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Seismic Response Reduction of a Timber Frame using Semi-Active Resettable Devices

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ABSTRACT

This paper presents research on a timber frame equipped with a semi-active resettable tendon to reduce the seismic response of the frame. The research involves analytical studies of a four-story timber frame subjected to seismic excitations and controlled by a semi-active resettable tendon. An experimentally validated resettable device is considered as the energy dissipation device. A numerical model is developed to evaluate the seismic performance of the control system. Eight earthquake ground motions are used to investigate the seismic response of the structural system. The effects on the seismic response induced by the addition of the semi-active resettable tendon are evaluated. Significant reductions in floor displacements and base shear of the timber frame are achieved for all the selected earthquake ground motions.

Keywords: seismic response reduction, energy dissipation, timber frame, resettable device, semi-active control.

INTRODUCTION

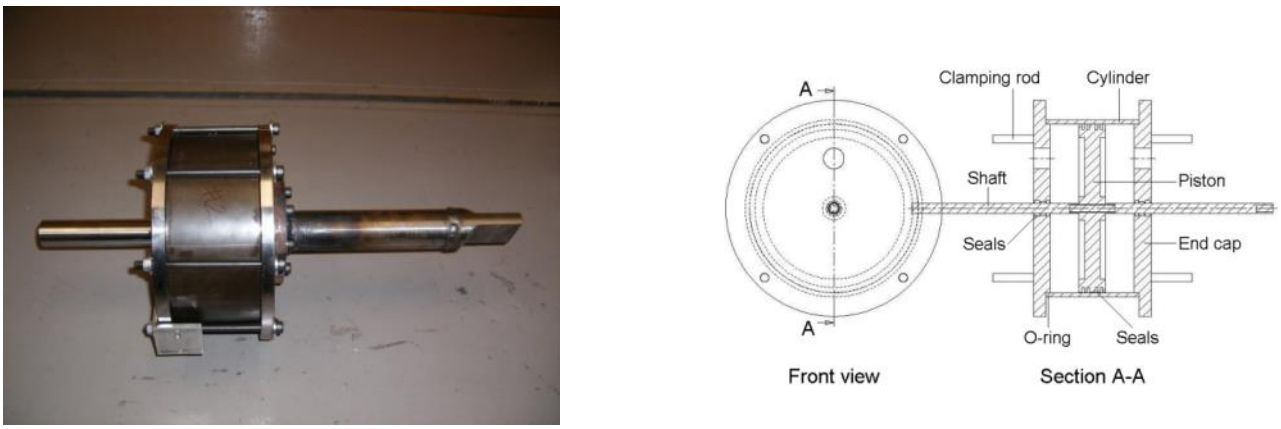
The construction of multi-story timber buildings in major urban areas of the world has greatly increased in recent years. Tall timber buildings can be prone to large amplitude vibrations due to strong winds and large earthquakes. The suppression of excessive vibration in a tall building can be managed, with limited success, in a variety of ways. Additional stiffness can be provided to reduce the vibration period of the building to a less sensitive range. Changes in the building mass can be effective in reducing seismic loads and excessive wind-induced excitations. Aerodynamic modifications to the shape of the building can result in reduced vibrations caused by wind. However, these traditional methods can be implemented only up to a point, beyond which the solution may become unworkable because of other design constraints, such as cost, space, or aesthetics. To achieve reduction in the vibration response, a practical solution is to install energy dissipation devices at discrete locations of the building to supplement its natural energy dissipation and/or absorption capability [1].

Semi-active resettable devices are an emerging technology that effectively improves the earthquake response of structures [2, 3]. Resettable energy dissipation devices are mainly used to reduce earthquake-induced displacements of the structure. The devices behave as nonlinear springs with adjustable mechanical characteristics. Resettable devices manipulate the stiffness properties of the structure and are able to develop large resisting forces. The basic design of the resettable device is feasible for both pneumatic and hydraulic implementations. Besides, the device employs relatively simple mechanisms and control logic. Resettable devices offer great reliability due to their reliance on standard hydraulic or pneumatic concepts, particularly when compared with other semi-active devices that employ more mechanically and dynamically complicated smart materials. The devices rely on very low power consumption and are subjected to a set of decentralized control logic. Resettable devices mitigate the seismic vibration of the structure that otherwise would cause higher levels of response and severe damage to the structural components.

