SCREW REINFORCEMENT AND REPAIR OF POINT-SUPPORTED CLT

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ABSTRACT: Self-tapping screws (STS) can be used for shear reinforcement of point-supported Cross-laminated timber (CLT) floors; however, the effect of reinforcement zone, level, and strength axis directions are not yet fully understood. Moreover, there is a lack of understanding of the post-failure performance of point-supported CLT floors and the feasibility of repair by means of screw reinforcement. In this research, STS-reinforced intact and STS-repaired CLT panels were tested under punching shear to study the impact of different reinforcement parameters. The re-tested panels without reinforcement reached up to 85% of their initial intact-panel capacity whereas the reinforced re-tested panels reached up to 96% to 124% of their initial load-carrying capacity. STS reinforcement increased the load-carrying capacity of the intact panels by up to 37%. The non-repaired and reinforced re-tested panels reached up to 61% and 78% of their initial elastic stiffness, respectively, and the repaired CLT series recovered up to 90% and 98% of their stiffnesses at 80% and 100% of ultimate load levels, respectively.

KEYWORDS: mass timber floors, cross-laminated timber, punching shear, reinforcement, self-tapping screws

1 – INTRODUCTION

Engineered mass-timber products are widely used in construction because of their lower carbon footprint compared to other building materials. Cross-laminated timber (CLT) has gained popularity as a sustainable and cost-effective alternative to traditional construction materials, particularly for floor applications [1]. The crosswise orientation of the layers in CLT provides resistance in both directions making this product suitable for point-supported applications, such as in the 18-storey Brock Commons [2]. In this system, the CLT panels are supported directly by columns, without the need for beams and their connections, reducing installation cost and time while allowing the layout to be readily changed by altering wall locations as well as increasing the free story height [3].

In the design of a point-supported CLT floor, punching shear resistance is a key property [4-6]. Uneven load distribution on the floor or localized loads in the vicinity of a point support may require a higher punching shear resistance. In such cases, in order to avoid increasing floor thickness, local reinforcement can lead to cost savings.

Self-tapping screws (STS) are the recognized state-of-the-art fastener technology for timber structures [7,8]; their threads provide a full mechanical connection along the screw's embedded length, which makes STS suited for the reinforcement of timber elements and connections prone to splitting, and point supports.

An analytical model [4] was proposed for STS shear reinforcement of CLT point supports where the screw contribution (SC) to CLT rolling shear (RS) is calculated as:

$$SC = \frac{R_{ax,k}/\sqrt{2}}{a_1 \times a_{2,eff}} \tag{1}$$

$$R_{ax,k} = min\begin{cases} 24.8 \times d^{0.8} \times l_{ef}^{\ 0.9} \\ R_{t,u,k} \end{cases} \tag{2}$$

$$a_{2,eff} = max\begin{cases} a_2 \\ b/n_{\perp} \end{cases} \tag{3}$$

$$l_{ef} = min\begin{cases} l_1 \\ l_2 \end{cases} \tag{4}$$

Where $R_{ax,k}$ is screw withdrawal strength; a_1 the distance between rows and $a_{2,eff}$ the minimum of distances a_2 (Fig. 1) and the ratio of width b and the number of screw lines $n_{\perp}$; d the diameter of the screws in mm; l_{ef} the effective embedment length of the screws in mm (Fig. 1) ; and $R_{t,u,k}$ the tensile capacity of the screws.

Based on Mestek and Dietsch [4], prEN1995 [9] provides guidance for CLT point-support shear reinforcement; however, the effects of reinforcement zone, level, and directions are yet to be investigated. Moreover, there is a lack of understanding of the post-failure performance of point-supported CLT and the feasibility of resistance and stiffness recovery after repair using STS reinforcement.

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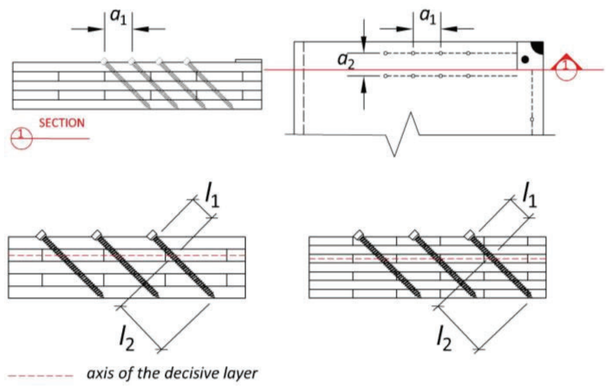

Figure 1. Geometric parameters of Mestek and Dietsch model.

