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A PARAMETRIC STUDY ON THE CYCLIC RESPONSE OF POST-TENSIONED LOW DAMAGE TIMBER WALLS WITH DISSIPATIVE DEVICES.

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Abstract

Low-damage Post-tensioned timber walls arose from the requirement to develop structural solutions capable of ensuring fast re-use of the structure without permanent damage after a seismic event while also protecting human life. These kinds of solutions require rocking timber walls equipped with hysteretic dampers. The rocking behavior guarantees the recentering of the walls, and it is mainly entrusted to post-tensioned bars placed in ad hoc cavities in the wall. Likewise, the energy dissipation mechanisms are provided by axial or shear hysteretic dampers which easily replaceable after a seismic event. In this context, the investigation presents a non-linear numerical model strategy able to reproduce the cyclic behavior of post-tensioned timber walls at global and local levels by non-linear static analyses. The proposed model considers both material and geometrical non-linearities: the former due to entering the plastic field of hysteretic dampers and the latter due to the rocking behavior which causes base uplifts. Along the same lines, in this paper, a parametric analysis is developed to investigate the various parameters that affect the local and global behavior of the systems and influence the recentering capacity and dissipative behaviors of the building. The main parameters investigated are: the initial level of post-tension in the bars, the number of axial dampers, the geometrical dimensions of the walls, the mechanical characteristics of the wall.

Keywords: post-tensioned timber walls, dissipative dampers, rocking timber walls, numerical modeling, parametric analysis.

1 INTRODUCTION

In the last decades, the ever-increasing need for structural solutions that are sustainable, seismically safe, and ensure rapid reuse of the buildings has drawn attention to Post-tensioned (PT) rocking dissipative timber wall systems, which are mainly comprised of timber walls equipped with Post-tesioned bar (PT-bar) which are able to guarantee system recentering, and provided by steel damper for energy dissipation. The idea is that, during a seismic event, the timber wall works in the elastic field, while the dampers, which provide energy dissipation, are vulnerable to damage owing to their entry into plastic field, which also guarantees the energy dissipation; then, the damaged dampers can be easily replaced. The global Force/Displacement (F/Δ) response of the PT wall system is a typical flag-shape behavior as shown in Figure 1: the bilinear backbone curve is mainly controlled by the system's rocking behavior due to the presence of PT- bars, but the amplitude of the flag is governed by the dissipative contribution of steel dampers. Several experimental campaigns on post-tensioned wall systems can be found in the scientific literature [1–6], but also on whole buildings or on multi-story/ multi-panel solutions [7–10]. The growing diffusion of this structural system suggests the significance of developing numerical models capable of capturing their experimental responses, indeed, several contributions can be found in this field [11–15].

In this framework, the non-linear numerical model implemented in the open-source software OpenSEES [16] and presented in [15], is here adopted to perform a parametric study, to investigate the effect of several different parameters, such as: timber wall dimensions, initial post-tensioned force in the bars, mechanical properties of the timber wall and the number of axial dampers, on the global response of PT-wall systems in terms of Force/Displacement curves and PT-Force responses.

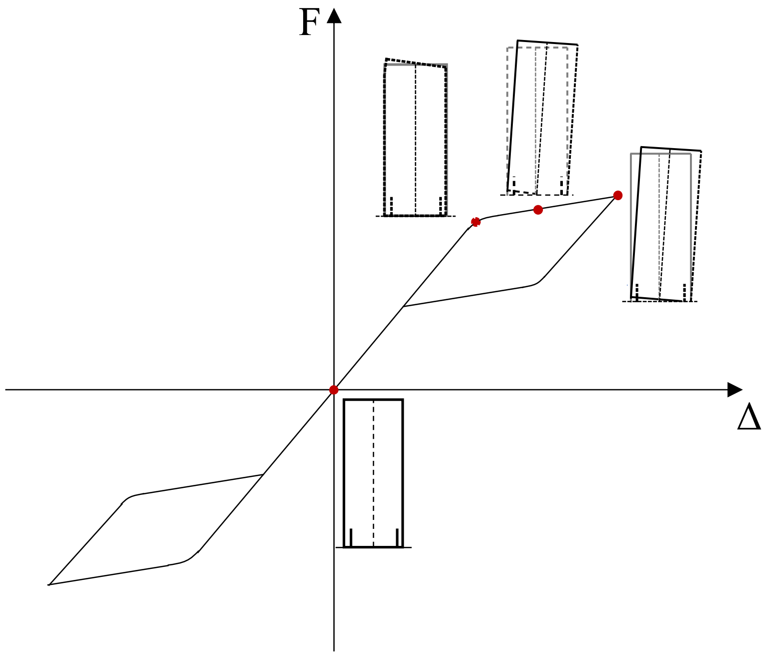


Figure 1: Typical flag-shape force/ displacement (F/Δ) curve of a PT- system subjected to cycling loading.

