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BRACED TIMBER FRAME WITH SEMI-ACTIVE DAMPERS

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Abstract

In recent years there has been a growing trend of building tall timber buildings. For this type of structures, it is often necessary to use braced frames to enhance capacity of the lateral load resisting system. Structural systems, with prefabricated members made of timber and connected with unbonded post-tensioning, have recently been developed for buildings. Post-tensioned timber frames have significant lateral load resistance capacity. In addition, the post-tensioning provides excellent self-centering ability.

As more and more tall timber buildings are planned for major urban areas all over the world, it is imperative to find solutions to design them for seismic loading. In addition to the gravity and other lateral load bearing capacity, a practical structure has to have the ability to dissipate seismic energy. With moderate damping properties of the material, it is necessary to provide additional damping mechanisms to achieve ductile performance in the structure.

Recent research indicates that semi-active resettable devices are a promising technology for applications in earthquake engineering. Resettable devices provide an effective means by which the seismic energy can be dissipated. The devices can work either as hydraulic or pneumatic spring elements. They are capable of releasing the stored spring energy at any time. The resettable devices nonlinearly alter the stiffness of the structure instead of altering the structural damping directly.

This paper proposes a timber-steel hybrid braced frame fitted with an energy dissipation device to improve its structural response under earthquake loading. A semi-active resettable device is considered as the energy dissipation device. A numerical model is developed to evaluate the seismic response of the proposed system. The effects of adding the resettable device to the timber frame are evaluated. The initial results of the overall response of the proposed structural system are presented.

Keywords: timber; braced frame; hybrid frame; semi-active damper; energy dissipation.

1. Introduction

Interests in building high-rises with timber have been increasing over the last two decades. Some of these structures are expected to be located in high seismic regions such as the west coast of North America and these buildings are subjected to considerable seismic forces. With low values of modulus of elasticity of timber, reducing seismic drifts is particularly challenging in tall timber structures. One possible alternative is used supplemental damping devices to reduce drifts. Semi-active resettable devices developed over the last two decades have been proven to reduce earthquake-induced displacements effectively [1-4]. Resettable energy dissipation devices are fundamentally hydraulic or pneumatic spring elements that possess the ability to release the stored spring energy at any time. Resettable devices behave essentially as nonlinear springs, where the unstressed position can be reset at any time. This resetting releases all the stored energy in the device, resulting in energy dissipation from the structure to which it is attached. The stored energy, that would normally be returned or restored to the structure in the subsequent reversal of motion, is released and hence dissipated from the structural system [2]. Instead of altering the damping directly, the devices nonlinearly alter the structural stiffness. The device offers great reliability due to its reliance on standard hydraulic or pneumatic concepts, particularly when compared with other semi-active control devices that employ more mechanically and dynamically complicated smart materials. Resettable devices rely on very low power consumption and are subjected to a set of decentralized control logic [3, 4].

This paper describes a study to predict the behavior of a four-story timber frame structure equipped with semi-active resettable dampers during seismic testing. Numerical studies are performed on the test structure both with and without a semi-active resettable tendon to test effectiveness of the damper. The resettable tendon consists of a resettable device, a steel tendon and a steel restraint. Eight different earthquake ground motions at various peak ground accelerations are used as input. Displacement time-histories at the top floor of the structure and base shears at a corner column are utilized to compare the results. The semi-active damper, with considerable energy dissipation capacity, is found to be effective in reducing frame displacements without significant increase in base shear.

