
Post-damage Repair of Radiata Pine CLT Panel-to-panel Connections Using Additional Fasteners

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ABSTRACT

Cross-laminated timber (CLT) is increasingly used as a sustainable and efficient construction material, particularly in earthquake-prone regions. In CLT structures, seismic damage concentrates in panel-to-panel connections, while the CLT panels generally remain intact. This study investigates whether damaged central spline CLT panel-to-panel connections can be repaired by installing additional fasteners adjacent to the original ones.

Birch plywood (BP0) and radiata pine plywood (RP0), with the outer veneer grain oriented parallel to the loading, were used as splines to connect 105 mm thick radiata pine CLT panels. The connections were fastened with 6 mm diameter, 140 mm long fully threaded self-tapping screws installed at a 45° angle. Monotonic and cyclic tests were conducted on original and repaired specimens, and their performance was compared in terms of stiffness, strength, and ductility.

Connections with BP0 splines showed minimal damage during initial testing and exhibited good repair performance. Repaired BP0 spline connections recovered approximately 95–100% of their original stiffness and strength under monotonic and cyclic loading. In contrast, RP0 spline connections experienced localized crushing and cracking during initial loading, which reduced repair effectiveness. Although repaired RP0 spline connections recovered up to 75% of their original strength, they showed reduced stiffness and ductility and failed abruptly after peak load due to crack interaction between original and newly formed.

The results indicate that the repairability of CS CLT panel-to-panel connections depends on the extent of damage in the spline, highlighting the importance of appropriate spline material selection and spacing of fasteners for repairable CLT structures.

1 INTRODUCTION

The 2010–2011 Canterbury earthquake sequence caused extensive structural and economic damage in Christchurch, New Zealand (Potter et al., 2015). While residential light timber frame (LTF) buildings met the New Zealand Building Code’s “life safety” objective, many suffered significant non-structural and structural damage, with large irreversible displacements or collapse (Buchanan et al., 2011), (Skidmore et al., 2022), (Liu & Carradine, 2019). This resulted in an estimated 10% loss in New Zealand’s GDP (Buchanan et al., 2011), (Parker & Steenkamp, 2012). Low-damage design is an emerging building philosophy considering the design of earthquake resilient buildings that not only preserve life but also leave the primary structure usable following a major event (Chouw, 2017). This benefits both, owners and occupiers, in terms of business continuity, insurance costs and commercial property income. The Canterbury Earthquakes Royal Commission (Canterbury Earthquake Royal Commission, 2012) recommended the adoption of low-damage building technologies.

In recent years, Cross-Laminated Timber (CLT) has become a key material in mass timber construction due to its high strength-to-weight ratio, sustainability, and suitability for low-damage seismic design (Tannert et al., 2018). During seismic testing, CLT wall panels typically remain undamaged, with inelastic behaviour localized almost entirely at mechanical panel-to-panel connections (Pei et al., 2017). Previous analysis of shear performance of central spline (CS) radiata pine CLT panel-to-panel connections revealed only localised damage to the spline material and leaving the timber panel itself intact. This opens the possibility of repairing such damaged wall systems by reinforcing or replacing only the connections, rather than replacing entire panels (Wright et al., 2022).

The aim of this study was to determine if a simple and practical repair method, i.e. adding new fasteners to previously damaged connections, can restore the connection’s original strength and stiffness, a prerequisite for resilient, repairable CLT structures.

2 MATERIALS AND METHODS

2.1 Materials

CS CLT panel-to-panel connections, creating double shear in fasteners, were investigated under monotonic and quasi-static reverse cyclic loading. Following ANSI/APA PRG 320 guidelines (“ANSI/APA PRG 320-2018: Standard for Performance-Rated Cross-Laminated Timber,” 2018), three-layer CLT panels with dimensions of 500 mm in length, 300 mm in width, and 105 mm in thickness were used (Figure 1a). These dimensions were chosen to minimize bending effects in the CLT panels and emphasize the shear behaviour of the spline connection. The CLT panels were manufactured with *Loctite HB S309 Purbond* (160 g/m²) (AG, 2020) following the technical data sheet provided by the manufacturer. Panels were pressed with a hydraulic press (0.9 MPa) at room temperature for at least 75 min. Timber used in CLT manufacturing was kiln-dried rough-sawn SG8 radiata pine (ICS Codes, 2022). The rough-sawn timber was processed into planed boards with dimensions of 500 mm × 100 mm × 35 mm for the major axis and boards measuring 300 mm × 125 mm × 35 mm for the minor axis. The timber pieces were conditioned at 20°C and 65% relative humidity as per ASTM D4933-16 (ASTM International, 2016) until they reached a stable moisture content of 12 ± 3%, as specified in ANSI/APA 320-2019 (“ANSI/APA PRG 320-2018: Standard for Performance-Rated Cross-Laminated Timber,” 2018). The CLT connections were tested using 6 mm diameter and 140 mm long fully threaded self-tapping screws (FTSTS) manufactured by SPAX (model: DELTA SEAL GZ), which were installed at 45° to the grain in the CLT surface. Spacing of the fasteners (Figure 1a) followed the recommendations in the National Design Specification (NDS) for Wood Construction (American Wood Council (AWC), 2017). CLT panels were connected with birch plywood (BP0) and radiata pine (RP0) (F8 grade, manufactured following AS/NZS 2269.0:2012 (Standards New Zealand, 2012)) spline members, with

