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CYCLIC PERFORMANCE OF SHEAR CONNECTIONS WITH SELF-TAPPING-SCREWS FOR CROSS-LAMINATED-TIMBER PANELS

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Abstract

Recent changes in North American building codes as well as supporting legislation have created new possibilities for the structural application of timber in mid-rise residential and non-residential construction. The introduction of Cross-Laminated-Timber (CLT) has added to the interest in wood-based structural systems. Structures need to be designed for appropriate capacity, stiffness, and if applied in seismic zones, ductility. As CLT panels are rigid, the desired ductility for seismic design must be obtained from the connections. Self-Tapping-Screws (STS) are the state-of-the-art in connector technology for CLT structures; however, current North American design standards have no guidelines for STS in CLT. The research presented in this paper examines the performance of 3-ply CLT panel assemblies connected with STS under quasi-static monotonic and reversed cyclic loading. Different joint types were tested: traditional surface spline with STS in shear and half-lap joints with STS in either shear or withdrawal, along with two novel assemblies using STS with double inclination of fasteners, and a combination of STS in withdrawal and shear. The results of 21 cyclic tests confirmed that: 1) connections with STS in shear can be ductile and can reach large relative displacements; 2) connections with STS in withdrawal are much stronger and stiffer, however, such joints fail at small displacements; and 3) connections that use a combination of STS in withdrawal and shear can allow for high strength, high stiffness and relatively high ductility.

Keywords: Cross-laminated-timber, Self-tapping-screws, Shear connections, and Cyclic loading

1. Introduction

Cross-laminated (CLT) timber technology has started to become widespread in North America including the earthquake prone areas. Therefore, it is important to quantify the overall performance of CLT buildings and specifically structural systems made of CLT under seismic actions, to add additional information to the existing regulations for CLT construction is available in the Canadian Standard for Engineering Design in Wood [1].

Extensive experimental programs on typical CLT connections subjected to cyclic loads were carried as a part of the SOFIE research project, coordinated and conducted by CNR-IVALSA, Italy [2-4] and at FPInnovations, Canada [5]. The aim of these projects was to quantify the seismic performance of multi-storey CLT buildings. Within the first part of the SOFIE project, Ceccotti et al. [2] performed cyclic tests focusing on CLT wall panels considering different connection layouts (hold downs, anchor brackets), openings, and boundary conditions. In the second part, Gavric et al. [3,4,6] performed cyclic tests focusing on the behaviour of coupled CLT wall panels with different types of screwed vertical joints (step and spline joint) with several different configurations of anchoring connectors and hold downs. Lauriola and Sandhaas [7] performed pseudo-dynamic tests on a full scale one-storey building. A 3-storey [8] and a 7-storey buildings [9] were also tested on a shake table in 2006 and 2007, respectively, and demonstrated that CLT buildings can have adequate performance under earthquakes ground motions, such as the 1995 Kobe earthquake.

The seismic behaviour of CLT wall panels with different lengths of 2.44 m and 3.2 m and a height of 2.44 m or 2.72 m were tested under different levels of vertical loads and quasi-static monotonic or cyclic horizontal load by Dujic et al. [10] and Dujic and Zarnic [11]. Boundary conditions, magnitudes of vertical load and type of anchoring systems were varied to investigate the wall deformation mechanisms and shear strengths of wall segments [12]. Further, shear properties of CLT wall panels with and without openings were investigated. Numerical models of CLT wall panels were developed, the model was validated by the obtained test results and a parametric study was performed to propose analytical formulas predicting the relationship between the shear strength and stiffness of CLT wall panels without and with openings [13,14].

