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Article

Experimental Evaluation of an Innovative Connection for the Reinforcement of Existing Infilled RC Buildings

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Abstract: The retrofitting of existing reinforced concrete (RC) buildings with Cross-Laminated Timber (CLT) panels presents a promising approach for enhancing seismic performance and overall structural resilience. However, effective integration of CLT with existing RC structures poses significant challenges, particularly concerning the design of connections between CLT panels and the RC structure. This paper introduces a novel connection that addresses these challenges by focusing on both structural and architectural considerations. Structurally, the connection is engineered to provide optimal stiffness, strength, and deformation capacity, ensuring robust performance under seismic and dynamic loads. Architecturally, the design incorporates a pre-defined weak component that facilitates easy access and rapid replacement of damaged parts, thereby reducing downtime and maintenance efforts. The proposed connection was evaluated through a series of monotonic and cyclic loading tests, demonstrating its structural efficiency and reliability. The results indicate that the new connection system not only meets the necessary structural requirements but also offers practical benefits for maintenance and repair, contributing to the overall sustainability and resilience of retrofitted RC buildings. This innovative approach represents a significant advancement in the field of structural retrofitting, providing a viable solution for integrating CLT panels into existing RC frameworks.

Keywords: RC buildings; cross-laminated timber; retrofitting; connection; experimental evaluation

1. Introduction

Retrofitting existing reinforced concrete (RC) buildings, especially those with masonry infills, is essential for enhancing overall structural performance and seismic resilience [1]. The use of Cross-Laminated Timber (CLT) panels to reinforce RC frameworks has emerged as a promising retrofitting strategy due to CLT's advantageous properties, such as its high strength-to-weight ratio, in-plane stiffness, ease of installation, and sustainability [2,3]. However, the effectiveness of this retrofitting approach relies on the development of efficient connections between CLT elements and RC components [4].

CLT is an engineered wood product renowned for its high strength and stiffness, making it ideal for resisting lateral loads in shear walls [5,6]. Nevertheless, externally connecting prefabricated CLT panels to existing RC structures poses significant structural challenges. These challenges include ensuring effective shear transfer, aligning the stiffness and strength of CLT and RC, and providing adequate deformation capacity [7]. The connection must facilitate efficient shear force transfer without slippage or failure at the interface, balance the differing stiffness and strength properties of CLT and RC to avoid uneven load distribution, and accommodate relative deformations while maintaining structural integrity and serviceability [8,9]. Addressing these issues is vital for achieving a reliable retrofit solution.

Various designs for integrating CLT with RC structures have been explored. The primary focus has been on connections, as they play a crucial role in controlling structural failures, given that the

panels tend to remain undamaged [10–12]. Generally, there are two categories of connections for attaching CLT panels to RC buildings, depending on the relative position of these shear walls compared to existing masonry infills: traditional and innovative. Traditional connections rely on direct contact between adjoining elements to transfer forces [13]. These connections typically exhibit single-axis behavior, like angle brackets handling shear forces and hold-downs resisting tension [14]. To enhance the combined performance in both tension and shear, more advanced connections with complex designs have been developed.

Numerous experimental studies have investigated traditional connections in CLT structures, such as angle brackets, hold-downs, and screws, with variations in connector thickness, geometry, and loading conditions [12,15–20]. These studies have demonstrated that CLT walls can serve as effective replacements for masonry infills in RC buildings. Additionally, substantial research has focused on innovative connection systems. For instance, Polastri et al. [21] developed a connector called X-RAD, which showed significant potential for resisting combined shear and tension loads with commendable ductility and high energy dissipation capacity. Loo et al. [22] introduced a slip-friction connector, while Kramer et al. [23] and Sarti et al. [24] developed energy dissipation systems for self-centering wall systems, based on steel buckling-restrained braces. Hashemi et al. [25] proposed a slip-friction connector that enables self-centering of the wall without the need for post-tensioned tendons. Smirollo et al. [26] developed a connection that integrates CLT into the frame by replacing the external wythe of the existing infill, attaching it to the internal wythe and beams using adhesive anchors and a timber subframe, respectively.

CLT panels can be externally added to the infilled RC frames without requiring building demolition. One such connection involves a custom angle bracket attached to the panel using specialized Sihga Idefix elements and self-tapping screws. A steel plate is then connected to the main structure using steel threaded rods anchored with epoxy resin [8]. Boggian et al. [27] introduced asymmetric friction connections (AFCs) featuring two profiles for upper and lower story connectors, interconnected at the interface with round and slotted holes. Both RC-CLT connectors significantly enhance the stiffness, strength, and ductility of the main frame, leading to substantial strengthening. Another connection method, although less robust due to the limited panel thickness, involves using dry screw anchors spaced along the beams to attach the panel to the frame, with adhesive anchors securing the panel to the masonry infill to prevent overturning during seismic out-of-plane loading [26].

This paper presents a novel connection that aims to balance structural performance with architectural practicality. The design features a predefined weak component intended to absorb and dissipate energy during seismic events, thus protecting both the CLT panel and the existing RC structure. Additionally, this component is easily accessible and can be quickly replaced if damaged. Experimental investigations were conducted to assess the performance of the proposed connection under monotonic and cyclic loading conditions. These tests provide critical insights into the connection's behavior, including its stiffness, strength, and deformation characteristics, as well as its failure modes.

2. Experimental Campaign

Here, the experimental evaluation performed in the laboratory of University of Minho, Portugal, is presented. The connections tested are composed by a Radial connector, designed by Rothoblaas for a different application, and by a steel plate designed specially to connect externally a CLT panel to an existing RC frame structure. Tensile tests are performed on the specimens under monotonic and cyclic loading to find out their uplift behaviour.

2.1. Connection

The connection externally attaches CLT panels to existing RC buildings infilled with masonry walls, as illustrated in Figure 1(a). The RADIAL-inspired connector (depicted in Figure 1(b)), comprises a principal component known as RADIAL, which connects to a triangular plate (TP) via an M12 bolt. Initially developed and manufactured by Rothoblaas, RADIAL is designed for

connecting CLT panels either wall-to-wall or wall-to-slab. The TP, in turn, is affixed to the RC beam using M20 bolts.

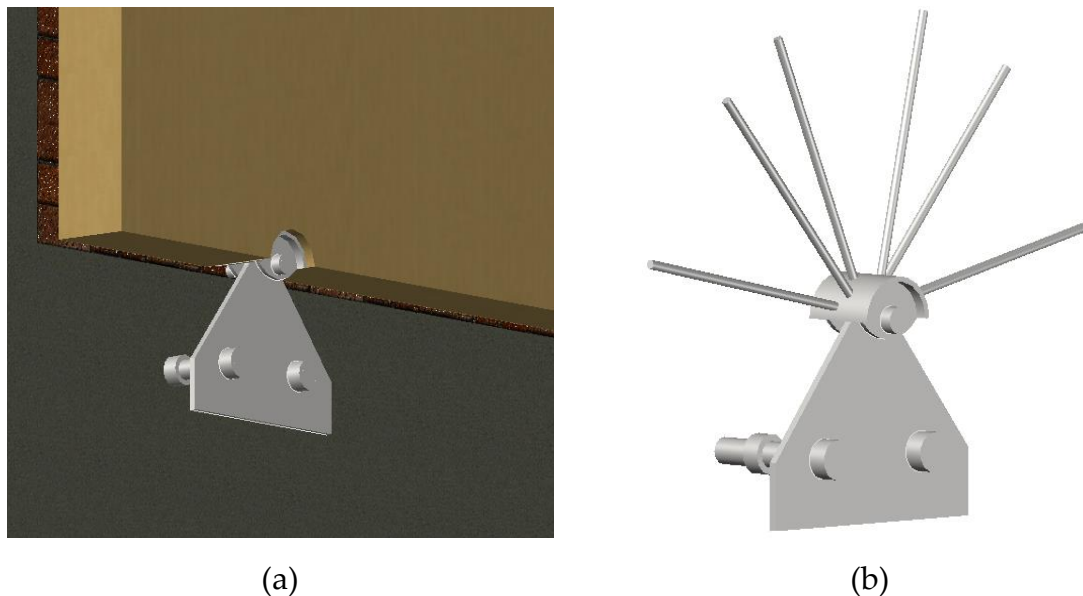


Figure 1. RADIAL-inspired connector, (a) CLT attached to RC beam, (b) Connector geometry.

Considering that RADIAL, which includes a pre-designed 12 mm hole for inserting the M12 bolt, was developed earlier, the TP at its head requires a hole of the same size to connect to RADIAL. The other bolts, with a free length of approximately 4-5 cm depending on the CLT panel thickness, must be designed to withstand high loads; otherwise, buckling of the bolts is anticipated. Such failure not only significantly reduces the connection capacity but also leads to a brittle mechanism that results in sudden damage to the connector, which is undesirable. Consequently, this TP, featuring a weak joint at the head (M12) and stronger joints at its base, is susceptible to failure under cyclic loads applied to the head, affecting both the M12 bolt and RADIAL. Therefore, the RADIAL-M12-triangle head assembly is identified as the most likely failure location.

The connection is designed to prioritize high stiffness and strength with ductile behavior structurally, while also facilitating easy repair after damage architecturally. To achieve the latter objective, it should include a predefined weak component that is readily accessible and quickly replaceable. A preferred structural failure mode is bending failure of the bolt, which meets the structural goal. In this scenario, plastic deformation occurs in the bolt, first at the midpoint where it connects to the TP and then at the corners where it connects to RADIAL, forming a ductile mechanism as established in prior researches. From an architectural perspective, it is essential that RADIAL, CLT panels, and screws remain undamaged to minimize costs and simplify and speed up repairs. As follows, details of the timber screws, RADIAL, and the TP are described.

- **RADIAL**

The RADIAL connector (see Figure 2) was designed for use in connecting CLT wall-to-floor or wall-to-wall panels. One notable distinction of this connector, compared to other traditional connections like angle brackets, is its attachment to the edge of panels rather than the face.

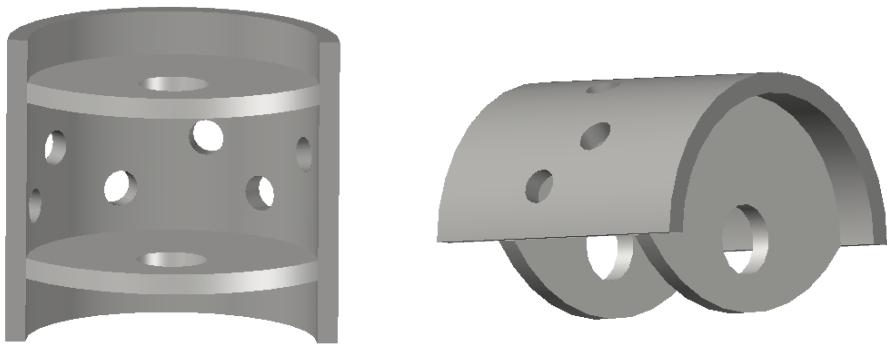


Figure 2. RADIAL details.

- Screws

The RADIAL connector can be attached to the CLT edge using up to six LBS 7x160 mm screws oriented variably (see Figure 3a). The positions of these six screws in RADIAL relative to the connector center are illustrated in Figure 3b in mm.

