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Cyclic model of post-tensioned low damage timber walls with dissipative devices

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Abstract

Post-tensioned rocking dissipative timber wall systems born from the idea to obtain structural solutions able to guarantee, after a seismic event, a rapid re-use of the buildings without permanent damage, as well as to guarantee the safeguarding of human life. In this framework, the rocking of timber walls is entrusted to post-tensioned bars, placed in ad hoc cavities of the panel, while the dissipative contribution is provided by steel dampers, which are sacrificial elements subjected to damage easily replaceable after an intense seismic event. In this context, it can be helpful to have a numerical model in order to support the design phase; indeed, the paper presents a non-linear numerical model of post-tensioned rocking dissipative timber walls able to predict the response of this innovative system. In particular, geometrical and material non-linearities, due to the rocking behavior of the system and to the material that characterize the dampers, are taken explicitly into account. Further, the proposed numerical modelling strategy has been validated on literature experimental campaigns performed on both single and double wall systems, with different damper configurations. The comparison between experimental and numerical cyclic responses are shown in term of global results, i.e. force/displacement curves and post-tension variation of the bars. The comparison demonstrates the effectiveness of the proposed model in predicting the behavior of post-tensioned walls subjected to cyclic loads.

Keywords: Post-tensioned timber walls; Dissipative dampers; Rocking walls; Numerical modeling.

1. Introduction

Post-tensioned rocking dissipative timber wall systems born from the idea to obtain structural solutions able to guarantee, after a seismic event, a rapid re-use of the buildings without permanent damage, as well as to guarantee the safeguarding of human life. Low damage timber systems are composed by rocking dissipative timber walls, provided

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by steel dampers, designed to dissipate energy through their entering in the plastic fields and to be easily replaced at the end of a critical seismic event. The rocking behavior is entrusted to post-tensioned bars placed inside the panel, which are fixed at the base and anchored at the top of the wall. The hysterical steel dampers can work in a different way according to their positioning on the wall: they can be positioned near the base corners of the wall working predominantly in the axial direction – axial dampers – as firstly proposed by Christopoulos et al. (2002) or they can connect along elevation adjacent timber panels, working predominantly in the transversal direction - shear dampers – as firstly proposed by Kelly et al. (1972). The global force/displacement response of the post-tensioned low damage system results in a typical flag-shape behavior (Fig. 1), in which both the re-centering contribution of the post-tensioned (PT)-bars and the dissipative contribution of the dampers are evident; indeed, while the bilinear envelope is mainly due to the rocking behavior controlled by the PT- bars, the amplitude of the flag is mainly due by the dissipative contribution provided by the steel dampers.

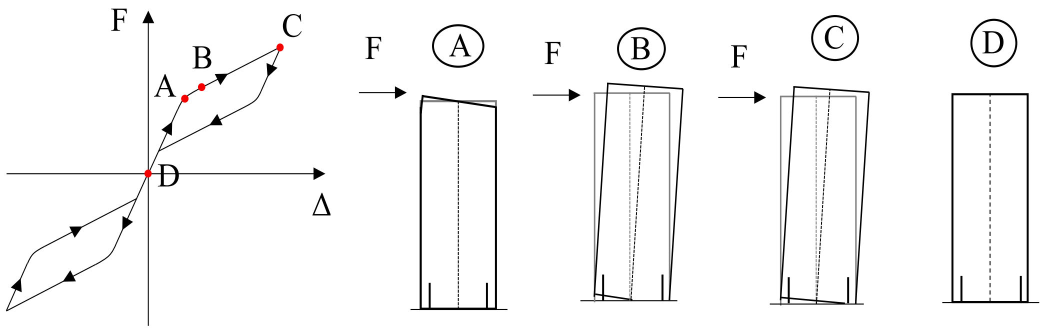


Fig. 1. Typical flag-shape force- top displacement (F-Δ) curve of a PT- system subjected to cycling loading

