.2	16.8	9.78
SA-3	50.6	17.1	29.7	1.82	17.7	17.8	9.69
Mean	51.2	14.2	28.6	1.53	15.4	21.3	10.2
CoV	11.6%	29.6%	3.74%	28.7%	22.8%	32.6%	7.49%
SAK-1	54.2	13.8	26.6	1.50	15.1	18.2	10.0
SAK-2	65.6	15.5	50.9	4.97	19.7	11.7	3.98
SAK-3	67.9	11.8	48.4	2.97	13.3	18.4	4.48
Mean	62.6	13.7	42.0	3.15	16.0	16.1	6.16
Cov	11.7%	13.5%	31.8%	55.2%	20.6%	23.6%	54.5%

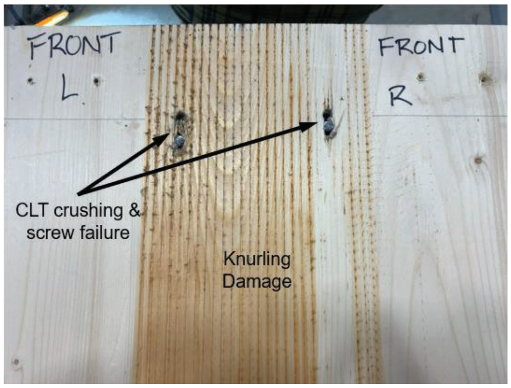


Figure 7. CLT post-testing damage due to knurls

in contact with the knurled top flange, shown in Fig. 7. This damage suggests that the knurls began cutting grooves into the CLT from 0-1.08 mm deep as slip increased.

As previously mentioned, many researchers have tested screwed connectors for timber-steel hybrid floors that are inserted below the top flange of the beam. The results of the tests described in this paper are compared against experiments which feature screws from below with a similar screw diameter, CLT thickness, embedment depth, steel flange thickness, and spacing as compared to our testing [4, 6].

Merryday et al. [6] tested three self-tapping screw (STS) types, denoted by the letters, ‘A’, ‘B’, and ‘C’. The screws had root diameters of 7.19, 6.86, and 6.81 mm for screw types A, B, and C, respectively. Multiple screw lengths were included in the study, but only the most similar screw length, 160 mm, were selected for comparison. The threaded length of the screws ranged from 130-145 mm. Similar to screw length, multiple spacings were implemented, but only the most similar spacing was selected, 200 mm. The CLT tested was 5-ply CLT 175 mm thick and was similarly loaded parallel to grain. The steel flange was slightly thinner at 11.2 mm thick.

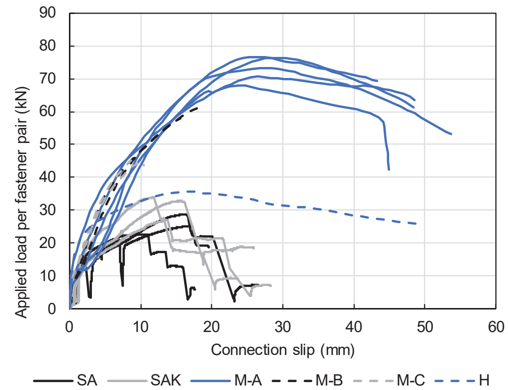


Figure 8. Testing data compared to previous research on pairs of screws installed from below.

Hassanieh et al. [4] tested multiple zinc-coated coach screws. Only that with the closest root diameter of 7.9 mm was selected. These screws were 100 mm in length, with threaded length not reported. The CLT was 120 mm thick, yet still 5-ply. The steel flange thickness was smaller at 8 mm thick.

Table 3 compares the results reported for direct shear tests on screws from below [4, 6]. Each column for each test parameter has the measured or calculated value on the left and the percent difference from series SA, “% dif. from SA”, on the right. All force and stiffness values were normalized to values per pair of fasteners. M-A refers to screw type A from Merryday et al. [6] and the same naming pattern is used for screws type B and C. The data from Hassanieh et al. [4] is denoted ‘H’. The comparison is visualized in Fig. 8.

Screws from above have lower strength and displacement capacity compared to similar configurations using screws from below, which had, on average, 108% higher peak forces. Similarly, yield forces of the specimens featuring screws from below were, on average, 197% greater than series SA. The specimen series H did not have a yield force as high as the other screws from below series, resulting in only a 23% increase compared to series SA.

Table 3. Experimental results compared to experimental results from previous literature.

Test Series	Peak force		Displacement at peak force		Yield force		Yield displacement		Ultimate displacement		Initial stiffness		Ductility	
	(kN)	% dif. from SA	(mm)	% dif. from SA	(kN)	% dif. from SA	(mm)	% dif. from SA	(mm)	% dif. from SA	(kN/ mm)	% dif. from SA		% dif. from SA
SA	25.6	-	14.2	-	14.3	-	1.53	-	15.4	-	10.7	-	10.2	-
SAK	31.3	22%	13.7	-4%	21.0	47%	3.15	106%	16.0	4%	8.10	-24%	6.16	-40%
M-A	73.0	185%	26.4	86%	62.1	334%	13.0	750%	46.7	203%	6.47	-40%	3.59	-65%
M-B	59.4	132%	16.8	18%	51.3	259%	8.17	434%	16.8	9%	7.29	-32%	2.05	-80%
M-C	44.7	75%	9.13	-36%	39.0	173%	4.61	201%	9.58	-38%	9.73	-9%	2.08	-80%
H	35.8	40%	17.7	25%	17.5	23%	0.63	-59%	39.5	156%	28.6	167%	62.3	511%

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Specimens with screws from below had higher values for displacement at peak force (23% greater), yield displacement (332% greater), and ultimate displacement (156% greater) as compared to series SA. However, screws from above produced higher stiffness and ductility than the screws from below tested in Merryday et al. [6]. Test series M-A, -B, and -C had 27% lower and 75% lower stiffnesses and ductilities, respectively, compared to series SA. Series H had remarkably higher ductility and stiffness than all other test series, being 511% greater and 167% greater than series SA respectively.

