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CYCLIC BEHAVIOR OF AN INNOVATIVE JOINT PROTOTYPE FOR CLT PANELS

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Abstract

CLT (Cross-Laminated Timber) panels represent one of the most used technologies for wooden structures. The design and the details of panel-to-panel connections represent an aspect of utmost importance to understand the overall behavior of timber structures subject to lateral loads, such as seismic loads. For these reasons, new solutions for connections have been -and continue to be- proposed in the last years.

In this framing of research, this paper proposes a new type of dissipative steel connection for timber structures. As an alternative to traditional solutions, such as hold-down and angle brackets, this connection is conceived to be easy to fabricate and to be installed, allowing, moreover, the use of a small number of connectors. Different joint-panel model combinations are presented, and numerical analyses are carried out to study the behavior of CLT panels equipped with the proposed connection under lateral load. The performed FEM analyses lead to the identification of two innovative optimized solutions of connections, recently patented by the authors, which will be prototyped in the next future.

Keywords: Cross-laminated timber, Wooden structures, Seismic behavior, Cyclic Analysis, Dissipative connection, Steel connection.

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1. INTRODUCTION

In recent years, X-LAM solid wooden panel technologies have been gaining increasing attention as a sustainable and low-impact solution for building construction. X-LAM is a construction system based on bi-dimensional panels made of solid cross laminated timber, which offers numerous advantages over traditional construction methods. Although relatively young, this technology has been already employed in many parts of the world to build multi-story residential and commercial buildings.

An X-LAM building is configured as a box structure made of vertical and horizontal panels with biaxial load-bearing performance. In the design process of X-LAM structures, connections between panels are crucial for the transmission of horizontal loads, as they have to ensure adequate load transfer between adjacent panels. Although many solutions are available to this purpose, however, the type of connection to use largely depends on the type of assemblies to be connected (i.e., panel-to-panel, floor-to-wall, etc.). Generally, they can be classified into traditional and innovative connections. The former group includes:

- hold-downs (HD): metal connections commonly placed at the corners of the panel to provide uplift resistance against the overturning moment of the wall under in-plane lateral loading (Figure 1).
- angle brackets (AB): metal connections typically located at the base of the panel to absorb in-plane shear loads and prevent sliding mechanisms (Figure 2).
- in-plane screwed joints: metal connectors used to connect each other adjacent panels and to take combined axial and lateral loads, preventing relative displacements.

Figure 1 Hold-downs (from[1])

Figure 2 Angle brackets (from[1])

Many studies about the behavior of traditional connections in CLT assemblies subjected to lateral loads are available in literature. Among these, it must be mentioned the study performed by Gavric et al. [3], who carried out both cyclic tensile tests on hold-downs and cyclic shear tests on angular brackets, stressing that all connections feature a cyclic behavior characterized by significant pinching phenomena. The experimental tests also revealed that both HDs and ABs own a significant deformation capacity, therefore a reasonable ductility, despite the low overall energy dissipation capacity.

Calderoni et al. [4] conducted a numerical study to investigate the role played by specific performance parameters of traditional connections, such as deformation and resistance capacity, in the seismic behavior of CLT structures They observed an increase in strength and ductility by considering larger strains for the metal components that work in tension (HD), as it allows the plastic hinge to develop in these elements. This facilitates easier replacement in case of damage. In the framing of the SOFIE project, Dujic et al [5], compared the results obtained from the shake table tests of a full-scale seven-story building made of X-LAM panels and traditional connections (HDs and ABs) with those obtained from numerical analyses in order to better investigate the seismic behavior and the influence of panels thickness and connectors arrangement.

On the other hand, innovative connections can be distinguished as follows:

- Point-to-point connections: dissipative connections designed to withstand simultaneously both shear and tensile stresses and typically installed in the peripheral areas of the panels. They require careful evaluations to determine the connection location. Examples include: (i) XL-stub, (ii) X-rad and (iii) X-bracket.
- Wall/core systems: systems made of several monolithic panels spanning the entire height of the building and designed to withstand all types of loads. Examples of these connections are: (i) PRES-LAM WALL/CORE and (ii) IPC – Integrated Panel Core.

