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POST-TENSIONED LOW DAMAGE TIMBER WALLS WITH DISSIPATIVE DEVICES BEHAVIOR: NUMERICAL PREDICTION

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Abstract

In the last decades, low-damage post-tensioned technologies have been introduced in the field of timber constructions, with the aim to obtain structural solutions able to guarantee, in case of seismic events, not only the safeguarding of human life, but also the rapid re-use of the buildings without permanent damage. To this aim, structural systems based on rocking dissipative timber walls have been conceived, which rocking behaviour is due to the presence of post-tensioning cables, and the dissipative contribution is provided by steel dampers, easily replaceable after an intense seismic event. The paper presents a numerical non-linear model to predict the response of PT-timber walls, particularly useful to support the design. In particular, the geometrical non-linearity due to the rocking behavior of the walls and material non linearities that characterize the dampers, are specifically taken into account. The post-tensioned systems characterized by the single wall configuration with axial dampers are analyzed by considering different initial post-tensioning levels. The proposed numerical modelling strategy has been validated with experimental literature tests, demonstrating its effectiveness in predicting the behavior of post-tensioned walls subjected to cyclic loads.

Keywords: post-tensioning timber walls, dissipative dampers, numerical modelling.

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1 INTRODUCTION

In the last two decades, the employment of timber buildings is increasing in seismic prone areas, thanks to the significant evolution of performances of these constructions against seismic actions, mainly due to the development of new technologies [1]. The most common timber buildings are composed of engineered timber walls, i.e. Cross Laminated Timber (CLT) or Laminated Veneer Lumber (LVL), connected to each other and to the foundation through steel connectors, such as angle-brackets, hold-downs, nails, and screws. During a seismic event, the energy dissipation is mainly devoted to connectors, which could be severely damaged [2-5]. Moreover, both internal and external timber walls are load bearing elements, leading to an excessive use of the material and to the impossibility of moving the internal walls, so their position constitutes an architectural constraint. In order to avoid these drawbacks, low-damage post-tensioned (PT) technologies have been introduced [6], which entrust the energy dissipation to rocking timber walls equipped with dampers, whose main advantages are: the re-centering of walls at the end of the seismic motion, additional energy dissipation, and easy replacement of dampers. Since this system is predominantly employed in seismic prone zones, the assessment of a numerical modelling strategy to predict the cyclic behavior of post-tensioned timber walls assumes significant importance within the structural engineering field. Downstream of this brief discussion, the paper presents numerical models to predict the response of PT-timber walls, particularly useful to support the design. In particular, the geometrical non-linearity due to the partial uplift of the walls and material non-linearities that characterize the dissipaters, are specifically taken into account. The responses in terms of horizontal load-displacement curves and post-tensioning (PT) force-displacement curves are presented. The post-tensioned systems characterized by the single wall configuration with axial dampers are analyzed by considering different initial post-tensioning levels. The proposed numerical modelling strategy has been validated with literature experimental tests, demonstrating its effectiveness in predicting the behavior of post-tensioned walls subjected to cyclic loads.

2 LOW DAMAGE TIMBER SYSTEMS

Low damage timber systems arise from the need to guarantee, in case of a critical seismic event, not only the safeguarding of human life, but also the rapid re-use of the buildings without permanent damage. Laboratory tests and numerical investigations highlight that CLT traditional buildings can resist high intensity seismic actions [7]; however, a high-permanent damage in connection steel elements and on timber panels is generally observed. From these observations comes the idea of conceiving a system able to prevent damage to the load-bearing structural elements. In this regard, low damage timber systems were thought to be constituted of timber elements destined to remain in the elastic field during a seismic event, and steel dampers, destined to be severely damaged and then easily replaced. It deals with rocking dissipative walls, which rocking behaviour is due to the presence of post-tensioning cables placed inside cavities in the wall, fixed at the base and anchored at the top of the wall, while the dissipative contribution is due to steel dampers. The dampers can work as axial dampers, positioned at the base of the walls, and/or shear dampers, i.e. connecting adjacent rocking timber elements along elevation [6, 8–12]. The contribution of post-tensioning cables and steel dampers could be simply recognizable by observing a typical flag-shape force-displacement curve of a post-tensioning wall subjected to cycling loading (Figure 1), in which the bilinear envelope is mainly due to the rocking behaviour, controlled by the post-tensioning cables, and the amplitude of the flag is mainly due to the dissipative contribution of the steel dampers. This system takes inspiration from precast post-tensioned concrete elements that were firstly developed by Stone et al. [13], and then investigated by Priestley *et al.* [14] within a five-story building.

