Experimental Investigation of Semi-Active Resetable Devices for Seismic Protection of Structures

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Abstract

Semi-active resetable devices have recently been considered to reduce the seismic response of civil engineering structures. Resetable energy dissipation devices are fundamentally hydraulic or pneumatic spring elements that possess the ability to release the stored spring energy at any time. Instead of altering the damping directly, resetable devices nonlinearly alter the stiffness of the structure. This paper describes a series of shaking table tests of a four-storey model structure subjected to seismic excitation. The model structure is a one-fifth scale steel moment-resisting frame and aims to model a typical reinforced concrete frame building. Two semi-active resetable devices were installed in the lateral bracing of the model structure to reduce the seismic response. The devices modified the stiffness of the model structure by following a control algorithm that utilised the measured seismic response of the structure. The results of the shaking table tests are presented and interpreted. A new fibre-optic gyroscope was used to measure inter-storey drifts.

Key words: Semi-active control, shake table, inter-storey drift measurement

1. Introduction

Different semi-active control systems have been proposed to reduce the seismic response of civil engineering structures (1). In particular, semi-active resetable devices are quite promising for earthquake engineering applications (2,3,4,5). Semi-active resetable devices are fundamentally hydraulic or pneumatic spring elements. They possess the ability to release the stored spring energy at any time. Instead of altering the damping directly, resetable devices nonlinearly alter the structural stiffness. Resetable devices also offer the opportunity to sculpt or re-shape hysteretic behaviour due to the possibility to control the device valve and reset times actively (5,6).

Semi-active control systems have only recently been considered for applications to large civil structures. Therefore, most of the research in this area has been devoted to analytical and numerical studies in which a number of idealized assumptions are made. The validity of such assumptions must be evaluated through experimental research (1). Experimental testing of semi-active control systems can be helpful to identify important aspects of eventual full-scale implementations, including non-linear structural effects, control-structure interaction, actuator and sensor dynamics, actuator saturation effects, system integration, etc. In addition, experimental testing can be important to detect potential obstacles and limitations for the implementation of semi-active control systems in actual structures.

This paper describes an experimental investigation of a four-storey model structure subjected to seismic excitation and controlled by two semi-active resetable devices. Shaking table tests were performed on the model structure both with and without the semi-active resetable devices. The devices were installed in the lateral bracing of the model structure. The mechanical properties of the devices were modified according to a control algorithm that took into account the measured response of the model structure. The model structure was subjected to four different simulated earthquake ground motions at various peak ground accelerations.

Reductions in relative displacements, absolute accelerations, inter-storey drift ratios and total base shear are used to evaluate the seismic performance of the model structure.

2. Description of the Model Structure

To assess the effectiveness of semi-active resetable devices in reducing the seismic response of structures, a series of shaking table tests were performed on the four-storey model structure shown in Figure 1. The model structure was designed and tested by Kao (7). A main feature of this steel moment-resisting frame structure is the incorporation of replaceable fuses located in critical regions of the structure to show the effects of inelastic structural performance under seismic loading.

Figure 1. Four-storey model structure.

Figure 2. System implementation.

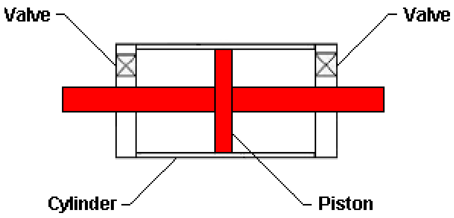
The model building is a 2.1 m high three-dimensional four-storey frame structure. The frames are built using square hollow steel sections for beam and column members. The fuses, beam-column joints and other connecting components are made of steel flat bars. Two frames in the longitudinal direction provide the lateral load resistance. 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 transverse beam at the mid-span at each level. In the transverse direction, three one-bay frames with 1.2 m long span provide lateral stability and carry most of the gravity load. A one-way floor slab 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 transverse frames and on the intermediate beam supported by the long span beams of the longitudinal frames (Figs 1 and 2).

The four-storey model building was designed as a one-fifth scale structure. It was intended to model the structure as a typical four-storey reinforced concrete frame building, therefore, the natural period of the model was required to be within 0.4 s to 0.6 s to obtain similar response under earthquake excitation (7). The equivalent static method, outlined in the New Zealand Loadings Standard NZS 4203: 1993, was employed to calculate the earthquake forces. The seismic weight of the one-fifth scale structure is 35.3 kN. A structural ductility factor of 6 was adopted for the structural design. Thus, the model structure was designed for a base shear force of 8.7% of its seismic weight.