This paper proposes a semi-active resettable tendon to reduce the seismic response of a four-story model structure. The semi-active resettable tendon consists of a resettable device attached to a steel tendon and connected to a steel restraint. The four-story frame structure is a one-fifth scale structure used for seismic testing. An analytical study is carried out to investigate the performance of the four-story structure subjected to earthquake excitations and controlled by the resettable tendon. Numerical simulations are performed on the test structure, with and without resettable tendon, to evaluate the effectiveness of the semi-active control system. The seismic response of the structure is analyzed using eight different earthquake ground motions at various peak ground accelerations. Force-displacement graphs are presented to show the hysteretic behavior of the resettable device. Displacement time-histories at the fourth floor and base shear at a corner column are used to compare the results. It is found that the proposed semi-active resettable tendon is effective in reducing floor displacements without significant increase in base shear.

SEMI-ACTIVE RESETTABLE DEVICE

An experimentally validated resettable device [4, 5] is proposed in this research to reduce the earthquake response of a four-story test structure. A photograph of a one-fifth scale prototype of the resettable device is shown in Figure 1(a). This novel device has a two-chambered design that allows the use of each side of the device piston independently. This approach treats each side of the piston as an independent device chamber with its own valve and control. Each valve of the device can be operated independently that allows the independent control of the pressure on each side of the piston. Therefore, the two-chambered design of the device enables a wider variety of control laws to be implemented. Figure 1(b) shows a schematic of the two-chambered design of the resettable device.



(a) *(b)*

Figure 1. Semi-active resettable device: (a) One-fifth scale prototype, (b) Two-chambered design.

The resettable device also has the ability to sculpt or re-shape the structural hysteretic behavior, because of the possibility to control the device valve and reset times actively [6, 7]. In addition, the device uses air as the working fluid for simplicity and can thus make use of the surrounding atmosphere as the fluid reservoir. The dynamic characteristics of the resettable device were identified by experimental tests exploring its 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 computer model was created and validated experimentally [8, 9].

FOUR-STORY TIMBER FRAME

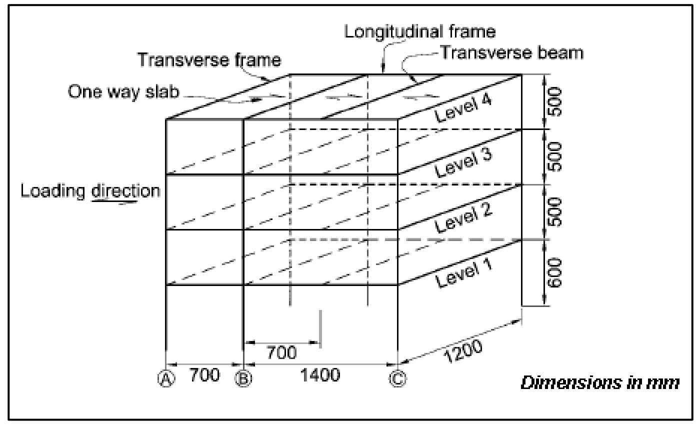
The four-story model structure shown in Figure 2(a) is used to analyze the seismic performance of the semi-active resettable device. The one-fifth scale structure is widely used for earthquake simulation testing in the Department of Civil and Natural Resources Engineering at the University of Canterbury, New Zealand [4, 5, 10].

The test structure is a 2.1 m high three-dimensional four-story frame structure. The two frames in the longitudinal direction provide the lateral load resistance. The frames are built using square hollow steel sections for the beam and column members Each frame has two bays with 0.7 m and 1.4 m long spans. The short bay is to show earthquake dominated response, while the long bay is to show gravity dominated response by having an extra point load induced by a transversal beam at the mid-span at each level. In the transversal direction, three one-bay frames with 1.2 m long span provide lateral stability and carry most of the gravity load. The beam-column joints and other connecting components are made of steel flat bars. Figure 2(b) shows an isometric view of the one-fifth scale structure.

The steel moment-resisting frame structure is built to respond in a similar manner of a full-scale building. The test structure has a similar natural frequency of a full-scale building, of approximately 0.6 seconds, rather than a natural frequency defined by laws of similitude. Since a large amount of added mass is required to achieve the same natural period, a one-way floor slab on each floor level provides a significant proportion of the model mass. The slab is made of steel planks and is connected to a rigid steel plate that acts as a diaphragm. The planks are simply supported on the beams of the transversal frames and on the intermediate beam supported by the long span beams of the longitudinal frames.