2 – MATERIALS AND METHODS

A total of 73 punching-shear tests on were conducted to study the impact of: i) three different reinforcement levels; ii) reinforcement direction; iii) distance between screws; and iv) reinforced zone length. The test series overview including CLT thickness and reinforcement types, is presented in Table 1, and illustrated in Fig. 2.

All panels were E1 graded with 1950 Fb-1.7E SPF and No.3 SPF in longitudinal and transverse layers, respectively, produced in accordance with ANSI/APA PRG 320 [10]. The panels were not edge glued and sized 1.7 m × 1.8 m. Edge columns were used to represent the most common column condition in a typical point-supported floor plan with line-supports on four edges along the length, see Fig. 2f.

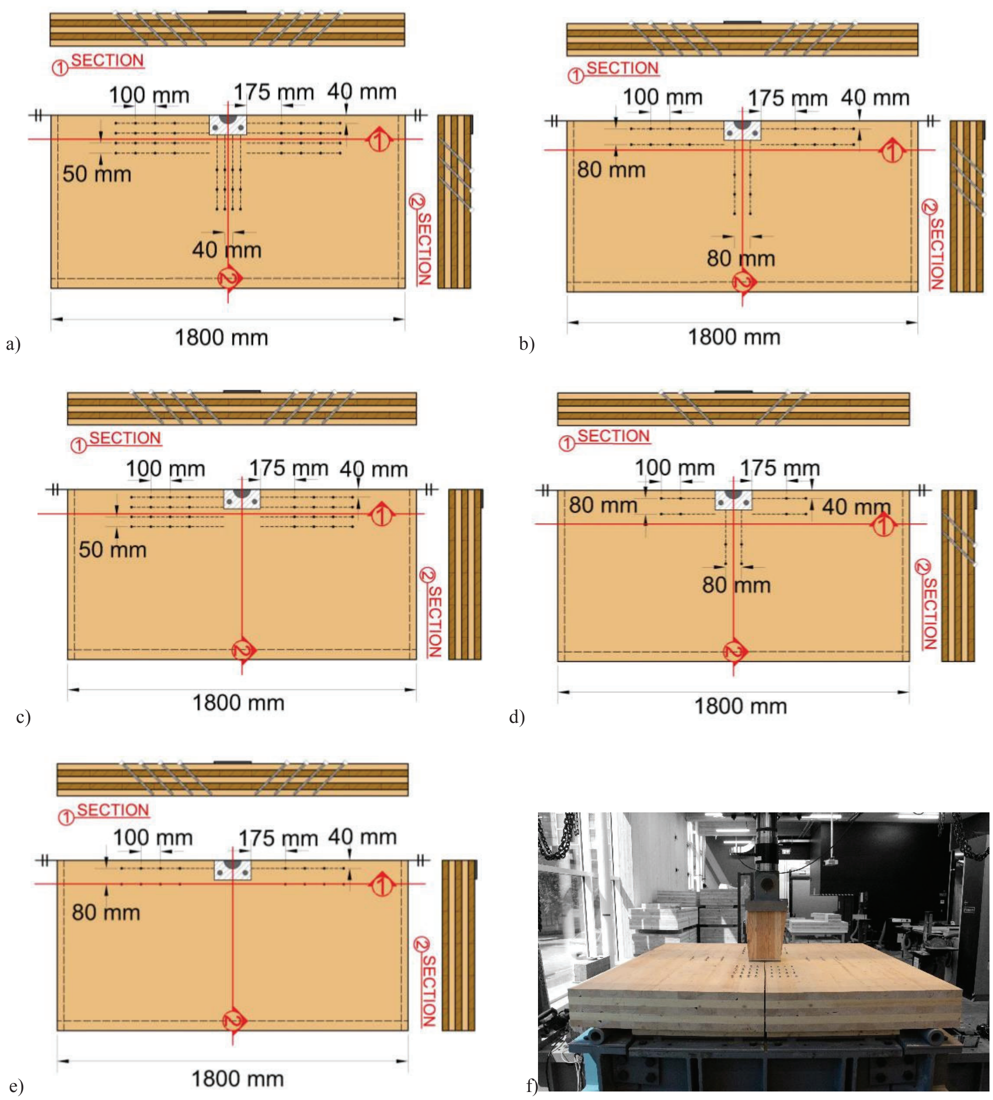

Figure 2. STS shear reinforced series: a) type 1 (S18); b) type 2 (S19); c) type 3 (S20); d) type 4 (S21); e) type 5 (S22); and f) type 1 exemplary photo.

