Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 247-254

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

NUMERICAL SIMULATION OF THE COUPLED TENSION-SHEAR RESPONSE OF AN INNOVATIVE DISSIPATIVE CONNECTION FOR CLT BUILDINGS

Luca Marchi[1], Davide Trutalli[1], Roberto Scotta[1], and Luca Pozza[2]

[1] Department of Civil, Environmental and Architectural Engineering
University of Padova
Via Marzolo 9 - Padova, 35131, Italy
luca.marchi@dicea.unipd.it, davide.trutalli@dicea.unipd.it, roberto.scotta@dicea.unipd.it

[2] Department of Civil, Chemical, Environmental and Materials Engineering
University of Bologna
Viale Risorgimento 2 - Bologna, 40136, Italy
luca.pozza2@unibo.it

Keywords: CLT Structures, Timber Structures, Dissipative Connection, Tension-shear Response, Numerical Simulations, Seismic Engineering.

Abstract. *This work presents a numerical macro-element model able to simulate the dynamic response of an innovative ductile and highly dissipative bracket for assembling of cross-laminated timber structures. This bracket resists to both tensile and shear forces and has been conceived to realize all the seismic-resistant joints of the building with a unique type of connection able to maximize the seismic capacity of the entire structure. The main issue of these kinds of connection is the reliability of numerical models in reproducing the coupled tension-shear behaviour and dissipative capacity with reduced computational effort, so as to simulate the non-linear response of complex buildings. With this aim, a numerical macro-element model was developed within the finite-element framework OpenSees using an assembly of linear beams and plastic hinges capable of simulating the complete tension-shear strength domain of the connection. The macro-element model was calibrated referring to the results from quasi-static cyclic-loading tests of the connector performed in pure shear and pure tension. The coupled tension-shear behaviour of the macro-element model was then validated on the results from independent numerical simulations performed using detailed 3D models with solid finite elements, including material and geometric non-linearity. Obtained results demonstrate that the developed macro-element model is able to describe accurately the hysteretic behaviour of the bracket with a very low computational effort. Therefore, it can be conveniently adopted to simulate the seismic response of complex structures.*

© 2017 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5419.17364

1 INTRODUCTION

Cross-laminated timber (CLT) has become a widespread material to realize multi-storey buildings. This precast system combines multiple layers of timber boards to realize large massive timber panels, which are fastened together and to foundation to build rapidly also complex structures. The in-plane stiffness and strength of the panels together with the reduced weight of the material and the potential ductility of the joints make CLT a valuable technique in high-seismicity areas.

In the last decade, the seismic performance of CLT structures has been experimentally and numerically studied (e.g., [1]-[7]) and the results confirmed that the cyclic behaviour of metal connections has a key-role in the seismic behaviour of the building. The traditional seismic-resistant connections, known as angle brackets and hold-downs, are composed of punched and cold-formed thin steel plates fastened to the panel with nails or screws. These brackets were conceived to withstand purely shear or tensile loads respectively. Actually, they may be subjected to coupled shear-tensile loading conditions which, in some cases, might involve anticipated brittle failures [8]. Resistant domains in terms of forces to design such connections are available in technical data provided by the connection producers (i.e., European Technical Approval ETA). Moreover, experimental campaigns were recently performed to build the domains not only in terms of forces but also displacements [9]. Based on strength domains according to ETA or to experimental evidences, advanced numerical models have been developed to simulate the coupled shear-tension behaviour of these connections ([10], [11]) and to analyse the behaviour of entire buildings [12].

An innovative high-dissipative connection system (X-bracket [13]) has been recently developed with the aim of optimizing the seismic response of CLT structures in terms of dissipative and ductility capacities. This element works both in tension and shear allowing to use a unique type of connection to realize all the seismic-resistant joints of the building. Moreover, this device assures a well-defined mechanical response (i.e., strength, stiffness, yielding limit and failure condition) both in shear and tension and its coupled shear-tensile response and strength domain can be easily predictable with detailed finite-element models [14]. These characteristics make more reliable the application of the capacity design rules required by current seismic design codes [15], with obvious implication in a more reliable energy dissipation capacity of the building.