A main feature of the test structure is the incorporation of replaceable fuses located in critical regions of the structure to show the effects of inelastic structural performance under earthquake loading. The replaceable yielding fuses are made of steel flat bars. Structural connections designed with yielding fuses accurately represent the full-scale structural behavior and provide the capacity to re-use the test structure after yielding has occurred by replacing the fuses.

(a)



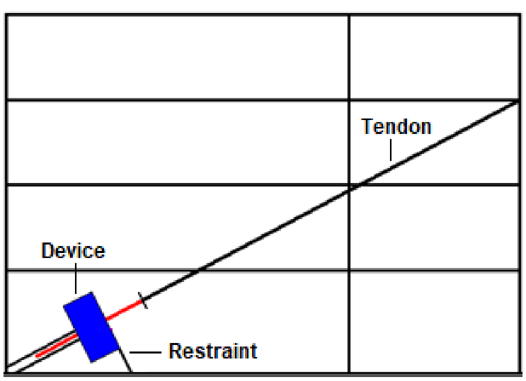
(b)

Figure 2. Four-story one-fifth scale structure: (a) Photograph of structure, (b) Isometric view of structure.

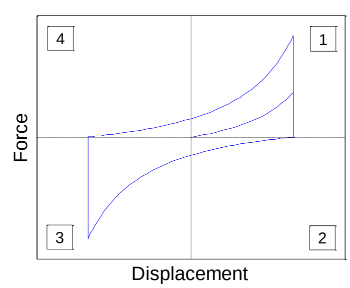
A two-dimensional computer model of the one-fifth scale structure was originally developed by Kao [10]. In this research, the computer model is modified to investigate the seismic response of the test structure as a four-story timber frame. All the elements, connections and material properties of the timber frame are calculated to accurately represent the original four-story test structure. A two-dimensional instead of a three-dimensional analysis is chosen. This is due to the response of the transversal frames and the out-of-plane behavior of the members are insignificant, and a two-dimensional analysis would give sufficient required information.

IMPLEMENTATION OF THE CONTROL SYSTEM

The control system proposed in this research uses a resettable device installed at the lower end of a steel tendon element. The steel tendon element is placed along the two bays and is connected to the test structure at the third floor to transfer the control forces. The control forces developed by the device are based on feedback from sensors that measure the excitation and/or the response of the structure. A steel restraint element prevents the lateral movement of the device and steel tendon and provides stability to the entire system. This control configuration is chosen based on extensive nonlinear finite element investigation of several device architectures. The semi-actively controlled resettable tendon basically connects the seismic center of mass of the first-mode dominant structure to the ground. Figure 3(a) shows a schematic of the resettable tendon configuration.



(a)



(b)

Figure 3. Control system implementation: (a) Tendon configuration, (b) 1-2-3-4 control law.

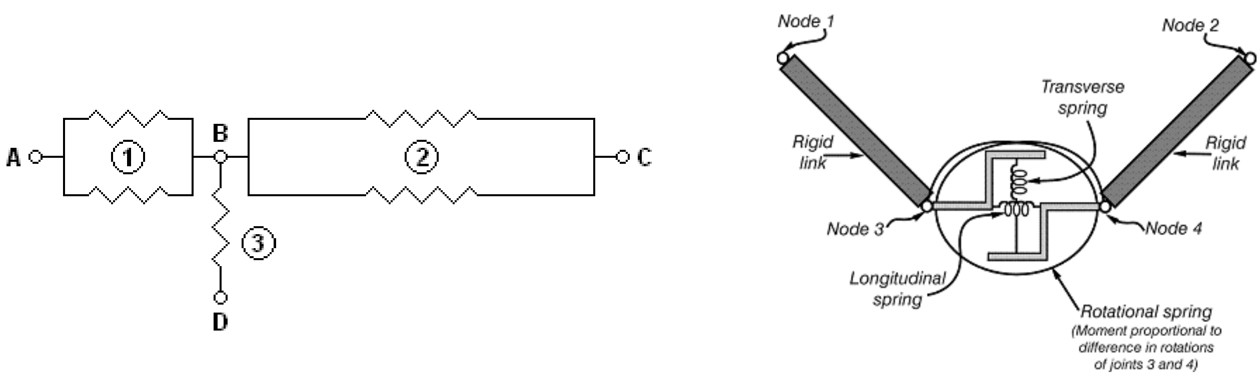
The two-chambered design of the resettable device enables different control laws to be imposed because each valve can be operated independently. This allows independent control of the chamber pressure on each side of the device piston. During a seismic event, the responses and loads of the building are measured by sensors and sent to a control computer. The control computer processes the responses according to a predetermined control algorithm and sends an appropriate command signal to the device valves.