the outer veneer grain oriented parallel to the loading direction, with thickness of 21 mm. These splines created two shear planes in each setup. The middle panel was offset by 100 mm to allow for appropriate clearance during testing (Figure 1a).

2.2 Experimental setup and loading protocol

Monotonic and cyclic tests were conducted using an E45.305 MTS uniaxial testing machine with a capacity of 300 KN. Specimens were placed flat on a hot rolled steel I section of 200UC @46.2 kg/m. The I section was designed as per NZS 3404:1997 (Standards New Zealand, 1997) to withstand shear and bending during the test. The I section rested on the T-slot table of the MTS machine and was fixed with six 10 mm diameter screws. The top portion of each outer CLT panel was clamped to the I section using 250 mm × 230 mm × 20 mm endplates (P1) with four 20 mm diameter bolts. Both ends of the central CLT panel were clamped with endplate (P2) of dimension 300 mm x 203 mm x 20 mm also using four 20 mm diameter bolts. The top P2 endplate was fixed to the actuator head with a 30 mm thick steel bearing pin (Figure 1b).

A load cell and linear variable differential transformers (LVDT) were attached to the specimen to measure the applied force and displacements, respectively. LVDTs 1 and 2 as shown in Figure 1b captured the relative input displacement. LVDT 3 was attached to the specimen to detect any unwanted in-plane rotation (tilting) of the CLT panel during the test. LVDT 4 was secured to the mid CLT panel and anchored to the MTS machine's frame to observe any out-of-plane rotation.

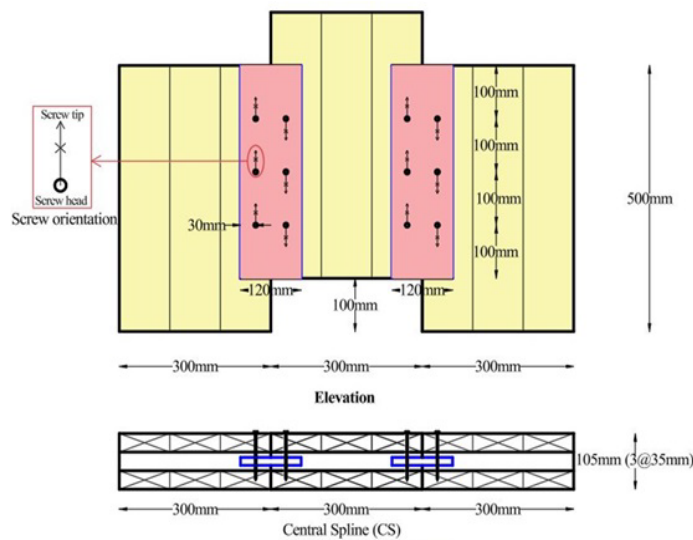
Monotonic tests were conducted using the displacement control method with a static load at a rate of 5 mm/min was applied until the force dropped to 60% of the maximum load. Reverse cyclic loading, in accordance with ASTM E2126-19 (ASTM International, 2015) using the CUREE protocol (Method C), was used at a rate of 1.5 mm/sec to replicate the behaviour of CLT shear connections under cyclic load. In accordance with ASTM E2126-19 (ASTM International, 2015), the reference displacement for each test series was chosen as 60% of the displacement at 80% post peak load in the corresponding average monotonic test.