The XL-stub connection is designed to take advantage of the dissipative characteristics of steel throughout its entire length. This is possible owing to the hourglass shape of the flange plate, which creates a weaker area that allows for plasticization and prevents failures in the flange-web link section and in the bolt area. A study by Latour et al. [6], who tested the XL-STUB connection through monotonic and cyclic load tests to verify its efficiency, showed that collapse occurred in the expected area and the hysteresis cycles revealed a hardening plastic trend without pinching effect.

The X-rad connection is designed for being installed at the corners of X-LAM panels and consists of three fundamental elements: an external enclosure combined with an internal steel plate, a seasoned wood core, and six fully threaded self-tapping screws. Polastri et al. [7] tested the shear-tension and shear-compression behavior of this type of connection through cyclic analyses. The hysteresis curves showed pinching, but, however, the connection featured good energy dissipation and ductility.

The X-bracket connection (Figure 3) is also designed for installation at the corners of X-LAM panels and features an X-shaped metallic profile screwed to timber panels that assures a spread plasticization of the material, thus preventing localized failures. Careful design is required for the anchorage to minimize the bearing effect in the wood-connector contact area. A study by Scotta et al. [2] evaluated the behavior of the X-bracket through laboratory tests of pure traction and pure shear cyclic load tests. The hysteresis curves showed an elastic-plastic behavior without pinching.

The Pres-Lam system [8] consists of coupled timber walls post-tensioned with steel tendons passing either externally or through internal ducts. To improve the dissipative behavior of such a system, Iqbal et al. [9] proposed a “hybrid” solution combining unbonded post-tensioned vertical tendons with U-shaped flexural plates (UFPs) inserted between panels. Energy dissipation occurs through metal yielding of the UFPs during rocking of the walls. The experimental investigation confirmed that the Pres-Lam system exhibits efficient energy dissipation.

The IPC (Integrated Panel Core) system is designed to resist forces through a central core constructed of integrated X-LAM panels running the full height of the building [10]. This system showcases several advantages, including: 1) integration of various X-LAM panels to create larger and stiffer components as compared to individual panels; 2) transfer of gravity loads parallel to the grain through proper positioning of vertical panels; 3) transfer of loads between panels through direct contact without the need of steel connectors.

This paper arises within the research framework outline above and intends to move a step forward towards the prototyping of enhanced dissipative steel connections for timber structures. The main purpose is to present an innovative connection technology that is easy to be installed and to be assembled, allowing to optimize time on site, as well as easy of fabrication, allowing for the use of local skilled labor, thereby providing a valid alternative to the most widely used connections such as hold-downs and angular brackets.

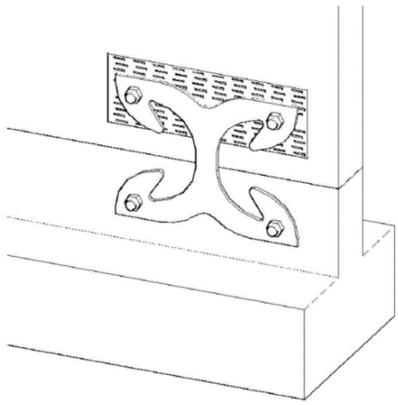

Figure 3 X-bracket (from [2])

In order to optimize the design of the proposed connection, many numerical analyses are conducted adopting different types of geometry, dimensions, and material for the connectors. In the present work, due to space constraints, only the two solutions meeting the criteria of capacity design (strong panel-weak connection) are described.

2. DESCRIPTION OF NEW JOINT PROTOTYPE

The proposed prototypes are composed of two different resisting systems, one designed to resist tensile forces and the other to resist shear forces (Figure 4). The system for tensile forces is the same for the two joint prototypes, whereas different solutions are adopted for the shear stress resisting system:

- Solution 1: system made of plates with simple curvature (Figure 5);
- Solution 2: system made of plates with double curvature (Figure 6).

The tensile connection is provided at the left and right sides of the panel and has been designed to resist only by contact with the panel, with no connector connecting it to the Cross Laminated Timber (CLT) panel. The connection is composed of a semi-circular shaped steel plate, housed in a space created inside the panel, and two steel bars inclined at 45° and placed outside to the panel, which connect the semi-circular plate to the intrados of the floor. The housing space created to insert the two semi-circular steel plates into the panel has a curvilinear shape at the bottom and a straight shape at the top, which allows for easy lifting of the panel an facilitates the positioning of the wall during installation.