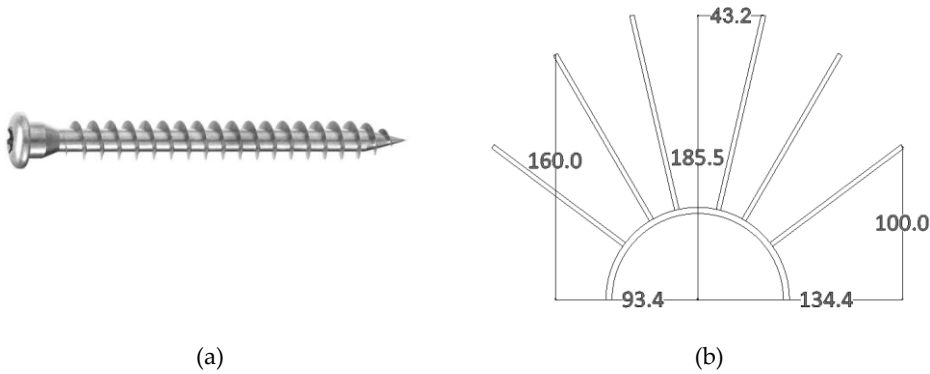


Figure 3. (a) LBS 7x160; (b) arrangement in the connector.

- Triangular plate (TP)

To facilitate the adaptation of RADIAL for external applications, a 6-mm thick plate was designed in accordance with Eurocode 3 [28] to connect it securely to the RC structural element, as depicted in Figure 4. The dimensions are specified in cmmm and the plate material is classified as S275 according to EN10025-2 [29].

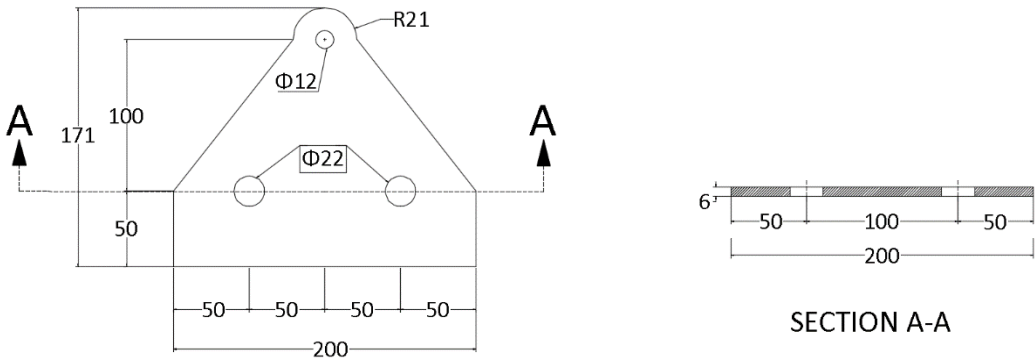


Figure 4. Geometry of the triangular steel plate.

The end distance along the load direction and the edge distance perpendicular to the load direction for the M12 normal round holes are both 21 mm, exceeding the minimum values of 16 mm

recommended by the Eurocode 3. However, these distances were initially established based on the internal radius of RADIAL, which was determined in previous designs.

The critical factor influencing the failure mode of the connection is the plate thickness. Insufficient thickness can lead to plate failure and a decrease in connector capacity. Conversely, excessive thickness can result in failure of the M12 bolt and RADIAL, which is architecturally unfavorable as previously noted.

According to static tests conducted by Rothoblaas, the tensile strength of RADIAL was estimated to be 70 kN. Assuming this load is transmitted through the M12 bolt to the plate as tension, the plate was consequently designed to withstand this tensile force (70 kN) in accordance with Eurocode 3 [28].

To assess the interaction between RADIAL, M12 bolts, and the TP, it is fundamental to predict the initial failure of the weakest component. Tests were conducted using M12 bolts of two classes - 8.8 and 10.9 - both with and without nuts. Specifically, there were 5 tests conducted with grade 8.8 bolts and 9 tests with grade 10.9 bolts.

The bolts used to secure the TP to the RC structural element must be designed to prevent any failure and ensure that failure occurs around the M12 region. If these bolts are weaker than the M12 bolt, it could lead to brittle failure due to buckling in their free length. Additionally, it would result in not fully utilizing the capacity of RADIAL, thereby reducing the connection's strength and stiffness, which is undesirable. To mitigate these issues, bolts with a diameter of 20 mm and grade 8.8, supplemented with nuts inside and outside their free length, are considered over-designed to handle the tensile load of 70 kN transferred from RADIAL and the TP.

2.2. CLT Panel

Two types of CLT panels were used in the tests. The first panel, called CLT I, which was predominantly used, comprises three layers of Spruce (*Picea abies*) with thicknesses of 27 mm, 33 mm, and 27 mm, respectively, resulting in a total thickness of 87 mm. However, in the second panel, called CLT II, the outer layers (longitudinal lamellas) are composed of Norway Spruce (*Picea abies*), each with a thickness of 19 mm, while the inner layer (transverse lamellas) is made of Maritime Pine (*Pinus pinaster Ait.*) with a thickness of 40 mm, resulting in a total thickness of 78 mm.

Each board in the panel has a width of 140 mm. The panels have plan dimensions of 500 mm along the longitudinal direction of the timber and 400 mm along the transverse direction. Tensile loads are applied parallel to the longitudinal direction. To accommodate the semicircular plate of the RADIAL connector, which has an external diameter of 62 mm, each panel was cut into a half-circle with a diameter of 65 mm, as depicted in Figure 5.

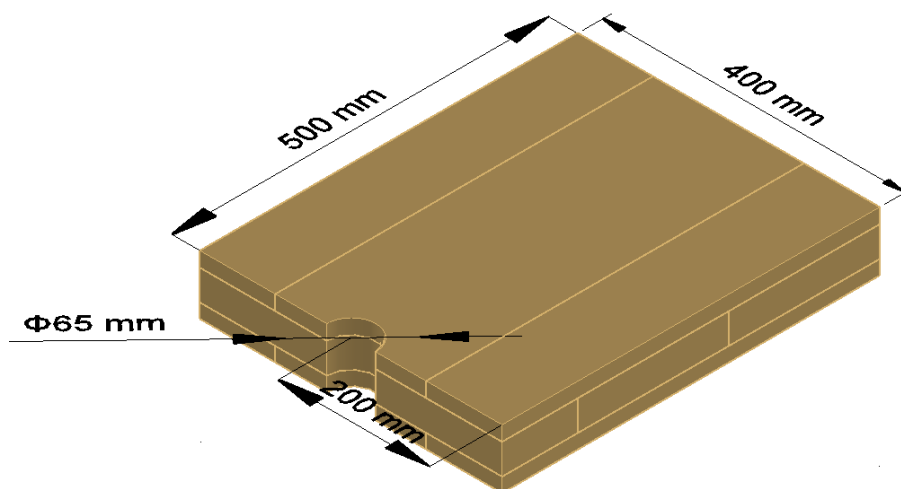


Figure 5. Geometry of the CLT specimen.

2.3. Test-Setup

As mentioned earlier, CLT shear walls are planned to be added to infilled RC-framed buildings to improve their structural behavior. Due to laboratory limitations, the CLT specimens cannot be tested as walls. Instead, they are positioned as slabs supported by a steel plate representing the RC beams in existing RC buildings for the tensile test, as illustrated in Figure 6. In this test setup, where the load is applied horizontally, the CLT's weight is transferred to the support, whereas in practice, the weight would be carried by the connection. However, this difference is negligible since the CLT's weight accounts for less than 2% of the connector's strength capacity.

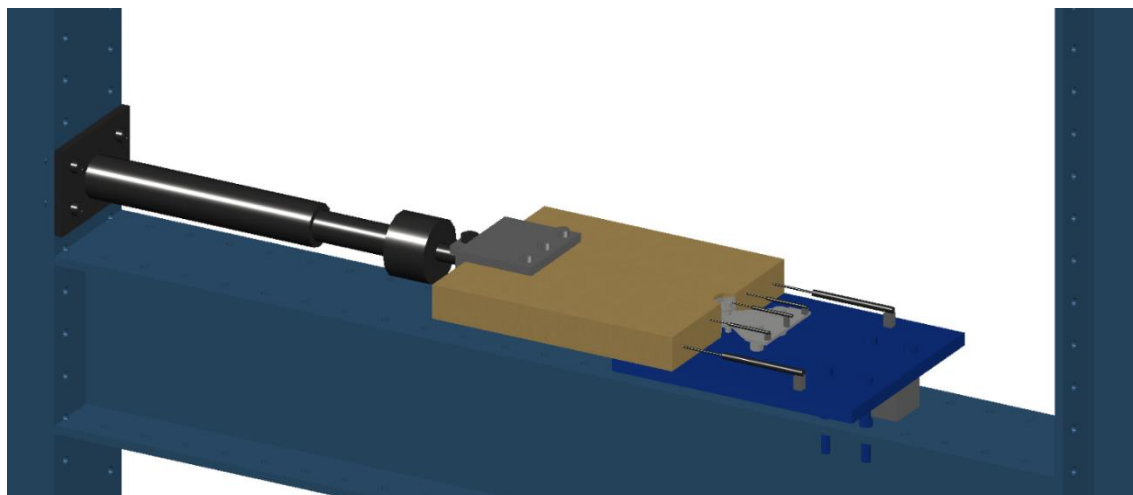


Figure 6. Test setup.

The test setup shown in Figure 7 was designed to simulate the tensile performance of an infilled RC building connected to a CLT shear wall through the proposed connection. The specimen was secured to the frame using four M20 bolts. Additionally, supports as shown in the figure are included to prevent out-of-the-plane deformations. As already described, two M20 bolts are used to fasten the TP to the base plate. This configuration aims to avoid any potential bending of the bolts and to distribute any concentrated damage around the RADIAL.

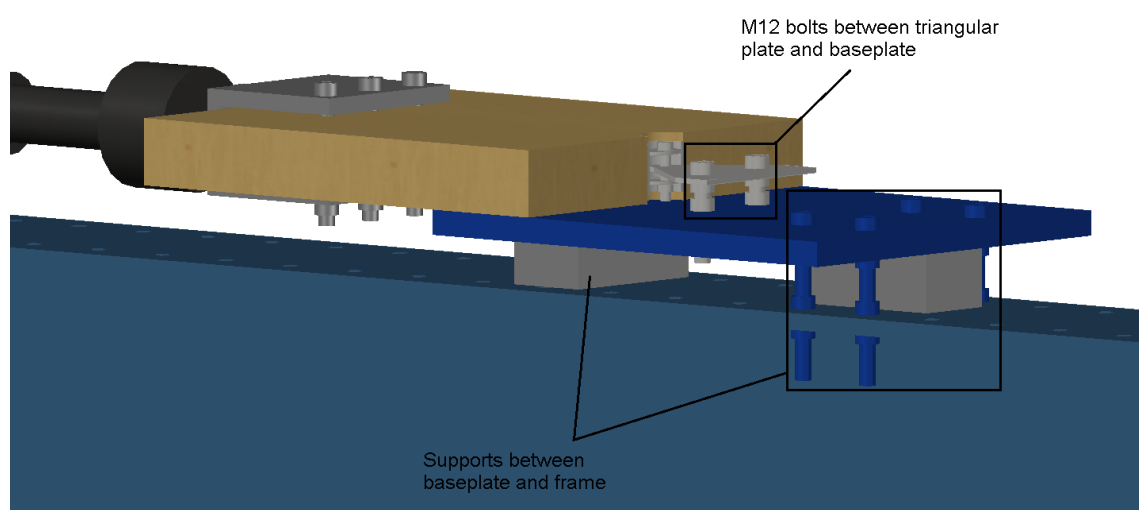


Figure 7. Joints between the plate, support and frame.