The independent control of the two device valves enables the re-shaping of the hysteretic behavior by using different control laws [6, 7]. Control laws are based on the four quadrants defined by a sine-wave motion cycle. The laws are termed according to the quadrant of the force-displacement graph in which the device provides resisting forces. Figure 3(b) shows the 1-2-3-4 control law studied here. This control law provides resisting forces in all four quadrants of the force-displacement curve.

SEMI-ACTIVE RESETTABLE TENDON

A numerical model is developed for application in the RUAUMOKO computer program [11] to simulate the behavior of the resettable tendon used in this research. The analytical model of the resettable tendon is shown schematically in Figure 4(a). The model has three main components [9]. All model 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. The degrees of freedom of nodes A and D are restrained for fully fixed boundary condition. Horizontal and vertical displacements of the node B are unrestrained however the rotation of the node is restrained. The three degrees of freedom of the node C are unrestrained.

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



(a) *(b)*

Figure 4. Analytical modelling: (a) Model of resettable tendon, (b) Computational spring member.

The force developed by the resettable device depends on the differential pressure between the two chambers. The greater this differential pressure, the greater the resisting force produced. The base pressure is the pressure in the chamber before the air is pressurized due to a change in chamber volume caused by the displacement of the device piston (x). For one change in the chamber volume, the resisting force can be calculated as follows:

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

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 are used to model the hysteretic behavior of the resettable device. These values are obtained by tuning the model according to experimental results [9]. The following input data, based on actual values of the device and working fluid (air), is used in the computer analyses: p_0 = 100 kN/m^2, γ = 1.4, and A = 0.03148 m^2.

A second spring member is used to model the friction of the device. The spring member follows the elasto-plastic hysteresis rule shown in Figure 5(a). The elasto-plastic spring has a stiffness of 1000 kN/m obtained by fine tuning of the computational model. A friction force of 430 N based on experimental results [4] is used in the analyses.

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.

Two mechanical springs placed in parallel are used to model the steel tendon. The assemblage tolerances and slackness of the steel tendon are accounted for by using one of the springs. The second spring is used to numerically stabilize the system. Two spring members are used to model the mechanical springs.

The assemblage tolerances and the slackness of the tendon are modelled by using one of the spring members with the bi-linear with slackness hysteresis shown in Figure 5(b). This hysteresis is used to represent diagonal-braced systems where yield in one direction may stretch the members leading to slackness in the bracing system. The hysteresis allows for either yield in compression in a cross-braced system or for simple elastic buckling in compression which is more appropriate in a single-braced member [11].

To find the appropriate slackness value (gap length) of the steel tendon is a difficult task. Computer simulations show that any small variation of the slackness value has a significant impact on the seismic response of the frame structure. Besides, the dynamic properties of the structure are affected dramatically. It is observed that a variation of 0.01mm in the slackness value considerably modified the natural frequencies of the frame structure. A slackness value of 0.2 mm delivers reliable results and therefore is adopted in the analyses.

The second spring member is mainly used for numerical stabilization. The stabilization is required to provide control of the node B, when the force in the device is zero and the steel tendon is in the gap region shown in Figure 5(b). In this case, none of the components has any stiffness, leading to difficulties in solving the equation of motion at node B. The spring member follows the linear elastic hysteresis shown schematically in Figure 5(c). The stiffness of the steel tendon is 35,430 kN/m. In the computer simulations, 90% of this stiffness value is assigned to the spring with gap and 10% of the value is allocated to the linear elastic spring.