Actually, different experimental campaigns have been performed on post-tensioned wall systems, as proposed by Iqbal et al. (2015), Sarti et al. (2016), Massari et al. (2017), Chen et al. (2020), Pozza et al. (2021a), Pozza et al. (2021b), but also on whole buildings; in this context, Pei et al. (2019) have recently conducted an experimental campaign on a two-story frame building provided by post-tensioned rocking walls, which puts in evidence the resilience provided by the structural system after a series of shaking table tests. In the last years, some investigations on multi-story/ multi-panel solutions have been varied out: in this framework, Brown et al (2022) investigated double multi-story walls coupled with self-tapping screws able to increase the strength and stiffness of the system, and equipped with U-shape dampers connected to the lower corners wall and to a short flange channel; Polastri and Casagrande (2022) analyzed the performance of multi-panel cross laminated timber shear-walls with stiff connectors; Thiers-Moggia and Málaga-Chuquitaype (2021) examined multi-story rocking panels equipped with inerter devices, inserted in order to control the rotation amplitude of the system. Another recent contribution is, instead, dedicated to designing strategies based on optimization: Huang et al. (2022) proposed an optimization strategy for the displacement-based design of mass timber rocking walls, which pursue the objective of minimizing the weight of the structural components by varying the aspect ratio of the rocking panels, the diameter of the post-tensioned bars, the value of initial post-tension force, the thickness of the panel, and the initial stiffness and yielding deformation of dampers, while respecting constraint conditions on inter-story drifts admissible for different limit states. This recent contribution highlights the growing diffusion of post-tensioned wall systems, as well as the introduction of the main step for the design of post-tensioned timber buildings in the Australian and New Zealand design guidelines (STIC, 2013). The previous discussion suggests the importance in developing numerical models able to capture the experimental responses of PT-wall systems, as already highlighted by Wilson et al. (2019) and Tomei et al. (2021).
In this context, the paper presents a non-linear numerical model implemented in OpenSEES, an open-source software developed by McKenna and Scott (2010). The model is able to account for both geometrical and material non-linearities and it is validated on both single and double wall setups. The comparison between numerical and experimental results is proposed in terms of global responses, i.e., Force/Drift curves and Post-tension force/Drift curves.

2. Description of the literature experimental campaigns

The results of the experimental literature campaign performed by Chen et al. (2020) have been taken into account to validate the proposed numerical model, described in Table 1. In particular, both single and double wall setups have been taken into account, made of Cross Laminated Timber (CLT). The single wall setup is equipped with one post-tensioned bar disposed along elevation in the middle of the panel and by two couples of axial dampers disposed at the base. The double wall setups is characterized by two single walls each one equipped with a post-tensioned bar and two couples of axial dampers, connected between them by two U-shape shear dampers disposed along elevation.
Detailed information on geometrical and mechanical characteristics, and initial PT-force imposed to the post-tensioned bars for the two setups are schematically reported in Table 1, where: E_L and E_T indicate the elastic moduli of the timber, G_{LT} and G_{LR} are the shear moduli of the timber, with subscripts L, T, R that indicate longitudinal, transverse and radial directions, respectively; E_b is the elastic modulus of the steel composing the post-tensioned bars, PT-F_{in} is the initial imposed post-tensioned; $f_{y,A}$ and E_A are the yielding stress and the relevant elastic modulus of the axial damper, respectively; $f_{y,S}$ and E_S are the yielding stress and the relevant elastic modulus of the shear dampers, respectively.

Table 1. (a) Single wall setup; (b) double wall setup.

SINGLE WALL

Element	Material	Property	Value
Wall	LVL	E_L=E_T	6000 MPa
		G_{LT}=G_{LR}	348 MPa
PT-bar	Steel	E_b	205 GPa
		PT-F_{in}	89 kN
		Diameter	20 mm
Axial Damper	Mild Steel	$f_{y,A}$	300 MPa
		E_A	200 GPa

Chen et al. 2020

(a)

DOUBLE WALL

Element	Material	Property	Value
Wall	LVL	E_L=E_T	6000 MPa
		G_{LT}=G_{LR}	348 MPa
PT-bar	Steel	E_b	205 GPa
		PT-F_{in}	89 kN
		Diameter	20 mm
Axial Damper	Mild Steel	$f_{y,A}$	300 MPa
		E_A	200 GPa
Shear Damper	Mild Steel	$f_{y,S}$	340 MPa
		E_S	200 GPa

Chen et al. 2020

(b)