2.4. Loading of Specimens

- The loading connection detail

A steel connection, illustrated in Figure 8, was designed to transmit tensile loads from the actuator to the CLT specimen. The plate in this setup was intentionally oversized to mitigate any potential damage. The figure depicts the 3D connection with its designed dimensions in mm. This connector is attached to the load cell in one direction and linked to the CLT specimen through 3 M20 bolts, as depicted in Figure 6.

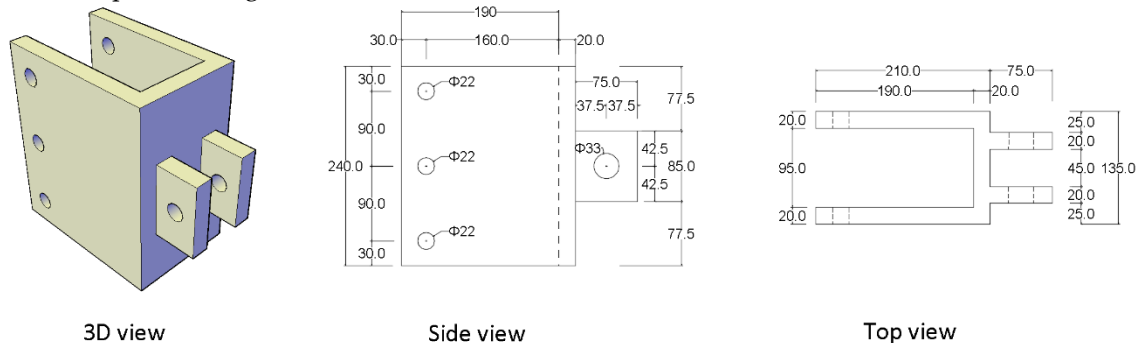


Figure 8. Loading steel connector (dimensions in mm).

- Loading procedure

Specimens are subjected to quasi-static displacement-based monotonic and cyclic loading to measure the tensile capacity of the connector. Monotonic and cyclic analyses are performed according to EN 26891 [30] and EN 12512 [31], respectively. For the monotonic tests, the specimen is loaded at a speed of 20 $\mu\text{m/s}$. During the quasi-static cyclic loading, tensile tests are conducted at a speed of 0.1 mm/s. As per EN 12512, the first and second cycles correspond to 0.25 V_y and 0.5 V_y , respectively. Subsequent cycles are repeated in groups of three until failure, progressing to slips of 0.75 V_y , 1 V_y , 2 V_y , 3 V_y , 4 V_y , etc., where V_y , the yielding displacement, is determined from the monotonic tests to be 7.481 mm. This value is calculated as the average from four monotonic tests that exhibited the same failure mode, despite slight differences in the connection configuration (M12 of different classes) that did not influence the failure mode.

2.5. LVDTs

As depicted in Figure 9, five Linear Variable Differential Transformers (LVDTs) are incorporated into the tests. Two of these (LVDT 1 and 2), affixed to the steel base plate with a capacity of 50 mm, measure the global displacement of the CLT. Another two (LVDT 3 and 4), fixed on the plate with a capacity of 10 mm, measure the relative displacement between the TP and the CLT panel. The last one (LVDT 5), situated in the middle and attached to the plate with a capacity of 10 mm, monitors the relative displacement between RADIAL and the TP.

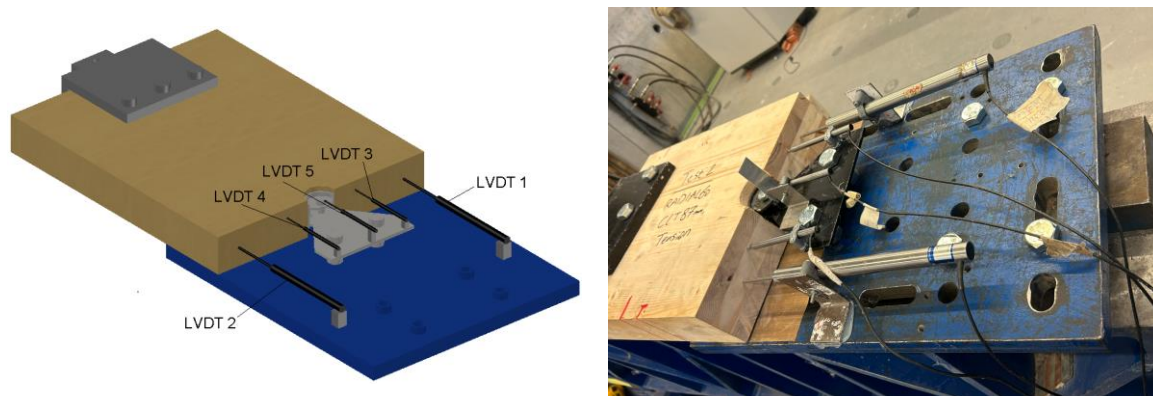


Figure 9. LVDTs number and arrangement (left), LVDTs in the test (right).

2.6. Tests Description

This experimental study examines several parameters that influence the ultimate strength of the connector, such as the number of screws, the placement and quantity of nuts in the bolt connecting RADIAL to the TP, RADIAL-to-TP bolt grade (R2TP-BG), and the bolt linking the TP to the base. In the initial test, the plate-support bolt was used without a nut, leading to a bending failure with a strength capacity approximately one-third of bolts equipped with nuts. To mitigate such failures, redistribute potential damage from this bolt to the RADIAL and enhance the overall connector capacity, nuts were subsequently added to the bolt in all subsequent tests.

In total, 17 tests were conducted on the connector, comprising 10 monotonic and 7 cyclic tests. The monotonic tests encompassed variations in loading type, number of screws, number of TPs, and the number and arrangement of nuts for the M12 bolt, alongside different classes of the M12 bolt, as detailed in Table 1. The configurations detail of the tests is shown in Figure 10. These monotonic tests were initially conducted to identify a configuration that would yield favorable structural and architectural failure outcomes. Subsequently, cyclic tests were exclusively performed on the connector using this optimized configuration.

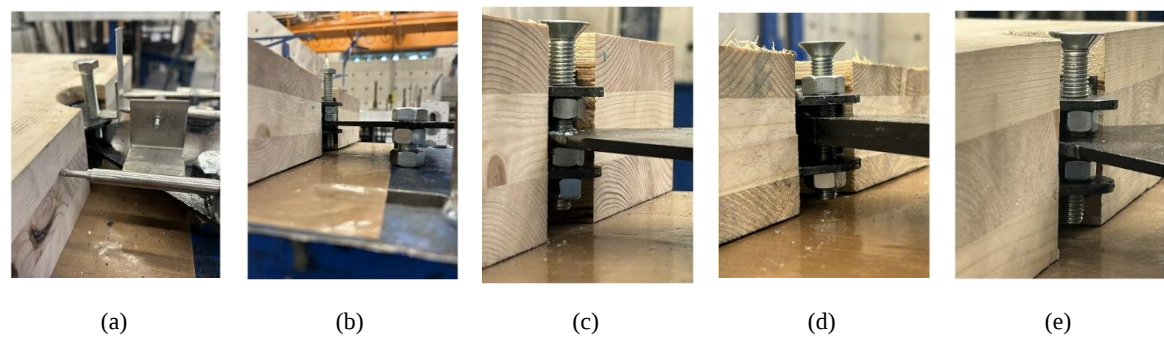


Figure 10. Different connection configurations tested: (a) R2TP-BG 8.8, no nuts, 1 TP, (b) R2TP-BG 8.8, 2 nuts, 1TP, (c) R2TP-BG 10.9, 3 nuts, 1 TP, (d) R2TP-BG 10.9, 2 nuts, 2 TP, (e) R2TP-BG 10.9, 2 nuts, 1 TP.

Table 1. Details of the tests performed.

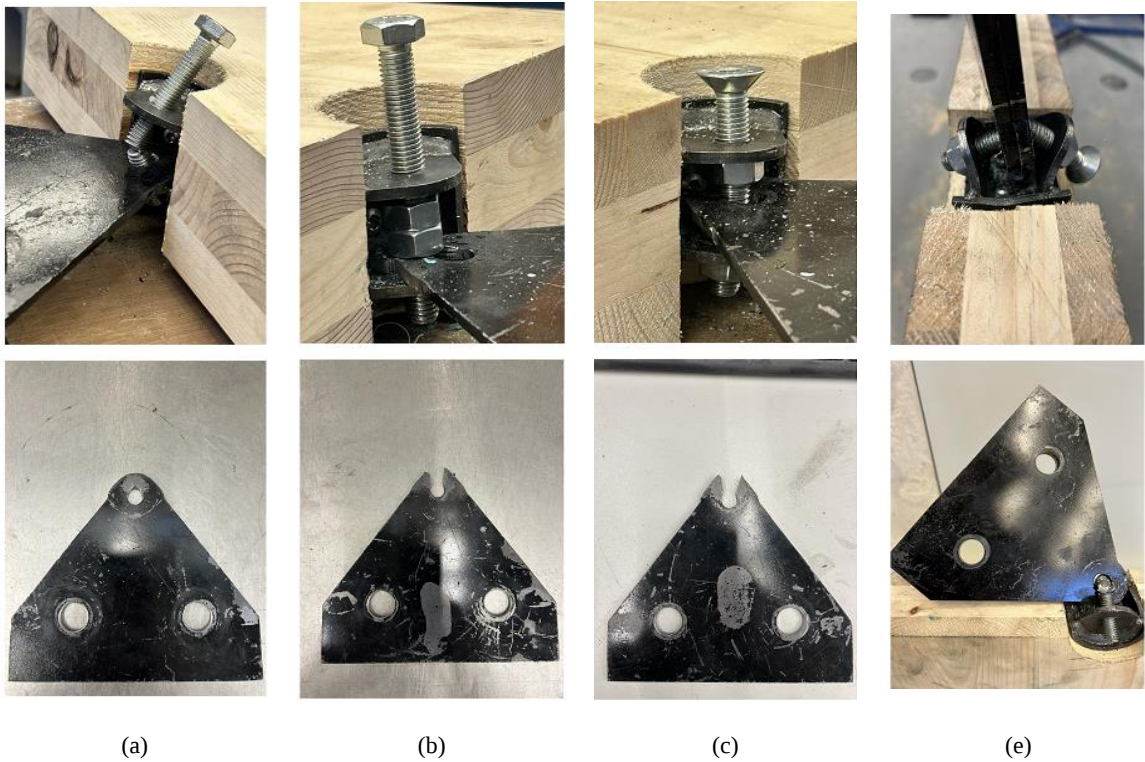
Configuration	Test Name	CLT	Loading	TP number	Screws	R2TP-BG	Nuts number
a	M1	I	Monotonic	1	6 LBS7x160	8.8	0
	M2						
	M3						
b	M4						2
	M5						
c	M6		Monotonic	1	6 LBS7x160	10.9	3
	M7				4 LBS7x160		
	C1				4 LBS7x160		
	C2		4 LBS7x160				
	C3		4 LBS7x160				
	C4	4 LBS7x160					
	C5	5 LBS7x160					
	C7	6 LBS7x160					
d	M8	II	Monotonic	2	5 LBS7x160		2
	M9				6 LBS7x160		
	M10				6 LBS7x160		
e	C6	I	Cyclic	1	6 LBS7x160		

3. Results

This section presents the responses of the tested connection from various perspectives, including the failure modes observed on the RADIAL and the steel plate (TP), experimental force-deformation curves of the connector and each of its components – TP and RADIAL - as well as the connector properties derived from these curves.