2 NUMERICAL MODEL

2.1 Description of the numerical model

The PT-wall configuration employed to carry out parametric analysis is a single wall configuration which has been equipped with one PT-bar and two couples of axial dampers disposed along the base of the wall [15]. The proposed numerical model, which is developed as a 2D model in OpenSEES [16], takes into account both geometrical and material non-linearities to get the rocking behavior of the timber wall and the entry into the plastic field of hysteretic dampers, respectively. As shown in Figure 2, the timber panel is schematized with 2D quad elements to which an orthotropic material is assigned in terms of stress/strain curve (σ/ε). The PT-bar is modeled with a two-node link element, fixed at the base and connected at the top of the wall, to which a steel material is assigned with an elastoplastic force-displacement curve, characterized by an elastic stiffness K and a yielding force F_y; further, an initial level of deformation ε_{in} is introduced to simulate the initial PT-Force. The axial dampers are modeled with zero-length elements and a hysteretic force-displacement curve is calibrated according to experimental results (section2.2). Furthermore, the wall is connected at the base with unilateral constraints able to provide displacements once upward (gap elements), in order to simulate the rocking behavior of the timber wall. The numerical model is subjected to cyclic static nonlinear analysis, and the control point is disposed at the top of the wall; the loading protocol is chosen in analogy to that employed in the experimental analyses used to validate the proposed numerical model.

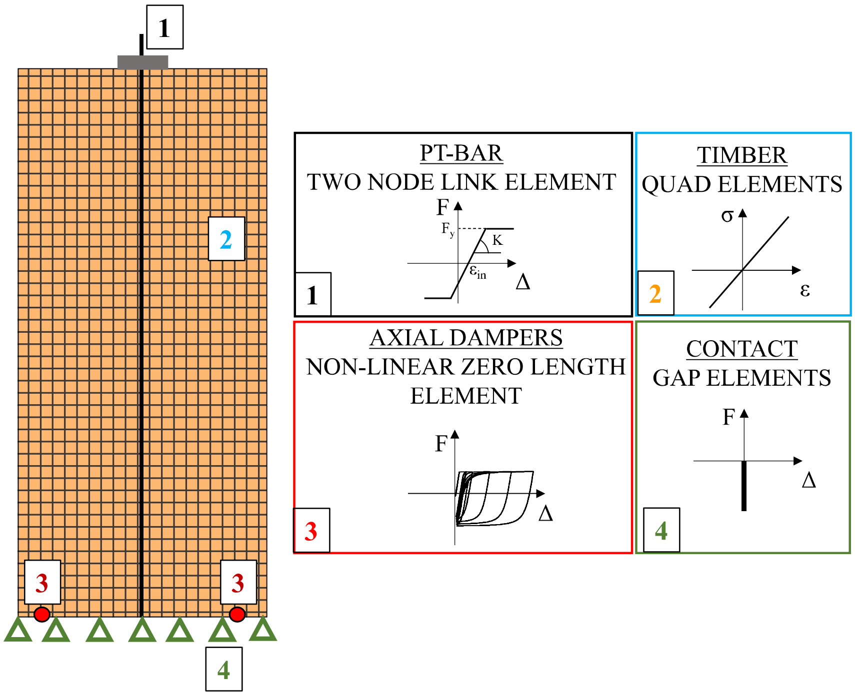


Figure 2: Numerical meshes of PT-wall setup.

In order to validate the numerical model, the experimental tests performed by Chen et al. 2020 [4] were employed as a reference. In particular, the setup has been characterized by a single CLT panel equipped with one PT-bar positioned in the middle of the wall, and with two couples of axial dampers located along the base. Further detailed information on the selected experimental campaigns are reported in Table; in particular, there are information on geometrical characteristic and material properties, where: E_L and E_T are 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 of the PT-bar, PT-F_{in} is the initial PT-Force imposed on the PT-bar; $f_{y,A}$ and E_A are the yielding stress and the relevant elastic modulus of the axial damper.