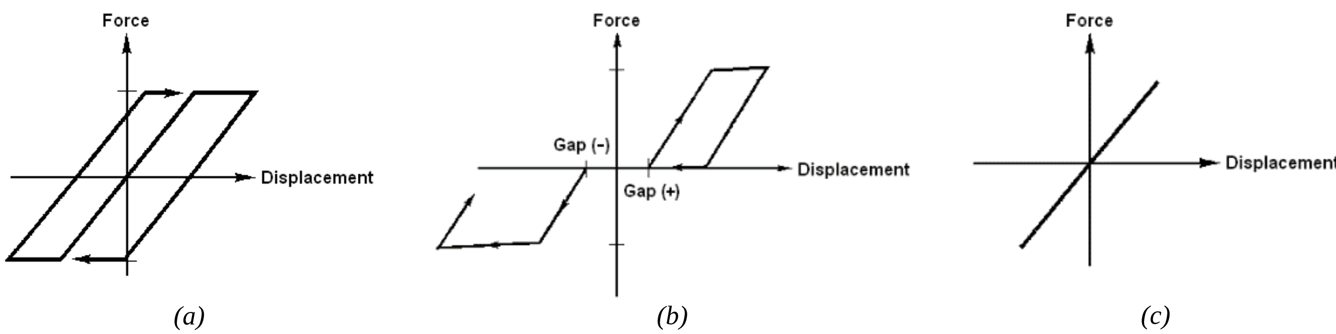


Figure 5. Hysteresis rules: (a) Elasto-plastic, (b) Bi-linear with slackness, (c) Linear elastic.

The numerical model of the resettable tendon is completed by a transversal mechanical spring (restraint). This spring prevents the movement normal to the axes of the other two components of the model and provides stability to the entire system. An assemblage of steel plates serves as the restraint element (3) during a seismic event. The steel plates are fixed to the ground to provide support to the resettable device and to suppress any slipping of the device and consequently of the steel tendon. The restraint element is modelled by using a spring member with the linear elastic hysteresis shown in Figure 5(c). Since a large stiffness is require for this elastic spring, a stiffness value of 180,800 kN/m is used in the numerical simulations.

SEISMIC PERFORMANCE OF THE TIMBER FRAME

Several two-dimensional nonlinear time-history analyses using the RUAUMOKO computer program [11] are carried out to examine the seismic performance of the four-story timber frame equipped with the semi-active resettable tendon.

Eight different earthquake ground motions are used in this research. These earthquakes include 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 earthquake records represent ground motions of pulse-type and long-period nature.

The overall seismic performance of the timber frame is evaluated in terms of reductions in displacements and base shear. The braced frame includes the contribution of the semi-active resettable tendon to the seismic response. Results are presented for comparison to the timber frame without semi-active resettable tendon referred to as the unbraced frame.

Displacement time-histories at the top left corner of the timber frame are presented in Figure 6 (a-h). Significant reductions in the floor displacements of the timber frame fitted with the resettable tendon are clearly visible from the graphs. This underlies the effectiveness of the semi-active resettable tendon for reducing the earthquake response of the timber frame.