3.1. Failure Modes

The overall load capacity of the connection is contingent upon its weakest component, similar to the principle governing a series of springs. Analysis of test results highlights significant failures within the RADIAL connector, specifically affecting the M12 bolt and TP. Although other components exhibited elastic deformation, they remained within acceptable limits. These findings emphasize the critical role of the RADIAL component in the connection's structural integrity and performance under operational loads. Table 2 summarizes the failures occurring in the screws, M12 bolt, RADIAL, and TP. The failure types classified in this table are illustrated in Figure 11.



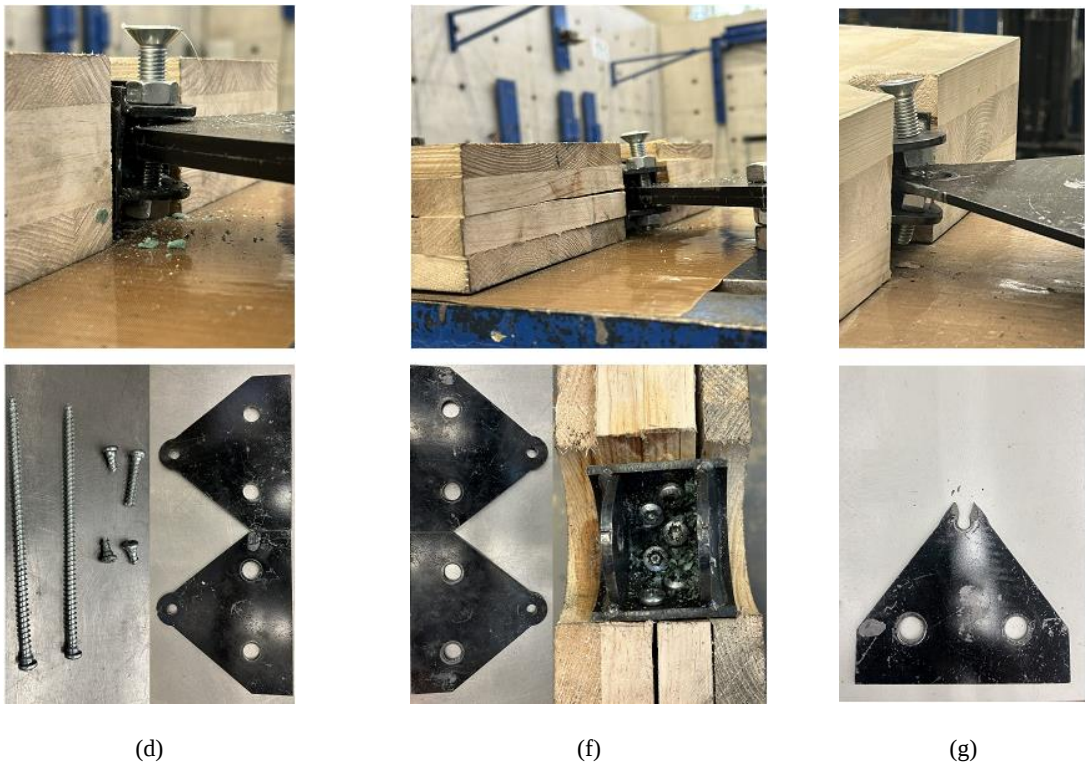


Figure 11. Failures modes observed in the tests performed.

Table 2. Failures observed in the connector’s components.

Failure	Test	CLT panel	Screws	Bolt	RADIAL flanges	TP		
a	M1	(-) *	(-)	Shear	Bending	Bearing		
	M2							
	M3							
b	M4			Bending				
	M5							
c	M6							
	M7							
	C1			Shear				
	C2							
	C3				(-)	(-)		
	C4							
	C5							
C7								
d	M8			Thread withdrawal				
e	M9	Shear	Bending	(-)				
f	M10	Delamination	(-)	(-)	(-)	Shear		
g	C6	(-)	Low bending	Low bending				

* No damage.

As shown in the figure above, seven different failures were observed in the connector’s elements and the CLT specimen, depending on the connector configuration and the CLT specimen. Except for test M10, where the CLT was delaminated, the failures can be categorized into four modes, as provided in Table 3. In test M10, where 2 TPs, 6 screws (LBS7x160), and an M12 bolt of class 10.9 were used, delamination of the CLT specimen or separation of its layers was the primary failure (Figure

11(f)), indicating that over-strengthening the connector components shifts the failure to the CLT panel, which is not favorable.

Table 3. Failure modes categories observed in the tests performed.

No.	Connector’s configuration	Predominant failure	Other failures
1	1 TP M12 C8.8 *, without nuts 4-6 screws LBS 7x160	Bending of bolt	Bending of flanges Bearing of TP
2	1 TP 4-6 screws LBS 7x160 M12: 2.1. C8.8, fully equipped with nuts 2.2. C10.9, fully equipped with nuts 2.3. C10.9, partially equipped with nuts	Shear of TP	2.1. Bending in bolt/flanges 2.2. No bending in bolt/flanges 2.3. Low bending in bolt/flanges
3	2 TP M12, C10.9, partially equipped with nuts 6 screws LBS 7x160	Bending of bolt	High bending of flanges Bearing of TPs
4	2 TP M12, C10.9, partially equipped with nuts Less than 6 screws LBS 7x160	Thread withdrawal of screws	-

* Bolt M12, class 8.8.

Each failure mode has a specific capacity and ductility that will be discussed in detail in the next section. Beyond the structural perspective, two other criteria are crucial in determining the most favorable failure: economic and architectural considerations. Economically, any failure that renders the panel or screws unusable must be avoided due to the high value of CLT panels compared to steel components. Additionally, for this renovation system, quick and easy repair is essential, requiring straightforward access to the damaged part and rapid replacement.

In Table 3, cases 1 and 3 show bolts that are completely bent, RADIAL flanges that are bent, and TPs with bearing damage, necessitating the replacement of all these components. In case 2, only the TP exhibits shear fracture, while the bolt and flanges display no bending in the bolt and flanges for the grade 10.9 bolt fully equipped with nuts, or low to medium bending for the grade 10.9 bolt partially equipped with nuts, and the grade 8.8 bolt fully equipped with nuts, respectively. In instances of low bending, RADIAL flanges can be repaired and reused. Therefore, using an M12 grade 10.9 bolt, fully or partially equipped with nuts, ensures that failure is confined to the TP, which needs replacement.

In the fourth case, where thread withdrawal of screws occurs, both panels and screws need to be replaced, which is not favorable as mentioned. To summarize, the only failure mode that satisfies both economic and architectural requirements is shear fracture in the TP, without any collateral damage to other parts of the connection. This failure mode was observed in the connection using one TP, an M12 grade 10.8 bolt fully equipped with nuts, and 4-6 LBS 7x160 screws. After determining this optimal configuration in the monotonic tests, cyclic tests were subsequently conducted using the same setup.

3.2. Structural Capacity of Connection

To measure the stiffness, strength, and deformation capacity of the connection, it is first necessary to analyse what each LVDT shown in Figure 9 measures and how these values are interconnected. The displacements indicated by LVDTs 1 to 5 are denoted as X_I , X_{II} , X_{III} , X_{IV} , and X_V , respectively. For the CLT panels, the total displacement is the sum of the displacement of the panel at the center of area ($x_{CLT,center}$) and the peak local deformation of the panel ($Def_{CLT,Local}$), as indicated in the equation below:

$$x_{CLT} = x_{CLT,center} + Def_{CLT,Local} \quad (1)$$

Here, it is assumed that the panels exhibit solid deformation with almost no cracks, and no major crushes around the loading bolts (3 M20) in the panel, implying that the second part of the equation above ($Def_{CLT,Local}$) is nearly zero. Under this assumption, the following relationships between the deformations registered by symmetric LVDTs I and III, and LVDTs III and IV in the tests are accepted:

$$x_{CLT} = \frac{x_{CLT,I} + x_{CLT,II}}{2} = \frac{x_{CLT,III} + x_{CLT,IV}}{2} \quad (2)$$

Where $x_{CLT,I}$ to $x_{CLT,IV}$ are the points on the CLT where LVDTs I, II, III, and IV are located. Assuming the baseplate has no displacement during the tests, x_I and x_{II} correspond to $x_{CLT,I}$ and $x_{CLT,II}$ respectively, or:

$$\begin{cases} x_I = x_{CLT,I} \\ x_{II} = x_{CLT,II} \end{cases} \rightarrow x_{CLT} = \frac{x_I + x_{II}}{2} \quad (3)$$

Furthermore, it is assumed that the displacement of the TP at its center of area is equal to the average displacement of the two points on the plate where LVDTs 3 and 4 are located. With this assumption and the panels exhibiting solid deformation, the relationships between the displacements of the LVDTs and the connector components are provided below, considering Equations 2 and 3.

$$\begin{cases} x_{III} = x_{CLT,III} - x_{TRI,III} \\ x_{IV} = x_{CLT,IV} - x_{TRI,IV} \\ x_{TRI} = (x_{TRI,III} + x_{TRI,IV}) / 2 \end{cases} \rightarrow x_{TRI} = \frac{x_I + x_{II}}{2} - \frac{x_{III} + x_{IV}}{2} \quad (4)$$

$$\begin{cases} x_{R60,rel} = x_V \\ x_{R60,abs} = \frac{x_I + x_{II}}{2} - \frac{x_{III} + x_{IV}}{2} + x_V \end{cases} \quad (5)$$

$$x_{actuator} = x_{screws} + x_{CLT} \rightarrow x_{screws} = x_{actuator} - x_{CLT} \quad (6)$$

In equations above, x_{TRI} is the deformation of the triangular-base plate bolts or/and deformation of the TP around these bolts, x_{CLT} is the deformation of the CLT panel where it is connected to RADIAL, $x_{actuator}$ is the force-deformation made in the actuator, and $x_{RADIAL,rel}$ is the shear crack in the TP plus deformation made in the head of RADIAL-TRI bolt due to its bending with the former being major. The deformation made in the bolt head can be representing the bending of the RADIAL flanges. So to figure out the behaviour of RADIAL, $x_{RADIAL,rel}$ is crucial and not $x_{RADIAL,abs}$.

