Moment resistance of bolted timber connections with perpendicular to grain reinforcements

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Summary

This paper reports the results of an experimental study to evaluate the contribution of self-tapping screws as perpendicular to grain reinforcements for bolted glulam connections with slotted in steel plates. Test results of beam-to-column connection specimens subjected to monotonic and reverse cyclic loading show that the connections reinforced with self-tapping screws have an increased capacity by a factor of 2 and 1.7 when compared to un-reinforced connections under monotonic and reverse cyclic loading, respectively. Retesting retrofitted failed un-reinforced connections with self-tapping screw reinforcements also show increase in the capacity by 1.87 and 1.53 times compared to the un-reinforced case connections under monotonic and reverse cyclic loading, respectively. An extremely ductile failure mode was also observed with the reinforced connection.

1 Introduction

It is well known that bolted timber connections with slotted in steel plates have poor ductility and low moment resisting capacity. Due to their simplicity and elegance, designers commonly use these connections to transfer shear forces and ignore the contribution of their moment carrying resistance. When subject to loading such as seismic forces, the connection may experience bending moments not intended in the design, and the connection could fail prematurely because it may not be able to provide the needed moment resistance as they are governed by the tension perpendicular to grain and longitudinal shear strengths of timber: the two weakest strength properties of wood.

Blaß and Bejtka [1], Bejtka [2], Blaß et al. [3] reported past research on using the self tapping screws as perpendicular-to-grain reinforcements. This paper reports an experimental study demonstrating that bolted timber connections can be easily made into a strong and ductile moment resisting connection when reinforced with these self tapping screws.

Fig. 1: Example of a bolted beam-column connection with slotted-in steel plate

A commonly used beam-to-column wood-steel-wood bolted connection was considered in the study (see Figure 1). A total of 30 connection tests were conducted under monotonic ("M" series) and reverse cyclic loading ("C" series). To investigate improvements in performance and ductility, regular connection specimens were tested as un-reinforced first- the "U" series". A second set of specimens was reinforced with recently invented long, self-tapping wood screws to prevent early brittle failure and then tested – the "R" series. The reinforcing screws were installed directly into the wood members without pre- drilling in the direction perpendicular to both the wood grain and the bolts.

Finally, the prior tested un-reinforced and broken specimens were retrofitted with the self-tapping screws and retested to prove the versatility of the reinforcing method as a tool to retrofit existing, damaged structures – the "D" series. The observed performance differences of reinforced and retrofitted connections as well as un-reinforced connections during monotonic and reverse cyclic loading are presented in this paper.

2 Materials and Methods

Canadian 24f-E Douglas fir/Larch Glulam members with a cross section of 304 mm x 130 mm were used to fabricate the connection specimens. The column and beam consisted of double and single members, respectively. Figures 2 and 3 show the schematics of the connection specimens.