2.3 Data analysis

Idealized curves were developed based on the load vs displacement plots from both monotonic and cyclic tests. The equivalent energy elastic-plastic (EEEP) curve described in ASTM E2126-19 (ASTM International, 2015) was used to determine performance parameters from the experiments. The bilinear EEEP curve was approximated in such way that it covers the area equal to the original test curve. The initial stiffness (K_e) was determined by the slope of the line passing from the origin to the point in the curve at 40% of the peak load (P_{peak}), while the ultimate displacement (Δ_u) was defined at 80% of P_{peak} . The position of the horizontal plateau (yield load (P_y)) was determined so that the area under the envelope curve, which terminates when 80% of P_{peak} , equals to the area under the EEEP curve as suggested by ASTM E2126-19 (ASTM International, 2015).

In monotonic tests, the test curve was taken as envelope curve. For cyclic tests, an idealized backbone curve was utilized as the envelope curve. This idealized backbone curve captures the extremes of the load vs displacement hysteresis loops, including the peak loads from the initial cycle of each phase of the cyclic loading process. Positive and negative envelope curves were drawn from each hysteresis curve by obtaining peak force values at corresponding displacement levels for each cycle. These data points were then used to generate smooth envelope curves through piecewise linear interpolation curve fitting techniques in Python language. The average envelope curve for each replica was calculated by averaging the positive and absolute negative envelope curves as suggested by ASTM E2126-19 (ASTM International, 2015). Once individual average envelope curves were obtained for each replica, they were further averaged to determine the final envelope curve for a given connection configuration. The EEEP curve was then used to calculate the strength

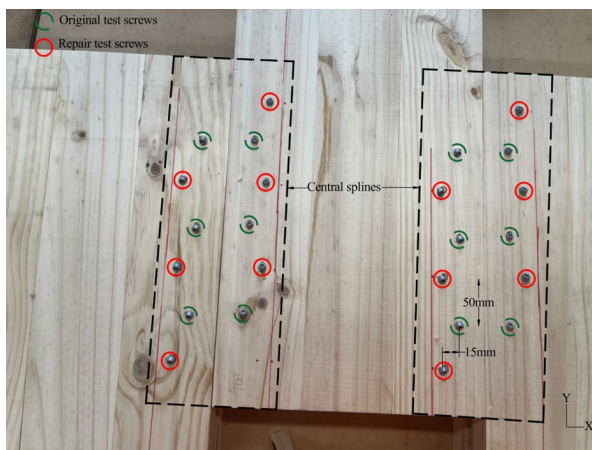
parameters of the connections. Ductility (μ) was measured by calculating the ratio of displacement at peak load to the displacement at yield load from the average envelope curve (Sullivan et al., 2018).



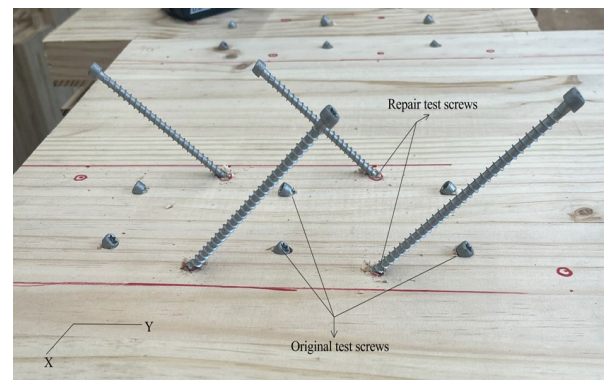
a)



b)



c)



d)

Figure 1: Test setup: a) layout of connection test specimen for screws inserted at 45° angle in central spline (CS) connection configuration (blue rectangles represent splines), b) Instrumentation of original splines, c) test specimen showing the spacing between original and repair fasteners: 50 mm in the Y-axis (loading) direction and 15 mm in the X-axis, and d) installation process.

2.4 Repair Strategy

Repaired specimens were created by adding new fasteners to previously tested and deformed connections (Figure 1c and Figure 1d). Table 1 summarizes the conducted tests and specimen types. For each spline type, two monotonic and three cyclic tests were first conducted on original (undamaged) specimens to observe the strength and hysteretic behaviour of CLT connections. Among the two original monotonic specimens, one was repaired and retested under monotonic loading. Similarly, among the three original cyclic specimens,

two were repaired and retested under cyclic loading. The remaining specimen of each category was utilized to observe the failure mode of the connection for the original (undamaged) specimen.

Table 1: Summary of tested and repaired specimens CLT splines. M and C represent monotonic and cyclic loading. RP0 and BP0 refer to radiata pine and birch plywood, respectively, with outer grain layers parallel to the loading direction.