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

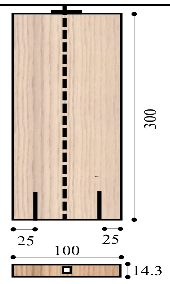


Table 1: Geometrical and mechanical parameters of the selected experimental campaign [4]

The nonlinear law adopted for the dampers is calibrated based on preliminary axial experimental tests performed on the axial dampers, by minimizing differences in terms of strength, stiffness and cyclic behavior between the numerical response and the experimental one. The adopted numerical law is the Giuffré-Menegotto-Pinto Model with Isotropic Strain Hardening [17], which is implemented in OpenSEES as “Steel 02”. Table 2 shows the values assigned to the parameters of the “Steel 02” law: F_y, the yield strength; E, initial elastic tangent stiffness; b, hardening ratio; R0, c_{R1} and c_{R2}, i.e. the parameters that control the transition from elastic to plastic branches [17].

Constitutive law	Parameters	Values
STEEL 02	F_y (kN)	42.5
	E (MPa)	43000
	b	0.02
	R0	50
	c_{R1}	0.955
	c_{R2}	0.2

Table 2: Parameters assigned to Steel 02” law for axial dampers.

2.2 Outcomes of the numerical evaluation

The comparison between the experimental cyclic behavior of the axial dampers and the calibrated numerical one, is reported in Figure 3 in terms of force-displacement curve. The Force/ Drift responses and Post-tension force/ Drift curves are reported in Figure 4a and b, respectively. The strong contribution of the hysteretic dampers is evident in the Force/ Drift response; in particular, a drift value other than zero at zero force is provided, due to the contribution of the dampers that is more pronounced than that of the PT-bars, leading to a poor recentering system and no evident flag behaviour, as illustrated in Figure 1. The high contribution of dampers is also evident in terms of strenght, since the Force/Drift envelope slightly differs from the bilinear trend, as shown in Figure 1. The rocking behaviour is emerged by the Post-tension force/ Drift curves, in which the PT-Force substantially increases while moving from the position of zero drift to the position of drift larger than zero in absolute value. Both the Force/ Drift responses and Post-tension force/ Drift ones are well captured by the numerical models, with the exception of a small difference in terms of PT-force variation which reaches 20% for the Drift of 2.5%.

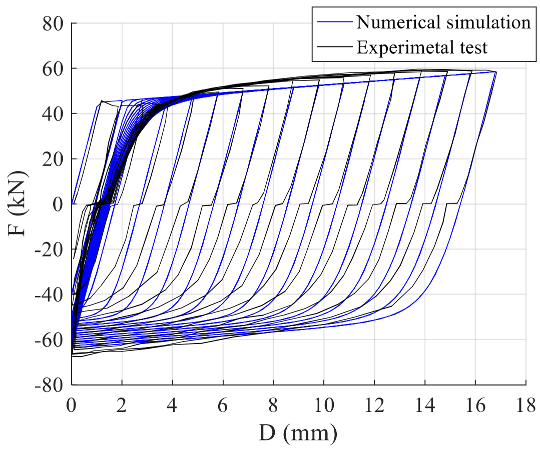
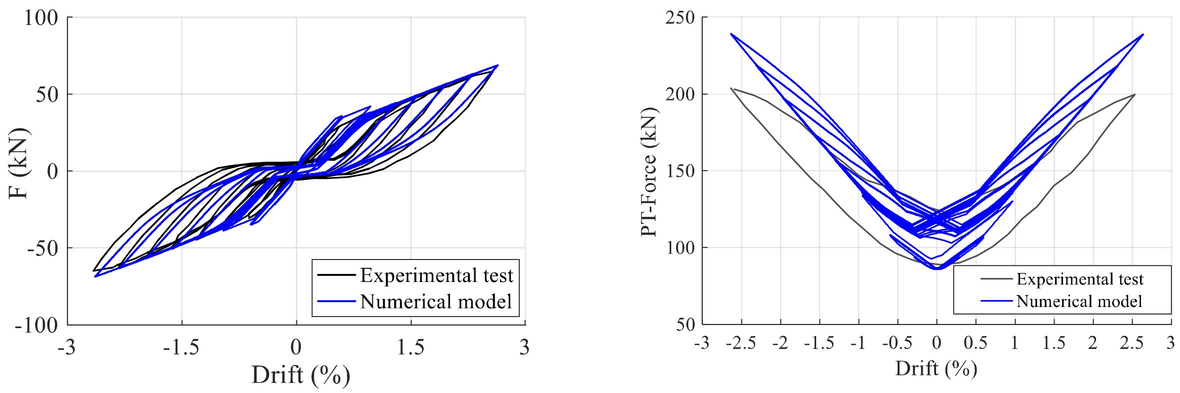


Figure 3: Calibration of axial dampers – Force/Displacement (F/D) response.