In the equations above, x_{TRI} represents the deformation of the triangular-base plate bolts and/or the deformation of the TP around these bolts. x_{CLT} is the deformation of the CLT panel where it is connected to RADIAL. $x_{actuator}$ denotes the force-deformation made by the actuator. $x_{RADIAL,rel}$ encompasses the shear crack in the TP plus the deformation made in the head of the RADIAL-TRI bolt due to its bending, with the former being the major component. The deformation in the bolt head can represent the bending of the RADIAL flanges. Therefore, to understand the behavior of RADIAL, $x_{RADIAL,rel}$ is crucial rather than $x_{RADIAL,abs}$. The accuracy of the aforementioned assumptions is verified by:

$$x_{actuator} = x_{screws} + x_{R60,rel} + x_{TRI} \quad (7)$$

The following section will present and discuss the results obtained from monotonic and cyclic tests using the equations mentioned above.

3.1.1. Monotonic Loading

In this section, load-deformation curves of the entire connection and its components, including CLT, screws, TP, and RADIAL, are presented. The properties of the connection are derived from these curves using the methods specified in the applicable codes.

Figure 12 shows the load-deformation capacity of the connection. Initial slips occurred in the setup during loading due to adjustments of the connectors or loosened bolts and screws. These slips were removed from the curves.

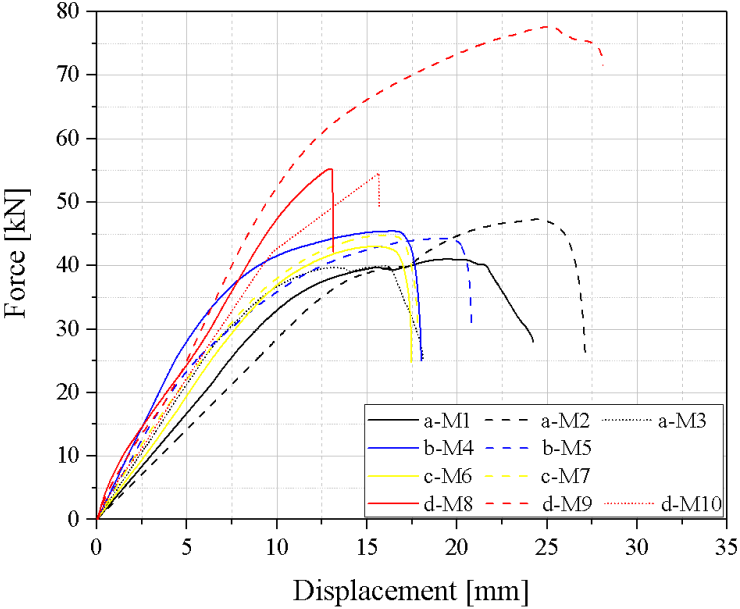


Figure 12. Force-Displacement of the connector under monotonic loading.

The properties of each curve, based on the method mentioned in EN 12512 [31], are measured and presented in Table 4 for each test and in Table 5 for each failure mode.

Table 4. Properties of the connector for each test under monotonic loading.

Test	V_y [mm]	F_y [kN]	V_{max} [mm]	F_{max} [kN]	V_u [mm]	F_u [kN]	$tg\alpha$	$tg\beta$	μ
M1	10.82	36.30	19.29	41.03	23.18	32.83	3.35	0.56	2.14
M2	15.07	42.90	24.32	47.29	26.74	37.88	2.85	0.47	1.78
M3	8.05	34.33	16.02	40.00	17.47	32.01	4.27	0.71	2.17
M4	6.08	35.41	16.42	45.47	17.81	36.32	5.83	0.97	2.93
M5	6.96	34.37	19.09	44.33	20.73	35.36	4.93	0.82	2.98
M6	10.30	39.83	15.29	43.05	17.34	34.52	3.88	0.65	1.68
M7	8.74	39.48	15.78	44.74	17.69	35.85	4.49	0.75	2.02
M8	11.72	54.37	12.95	55.28	13.13	42.51	4.41	0.74	1.12
M9	13.49	68.09	25.06	77.61	28.10	71.60	4.94	0.82	2.08
M10	12.02	52.02	15.65	54.58	15.68	49.23	4.24	0.71	1.30
Mean	10.33	43.71	17.99	49.34	19.79	40.81	4.32	0.72	2.02
CoV (%)	27.89	25.40	22.11	22.64	24.45	29.28	19.49	19.48	29.94

Table 5. Properties of the connector for each failure mode under monotonic loading.

Predominant failure		V_y	F_y	V_{max}	F_{max}	V_u	F_u	$tg\alpha$	$tg\beta$	μ
		[mm]	[kN]	[mm]	[kN]	[mm]	[kN]			
Shear in Bolt of grade 8.8	Mean	11.31	37.84	19.88	42.77	22.46	34.24	3.49	0.58	2.03
	CoV (%)	31.25	11.86	21.03	9.22	20.82	9.28	20.64	20.90	10.69

Shear in Bolt of grade 10.9	-	13.49	68.09	25.06	77.61	28.10	71.60	4.94	0.82	2.08
Shear in TP	Mean	8.02	37.27	16.65	44.40	18.39	35.51	4.78	0.80	2.40
	CoV (%)	23.44	7.48	10.18	2.29	8.54	2.17	17.15	16.87	27.19
Screw thread withdrawal	-	11.72	54.37	12.95	55.28	13.13	42.51	4.41	0.74	1.12
CLT delamination	-	12.02	52.02	15.65	54.58	15.68	49.23	4.24	0.71	1.30

In Tables 4 and 5, (V_y , F_y), (V_{max} , F_{max}), and (V_u , F_u) represent the displacement-force points for yielding, peak, and ultimate strength cases, respectively. Additionally, $tg\alpha$ and $tg\beta$ denote the linear and nonlinear stiffness of the equivalent bilinear curve. Finally, μ represents the ductility, calculated as the ratio of ultimate slip to yield slip. Generally, the CoV values for all parameters range between 10% and 30%, indicating moderate variability and reliable results.

Table 5 shows that the mean shear strength of the M12 bolt, Grade 8.8, from tests M1, M2, and M3 is 42.77 kN. In comparison, the Grade 10.9 bolt exhibits a shear strength of 77.61 kN. The shear fracture of the TP, recorded in tests M4, M5, M6, and M7, has an average strength of 44.40 kN with a Coefficient of Variation (CoV) of 2.29%, demonstrating the reliability of this value. Additionally, five LBS7x160 screws failed at a strength of 55.28 kN in test M7. Finally, the delamination of CLT panel occurred at a peak strength of 54.58 kN.

The deformation capacities for the shear of M12C8.8 and M12C10.9 bolts are 20.46 mm and 28.10 mm, respectively. The shear fracture of the plate results in 18.39 mm of deformation with a CoV of 8.54%, while screw failure leads to a deformation of 13.13 mm. Regarding yield displacement, the shear of M12C8.8 and M12C10.9 occurs at displacements of 11.31 mm and 13.49 mm, respectively. The plate's shear fracture yields at 8.02 mm with a CoV of 23.44%, and screw failure causes the connector to reach the yield point at 11.72 mm.

In terms of stiffness, the M12C8.8 bolt exhibited a stiffness of 3.49 kN/mm, while the M12C10.9 bolt had a stiffness of 4.94 kN/mm. For the plate fracture, the stiffness measured 4.78 kN/mm, for screw failure it was 4.41 kN/mm, and for CLT delamination, it was 4.24 kN/mm. These results demonstrate that the lowest and highest strengths of the connector are associated with the shear of the M12 bolts of class C8.8 and C10.9, respectively. The least deformation capacity is associated to the thread withdrawal of screws, highlighting the brittleness of this failure mode. Conversely, the best deformation capacities are observed in the failure mode due to shear of bolts of class 8.8 or 10.9. The shear fracture of the plate results in the shortest elastic deformation, while the largest elastic deformation occurs with the shear of bolts of class 10.9. Additionally, the highest stiffness is observed with the shear of M12C10.9, and the lowest with the shear of M12C8.8.

To assess the ductility level of a connection, a cyclic analysis should be performed according to Eurocode 8, clause 8.3.3 [32]. However, under monotonic loading, the connection in all tests conducted was found to be non-dissipative, as the ductility factor was less than the medium ductility class, $DCM=4$. In the following section, where cyclic analyses are discussed, the ductility level of the connection will be clearly determined.

To summarize, the shear of M12C10.9 provides the highest strength, stiffness, and both elastic and plastic deformation capacities. The lowest strength and stiffness are observed in the shear of M12C8.8, while the lowest deformation capacity is associated with screw thread withdrawal. The shear fracture of the plate exhibits mediocre performance in terms of strength, stiffness, and deformation capacity compared to other failure modes. Structurally, the shear failure of the M12C10.9 bolt is the most favorable in terms of elastic stiffness and strength compared to the other failures observed, but it is unfavorable in terms of ductility and energy dissipation. However, architecturally, this failure mode leads to extensive damage to the RADIAL flanges and the plate, necessitating their replacement. On the other hand, the shear fracture of the plate only requires the replacement of the plate with no effect on the RADIAL. Thus, considering both structural and architectural aspects, the most favorable damage is the shear fracture of the plate.

The following section presents the force-deformation curves for each component, including CLT specimens, RADIAL, TP, and screws, as calculated by Equations 1-7. These curves are displayed separately in Figure 13.