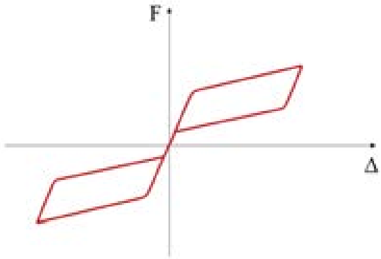


Figure 1: Typical flag-shape force- top displacement (F-Δ) curve of a PT- wall subjected to cycling loading.

To confirm the validity and the growing diffusion of this structural idea, some buildings are recently constructed in New Zealand adopting this innovative solution. Furthermore, it is important to underline that the design of post-tensioned timber buildings is also proposed in the Australian and New Zealand design guidelines [15].

3 LITERATURE EXPERIMENTAL CAMPAIGNS

The firsts experimental campaigns have been performed on Laminated Veneer Lumber (LVL) PT- walls, in reference to single-wall [9] and double [6] systems. In particular, these configurations have been tested with and without dampers to highlight their benefits in terms of dissipative contribution. The dampers employed for the single wall systems are fuse-type dampers [8, 16, 17], which connect the PT wall to the foundation and works along the axial direction. These are characterized by a mild steel round bar placed inside a confining tube, and the space between them is filled with grout or epoxy, which act as a buckling restraint. Instead, the dampers employed for the double-wall systems are U-shape dampers [18, 19] connecting the walls along elevation.

Similarly, Ganey et al. [10] carried out an experimental campaign on single PT- wall systems without damping, and on double walls connected by U-shape dampers, while Massari et al. [11] conducted experimental tests on a single PT-wall system provided by fuse-type dissipaters, but using CLT walls.

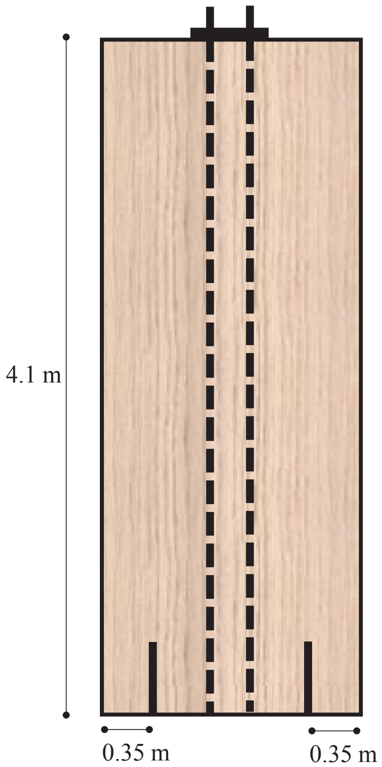
Some authors have also proposed a configuration in which the PT- walls are connected to boundary columns by means of dampers [20], ensuring the support to the inter-floor beams connected to the diaphragm. This system avoids the vertical uplift generated by the rocking behaviour that causes vertical displacements incompatible with the diaphragm system, leading to unexpected damage.

In the present paper, the results of the experimental campaign conducted by Sarti et al. [9] was employed to validate the proposed numerical model, which will be presented in the next section. The experimental campaign concerns single wall systems, made of LVL characterized by a modulus of elasticity E_t of 11 GPa. The rocking behavior is entrusted to two post-tensioned steel bars characterized by a diameter of 32 mm, a Young modulus of E_p of 170 GPa, and a yield strength f_{py} of 835 MPa. The dissipative contribution is due to fuse-type dampers characterized by a diameter of 14 mm, a mild steel with a Young modulus of E_s of 200 GPa, and yield stress f_{sy} of 400 MPa. The single wall system has been tested in the various configuration:

- post-tensioned configuration (no dampers), with initial post-tensioning levels of 200 kN, 400 kN, and 600 kN;

- post-tensioned configuration with two couple of fuse-type dampers, with initial post-tensioning levels of 400 kN and 600 kN;
- post-tensioned configuration with four couple of fuse-type dampers, with initial post-tensioning level of 400 kN.

Figure 2 shows the geometric and mechanical characteristics of the experimental setup.



Material	Property	Value
LVL	Young Modulus E_t	11 GPa
	Compression strength parallel to grain f_{ct}	45 MPa
PT- bar steel	Yield stress f_{py}	835 MPa
	Ultimate stress f_{pu}	1030 MPa
	Young Modulus E_p	170 GPa
Mild steel	Yield stress f_{sy}	400 MPa
	Ultimate stress f_{su}	500 MPa
	Young Modulus E_s	200 GPa

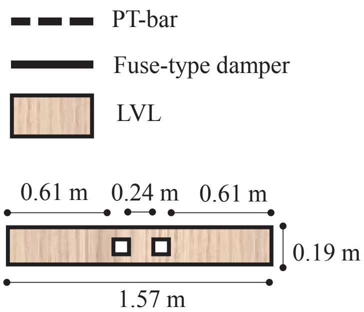


Figure 2: Geometric and mechanical characteristics of the reference experimental setup.