(a) (b)

Figure 4: Comparison of numerical and experimental Force/Drift responses.

3 PARAMETRIC INVESTIGATION

Starting with the setup analysed in section 2.2, a set of parametric analysis is carried out to assess the effect of different paremeters on the response of PT-wall systems. The investigated parameters are the main geometrical and mechanical parameters, as well as the applied post-tensioned force, which are as follows: B = the wall base; H = the wall height; the initial PT-force of the bars, E= the timber characteristics in terms of elastic modulus (that indicates, for simplicity, the value of E_L=E_T defined in section 2.2) and G= shear modulus (that indicates the value of G_{LT} =G_{LR} defined in section 2.2) and the number of axial dampers. All the analysis are carried out imposing an initial level of PT-Force of 135 kN, unless otherwise indicated.

Figures 5 to 7 illustrate the results in terms of Force/Drift curves. Figure 5 shows the effect of wall dimensions on increasing strength and stiffness. These increases become more evident as B increases (Figure 5a), due to the presence of axial dampers, which are subjected to higher displacement if the distance from the corners remains constant, and therefore they provide an ever more evident contribution in terms of strength, stiffness and dissipative capacity. Figure 6 shows the variety of mechanical properties in terms of E and G (Figure 6a) as well as PT-force

(Figure 6b). As seen in Figure 6a, strength and stiffness may be slightly influenced by changing E and G, while, as expected, no effective difference in terms of dissipative capacity is provided, since no difference in the amplitude of the Force/Drift curves is noticed The effect of the initial value of PT-Force is shown in Figure 6b: increasing this value, the system's strength , stiffness and re-centering capability enhance, as shown by the well defined flag shape of the Force/ Drift curve obtained for an initial PT-Force of 270 kN. Figure shows the influence of the number of axial dampers: a greater number of axial dampers assures higher strength, stiffness and dissipative capacity of the system, at the detriment of the re-centering capability, which instead reduces.

In syntesis, the effect of the analysed parameters on the global behaviour of the system can be summarized as follows:

- increasing the base of the wall B, also initial stiffness, strength, and dissipative capacity significantly increase;
- increasing height of the wall H, the initial stiffness and strength show a slight variation;
- there is a slight effect of changing mechanical properties in terms of E and G on strength, stiffness and energy dissipation;
- increasing initial PT-Force of the bar, strength and stiffness of the system increase, but the most important effect is in significantly improve the re-centering capacity of the system;
- increasing number of axial damper, strength and dissipative capacity of the system increase, while the the re-centering capacity decreases.

Downstream of this brief description, in order to design a PT-wall system with good re-centering capacity and a good dissipative capacity, it is important to pay attention to the number of dampers to provide in the function of the initial PT-Force of the bars. Moreover, with the same number of dampers and initial PT-Force, it is possible to improve strength and stiffness of the system by increasing the dimensions of the walls.