3. Numerical modeling

The proposed numerical models have been implemented in OpenSees, as a 2D model, which accounts for both geometrical and mechanical non-linearities. The geometrical non-linearity is related to the rocking behavior of the walls, while the mechanical one is due to the entering into the plastic field of axial and shear steel dampers, which have been simulated through non-linear springs able to reproduce their hysteretical response. The description of the numerical models is shown in Fig. 2 for the single wall (Fig. 2a) and double wall (Fig. 2b) setups. In particular, timber walls have been modeled as elastic 2D Quad elements characterized by an orthotropic material; the post-tensioned bars have been modeled with two node link elements, characterized by an elastoplastic force-displacement curve (Fig. 2), while the initial level of pretension provided at the beginning of each test is simulated by assigning an initial elastic deformation ε_{in}. These elements are fixed at the base and connected at the top to the relevant panel. Axial and shear dampers are modeled with non-linear springs that specifically take into account their hysteretical behavior under cyclic loading. The force-displacement law assigned to the non-linear springs has been calibrated on the experimental force-displacement response, as will be explained in section 3.1. Furthermore, the panels are constrained at the base by means of zero-length elements to which a no-tension material is associated, which is characterized by an infinite stiffness in compression in order to simulate a series of unilateral constraints (gap elements) that capture the rocking behavior of the system. Moreover, the shear transfer devices for the double wall setup have been modeled by imposing equal horizontal displacement (EqualDOF in OpenSEES) to the nodes of adjacent timber panels disposed at the interface between the timber element and the shear transfer device. Increasing cycling displacements have been imposed to both single and double wall setups at the top of the walls, according to the load history employed during the experimental campaign.

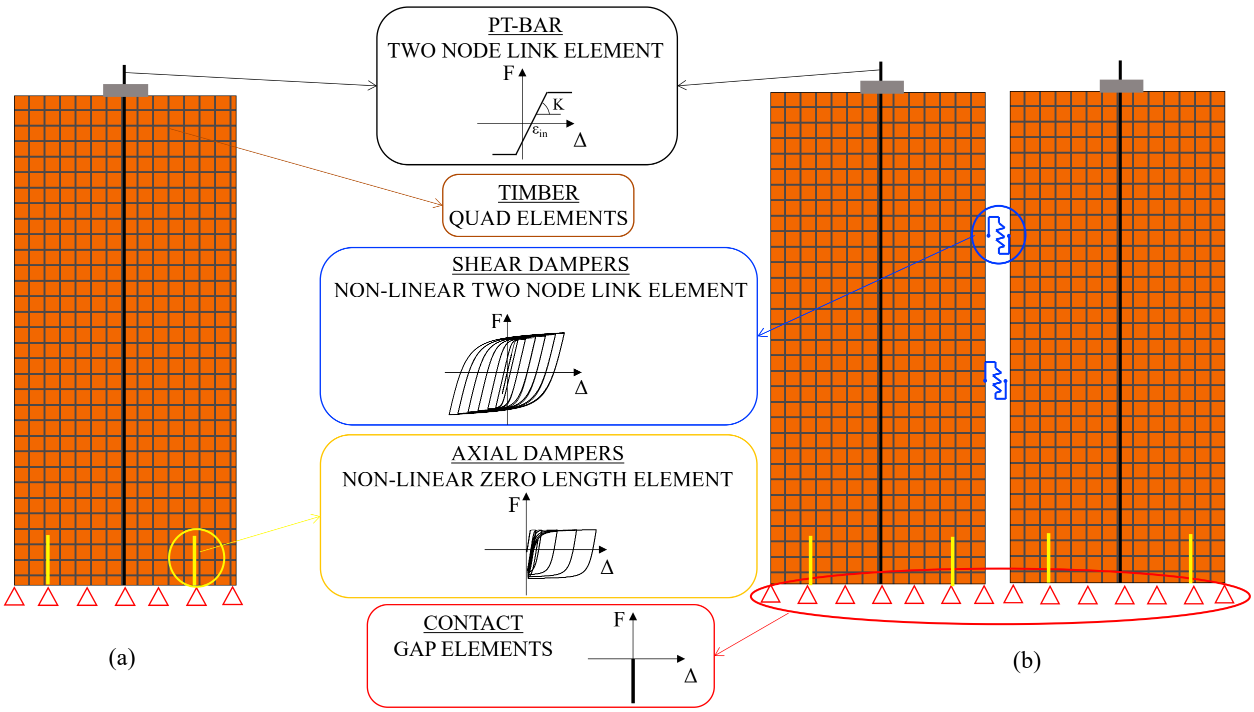
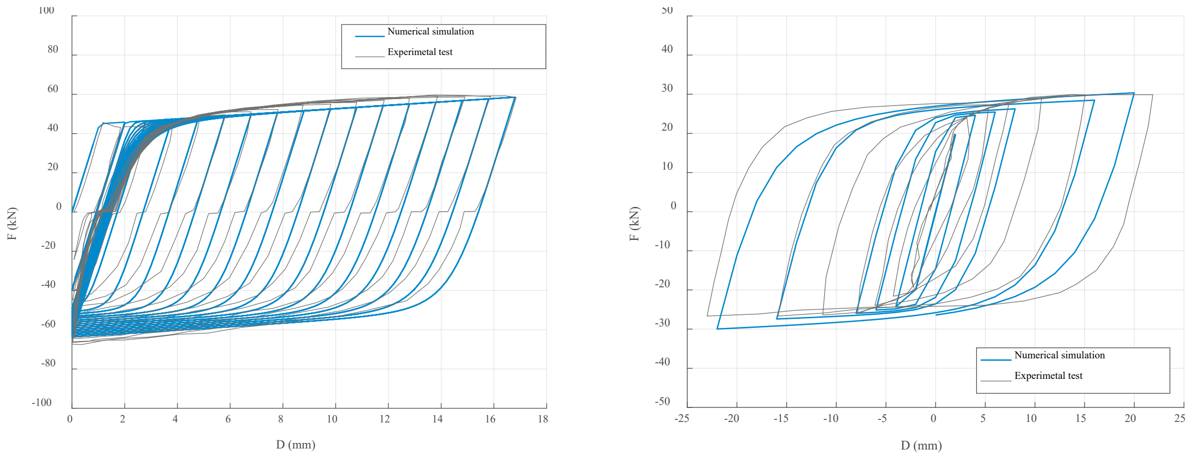