3. Description of the Resetable Device

The resetable device used in this research dissipates energy by using a two-chambered design that utilises each piston side independently (4,5,6). This approach treats each side of the piston as an independent chamber with its own valve and control, as shown in Figure 3. The two-chambered design also allows a wider variety of control laws to be imposed, as each valve can be operated independently, allowing independent control of the pressure on each side of the piston.

During a seismic event, energy is stored in the device by compressing air as the piston is displaced from its centre position. When the piston reaches its maximum displaced position, the stored energy is also at a maximum. At this point the stored energy is released by discharging the air through the device valve. As the piston begins moving in the other direction, the device resists that motion until the next change of direction. Air is used as the working fluid because of its simplicity and the possibility to use the surrounding atmosphere as the fluid reservoir. In combination with independent valves, it allows more time for the device pressures to equalise. Therefore, while the opposing chamber is under compression, the previously reset chamber can release pressure over a longer period of time by having its valve open. This allows significant amounts of energy to be stored and dissipated (4,5,6).



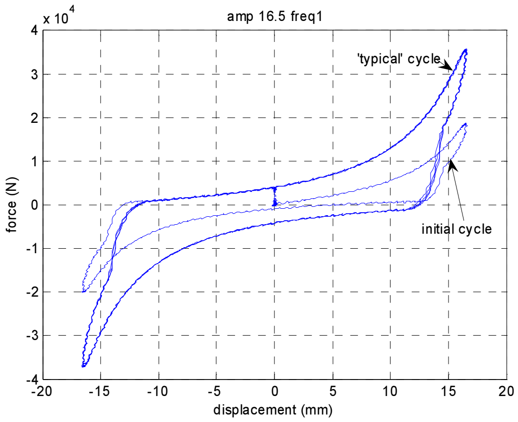


Figure 3. Schematic of the two-chambered design.

Figure 4. Force-displacement curve of the device.

The dynamic characteristics of the device were established by experimental tests exploring the response to various input signals. Additionally, the impact and efficacy of different device control laws in adding supplemental damping was 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 characterised, a detailed model was created and validated experimentally (4,5).

Figure 4 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. It can be seen that the peak force developed at 16.5 mm displacement is approximately 35 kN. The frequency of experimental testing is an important factor for practical implementation of resetable devices and should be done at frequencies similar to those expected for earthquake induced vibrations in structures (6).

Figure 5. Semi-active resetable device.

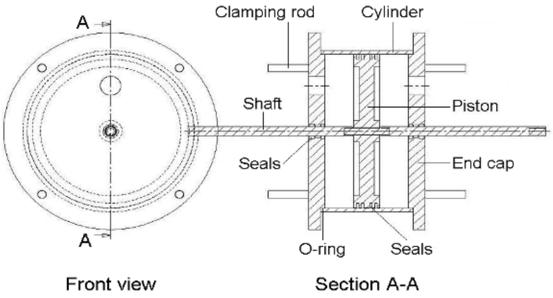


Figure 6. Semi-active resetable device layout.

A photograph of the resetable device is shown in Figure 5. 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. 6). The fundamental design parameters of the device are the diameter, individual chamber length and maximum piston displacement. These parameters can be used to control the stiffness of the device (4,5).

4. Implementation of the Control System

Irrespective of the type of device used, adding supplemental devices to a frame structure involves increasing the lateral stiffness of the structure. However, a reduction in the lateral stiffness may also be observed when a braced-frame structure is replaced by a damper-braced-frame structure (8). An increase in stiffness leads to an increase in the seismic energy input which in turn must be dissipated by the damping devices and/or inelastic action of the structural members. Lateral forces as well as deformations may increase or decrease in the structure, depending on the effect of devices and connections on the dynamic characteristics of the structure, and on the characteristics of the ground motion. Moreover, the magnitude of the increased lateral stiffness in a structure varies depending on the type of device used (8, 9).