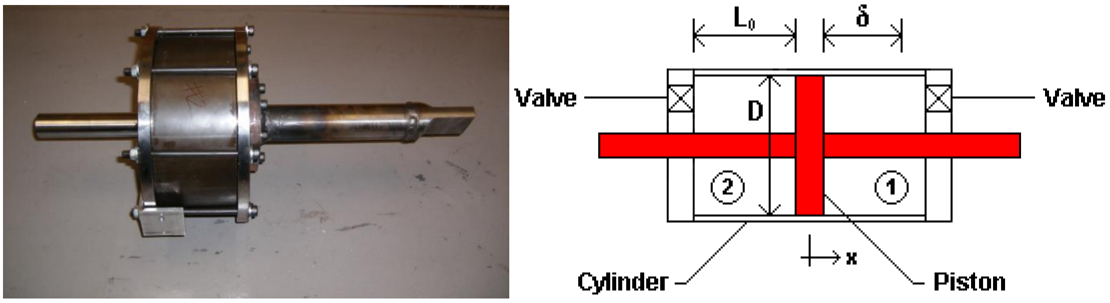
2. Semi-Active Resettable Damper

Semi-active resettable device has been developed in New Zealand in the last decade [2, 4]. The device utilizes air as the working fluid for simplicity and does not require any fluid reservoir. The device has a two-chambered design that enables the use of each side of the device piston independently (Fig. 1). This approach treats each piston side as an independent chamber with its own valve and control arrangement. Independent chamber design allows a wider variety of control laws to be imposed. Each valve can be operated separately, allowing independent control of the pressure on each side of the piston. The resettable device also offers the opportunity to adjust hysteretic behavior by actively controlling the device valves and reset times [4, 6].

The piston located inside the cylinder has four seals to ensure minimal air movement between the two chambers, each of the seals is located in a groove. It is important to notice that such air movement would reduce the effective stiffness and energy dissipated by the device. The end caps are press fitted into the cylinder and held in place by eight clamping rods. An O-ring located between the end caps and the cylinder further ensures no leakage of air. Where the piston shaft passes through the end caps, air is prevented from escaping by two seals located in the end caps. Fig. 2 shows details of the semi-active resettable device and typical force-displacement plot.

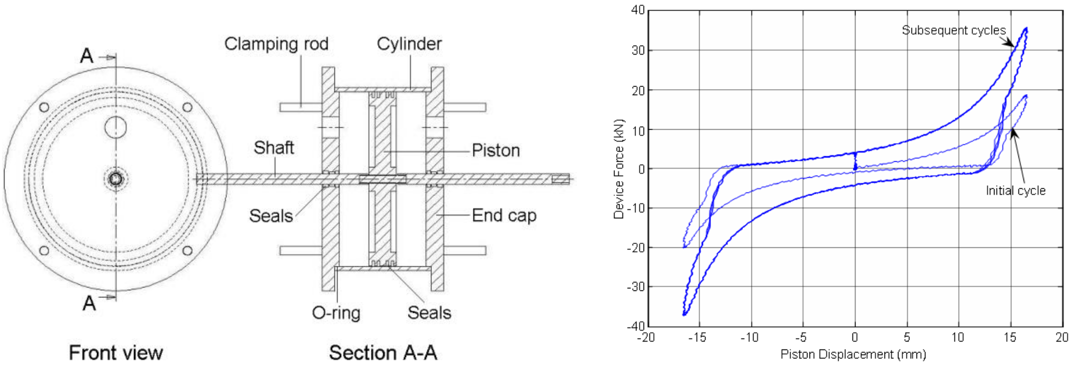
The size of the device and the nominal stiffness required from the device are the principal considerations for the design of the resettable device. Size restrictions may be present during the implementation of the device in structural applications. The device stiffness in turn determines the magnitude of the resisting forces delivered by the device. Additionally, the development of particular forces at specified piston displacements also takes into consideration the size parameters and the stiffness [7]. The fundamental design parameters of the device are the individual chamber length L_0, the maximum piston displacement δ, where $\delta \leq L_0$, and the piston diameter D. The design parameters are shown schematically in Fig. 1. These parameters can be used to control the stiffness of the device [4, 7].