Gavric et al. [15] conducted testing on 12 different screwed connections between adjacent CLT wall-to-wall, wall-to-floor, and floor-to-floor panels both parallel and orthogonal under monotonic and cyclic loading in order to quantify their performance under seismic events. The results were analyzed according to EN 12512 [16] procedures in terms of stiffness, strength, ductility, over-strength, and equivalent damping ratios. A conservative value of 1.6 for over-strength factor was recommended for screwed CLT connections. Similarly, Popovski et al. [5] conducted testing on CLT wall panels subjected to monotonic and cyclic lateral loads. They tested single panel walls with different aspect ratios, multi-panel walls with step joints and different connections (types of screws), as well as one- and two-storey wall assemblies. They considered various types of fasteners such as annular ring nails, spiral nails, and screws with different diameters and lengths. In addition, a two-storey CLT house was tested at FPInnovations to quantify the performance of such structures under lateral loads [17].

As CLT panels are very rigid, the desired ductility for seismic design must be obtained from the connections. Self-Tapping-Screws (STS) are widely recognized as being the state-of-the-art in connector technology for CLT structures [18]. STS are dowel-type threaded fasteners with diameters up to 14mm and lengths up to 1500mm. They have improved thread geometry and are made of hardened steel which increases their axial, bending, and torsional capacities. Combined these attributes provide STS with significantly higher withdrawal resistance and tensile strength than traditional screws. STS are a cost efficient timber connector appropriate for many structures as they do not require pre-drilling and are therefore faster to install than traditional lag or wood screws [18]. However, the current Canadian Standard for Engineering Design in Wood [1] has no guidelines for STS in CLT. There are a number of available options for in-plane shear connections between CLT panels using STS, most common and previously tested in Europe, [19,20] are plywood surface splines and half-lap joints.

This paper presents the experimental results on STS shear connections in 3-ply CLT under reversed cyclic loading considering different joint types.

2. Experimental investigation

2.1 Materials

CLT panels (3-ply), fabricated by Structurlam Products Ltd. according to ANSI/APA PRG-320 [21] were used. The main CLT properties are: CLT grade V2M1; mean oven dry relative density 0.42; wood species and grade SPF No.1/No. 2moisture content 12% (+/-2%) at time of production; and Purbond polyurethane adhesive.

Different types and lengths of 8mm diameter SWG ASSY STS provided by MyTiCon Timber Connectors Ltd. were used: partially threaded Ecofast CSK (80 mm, and 90 mm) for shear action and fully threaded VG CSK (140 mm) or cylindrical head (180 mm) for withdrawal action. Different lengths were chosen based on the joint type to ensure proper fastener engagement and load transfer. For the spline joints, 19 mm (3/4 inch) plywood sheet (Grade D, Douglas Fir) was used.

2.2 Connection configurations

Six different joint types (Fig 1) were manufactured and subsequently tested in seven series considering different actions (shear, withdrawal, and combination of both) of STS. The test series are summarized in Table 1.

a) Single surface spline with STS in shear (series 1);

b) Half-lap with STS in shear (series 2);

c) Half-lap with STS in withdrawal (series 3);

d) Half-lap with STS in combination of shear and withdrawal (series 4 and 5);

e) Butt-joints with STS in withdrawal inclined at double angles (series 6); and

f) Butt-joints with STS in shear (series 7).

In series 1, surface spline joints were investigated. Plywood sheets 19 mm thick and 160 mm wide were used as splines and 80 mm long ASSY Ecofast STS was used as screws.

Different half-lap joints (laps 80 mm wide) were investigated in series 2 to 5. In series 2, 90 mm long ASSY Ecofast STS were placed such that they were loaded in shear. In series 3, 140 mm long ASSY VG CSK head type STS were placed at an angle of 45° in two different directions to load these in withdrawal. Series 4 and 5 combined STS in shear and withdarwal. Two different layouts (WSSW and SWSWS) were tested: in the WSSW layout (Series 4), four STS loaded in shear were placed in the middle of the panels in two rows and four STS were loaded in withdrawal were placed towards the ends of the panel. In the SWSWS layout (Series 5), pairs of STS loaded in shear or withdrawal were placed in alternating order.