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Table 1: Test series overview

Series	Thick. [mm]	Species	Support [mm^2]	Reinf.	Count
S7	175	SPF	200 × 200	None	6
S8	175	D. Fir	200 × 200	None	6
S9	175	Hem.	200 × 200	None	6
S17	245	SPF	300 × 300	None	6
S18	175	SPF	200 × 200	Type 1	6
S19	175	SPF	200 × 200	Type 2	6
S20	175	SPF	200 × 200	Type 3	6
S21	175	SPF	200 × 200	Type 4	6
S22	175	SPF	200 × 200	Type 5	6
S07 R	175	SPF	200 × 200	None	1
S08 R	175	SPF	200 × 200	None	1
S09 R	175	SPF	200 × 200	None	1
S07 RR	175	SPF	200 × 200	Type 2	4
S08 RR	175	SPF	200 × 200	Type 2	3
S09 RR	175	SPF	200 × 200	Type 2	3
S17 RR	245	SPF	300 × 300	Type 1	6

The punching shear test results on intact CLT panels (series S7, S8, S9, and S17) having the same dimensions and stress grade from the previous phase of this project [6], were regarded as benchmark for the STS repaired and reinforced series. Five series were reinforced with fully threaded Ø10×240 mm (5-ply panels) and Ø10×340 mm (7-ply panels) STS with a specified tensile resistance of 28.37 kN, installed at a 45º angle, as shown in Fig. 2a-e.

To assess the potential of repair, one panel from S7, S8, S9 was re-tested to failure with a non-repaired condition. To study the post failure punching-shear behaviour of CLT and repairability of point supported CLT by means of STS, 4 panels from S07, and 3 panels from S08 and S09, were repaired with STS "type 2" level (Fig. 2b) and 6 panels from S17 were repaired with STS "type 1" level (Fig. 2a) and loaded until failure, defined as 10% drop in the load carrying curve. The retested non-repaired panels are denoted "R" and repaired-retested are denoted "RR".

The tests were conducted according to ISO 6891 [11] at a monotonic loading rate of 5 mm/min. The displacement of the tension side of the panels (underside) was recorded using string pots at various locations.

3 – RESULTS AND DISCUSSION

3.1 LOAD-DISPLACEMNET BEHAVIOUR

The average load-displacement curves from reinforced series, and representative curves from STS repaired panels are shown in Fig. 3. The curves of both reinforced and repaired series had similar behaviours where two distinct phases were observed. In the first phase, the specimens exhibited quasi-linear behaviour up to the ultimate load. In the second phase, the load was redistributed multiple times before and after the major load drop.