Similarly, the connection designed to resist shear stresses is provided at the left and right edges of the panel, which is properly shaped in order to accommodate it. Like the tensile connection, this connection is conceived to resist only by direct contact without the need for additional connectors to the CLT panel. The connection consists of a plate with a straight base and a semi-circular section that has an interruption at about 2/3 of its development, thus providing greater flexibility to the connection and reducing stresses when it reaches plastic deformation. The straight section of the plate allows the connection to the floor through a steel bar.

3. NUMERICAL MODELLING AND ANALYSES

In order to study the behavior of the connection and its interaction with a X-LAM shear panel under horizontal forces, a FEM model was created, also to understand the different reaction of the components (plates, bars, nuts, panel), with the goal of proving if the assumed design criteria, concerning most of all the first component that have to yield, work well.

Figure 4 Example of CLT panel with tensile and shear connections

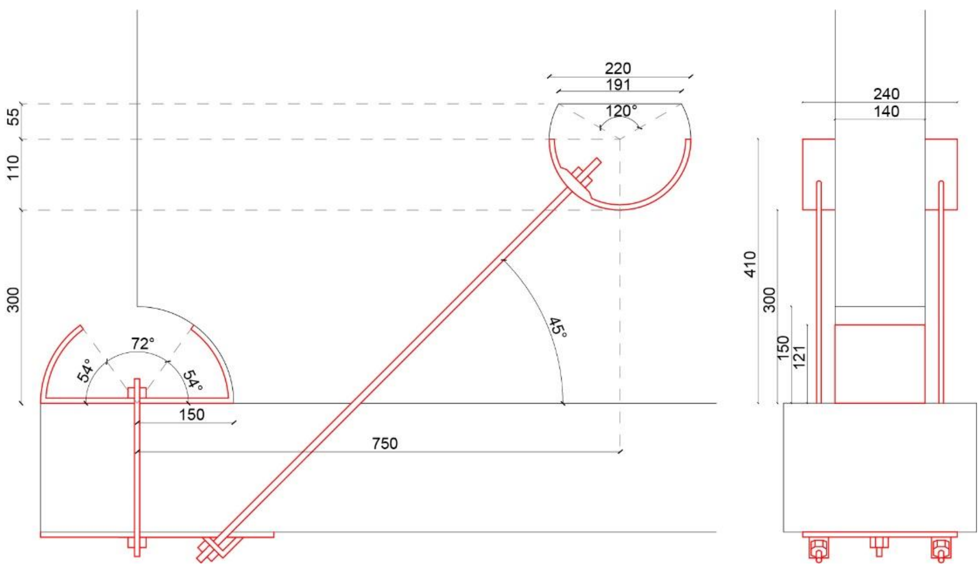

Figure 5 Prototype with simple curvature

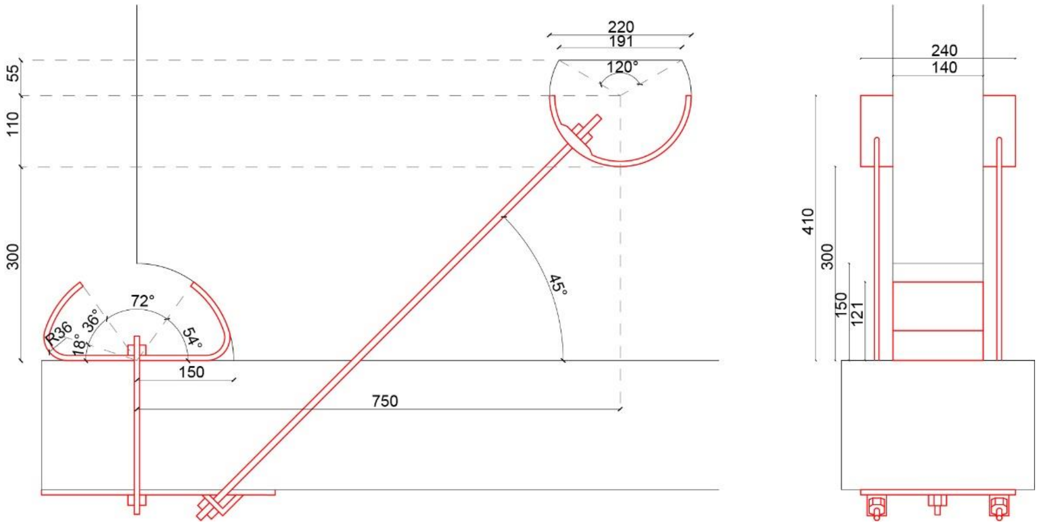

Figure 6 Prototype with double curvature

The proposed joint prototypes were modelled through the ABAQUS [11]software and analyzed. To this end, a floor-to-wall system was created assuming the following hypotheses:

- Infinitely rigid floor slab, fixed at the base.
- Infinitely rigid ceiling slab subjected to horizontal and vertical translations and rotation about the center of mass.
- Connection between CLT panel and floor slab: a constrain is adopted that allows the transfer of force and displacement between two parts in contact.

