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EDGE CONNECTIONS FOR CLT PLATES: IN-PLANE SHEAR TESTS ON HALF-LAPPED AND SINGLE-SPLINE JOINTS

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ABSTRACT: A crucial aspect of fully realising the potential of cross-laminated-timber (CLT) as a structural material is ability to interconnect it to similar and dissimilar materials. This paper primarily reports in-plane shear tests on half-lapped and single-spline joints that make edge-to-edge connections between CLT panels using screws. A novel aspect of the study is investigation of how placing washers under screw heads alters stiffness and strengths of joints. Subsidiary axial load tests on screws assisted explanation of the shear joint results. Conclusions include the importance of accounting for large displacement effects on how screws transfer forces across joint-planes, and need to improve current generation joint design methods so that they account for effects of eccentricities that result from construction arrangement and detailing decision.

KEYWORDS: Connections, Cross-Laminated-Timber, Lateral load, Self-Tapping Screws, Shear, Washers, Withdrawal

1 INTRODUCTION

Cross-laminated-timber (CLT) has great potential as a slab construction material, because it can be manufactured to have rigidity and strength similar to that of an equal thickness of reinforced-concrete (RC) [1]. Attractiveness of CLT is further enhanced by it having only about one-third of the mass of normal-weight RC, and its availability in widths of 2-5m, lengths of 20m and thicknesses of up to 0.5m [2-5]. Yet, as with other engineered-wood-products (EWP), the crucial structural questions about CLT are those concerning ability to interconnect discrete pieces of it to form superstructures or large substructures. To date only relatively simple techniques like half-lapped and spline joints that employ slender fasteners like self-tapping screws have found their way into common construction practice [4,7-9]. Such techniques are able to effectively transfer in-plane shear force flows; and in some instances also in-plane tension and in-plane and out-of-plane bending/torsion force flows. However, the stiffness and strength of such connections tends to be limited [6,8,9].

Ideally intra-slab CLT edge-to-edge connections would enable creation of slabs/plates that act monolithically under effects of serviceability loadings or effects of ultimate seismic loadings when used as diaphragms. Plus, ideally intra-slab edge-to-edge connections and/or boundary connections would form yield zones in any other situation [4,10]. Importance of these attributes would be that would ensure that CLT would perform in a manner equivalent to RC slabs, thereby avoiding a gamut of potential problems, especially in the case of hybrid superstructure systems [4].

CLT products have particular characteristics that need to be considered when addressing design and construction of joints in them. As their collective name implies, CLT products have pieces of lumber placed in three or more layers that cross-reinforce one another, with adjacent layer faces bonded using mechanical fasteners or adhesives. Products bonded with melamineurea-formaldehyde or polyurethane adhesives are most common, because that maximises both rigidity and strength. The cross-lamination toughens CLT against through thickness splitting due to tension or shear. This overcomes what has proven to be the primary weakness of most other types of EWP, and that has limited their usage as general purpose structural materials.

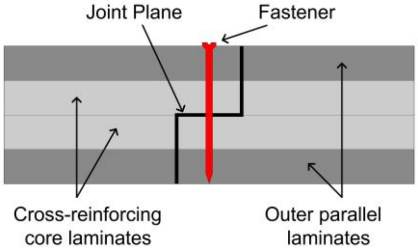

Figure 1: *Example of necessary penetration of faster to mobilize cross-reinforcement toughening in CLT*

To activate toughening against splitting caused by laterally loaded fasteners, it necessary that fasteners penetrate sufficiently deeply into CLT to be anchored into at least

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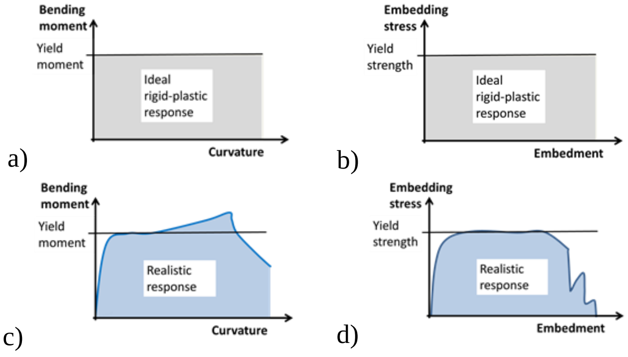
one lamination that cross-reinforces a face lamination, Figure 1 [9]. How deeply fasteners must penetrate to be suitably anchored depends on the layups of particular CLT products, but it is usually necessary to penetrate two or three laminations at one side of a joint plane. Lamination thicknesses vary between 17mm and 38mm, meaning that suitable fasteners are quite long. Proprietary self-tapping screws are a common choice of fastener because they are available in suitably large lengths and their threads cause them to anchor properly in CLT [e.g. 11]. Also, preferences commonly favour use of relatively small diameter self-tapping screws (~ 10mm) because that mitigates proneness to intra-lamination splitting when lateral forces on screws makes them embed into CLT [9].



