HIGH PERFORMANCE CONNECTIONS TO MITIGATE SEISMIC DAMAGE IN CROSS LAMINATED TIMBER (CLT) STRUCTURES

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Abstract

The present study proposes a new connection system for Cross Laminated Timber (CLT) structures in earthquake prone areas. The system is suitable for creating wall-floor-wall and wall-foundation connections, where each connection device can transfer both shear and tension forces, thus replacing the role of traditional “hold downs” and “angle brackets”, and eliminating possible uncertainty on the load paths and on the force-transfer mechanism. For design earthquakes intensity, the proposed system is designed to remain elastic without accessing the inelastic resources, avoiding in this way permanent deformations in both structural and non-structural elements. However, in case of unforeseen events of exceptional intensity, the system exhibits a pseudo-ductile behaviour, with significant deformation capacity. Furthermore, in the proposed system the vertical forces are directly transferred through the contact between wall panels, avoiding compressions orthogonal to the grain of the floor panels. In this research, the connection system was analysed via finite element modelling based on numerical strategies with different levels of refinements. Nonlinear analyses were performed in order to investigate the response of the connection to shear, tension and a combination of such forces. The numerical responses were compared with those of full-scale experimental tests performed on the proposed connection subjected to different kind of loading configuration. The results appear as promising, suggesting that the proposed connection system could represent a viable solution to build medium-rise seismic-resistant CLT structures, that minimise damage to structural and non-structural elements and the cost of repair.

Keywords: CLT structures; Timber connections; Seismic engineering; Finite-element modelling; Nonlinear analyses

1. Introduction

The increasing interest among researchers in developing new solutions for CLT structures in earthquake-prone areas, led to the development of innovative connections for timber buildings with high energy dissipation capacity [1]. In these structures, the combination of "hold downs" and "angle brackets" are one of the most popular connection systems. Simplified models allow to assign tension to "hold downs" and shear to "angle brackets" independently. However, these connectors can fail in presence of unexpected conditions, such as unforeseen load paths and force-transfer mechanisms [2]. A solution to this issue can be found in connectors designed to resist to both tension and shear. One example is the Titan V, an "angle bracket" with improved tension resistance which has been proposed by [3]. Other innovative connectors of this type are the X-rad [4] and the X-bracket [5]. The connectors mentioned before can reach high ductility factors for design earthquakes thanks to the fasteners [3], to the steel plate [5] or both [4]. However, relevant permanent deformations and, consequently, costs for repairing structural and non-structural elements must be considered in case of design earthquakes.

In this research, a novel connection system has been developed to support both tension and shear and to behave elastically for design earthquakes. Furthermore, ductility is still guaranteed for earthquakes of exceptional intensity thanks to the arrangement of the screws. Finite element (FE) models and experimental tests characterised the behaviour of the connector for three load directions: pure traction, shear and a combination of traction and shear. FE models were developed both at a very refined level through the software Abaqus and at a simplified level through the software SAP2000. The simplified model, calibrated through the refined one, has been developed in order to optimise the connection system with less computational effort. Firstly, the proposed connection system is defined along with its components and materials, and its possible applications in CLT structures. Then, the FE refined model and the simplified one are described defining the parameters and properties that lead the numerical analysis carried out. Finally, the experimental tests are introduced, and their results are compared to the numerical outputs.

2. Proposed connection system

In the present research, a novel high-performance connection system for CLT structures in earthquake-prone areas is proposed (Fig. 1a). Because this system is able to resist shear and tension forces by using a unique connection typology (Fig. 1b) it can replace the role of traditional "hold downs" and "angle brackets", eliminating potential uncertainty on the load paths and on the force-transfer mechanism.

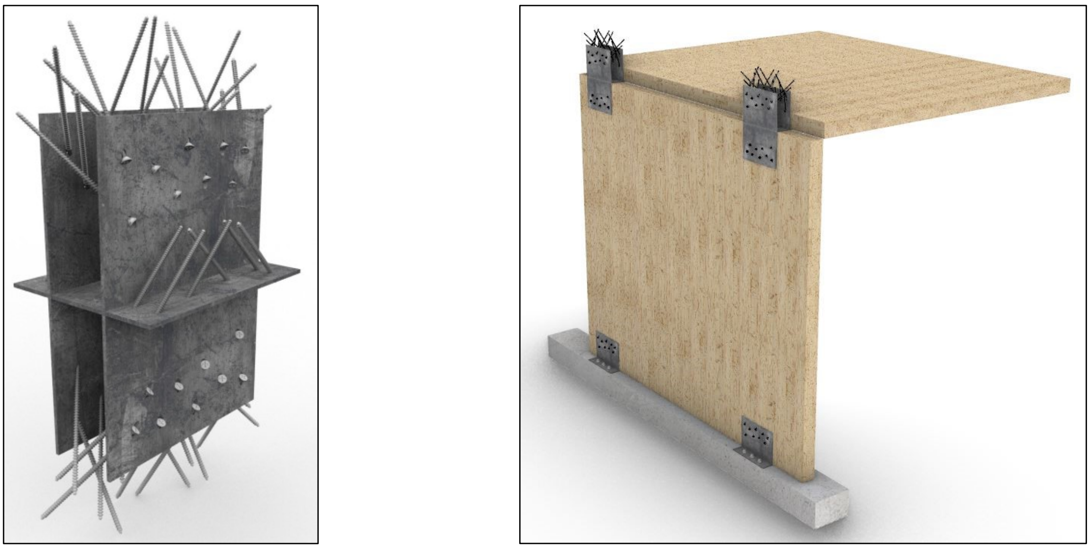

(a) (b)

Fig. 1 - Proposed connection system

This connector can be used to make three different structural connections: wall-wall (Fig. 2a), wall-floor-wall (Fig. 2b) and wall-foundation (Fig. 2c).