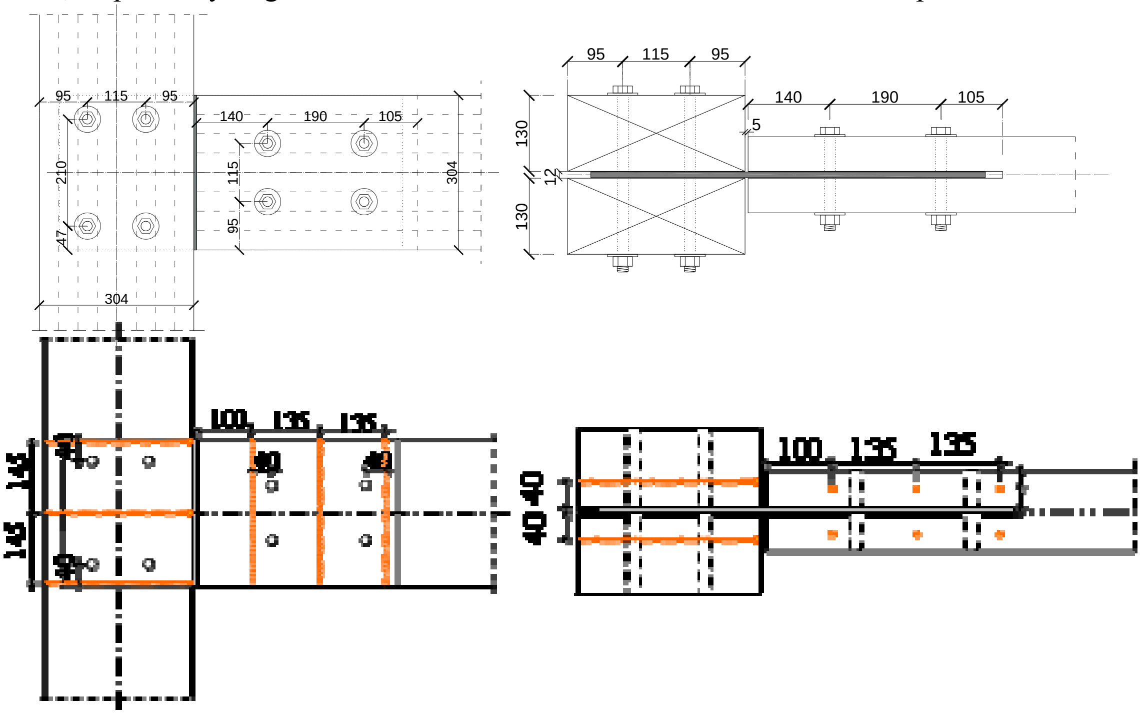


Fig. 2: Side and top views of connection layout (all measurements in mm)

The Hundegger K2 fully automated joinery machine in University of BC (UBC) was used to manufacture the specimens. The bolt holes were drilled with the available 19.1 mm diameter drill in the Hundegger machine which matched the bolt diameter without any extra oversize fabrication tolerance. The performance of the tight-fitting connection is likely to be better than that with poorer tolerance but relative comparison between the examined connection types is still valid. The final lengths of the wooden parts of the connection were 1000 mm for the column members and 820 mm for the beam members. The moisture content of each specimen element was measured prior to testing with a resistance moisture detector and they ranged from 11 to 14%.

The steel bolts were “SAE J429 Grade 5 Cap screws – NC Plain”, fabricated of medium carbon steel, quenched and tempered. The bolts applied in the column and the beam connections had lengths of 305 mm and 165 mm, respectively. Steel plates with dimensions of 675 mm x 300 mm and a thickness of 9.5 mm were used. In each plate, eight holes with a diameter of 19.1 mm were drilled according to the fastener group pattern (See Fig 2.). After every test, the used steel plate was visually examined for any hole bearing deformations. Very little deformation was noticed and reusing the steel plates was assumed to be of negligible influence.

Würth ASSY VG plus self-tapping wood screws continuous threads were used to reinforce the connection specimens. The screws were 300 mm in length and 8 mm in diameter. The tread is galvanized and plastic-coated. For the design according to DIN1052:2004-08 and DIN V ENV 1995-1-1:1994-06, the characteristic value of the screws’ yield moment ($M_{y,k}$) is 17600 Nmm. The withdrawal resistance and further information concerning different loading conditions, spacing requirements and limitations on implementation may be obtained from DIBt [4].

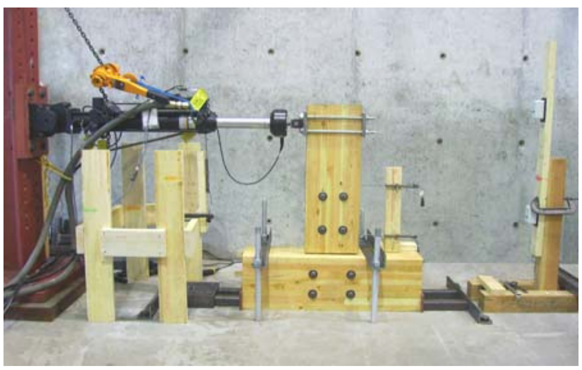


Fig. 3: Test Set up

All tests of this investigation were conducted at UBC Timber Engineering and Applied Mechanics Laboratory. A general view of the test setup is depicted in Figure 3. Six sub-series with 5 replications each were tested. In monotonic tests, the connection specimens were pushed to failure first (i.e., load dropped to 80% of the peak load); after which the displacement was brought back to zero. In the reverse cyclic tests, the Consortium of Universities for Research in Earthquake Engineering (CUREE) displacement controlled reverse cyclic protocol was followed Krawinkler et al. [5].