Fastener *Embedment/bearing*

Figure 2: *EYM and realistic joint component responses*

For all cases where lapped type joints (Figure 1) transfer in-plane internal force flows within slabs/plates across edge-to-edge connections between CLT plates, there are primary lateral surface pressures on fasteners. Unless joint planes lie at mid-depth and parallel to neutral axes of uniformly thick slabs and fasteners are oriented normal to joint planes, there can also be other primary surface forces on fasteners. Most often other primary surface forces will be shearing forces parallel to fastener axes caused tendencies of fasteners to pull out of or through CLT. Even when initially there are only surface pressures on fasteners, surface shearing forces and therefore axial fastener forces will develop at large amplitude joint deformations through large displacement effects. If large displacement effects occur they can also cause frictional resistance at joint planes, or will close gaps that exist between structural elements facing joint planes. Force flow transfers across lap type joints can be associated almost exclusively with bending action of fasteners, or also be associated with axial forces in the fasteners irrespective of whether or not fasteners are initially inclined relative to joint planes. The former results in what is often termed lateral load effect resistance, and that latter results in what is termed the rope effect resistance. Either or both these resistance components can dominate ultimate capacities of joints/connections.

The lateral load resistance of dowel-type fasteners (nails, screws, plain dowels, bolts, etc.) is widely taken to be adequately explained by so-called European Yield Models (EYM). The original EYM [12], and variants of it assume an ideal rigid-plastic response of fasteners in bending and wood material on which they bear, Figures 2-a and 2b. Were fasteners and CLT to have such ideal responses it would give engineers ability to create connections in CLT slabs that could result in ideal elastic-plastic slab responses to in-plane or out-of-place forces. Realistically however fastener loaded in bending and embedment responses of CLT elements are not ideal rigid plastic and instead approximate elasto-plastic behaviours, Figures 2-c and 2d). Nevertheless real behaviours of fasteners and CLT are close enough to the ideal that EYM models have been found estimate failure loads quite well [9]. This is statement comes however with the proviso that fasteners must penetrate laminations sufficiently to mobilize cross-reinforcement within CLT. Plus as discussion below shows capabilities of EYM to accurately predict joint capacities also comes with other provisos related to how forces will flow within slabs/plates containing joints.

Various timber design codes use EYM capacities directly as the basis of design strengths of joints [e.g. 13], while others supplement EYM capacities with an allowance for rope effect resistance [e.g. 14]. Codes that base design strengths on yield capacities nominally attempt to replicate the load value beyond which deformation would result in irrecoverable damage. Those that add an allowance for rope effect resistance attempt to replicate the ultimate load capacities of joints. Engineers also need to consider whether structural systems can accommodate large deformations associated with realisation of rope effect resistances [4].

Figure 3 shows possible lateral loading failure mechanisms considered under EYM models (i.e. defining joint yield strength). Which mechanism governs (i.e. produces the lowest estimate of strength) is determined by geometric variables and fastener yield moment and wood/CLT embedment strength. However, with slender fasteners mechanism IV often governs EYM calculations.

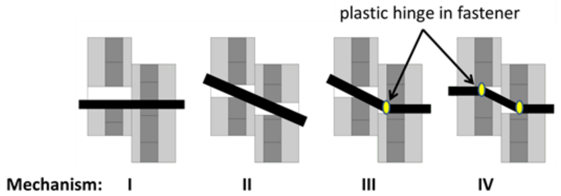


Figure 3: *EYM mechanisms for a single-shear CLT-to-CLT joint*

This paper discusses and interprets tests on half-lapped and single-spline CLT connections made using self-tapping screws. Specimens were subjected to in-plane shear forces that simulated force flows that would occur in edge-to-edge CLT plate connections within CLT slabs that perform diaphragm or shear wall functions. Supplementary screw withdrawal and pull through tests were carried out to facilitate explanation of the shear force test results.

2 METHOD

Test were carried out according to methods specified in ASTM D1761-12 [15].

2.1 SHEAR FORCE TESTS

Shear force test specimens were designed to simulate antisymmetric lapped joints and non-symmetric single-spline joints as occur in connections in CLT slabs, Figure 4.

In practice construction of slabs normally results in approximately concentric shear force flows through CLT panels and lapped joints in slabs, resulting in close to pure shear force transfer across joint planes within the lapped joints. Consequently in such situations fasteners are loaded only laterally, or nearly so at small amplitude deformations. When slab connections contain a single-spline joint the arrangement is by default explicitly non-symmetric because joint planes do not lie within the mid-depth planes of slabs. The resulting eccentricities cause out-of-pane bending, and sometimes also torsional moments. Even if slabs are discretely constrained against out-of-plane deformations by measures like fixing slabs to structural frameworks and walls, eccentricities in internal force flows within slabs will cause some axial forces in fasteners in single splice joints at all displacement amplitudes. Sensitivity of test specimen and real slab structural responses to effects of such eccentricities is proportional to the thickness of the CLT plates being edge-to-edge connected.