The four-storey model structure was tested on a unidirectional shake table. The model structure was bolted to the shake table in such a way that the longitudinal frames of the model were parallel to the motion of the table. The model structure was tested without resetable devices (uncontrolled case) and with two resetable devices (controlled case). Each device was placed at the lower end of a steel tendon element (Fig. 2). The steel tendon element was installed along the two bays and was connected to the model structure at the third floor to transfer the control forces (10).

The dynamic properties of the model structure with and without resetable devices were identified by using free vibration tests. The free vibration tests were carried out by pulling the model structure to one side using a steel wire. After achieving a target floor displacement, the steel wire was cut to allow the structure to vibrate freely. Before attaching the resetable devices to the model structure, free vibration testing was carried out with a maximum 2.5 mm displacement at the top floor to ensure that the test structure remained elastic. The natural period of the structure was found to be 0.44 s with the corresponding equivalent viscous damping ratio of 1.21%.

Experimental tests using a sine wave piston displacement input were undertaken to determine the dynamic characteristics of the semi-active resetable devices. For each of the tests, the frequency and the amplitude of motion of the piston were specified. It was found that higher frequencies produced a higher peak force for the same displacement (4,5).

After the 1994 Northridge and 1995 Kobe earthquakes, engineers realized that the near-source ground motions may be detrimental for tall flexible building structures due to a high initial pulse in the ground acceleration history. Traditional supplemental damping devices may be ineffective to mitigate the effects of this type of ground motion (8). In this research, four different earthquake ground motions were used as input to the shaking table, namely El Centro 1940 NS, Taft 1952 S21W, Sylmar County 1994 and Kobe 1995 N000E. The amplitude of the earthquake records was scaled in order to excite the model structure with earthquake ground motions of different intensity.

Various linear potentiometers and accelerometers were used to measure the response of the model structure and the motion of the shaking table. A linear potentiometer located along the axis of each resetable device was used to measure the displacement of the piston shaft with respect to the device housing. The force in each device was measured by a load cell placed between the device and the steel tendon element. During the shaking table testing, responses and loads of the model structure were measured and sent to a control computer. The control computer processed the responses according to a predetermined control algorithm and sent an appropriate command signal to the device valves. Figure 2 shows a photograph of the system implementation on the model structure.

5. Experimental Results of Shaking Table Tests

An assessment of the effectiveness of the semi-active resetable devices in reducing the seismic response is made by comparing the response of the model structure with and without devices for the same earthquake ground motion. In presenting the shaking table tests results major emphasis is given to the overall response of the model structure. The effects of adding the resetable devices to the model structure are identified from the shaking table tests in terms of relative floor displacements, absolute floor accelerations, inter-storey drift ratios and total base shear (i.e. including the contribution of the semi-active tendon element).

The four-storey model structure was first tested with resetable devices (controlled case) and then without resetable devices (uncontrolled case). Different device control laws were used for the controlled case. The device control law presented in this paper corresponds to the 1-4 device control in which the stored spring energy is released at the peak of each cycle while all other motion is resisted by the device (4,5,6). Several shaking table tests were conducted using the above-mentioned earthquake ground motions at various peak ground acceleration levels. In this paper, maximum response profiles for the following ground motions are presented: El Centro 40%, Taft 40%, Sylmar 10% and Kobe 10% corresponding to peak ground accelerations of 0.14g, 0.07g, 0.08g and 0.08g respectively. These earthquake intensities were chosen in order to prevent inelastic deformations in the model structure during the uncontrolled seismic testing.

Figure 7 shows maximum response profiles for the N-S component of the 1940 El Centro acceleration record scaled by 40% of its actual intensity. A reduction of up to 79% in the maximum relative displacement at the fourth floor is observed (Fig. 7a). A 12% reduction in the maximum absolute acceleration at the fourth floor is achieved (Fig. 7b). The maximum inter-storey drift ratio at the second floor is also reduced by up to 79% (Fig. 7c). The total base shear is reduced by up to 8% (Fig. 7d). The effectiveness of the control system in reducing the seismic response is demonstrated for the El Centro ground motion.

Maximum response profiles are shown in Figure 8 for the 1952 Taft earthquake record scaled by 40% of its intensity. The maximum recorded relative displacement at the fourth floor is reduced by up to 75% (Fig. 8a). A 9% reduction in the maximum absolute acceleration at the fourth floor is observed (Fig. 8b). The maximum inter-storey drift ratio at the first floor is reduced by up to 72% (Fig. 8c). A 21% reduction in the total base shear is achieved (Fig. 8d). These results confirm the effectiveness of the control system to reduce the seismic response under the Taft earthquake record.