Fig. 2. Numerical model: (a) single wall setup; (b) double wall setup.

3.1 Calibration of hysteretic dampers

The hysteretic dampers have been simulated by springs, to which a non-linear law is associated. The non-linear force-displacement curves for both axial and shear dampers have been calibrated on the basis of shear and axial experimental tests performed on the single components (REF), by minimizing the differences in terms of strength and stiffness

between the experimental response and the numerical one. In particular, the adopted numerical law is the OpenSEES "Steel 02" one for both axial and shear dampers, i.e. the Giuffré-Menegotto-Pinto Model with Isotropic Strain Hardening described by Filippou et al. (1983).
The comparisons between the experimental cyclic behavior of dampers and the numerical responses are reported in terms of force-displacement curves in in Fig. 3a and b for axial and shear dampers, respectively.
The plots show a good agreement in terms of backbone curve, and so in terms of strength and stiffness, but also in terms of cyclic behavior. Some local differences can be found in the unloading branches of axial dampers (Fig. 3a), mainly due to some shifts in terms of displacement at zero-force in the experimental response and in the asymmetric experimental response of shear dampers in terms of forces (Fig. 3b).



(a) (b)

Fig. 3. Calibration of hysteretic dampers (a) axial damper; (b) shear damper.

4. Validation of the numerical model

Results in terms of Force/ Drift responses and Post-tension force/ Drift curves are reported in Fig. 4 for single wall setup (Fig. 4a and b), and double wall setup (Fig. 4c and d). Both the Force/ Drift curves show an almost bilinear trend, in which the transition point between the first branch and the second one corresponds to the drift to which the post-tensioned bar is subjected to an axial deformation and so to an increment of tension. The contribution of the hysteretic dampers is evident in the global cyclic response and is mainly responsible for energy dissipation, less than some frictional effects neglected in the numerical model. The response of the single wall setup is characterized by a Force/Drift curve (Fig. 4a) which provides values of drift different from zero at zero force due to the fact that the dissipation energy provided by the dampers is more pronounced than the recentring contribution provided by the post-tensioned bar, so the typical flag behavior is not so pronounced. For the same reason, the backbone curve slightly differs from the classic bilinear curve shown in Fig. 1, since the envelope curve is strongly affected by the contribution of dampers also in terms of strength. About Post-tension force/ Drift curves (Fig. 4b), it is evident an increment of post-tension force moving from the position of zero drift towards a drift larger than zero in absolute value, strictly related to the rocking behavior of the walls, which causes an elongation of the post-tensioned bars. By observing the post-tension forces at zero drift, it is evident the poor re-centering of the wall, since as the number of cycles increases, the post tension-force at zero drift also increases. This behavior is well-captured by the numerical model, also if some difference is present in terms of PT-force variation, which reaches the 20% for the maximum imposed drift of 2.5%. Similar considerations apply to double wall setups (Fig. 4c and d). In addition, focusing on the double wall setups, the numerical model overestimates the stiffness of the initial branch of the Force/Drift curve (Fig. 4c) but captures the stiffness of the second branch well. About Post-tensioned force/ Drift curves (Fig. 4d), only the numerical results are available, which show, by observing the single post-tensioned bar belonging to one of the two walls, an asymmetrical behaviour in terms of post-tension force variation for the positive and negative branch: this behavior is due to an incomplete transfer of uplifts between the connected sides of the panels, due to the presence of shear dampers. In any case, the behavior is the same for the two post-tensioned bars belonging to the two panels.