Series 6 and 7 consisted of butt joints with STS in withdrawal (series 6) and STS loaded in shear (series 7). For butt joints with STS in withdrawal, 180 mm long fully threaded ASSY VG CSK were installed at an angle of 45° to the edge of the CLT panels, and at an angle of 33° to the face of the CLT panels. For butt joints with STS in shear, 140 mm long fully threaded ASSY VG CSK were installed at an angle of 45° to the face of the panels.

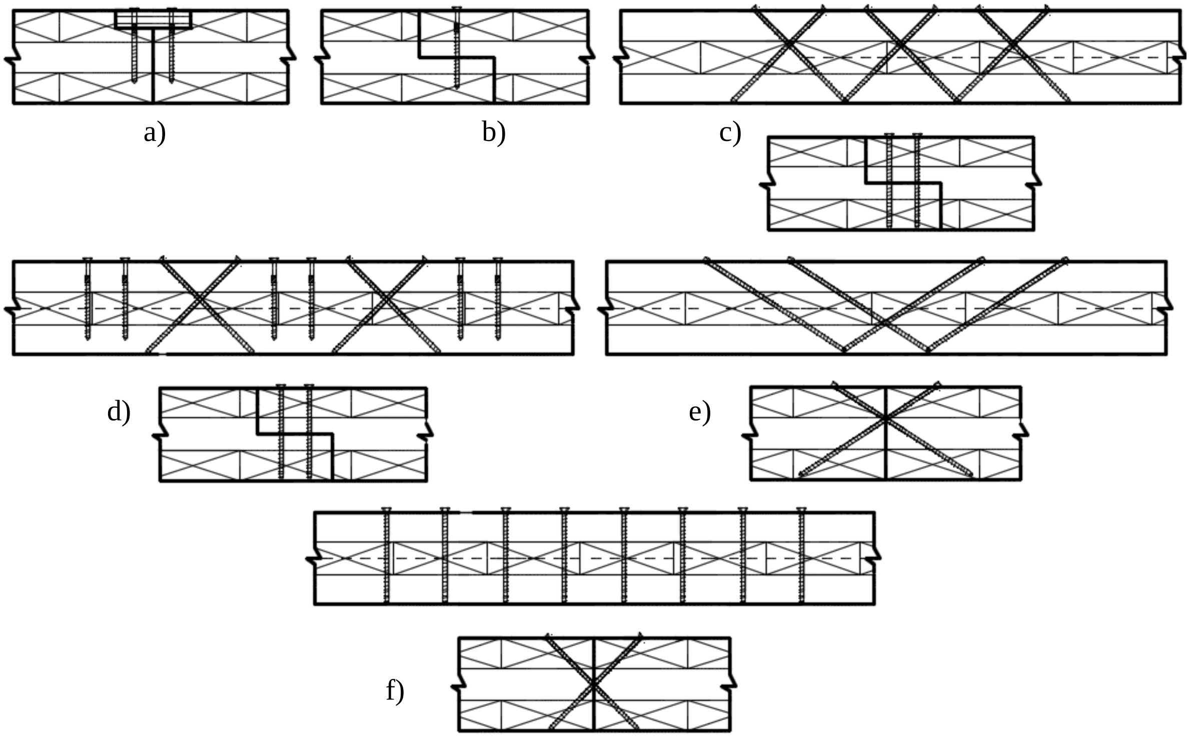

Fig 1 – Joint types: a) Spline with STS in shear; b) Lap with STS in shear; c) Lap with STS in withdr.; d) Lap with STS in shear & withdr; e) Butt with STS in withdr; f) Butt with STS in shear

Table 1 – Connection configurations

Series	Joint Type	STS length [mm]	STS #	STS action
1	Spline	80	16	Shear
2	Lap	90	8	Shear
3		140	12	Withdrawal
4		90+140	4+4	Combined
5		90+140	6+4	Combined
6	Butt	180	8	Withdrawal
7		140	8	Shear

2.3 Methods

Previous work investigated the performance of the before specified joint types and several other joint variations under quasi-static monotonic loading [22,23]. Herein, only the results of the tests on the joint configurations as listed in Table 1 are summarized. 3-ply specimens 290 mm wide, 700 mm high, 105mm thick were tested. Each specimen consisted of two CLT panels of 145 mm wide exhibiting one shear plane (Fig 2, left). The test setup, shown in Fig 2 (left) followed the EN 408 [24] recommendations and was successfully used by Brandner et al. [25], where the specimens were rotated 13.5 so that the resultant forces of loading and support are aligned.