4 NUMERICAL MODELING

In order to predict the response of PT-timber walls, a numerical model was developed, particularly useful to support the design of the described system. The proposed numerical model has been validated on the experimental campaign results conducted by Sarti et al. [9] described in section 3. For the sake of brevity, the comparison between experimental and numerical results will be shown for post-tensioned configurations with two couple of fuse-type dampers, and initial post-tensioning levels of 400 kN and 600 kN.

4.1 Description of the numerical model

The proposed numerical model has been developed in the OpenSees [21], a software framework for simulating the seismic response of structural and geotechnical systems, realized by the Pacific Earthquake Engineering Research Center.

The numerical model of the structural system, shown in Figure 3, accounts for the geometrical and mechanical non-linearities. In particular, the first is due to the rocking behaviour of the system allowed by introducing unilateral constraints at the base, the second is mainly due to the presence of axial dampers simulated by non-linear springs. LVL walls and columns have been schematized with 2D Quadrilateral elements (Quad) associated with an elastic orthotropic material, supposing that timber elements remain in the elastic range.

The PT- bars have been modelled with truss elements, which is associated with an elastic-plastic force-displacement response with an initial imposed strain that simulates the initial post-tensioning level. Furthermore, to capture the rocking behaviour of LVL panels, the unilateral constraints at the base have been represented by inserting zero-length elements, characterized by an elastic no-tension material (gap elements).
For the simulation of the test performed with axial dampers, non-linear springs that simulate their behaviour are included in the model. The two pairs of axial dampers, placed at the base, are simulated with non-linear springs using zero-length elements.

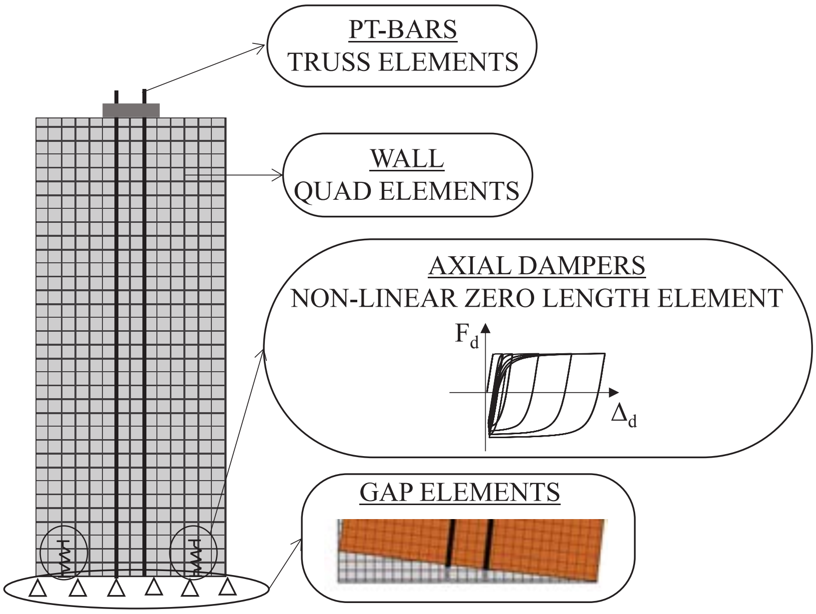
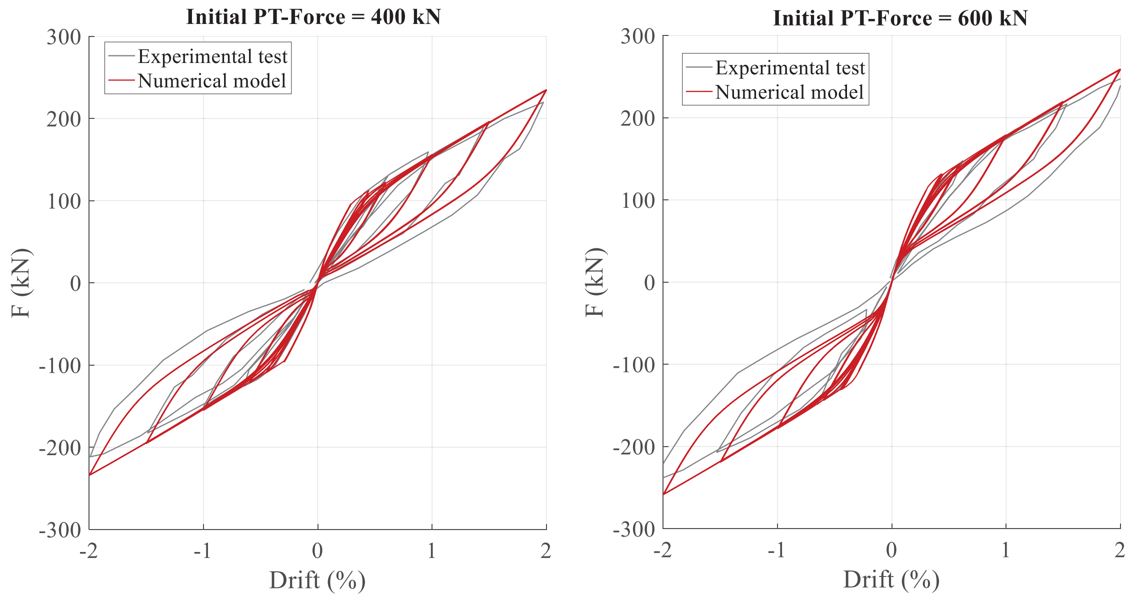