Tests were performed using a specially designed apparatus that applied as close as practical pure shear force to the CLT elements, Figure 5. As shown in the figure the panel element on the left was pushed down relative to the piece on the right, with the apparatus constraining other distortions. The CLT used was 180mm thick Nordic X-Lam manufactured in Canada, having five equal thickness laminations/plies and an average density of 512kg/m^3 [16,17]. In tests the grain in face and middle laminations was orientated parallel to the lines of the edge-to-edge connections. Cross-reinforcing interior laminations were oriented normal to the lines of edge-to-edge connections. Self-tapping screws used were type Eco-Fast ASSY 3.0 manufactured by Würth [18]. They had nominal shank diameters of 6mm, were 160mm long and thread to 70mm from the tip; and were installed without predrilling. The splice elements in single-spline tests were 19mm thick Douglas fir plywood, with the face rain oriented parallel to lines of edge-to-edge connections [19].

As specimens had only two screws attaching any piece of CLT panel to another piece, or to a spline plate, it can be assumed that the lateral force applied to one screw was half the force applied by the loading actuator. Loading was applied monotonically at a displacement rate of 3mm per minute. The maximum resistance/load was reached between 8 and 18 minutes after the commencement of a test. Therefore, the measured responses correspond to what is commonly termed short-term testing duration or static loading conditions.

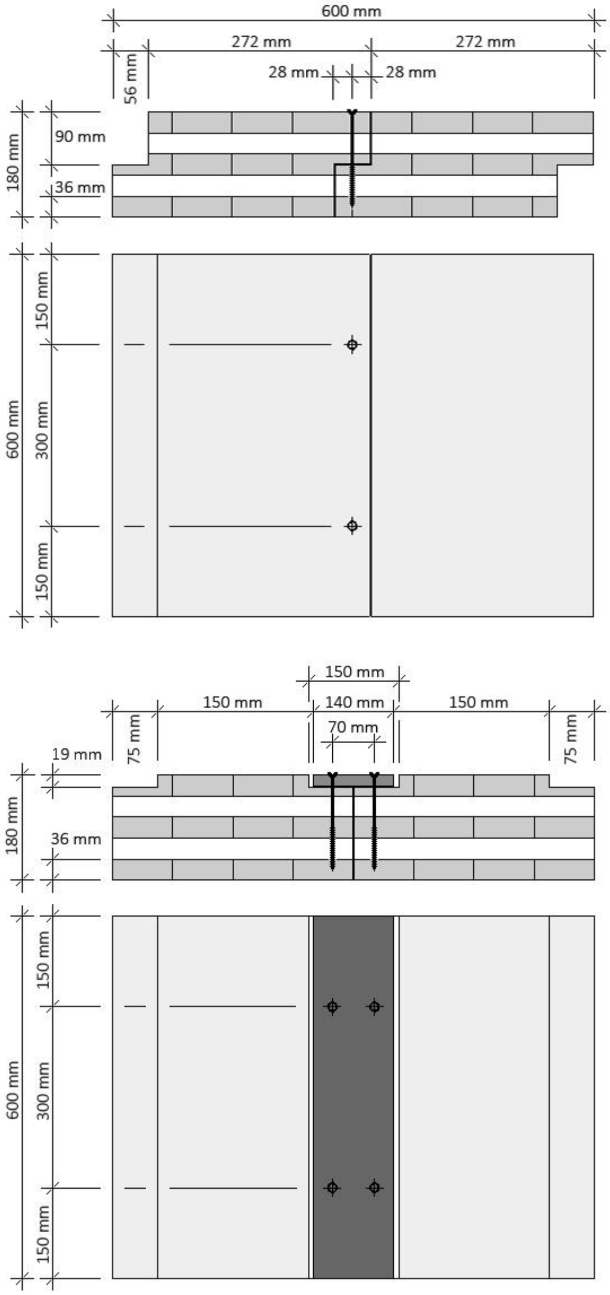


Figure 4: *Shear test configurations*
Top) half-lapped joint
Bottom) single-spline joint

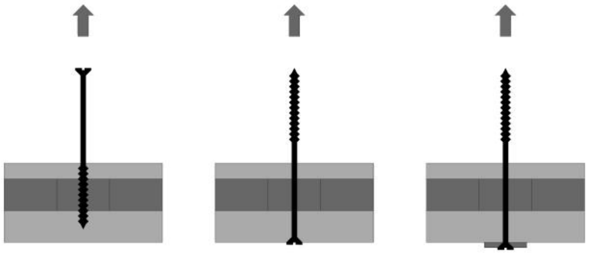
For each type of joint two fasteners situations were considered, with those being use of only self-tapping screws and use of self-tapping screws with washers placed under their heads. Washers used were flat shaped steel with a thickness of 3mm, and having outer and inner diameters of 19mm and 7mm respectively.

CLT was preconditioned to 12% moisture content (m) prior to specimen fabrication. Specimens were restored in a climate chamber set to maintain constant *m* of 12% for 24 hours prior to testing. The delay between fabrication and testing was to allow CLT to around screws to relax stress caused by driving screws that would inflate resistance relative to what is achievable under site conditions [20]. The material condition corresponded to what is termed dry fabrication and dry loading conditions [13]. There were five replications per test combination of variables, resulting in a total of 20 shear tests.