For the reversed cyclic tests, 21 specimens 600 mm wide, 1600 mm high and 105 mm thick, were tested. Specimens were manufactured longer to facilitate attachment to a loading fixture. Each specimen consisted of two CLT panels of 300 mm wide and 800 mm long exhibiting one joint plane. Similarly to the monotonic tests, the specimens were rotated 13.5° in a way that the line of action and the center of the specimens were aligned, see Fig 2 (middle and right).

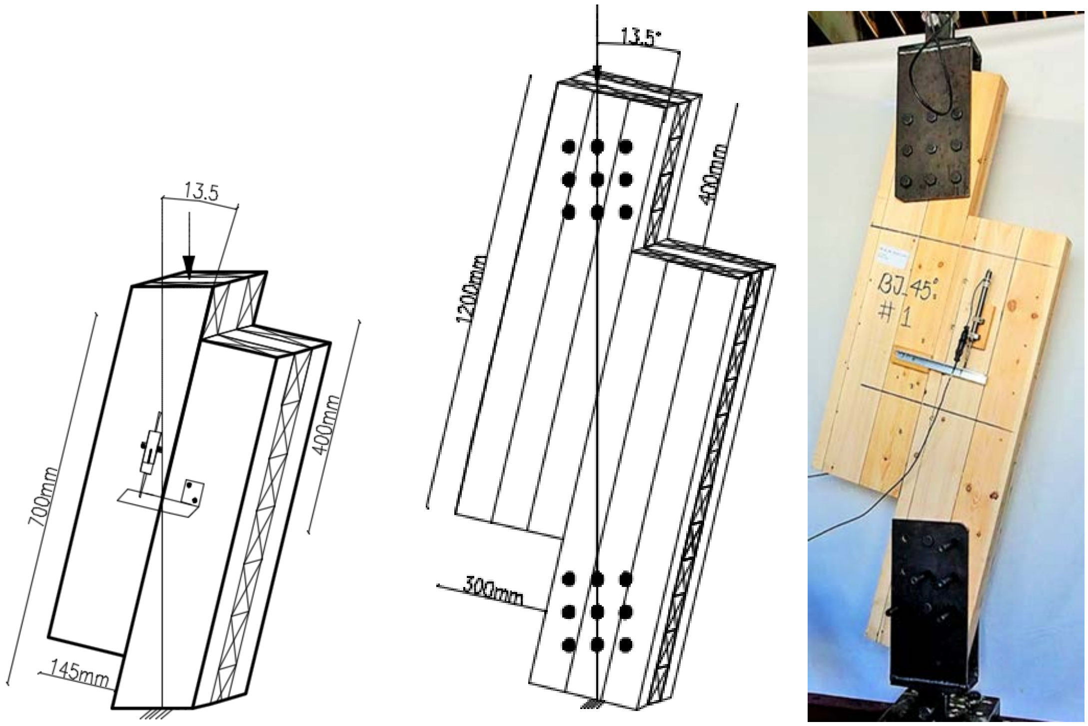

Fig 2 – Schematic of specimen

The actuator load and the relative vertical displacements between two panels using two transducers attached at front and back of the assembly were recorded at a sampling rate of 10 Hz. The actuator load was applied according to a CUREE loading protocol specified in ASTM 2126-09 [26], illustrated in Fig 3, at a displacement controlled rate of 2.5 mm/sec. ASTM D1761 [27] recommends ten replicates for mechanical fasteners in wood. In this study, however, in each test specimen, multiple mechanical fasteners are tested, therefore the number of replicates was reduced to six in the monotonic tests and three in the reversed cyclic tests.