Figure 4 shows the protocol with the reference deformation (Δ) taken as 60% of the monotonic displacement capacity $\Delta_{ultimate}$.

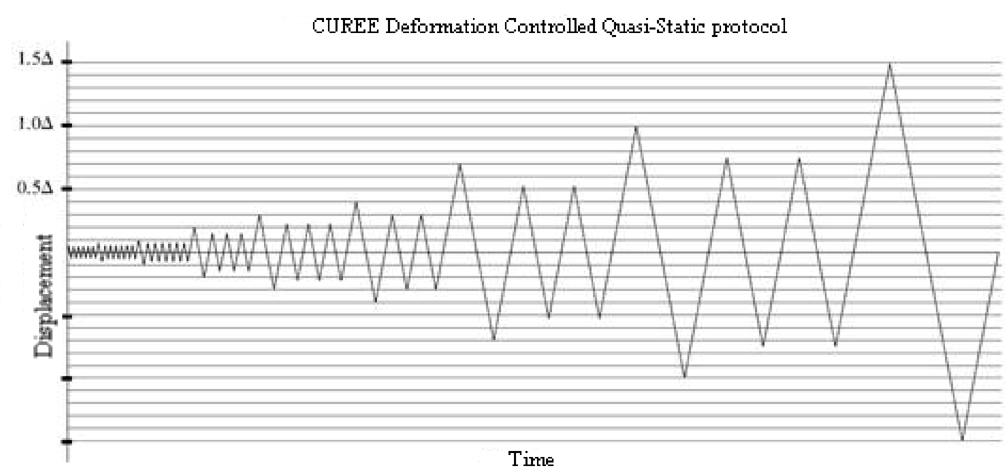


Fig. 4: CUREE Deformation Controlled Quasi-Static Protocol

3 Results and Discussion

Summary test results of the six test series are shown in Table 1. The results show a significant improvement of performance when the undamaged connections were reinforced with the self-tapping wood screws as the average maximum capacity was increased and the coefficient of variance for the maximum capacity was decreased. The failure mode was changed from brittle to a very ductile mode.

Table 1: Summary Statistics of test results

	MU Mean (STDV)	**MR** Mean (STDV)	**MD** Mean (STDV)	**CU** Mean (STDV)	**CR** Mean (STDV)	**CD** Mean (STDV)
Max Moment [kNm]	31.49 (5.06)	65.88 (2.12)	58.85 (4.36)	35.70 (1.63)	62.54 (1.55)	54.54 (3.27)
@ Rotation [°]	2.97 (0.70)	16.59 (0.06)	13.29 (2.00)	4.01 (0.17)	15.90 (0.17)	12.65 (1.26)
Failure Moment (80% Max moment) [kNm]	25.19 (4.05)	-	47.08 (3.49)	28.83 (1.85)	-	41.14 (2.33)
@ Rotation [°]	3.00 (0.65)	-	14.42 (1.96)	5.15 (1.24)	-	11.96 (0.39)
Yield Moment [kNm]	-	41.20 (1.58)	41.16 (7.36)	34.29 (0.30)	41.83 (0.83)	45.49 (1.70)
@ Rotation [°]	-	2.80 (0.26)	3.87 (1.55)	2.22 (0.01)	3.00 (0.20)	5.90 (0.40)
Elastic Stiffness [kNm/°]	13.73 (1.32)	14.54 (1.16)	12.38 (3.81)	14.96 (0.69)	14.02 (0.77)	9.33 (0.84)
Ductility Ratio [-]	-	>5.97 (0.62)	4.21 (1.50)			

The un-reinforced specimens tested under monotonic loading (MU) showed a maximum moment resistance ranging between 25.07 kNm and 38.21 kNm with maximum rotations ranging from 2.2° to 4.1°. The failures were brittle with rapid decrease in capacity after crack formation was developed from tension perpendicular to grain and/or longitudinal shear stresses in the beam member (Figure 5). Limited wood crushing in the dowel holes and virsually no bolt bending was observed in the connection. A yield point could not be determined from monotonic load curves of the MU specimens, as splitting failure occurred before the curve flattened enough to match the second tangent line.