Figure 5: *Shear test apparatus*

During test LVDTs (one on each face of a specimen, Figure 5) measured joint slip, which corresponds to relative movement of CLT element parallel to the line of the connection. Averaged LVDT measurements combined with actuator force measurements permitted real-time plotting of load versus deformation relationships. Post testing analysis determined stiffness and strength information in manners consistent with various practices for assigning design properties for joints/connections.

2.2 AXIAL LOAD TESTS



a) b) c)

Figure 6: *Axial test configurations*

a) withdrawal of screw thread
b) pull-through of screw head
c) pull-through of screw head and washer

Figure 6 summarises the scope of axial load tests carried out, with intend that they represent behaviours of self-tapping screws subjected to longitudinal shearing surface forces similar to those developed due to initial eccentricities or large deformations in joints/connections. Withdrawal tests (Figure 6-a) characterised behaviour of point-side threaded portions of screws being pulled out of CLT. Pull-through tests (Figures 6-b and 6-c) characterised behaviours of unthreaded portions of screw shanks, with and without a washer under the head, being pulled through CLT. Screws were inserted into CLT normal to face plane of a CLT member. The CLT and fasteners were the same as in the shear tests. Each type of test was replicated six times.

For withdrawal tests the screws were inserted 70mm into the CLT, meaning that the anchoring resistance was provided along the interaction of the threaded portion of their lengths. In pull-through tests the screws fully penetrated a 90mm thickness of CLT, corresponding to a half CLT plate thickness as would occur in a half-lapped edge-to-edge joint.

The applied rate of loading was 2.5mm per minute, resulting in attainment of peak withdrawal resistance in about 1 minute from commencement of loading. In pull-through tests the peak resistance was reached in about 4 and 9 minutes for screws without and with washers respectively.

3 RESULTS

Data from shear and axial load tests were analyses in the same manner to determine engineering parameters that quantify the stiffness, strength, ductility, and energy absorption characteristics. The chosen range of parameters encompasses those currently employed as the basis of design code resistances, and others that some designers might find useful. Figure 7 shows how stiffness, and strength values and associated displacements were estimated from individual load versus displacement response curves.

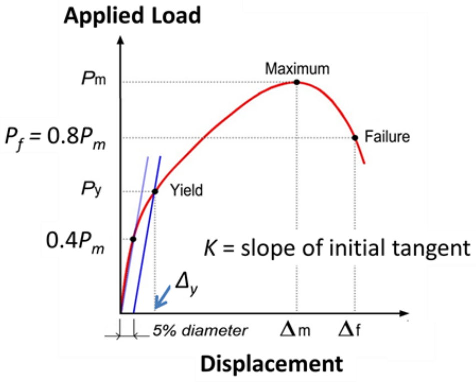


Figure 7: *Definition of stiffness (K), and strength values (P_y, P_m, P_f) and associated displacements (Δ_y, Δ_m, Δ_f) from which engineering design properties can be determined*

The yield load (P_y) and yield displacement (Δ_y) were defined using the 5% fastener diameter offset method, as illustrated in Figure 7. This is approach is consistent with practices adopted in other North American studies on CLT connections [21]. Other parameters, maximum load (P_m), displacement at maximum load (Δ_m), failure load (P_f), displacement at failure load (Δ_f), dissipation energy at 30mm slip (W_{30}), dissipation energy at failure point (W_f), stiffness (K), and ductility ratios were also defined from load-displacement test curves. Ductility ratio (D) is defined as Δ_m/Δ_y, and the failure ductility ratio (D_f) as Δ_f/Δ_y.

The parameters W_{30} and W_f are ones that can be used to subjectively estimate relative merits of particular joints/fasters in terms of ability to absorb energy under high amplitude deformation, or as the basis of energy based structural design calculations [22].

3.1 SHEAR TEST RESULTS

3.1.1 Joints without washers under screw heads

Average load versus deformation responses of half-lapped and single-spline joints without washers inserted under screw heads are shown in Figure 8. Table 1 summarises corresponding derived engineering parameters.

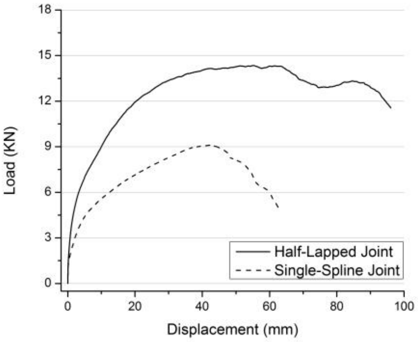


Figure 8: *Average load-displacement curves for shear tests: half-lapped and single-spline joints* *<u>without washers</u>*

Table 1: *Derived engineering parameters from shear tests: half-lapped and single-spline joints without washers**