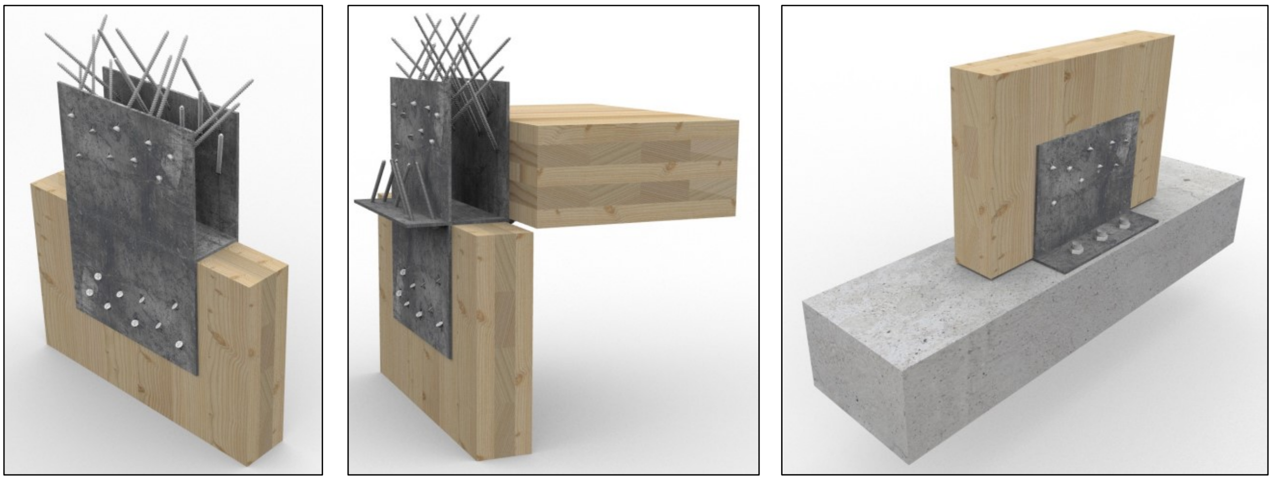

(a) (b) (c)

Fig. 2 - Structural connections

The proposed system consists in the union of steel plates which are connected to the panels by using screws and to the concrete foundation by using threaded bars and nuts. The plates are arranged symmetrically with respect to the middle plane of the panels in order to eliminate any parasitic moments due to eccentric loads. Additionally, the plates are designed to have an overstrength factor that prevents them from collapsing prior to the fasteners, thus avoiding sudden connection failures. Holes are drilled in the plates to allow for screw insertion. These holes have a countersink that increases the contact surface of the screw head.

The screws, which are fully threaded with a countersunk flat head (Fig. 3), are arranged at an angle of 30° with respect to the panel plane to engage their high withdrawal resistance.

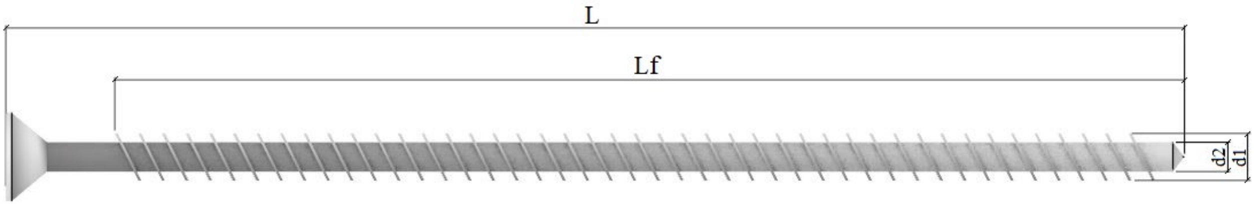


Fig. 3 – Fully threaded screw

Because the extraction mechanism is characterised by high resistance and stiffness, the proposed system results in higher capacity and smaller deformation compared to the most common connections used in CLT buildings, which are based on the shear resistance of the fasteners. The length and diameter of the screws depend on the size of the panel used and on the design actions. In the present study, 3-layered CLT panels (grade class C24 according to [6]) 100 mm thick have been considered. The mechanical properties and the density of the panels are reported in Table 1. The geometrical and mechanical properties of the screws, provided by the relevant European Technical Approval (ETA) [7], are reported in Table 2.