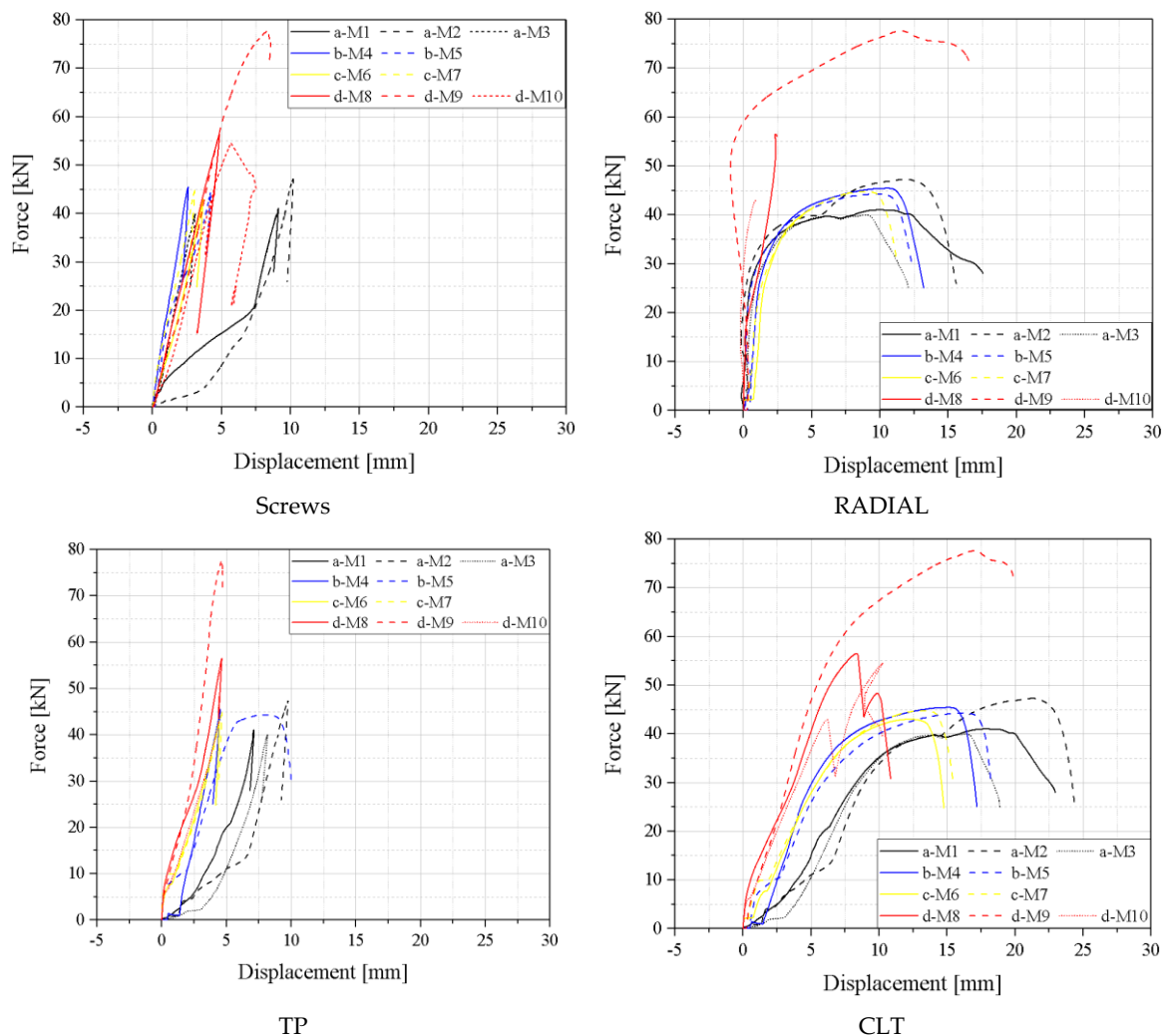


Figure 13. Force-Displacement of the connector's components in monotonic tests.

The figures illustrate where fasteners were loosely fixed or where slippage occurred. For instance, in Figure 13(c), the TP in tests M2 and M3 shows an initial stiffness significantly lower than the subsequent stiffness, indicating slippage in the two M20 bolts at the beginning of loading before the actual stiffness of the component was established. Another example can be seen in Figure 11(a), where the screws in tests M1 and M2 exhibit more deformation at the start of loading, suggesting slippage of screws that might not have been adequately driven during the specimen preparation process. Note that the deformation of the CLT (Figure 13(d)) represents the total deformation, including contributions from both RADIAL and TP. However, previous studies suggest that the CLT will generally remain within the elastic range, similar to the screws.

The figures also depict the behavior of each component. By excluding the slipping parts of the figures, except for tests M8 and M10, which resulted in thread withdrawal of screws or delamination of CLT, it is evident that in most cases, the screws and TPs remained within the elastic range, while the RADIAL components demonstrated ductile performance. Therefore, structurally, it is beneficial to shift the damage to the RADIAL component, particularly to the Grade 10.9 bolt connecting RADIAL to TP, in order to achieve higher strength (+78.80%) and stiffness (+3.35%), and improve deformation capacity (+68.20%).

Figure 14 compares the actuator displacement with the combined displacement from screws, RADIAL, and TP, as provided in Equation 7. This comparison validates the assumptions made in formulating the relationships between LVDTs, such as the solid behavior of CLT and nearly zero displacement in the bolts connecting the baseplate and frame. The discrepancies between the two aforementioned displacements in the tests are minimal, confirming the assumptions, except for tests M8 and M10, where CLT delamination followed by thread withdrawal of screws was observed. Additionally, for test M9, where failure was primarily due to the bending of the M12 bolt, the accuracy is compromised. This discrepancy is mainly due to significant bending of the RADIAL flanges, which was not captured by the LVDTs. Also, this issue is likely caused by incorrect measurements from LVDT 5, which intermittently stopped recording and had to be manually restarted during the test.

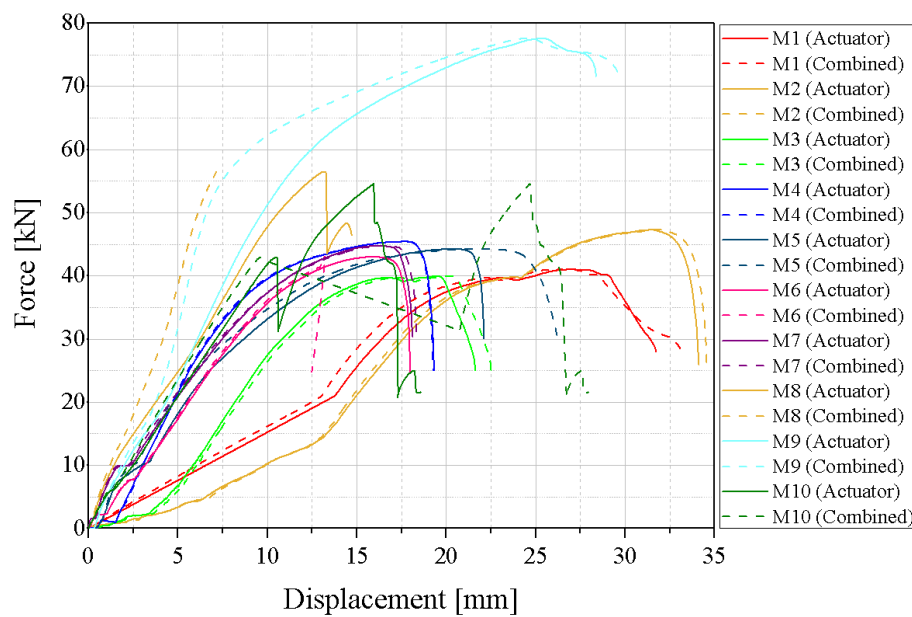


Figure 14. Force-displacement curves registered by the actuator and the combined displacement from Equation 7.

3.1.1. Cyclic Loading

The cyclic analysis was performed on the connection with the configuration that exhibited a favorable failure mechanism in monotonic loading: shear fracture in the TP, with minimal damage to the rest of the connector, including the CLT, screws, RADIAL, M12 bolt, and M20 bolts connecting the TP to the baseplate. This damage, intentionally concentrated on a weaker part of the connector, occurs when the configuration includes 6 LBS7×160 screws, an M12 bolt of class 10.9 fully symmetrically equipped with nuts (2 inside and 2 outside of the RADIAL flanges, thus effectively stiffening the connection), and one TP connected to a 30 mm thick baseplate using 2 M20 bolts. Seven specimens were loaded under the loading protocol described in section 2.4. Figure 15 shows the load-displacement curved registered by the actuator, representing the load-carrying capacity curves observed in the cyclic tests C1 to C7.

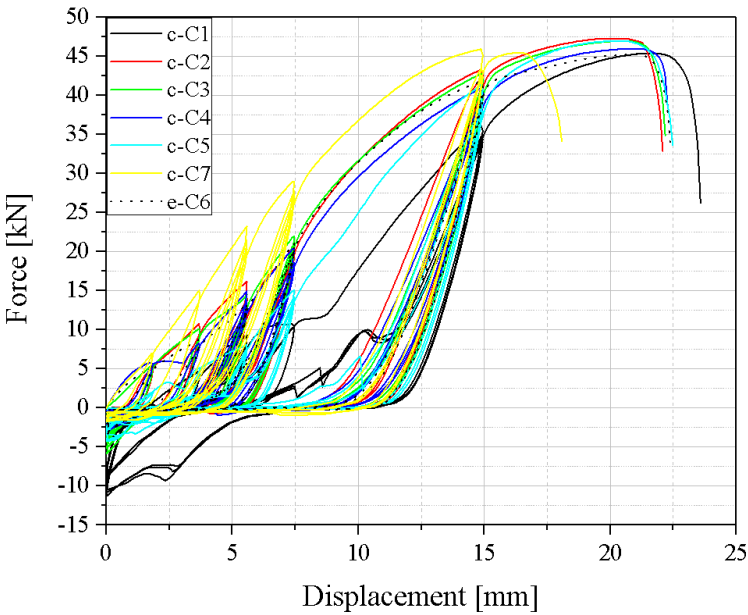


Figure 15. Force-Displacement experimental curves observed in the connector during the cyclic tests.

The mechanical properties of the connector, derived from the backbone curves using the methodology outlined in EN 12512 [31], are detailed in Table 6. The findings indicate that the connector's ductility and strength are unaffected by the number of screws connecting the RADIAL to the CLT, as the damage occurred primarily in the TP and to a lesser extent in the RADIAL flanges and the M12 bolt. Similar to the monotonic tests, variations in key displacements are relatively higher than their corresponding forces, and both are less than those observed in monotonic tests. When comparing properties from cyclic and monotonic tests, the yield displacement doubled, ultimate displacement increased by 20%, strength increased by 10%, while stiffness and ductility decreased by 45%. The reduction in stiffness and ductility, which are based on yield and ultimate displacement and yield strength, is 45% and 40%, respectively, aligning closely with direct observations from the tests. The specimen's displacement is resulted from the displacement of the RADIAL (or TP) and the longitudinal deformation of the screws. The increased displacement during cyclic loading, especially the yield displacement, can be attributed to potential deformations within the CLT specimen and around the screws. This is primarily due to degradation typically occurring in consecutive cyclic displacements in terms of stiffness and strength, especially the former.

Table 6. Properties of the connector derived from the cyclic tests.

Test	V_y [mm]	F_y [kN]	V_{max} [mm]	F_{max} [kN]	V_u [mm]	F_u [kN]	$tg\alpha$	$tg\beta$	μ
C1	21.47	45.28	21.76	45.39	22.24	36.31	2.28	0.38	1.04
C1	16.22	45.32	20.46	47.3	20.89	37.84	2.79	0.46	1.29
C3	16.16	44.9	20.67	46.97	21.23	37.57	2.75	0.46	1.31
C4	16.72	44.07	21.17	45.98	21.51	36.78	2.58	0.43	1.29
C5	18.37	46.02	20.47	46.98	20.99	37.59	2.76	0.46	1.14
C6	16.36	43.2	21.07	45.24	21.87	36.19	2.61	0.43	1.34
C7	10.1	42.53	14.87	45.93	17.33	36.74	4.27	0.71	1.72
Mean	16.49	44.47	20.07	46.25	20.86	37.00	2.86	0.48	1.3
CoV (%)	20.63	2.83	11.65	1.78	7.82	1.79	22.51	22.54	16.31

Figure 16 displays the force-displacement behavior of each connector's components. Similar to the monotonic results, it can be observed that the screws and TP exhibit linear behavior, while the RADIAL, designed as the sole component for nonlinear behavior, demonstrates ductile behavior with

significant plastic deformation. The measurements made in the CLT actually reflect the global deformation of the connector, which depends on both the RADIAL and TP. Consequently, the CLT's performance is neither as ductile as the RADIAL nor as elastic as the TP.