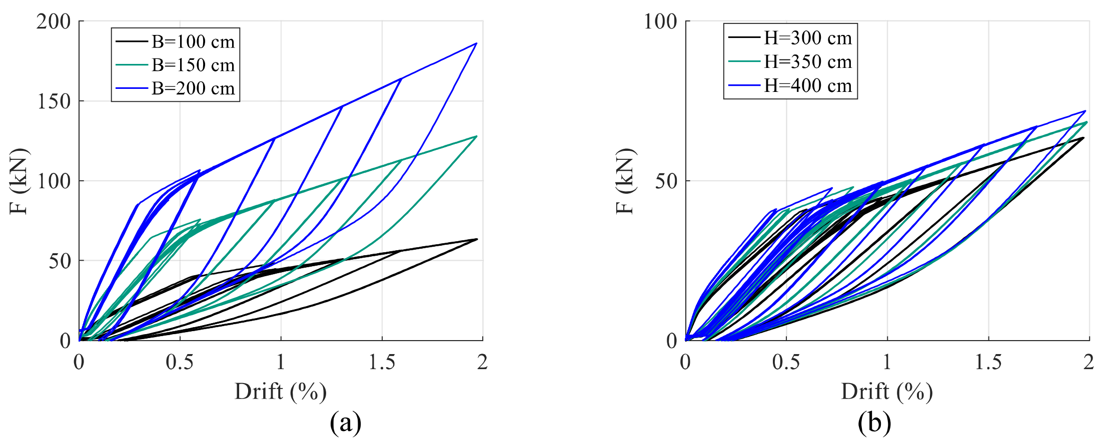


Figure 5: Effect of the timber wall geometrical parameters on Force/ Drift response: wall base B (a) and wall height H (b).

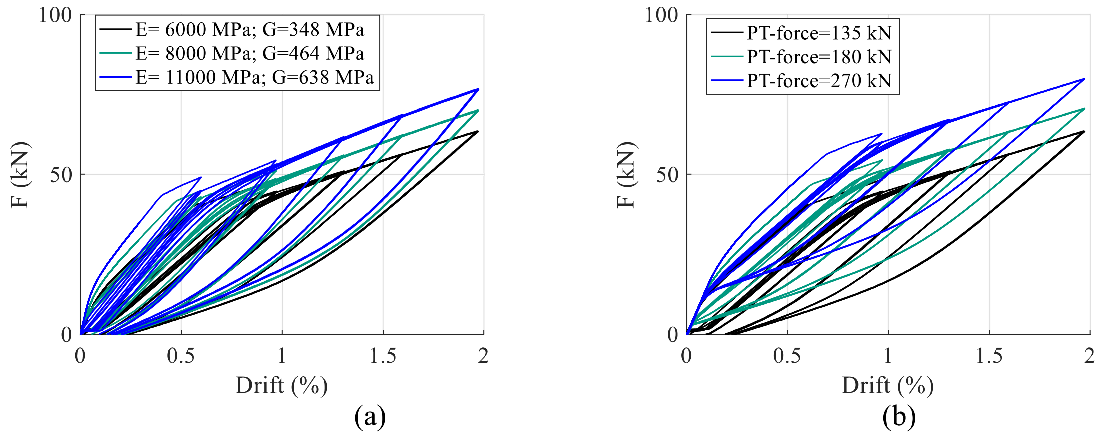


Figure 6 Effect of the mechanical characteristics E and G (a) and of the initial PT-Force on Force/ Drift response (b).

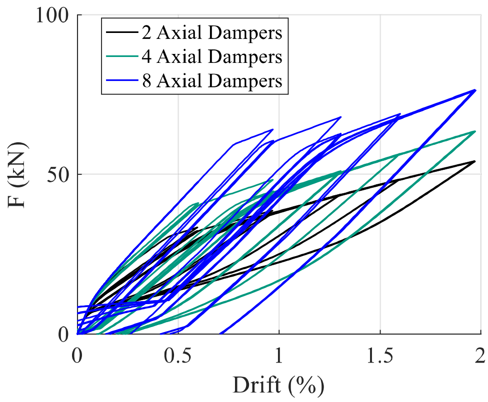


Figure 7:Effect of the number of axial dampers on the Force/ Drift response.

4 CONCLUSIONS

A Finite Element nonlinear numerical model was developed in the OpenSEES environment for the evaluation of the cyclic response of Post-Tensioned dissipative timber walls systems. The numerical model, which takes into account of both material and geometrical non-linearities, was validated firstly with the results of an experimetal campaign carried out on a single wall system equipped with one PT-bar and two couples of axial dampers disposed near the corners, along the base. The validation was performed by comparing the global results in terms of Force/Drift curves and PT-bar/Drift responses, showing a good agreement in terms of stiffness, strength, cyclic behaviour, and energy dissipation. After validation, a parametric analysis was carried out in order to analyse the role of different parameters on the global behavior of post-tensioned timber walls: the wall base; the wall heigh; the initial post-tensioned force of the bars; the timber mechanical properties; the number of axial dampers. The results highlight that an important effect on initial stiffness, strength, and PT-Force variation is due to the variation of the base wall, while the initial post-tension in the bar has an important role on the re-centering capacity of the system; the number of dampers strongly affects both the dissipative capacity and the recentering contribution of the system.

5 ACKNOWLEDGEMENT

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