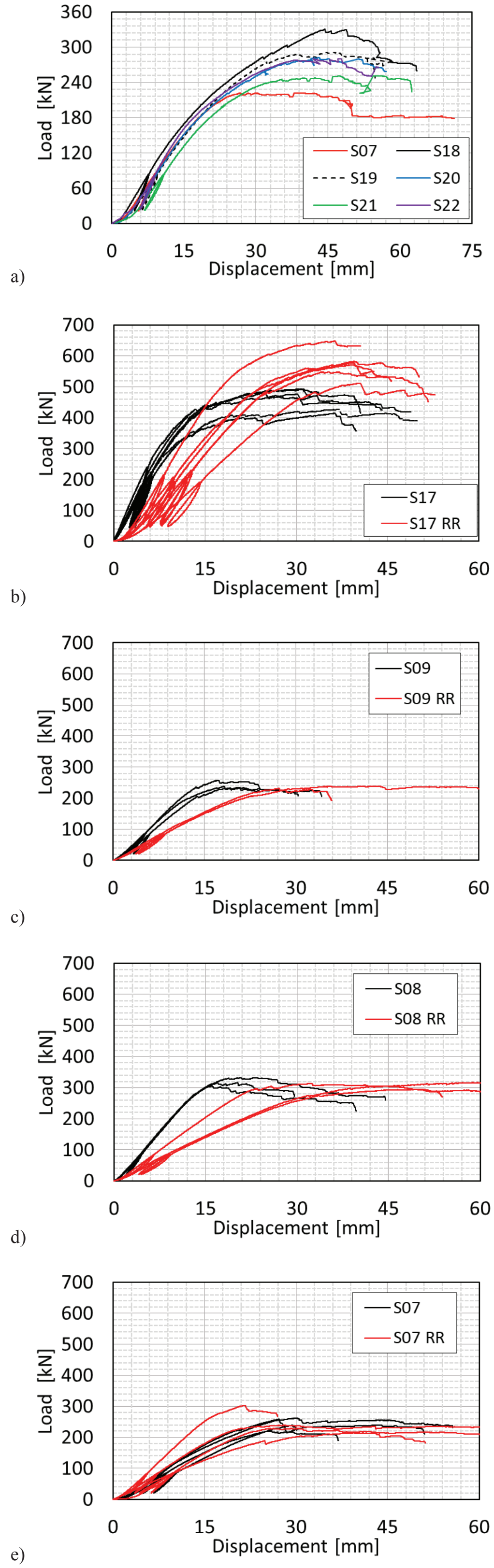

Figure 3. Average load-displacement curves of: reinforced series (a); repaired series S17 (b), S09 (c), S08 (d), and S07 (e).

3.2 FAILURE MODES

In the reinforced panels, cracking was audible around 80-90% of the peak load without causing any drop in the load carrying capacity. However, no signs of rolling shear cracks in the vicinity of the loading area were evident once the tested panels were inspected after testing; likely the minor cracks closed after unloading, Fig. 4a. Failure in the STS reinforced panels was mainly accompanied by tensile cracks of the underside boards, see Fig. 4b, minor screw withdrawal, and failure at interface of single layers outside the reinforced zones (Fig. 4c), which was more pronounced in the series with lower reinforcement levels. Since re-tested series had already experienced RS failure, when loaded for the second time, due to the presence of the STS, no board failure was observed inside the repaired zone, and they sustained larger displacements before delamination happened outside the repaired zones (Fig. 4d).

3.3 PUNCHING SHEAR RESISTANCE

The average punching shear resistance, $R_{pu,av}$, of each series and the corresponding CoV are summarized in Table 2. The results of the screw-reinforced series normalized with respect to the benchmark series (S07) are presented in Fig. 5a. S07 had a punching shear resistance of 231 kN. Compared to S07, the highest increase in the punching shear capacity equal to 37% (316 kN) was achieved when the larger zone was reinforced (475 mm) with a tighter distance between screw rows (50 mm) in both directions (S18). Using a larger distance between the screw rows (80 mm) but reinforcing the same zone and in both directions (S19) resulted in a 28% increase (296 kN) compared to (S07).

Figure 4. The vicinity of the point-support after unloading (a); tensile failure of the underside boards (b); failure at interface of single layers outside the reinforced zones in S21 (c); and failure outside the point support zone of the repaired panels (d).

Keeping the distance between rows equal to 80 mm and reinforcing in both directions but reducing the reinforced zone to 275 mm (S21) resulted in an 11% capacity increase (256 kN); this shows the effect of reinforcement zone length. Using the same level of reinforcement as S18 and S19 but only in the major-strength direction of the panels did not result in the same increase in S20 and S22 where they took 285 kN and 282 kN respectively. However, this effect was more pronounced for higher STS reinforcement level (type 1) due to the fact that in a point-supported CLT floor having symmetrical layups, the contribution of each strength axis to shear resistance is different resulting in one strength-axis governing the design while the other being underutilized.

Therefore, as the results showed, if the chosen level of reinforcement in the governing direction leads to an overall point-support punching shear resistance exceeding the resistance of the initially underutilized direction, in order to achieve the desired increase in the punching shear resistance, reinforcing in both strength-axes is needed.

As shown in Fig. 5b, the non-reinforced re-tested panels reached up to 85% of their initial capacity before experiencing a second major load drop; S07R, S08R, and S09R reached 185 kN, 233 kN, and 208 kN respectively. The two levels of reinforcement, type 1 for S17RR and type 2 for S07RR, S08RR, and S09RR, in the re-tested panels led to 124%, 110%, 96%, and 100% of the resistance of their corresponding intact panel series, respectively.