Table 1: Mechanical properties and density for the CLT panels

Bending	Tension		Compression		Shear	Elastic modulus	Shear modulus	Density
$f_{m,k}$ [MPa]	$f_{t,0,k}$ [MPa]	$f_{t,90,k}$ [MPa]	$f_{c,0,k}$ [MPa]	$f_{c,90,k}$ [MPa]	$f_{v,k}$ [MPa]	$E_{0,mean}$ [MPa]	$G_{0,mean}$ [MPa]	ρ_{mean} [kg/m^3]
24.00	14.50	0.40	21.00	2.50	4.00	11000	690	420

Table 2: Geometrical and mechanical properties for the screws

Yield moment	Yield strength	Elastic modulus	Dimensions			
$M_{y,k}$ [Nmm]	$f_{y,k}$ [MPa]	E_k [MPa]	L [mm]	Lf [mm]	d1 [mm]	d2 [mm]
23000	1000	210000	200	181	8	5

Due to the high values of elastic stiffness and resistance, the proposed connection system is a suitable option for the elastic design of buildings which requires limited displacements in case of earthquakes of design intensity. Because of the high strength of this connection, an optimised use of the timber material can be guaranteed. Commonly, in fact, because of the limited capacity of the dissipative connections used in CLT structures, the timber panels are subjected to relatively low work-rates. The connector presented in the present research involves, instead, an improved use of the material, a limitation in damage and a consequent reduction in restoration or replacement costs during the service life of the building.

Furthermore, in the proposed connector, the inclined screws are arranged in a “fan-shape” in order to support different load orientations. In case of unforeseen events of exceptional intensity, this arrangement results in a failure behaviour based on the progressive extraction of the fasteners, which leads to a pseudo-ductile overall response.

Referring to the wall-floor-wall connection (Fig. 2b) it is possible to notice that the upper-level wall does not transfer the vertical load to the floor (which is typical of the ordinary CLT buildings), but directly to the lower-level wall. In this way, it is possible to avoid detrimental compression perpendicular to the grain of the floor panels.

3. Refined finite element model

The proposed connection was studied via finite element (FE) modelling by performing nonlinear quasi-static analyses with the software Abaqus [8]. In order to increase the convergency rate in the presence of numerous contact surfaces Abaqus/Explicit analyses were adopted.

The FE model (Fig. 4) consists in the assembly of CLT panels, screws and steel plates. The three-dimensional geometric models of these elements were designed using AutoCAD [9] and imported as separate parts. The characteristics of the mesh were defined in accordance with the geometrical properties of the elements and with the modelling needs.

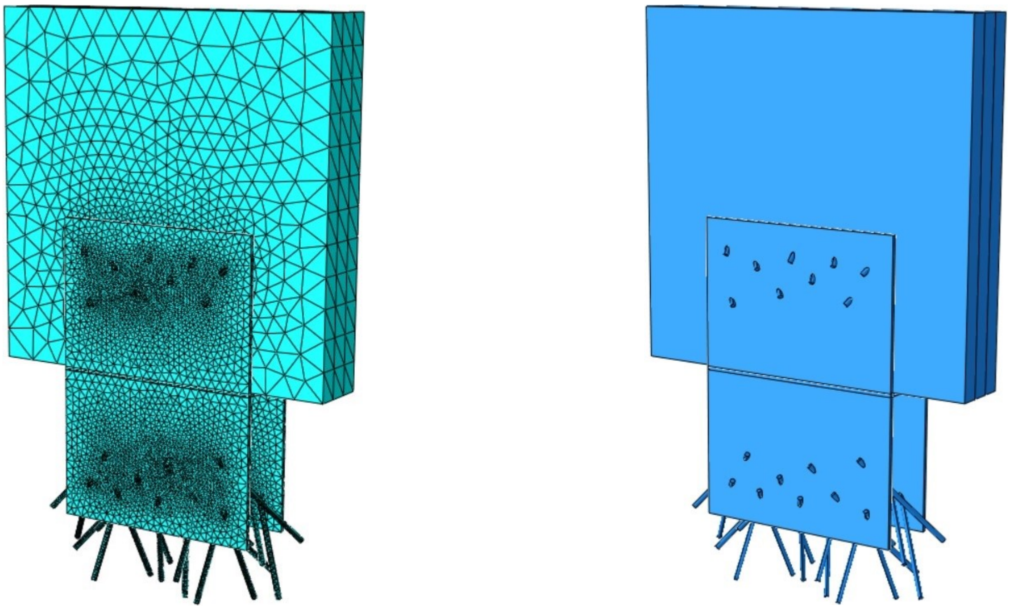

(a) (b)

Fig. 4– FE model (Abaqus)

The CLT panel was simulated by dividing the panel mesh-set (Fig. 4b) into three orthotropic layers with alternate orientations so as to reproduce the CLT layers. These layers present an elastoplastic behaviour which can take into account the damage to the material due to the interaction with the fasteners. In particular, the embedment strength was evaluated according to the provisions of [10] and it depends on the angle between the loading direction and the direction of the grain. Because of the complex geometry due to the presence of inclined holes, the panel was meshed using tetrahedral quadratic elements (C3D10) for a better definition of the contacts. By performing a sensitivity analysis, it was possible to minimise the number of elements without altering the quality of the results. The result of the mesh optimization, with a denser mesh in the region closer to the screws, is visible in Fig. 5a.