Figure 9 shows maximum response profiles for the Sylmar County 1994 acceleration record scaled by 10% of its intensity. A reduction of up to 73% in the maximum relative displacement at the fourth floor is achieved (Fig. 9a). The maximum measured absolute acceleration at the fourth floor is reduced by up to 21% (Fig. 9b). A 72% reduction in the maximum inter-storey drift ratio at the first floor is observed (Fig. 9c). The total base shear is reduced by up to 2% (Fig. 9d). These reductions validate the effectiveness of the control strategy for the Sylmar earthquake ground motion.

Maximum response profiles are shown in Figure 10 for the 1995 Kobe earthquake record scaled by 10% of its original intensity. The maximum relative displacement at the fourth floor is reduced by up to 72% (Fig. 10a). A 17% reduction in the maximum absolute acceleration at the fourth floor is observed (Fig. 10b). The maximum inter-storey drift ratio at the first floor is reduced by up to 75% (Fig. 10c). An 11% reduction in the total base shear is achieved (Fig. 10d). Control effectiveness is demonstrated by using the Kobe acceleration record as input to the shake table.

It can be seen that the absolute floor acceleration increases in some storeys of the model structure (Figs 7b, 8b, 9b and 10b). However, this represents a common trade-off with resetable stiffness-based devices (3). Although increased accelerations may damage contents and/or disturb occupants, this trade-off depends on the building use and on any other isolation or protection systems employed. Figures 7, 8, 9 and 10 show that considerable response reductions are achieved by the semi-active control system. These results demonstrate that semi-active resetable devices are quite effective to reduce the seismic response of structures over a wide range of earthquake excitations.

It must be noted that whilst the maximum deformations and member forces have been reduced using this form of control, the forces transmitted to the foundation by both the structure and the control system have not increased the forces required to be resisted by the foundation. This is because the force in the control system is not purely a function of the displacements of the structure as found in hysteretic control systems, but is similar to that in visco-elastic systems where the control forces are not always in phase with the displacements.

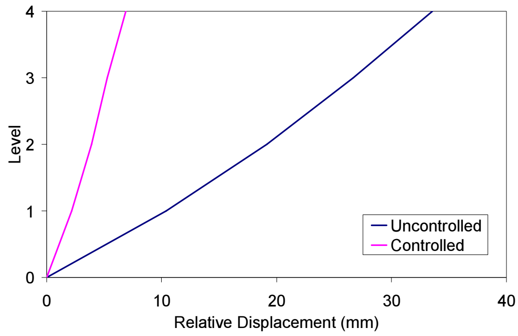
6. Inter-Storey Drift Measurements using Fibre-Optic Gyroscope

Fibre-Optic Gyroscopes (FOGs) are passive interferometers where a light beam is split in two equal parts. These parts then travel around an approximately 1 km glass fibre coil, one in the clockwise and the other in the anti-clockwise sense. When the beam is recombined upon exiting the fibre, it shows a fringe pattern, which depends on the rate of rotation, but does not change with translation. It is important to note that the rotation measured in this way is absolute. Therefore, the measurement device does not require an external reference frame to operate. The shake table measurements have validated the suitability of these sensors for the determination of inter-storey drifts of civil engineering structures, since the relative movement between building floors corresponds to a rotation. In laboratory tests, the inter-storey drifts can be measured using displacement potentiometers with a laboratory fixed reference frame. However, for real structures, the inter-storey drift is not easily determined as there is no reference frame that may be used to measure the floor displacements. Although it is possible to set up a frame attached to the floor below in order to measure the relative displacement at the floor above, this is not a very practical solution. As shown in Figure 11, the FOG is approximately 100 x 80 x 25 mm in size and can be clamped to a member connecting two floors of a structure. The FOG needs to be connected to a computer and a power supply.