Starting from available experimental and numerical results, a macro-element model (MEM) of the X-bracket was developed within the finite-element framework OpenSees [16] with the aim of reducing the computational effort in the simulation of the response of entire shear walls and also complex structures. The MEM was calibrated referring to the results from quasi-static cyclic-loading tests, performed in pure shear and pure tension. Then, the coupled tension-shear behaviour was validated on the results from independent numerical simulations performed using a detailed 3D model with solid finite elements, including material and geometric non-linearity. Finally, simulations of cyclic-loading tests of CLT shear walls were performed obtaining a close agreement with experimental results.

2 OVERVIEW OF DESIGN AND TESTING OF THE X-BRACKET

The shape and dimensions of the X-bracket were obtained from parametric numerical analyses to optimize ductility and dissipative capacity both in shear and tension, guarantying at the same time sufficient strength and high elastic stiffness. A further condition of the parametric design was the possibility of realizing multiple brackets with a single laser cutting of a flat steel sheet, in order to minimize the production refuses and costs. Such parametric design resulted in the original "X" shape in Figure 1a: the lateral displacement capacity is mainly due to the plastic shear deformation of the web, whereas the axial displacement capacity is mainly due to the bending deformation of the four arms. The dimensions of the X-bracket can be scaled proportionally to obtain different strength and displacement levels. 70 different combinations of the geometrical parameters were considered with the aim to obtain displacement capacity not less than 30 mm, high ductility class according to EN1998 - Eurocode 8 [15] and resistance comparable to the traditional connectors for CLT buildings [17].

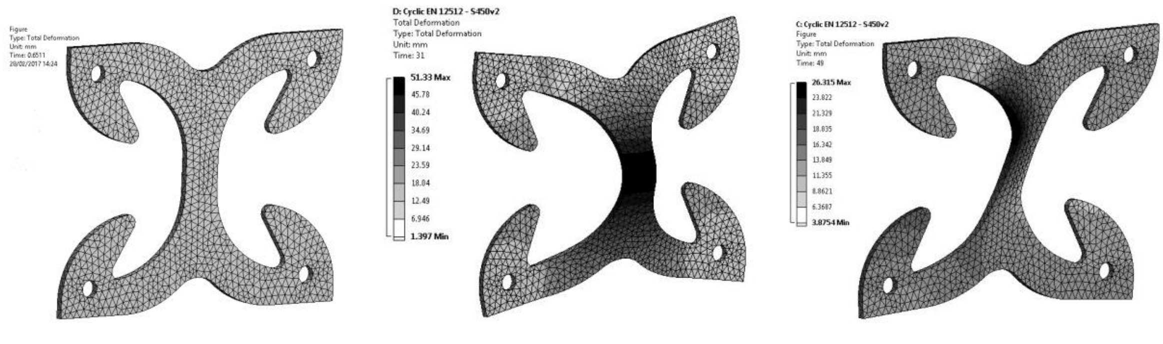
The X-brackets can be used as panel-to-foundation, panel-to-panel and floor-to-wall joints. To realize a rigid anchoring to the CLT panel, calibrated steel bolts can be used, interposing between the bracket and the panel a simple thin steel plate fastened with screws to CLT, so as to employ the embedment strength of steel and to comply with the capacity design. Such detail will be presented in a forthcoming work, to demonstrate its effectiveness.

Quasi-static cyclic-loading tests of the latest prototype were performed according to EN 12512 [18]. The same symmetric test setup presented in [13] was realized, anchoring a couple of X-brackets to a rigid steel frame. Three tests were performed in shear and three in tension, therefore, twelve brackets were tested. Obtained results show that the proposed connector is characterized by very high ductility due to high displacement capacity and high elastic stiffness. The combination of them confers to the building a rigid behaviour with low damage for low-intensity earthquakes, whereas the high displacement capacity and the plastic behaviour are exploitable by high-intensity seismic shocks.