The nominal device stiffness is dependent on the initial chamber volume and the rate of change of the chamber volume with piston displacement. Both the chamber volume and rate of change of the chamber volume are themselves functions of the device diameter and length, with respect to a given input motion. The semi-active resettable device was designed for a nominal stiffness of 250 kN/m. The device stiffness can be altered by changing the piston design and the chamber length and thus modifying the initial chamber volumes [7]. The resisting force delivered by the device depends on the differential pressure between the two chambers of the device. Therefore, the larger the differential pressure the larger the resisting force produced by the semi-active resettable device.



(a) Resettable device (b) Two-chambered design

Fig. 1 – Semi-active resettable device



(a) Schematic of the resettable device (b) Experimental force-displacement curve

Fig. 2 – Schematic of the test device and force-displacement relationship

The dynamic characteristics of the resettable device were identified by experimental tests done as part of earlier research exploring the response to various input signals. Additionally, the impact and efficacy of different device control laws in adding supplemental damping were investigated. Particular focus was given to the amount of time required to dissipate large amounts of stored energy and its impact on performance, as well as the impact of different control laws on the resulting hysteresis loop. Once the device was characterized, a detailed model was created and validated experimentally [4, 7]. Fig. 2 shows experimental results for the device when subjected to a sine wave input at a frequency of 1 Hz and amplitude of 16.5 mm. The force-displacement curve corresponds to the 1-2-3-4 control law described below. It can be seen that the peak force developed at 16.5 mm displacement is about 35 kN. The frequency of experimental testing is an important factor for practical implementation of resettable devices and should be done at frequencies similar to those expected for earthquake-induced vibrations in structures [6].

The independent control of the device valves enables the re-shaping of hysteretic behavior by using different control laws. The control laws are based on the four quadrants defined by a sine-wave motion cycle and they are termed according to the quadrant of the force-displacement relationship in which the device provides resisting forces [4, 6]. Fig. 3 shows the 1-2-3-4 control law used in this research, which provides resisting forces in all four quadrants of the force-displacement curve. The 1-2-3-4 control law is used for controlling the resettable tendon installed in the frame structure considered here.

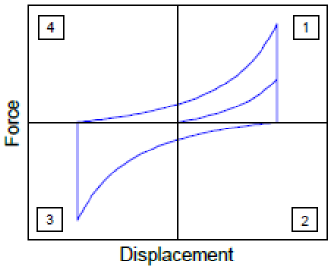
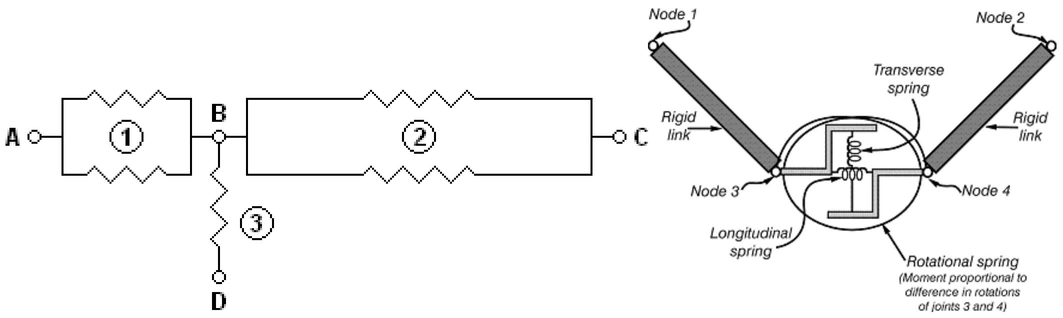


Fig. 3 – 1-2-3-4 control law

3. Modelling of Damper

A numerical model developed as part of the computer program RUAUMOKO [8] is used to simulate the behavior of the resettable tendon. The analytical model of the resettable tendon is shown schematically in Fig. 4a. The model has three main components. All components are modelled as only carrying forces along the axis of the members. The first component simulates the resettable device (1), the second component represents the steel tendon (2) and the third component models the steel restraint element (3). Each of the nodes of the model has three degrees of freedom. All degrees of freedom of the nodes A and D are restrained for fully fixed boundary condition. The horizontal and vertical displacements of the node B are unrestrained; however, the rotation of the node is restrained. The three degrees of freedom of node C are unrestrained [9].