Parameter	Unit	Half-Lapped	Single-Spline
P_y	kN	6.1 (4)	3.9 (5)
Δ_y	mm	3.4 (39)	3.7 (17)
P_m	kN	14.3 (3)	9.1 (5)
Δ_m	mm	54.9 (30)	42.2 (12)
P_f	kN	12.8 (3)	7.3 (5)
Δ_f	mm	74.8 (14)	54.5 (9)
K	kN/m	1.8 (39)	1.0 (14)
W_{30}	kN*mm	299 (7)	182 (4)
W_f	kN*mm	922 (14)	393 (8)
D	Δ_m/Δ_y	16.2 (47)	11.7 (13)
D_f	Δ_f/Δ_y	22.2 (33)	14.6 (13)

* *Average value and CoV (%) in parenthesis*

As the figure shows, half-lapped joints are superior in all respects (i.e. initial stiffness, strength, ductility, ability to absorb energy) to single-splice joints. In rough terms it is appropriate to think for the joint types investigated, that using of half-lapped CLT plate edge-to-edge connections is 50% superior to using of single-spline edge-to-edge connections to resist shear flows in diaphragm slabs. The difference is attributed to combined effects of using relatively thin plywood as the head-side member and eccentricities that complicate force flows in single-spline joints.

Examination of plastically deformed screws from failed specimens revealed that half-lapped and single-spline joints failed by type IV and type III mechanisms respectively, based on the classification shown in Figure 3. This agreed with mechanisms predicted to govern by EYM equations. However, this does not mean that that type of design level model accurately predicts observed joint capacities.

Table 2 shows EYM model predictions of P_y and P_m and their ratios to values estimated from test data. The model values were calculated using the Eurocode 5 version of EYM equations [14] in conjunction with screw embedment strength estimated from density of the CLT [8], and manufacturer suggested yield moments of screws [11]. To note is that the $P_{y\text{-}EYM}$ values do not include any allowance for the rope effect enhancement of capacities at large deformation. Estimates of $P_{m\text{-}EYM}$ do include rope effects. According to the Eurocode 5 methods the rope effect contribution to P_m can be taken to be 0.25 times the characteristic axial withdrawal capacity of a fastener, but not exceeding P_y. However, as in axial load tests (Section 3.2) the head-side pull-through capacity for a screw was less than the point-side withdrawal resistance the rope effect calculations in Table 2 are based on measured head pull-through resistance.

Table 2: *European Yield Model predictions of yield and maximum shear capacities of half-lapped and single-spline joints without washers**

Joint type	Yiled load		Maximum load	
	$P_{y\text{-}EYM}$ (kN)	$P_{y\text{-}EYM}$ / $P_{y\text{-}test}$	$P_{m\text{-}EYM}$ (kN)	$P_{m\text{-}EYM}$ / $P_{m\text{-}test}$
Half-lapped	6.96 (mech. IV)	1.14	9.06	0.63
Single-spline	5.17 (mech.III)	1.32	7.27	0.80

* *Two screws per joint*

Magnitudes and inconsistencies of ratios $P_{y\text{-}EYM}$ / $P_{y\text{-}test}$ and $P_{m\text{-}EYM}$ / $P_{m\text{-}test}$ in Table 2 suggests need to more deeply examine how to estimate design resistances of types of joints/connections like those discussed here.

CoV values in Table 1 indicate that for joints that do not have washers placed under screw heads variability in design strength related parameters (P_y, P_m, P_f) is low.

Therfore it is arguably reasonable to base design capacities of shear connections in diaphragms (which usually will have many screws) on the average strength per screw. Variability in displacement related paramters (Δ_y, Δ_m Δ_f, D, D_f) is relatively high, especially in the case of lapped joints. Variability in parameters related to energy absorption capabilities (W_{30}, W_f) is intermediate to variable in strength and displacement related parameters; which is to be expected as they are derived by integration of load-displacent relationships. Many past investigations support the finding that diplacemet related parameters are more variable than strength related parameters [e.g. 23].

3.1.2 Effects of washers under screw heads

3.1.2.1 Half-lapped joints

Figure 9 compares average load-displacement responses for half-lapped joints with and without washers placed under the heads of screws. From that comparison it is clear that addition of washers has slight effect on initial stiffness of a joint (K), increases strength (P_y, P_m, P_f) moderately, and decreases the post-yield point deformation (i.e. reduces Δ_m, Δ_f, D, D_f, W_{30}, W_f). In terms of decreaced post-yield dformation it is important however to recognise that the result of adding washers does not create a non-ductile response, because inelastic deformations remain significant. Explanation of the observed effects lies in how addition of washers changed the deformation and failure mechanisms after the response exceeded the small deformation regime.