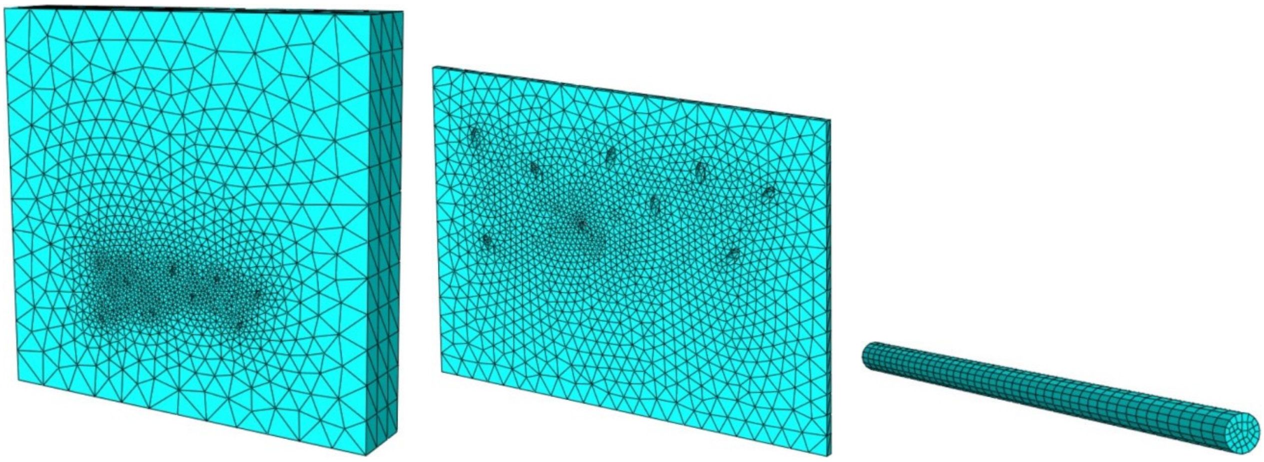

(a) (b) (c)

Fig. 5 – Components of the FE model: (a) CLT panel, (b) steel plate, (c) screw

The mechanical properties of the considered CLT panel are reported in Table 2. The subscripts "*L*", "*R*" and "*T*" refer respectively to the longitudinal, the radial and the tangential direction of the grain.

Table 2: Mechanical properties of the CLT panels

Elastic modulus [MPa]			**Shear modulus [MPa]**			**Poisson's ratios**		
E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}
11000	370	370	690	690	69	0.347	0.316	0.469

The steel plates were modeled by using an elastoplastic isotropic material. Due to the presence of the inclined holes, the mesh was defined using quadratic tetrahedral elements (C3D10). As for the panels, a sensitivity analysis led to a denser mesh near the holes (Fig. 5b).

The screws were modelled as cylindrical elements with a diameter equal to *d2* and an elastoplastic isotropic material. The extraction behaviour, which was defined considering [11] and [12], is regulated by the interaction between the external surface of the screws and the internal surface of the holes in the panel. This interaction was simulated by a "surface-to-surface" formulation based on the combination of a "normal" and a "tangential" behaviour. The normal behaviour was simulated by assigning a *Hard contact* between the master surfaces (screws) and the slave surfaces (CLT panel). This formulation prevents interpenetration between the elements. In particular, in order for the nodes of the slave surfaces not to penetrate the master nodes, the master surfaces must have a less dense mesh. The mesh of the screws was therefore obtained by using prismatic elements (C3D8) (Fig. 5c). The tangential behaviour was defined by assigning a *Cohesive contact*, which required the definition of a *Damage initiation* and a *Damage evolution*. The Damage initiation was defined with the "maximum nominal stress" criterion (MAXS):

$$\max\left\{\frac{t_n}{t_n^0}, \frac{t_s}{t_s^0}, \frac{t_t}{t_t^0}\right\} = 1$$

where t_n, t_s and t_t are the stresses associated respectively to the normal- and the two shear-directions, and t_n^0, t_s^0 and t_t^0 are the corresponding reference stresses. The Damage evolution was instead defined with the linear behaviour reported in Fig. 6.

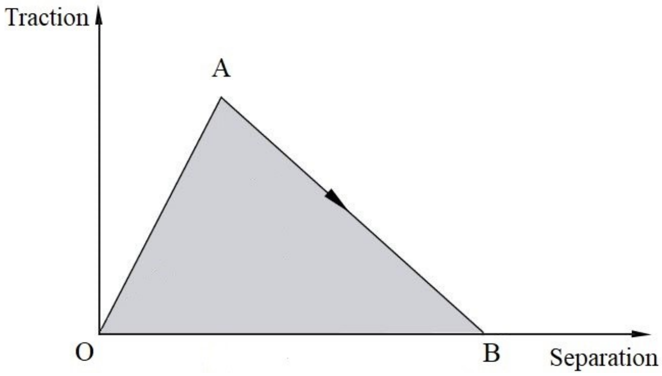


Fig. 6 – Cohesive contact: damage evolution

The parameters that characterize the contact were calibrated on evidence from literature [13] and on extraction tests of single fasteners carried out in the Materials and Structures Testing Laboratory (MSTL) of the University of Trento.

The connection between the screws and the steel plates was modelled by imposing a *Hard contact* behaviour and a tangential *Penalty* friction. Furthermore, the screws can both rotate and slide off the plates if subjected to compression.

4. Simplified finite element model

In order to reduce the duration of the analyses and permit a faster preliminary optimization of the connection system, a simplified bidimensional model was defined by using the software SAP2000 [14] (Fig. 7). The simplified model is expected to simulate adequately the overall behaviour of the proposed connection but not to provide detailed information on the stress level in the steel plates and in the screws.