The semi-active resettable device (1) was modelled by utilizing two mechanical springs in parallel. One spring models the hysteretic behavior of the device and the other spring simulates the friction of the device. The spring member available within the RUAUMOKO program and shown in Fig. 4b is used to represent the device. The computational spring member follows the 1-2-3-4 control law shown in Fig. 3.



(a) Model of the resettable tendon (b) Computational spring member

Fig. 4 – Analytical model of the resettable tendon and spring member

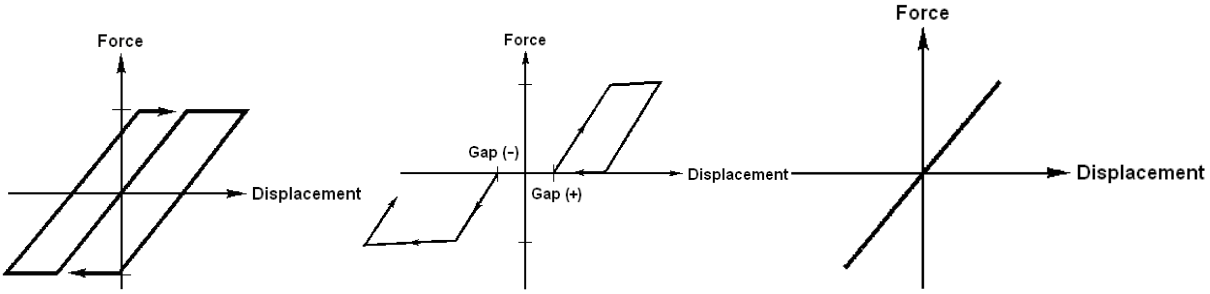
The force developed by the device depends on the pressure of the active chamber and the change in the chamber volume depends on the displacement of the device piston (*x*). For one change in the chamber volume, the resisting force can be calculated as follows:

$$F(x) = sign(\dot{x})p_0 A\left[\left(\frac{V_1}{V_2}\right)^{\gamma} - 1\right] \qquad (1)$$

where γ is the ratio of specific heats, V_1 is the volume of the chamber before the piston displacement, V_2 is the volume of the chamber after the piston displacement, p_0 is the initial pressure (atmospheric), A is the piston area and $\dot{x}$ is the velocity of the device piston.

The device force is set to zero on any change of direction of the displacement. A stiffness of 750 kN/m and a saturation force of 7.295 kN were used to model the hysteretic behavior of the device. These values were obtained by tuning the model according to the experimental results. The following input data based on actual values of the device and working fluid (air) was used in the computer analyses: $p_0 = 100$ kN/m^2, $\gamma = 1.4$, $A = 0.03148$ m^2 and $L_0 = 18$ mm.

A second spring member is utilised to simulate the friction of the device. The spring member follows the elasto-plastic hysteresis rule shown in Fig. 5a. The elasto-plastic spring has a stiffness of 1000 kN/m obtained by fine tuning of the model. A friction force of 430 N based on experimental results [2] was used in the analyses.



(a) Elasto-plastic (b) Bi-linear with slackness (c) Linear elastic

Fig. 5 – Hysteresis rules

The analytical model of the resettable device assumes an ideal behavior of the device response. This includes the assumptions of instantaneous energy release and exactly symmetrical behavior. Instantaneous energy release indicates that the response force returns to zero immediately after the device valve is opened. Symmetrical behavior requires that the center position of the piston is assigned perfectly.