Figure 3: Numerical model.

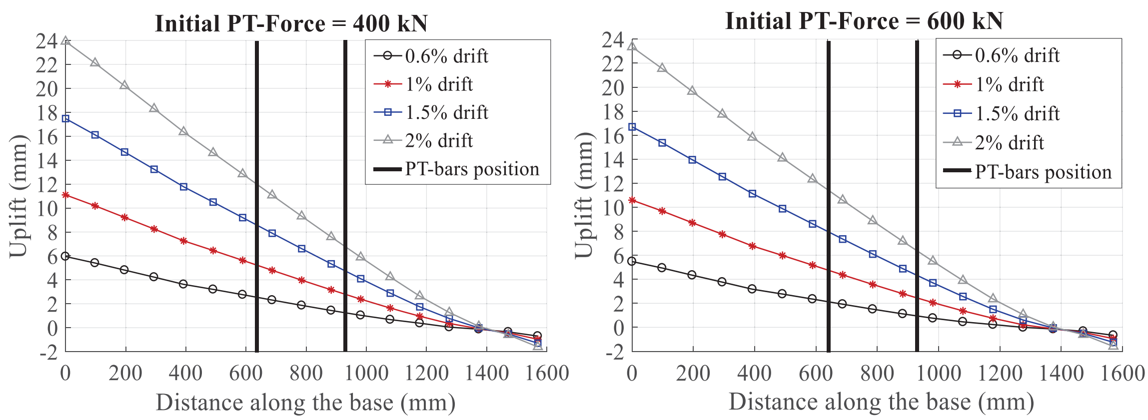
4.2 Validation of the proposed numerical model

In this section, a comparison between experimental results and numerical simulations is reported in terms of horizontal load/ drift curves and PT-force/ drift curves, by considering the post-tensioned configuration with two couple of fuse-type dampers, with initial post-tensioning levels of 400 kN and 600 kN. The horizontal load/ drift curves are shown in Figure 4(a) and Figure 4 (b) for initial post-tensioning levels of 400 kN and 600 KN, respectively. The monotonic envelopes are characterized by a well-defined bilinear curve, in which the transition point between the first branch and the second one, corresponds to the drift at which the first cable is subjected to an increment of tension due to the wall rocking. The comparison shows a good agreement between experimental and numerical results, in terms of initial stiffness, strength and cyclic behaviour. In this regard, the predicted cyclic behaviour is slightly underestimated, because of the presence of frictional dissipations not included in the numerical model. It is interesting observing that the model is able to capture also the effect of increasing the initial post-tensioning level on the global response of the system: a greater strength characterizes the configuration with the higher PT-level, and it shows a greater re-centering capacity, recognizable by the typical flag shape. Focusing on the behaviour of the PT-bars, these are subjected to an axial deformation make the PT force increase with respect to the initial imposed load, due to the wall uplift. This variation will be higher for the cable close to the wall edge that is uplift. To clarify this behaviour, the numerical wall base uplifts, evaluated at 20 cm from the base, are reported in Figure 5 for various drift levels, where the position of the cables is drawn in order to perceive their increasing deformation as the drift of the wall increases. It is interesting to highlight that the base uplifts for fixed values of drift are similar for both the post-tensioning levels of 400 kN (Figure 5(a)) and 600 kN (Figure 5(b)), suggesting that the kinematic of the system is almost independent from the initial post-tensioning level. However, it affects the lateral strength of the wall (Figure 4). The good agreement between experimental tests results and numerical simulations is well confirmed also by the comparison in terms of PT force-drift response of the walls for both the initial post-tensioning levels of 400 kN (200 kN for each cable) and 600 kN (300 kN for each cable) reported in Figure 6(a) and (b), respectively. For both the post-tensioning levels, graphs show that the numerical model well captures the PT force variation in both the loading and unloading phases, showing a slight difference for the cable further from the uplifted wall corner.