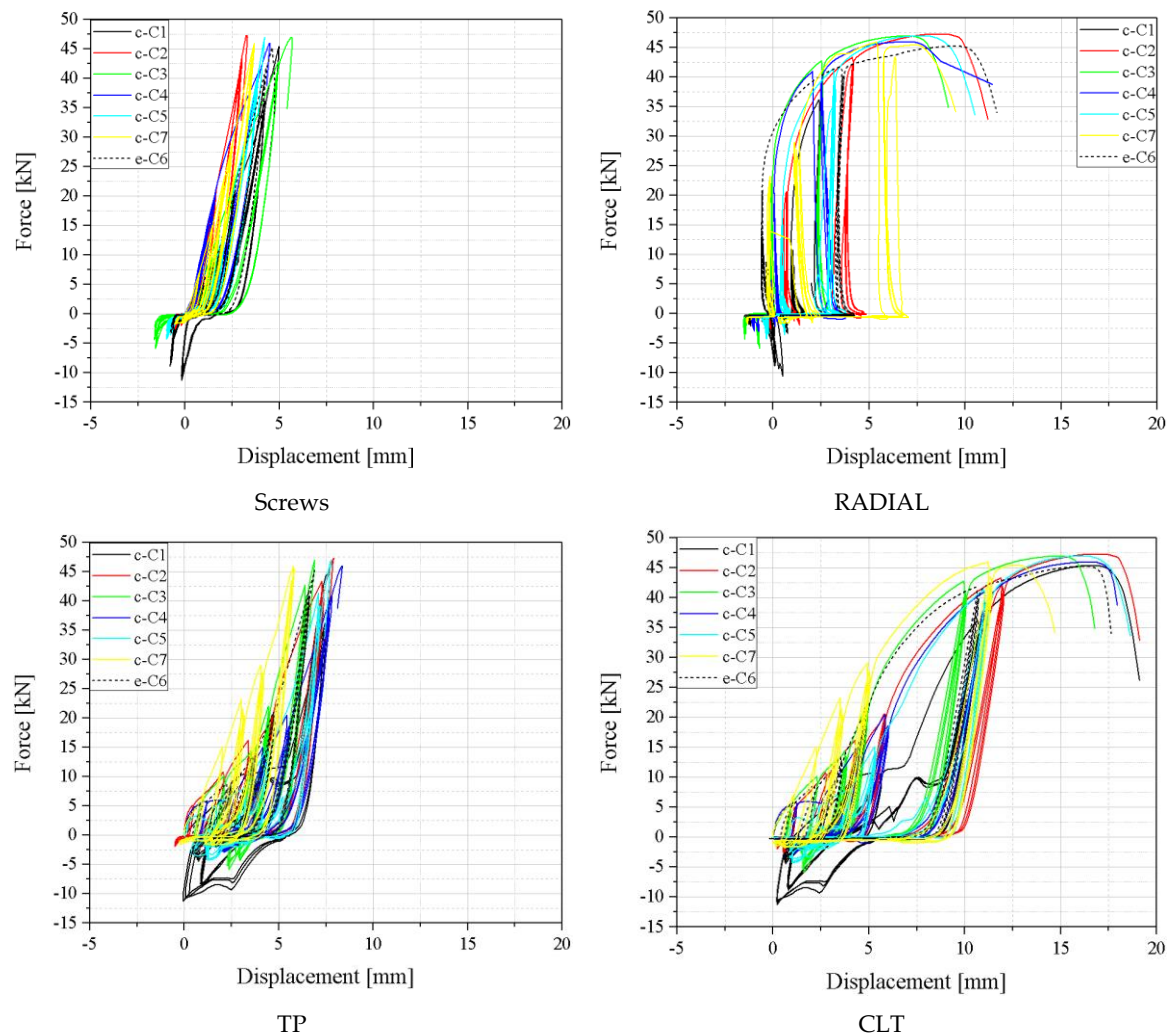


Figure 16. Force-Displacement of the connector's components in cyclic tests.

Finally, Figure 17 shows the displacement measured by the actuator compared with the combined displacements of the components (Equation 7) across all cyclic tests. The minimal discrepancies observed between the two displacements confirm the accuracy of the assumptions mentioned before. This is further supported by the absence of damage to the CLT specimen following the tests.

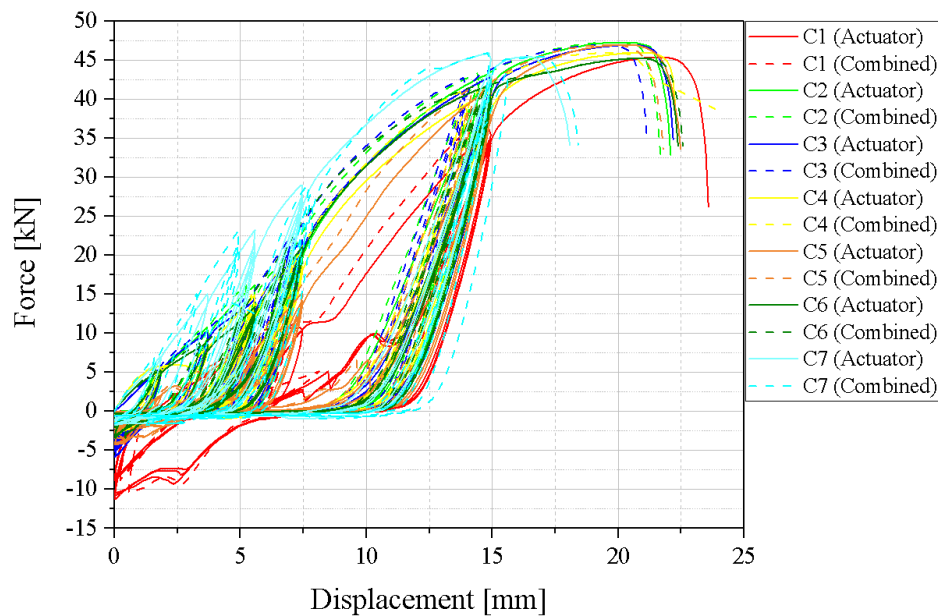


Figure 17. Force-displacement curves registered by the actuator and the combined displacement from Equation 7.

The key parameters derived from the cyclic analysis for evaluating the connector's performance include ductility, energy dissipation, strength degradation, and stiffness deterioration, which are detailed below.

- Connector ductility-level

There are two approaches to determine the ductility level of a connection, as shown in TS1125/1 [33] and TS12512/2 [34]. Both approaches are based on the clause 8.3.3 of Eurocode 8 [32] reporting that a “dissipative zone shall be able to deform plastically for at least three fully reversed cycles at a static ductility ratio of 4 for ductility class medium (DCM) structures and at a static ductility ratio of 6 for ductility class high structures (DCH), without more than a 20% reduction of resistance”.

According to TS1125/1, the mean yield displacement of the connector under monotonic loading is 9.08 mm, as provided in Tables 4 and 5. To assign the connector a DCM class, (1) the ultimate displacement of the connector, at which all the triple cycles are repeated completely, under cyclic loading must be greater than four times this displacement (36.32 mm), and (2) the strength reduction of the third cycles compared to first cycles must be less than 20%. According to Table 6, the maximum of the ultimate displacement of the connector under the 7 cyclic tests is 22.24 mm, which is far away from the limitation mentioned above. As a result, the connector is non-dissipative.

Based on TS12512/2, in any of the seven cyclic tests conducted, there is no displacement in the envelope curve of the first cyclic curves at which the strength reduction factor become equal to or higher than 0.8, meaning that the connector is non-dissipative. This factor is the ratio between the load corresponding to the displacement and the mean value of the maximum load taken from the monotonic tests. This result corresponds to the shear failures observed in the bolt and plate, thread withdrawal of screws, and CLT delamination, as these failures, caused by shear and axial loads have been proven to be non-ductile and do not involve the formation of a plastic hinge as seen in bending loading.

- Energy dissipation

The next important characteristic extracted from a cyclic analysis is energy dissipation, which is measured as the area enclosed in the cyclic curves as defined by code EN 12512 [31]. The accumulated dissipated energy of each test is shown versus the displacement of the panel (average displacement of LVDT 1 and 2) in Figure 18. Except for the curve for C7, the variation in the remaining curves is small. In this test, 6 screws were used to connect RADIAL to CLT, and the M12 was fully equipped

with nuts. In the rest, either 4 or 5 screws were adopted, or the nuts were not fully added to the bolt, indicating that the fasteners play an important role in dissipating energy.

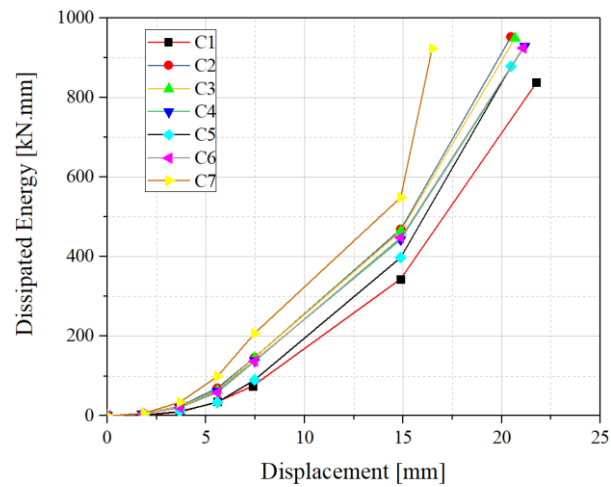


Figure 18. Accumulated total energy versus displacement.

- Impairment of strength
The strength impairment, observed in triple cycles (e.g., 3, 4, 5), represents the loss of strength from the first to the third cycle as a percentage of the strength in the initial cycle according to EN 12512 [31], as provided in Table 7 for the triple cycles with peak displacements of 0.75V_y, V_y, and 2V_y. It is directly linked to stiffness degradation. It is normally measured for both positive and negative cycles, but here only positive cycles are considered, taking into account the tensile test being loaded in only one direction. It is shown that the mean (12.41 kN, 6.69 kN, and 6.34 kN) and variation (44%, 43%, and 19%) of this strength from the first triple to the last one are decreasing. Also, C6 presents the least strength impairment compared to the others, possibly due to adopting the least number of nuts added to the M12 bolt (2 nuts).

Table 7. Impairment of strength [%].

Test	0.75V _y		V _y		2V _y	
	EC1-EC2	EC1-EC3	EC1-EC2	EC1-EC3	EC1-EC2	EC1-EC3
	EC1	EC1	EC1	EC1	EC1	EC1
C1	12.89	14.48	3.70	4.46	3.84	5.14
C2	13.64	22.42	2.39	3.75	2.61	5.28
C3	7.25	10.03	3.93	5.80	4.55	6.73
C4	8.15	14.30	9.17	11.88	4.94	6.73
C5	4.60	6.82	6.02	8.75	5.37	8.12
C6	4.53	6.33	2.54	3.78	3.42	5.09
C7	7.62	12.42	4.41	7.48	5.43	7.42
Mean	8.38	12.40	4.59	6.56	4.31	6.36
CoV (%)	43.29	44.41	51.30	45.99	24.59	19.01

In Table 7, "EC" refers to the envelope curve. It is noted that the peak displacement of 0.75V_y is observed in cycles 3, 4, and 5. The displacement V_y occurs in cycles 6, 7, and 8, while 2V_y is recorded in cycles 9, 10, and 11.

- Stiffness degradation
In cyclic analysis, reduction of elastic stiffness of consecutive triple cycles is known as stiffness degradation. The gradual decrease in stiffness across consecutive loops reduces the area enclosed by the hysteresis curves, a phenomenon referred to as the pinching effect. Stiffness degradation is typical features of CLT panels and connections subjected to cyclic loading. Table 8 presents the stiffness

degradation of the cyclic tests C1, C7, showing the percentage reduction in elastic stiffness of the envelope curve for the second and third cycles compared to the first cycle.