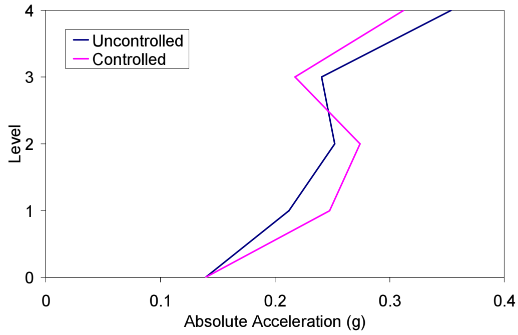
Figure 12 shows a comparison between the floor displacement obtained with the gyroscope (without an external reference) and the displacement obtained by taking the differences from displacement potentiometers on the first floor and the shake table during the experiment. Excellent agreement is obtained between both sensors. The breaks in the FOG data occur when the recorded data is plotted as it is being recorded. Every time that the plot is rescaled, the computer does not poll the FOG for the next block of data. This was not recognised at the time the experimental work was being carried out. The data appeared to be continuous but, in fact, it was not. This problem disappears provided the version of the recording program is used, which does not concurrently plot the results. The results shown here have been corrected to allow for these gaps in the recordings. The FOG was also used to check torsional velocities in the model structure, but as the structure is symmetric, there were only very small torsional motions detected.

The device has more recently been used to measure drifts in the Sky-Tower (356m) in Auckland, New Zealand. Here, the device was clamped to antennae frames on the outside of the tower at level 52 and to window supports at level 60, taking only a few minutes to set up the instrument and start taking readings.

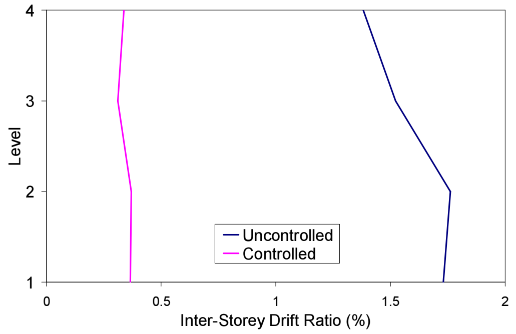
EL CENTRO 40%



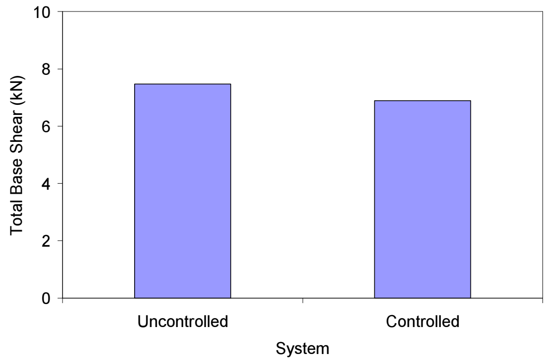
(a) Maximum relative displacements



(b) Maximum absolute accelerations



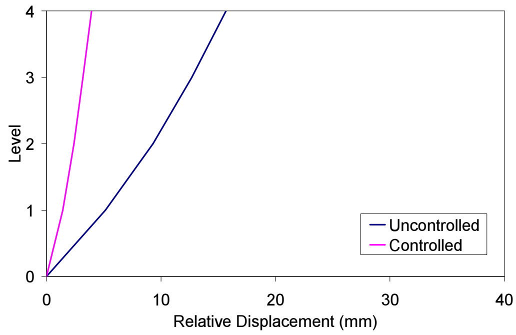
(c) Maximum inter-storey drift ratios



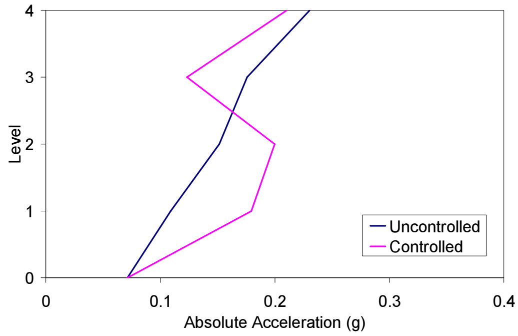
(d) Total base shear

Figure 7. Maximum response envelopes.