3 NUMERICAL MODELS OF THE X-BRACKET

3.1 Detailed 3D model

The mechanical performances of the X-bracket subjected to monotonic, cyclic, coupled and uncoupled loading conditions were evaluated numerically with a 3D Finite-Element (FE) model implemented into ANSYS Workbench [19]. The X-bracket was modelled with *SOLID187 tetrahedral elements* in order to include non-linear geometrical analysis and to account for possible buckling phenomenon (Figure 1b-c). Minimum element size of 4mm was adjusted according to the curvature radius of the edges and to the zones characterized by high accumulation of plastic strains. Compression-only boundary conditions were added on one side to simulate the presence of the CLT panel.



(a) (b) (c)

Figure 1: (a) detailed model of the X-bracket; (b) out of plane buckling during tension unloading at high displacements; (c) out of plane buckling during shear loading.

To obtain an accurate reproduction of test results, the mechanical properties of a S450JR steel grade were implemented using a Ramberg-Osgood elastoplastic material model [20] based on results from tensile tests of the material used to realize the specimens. A kinematic hardening model was chosen to reproduce the hysteretic behaviour of the steel connector.

This model demonstrated to predict very accurately the experimental results; therefore, it was used to evaluate the coupled tension-shear behaviour of the X-bracket and the resulting domain in terms of strength and displacements. Finally, cyclic-loading tests of entire shear walls were simulated to have a direct comparison with the usage of traditional connections. It is worth noting that this model allows an optimal prediction of the actual mechanical behaviour of the X-bracket. However, the high computational effort demonstrated during the simulation of the shear-wall behaviour, makes this modelling strategy not particularly effective to simulate the response of entire buildings with time-history analyses and led to the need of developing a simplified but accurate MEM.

3.2 Macro-Element Model

A simplified numerical model was implemented in the research-oriented numerical code OpenSees [16] with the aim to perform dynamic analyses with low computational effort. It is therefore suitable to perform complex building models characterized by several non-linear elements, without neglecting the coupled shear-tensile response of all the brackets. The main idea was to simplify the X-bracket's shape with a MEM composed by few sub-elements with specific mechanical parameters according to the available material models in the OpenSees library. Figure 2 shows a superposition of the outline of the X-bracket and the 6-node MEM composed by a set of five *beam* elements connecting the two lower fixing points of the brackets, with the 2 upper ones. The beams are reciprocally connected with elastoplastic hinges. According to Figure 2, the conceptual model is composed by:

- six *nodes*: nodes 1 to 4 have the actual spacing of the X-bracket's fixing points; nodes 5 and 6 connect the vertical web to the horizontal arms;
- four elastic *beam elements* representing the X-bracket's arms, having a *plastic hinge element* at one end responsible for the inelastic response of the bracket subjected to shear and/or tension and calibrated through a moment/curvature relationship (red hinges in Figure 2);
- one vertical *beam element* representing the web of the X-bracket, which connects the four horizontal arms (flanges) and has a *plastic hinge element* at both ends, responsible for the inelastic response of the bracket subjected to shear and calibrated through a moment/curvature relationship (green hinges in Figure 2);

Beam elements and *plastic hinge elements* were modelled exploiting *beamWithHinges* elements [21], which consider plasticity to be concentrated over a specified length from the end nodes. A *Hysteretic material model* was applied to the hinges to simulate the actual hysteretic response of the X-bracket. As evidenced above, the X-bracket is characterized by a buckling phenomenon of the web during the unloading phase (Figure 1b) for high vertical displacements. This phenomenon results in a reduction of unloading stiffness when the web is compressed. A *column element,* working only in compression (element 12 of Figure 2), was therefore added between nodes 5 and 6 to simulate the secant stiffness acting in the unloading phase.

It is worth noting that the *plastic hinge elements* of the *beam elements* representing the X-bracket's arms (red hinges in Figure 2) work both when the bracket is subjected to shear and to tension. Therefore, such hinges allow the model to reproduce the actual shear/tensile coupled behaviour of the X-bracket, provided that an accurate calibration is made according to results from experimental tests and from simulations with the detailed 3D model.