Connection configuration	No of test for original specimens		No of test for repaired specimens	
	M	C	M	C
RP0_CS	2	3	1	2
BP0_CS	2	3	1	2

3 RESULTS AND DISCUSSION

3.1 Monotonic test results

Table 2 and Figure 2 present the monotonic test results, while Figure 3a shows the damage caused by monotonic loading for the original and repaired specimens using birch (BP0) and Figure 3b demonstrates the damage in repaired radiata pine (RP0) plywood spline due to monotonic loading.

The in-plane behaviour of the repaired CLT connections using birch plywood (BP0) splines was comparable to that of the original specimens in monotonic tests. The peak load of the repaired specimens was within $\pm 10\%$ of the original specimens, satisfying the ASTM E2126 (ASTM International, 2015) acceptance criterion. The repaired specimen recovered approximately 95% of the original stiffness (4.1 kN/mm) and yield capacity (10.3 kN). Similarly, the strength of the repaired specimen was almost identical to that of the original specimens (10.8 kN), achieving approximately 98% recovery. A similar level of capacity recovery has been reported for hold-down connections for Douglas fir CLT with localized damage in the original specimens, where new fasteners were installed with a small offset from the original position (Wright et al., 2022). In that case, the performance parameters even exceeded 100% as it was possible to remove the original fasteners and fill the holes with epoxy, what reinforced the connection.

Stiffness recovery for the radiata pine (RP0) connections was satisfactory, with the repaired specimens regaining approximately 87% of the original stiffness (Table 2 and Figure 2). Although the strength recovery was also around 87%, the repaired specimen failed immediately after reaching peak load, exhibiting no post-peak resistance. Consequently, yield capacity recovery was limited, reaching only about 60% of the original value, showing a substantial reduction to resistance to plastic deformation. This indicated that the damage in the RP0 splines, where a crack approximately 50 mm long had formed along the loading direction during the initial testing, influenced the performance of the repaired connection. As the crack in the repaired specimens propagated and intersected with the pre-existing crack from the original testing, the connection was unable to sustain additional load, resulting in abrupt failure immediately after reaching peak capacity (Figure 2 and Figure 3b). This may be mitigated by increasing spacing between fasteners as well as end and edge distance to avoid interaction of cracks in the spline which occurred before and after repair (Abdoli et al., 2023).

Table 2: Performance parameters form monotonic test of central spline (CS) radiata pine CLT panel-to-panel connections using radiata pine (RP0) and birch (BP0) plywood with outer veneer parallel to grain as spline material. K_f : average stiffness per fastener, P_{yf} : average yield capacity per fastener, $P(\text{peak})_f$: average peak load per fasteners.

Spline	Test	Stiffness per fastener (kN/mm)	K_f (kN/mm)	Yield per fastener (kN)	P_{yf} (kN)	Peak load per fastener (kN)	$P(\text{peak})_f$ (kN)
BP0	Original (test 1)	4.3	4.1	10.6	10.3	10.7	11.1
	Original (test 2)	4.0		10.0		11.5	
	Repaired	3.9	-	9.8	-	10.8	-
RP0	Original (test 1)	3.4	3.3	7.8	7.7	9.1	9.5
	Original (test 2)	3.3		7.6		9.9	
	Repaired	2.9	-	5.5	-	8.4	-