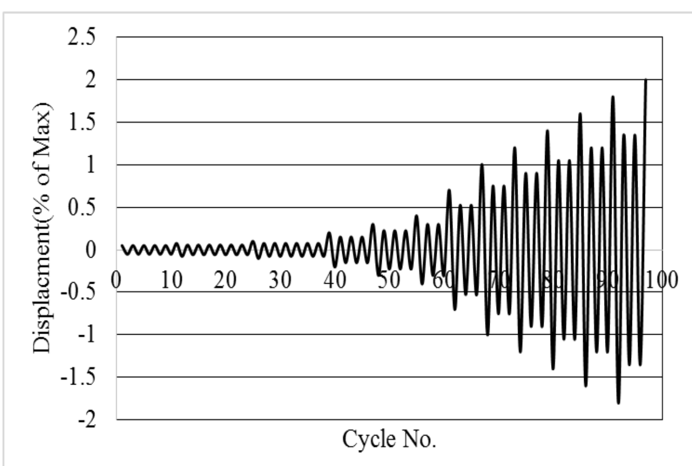

Fig 3 – CUREE reversed cyclic loading protocol

From the tests, following connection characteristics were obtained and evaluated:

- Capacity (ultimate resistance); labeled F_{max}
- Yield load; labeled F_Y
- Displacement at capacity; labeled $d_{F,max}$
- Displacement at yield load; labeled $d_{F,Y}$
- Stiffness; labeled k
- Ductility; labeled μ

Stiffness was calculated in accordance with EN-26891 [28] for the range of the load-displacement curves between 10% and 40% of capacity. To calculate yield strength and displacement at yield, equivalent energy elastic-plastic (EEEP) curves according to ASTM 2126-09 [26] were developed. For the cyclic tests, EEEP curves were developed for both positive and negative loading envelopes for each specimen. Ductility was calculated taking the ratio between the displacement at maximum load and the yield displacement.

2.4 Results

Table 2 and Fig 4 summarize the test results, each presenting the averages load-deformation curves and results for the loads obtained per screw. The monotonic tests demonstrated that ductile connections can be achieved using STS in shear, both in surface-spline and half-lap joints. These joint layouts exhibited low stiffness. Much stiffer connections can be achieved by activating the withdrawal resistance of STS when installed at an angle of 45° to the shear plane, both in surface half-lap and butt joints. These connection configurations, however, exhibit low ductility. The novel layout combining STS loaded in shear with STS loaded in withdrawal combines high capacity with high ductility. The reversed cyclic tests confirmed these findings. All series with STS in shear (1, 2, 7) achieved moderate to high ductility, however significantly lower stiffness when compared to the series with STS in withdrawal. The series with STS in withdrawal (3 and 6) had 10-30% higher capacity, 2 times higher stiffness, however, 40-70% less ductility compared to the series with STS in shear and combined action. Combining the STS in shear and withdrawal (4 and 5) action increased both stiffness (compared to series with STS in shear only) and ductility (compared to series with STS in withdrawal only) by 20-80% and 10-60%, respectively. Series 7 reached similar capacity as the other series with STS in shear, however, lower stiffness and lower cyclic ductility.

Table 2 – Test results summary

Series	F_{max} [kN]		F_Y [kN]		$d_{F,max}$ [mm]		$d_{F,Y}$ [mm]		μ		k [kN/mm]	
	Mono	Cycl	Mono	Cycl	Mono	Cycl	Mono	Cycl	Mono	Cycl	Mono	Cycl
1	6.5	5.1 -3.8		4.3 -3.1		35.0 -23.0		6.2 -6.5	5.5	5.5 -3.8	0.5	0.9 -0.5
2	6.6	5.5 -4.4		3.9 -3.6		25.0 -18.0		3.5 -4.8	9.9	8.8 -3.7	1.0	0.6 -0.7
3	6.9	6.4 -5.2		5.7 -4.7		4.2 -3.9		2.7 -1.6	4.3	1.6 -2.3	5.1	2.1 -2.4
4	7.4	4.8 -4.0		4.3 -3.4		21.0 -14.0		1.6 -1.1	16.5	14.0 -11.0	8.9	2.2 -3.9
5	4.7	4.2 -3.5		3.8 -3.2		11.0 -14.0		1.3 -1.3	15.3	8.4 -11.0	5.7	3.4 -1.6
6	7.5	7.9 -5.5		7.0 -4.5		5.5 -2.9		2.0 -1.6	3.4	3.1 -2.3	9.0	2.7 -2.3
7	6.7	7.4 -5.2		6.5 -5.7		34.0 -27.0		10.0 -7.0	4.2	3.8 -3.8	0.5	0.7 -0.7