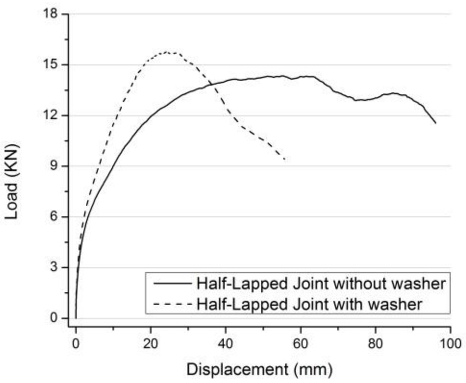


Figure 9: *Effect of washers on average load-displacement responses of half-lapped joints*

Figure 10 shows tyical post-failure residual deformations in lapped-joint speciments with and without washers placed under screw heads. In both instances the failure mechanism involved plastic bending deformation of the screw on either side of the joint plane. The greatest bending distortion occured in either instance on the side of the joint where the screws were most effectively anchored into the CLT. When there were no washers the anchoring was most effective on the point-side of the joint, and therefore development of axial forces in screws was controlled by pull-through resistance of the head-side portions of screws. By contrast, when there were washers the screws were anchored most effectivey on the head-side of the joint, with development of axial forces in screws controlled by withdrwal resistance of threaded portions of screws. As addressed below, this is entirely consistent with results of axial load tests on screws.

a) without washers b) with washers

Figure 10: *Residual deformations in half-lapped joints*

Relative to EYM assumptions, it is to be noted that post-yielding distrotions in screws approximated but did not fully attain the antisymmetric shape consistant with mechanism IV failures (Figure 3).

Table 3 gives a quantitative comparison of derived engineering parameters for half-lapped joints with and without washers under screw heads.

Table 3: *Average values of engineering parameters from shear tests on half-lapped joints with and without washers*

Parameter	Unit	Value	
		No washers	With washer
P_y	kN	6.07	6.71
Δ_y	mm	3.37	2.96
P_m	kN	14.3	15.8
Δ_m	mm	54.9	24.4
P_f	kN	12.9	12.6
Δ_f	mm	74.8	40.0
K	kN/m	1.80	2.27
W_{30mm}	kN*mm	299	371
W_f	kN*mm	922	512
D	Δ_m/Δ_y	16.2	8.2
D_f	Δ_f/Δ_y	22.2	13.5

3.1.2.2 Single-spline joints

Figure 11 compares average load-displacement responses for single-spline joints with and without washers placed under the heads of screws. Immediately obvious is that the effects of addition of washers are more accentuated than for half-lapped joints. Again relative anchoring characteristics of screws in head-side and point-side members were important. With single-spline joints incorporating washers significantly increases the rotational restraint of screw at their heads, which altered the bending deformations in screws. Post-testing examination of plastic deformation of screws from joints with washers indicated that the behaviour approached that associated with an EYM mechanism IV failure.

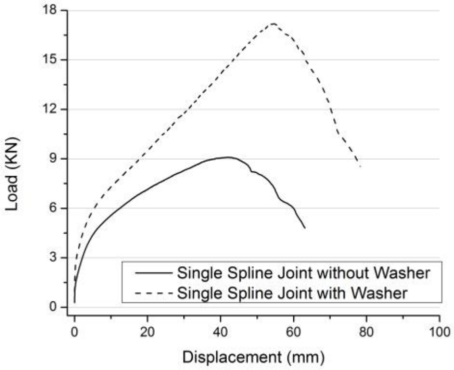


Figure 11: *Effect of washers on average load-displacement responses of single-spline joints*

For single-spline joints addition of washers had slight effect on initial stiffness (K) and ductility ratios (D, D_f) of a joint, but altered all other engineering parameters significantly. When washers were present, post-yield deformation was strongly influenced by large deformation effects and resulting developmemt of axial forces in screws. Because screws are well anchored on the point side of the joint plane and were resistant to pull-through failure on the head side of the joint plane, the rope effect played a strong role in determining the maximum resistance. On average P_m increased by nearly 90% because of the addition of washers. Figure 12 illustrates how the increased bearing contact area on the outer surface of the plywood spline (head-side member) prevented pull-through failure. Attainment of P_m corresponded to reaching the withdrawal resistance of threaded portions of screws. Again this was fully consistent with results of axial load tests on screws.

Table 4 gives a quantitative comparison of derived engineering parameters for single-spline joints with and without washers underneath screw heads.

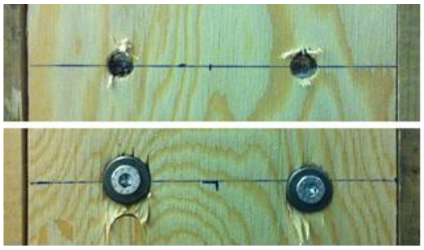


Figure 12: *Residual indentation of screws into head-side members of single-spline joints*
Top) no washers
Bottom) with washers

Post testing examination of plastic deformation in screws from joints with washers indicated that the behaviour approached that associated with an EYM mechanism IV. EYM calculations according to Eurocode V imply that transition from a mechanism III failure when there are no washers to a mechanism IV failure when there are washers will increase P_y by 39% and P_m by 64% [14]. Corresponding actually observed increases in capacities due to presence of washers were 52% for P_y and 89% for P_m (based on Table 4). Again the findings indicate some limitations in applicability of current generation EYM calculation methods for types of joints/connections investigated.