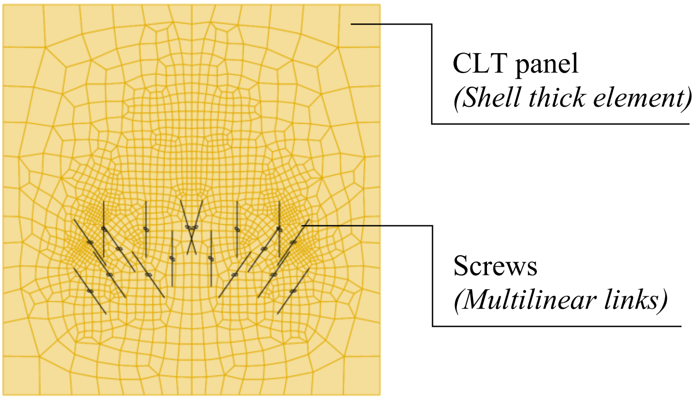


Fig. 7 – Simplified model (SAP2000)

In this model, the CLT panel was modelled using a *shell thick element* composed of a single orthotropic layer whose mechanical properties simulate the average characteristics of the panel. The screws were represented by using *link elements* with a multilinear behaviour. In particular, in the axial direction these links simulate both the extraction of the fastener and its shear response (Fig. 8a). In the in-plan directions instead, only the shear behaviour is simulated (Fig. 8b). The behaviour of these links was defined considering the tests made at the MSTL of the University of Trento and the provisions of [10].

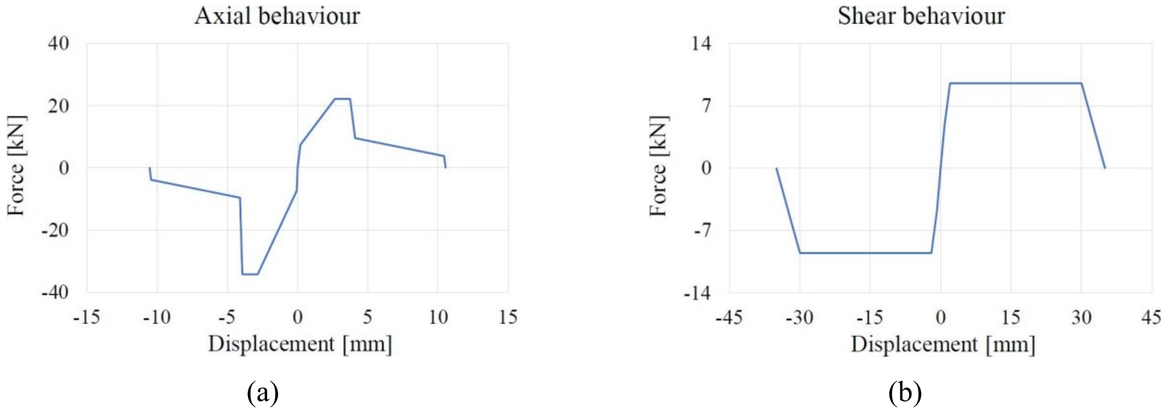


Fig. 8 – Simplified model: multilinear behaviours of the link

All the link nodes at the locations where the screw heads are supposed to be, are connected to one another through a rigid constraint that simulates the presence of the steel plates.

5. Numerical and experimental analyses

The proposed connection was studied considering three principal direction of loading: pure tension (Fig. 9a), pure shear (Fig. 9b) and tension inclined at 45° (Fig. 9c). These principal directions, from here on will be referred to as T0, V and T45 respectively.

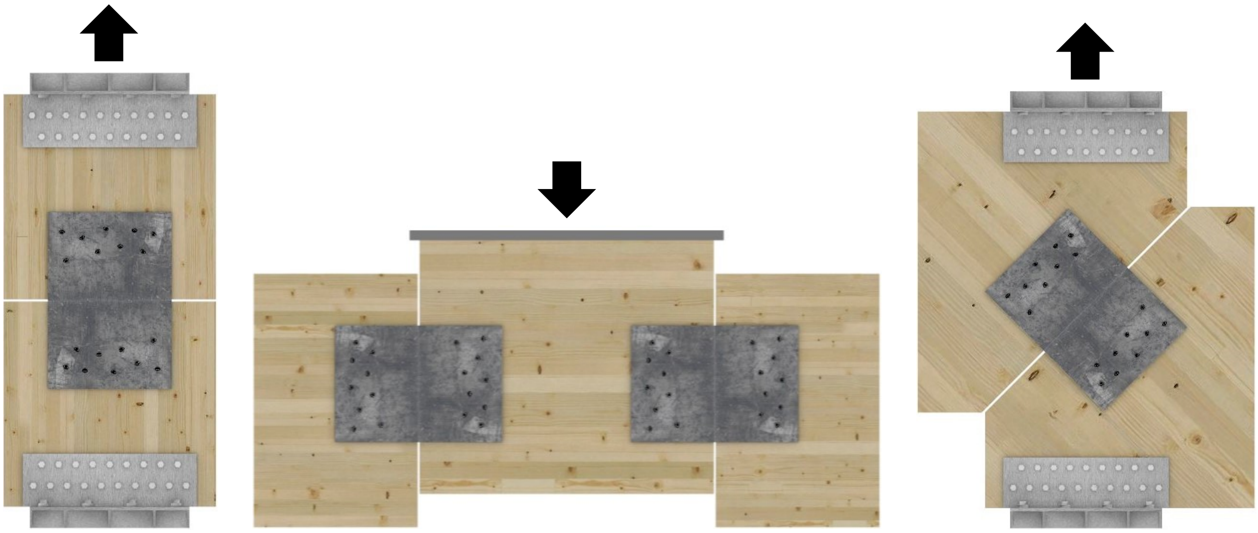

(a) (b) (c)