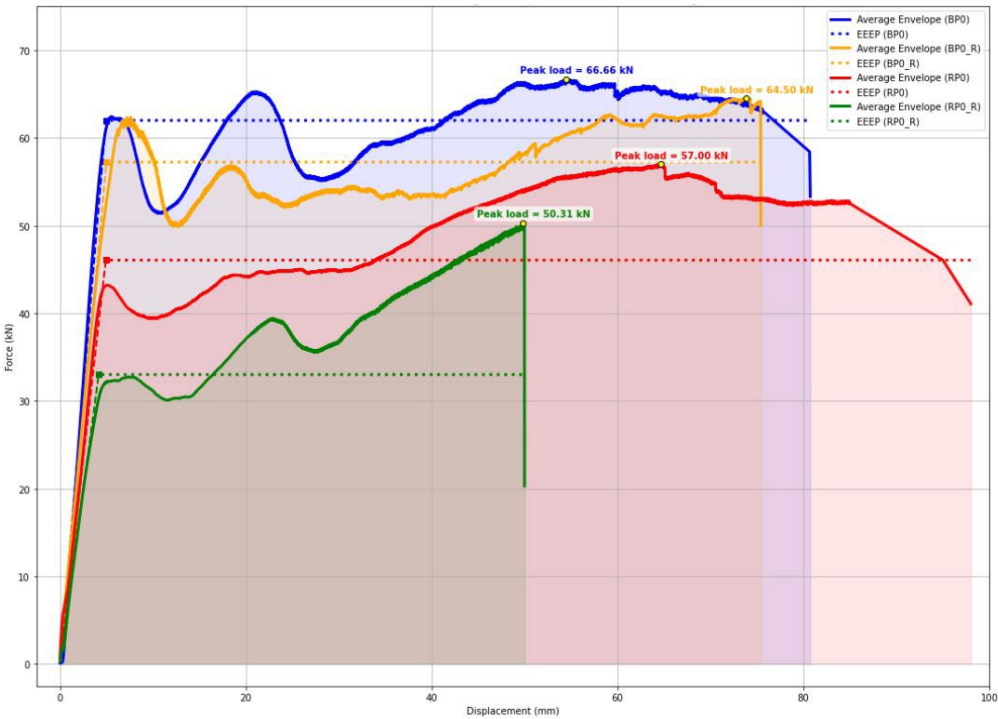
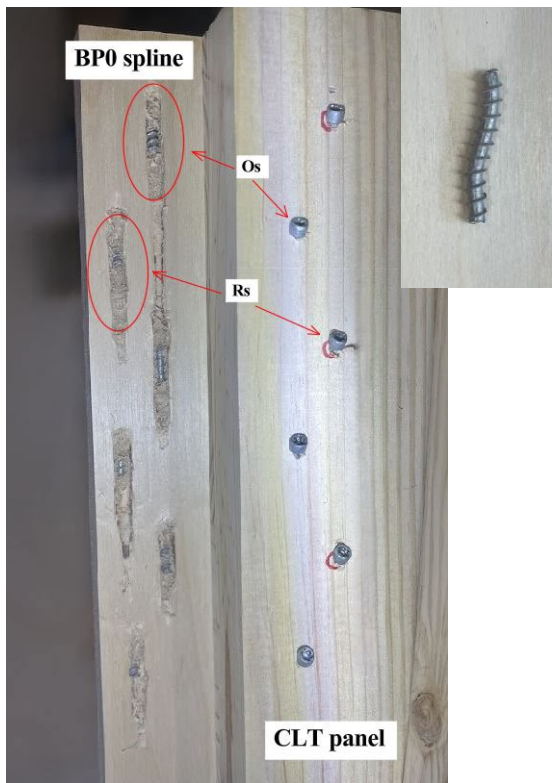


Figure 2: Monotonic test results of the CS radiata pine CLT panel-to-panel connection using birch plywood (BP0) and radiata pine (RP0) as spline material. The blue curve represents the average force vs displacement response of the two undamaged original specimens using BP0 splines; the orange curve represents the response of the repaired specimen using BP0 splines. The red curve represents the average force vs displacement response of the two undamaged original specimens with RP0 spline, while the green curve represents the response of the repaired specimen using RP0 spline.



a)



b)

Figure 3: Damage in the central spline radiata pine CLT panel-to-panel connections of repaired specimens after monotonic loading using (a) birch plywood (BP0) with location of screw in original testing (Os) and testing after repair (Rs) (part of a failed original screw in inset) and (b) radiata pine plywood (RP0) as spline material.

3.2 Cyclic test results

Cyclic test results for the undamaged and repaired BP0 and RP0 radiata pine CLT central splines specimens are tabulated in Table 3; the associated hysteresis and envelope curves are depicted in Figure 4 and the resulting average envelope and EEEP curves in Figure 5.

The repaired birch plywood (BP0) central spline (CS) CLT connections performed, consistent with monotonic loading, comparably to the undamaged specimens (Table 3, Figure 4a and b, and Figure 5). Yield and peak load capacity recovery of repaired specimens even slightly exceeded the performance of the undamaged specimens; by 3% and 4%, respectively. This may be explained by the failure mode. The failure in BP0 spline connections was due to the screw head being pulled into the CLT panel with minimum damage to BP0 spline. The deformed but still intact original screws remained in the specimen after the repair, able to take up load once the connection entered the plastic stage. However, in contrast to the original test the original screws failed catastrophically in repaired specimens (Figure 3a). Increased performance in cyclic

testing was reported for repaired hold down connections of Douglas-fir CLT connections (Wright et al., 2022), (Moerman et al., 2024). This was attributed to inclined fasteners intersecting with epoxy which had been injected into the holes after removal of the original fasteners.

