Modelling of post-tensioned timber framed buildings with hysteretic bracing system: preliminary analysis

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Abstract. The increasing demand for multi-storey timber framed buildings in seismic areas has led to the developing of damage limiting systems. The self-centering rocking mechanisms combined with dissipative systems, such as dissipative bracing is a high-performance system that can prevent major structural damage and minimize residual drifts during strong earthquakes. This paper shows the modelling of a three-dimensional, three-storey, two-third scaled, post-tensioned timber framed model equipped dissipative bracing systems and compares the numerical simulations with the experimental results obtained at the structural laboratory of the University of Basilicata. The hysteretic bracing system is composed by V-inverted timber brace in series with U-shaped flexural steel plates. During preliminary shaking table tests, the specimen was subjected to two earthquake inputs at different intensity levels. The braced model was developed using an appropriate combination of elastic elements with lumped rotational and linear springs, by means of two different software: OpenSees and SAP2000. Both numerical outcomes of nonlinear dynamic analysis are in good agreement with the global and local seismic experimental response of the braced model and of the hysteretic dampers. Based on the validation of the numerical models, further studies of optimization of design methods and a complete probabilistic characterization of Pres-Lam building performances will be developed.

1. Introduction

Timber has been one of the oldest building materials available, extensively used for low-rise structures for many years. The seismic response of timber structures traditionally relies on the yielding of steel fasteners to provide non-linear structural behaviour and ductility. Although acceptable, this method of seismic design has significant degradation of stiffness and strength, and hence creates irreparable damage in or around the fasteners. In medium and high seismic hazard areas a recent technology, called Pres-Lam system, originally applied to precast concrete frame and wall systems, was developed ([1], [2]). This system allows a combination of unbounded post-tensioned tendons with different form of replaceable and cost efficient dissipation devices such as steel angles [3], steel U-shaped flexural plates [4]. While the post-tensioning or the axial load contribution in case of columns provides the required re-centering capability to mitigate the consequences of residual drifts, the energy dissipation devices allow adequate energy dissipation as well as increase the moment resistance [5], [6]. During lateral movement, a controlled rocking mechanism occurs at beam-column and column base joints, which exhibit a dissipative re-centering ‘flag-shaped’ hysteretic behaviour ([7], [8]).
During the experimental campaign in progress at the structural laboratory of University of Basilicata, a 3-dimensional, 3-storey, 2/3 scaled post-tensioned timber framed specimen with dissipative bracing system and with dissipative rocking mechanism at the base of the columns (see figure 1), designed to withstand high levels of seismic loading without damage, has been preliminary tested on shaking table.

The main objective of this paper is the validation of the seismic performance of the experimental braced frame through simple and robust numerical model, developed with two different software: SAP2000 [9] and OpenSees (Open System for Earthquake Engineering Simulation) [10]. Predicting accurately the global and local seismic behaviour through non-linear time history analyses (NTHA) without requiring a large amount of computational time is an important task for an adequate modelling. Based on the effectiveness of the numerical modelling, in future development the models will also be employed for an accurate probabilistic characterization of Pres-Lam building performances with different dissipative systems and for the optimization of design procedures.

2. Experimental model and testing program

The experimental model was built and tested at structural laboratory of University of Basilicata (Potenza, Italy), and it was a part of a collaborative campaign with University of Canterbury, in Christchurch, New Zealand [3], [8]. The specimen was three-dimensional, three-storey post-tensioned timber frame and had single bays in both directions. The inter-storey height was 3 m and the frame footprint equal to 6 m x 4.5 m. A scale factor of two-third was applied to the prototype building obtaining an inter-storey height of 2 m and a scaled structure footprint of 4 m x 3 m (figure 1a). The frame was post-tensioned in both directions with the post-tensioning bars crossing at the beam-column joint. During the experimental campaign three testing sessions of the model were performed in different configurations (table 1). During Session 1 and Session 2 the specimen was tested without (free rocking) or with dissipative steel angles (dissipative rocking) placed at beam-column and/or at column-foundation connections [11]. During Session 3 the prototype building was equipped also with V-inverted dissipative bracing systems (figure 1a). The beam and column elements were made of Glulam grade GL32h [14]. At each floor the dissipative bracing system was made of two V-inverted timber rods made of glulam grade GL24h in series with two U-shaped Flexural Plates dampers of C60 steel type (see figure 1b) [4].

![Figure 1](image1.png)  
(a)  
(b)  

Figure 1. (a) Experimental model with dissipative bracing systems tested at UNIBAS laboratory; (b) Detail of the UFP hysteretic dampers of the bracing system.
During the seismic motion, the post-tensioning gives to the Pres-Lam system the re-centering capability and uses additional dissipation to provide non-linear response, activated by the dissipative devices, in order to improve the earthquake performances of the structures. The passive hysteretic devices, which were designed to yield in a controlled manner, were added to the Pres-Lam structure in Session 3 [4] in order to increase strength, stiffness and damping and reduce displacements without increasing acceleration and/or base shear [3], [12], [13]. Design drift levels of 3%, 1.9% % and 1.1% under ultimate limit state (PGA 100%) loading were selected for the testing configurations Session 1, Session 2 and Session 3, respectively.