Fig. 9 – Considered directions of load: pure traction T0 (a), shear V (b) and traction inclined by 45° T45 (c)

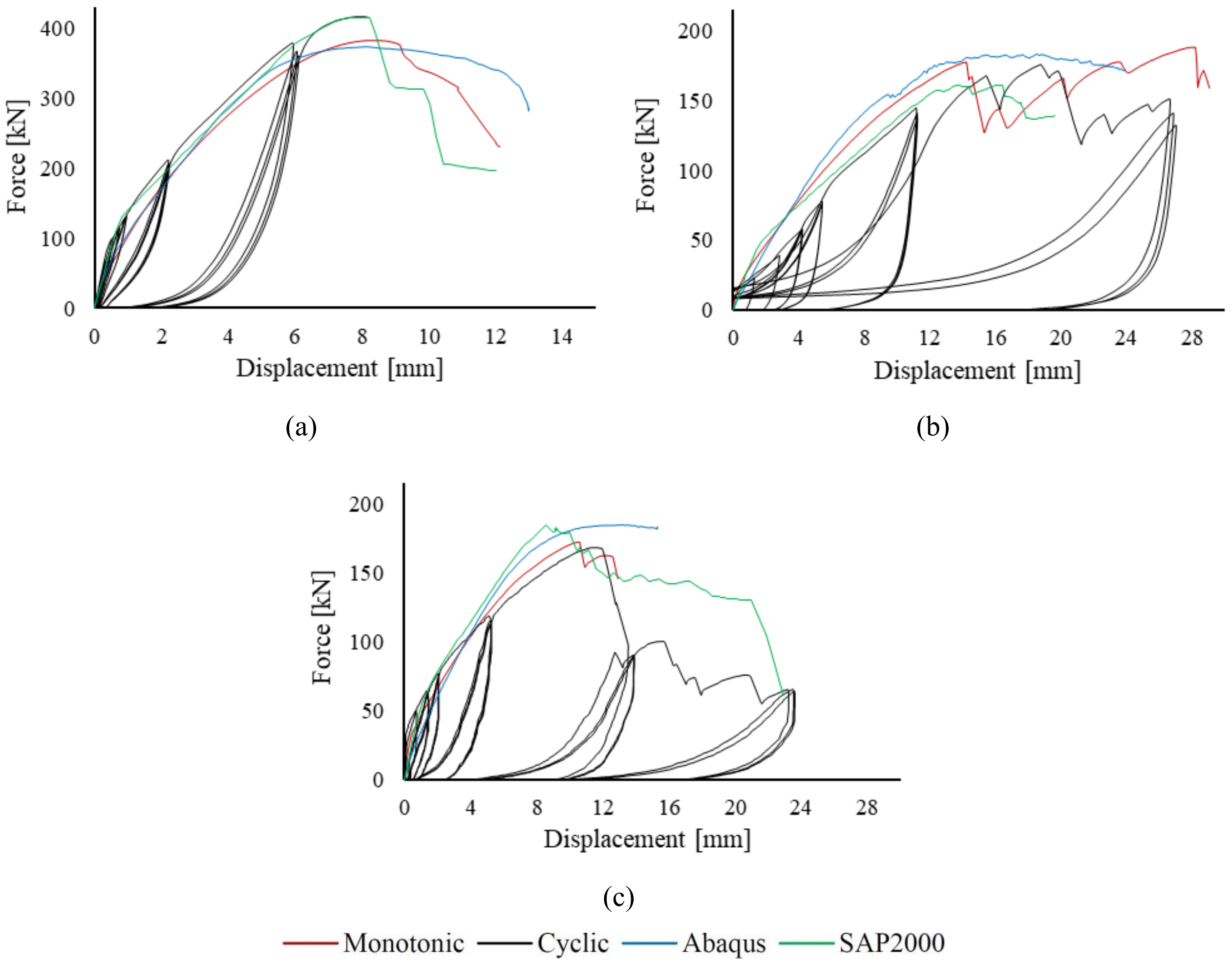
Each configuration was analysed both via FE modelling (using the refined Abaqus model and the simplified SAP2000 model) and via displacement-controlled experimental testing (performed at the MSTL laboratory of the University of Trento). The experimental tests comprised monotonic and cyclic loading procedures (in accordance with [15]) that were applied using the setup reported in Fig. 10. In the T0 and V experimental tests the hydraulic actuator was fixed to the frame, while in the T45 tests, in order to limit the shear and bending forces acting on the actuator stem, the actuator was connected to the steel frame using two hinges.

Fig. 10 – T45 experimental setup

The numerical models were designed considering the geometries, load applications and external restraints as per the experimental tests. To simplify the numerical models and reduce the computational effort, the problem symmetry was exploited by imposing appropriate restraint conditions.