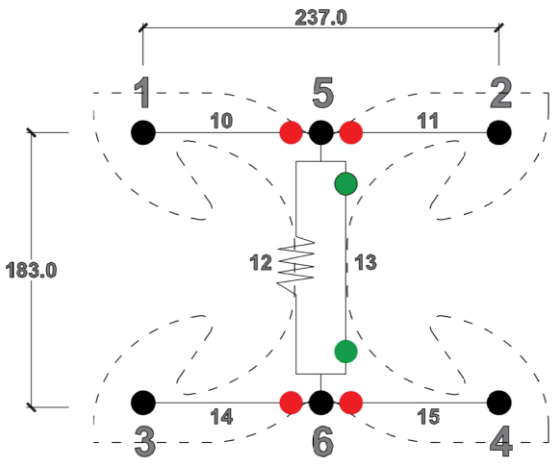


Figure 2: Macro-element model

4 NUMERICAL SIMULATIONS OF CLT SHEAR WALLS

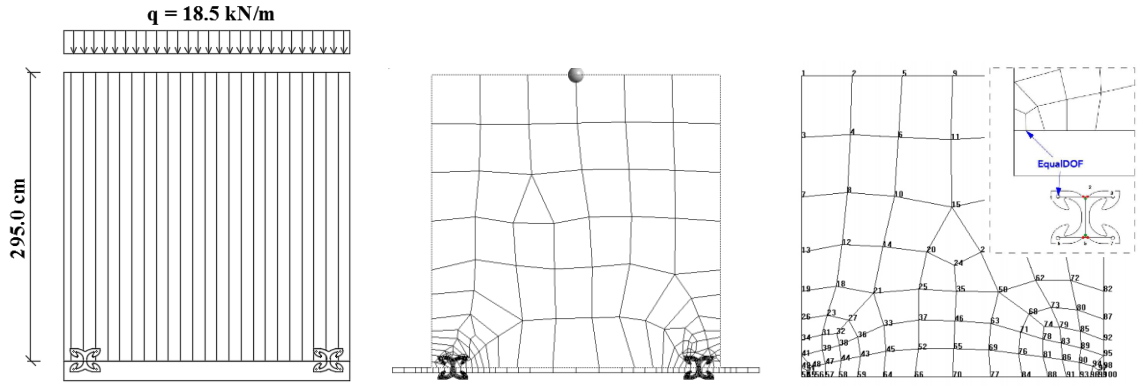
The shear-tensile interaction of the connections at the base of a CLT shear wall is strictly correlated to their number and position, to the panel aspect ratio (e.g., large panels have a predominant sliding behaviour whereas narrow panels have a predominant rocking behaviour) and to vertical loads. Numerical non-linear static analyses were conducted to simulate cyclic-loading tests of three shear walls, characterized by different aspect ratio and number and position of the X-brackets: a 85mm thick CLT panel with dimensions of 295 x 295mm anchored with one bracket at each corner (Wall A, Figure 3a); a CLT panel with same dimensions and an additional X-bracket placed in the middle (Wall B); a larger panel with dimensions of 590 x 295mm (aspect ratio equal to 2:1) with three equally spaced X-brackets (Wall C). The simulations were performed using both the detailed 3D model and the MEM. Displacement-driven cyclic-loading procedure according to EN 12512 [18] was followed applying a horizontal displacement to the top edge of the wall and assuming a yielding horizontal displacement $V_{y,est}$ equal to 10mm.

4.1 Detailed 3D model

The same detailed model of the X-bracket described in section 3.1 was employed in the analyses of the shear walls. The CLT panels were modelled into ANSYS Workbench [19] with 2D shell elements with an orthotropic material model. The minimum mesh size was about 10 times the connection mesh size (Figure 3b). Constraint equations were also adopted to simulate the cylindrical joint between panel and brackets at the fastening points, to allow the brackets' arms to rotate and dissipate energy. Frictionless *contact elements* were also added to simulate the foundation of the wall.

4.2 Simplified model

Simplified models of the three shear walls were implemented into OpenSees [16] using 4-node quadrilateral element (*ShellMITC4*) (Figure 3c). According to the detailed model, the mesh size was chosen to balance speed and accuracy with the same orthotropic material model properties. The concrete curb was modelled including *compression-only truss* elements fixed to the nodes of the panel base. Each bracket, modelled with the described MEM, was connected to the mesh of the wall by using *equalDOF* commands, resulting in a multi-point constraint among chosen nodes. In detail, nodes 1 and 2 of each bracket (Figure 2) were connected to two panel nodes at their actual position.