MU Series CU Series

Fig. 5: Typical examples of failed un-reinforced specimens

Therefore, no ductility ratios could be determined for the un-reinforced connections affirming the very brittle behaviour. In the un-reinforced specimens under reverse cyclic loading CU, splitting failure occurred at an overall rotation between 2° and 3° in cycles on either side. As bearing of the beam member's bottom end occurred on the column member on both sides, the beam member sheared up to its top end at two planes through the left and right vertical bolt lines. The peak loads of the trailing cycles were generally much lower. One reason for this was that the driven displacement was only 75% of the respective primary cycle. The second reason was that with the wood crushing during the primary cycle, resistance did not increase until higher rotation levels.

Typical MU and CU moment-rotation plots are shown in Figure 6. The CU moment-rotation plots exhibit higher rotations in the negative quadrant. During negative rotation of the beam member, when the crack opened on the opposite side where the string pots were measuring the horizontal displacements, the split off part was tilted more towards the vertical compared to the rest of the member, so the recorded values led to a higher rotation. In a positive cycle, the crack diverged on the other side, hence did not influence the string pot recording. Visually no bolt bending was observed after disassembly. Therefore, ductility ratios derived from the envelope curves may not be as meaningful as in the monotonic tests evaluation.

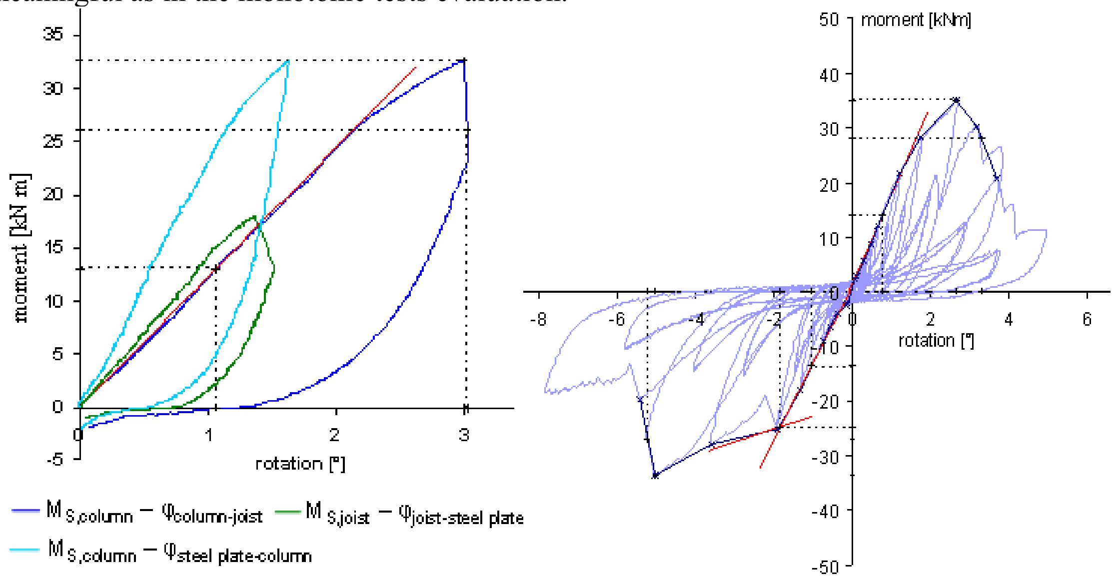
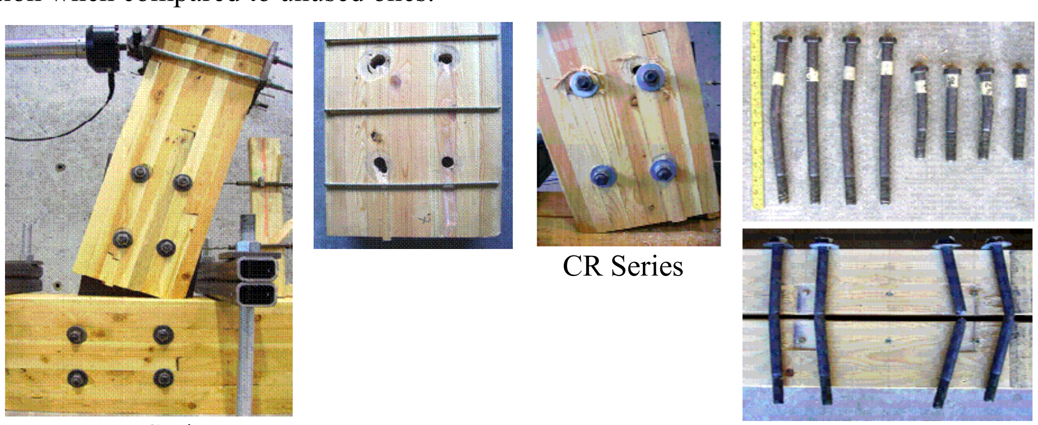