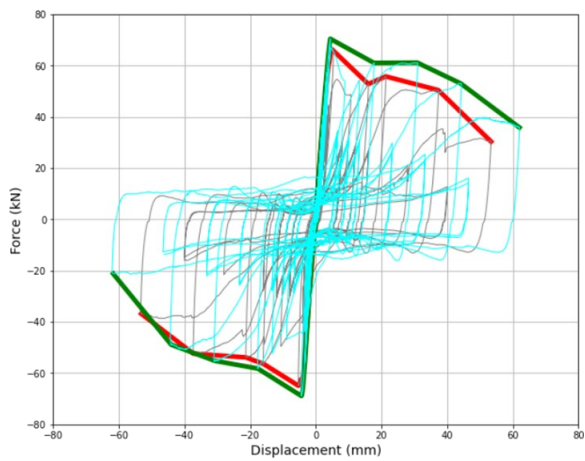
Repaired RP0 CS CLT connections showed a marked reduction in structural performance compared to the undamaged connection. Around 40% stiffness was recovered from the original, while approximately 75% of the yield and peak capacity was recovered (Table 3, Figure 4c and d, and Figure 5). This may be explained by the significantly more pronounced wood fibre crushing of the radiata pine plywood spline in the initial test. Damage after cyclic loading matched that observed under monotonic loading (Figure 3). At the end of the test CLT panels of the repaired connections separated from each other as a crack had propagated through the entire the length of the RP0 spline (Figure 3b).

While the repaired BP0 central spline connections regained 70% of their limited original ductility (μ) = 2.5, the high ductility of the undamaged RP0 connections (μ = 12.2) was lost in the repaired state (μ = 1.5) (Table 3 and Figure 5). This was because the damage to the spline allowing for the original ductility allowed intersection of old and new cracks after repair. RP0 spline connections might still be repairable, if enough undamaged spline material remains between the fasteners, for connection with wider fastener spacings.

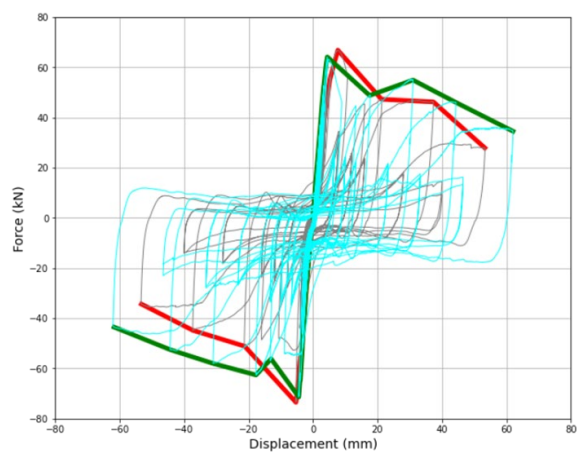
Overall, it can be concluded that the less the damage in the spline caused by the fastener in in-plane loading, the better will be the recovery of its structural performance after repair.

Table 3: Performance parameters of central spline radiata pine CLT connections using birch plywood (BP0) and radiata pine (RP0) plywood with outer veneer direction parallel to the grain as spline materials. K_f : average stiffness per fastener; P_{yf} : average yield load per fastener; $P(\text{peak})_f$: peak load per fastener; Δy : average yield displacement; Δ_{max} : displacement at peak load; μ : ductility of the system. Values in parentheses at $P(\text{peak})_f$ show the percentage difference between the maximum and minimum peak load per fastener across the three test samples for each configuration which should be within 10% as per (ASTM International, 2015)

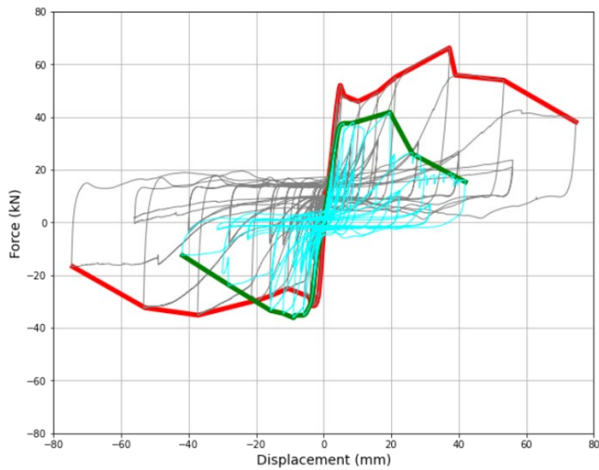
Spline	Test	K_f (kN/mm)	P_{yf} (kN)	$P(\text{peak})_f$ (kN)	Δy (mm)	Δ_{max} (mm)	μ
BP0	Original	3.5	9.8	11.0 (6.8)	1.7	5.7	3.4
	Repaired	3.5	10.1	11.5 (4.8)	2.1	5.1	2.5
RP0	Original	2.2	6.4	7.2 (6.7)	2.9	35.4	12.2
	Repaired	1.4	5.1	5.7 (12.4)	3.8	5.8	1.5