The seismic response of the specimen was recorded in real time by a combination of 54 instruments, including displacement potentiometers, load cells and accelerometers. Local deformations were also recorded across the gap opening of beam-column, column-foundation connections and UFP hysteretic dampers.

| Testing session | Dissipative rocking | Dissipative braces |
|-----------------|---------------------|-------------------|
| 1               | NO                  | NO                |
| 2               | YES                 | YES               |
| 3               | NO                  | YES               |

The testing input considered for preliminary experimental tests consisted of two earthquakes selected from the European strong-motion database. The design spectrum used to select this set corresponded to a high seismic zone having a PGA of 0.44 g (Soil class B – medium soil, [14]). In figure 2 the main characteristics of the selected input earthquakes are reported and compared with the design spectrum.

| ID Code | Location          | MW | PGA (g)  |
|---------|-------------------|----|----------|
| 196     | Montenegro        | 6.9| 0.454    |
|         | Serbia            |    |          |
| 291     | Campano Lucano, IT| 6.9| 0.264    |
|         | IT                |    |          |

Figure 2. Main characteristics and elastic spectrum of seismic inputs.

3. Numerical modelling of the test structure

The numerical modelling of the test frame with dissipative rocking mechanism at the column-foundation connections and with dissipative bracing systems was developed in 2-D using a lumped plasticity approach which combines the use of elastic elements with springs representing plastic deformations in the system (figure 3a). The model was developed with two different finite element software to simulate the seismic non-linear dynamic response: SAP2000 [9] and OpenSees [10].

The structural elements (beams, columns and braces) were modelled as elastic elements with anisotropic glulam timber material in SAP2000 and uniaxial material elastic in OpenSees.

The specimen at the beam-column joints was modelled considering a combination of rotational springs to represent the contribution of the post-tensioning and the flexibility of the joint panel (figure
Post-tensioning response was represented using tri-linear-elastic moment–rotation springs [15] and the joint panel was accounted for introducing an additional linear rotational spring, with stiffness value opportune arranged for each model. The flexibility of the joint panel influenced the response of SAP2000 and OpenSees models, for this reason different amounts of stiffness of the rotational spring were tested to check the sensitivity of both models.

The column base connection was modelled with 3 rotational springs in parallel (figure 3d), which considered the moment resistance given by the contribution of the gravity plus seismic axial load and the additional moment contribution of hysteretic steel elements [11].

Figure 3. (a) Numerical modelling of the frame with dissipative bracing systems and details of: (b) dissipative bracing connection; (c) beam-column joints and (d) column-foundation joints.
When dissipative bracing systems were introduced to the bare structure, the hysteretic contribution of UFP dampers was modelled by considering a linear spring with hysteretic behaviour in series with V-inverted elastic elements (figure 3b). In order to represent the hysteretic steel elements (steel angles and UFPs) the Bouc-Wen spring model [16], [17] and the Giuffré Menegotto-Pinto hysteresis rule ("uniaxialMaterial Steel02") were adopted respectively, in SAP2000 and OpenSees models. Inherent damping was provided using Raleigh damping of 2% in modes 1 and 3 for both models.

The key parameters of the OpenSees and SAP2000 link modelling of the connection between the bracing systems and the beam (as shown in figure 3b) at each level are listed in table 2, in terms of the yielding force \( F_1 \), the initial stiffness \( K_1 \) and the post-yielding stiffness ratio \( K_2/K_1 \). The characteristics of the link elements considered for the beam-column, joint panel and column-foundation are the same reported in Ponzo et al. [11].

| Floor | Mass (kN) | Hysteretic damper | \( F_1 \)  | \( K_1 \) (kN/mm) | \( K_2/K_1 \) |
|-------|----------|------------------|---------|------------------|----------------|
| 1st   | 27.6     | UFP 1            | 13.5    | 1.70             | 0.3            |
| 2nd   | 27.6     | UFP 2            | 10.0    | 1.15             | 0.3            |
| 3rd   | 27.2     | UFP 3            | 6.0     | 0.63             | 0.3            |

4. Experimental results and comparison to model prediction

This paper discusses in detail the experimental results considering a smaller set of two ground motions which provide a good representation of the design spectra (figure 2).

In order to find the natural frequencies of vibration of the experimental model with dissipative rocking mechanisms (Session 2) and with dissipative bracing systems (Session 3), the power spectral density (PSD) estimation [18] of the earthquake signal 196 at PGA level of 50% was carried out. As highlighted from the figure 4, the dissipative bracing systems increased the stiffness of the frame reducing the period of the first mode of vibration in loading direction from 0.58 secs to 0.45 secs. In table 3 the first three periods of the frame were compared with the 2-D OpenSees and SAP2000 numerical predictions. The numerical predictions \( T_{i,num} \) for both models matched well with experimental results \( T_{i,exp} \).