Fig. 6: Typical moment-rotation plot of the un-reinforced connection

The undamaged specimens tested under monotonic loading with reinforcing screws (MR) showed moment capacities ranging between 62.26 kNm and 67.86 kNm with maximum rotations ranging between 16.51° and 16.66°. These levels of deformation reached the stroke limit of the actuator; hence, some reserve capacities may still be available in the connections (at higher rotations). Splitting did not occur in any specimen. The only visually detectable damage of the connection was a plug shear failure on the tension side of the beam member under the bolt towards the bottom end (Figure 7). This indicates the screws have the capacity to carry the imposed stresses in the perpendicular to grain direction, thereby changing the failure mode to parallel to grain axis failures. Disassembling the failed specimens showed Mode I (Johanson Yield Model) type failure in the beam members with heavy wood crushing through the whole length in some of the dowel holes. In some cases, the transition to Yield Mode II was smooth as the bolts showed significant bending with one plastic hinge in the middle where they bore on the hole in the steel plate. Bolt bending and associated Yield Mode II was observed in the column connection. Here, different from the heavy wood crushing on the inside plane adjacent to the steel plate, no wood crushing was noticed at the specimens' outer surface. The self tapping screws were also removed after testing and showed no elongation when compared to unused ones.



CR Series

MR Series

Figure 7: Tested reinforced connection specimens MR and CR series

The moment-rotation plots do not show any significant load drop up to the maximum possible rotation (Figure 8). Although the plot of yield region appeared to be almost linear, determination of the yield point except for 4th specimen of MR series was done by matching the second tangent line to the curves with a slope of 1/6 of the initial stiffness. Because there was no point of failure (the load never dropped below 80% of its maximum), a corresponding failure rotation for the ductility ratio calculation could not be determined.

In the CR series, the mean value of maximum resistances attained at the maximum possible displacement increased by 72% in the positive and 78% in the negative side compared to the CU resistances. Brittle failure did not occur even when the maximum actuator stroke to either side was reached, at rotations of around 16°. Instead, the connections showed explicit yielding. In the beam members, a combination of Yield Mode I and II was noticed, with wood crushing in every dowel hole all the way up to the members' outer surface and bolt bending with one plastic hinge at the steel plate plane. The column member yielded according to Mode II, with visible dowel hole deformations only at the inner surface and severe bolt bending with one plastic hinge. Some axial rotation of the bent bolts in their holes could also be observed during testing when the load was reversed. Furthermore, the CR tests marked the only series of this investigation where the bolts were stressed to their limit, as in two specimens, and although fabricated of mild steel, bolt #3 broke at the plastic hinge because of material fatigue.