4. Timber Braced Frame with Semi-Active Resettable Damper

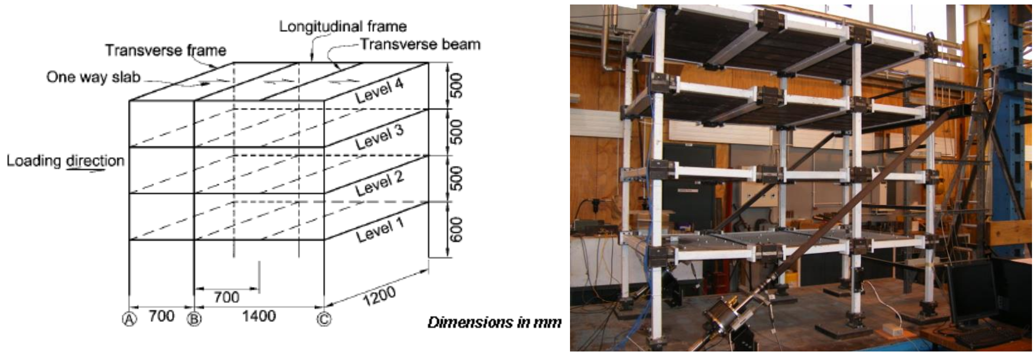


Fig. 6 – Schematic and test model of four-story structure

Numerical model of a four-storied timber frame was analyzed to verify the effectiveness of the semi-active damper with timber braced frames. Dimensions of the model are given in Fig. 6. Cross-sections and material properties of the timber frame were carefully calculated to proportionately represent the structure tested as part of the original investigation.

Eight different earthquake ground motions were used in this investigation, namely El Centro 1940 NS, Taft 1952 S21W, Kobe 1995 N000E, Sylmar County 1994, San Fernando 1971 S16E, Bucharest 1977 NS, Mexico City 1985 S00E and an artificial earthquake. The selected seismic records represent ground motions of vibratory, pulse-type and long-period nature. The amplitude of the earthquake records was scaled to excite the model structure with earthquake ground motions of different intensity.

5. Performance of Braced Frame

Displacements at the top left corner of the frame, with and without resettable brace, subjected to the ground motions are presented in Fig. 7 (a-h). The general reduction in the response of the frame with the damper is clearly visible from the plots underlying the usefulness of the damper in controlling drifts.