Preliminary shaking table test results of the Pres-Lam specimen with dissipative bracing systems were compared with non-linear dynamic analysis results of the proposed models developed in OpenSees and SAP2000. The key indicators used in order to describe the frames seismic global behaviour are first floor drift and base shear. The local behaviour of hysteretic dissipation of the bracing system was described in terms of force-displacement of the U-shaped Flexural Plates at first level of the structure. The outcomes reported in this work refers to the earthquake inputs Montenegro (ID 196) at PGA level of 50% and Campano-Lucano (ID 291) at PGA level of 75%.

![Session 2](image1.png) ![Session 3](image2.png)

Figure 4. Welch’s Power Spectral Density estimation of experimental testing Session 2 and Session 3.
Table 3. Comparison between dynamic experimental and numerical results of Session 2 and Session 3.

| Mode | $T_{i,exp}$ (sec) | $T_{i,num}$ OpenSees (sec) | $T_{i,num}$ SAP2000 (sec) | $T_{i,exp}$ (sec) | $T_{i,num}$ OpenSees (sec) | $T_{i,num}$ SAP2000 (sec) |
|------|-----------------|-------------------------|--------------------------|-----------------|-------------------------|--------------------------|
| 1    | 0.58            | 0.56                    | 0.55                     | 0.45            | 0.45                    | 0.41                     |
| 2    | 0.13            | 0.12                    | 0.13                     | 0.12            | 0.11                    | 0.12                     |
| 3    | 0.06            | 0.04                    | 0.06                     | 0.06            | 0.04                    | 0.05                     |

Figure 5 shows the numerical predictions of OpenSees and SAP2000 models for the seismic input 196. The prediction of both models presented an adequate representation of global preliminary experimental results, only with few discrepancies of the maximum peak values. The hysteretic behaviour of UFPs dissipaters was reliably predicted by numerical models. It can be observed that the OpenSees model well represented maximum peak values of the base shear, while slightly overpredicting maximum force and displacement of hysteretic steel dampers.

Figure 6 shows the numerical outcomes of OpenSees and SAP2000 braced models, subjected to seismic input 291. Also in this case, both numerical models provided a reliable representation of global and local behaviour recorded during preliminary shaking table results of testing Sessions 3.

As can be observed for both earthquake cases analysed (196 and 291), the comparisons between numerical predictions and preliminary experimental results showed that models constructed with OpenSees and SAP2000 software provided an efficient representation of the seismic response of the braced testing frame. It can be pointed out that the OpenSees model provided non-linear dynamic outcomes with reduced computational time.

For all numerical simulations, the study of the base shear versus drift response showed that numerical models approximated sufficiently well the stiffness of the test frame with dissipative bracing systems. The flag-shaped hysteretic behaviour of the frame was not very prominent because low PGA levels of earthquake input were performed in preliminary shaking table tests.

5. Conclusions

An experimental campaign was performed at the structural laboratory of the University of Basilicata, on a three-storey, two-third scaled post-tensioned timber frame in different testing configurations.

Preliminary shaking table tests are in progress on the specimen with hysteretic steel angles at the base of the columns also equipped with V-inverted timber rods in series with two hysteretic U-shaped Flexural Plates.

This paper focuses on numerical modelling of Pres-Lam timber framed buildings with dissipative bracing systems and with dissipative rocking mechanism at the column-foundation connections. The numerical model was developed in 2-D with two different software: SAP2000 and OpenSees, in order to assess the seismic response of the experimental model. Numerical simulations of both models were compared with the preliminary experimental results of Montenegro earthquake input at PGA level of 50% and Campano-Lucano at PGA level of 75%. Dynamic characteristics, in terms of the first three natural periods of vibration of the test frame without and with dissipative bracing systems were well approximated by numerical models. As expected, the activation of the dissipative bracing system increased the stiffness of the frame, reducing the first period of vibration of 20% respect to the specimen with only dissipative rocking mechanisms.

Non-linear time history analyses performed with SAP2000 and OpenSees models of the braced Pres-Lam frame provided a sufficiently accurate response of the seismic global behaviour in terms of base shear and first floor drift and of force-displacement behaviour of hysteretic UFP dampers. The OpenSees model required less time of processing than the SAP model, with almost the same time of programming. The promising results of numerical models presented in this paper and obtained from
previous works are the basis for further studies aiming to: i) optimize design procedures based on Displacement Based Design method of Pres-Lam structures characterised by hysteretic flag-shaped behaviour; ii) derive the seismic fragility curves and hazard level for each limit state and determine the mean annual frequency of exceeding a threshold level of damage for the proposed high-performance timber buildings with different energy dissipation systems.

Figure 5. Testing Session 3: comparisons between experimental and numerical results of OpenSees and SAP2000 models with dissipative bracing systems for 196 seismic input at 50% of PGA intensity.
Figure 6. Testing Session 3: comparisons between experimental and numerical results of OpenSees and SAP2000 models with dissipative bracing systems for 291 seismic input at 75% of PGA intensity.

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