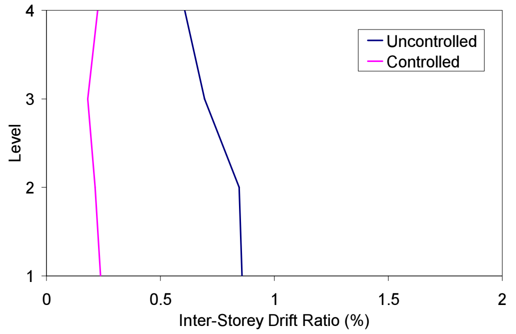
TAFT 40%



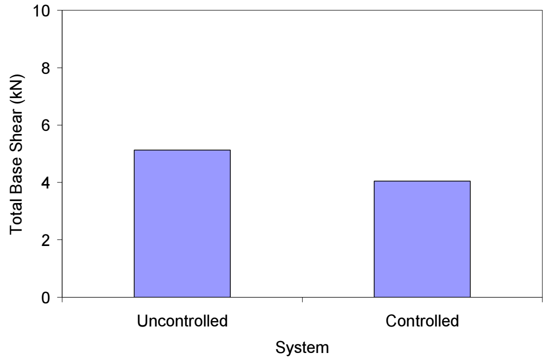
(a) Maximum relative displacements



(b) Maximum absolute accelerations



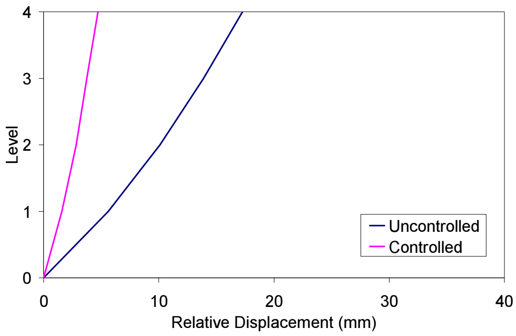
(c) Maximum inter-storey drift ratios



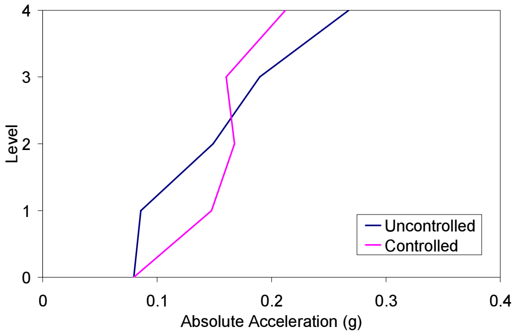
(d) Total base shear

Figure 8. Maximum response envelopes.

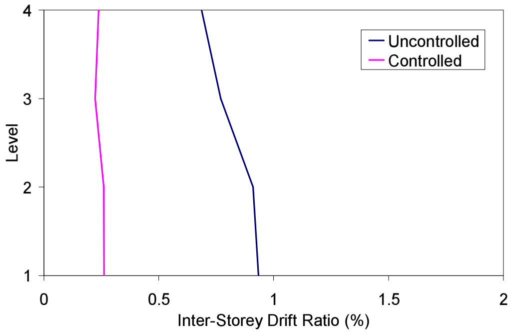
SYLMAR 10%



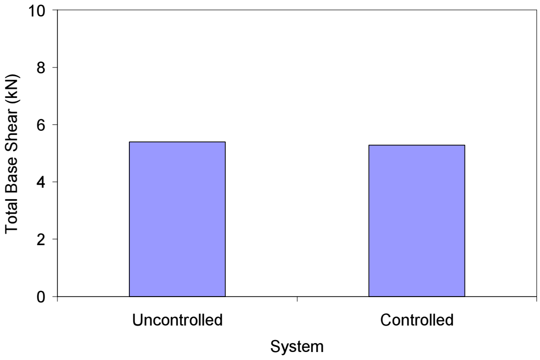
(a) Maximum relative displacements



(b) Maximum absolute accelerations



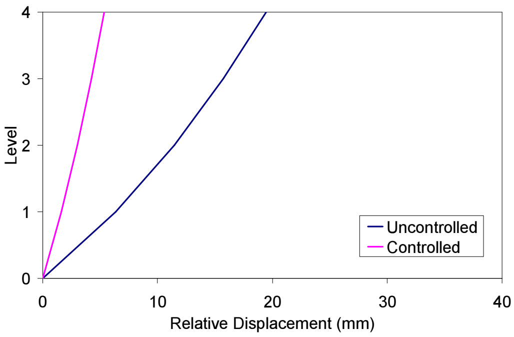
(c) Maximum inter-storey drift ratios



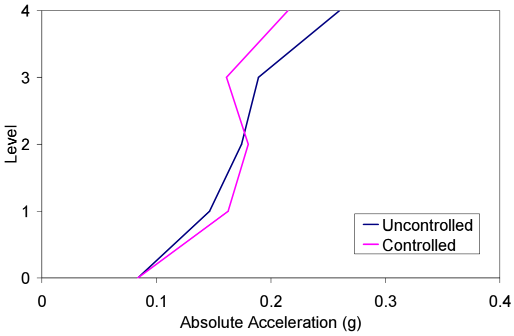
(d) Total base shear

Figure 9. Maximum response envelopes.