3.4 POINT SUPPORT STIFFNESS

The average point support stiffness at 40% ($k_{40\%}$), 80% of ultimate load ($k_{80\%}$), and at ultimate load (k_{ult}) are reported in Table 2. The stiffness of reinforced series is compared to an intact panel series (S07) in Fig. 6a. Except for S22, at 40% of $R_{pu,av}$, the stiffness of S18 with the highest reinforcement level in both directions was highest of all series. Reinforcement in both directions impacted the stiffness of the panels at all three load levels (S18 and S20). Compared with S07, all reinforced series had higher stiffness at all load levels. STS shear reinforcement also helped the panels to maintain their initial stiffness up to 80% of the ultimate load which indicates that the panels did not experience any considerable damage up to that point.

The stiffness of the STS repaired tests at 40%, 80%, and 100% of ultimate load levels are depicted in Fig. 6b-d. The non-repaired and screw-repaired re-tested series reached up to 61% and 78% of their initial elastic stiffness, respectively. However, at 80% and 100% of ultimate load levels, the reinforced re-tested series recovered up to 90% and 98% of their stiffnesses, respectively. Although a higher reinforcement level resulted in a higher punching shear resistance recovery in S17, it did not lead to higher initial stiffness recovery where, on average, S17-RR had 55% of S17 initial stiffness.

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Table 2: Test results

Series ID	$R_{pu,av}$ [kN]	CoV [%]	$k_{40\%}$ [kN/mm]	$k_{80\%}$ [kN/mm]	k_{ult} [kN/mm]
S7	231	6.8	15.4	13.1	11.5
S8	322	3.2	20.2	20.9	16.8
S9	244	4.8	15.7	16.3	11.4
S17	463	7.3	35.4	31.6	15.4
S18	316	8.0	18.2	17.8	13.9
S19	296	5.1	17.7	17.9	13.2
S20	285	4.4	17.0	16.9	12.8
S21	256	5.2	17.2	17.2	12.9
S22	282	6.9	19.7	18.7	14.4
S07 R	185	[-]	9.3	[-]	[-]
S08 R	236	[-]	9.1	[-]	[-]
S09 R	208	[-]	8.2	[-]	[-]
S07 RR	255	14.5	11.9	11.8	9.0
S08 RR	308	3.9	10.8	10.5	7.0
S09 RR	243	6.9	10.9	10.2	5.7
S17 RR	573	7.8	19.6	20.8	15.1

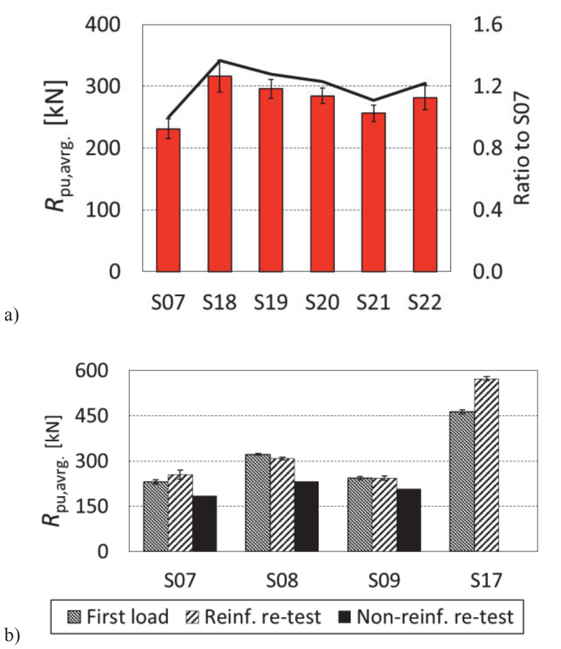

Figure 5. Impact of screw reinforcement on punching shear capacity (a); STS repaired punching shear test results (b).

3.5 ANALYSES

The expected increase in the punching shear resistance of the five reinforced series determined with Mestek and Dietsch [5] using (1)-(4) normalized with respect to the punching shear resistance of the benchmark series, S07, are reported in Table 3 and compared to the experimental test results in Fig. 7.