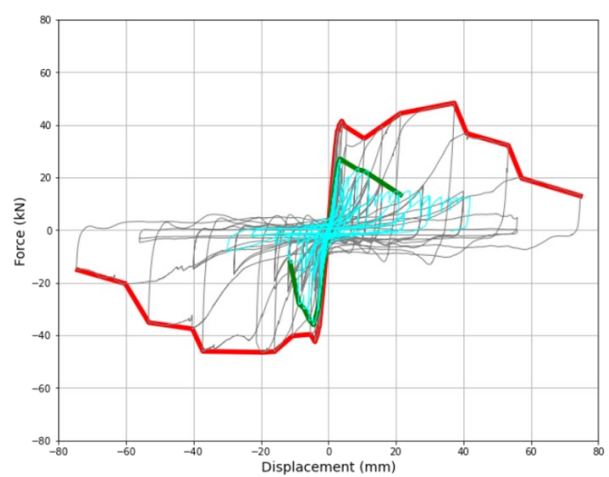
a)



b)



c)



d)

Figure 4: Hysteresis loops and envelope curves from the cyclic tests of CS radiata pine CLT panel-to-panel connections using BP0 and RP0 as the spline material. The grey and cyan hysteresis curves represent the responses of the original and repaired specimens, respectively, while the red and green curves represent the corresponding envelope curves for: a) Test 1 with BP0 splines, b) Test 2 with BP0 splines, c) Test 1 with RP0 splines, and d) Test 2 with RP0 splines