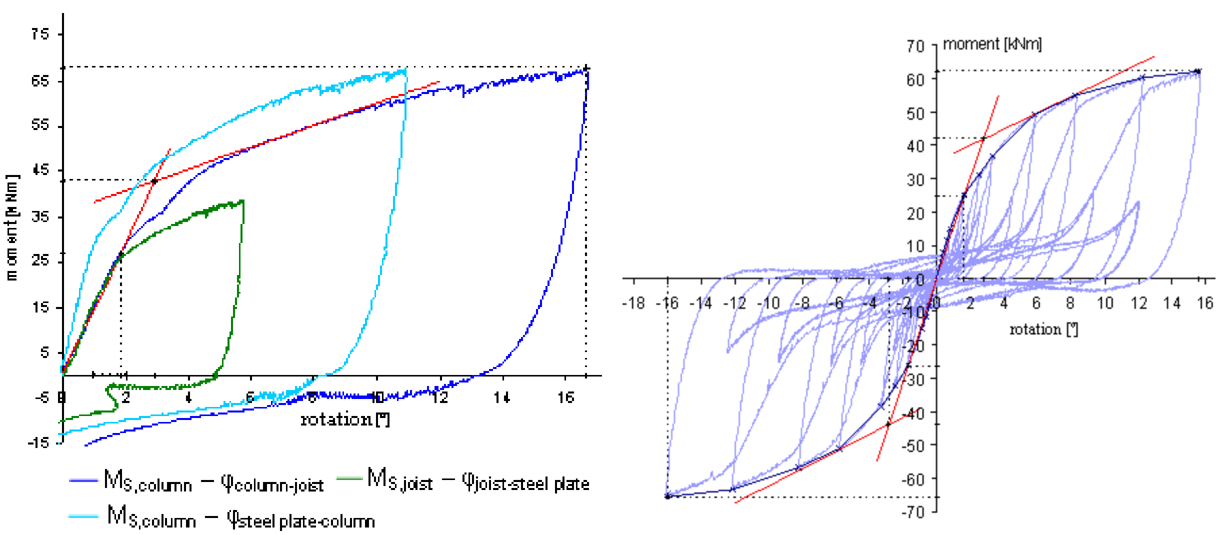
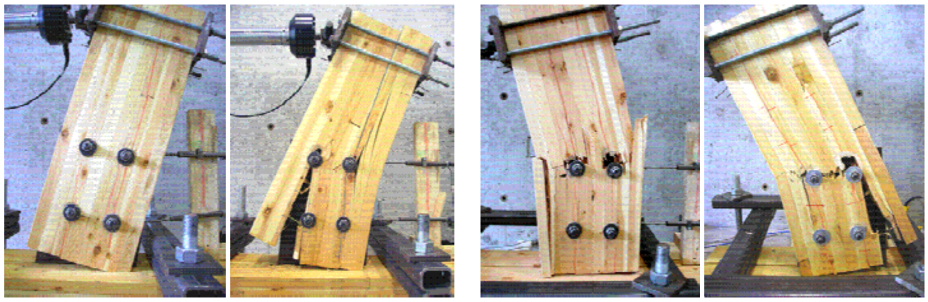


Fig. 8: Typical moment-rotation plot of the reinforced connection

Specimens for the MD and CD series were prepared using the the heavily damaged specimen from the MU and CU series. The original cross-section of the damaged specimens was first restored by clamping the beam members with screw-clamps and closing the cracks. Then, three reinforcing screws per side member were installed with an identical pattern as the MR and CR series. The same bolts were employed that had been used in the U series, as they were almost not deformed.

The observed failure modes were quite different between the D and R series. Two D series specimens showed little damage at the point of maximum rotation, with some plug shear failures and little relative shifting along the existing shear plane on the compression side (Figure 9). Here the screws not only prevented crack opening but also reinforced the shear capacity up to a certain level. The other three specimens failed similar to the MU series with opening of the pre-existing crack on the tension side. As the already separated wood could not contribute to any load resistance and distribution, the forces perpendicular to the grain were concentrated on the middle and bottom screws which were eventually bent and gradually pulled through the outer lamellae.