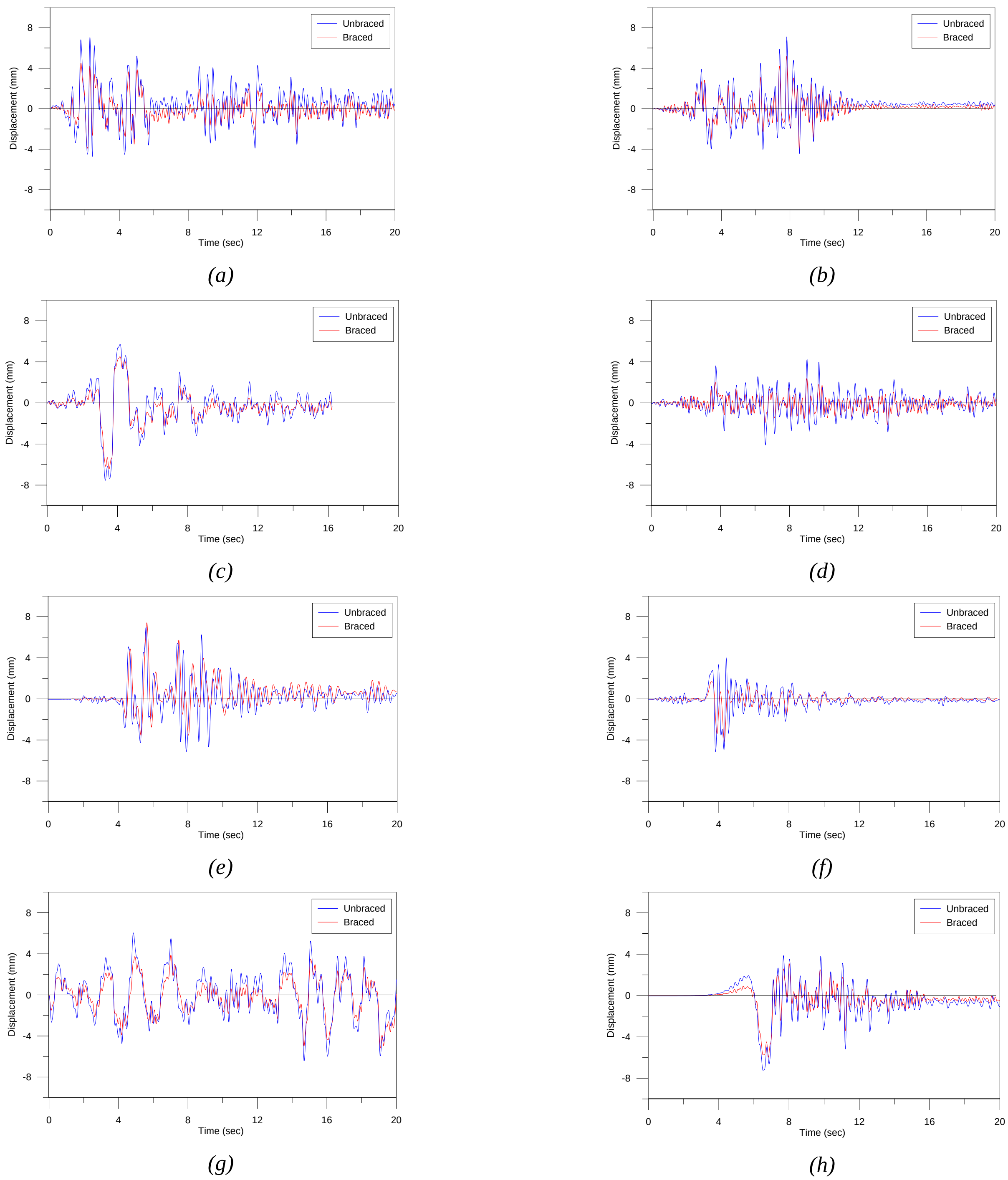


Figure 6. Displacement at the top left corner under: (a) El Centro, (b) San Fernando, (c) Bucharest, (d) Taft, (e) Kobe, (f) Sylmar, (g) Mexico City, (h) Artificial earthquake.

Figure 7 (a-h) shows time-histories of the base shear at the left column of the timber frame. It can be observed that the forces are at comparable level with an occasional modest increase in some magnitudes. It indicates that the columns can be designed for similar force level when the semi-active resettable tendon is added to the timber frame.