Note: Negative values are results from negative envelopes

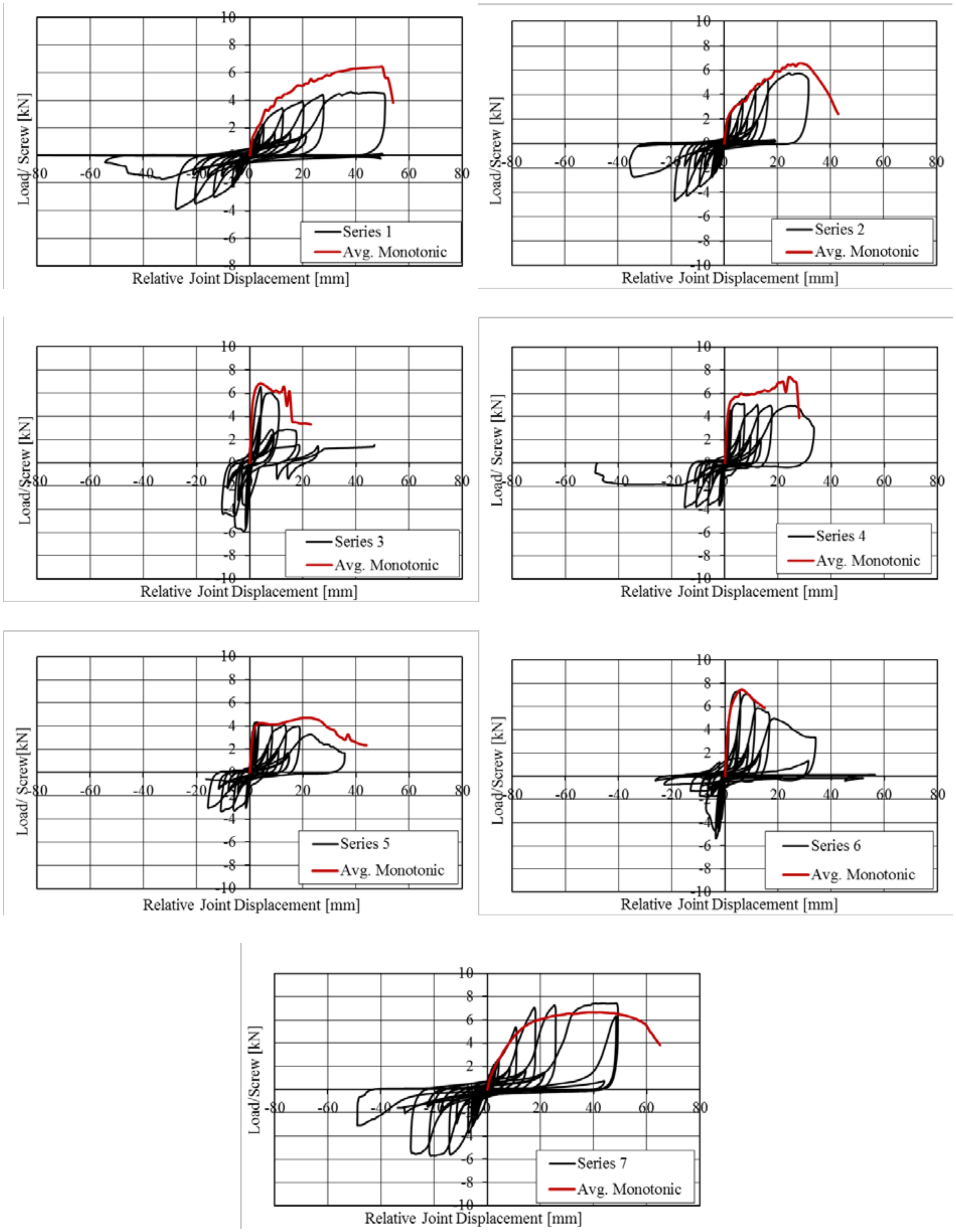

Fig 4– Typical load-displacement curves from different test series

2.5 Discussion

A comparison between monotonic and cyclic tests showed that joints under cyclic loading reached 5-40% lower capacity, 10-55% less ductility, and 30-70% less stiffness compared to the joints under monotonic loading. While the response parameters of connections under cyclic loads are expected to be slightly lower than those obtained from static ones, the surface spline and butt joint with STS in shear reached 40% higher stiffness under cyclic than under monotonic loading.

A comparison between positive and negative envelopes in the cyclic curves showed that joints reached 20-40% higher capacity in their positive envelope compared to the negative envelope. In the positive envelope (where loading was initiated), the compression force pushed the two panels together, while in the negative envelopes (under tension), the chosen test set-up created a tension force perpendicular to the shear plane. No such clear trend was found for ductility and stiffness. Ductility was higher in the positive envelope for most joints except in lap joint with STS in withdrawal and SWWS. Some joints (spline, SWWS, butt) had higher stiffness in the positive envelope while other joints (lap, WSSW) were less stiff in the positive envelopes compared to the negative envelopes.

Fig 5 illustrates the failure modes observed in the reversed cyclic tests. In the surface spline joints, the screws first yielded, and after repeated load cycles, almost all screws broke (Fig 5 left). In the static tests, the screws yielded and deformed but did not break. The failure the reversed cyclic could be caused by low-cycle steel fatigue. In the half lap joints with STS in shear, first failure was screws yielding, then the two CLT panels separated but the joints experienced very large displacement before failing. For lap joints with screws loaded in withdrawal, the test specimens rotated in in-plane and out-of-plane during testing and head pull in and head push out failures were observed (Fig 5 middle). The failure mode