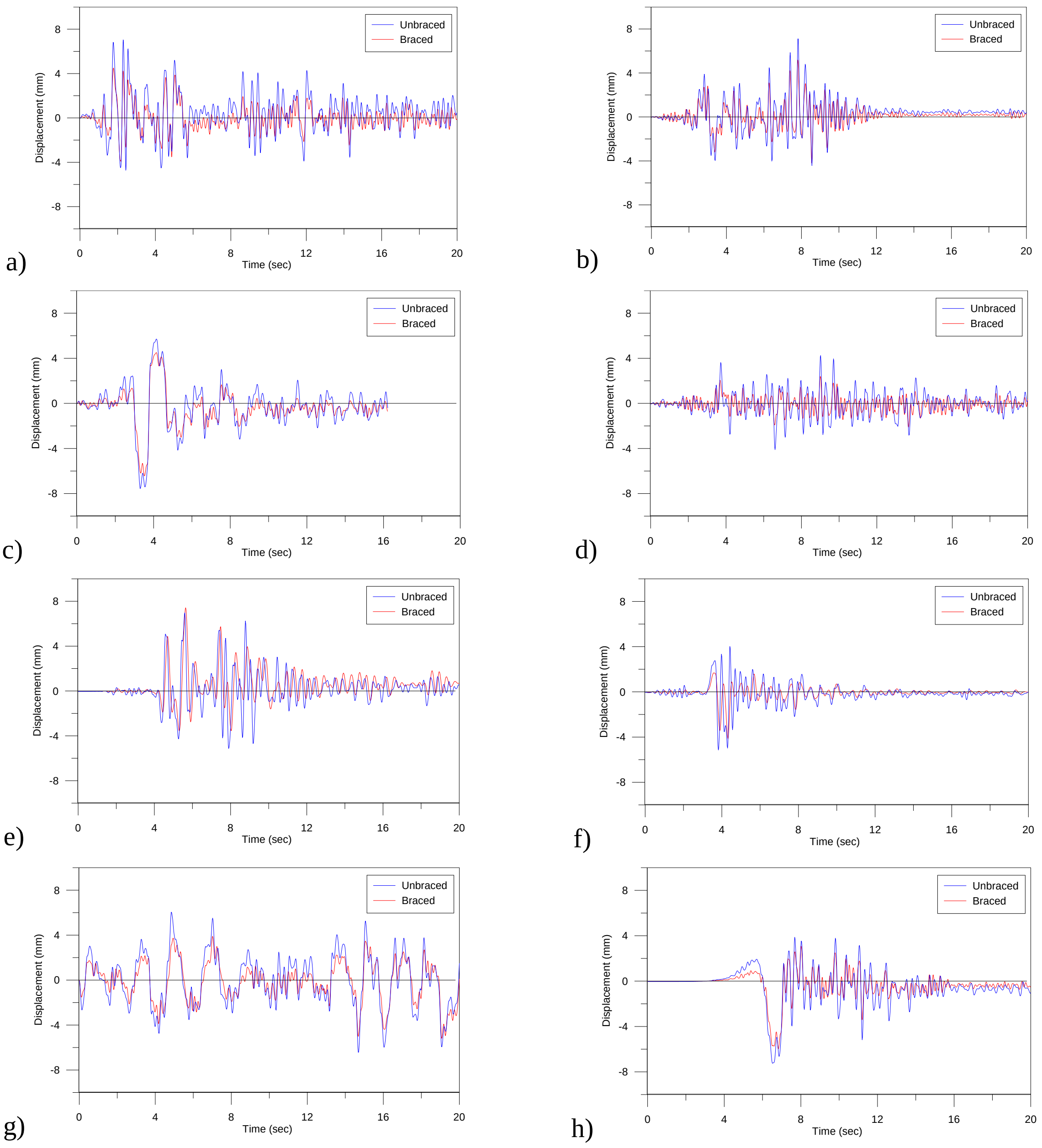


Fig. 7– Displacement at top left corner under: a) El Centro, b) San Fernando, c) Bucharest, d) Taft, e) Kobe, f) Sylmar, g) Mexico City and h) Artificial earthquake

Fig. 8 (a-h) shows the base shears at the left column of the frame under the earthquake ground motions (with and without the damper). Overall, the forces are at comparable level with occasional modest increase in some magnitudes. Significantly, it indicates that the columns can be designed for similar level of forces when the damper is added to the structure.