5 – CONCLUSION

This paper summarizes a direct shear testing series on timber-steel hybrid floors. The results and analysis of testing data can inform the failure mechanisms, strength, and ductility of steel-tapping screws used as shear connectors for this floor system.

The addition of knurling to the steel beam top flange increased the peak force, yield strength, and yield slip while decreasing the ductility and stiffness. This behaviour was similar to previous attempts by researchers to increase friction to screwed connections through the addition of nail plates and adhesives. The addition of knurling to the connection increased the shear strength of the system; however, decreased the ductility. Peak forces increased on average 22% with the addition of knurling and yield forces increased on average 47%. The displacement at yield was also much larger, increasing by an average 106%. However, ultimate displacement remained relatively unchanged (4.3% increase). As a result, ductility was 39% lower for series SAK regardless of a similar observed failure mechanism and displacement capacity. Series SAK was also less stiff than series SA with a 24% decrease on average. This could be a result of the fasteners acting as fully threaded screws and not providing a clamping force between the CLT and the steel therefore not maximizing the benefits of the increased friction with the presence of knurls.

Compared to screws tested by previous research that would be inserted into the top flange from below, the screws from above had lower peak forces and lower yield forces. The screws from above also produced displacement capacities lower than the previous literature on screws from below.

Despite these differences, the screws from above are viable options for connectors for steel-timber hybrid floors. Future research on the behaviour of these connectors should include the behaviour of floor system with these connectors under serviceability loading demands.

6 – ACKNOWLEDGEMENT

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7 – REFERENCES

[1] World Steel Association, "Circular Economy," World Steel Association. Accessed: Feb. 18, 2025. [Online]. Available: https://worldsteel.org/wider-sustainability/circular-economy/

[2] A. Hassanieh, H. R. Valipour, and M. A. Bradford, "Experimental and numerical study of steel-timber composite (STC) beams," *J Constr Steel Res*, vol. 122, pp. 367–378, Jul. 2016, doi: 10.1016/j.jcsr.2016.04.005.

[3] A. Hassanieh, H. R. Valipour, and M. A. Bradford, "Experimental and analytical behaviour of steel-timber composite connections," *Constr Build Mater*, vol. 118, pp. 63–75, May 2016.

[4] A. Hassanieh, H. R. Valipour, and M. A. Bradford, "Composite connections between CLT slab and steel beam: Experiments and empirical models," *J Constr Steel Res*, vol. 138, pp. 823–836, Nov. 2017, doi: 10.1016/j.jcsr.2017.09.002.

[5] A. Asiz and I. Smith, "Connection System of Massive Timber Elements Used in Horizontal Slabs of Hybrid Tall Buildings," *Journal of Structural Engineering*, vol. 137, no. 11, pp. 1390–1393, Nov. 2011, doi: 10.1061/(asce)st.1943-541x.0000363.

[6] H. C. Merryday, K. Sener, and D. Roueche, "Pushout Tests on Steel-Timber Connections Using Self-Tapping Screws," in *Structures Congress*, ASCE, 2023, pp. 312–327.

[7] C. L. Wang, J. Lyu, J. Zhao, and H. Yang, "Experimental investigation of the shear characteristics of steel-to-timber composite joints with inclined

self-tapping screws," *Eng Struct*, vol. 215, Jul. 2020, doi: 10.1016/j.engstruct.2020.110683.

[8] Y. Zhao, Y. Yuan, C. L. Wang, J. Zheng, and Y. Zhou, "Experimental study on shear performance of steel-timber screw connectors with grout pockets," *Eng Struct*, vol. 266, Sep. 2022, doi: 10.1016/j.engstruct.2022.114535.

[9] J. H. Nicholas, "Pilot Study of a High Capacity Ductile Seismic Holdown for Cross Laminated Timber," Montana State University, 2019.

[10] R. Yang, H. Li, R. Lorenzo, Y. Sun, and Q. Yuan, "Mechanical Behaviors of Steel-Timber Composite Shear Connections," *Constr Build Mater*, vol. 258, Aug. 2020, doi: https://doi.org/10.1016/j.conbuildmat.2020.119605.

[11] C. Loss, M. Piazza, and R. Zandonini, "Connections for steel–timber hybrid prefabricated buildings. Part I: Experimental tests," *Constr Build Mater*, vol. 122, pp. 781–795, Sep. 2016, doi: 10.1016/j.conbuildmat.2015.12.002.

[12] A. Hassanieh, H. R. Valipour, and M. A. Bradford, "Load-slip behaviour of steel-cross laminated timber (CLT) composite connections," *J Constr Steel Res*, vol. 122, pp. 110–121, Jul. 2016, doi: 10.1016/j.jcsr.2016.03.008.

[13] The European Committee for Standardization, "EN 26891 Timber structures - Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics," Feb. 1991, *International Organization for Standardization*.

[14] European Committee for Standardization and British Standards Institution, *EN 12512 Timber structures - Test methods - Cyclic testing of joints made with mechanical fasteners*. 2001.

[15] Forest Products Laboratory, *Wood handbook - wood as an engineered material*. United States Department of Agriculture, Forest Service, 2021.

https://doi.org/10.52202/080513-0536