The CLT panel was created by replicating the geometric dimensions (B, H) of the wall tested in the SOFIE project (Ceccotti el at. [1]), which was 2950 mm wide and 2950 mm high with a thickness of 140 mm. The panel is composed of three layers, the outer ones with fibers arranged longitudinally and the intermediate layer with fibers in the transverse direction.

The model was created and meshed with different type of elements corresponding to different type of material described (Figure 7).

The wall modeling in the calculation software was carried out using continuum SC8R shell elements (8-node quadrilateral in-plane general-purpose continuum shell, reduced integration with hourglass control, finite membrane strains). The type of wood adopted is a homogeneous glued laminated timber with strength class GL24h (Table 1), described as elastic using the Tsai-Wu failure criterion (Figure 8) for orthotropic materials which have different strengths in tension and compression.

The steel connection elements were modelled through solid 3D elements of the C3D8R type (8-node linear brick, reduced integration, hourglass control). The material was described using a bi-linear hardening curve (Figure 9). Different types of steel were used for the various components of the connection: class 3.6 elements for the nuts, B450C steel for the cylindrical bars and S235 steel for the plates.

The CLT system was subjected to both vertical and lateral loads. To limit instability phenomena of the bars, a preload $F_{p,Cd}$ was applied.

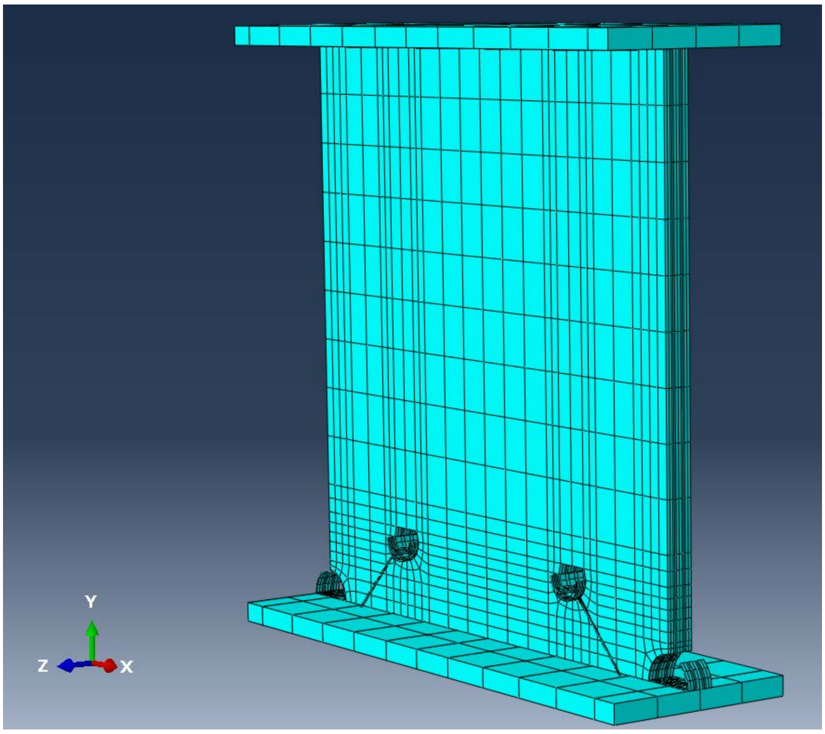

Figure 7 Model meshed

GL24h				
σ_{t0} (MPa)	σ_{c0} (MPa)	σ_{t90} (MPa)	σ_{c90} (MPa)	τ_{90} (MPa)
14	-21	0.4	-2.5	4