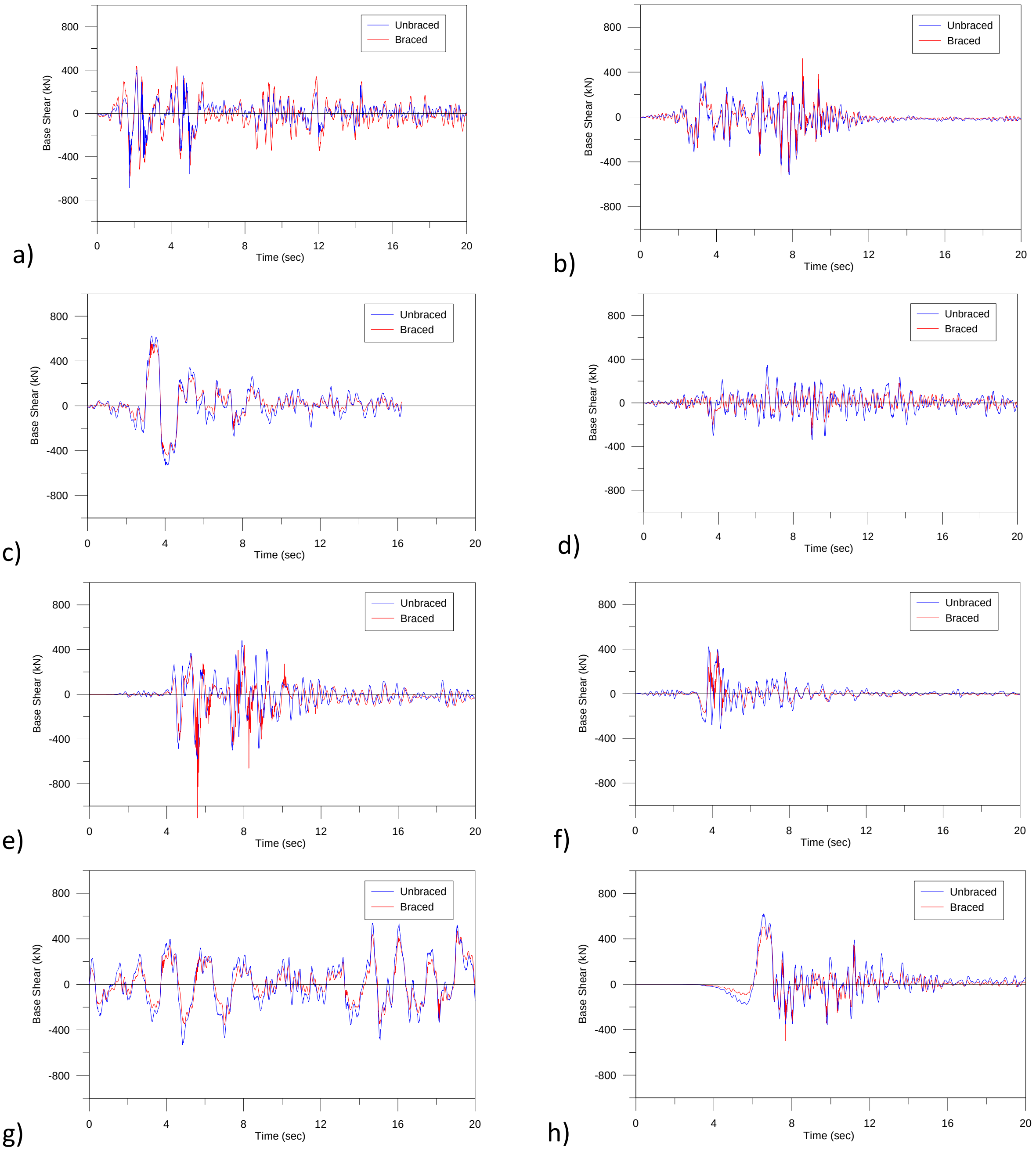


Fig. 8 – Base shear at left column under: a) El Centro, b) San Fernando, c) Bucharest, d) Taft, e) Kobe, f) Sylmar, g) Mexico City and h) Artificial earthquake

Force-displacement plots of the damper for the different ground motions are presented in Fig. 9 (a-h). The maximum forces can be used for designing members and connections of the structure, while the displacements have to be accommodated in the details.