Table 4: *Average values of engineering parameters from shear tests on single-spline joints* *<u>with and without washers</u>*

Parameter	Unit	Calculated value	
		No washers	With washers
P_y	kN	3.89	5.90
Δ_y	mm	3.74	5.25
P_m	kN	9.10	17.2
Δ_m	mm	42.2	54.9
P_f	kN	7.28	13.7
Δ_f	mm	54.5	66.8
K_c	kN/mm	1.04	1.13
W_{30mm}	kN*mm	182	246
W_f	kN*mm	393	799
D	Δ_{fr}/Δ_y	11.3	10.5
D_f	Δ_{fr}/Δ_y	14.6	12.7

3.2 AXIAL LOAD TEST RESULTS

Figure 13 and Table 5 summarise results of axial load tests on screws in CLT. As those results show, it took more force to withdraw a self-tapping screw inserted 70mm along its threaded portion into CLT than to pull an unthreaded screw shank and screw head through a 90mm thickness of CLT. However, it took more force to pull an unthreaded shank and a washer beneath a screw head through a 90mm thickness of CLT than to withdraw a threaded self-tapping screw inserted 70mm into CLT. This matches the findings from shear test on joints (Section 3.1).

The quite sudden drop off in residual capacity of screws in withdrawal after attainment of peak resistance at a relatively small Δ_m (average 1.6mm), and associate low values of D (average 1.2) and D_f (average 2.2) imply desirability of conservative sizing of screw point-side penetrations into CLT. If that were done it would make joints with laterally loaded screws more likely to fail benignly by a combination of EYM bending and head pull-through mechanisms.

In general the variability in derived engineering parameters (Table 5) was small or negligible. This implies that axially loaded screws within joints and connections exhibit consistent and therefore predictable performances.

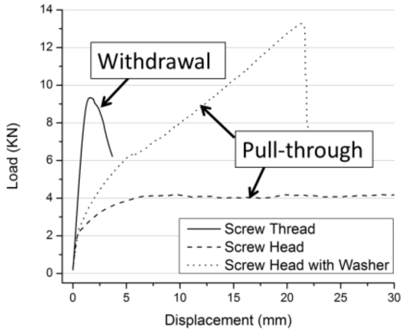


Figure 13: *Average load-displacement responses of axially loaded screws in CLT*

Table 5: *Derived engineering parameters from axial load tests on screws in CLT****

Parameter	Unit	Withdrawal	Pull-through	
			Head	Head + washer
P_y	kN	9.1 (7)	2.3 (4)	5.7 (1)
Δ_y	mm	1.4 (7)	0.7 (11)	4.2 (22)
P_m	kN	9.3 (6)	4.2 (2)	13.3 (1)
Δ_m	mm	1.6 (8)	9.8 (16)	21.4 (2)
P_f	kN	7.5 (6)	4.2 (2)	12.9 (1)
Δ_f	mm	3.1 (5)	30******* (0)	21.7 (2)
K	kN/mm	6.7 (5)	3.3 (11)	1.3 (21)
W_f**	kNmm	22 (16)	118 (1)	180 (5)
D	Δ_m/Δ_y	1.2 (13)	15.1(12)	4.9 (21)
D_f	Δ_f/Δ_y	2.2 (10)	42.4(10)	5.1 (21)

* *Average value and CoV (%) in parenthesis*
****** *Work up to 30mm displacement*
******* *Adopted limiting value (30mm)*

4 GENERAL DISCUSSION

Results presented here, and others by Muñoz et al [21], indicate that half-lapped joints can create effective edge-to-edge connections in CLT slabs. However, it also needs to be acknowledges that such connections have been found to perform poorly in terms of out-of-plane behaviour of CLT slabs [24]. Specifically presence of half-lapped connections can cause clustering of out-of-plane modal frequencies that amplifies motions to an extent that adversely affects dynamic serviceability of CLT floor slabs. This indicates need to consider functionality of half-lapped, or other, potential slab connection methods from broad perspectives associated with performance of superstructure systems, and not to simply focus on an isolated question like the in-plane shear strength or stiffness of connections.

Ongoing studies by the authors are addressing holistic definition of CLT slab connection methods that can address spectrums of requirements applicable to various design situations. What is reported here is therefore only one of the building blocks toward an eventual goal.

Although not initially intended as a primary purpose of what was done, the present study has highlighted need to address adequacy of contemporary EYM type joint design methods. In particular there is need to investigate further:

- Influences that eccentricities in structural arrangements have on flows of forces through connections and joints within CLT slabs.
- Adequacy of simplified approaches for estimating rope effect contributions toward ultimate design capacities of joints with laterally loaded self-tapping screws.

Comparison of single-spline test data with EYM predictions indicated that current generation models [e.g. 8,14] can fail to capture true ultimate load performances of commonly employed types of joints. Tests on axially load screws and shear tests on half-lapped and single-spline joints all indicated that contemporary practices for accounting for rope effect contributions to joint capacities are unreliable and too simplistic. The authors intend to investigate how to improve design level calculations models.