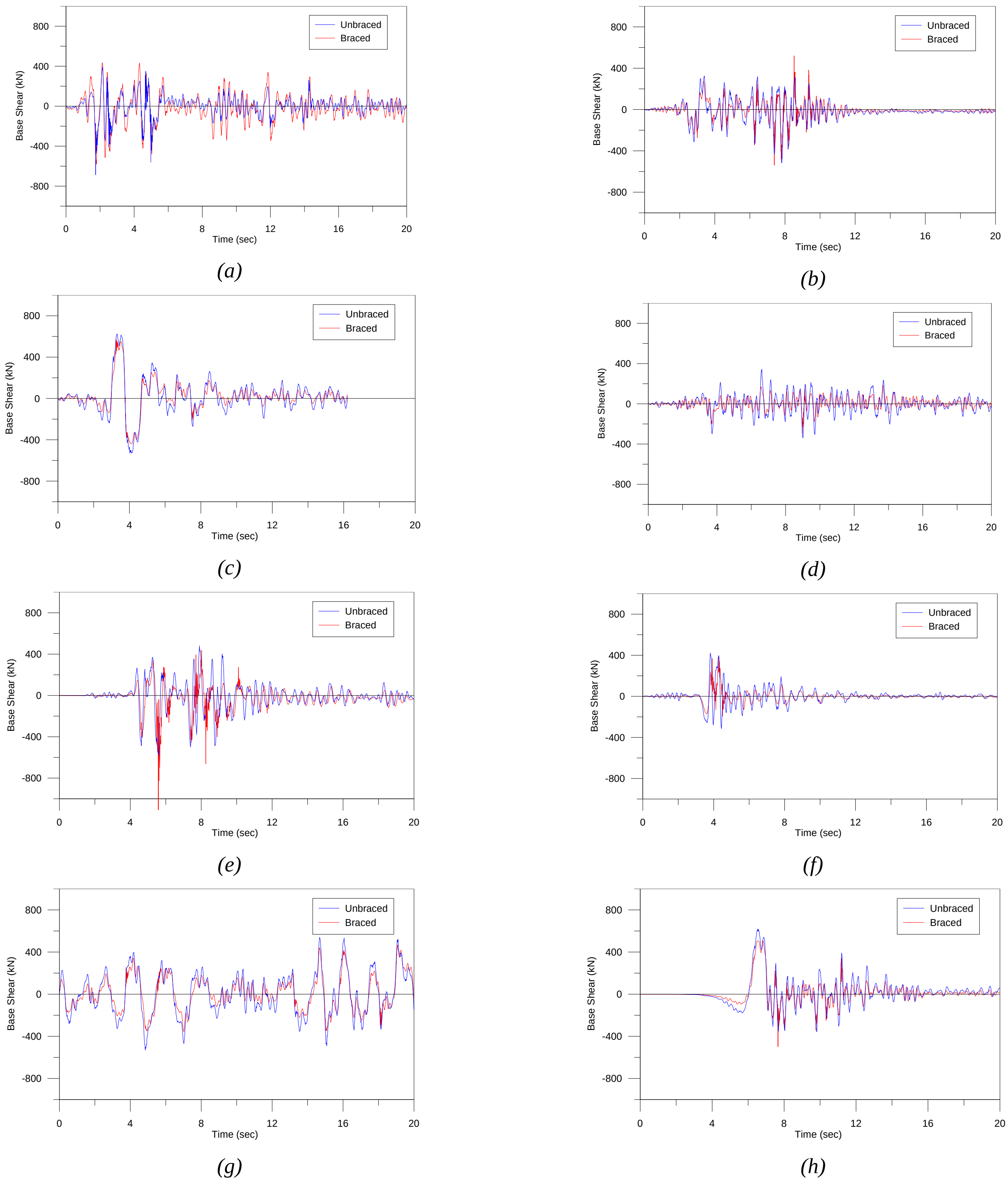


Figure 7. Base shear at the left column under: (a) El Centro, (b) San Fernando, (c) Bucharest, (d) Taft, (e) Kobe, (f) Sylmar, (g) Mexico City, (h) Artificial earthquake.

Since the device valves and reset times can be controlled actively, the resettable device offers the unique opportunity to sculpt or re-shape structural hysteretic behavior to meet different design needs. The hysteretic response of the resettable device can be determined by the control system managing each valve of the device chambers. The 1-2-3-4 control law enables the device to provide resisting forces in all quadrants of the force-displacement curve. Figure 8 (a-h) shows force-displacement graphs of the resettable device for the different earthquake ground motions.