Table 8. Ratio of stiffness degradation [%].

Test	EC1-EC2	EC1-EC3
	EC1	EC1
C1	7.20	8.88
C2	12.58	17.96
C3	7.58	10.71
C4	12.09	17.93
C5	9.51	13.94
C6	5.52	7.75
C7	6.07	10.00
Mean	8.65	12.45
CoV (%)	32.60	33.83

4. Conclusions

The experimental campaign aimed to evaluate the structural performance of an innovative connection that externally attaches CLT panels to infilled RC frames. This connection consists of a main component, termed RADIAL, which is fastened to the CLT using screws and to the RC/steel beams using a TP and bolts. Various configurations of bolts, screws, and TPs were investigated. The key findings can be summarized as follows:

- Failure Modes and Structural Integrity

The RADIAL connector, specifically the M12 bolt and the TP, was identified as the critical component influencing the overall load capacity of the connection. Additionally, seven distinct failure modes were observed, each impacting the structural integrity of the connection to varying degrees. Among these, shear fracture of the TP was deemed the most favorable failure mode, as it minimizes collateral damage to other parts of the connection.

- Economic and Architectural Considerations

From an economic and repair standpoint, shear fracture in the TP, which leaves the RADIAL components unaffected, was identified as the most advantageous failure mode. This mode facilitates easy and quick replacement of the TP, thereby preserving the high-value CLT panels and minimizing downtime for repairs.

- Load-Displacement Characteristics

Monotonic loading tests demonstrated that the connection's stiffness, strength, and deformation capacities varied with different bolt and TP configurations. The M12 grade 10.9 bolt exhibited the highest strength and deformation capacity, whereas screw thread withdrawal showed the lowest deformation capacity. Additionally, based on the criteria specified in the code, the connection's ductility under both monotonic and cyclic loadings was determined to be non-dissipative.

- Component Behavior

Force-displacement curves for individual components (CLT, screws, TP, RADIAL) demonstrated that while most components remained within the elastic range, the RADIAL components exhibited ductile behavior. Ensuring ductile performance by concentrating damage on the RADIAL component, particularly the bolt connecting RADIAL to TP, is advantageous for overall structural resilience.

- Validation and Reliability

The assumptions regarding the solid behavior of CLT and nearly zero displacement in the baseplate-frame bolts were validated by the minimal discrepancies observed between actuator deformations and the combined deformations from screws, RADIAL, and TP. Additionally, the

coefficient of variation (CoV) values indicated moderate variability, suggesting reliable and consistent results across different tests.

In conclusion, the optimal configuration for the connection involves using an M12 grade 10.9 bolt, fully or partially equipped with nuts, and 4-6 LBS 7x160 screws, ensuring shear fracture of the TP as the predominant failure mode. This setup not only provides favorable structural performance but also aligns with economic and architectural considerations, facilitating efficient maintenance and repair. Tests on the shear performance of the connector are recommended to fully assess its ductility capacity.

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References

1. A. Furtado, H. Rodrigues, A. Arêde, and H. Varum, "A review of the performance of infilled rc structures in recent earthquakes," *Appl. Sci.*, vol. 11, no. 13, p. 5889, 2021.
2. A. Ceccotti, "New technologies for construction of medium-rise buildings in seismic regions: The XLAM case," *Struct. Eng. Int. J. Int. Assoc. Bridg. Struct. Eng.*, vol. 18, no. 2, 2008, doi: 10.2749/101686608784218680.
3. M. Popovski and I. Gavric, "Performance of a 2-story CLT house subjected to lateral loads," *J. Struct. Eng.*, vol. 142, no. 4, p. E4015006, 2016.
4. Z. Mehdipour, E. Poletti, J. M. Branco, and P. B. Lourenço, "Numerical Analysis of Masonry-Infilled RC-CLT Panel Connections," *Buildings*, vol. 12, no. 11, 2022, [Online]. Available: <https://doi.org/10.3390/buildings12112009>.
5. I. Lukacs, A. Björnfor, and R. Tomasi, "Strength and stiffness of cross-laminated timber (CLT) shear walls: State-of-the-art of analytical approaches," *Eng. Struct.*, vol. 178, 2019, doi: 10.1016/j.engstruct.2018.05.126.
6. F. Stazi, M. Serpilli, G. Maracchini, and A. Pavone, "An experimental and numerical study on CLT panels used as infill shear walls for RC buildings retrofit," *Constr. Build. Mater.*, vol. 211, pp. 605–616, 2019, doi: 10.1016/j.conbuildmat.2019.03.196.
7. S. Tesfamariam, J. Madheswaran, and K. Goda, "Displacement-Based Design of Hybrid RC–Timber Structure: Seismic Risk Assessment," *J. Struct. Eng.*, vol. 145, no. 11, p. 4019125, 2019, doi: 10.1061/(asce)st.1943-541x.0002415.
8. I. Šušteršič, "Utrjevanje stavb s križno lepljenimi lesenimi ploščami: doktorska disertacija," Univerze v Ljubljani, 2017.
9. A. Aloisio, F. Boggian, and R. Tomasi, "Design of a novel seismic retrofitting system for RC structures based on asymmetric friction connections and CLT panels," *Eng. Struct.*, vol. 254, 2022, doi: 10.1016/j.engstruct.2021.113807.
10. I. Gavric, M. Fragiaco, and A. Ceccotti, "Cyclic Behavior of CLT Wall Systems: Experimental Tests and Analytical Prediction Models," *J. Struct. Eng.*, vol. 141, no. 11, 2015, doi: 10.1061/(asce)st.1943-541x.0001246.
11. D. Casagrande, A. Polastri, T. Sartori, C. Loss, and M. Chiodega, "Experimental campaign for the mechanical characterization of connection systems in the seismic design of timber buildings," 2016.
12. J. Schneider, E. Karacabeyli, M. Popovski, S. F. Stierner, and S. Tesfamariam, "Damage Assessment of Connections Used in Cross-Laminated Timber Subject to Cyclic Loads," *J. Perform. Constr. Facil.*, vol. 28, no. 6, 2014, doi: 10.1061/(asce)cf.1943-5509.0000528.

13. M. A. Parisi and M. Piazza, "Mechanics of Plain and Retrofitted Traditional Timber Connections," *J. Struct. Eng.*, vol. 126, no. 12, 2000, doi: 10.1061/(asce)0733-9445(2000)126:12(1395).
14. G. D'Arenzo, W. Seim, and M. Fossetti, "Experimental characterization of a biaxial behaviour connector for CLT wall-to-floor connections under different load directions," *Constr. Build. Mater.*, vol. 295, 2021, doi: 10.1016/j.conbuildmat.2021.123666.
15. M. Popovski, J. Schneider, and M. Schweinsteiger, "Lateral load resistance of cross-laminated wood panels," in *11th World Conference on Timber Engineering 2010, WCTE 2010, 2010*, vol. 4, pp. 3394–3403.
16. R. Tomasi and I. Smith, "Experimental Characterization of Monotonic and Cyclic Loading Responses of CLT Panel-To-Foundation Angle Bracket Connections," *J. Mater. Civ. Eng.*, vol. 27, no. 6, 2015, doi: 10.1061/(asce)mt.1943-5533.0001144.
17. M. Latour and G. Rizzano, "Seismic behavior of cross-laminated timber panel buildings equipped with traditional and innovative connectors," *Arch. Civ. Mech. Eng.*, vol. 17, no. 2, 2017, doi: 10.1016/j.acme.2016.11.008.
18. L. Pozza, B. Ferracuti, M. Massari, and M. Savoia, "Axial–Shear interaction on CLT hold-down connections – Experimental investigation," *Eng. Struct.*, vol. 160, 2018, doi: 10.1016/j.engstruct.2018.01.021.
19. J. Liu and F. Lam, "Experimental test of cross laminated timber connections under bi-directional loading," 2016.
20. T. M. Laggner, G. Flatscher, and G. Schickhofer, "Combined loading of self-tapping screws," 2016.
21. A. Polastri, I. Giongo, A. Angeli, and R. Brandner, "Mechanical characterization of a pre-fabricated connection system for cross laminated timber structures in seismic regions," *Eng. Struct.*, vol. 167, 2018, doi: 10.1016/j.engstruct.2017.12.022.
22. W. Y. Loo, P. Quenneville, and N. Chouw, "A new type of symmetric slip-friction connector," *J. Constr. Steel Res.*, vol. 94, 2014, doi: 10.1016/j.jcsr.2013.11.005.
23. A. Kramer, A. R. Barbosa, and A. Sinha, "Performance of Steel Energy Dissipators Connected to Cross-Laminated Timber Wall Panels Subjected to Tension and Cyclic Loading," *J. Struct. Eng.*, vol. 142, no. 4, 2016, doi: 10.1061/(asce)st.1943-541x.0001410.
24. F. Sarti, A. Palermo, and S. Pampanin, "Fuse-Type External Replaceable Dissipaters: Experimental Program and Numerical Modeling," *J. Struct. Eng.*, vol. 142, no. 12, 2016, doi: 10.1061/(asce)st.1943-541x.0001606.
25. A. Hashemi, P. Zarnani, R. Masoudnia, and P. Quenneville, "Seismic resistant rocking coupled walls with innovative Resilient Slip Friction (RSF) joints," *J. Constr. Steel Res.*, vol. 129, 2017, doi: 10.1016/j.jcsr.2016.11.016.
26. F. Smiroldo, I. Paviani, I. Giongo, S. Zanon, R. Albatici, and M. Piazza, "An integrated approach to improve seismic and energetic behaviour of rc framed buildings using timber panels," *Sustain.*, vol. 13, no. 20, 2021, doi: 10.3390/su132011304.
27. F. Boggian, C. Tardo, A. Aloisio, E. M. Marino, and R. Tomasi, "Experimental Cyclic Response of a Novel Friction Connection for Seismic Retrofitting of RC Buildings with CLT Panels," *J. Struct. Eng.*, vol. 148, no. 5, 2022, doi: 10.1061/(asce)st.1943-541x.0003313.
28. B. Standard, "Eurocode 3—Design of steel structures—," *BS EN*, vol. 1, no. 1, p. 2005, 1993.
29. EN-10025, "EN10025: 2 (2005)—Hot rolled products of structural steels," 2005.
30. BSI, "BS EN 26891:1991. Timber Structures - Joints Made With Mechanical Fasteners - General Principles For The Determination Of Strength And Deformation Characteristics," Bsi, 1991.
31. EN 12512:2001. Timber structures - Test methods - Cyclic testing of joints made with mechanical fasteners.
32. EN 1998-3:2005 - Eurocode 8: Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings. European Committee for Standardization.
33. C. Sigrist, D. Casagrande, and M. Piazza, "Revision of testing standards to determine the seismic capacity of timber connections according to Eurocode 8," 2021.
34. D. Casagrande et al., "A methodology to determine the seismic low-cycle fatigue strength of timber connections," *Constr. Build. Mater.*, vol. 231, 2020, doi: 10.1016/j.conbuildmat.2019.117026.

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