5 CONCLUSIONS

Primary conclusions from the presently reported study are:

- Half-lapped self-tapping joints are about 50% stronger and stiffer than single-spline joints when acting as plate edge-to-edge in-plane shear connections in CLT slabs.
- Placing washers in under heads of self-tapping screws can significantly increase the capacities of either half-lapped or single-spline shear joints in CLT slabs.
- It is important to consider eccentricities that affect the behaviour of shear joints in CLT slabs, as can occur for example when single-spline connections are employed.
- Some inadequacies exist in contemporary European Yield Model type methods for calculating design capacities of self-tapping screw joints in CLT.

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REFERENCES

[1] American National Standards Institute (ANSI): Standard for performance-rated cross-laminated timber, Standard ANSI/APA PRG 320-2012, ANSI, New York, NY, USA, 2012.

[2] Asiz A. and Smith I.: Demands placed on steel frameworks of tall buildings having reinforced concrete or massive wood horizontal slabs, Struct. Eng. Int., 19(4):395-403, 2009.

[3] Asiz A. and Smith I.: Tall hybrid RC framed buildings with massive timber floor plates, Proc. 1st Int. Conf. Struct. & Arch., CRC Press, 2010.

[4] Smith I. and Frangi, A.: Use of timber in tall multi-storey buildings, Struct. Eng. Doc. 13, Int. Assoc. Bridge & Struct. Eng., Zurich, Switzerland, 2014.

[5] Ceccotti A.: New technology for construction of medium-rise buildings in seismic regions: the X-lam case, Struct. Eng. Int., 18(2):156-165, 2008.

[6] Gagnon S. and Pirvu C.: CLT handbook, Special Pub. SP-528E, FPInovations, Quebec City, Canada, 2011.

[7] Harris R., Ringhofer A. and Schickhofer G. (Eds.): Focus solid timber solutions - European Conference on Cross Laminated Timber, Univ. Bath, Bath, UK, 2013.

[8] Uibel T. and Blaß H.: Edge joints with dowel type fasteners in cross laminated timber, Proc. CIB-W18 Meeting, International Council for Building Research Studies and Documentation, Rotterdam, The Netherlands, 2007

[9] Joyce T.: Connections for CLT Diaphragms in Steel-Frame Buildings, MSc thesis, Univ. New Brunswick, Fredericton, Canada, 2013.

[10] Shukla, S.N.: Handbook for design of slabs by yield-line and strip methods, Structural Engineering Research Centre, Univ. California, Berkley, 1973.

[11] Institut fur Bautechnik (IfB): Würth self-tapping screws, European Technical Approval ETA-11/0190, IfB, Berlin, Germany, 2011.

[12] Johansen K.W.: Theory of timber connections, Proc. Int. Assoc. Bridge & Struct. Eng., Zurich, Switzerland, 9: 249-262, 1949.

[13] Canadian Standards Association (CSA): Engineering design in wood, Standard 086-09, CSA, Toronto, Canada, 2009.

[14] European Committee for Standardisation: Eurocode 5—Design of timber structures, Part 1-1: General—Common rules and rules for buildings, EN 1995-1-1:2004 (E), English version, British Standards Institution, London, UK, 2004.

[15] ASTM International: Standard test methods for mechanical fasteners in wood, Standard ASTM D1761, ASTM International, West Conshohocken, USA.

[16] Nordic Engineered Wood Products (Nordic): Design properties of Nordic cross-laminated-timber, Tech. Note S21, Nordic, Montreal, Canada, 2012.

[17] Nordic: Technical data, Tech. Note S22, Nordic, Montreal, Canada, 2012.

[18] Myticom: A specifiers guide for safe and efficient use of structural ASSY screws in timber construction, Myticom, Vancouver, Canada, 2012.

[19] Canadian Standards Association (CSA): Canadian softwood plywood,Standard O151, CSA, Toronto, Canada, 2009.

[20] Mohammad M.A.H. and Smith I.: Nail embedment responses of lumber and OSB: Influences of moisture conditioning, J. Inst. Wood Sci., 14(3): 131-139, 1997.

[21] Muñoz W., Mohammad M., Salenikovich, A. and Quennevill P.: Determination of yield point and ductility of timber assemblies: in search for a harmonised approach, Proc. CIB-W18, Int. Coun. Building Res. Studies & Doc., Rotterdam, The Netherlands, 2008.

[22] Smith I. and Frangi A.: Overview of design issues for tall timber buildings, Struct. Eng. Int., 18(2/2008): 141-147, 2008.

[23] Smith I., Daneff G., Ni C. and Chui Y.H.: Performance of bolted and nailed timber connections subjected to seismic loading, Special Pub. 7275, Forest Prod. Soc.: 6-17, 1998.

[24] Weckendorf J. and Smith I.: Dynamic characteristics of shallow floors with cross-laminated-timber spines, Proc. World Conf. Timber Eng., New Zealand Timber Design Society, Auckland, NZ, 2012.