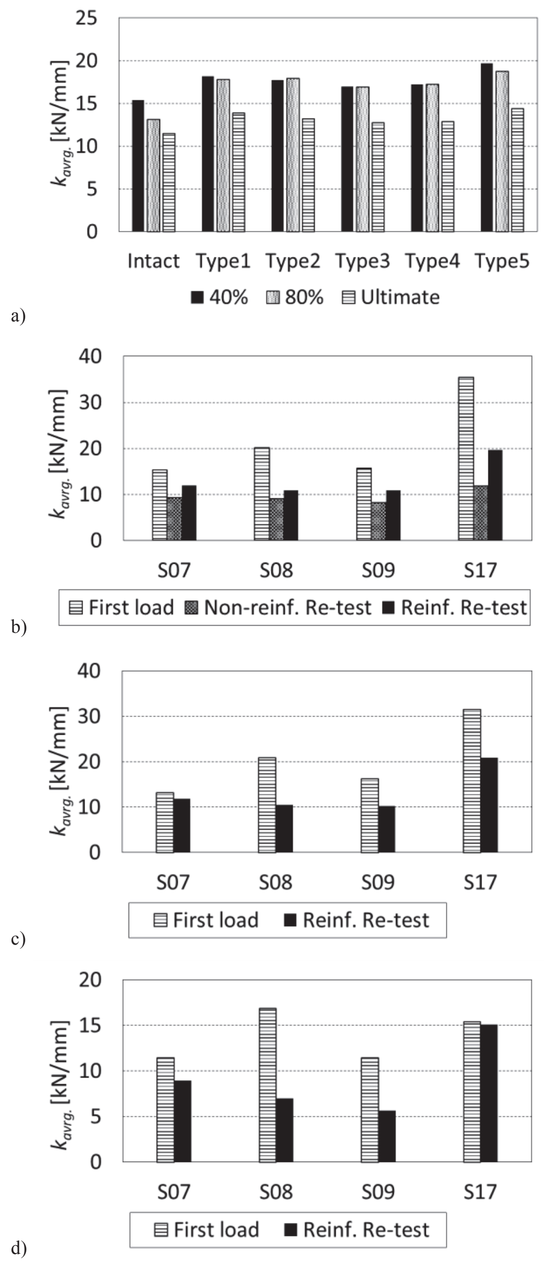

Figure 6. Stiffness of the STS reinforced series (a); stiffness at 40% of ultimate load (b); 80% of ultimate load (c); and ultimate load (d).

Table 3: Punching shear test results vs. analytical model's results.

Ratio	S18	S19	S20	S21	S22
R_{pu}/ R_{07}	1.37	1.28	1.23	1.11	1.22
R_{Mestek} / R_{07}	1.40	1.25	1.40	1.25	1.25

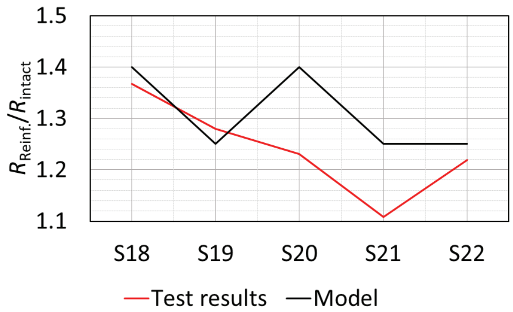

Figure 7. Punching shear test results vs. analytical model.

It can be seen that the prediction of the analytical model is close to the observed resistance increase in S18, S19, and S22, whereas, for the rest of the series there is a discrepancy. Although S21 and S19 had the same screw spacing and distance between screw rows, since in S21 a shorter zone was reinforced, 11% increase in the punching shear resistance of this series compared to the benchmark series, S07, was observed whereas the increase was 28% for S19. This finding highlights the necessity of specifying a required reinforced length in order to achieve the predictions of Mestek and Dietsch's [4] model.

4 – CONCLUSIONS

The effect of screw reinforcement parameters on the punching shear resistance of point-supported CLT and the post failure behaviour of STS repaired CLT point supports were studied. The following conclusions can be drawn:

- The reinforcement pattern used in this study compatible with CLT point supports having column-to-column connections resulted in up to 37% increase in the punching shear resistance of the tested series.
- Tighter screw spacing and larger reinforced zone resulted in higher punching shear resistance.
- Having reinforcement only in one direction impacted the percentage increase in the load-carrying capacity of the series. This effect was more pronounced in the higher reinforcement level.
- The experimental results were close to the predictions of the analytical model when 4 and 3 rows of screws were used in major- and minor-strength axis, respectively.
- The screw repaired series were up to 1.24 times stronger than intact CLT panels, could recover up to 78% of their initial stiffness, and up to roughly 100% of their ultimate stiffness.

Drawing upon the findings of this research due to promising performance STS as shear reinforcement and means of repair in point supported CLT panels, further experimental studies should aim to investigate the required reinforced zone length and the effect of CLT thickness and advance the current CLT point-support STS shear reinforcement model.

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