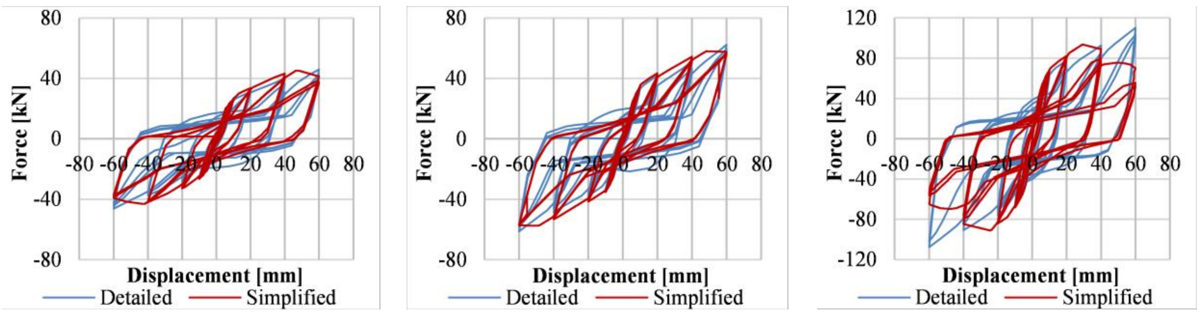


(a) (b) (c)

Figure 3: (a) Wall A geometry; (b) discretization of the detailed model; (c) discretization of the simplified model.

4.3 Results

The direct comparison between detailed and simplified model in terms of base shear force *vs.* top displacement curves for each wall in Figure 4 evidences clearly that there is a good agreement between the two modelling strategies. This evidence demonstrates that the developed MEM is adequate to simulate the seismic response of entire cross-laminated timber shear walls. The studied walls presented different failure mechanisms, and brackets were subjected to different ratios between shear and tensile forces. Nevertheless, the MEM has adapted very well to the different responses, demonstrating that it is able to take into account correctly the strength domain of the connection. The CPU time was reduced of more than one hundred times demonstrating the high computational effectiveness of the model and the possibility of extending the analyses to more complex structures.



(a) (b) (c)

Figure 4: Comparison between detailed and simplified models in terms of base shear force *vs.* top displacement curves. (a) Wall A; (b) Wall B; (c) Wall C.

5 CONCLUSIONS

In this work a simplified numerical model able to reproduce the non-linear coupled behaviour of a dissipative connection device optimized for CLT structures has been analysed and validated through experimental tests.

The detailed 3D numerical model, originally developed for the optimal design of the bracket, has been replaced with a more computationally efficient model in order to extend simulations to entire CLT shear walls and possibly complete structures. The simplified model makes use of elastic beam elements coupled with elastic-plastic hinges. It was calibrated through experimental pure shear and pure tensile cyclic tests. Then, the model has been used to simulate the seismic response of three CLT shear walls anchored to the foundation with the innovative connectors.

The results showed that the macro-element model is able to simulate elastic and post-elastic stiffness of the connector, as well as its complete hysteretic response and dissipative capacity even for high displacements. The reliability in simulating the coupled shear-tension response of the connector has been confirmed by the comparison between the detailed and the simplified model of the entire shear walls in terms of force-displacement results. These outcomes proved that the chosen strategy is suitable to extend the seismic analyses to entire CLT structures.

ACKNOWLEDGEMENTS

The authors acknowledge the contribution to the research given by Alessandro Basutto with the development of his master thesis.

REFERENCES

[1] A. Ceccotti, New technologies for construction of mediumrise buildings in seismic regions: the XLAM case. Structural Engineering International **18(2)**, 156–165, 2008.

[2] A. Ceccotti, C. Sandhaas, M. Okabe, M. Yasumura, C. Minowa, N. Kawai, SOFIE project–3D shaking table test on a seven-storey full-scale cross-laminated timber building. *Earthquake Engineering & Structural Dynamics,* **42**, 2003-2021, 2013.

[3] G. Flatscher, G. Schickhofer, Shaking-table test of a cross-laminated timber structure. *Proceedings of the ICE - Structures and Buildings,* **168(11)**, 878-888, 2015. DOI:10.1680/stbu.13.00086.