In the refined Abaqus model, in order to obtain results comparable with those of the experimental tests, dynamic quasi-static analyses were performed. To reduce the dynamic effects due to the application of the load, the incremental force was applied with the command *Smooth*. In addition, the "Mass Scaling Factor" (MSF) was used to reduce the duration of the analyses. The value of this coefficient was defined based on sensitivity analyses aimed at guaranteeing adequate precision in the results. Verification of the quality of the analyses was performed by checking that the contribution of the kinetic energy to the total energy was small. This procedure, which leads to shorter analysis durations while guaranteeing reliable results, is recommended by the software manual and has been adopted by [16] and [17].

The results achieved from the numerical analyses and the experimental tests are reported in Fig. 11. In Fig. 11b, the shear capacity values obtained from the experimental tests were halved to consider the resistance of a single connection.



(a)

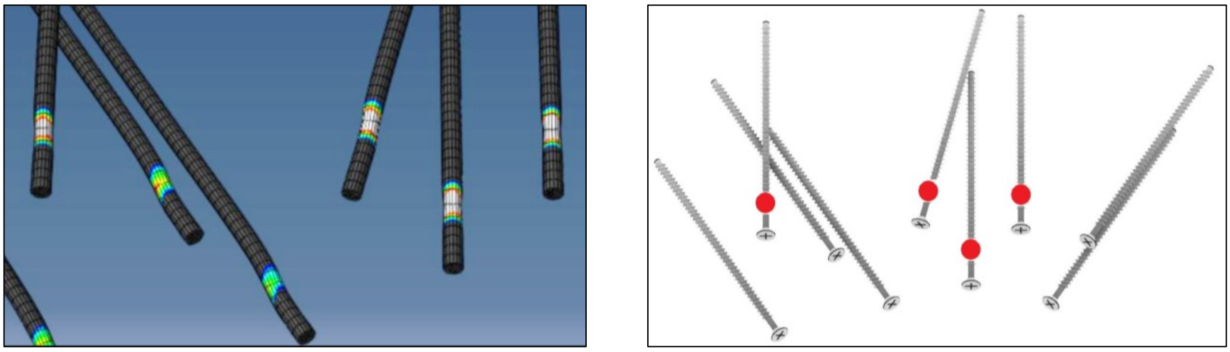
(b)

(c)

Fig. 11 – Force-displacements curves for T0 (a), V (b) and T45 (c). Curves were obtained by performing the experimental monotonic and cyclic tests, and by analysing the refined Abaqus models and the simplified SAP2000 models.

Overall, the proposed connection system showed high resistence values and a pseudo-ductile behaviour due to the prgressive collapse of the fasteners. The system appears therefore to be suitable for elasic design of buildings, ensuring a reserve of ductility for earthquakes of exceptional intensity.

As it can be observed from Fig. 11, the Abaqus model and the simplified SAP2000 model can adequately represent the overall behaviour of the connection both in terms of initial stiffness and maximum capacity. Furthermore, through the Abaqus models it was possible to study the stress level on the elements, confirming that the most stressed screws were those oriented according to the load direction (Fig. 12a) due to the high stiffness of the withdrawal mechanism. These screws were also the first to fail in the experimental tests (Fig. 12b).



(a) (b)

Fig. 12 – Screws in the T0 test: (a) most stressed screws in the Abaqus model, (b) screws that failed first in the experimental tests.

The stepwise progressive reduction in load bearing capacity observed in the experimental results (Fig. 12) is not notable in the Abaqus models, where the screws gradually pulled out instead of breaking. In the experimental tests, in fact, some of the most stressed screws snapped near the head. This phenomenon was tentatively attributed to the confinement effect produced by the surrounding screws, which led to an increase in the withdrawal resistance compared to that expected from the tests on the isolated single fastener. In the experimental tests, the combination of this effect with stress concentration due to imperfect contact between the screw heads and the steel plate, resulted in some of the screws breaking rather than being pulled out. Although the Abaqus model did not capture the breaking of the screws, it permitted to locate the most stressed areas (Fig. 13). By virtue of these preliminary results, future developments of the study will aim at favouring the screw withdrawal at improving the screw-plate contacts.