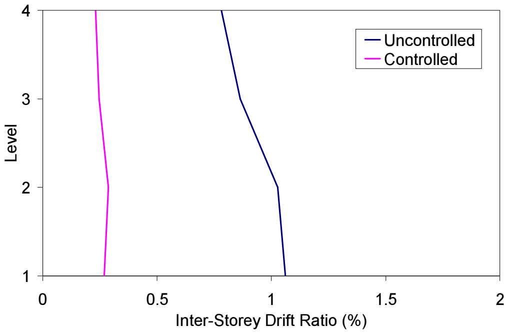
KOBE 10%



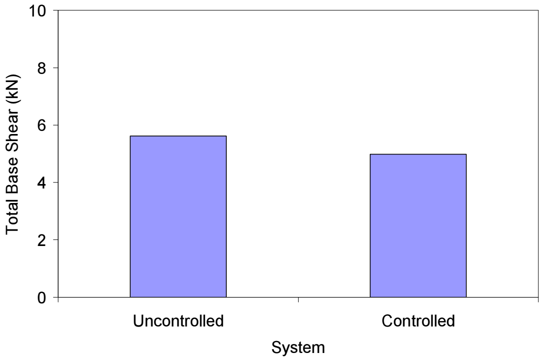
(a) Maximum relative displacements



(b) Maximum absolute accelerations



(c) Maximum inter-storey drift ratios



(d) Total base shear

Figure 10. Maximum response envelopes.

Figure 11. FOG attached to column.

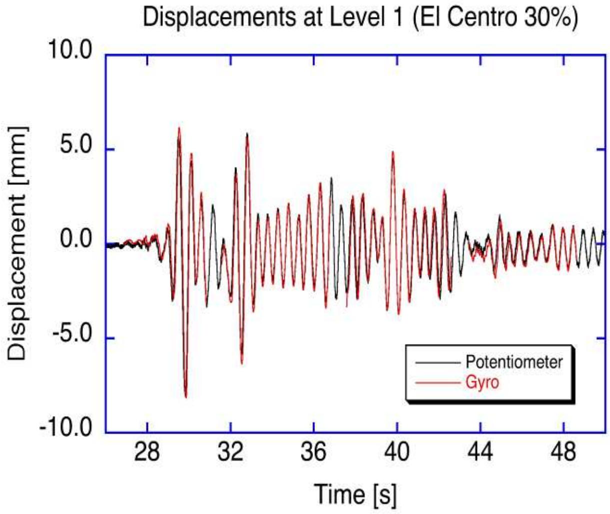


Figure 12. Comparison of floor displacements.

7. Conclusions

This paper has presented an experimental investigation on the effectiveness of semi-active resetable devices to reduce the seismic response of structures. A four-storey model structure was subjected to a series of shaking table tests. The dynamic response of the model structure was controlled by two semi-active resetable devices. The devices were installed in the lateral bracing of the model structure. The resetable devices modified the stiffness of the structure by following a control algorithm that utilised measured structural responses. Four earthquake records at different levels of intensity were used to investigate the effect of the semi-active control system in reducing the seismic response of the model structure. Maximum response profiles for selected earthquake ground motions were presented. Significant reductions in relative floor displacements and inter-storey drift ratios were achieved for all of the earthquakes selected. Modest reductions in total base shear and absolute floor accelerations were also observed. These results demonstrate the significant potential of the semi-active resetable devices for the seismic protection of civil engineering structures.

This paper has also shown the ease of use of a fibre-optic gyroscope (FOG) to measure inter-storey drifts. During the shaking table tests, the FOG was attached to one of the first-storey columns of the model structure. Relative displacements at the first floor were obtained from the measurements provided by the FOG. Good agreement was observed between the displacements obtained with the FOG and those obtained by using a conventional linear potentiometer. These results verified the accuracy of the measurements recorded by the FOG.

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