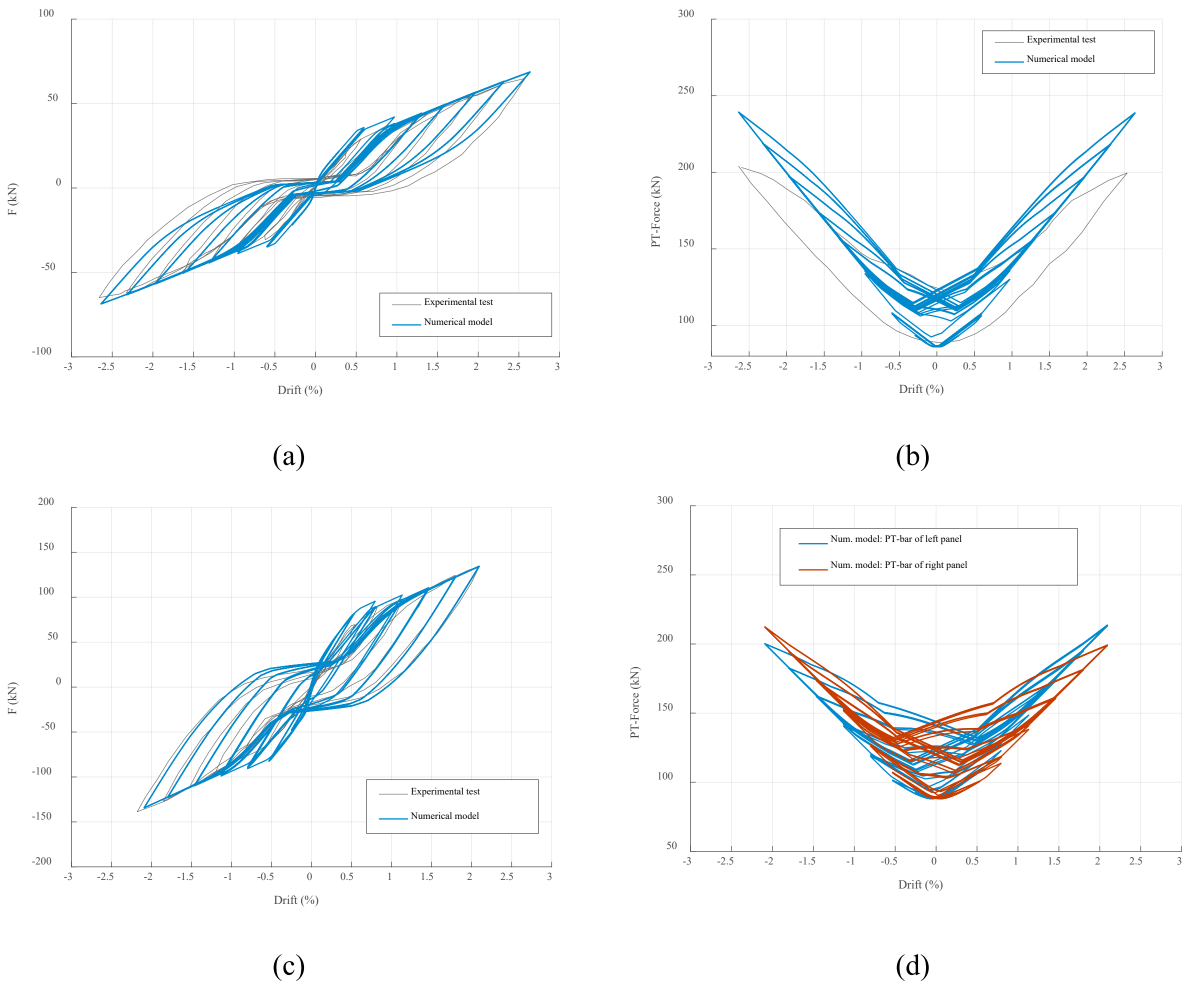


Fig. 4. Single wall setup: (a) force/drift curve; (b) post-tension force/drift curve; double wall setup: (c) force/drift curve; (d) post-tension force/drift curve