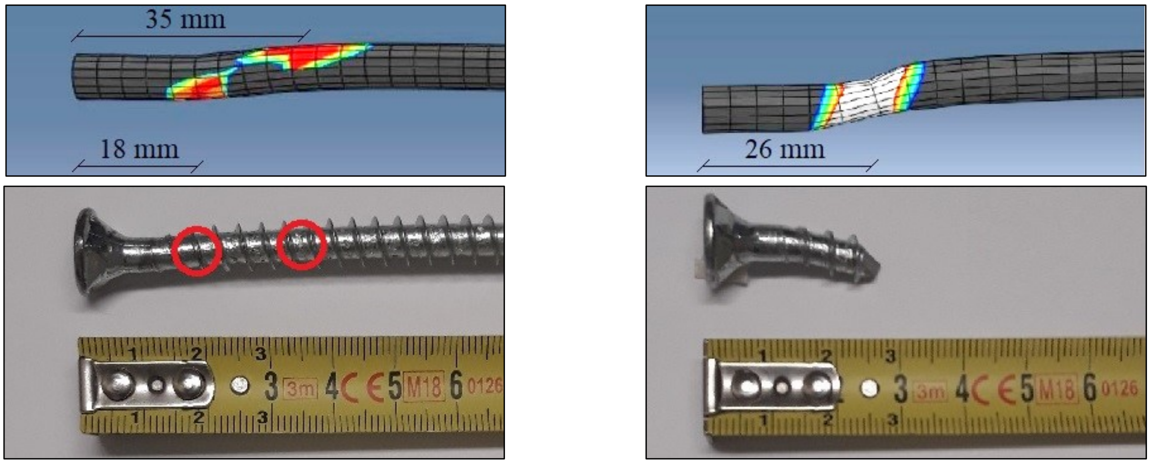


Fig. 13 – Solicitations on the screws – Comparison between the numerical and the experimental results

Both the refined and the simplified FE models adequately reproduced the behaviour of the connector observed in the experimental tests. Consequently, additional loading configurations were analysed via numerical modelling. Because the additional configurations were analysed solely via FE modelling, the effects of the hinges used in the experimental setup to avoid damaging the actuator stem, were not simulated (NH). The further tests performed included traction inclined by angles of 22,5° (T22,5-NH), 45° (T45-NH) and 67,5° (T67,5-NH). The results achieved are reported in Fig. 14. In order to make a comparison with the capacity of high-performance connection systems currently available on the market, the response of a commercial reference-connector capable of simultaneously resisting to both tension and shear is reported in the graph below. The capacities associated to this connector were extrapolated from the analysis results provided by [18].

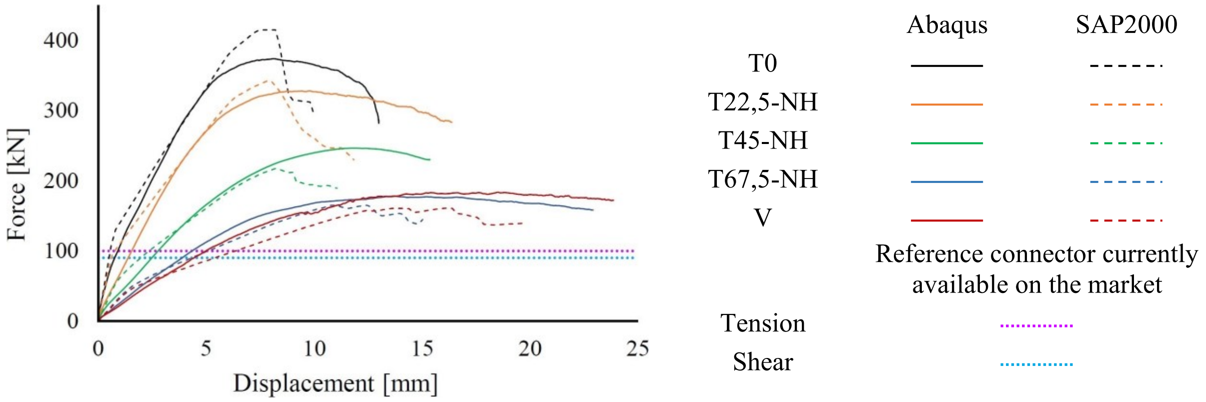


Fig. 14 – Force-Displacement curves related to the proposed connection system and to the reference connector.

Expectedly, both the refined and the simplified model showed that the smaller the loading angle (0° corresponds to pure tension), the higher the capacity of the connection system. The ductility of the connector, instead, increased with larger angles, reaching the maximum value in case of pure shear.

By comparing the capacity of the proposed connection system with that of the commercial reference-connector, it is possible to notice significantly higher values both in tension and shear. This outcome seems to confirm that the proposed system can represent a valid option in case of high resistance demand and could be used for the elastic design of buildings.

6. Conclusions

In the present research, a novel high-performance connection system for CLT buildings in earthquake-prone areas was proposed. Thanks to high stiffness and strength, the connector is intended to be compatible with the elastic-design of buildings. In particular, the proposed system could replace the commonly used "hold-downs" and "angle brackets" with a unique solution, eliminating the uncertainty on the load paths. The connector can be used to create wall-wall, wall-floor-wall and wall-foundation connections. Furthermore, the vertical loads are transferred directly from the upper wall to the lower wall, thus eliminating possible issues resulting from compression perpendicular to the grain on the floor panels. The connection system was studied via FE modelling by using Abaqus and SAP2000. The first software was used to define a refined model that allowed to investigate the overall connection response and also the behavior of single components, while the second software was used to define a simplified model characterized by lower computational costs. The behaviour of the connection was investigated by performing nonlinear analyses considering three main loading directions. The results from the numerical analyses were compared with the results obtained from monotonic and cyclic experimental testing. The analyses evidenced that the proposed connection system can elastically resist large forces and, once the elastic field is exceeded, it manifests a pseudo-ductile behaviour. The experimental tests showed that some of the screws closely aligned with the loading direction broke instead of being pulled out, determining a more pronounced progressive reductions in the load bearing capacity. This phenomenon was attributed to a confinement-effect that increased the withdrawal resistance of the screws and to the concentration of stress near to the screw heads due to non-optimal contact. Future studies will build on such input and will focus on further improving the behaviour of the proposed connection.

7. Acknowledgements

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