[4] M. Popovski, I. Gavric, Performance of a 2-story CLT house subjected to lateral loads. *ASCE Journal of Structural Engineering*. DOI:10.1061/(ASCE)ST.1943-541X.0001315.

[5] I. Gavric, M. Fragiacomo, A. Ceccotti, Cyclic behavior of cross-laminated timber (CLT) wall systems: Experimental tests and analytical prediction models. *ASCE Journal of Structural Engineering,* 2015. DOI: 10.1061/(ASCE)ST.1943-541X.0001246.

[6] S. Pei, J.W. Van de Lindt, M. Popovski, Approximate R-factor for cross-laminated timber walls in multistory buildings. *Journal of Architectural Engineering,* **19(4)**, 245–255, 2013.

[7] L. Pozza, D. Trutalli, An analytical formulation of q-factor for mid-rise CLT buildings based on parametric numerical analyses *Bulletin of Earthquake Engineering*, 2016. DOI: 10.1007/s10518-016-0047-9.

[8] I. Gavric, M. Fragiacomo, A. Ceccotti, Capacity seismic design of X-LAM wall systems based on connection mechanical properties. *Proceeding of Meeting 46 of the Working Commission W18-Timber Structures, CIB,* Vancouver, Canada, paper CIB-W18/46-15-2, 2013.

[9] L. Pozza, M. Massari, M. Savoia, B. Ferracuti, Experimental campaign of mechanical CLT connections subjected to a combination of shear and tension forces. *Structures and Architecture*, 110-118, 2016. DOI: 10.1201/b20891-13.

[10] G. Rinaldin, C. Amadio, and Fragiacomo M. A component approach for the hysteretic behaviour of connections in cross-laminated wooden structures. *Earthquake Engineering and Structural Dynamics*, **42**, 2023–2042, 2013.

[11] D. Talledo, L. Pozza, A. Saetta, M. Savoia, Coupled shear-tension numerical model for modelling of CLT connections. *In proceedings of the World Conference on Timber Engineering (WCTE)*, Wien, Austria, August 22-25, 2016.

[12] G. Rinaldin, M. Fragiacomo, Non-linear simulation of shaking-table tests on 3- and 7-storey X-Lam timber buildings. *Engineering Structures,* **113**, 133-148, 2016.

[13] R. Scotta, L. Marchi, D. Trutalli, and L. Pozza. A dissipative connector for CLT buildings: concept, design and testing. *Materials*, **9(3)**, 139, 2016. DOI:10.3390/ma9030139.

[14] L. Marchi, D. Trutalli, R. Scotta, L. Pozza, and A. Ceccotti. A new dissipative connection for CLT buildings. *Structures and Architecture,* 169-177, 2016. DOI: 10.1201/b20891-20.

[15] European Committee for Standardization (CEN), *EN 1998-1-1 Eurocode 8 - Design of structures for earthquake resistance, part 1: general rules, seismic actions and rules for buildings,* CEN, Brussels, 2013.

[16] F. McKenna, G.L. Fenves, M.H. Scott, B. Jeremic, Open System for Earthquake Engineering Simulation (OpenSees). Pacific Earthquake Engineering Research Center, University of California, Berkeley, 2000.

[17] I. Gavric, M. Fragiacomo, A. Ceccotti, Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures. *Materials and structures,* **48**, 1841-1857, 2015.

[18] European Committee for Standardization (CEN), *EN 12512 Timber Structures. Test Methods. Cyclic Testing of Joints Made with Mechanical Fasteners*. CEN, Brussels, 2006.

[19] ANSYS Mechanical Workbench; R14; ANSYS, Inc.: Canonsburg, PA, USA, 2012.

[20] W. Ramberg, W.R. Osgood, Description of stress-strain curves by three parameters. *National Advisory Committee for Aeronautics*, Washington, DC, United States, 1943.

[21] M.H. Scott, G.L. Fenves, Plastic Hinge Integration Methods for Force-Based Beam-Column Elements. *Journal of Structural Engineering,* **132(2)**, 244-252, 2006.