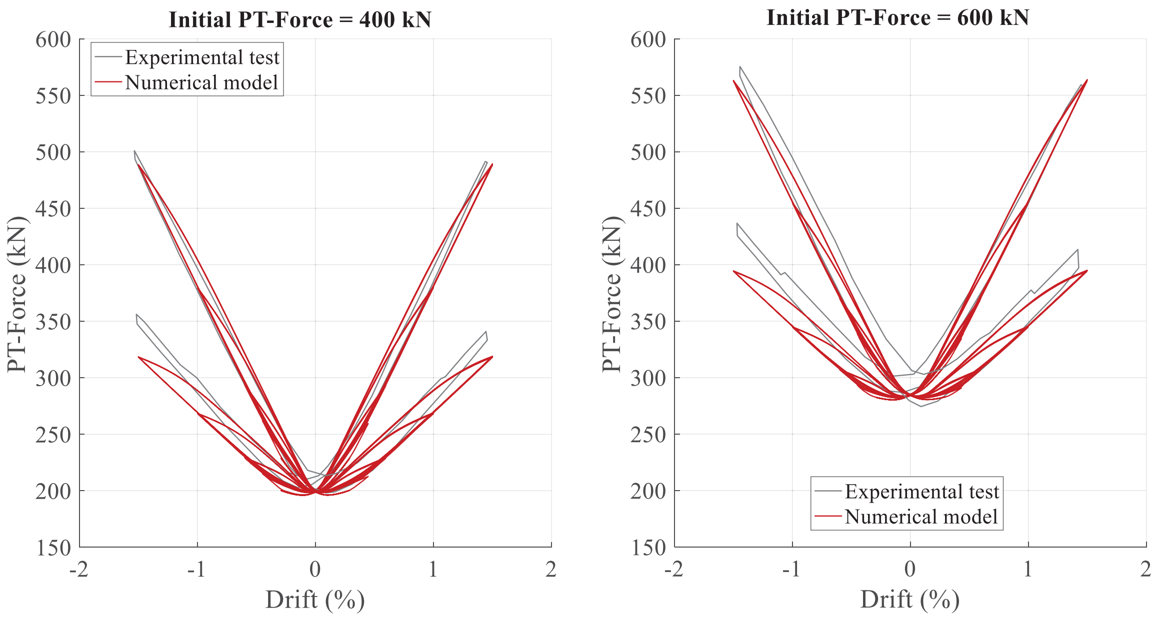
(a) (b)

Figure 4: Horizontal load/ drift curves: (a) initial PT-force of 400 kN and (b) initial PT-force of 600 kN.



(a) (b)

Figure 5: Numerical wall base uplift for various drift levels, evaluated at 20 cm from the base: (a) initial PT-force of 400 kN and (b) initial PT-force of 600 kN.



(a) (b)

Figure 6: PT-force/ drift curves: (a) initial PT-force of 400 kN and (b) initial PT-force of 600 kN.

CONCLUSIONS

The paper deals with a proposal for a non-linear numerical model, developed in the OpenSees framework, for the prediction of the cyclic response of rocking dissipative timber walls, by virtue of the fact that in the last decade, a diffusion of low damage systems have been observed, so it is particularly important to develop numerical models that can support the design phase. The proposed numerical model specifically considers geometric and material non-linearities associated with the rocking behavior and the entry into the plastic field of the dampers, respectively. A first validation with experimental results from literature is presented here. In particular, the global response in terms of horizontal load-displacement curves and post-tensioning force-drift curves has been investigated, demonstrating its effectiveness in predicting the behavior of post-tensioned walls subjected to cyclic loads with different levels of post-tensioning force.

Further developments will be to verify the numerical model's capability to predict the non-linear response of different experimental tests on various PT wall configurations, also including shear dampers. After the proper validation of the rocking wall numerical model, it will be employed for design purpose in a more complex framework, togheter with the timber frame structure designed for gravital loading.

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