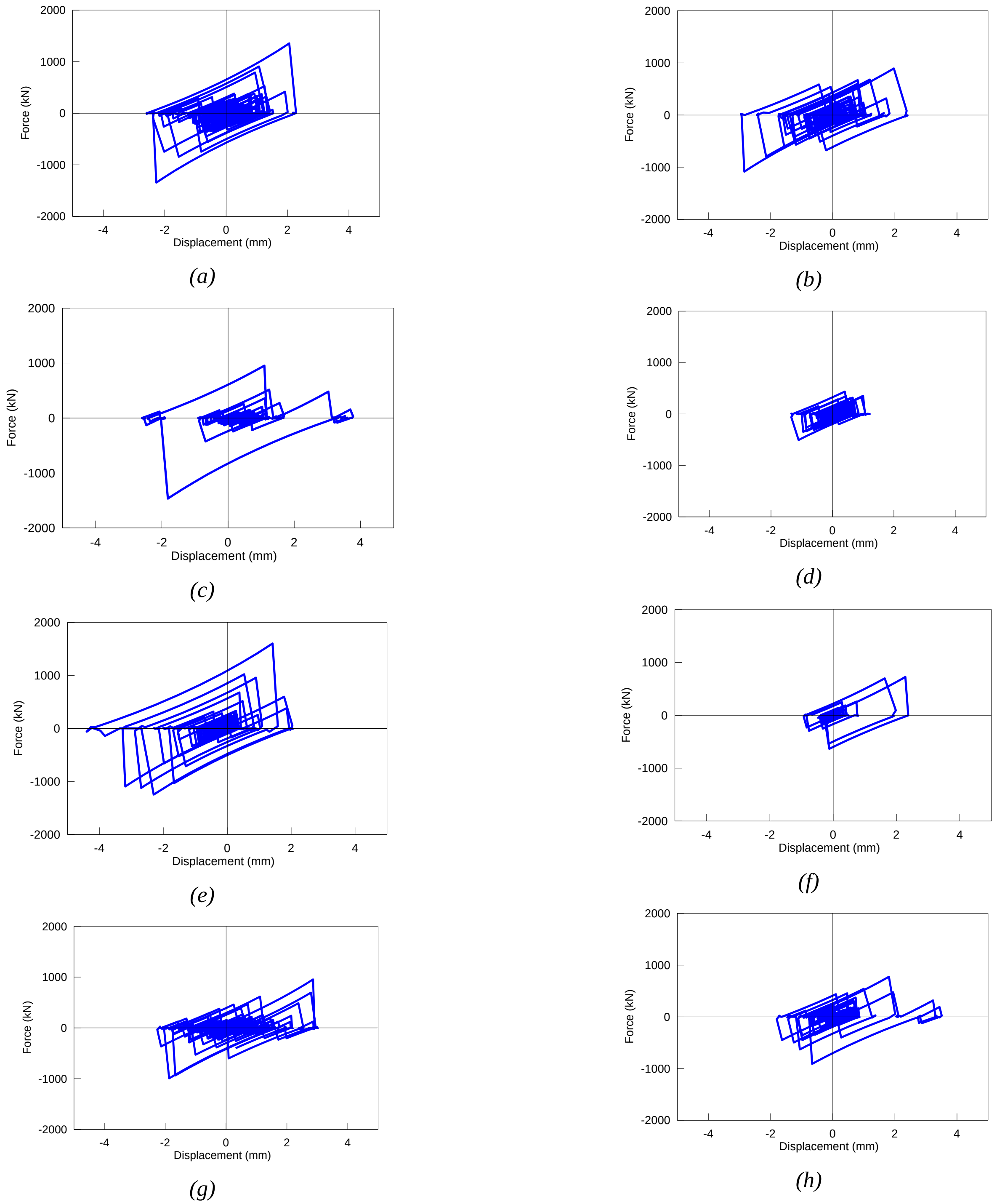


Figure 8. Force-displacement graphs of the resettable device under: (a) El Centro, (b) San Fernando, (c) Bucharest, (d) Taft, (e) Kobe, (f) Sylmar, (g) Mexico City, (h) Artificial earthquake.

CONCLUSIONS

This paper has presented analytical research into the effectiveness of semi-active resettable devices for the seismic response reduction of timber frames. The seismic response of a four-story timber frame equipped with a semi-active resettable tendon is examined. The hysteretic behavior of the resettable device is manipulated by the 1-2-3-4 control law. The timber frame is subjected to eight different earthquake ground motions. Force-displacement graphs are used to show the hysteretic behavior of the resettable device under earthquake loading. Reductions in floor displacements and base shear are used to evaluate the seismic performance of the four-story timber frame.

The addition of the semi-active resettable tendon greatly improves the structural performance of the four-story timber frame under seismic loads. The control system implemented generally results in an improvement of the earthquake response of the timber frame. The 1-2-3-4 control law achieves large reductions in floor displacements without considerable increase in base shear. This finding is particularly important for retrofit applications where reduction in structural displacements is necessary to minimize structural damage, but the foundations may have insufficient strength to meet increased demand. The analytical results demonstrate the significant potential of the semi-active resettable devices for the seismic response reduction of timber frame structures.

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