5. Conclusions

The paper deals with a proposal for an advanced non-linear numerical model developed in the OpenSees framework to predict the cyclic response of rocking post-tensioned dissipative timber walls. The proposed numerical model specifically takes into account the geometric non-linearity, associated with the rocking behavior of the system, and the material non-linearity, due to the entry into the plastic field of the dampers. The numerical results have been validated with some experimental literature results. In particular, the global response in terms of force/displacement curves and post-tension force/drift curves has been investigated, and the comparisons between numerical and experimental responses demonstrate the effectiveness of the numerical model in predicting the behaviour of post-tensioned walls subjected to cyclic loads. Further developments will be to verify the numerical model's capability to predict the non-linear response of different experimental campaigns. Then, after a proper validation of the rocking wall numerical model, further developments could be to employ it in a more complex framework, together with the timber frame structure designed for gravity loads.

Acknowledgements

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References

Brown, J.R. , Li, M., Palermo A., Pampanin S., Sarti, F., Nokes, R., 2022. Experimental testing and analytical modelling of single and double post-tensioned CLT shear walls. Engineering Structures 256.

Chen, Z., Popovski, M., Iqbal, A., 2020. Structural Performance of Post-Tensioned CLT Shear Walls with Energy Dissipators. Journal of Structural Engineering 146.

Christopoulos, C., Filiatrault, A., Uang, C.M., Folz, B., 2002. Post-tensioned energy dissipating connections for moment-resisting steel frames. Journal of Structural Engineering 128.

Huang, D., Pei, S., Busch, A., 2021. Optimizing displacement-based seismic design of mass timber rocking walls using genetic algorithm. Engineering Structures 229.

Iqbal, A., Pampanin, S., Palermo, A., Buchanan, A.H., 2015. Performance and design of LVL walls coupled with UFP dissipaters. Journal of Earthquake Engineering 19, 383-409.

Kelly, J.M., Skinner, R.I., Heine, A.J., 1972. Mechanisms of energy absorption in special devices for use in earthquake resistant structures. Bulletin of New Zealand Society for Earthquake Engineering 5, 63-88.

Massari, M., Savoia, M., Barbosa, A.R., 2017. Experimental and Numerical Study of Two-Story Post-Tensioned Seismic Resisting CLT Wall with External Hysteretic Energy Dissipaters. XVII Convegno ANIDIS L'ingegneria Sismica Italiana di Ingegneria Sismica, Pistoia, Italia.

Pei, S., Van De Lindt, J.W., Barbosa, A.R., Berman, J.W., McDonnell, E., Daniel Dolan, J., Blomgren, H.E., Zimmerman, R.B., Huang, D., Wichman S., 2019. Experimental Seismic Response of a Resilient 2-Story Mass-Timber Building with Post-Tensioned Rocking Walls. Journal of Structural Engineering (United States) 145.

Polastri, A., Casagrande D., 2022. Mechanical behaviour of multi-panel cross laminated timber shear-walls with stiff connectors. Construnction and Building Materials 332.

Pozza, L., Benedetti, L., Tomei, V., Ferracuti, B. , Zucconi, M., Mazzotti, C., 2021. Cyclic response of CLT Post-Tensioned Walls: Experimental and numerical investigation. Construnction and Building Materials 308.

Pozza, L., Benedetti, L., Tomei, V., Ferracuti, B., Zucconi, M., Mazzotti, C., 2021. Post-Tensioned low damage CLT walls with replaceable hysteretic devices – concept, experimental and numerical characterization. 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Streamed from Athens, Greece.

Sarti, F., Palermo, A., Pampanin, S., 2016. Development and Testing of an Alternative Dissipative Posttensioned Rocking Timber Wall with Boundary Columns. Journal of Structural Engineering (United States) 142.

STIC, 2013, Design guide Australia and New Zealand – Post-tensioned timber buildings.

Thiers-Moggia, R., Málaga-Chuquitaype, C., 2021. Performance-based seismic design and assessment of rocking timber buildings equipped with inerters. Engineering Structures 248.

Tomei, V., Zucconi, M., Ferracuti, B., 2021. Post-Tensioned low damage timber walls with dissipative devices. 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Streamed from Athens, Greece.

Wilson, A.W., Motter, C.J., Phillips, A.R., Dolan, J.D., 2019. Modeling techniques for post-tensioned cross-laminated timber rocking walls. Engineering Structures 195, 299-308.