observed in half-lap joints with STS combined in shear and withdrawal was the pulling out of the withdrawal screws and yielding of shear screws. The separation of the two pieces was observed after reaching capacity, and some shear screws broke. For the Butt joints with STS in withdrawal, the failure mode with screws withdrawal followed by yielding which initiated a big gap between two pieces, see Fig 5 right.

Fig 5 – Failure modes: screw breaking (left), withdrawal (middle) and yielding (right)

3. Conclusions

The performance of different connections with STS in 3-ply CLT panels was evaluated in a total of 42 monotonic and 21 reversed cyclic tests. The results presented in this paper allow for drawing the following conclusions:

1) The results confirmed that using STS in shear can lead to a ductile connection, which can reach large relative displacements. Using STS in withdrawal leads to much stiffer joints, however, such joints fail at small displacements and do not exhibit high ductility. The connector assembly with double inclination of STS

provided high capacity and stiffness and adequate ductility. Finally, the combination of STS in withdrawal and shear seems to allow for joints that exhibit high capacity, high stiffness and high ductility.

2) The reversed cyclic tests confirmed the differences in terms of stiffness and ductility depending on the screw layout as determined in the monotonic tests. A reduction in capacity and ductility was observed in the reversed cyclic tests when compared to the quasi-static monotonic tests. Further investigation need to identify the impact of the chosen test set-up in relation to the actual impact of the loading.

3) The inclined set-up with one shear plane proofed adequate for monotonic loading; for revered cycling loading, however, the tension component perpendicular to the shear plane negatively affected the results, specifically in terms of lower capacity and ductility in the negative envelopes.

The results will allow for comparisons against design values in accordance with future CSA-O86 provisions for connections in CLT as well as reliability analyses

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