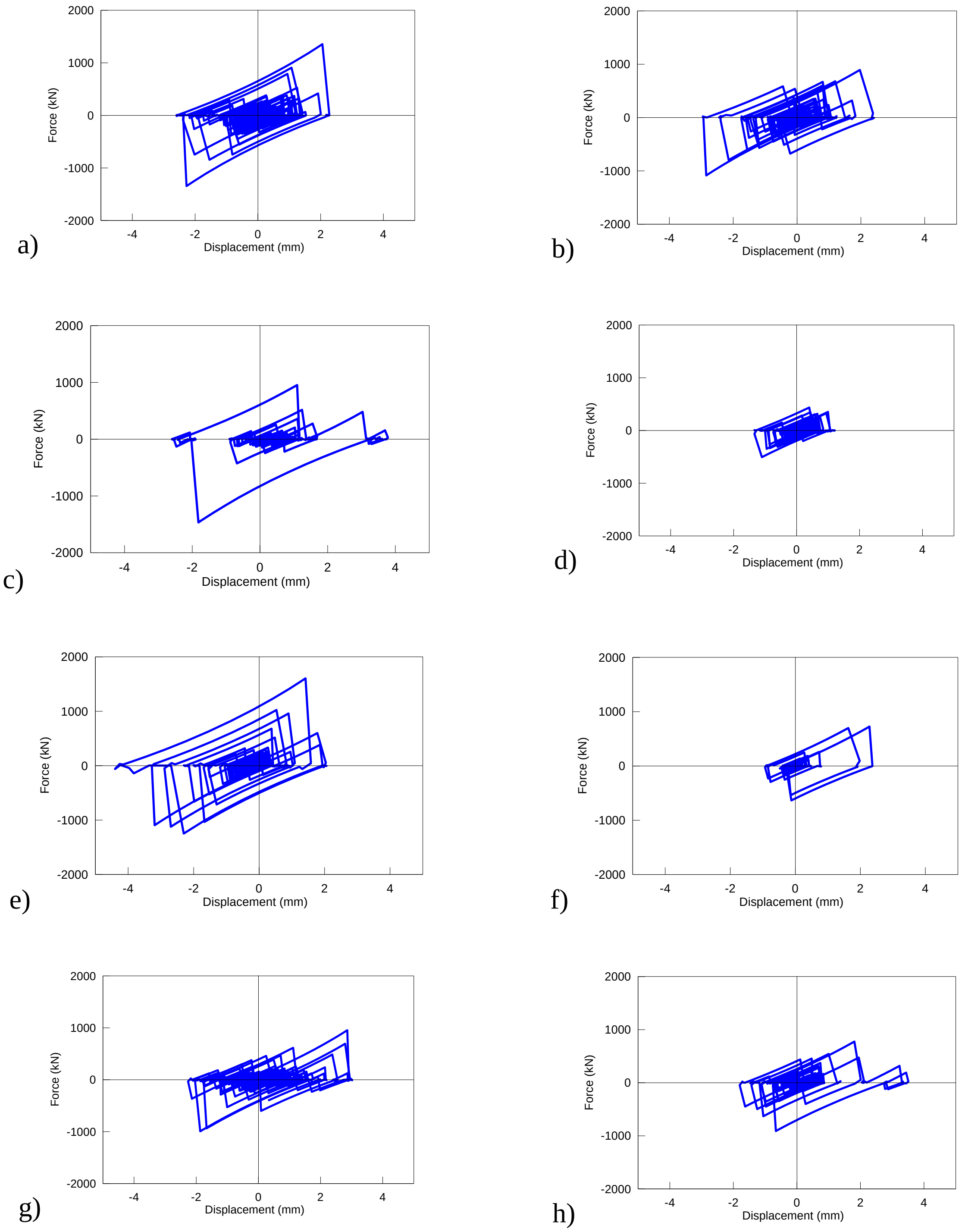


Fig. 9 – Force-displacement plots of damper under: a) El Centro, b) San Fernando, c) Bucharest, d) Taft, e) Kobe, f) Sylmar, g) Mexico City and h) Artificial earthquake

6. Conclusions

The applicability of semi-active resettable dampers with timber frames is investigated through analysis of a numerical model. The earthquake response of a four-storied structure equipped with a semi-active resettable damper is examined. Displacement time-histories at the top and base shear as well as hysteresis are used to identify the effectiveness of the damper. Comparisons of the unbraced and braced frames indicate usefulness of the concept in reducing the displacements without considerable increase in base shear. Significant energy dissipation by the damper is achieved as an additional benefit. Further research is currently ongoing to find more details about this technology and develop guidance for its application in practical structures.

7. Acknowledgements

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