Table 1 Material properties

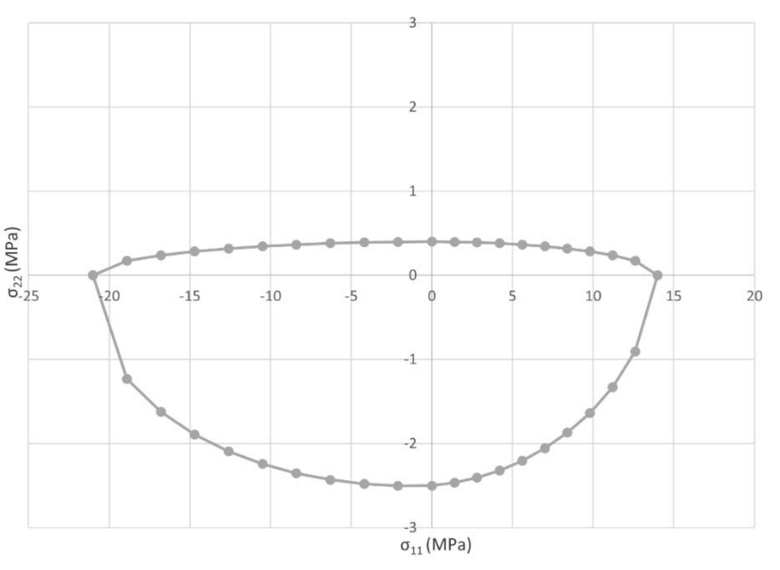

Figure 8 Tsai-Wu failure criterion

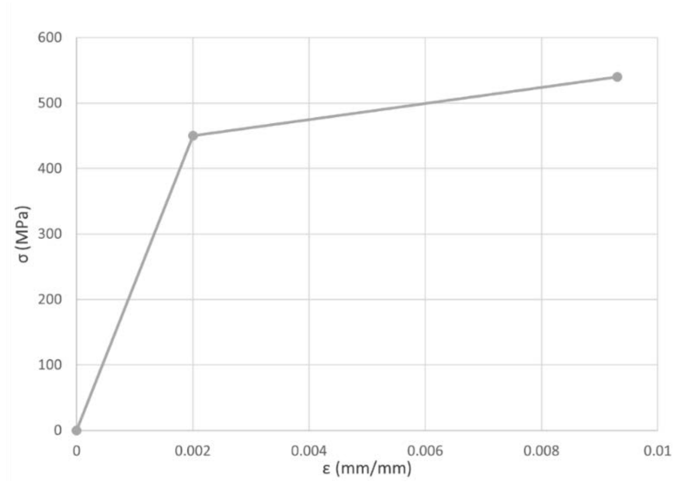

Figure 9 Steel inelastic behavior (B450C)

This value was calculated using the expressions of the Italian building code, based on the connector diameter and the ultimate strength of the material. As such, the preload was computed as reported in eq. (1)

$$F_{p,Cd} = \frac{0.7 f_{tbk} A_{res}}{\gamma_{M7}} \tag{1}$$

To properly evaluate the behavior of CLT panels under cyclic loading, the ECCS 85 loading protocol [12] was used as a reference. The protocol recommends to impose the following cyclic history depending on an esteem of the lateral displacement at the yielding attainment u_y:

- A symmetric displacement cycle for each displacement equal to $0.25u_y$, $0.50u_y$, $0.75u_y$ and $1.00\ u_y$.
- Three displacement cycles equal to $2.00u_y$, $4.00u_y$, $6.00\ u_y$.

In this study, in order to reduce the computational effort, the applied loading protocol differs from the reference protocol and includes:

- One cycle of symmetric displacement equal to $1.00\ u_y$.
- ¼ cycle of displacement at u_y .