MD Series CD Series

Figure 9: Tested retrofitted connection specimens MD and CD series

After disassembly, the bolts showed deformations according to Yield Mode I and II with noticeable bending deflections in some bolts. This fact and observations of the moment-rotation plots (Figure 10) proved that connections which had been damaged and restored with screws behaved in a ductile manner. Even after crack opening, the curves of the respective specimens did not instantly drop to failure level which can be explained by as the fact the screws maintained some tension resistance perpendicular to the wood grain. The variation of and an initial slip in the MD load deformation plot is dependent on the different initial damage levels of the connections.

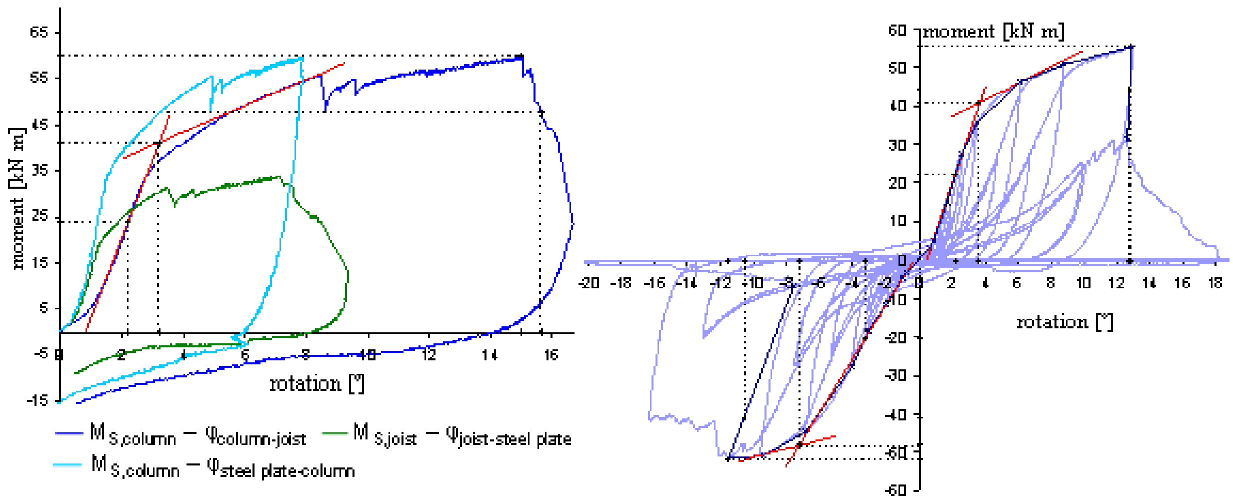


Fig. 10: Typical moment-rotation plot of the retrofitted connections MD and CD series

The mean maximum moment in the CD series increased by over 50% on the positive and negative side compared to the mean value of the CU series. Although every specimen failed before the maximum possible displacement as limited by the actuator stroke was reached, the ductility still improved which can be derived from a distinct plastic segment of the envelope curves.

Displacement along the existing damaged shear planes in the beam members was observed in early cycles. This movement could not be totally prevented by the screws, which showed some buckling deformations when they were removed after the tests. However, the peak loads of the following cycles kept increasing, and definitive yielding of the bolts could be noticed. Similar to previous reinforced test series, the highest bolt bending moment according to Yield Mode II took place in the column members, while the stocky bolts in the beam members almost remained straight but enlarged the dowel holes according to Yield Mode I.

4 Conclusions

The primary focus of this investigation was to ascertain whether long length self-tapping wood screws employed as reinforcements can improve the performance of bolted timber connections subjected to a moment load. Test results of a representative connection layout subject to monotonic and reverse cyclic loading show that the connections reinforced with self-tapping screws have an increased moment capacity by a factor of 2 and 1.7 when compared to un-reinforced connections under monotonic and reverse cyclic loading, respectively. Retesting retrofitted failed un-reinforced connections with self-tapping screw reinforcements also show increase in the capacity by 1.87 and 1.53 times compared to the un-reinforced connections under monotonic and reverse cyclic loading, respectively. A ductile failure mode was achieved with the reinforced connections.

5 References

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