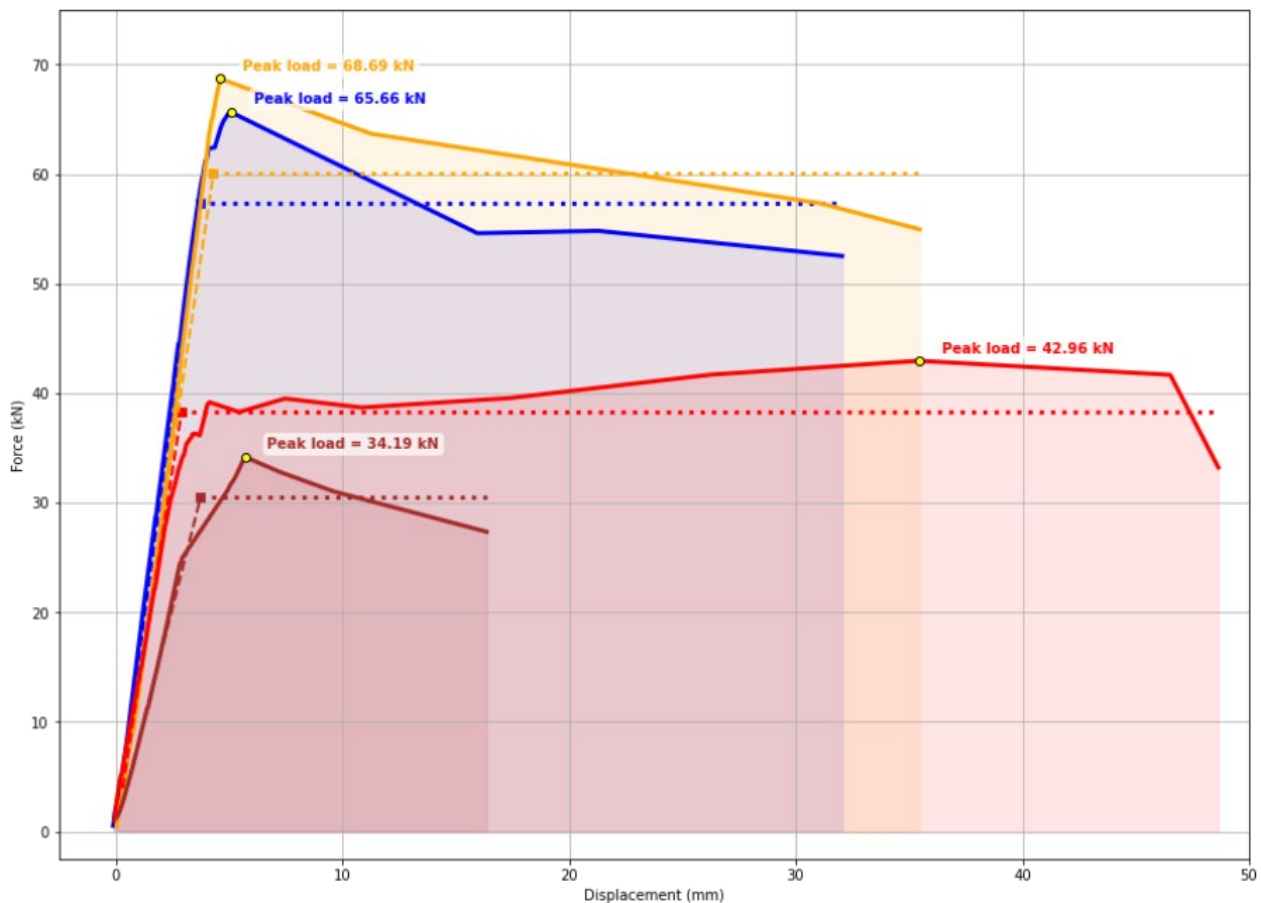


Figure 5: Average envelope curve and EEEP curve of BP0 and RP0 splines in CS radiata pine CLT panel-to-panel connections due to cyclic loading; blue and yellow solid and dotted line represents average envelope curve and EEEP curve of BP0 splines CLT connection respectively for original (blue) and repaired (yellow) specimens; red and brown solid and dotted line represents average envelope curve and EEEP curve of RP0 splines CLT connection respectively for original (red) and repaired (brown) specimens.

4 CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study investigated repairability of central spline (CS) radiata pine CLT panel-to-panel connections using birch plywood (BP0) and radiata pine plywood (RP0) splines with the outer veneer grain oriented parallel to the loading direction, which had failed in shear. A simple repair technique was adopted by installing additional fasteners offset from the original fastener locations. Experimental results confirmed that CS CLT connections using BP0 splines restored the structural performance of the connection to near-original levels. This was possible due to the negligible damage observed in the BP0 splines during the original displacement. On the contrary, CS CLT connections using RP0 splines, where localized damage occurred within the spline during original specimen displacement, repaired specimens did not recover original connection capacity. Overall, the results indicated that lower damage in the spline material allows higher strength and stiffness recovery of repaired CLT connections. The key observations are summarized below:

- **Stiffness**
Repaired CS spline CLT connections using BP0 recovered 95 to 100% of the original stiffness under both monotonic and cyclic loading, indicating that elastic behaviour and deformation control were comparable to those of the original connections. In contrast, connections using RP0 as spline

material recovered only 85% under monotonic and 40% under cyclic loading of the original stiffness, suggesting limited restoration of elastic load transfer under earthquake-like loading.

- **Strength**
Yield and peak load capacities of repaired BP0 spline specimens were slightly higher (approximately 3–4%) than those of the original specimens under cyclic loading, due to the contribution of the remaining original fasteners. Moreover, the repaired BP0 spline CLT specimens showed comparable or slightly improved cyclic degradation behaviour relative to the original specimens. While repaired RP0 spline connections recovered 60 to 75% of the original yield capacity, these specimens exhibited abrupt post-peak failure. This was due to crack propagation in the repaired specimens intersecting with pre-existing cracks from the original displacement. This was also reflected by the strength degradation values.
- **Ductility**
BP0 spline connections retained most of their limited original ductility after repair. In contrast, the ductile RP0 spline connections experienced a substantial reduction in ductility, decreasing by almost an order of magnitude, related to the absence of post-peak load-carrying capacity after repair.

4.2 Recommendation

Although RP0 spline CS CLT panel-to-panel connections displayed some strength and stiffness recovery after repair, repairability seemed to be influenced by the extent of damage in the spline material, due to intersection of newly propagating cracks with pre-existing damage. These limitations may be mitigated by increasing fastener spacing as well as end and edge distances. Greater distances between fasteners ensure more undamaged material for load transfer, reducing the risk of crack interaction and thereby enhancing the effectiveness of the repair. Therefore, further experimental investigations evaluating the influence of the proximity of spline damage to the newly installed fasteners and edges are recommended.

BP0 spline CS CLT connections showed high repair efficiency due to negligible damage in the spline material. The results indicate that such connections can be repaired more than once, provided that adequate spacing, end distance, and edge distance are maintained when installing additional fasteners. It is recommended that future studies investigate multiple repair cycles for central spline connections. This is in line with the concept of deconstructable buildings (Patrizi et al., 2026) to reuse the building materials which requires replacement of fasteners after minimal damage.

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