As for the single curvature model shown (detail in Figure 5), a stiff behavior with a re-centering mechanism and low ductility was observed (Figure 10). The connection allowed the panel to automatically reposition itself to the initial configuration after the seismic event, thanks to the imposed gravitational loads. During the input application, energy dissipation occurred through rocking. The behavior of the connection system throughout the cyclic loading, expressed in terms of base shear versus top displacement, is shown in Figure 10. It is observed that the system maintains its full capacity during the cycle and a low energy dissipation.

Conversely, the analysis of the double curvature connection (detail of Figure 6) showed the occurrence of both rocking and sliding phenomena. The latter can be explained by the presence of a gap between the wall and the shear-resisting connection. This gap causes a delay in the plasticization of the panel near the shear connection, also leading to sliding, which resulted in a loss of self-centering capacity, but in supplemental damping (Figure 11). It is observed that the system maintains a shear capacity similar to the configuration with single curvature but had a better capacity to dissipate energy.

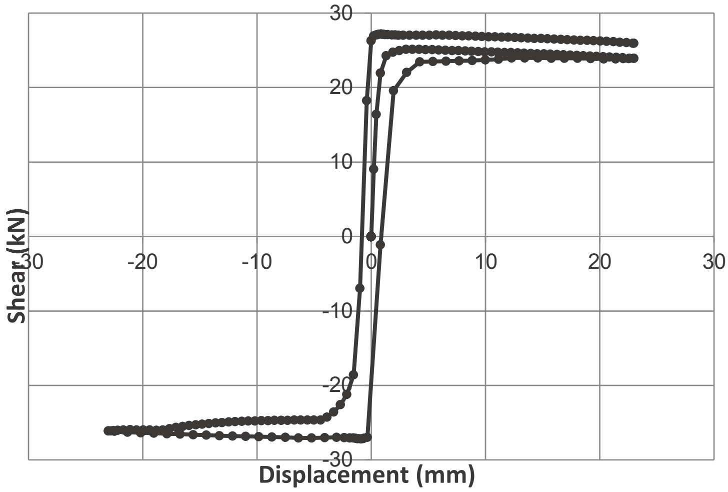

Figure 10 Cycle behavior of single curvature model, base shear and displacement at the top

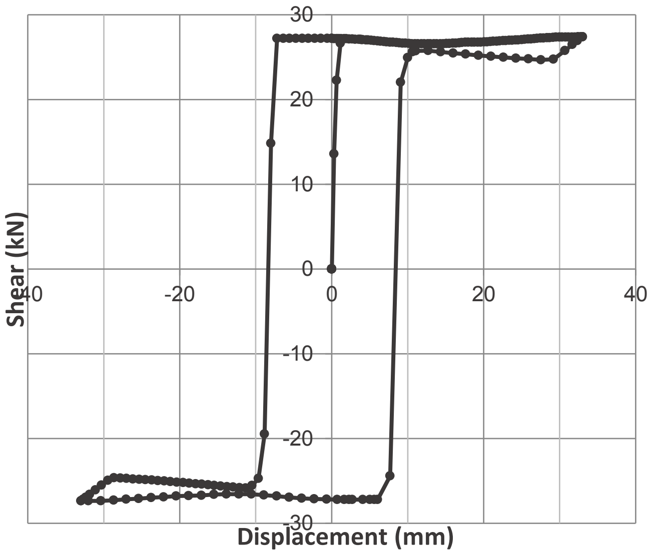

Figure 11 Cyclic behavior of double curvature model, base shear and displacement at the top

4. CONCLUSION

The study carried out in this paper led to the definition of two innovative types of steel connections for X-Lam wooden panels. The connections work for tension and shear, taking advantages from the following characteristics:

- Loads are transmitted exclusively by contact, thus avoiding the problem of material bearing.
- Connections are attached to the floor using only threaded bars and steel fixing bolts, simplifying the installation process and reducing the construction time.

The two modeled connection types, in the “single curvature” and the “double curvature” configurations, showed different behaviors both in terms of ductility and developed kinematics but a similar shear capacity.

The natural empirical continuation of the modeling activity involves a significant campaign of experimental investigations aimed at validating the results obtained from numerical analyses.

5. ACKNOWLEDGEMENTS

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