SEMI-ACTIVE RESETTABLE DEVICES FOR SEISMIC PROTECTION OF CIVIL ENGINEERING STRUCTURES

R. Franco-Anaya[1], A.J. Carr[2] and J.G. Chase[3]

[1] *PhD Candidate, Dept. of Civil and Natural Resources Eng., University of Canterbury, New Zealand*
[2] *Professor, Dept. of Civil and Natural Resources Eng., University of Canterbury, New Zealand*
[3] *Professor, Dept. of Mechanical Eng., University of Canterbury, New Zealand*
[2] *Email: a.carr@civil.canterbury.ac.nz*

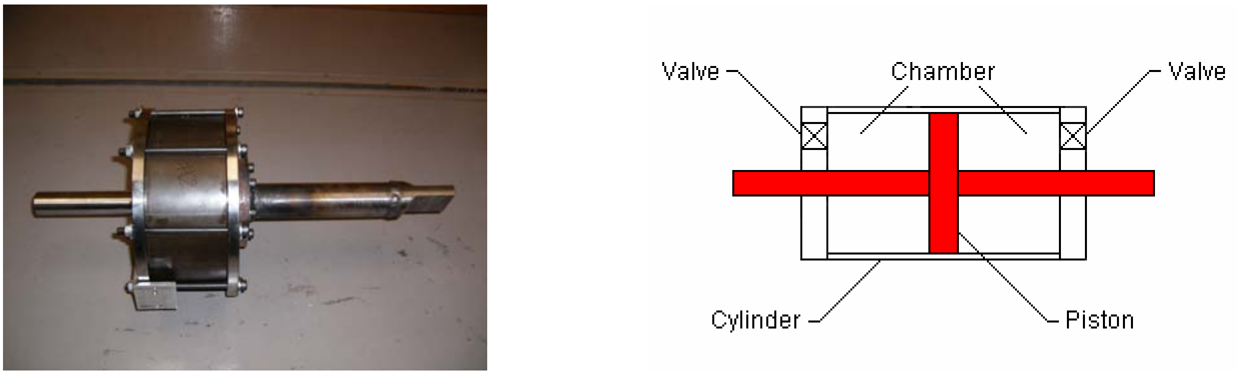
ABSTRACT:

This paper describes analytical and experimental studies into the effectiveness and feasibility of semi-active resettable devices for seismic protection of civil engineering structures. A series of shake table tests were performed on a one-fifth scale structure equipped with two newly developed resettable devices. The devices were installed as part of the lateral bracing of the structure to reduce structural responses induced by different seismic excitations. The independent chamber controlled devices can modify the hysteretic behavior of the structure by using different control laws. The results of the shake table tests are presented and interpreted in this paper. Following the experimental validation of the resettable devices, analytical studies were carried out to investigate the performance of a twelve-storey reinforced concrete building subjected to earthquake loading and controlled by resettable devices. Computer simulations were carried out to determine the optimal utilization of the resettable devices in the structure. In this paper, the optimal distribution of the devices is investigated and the effects of different control laws on the seismic response are discussed.

KEYWORDS: Resettable devices, seismic protection, semi-active structural control.

1. INTRODUCTION

Semi-active resettable devices have recently been considered for structural and earthquake engineering applications (Jabbari and Bobrow 2002, Barroso et al. 2003, Chase et al. 2006, Mulligan 2007). These devices offer several advantages in comparison to other semi-active control devices. Resettable devices manipulate the stiffness properties of the structure and are capable of producing large resisting forces. The basic design of the device used here is feasible for pneumatic and hydraulic implementations, and employs relatively simple mechanisms and control logic. The device offers great reliability due to its reliance on standard hydraulic or pneumatic concepts, particularly when compared to devices that employ more mechanically and dynamically complicated smart materials such as electro-rheological and magneto-rheological fluids. Resettable devices rely on very low power consumption and are subjected to a set of decentralized control logic (Chase et al. 2006).



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

Figure 1. Semi-active resettable device.

In this research, a newly developed resettable device (Chase et al. 2006, Mulligan 2007) is proposed to reduce the seismic response of civil engineering structures. Figure 1a shows a photograph of the semi-active resettable device. This novel device has a two-chambered design that enables the use of each side of the device piston independently. This approach treats each piston side as an independent chamber with its own valve and control. The independent chamber design allows a wider variety of control laws to be imposed, because each valve can be operated independently, allowing independent control of the pressure on each side of the piston. A schematic of the two-chambered device design is shown in Figure 1b. The device also offers the opportunity to sculpt or re-shape structural hysteretic behavior due to the possibility to control the device valve and reset times actively (Chase et al. 2006, 2007, Rodgers et al. 2007). Furthermore, this specific resettable device utilizes air as the working fluid for simplicity and can thus make use of the surrounding atmosphere as the fluid reservoir.

2. EXPERIMENTAL STUDIES

A large number of shake table tests were performed on a four-storey one-fifth scale test structure to assess the effectiveness of the resettable devices in reducing the seismic response of structures. The test structure was designed to model the structural behavior of a typical four-storey reinforced concrete frame building (Rodríguez et al. 2006). The equivalent static method, outlined in the New Zealand Loadings Standard NZS 4203: 1993, was employed to calculate the earthquake forces. A photograph of the test structure is shown in Figure 2a. The four-storey test structure was tested on a unidirectional shake table. The structure was bolted to the shake table in such a way that the longitudinal frames of the structure were parallel to the motion of the table. The test structure was tested without resettable devices (uncontrolled case) and with two resettable devices. Each device was placed at the lower end of a steel tendon. The steel tendon was installed along the two bays and was connected to the test structure at the third floor to transfer the control forces (Franco-Anaya et al. 2007). Figure 2b shows a photograph of the system implementation.

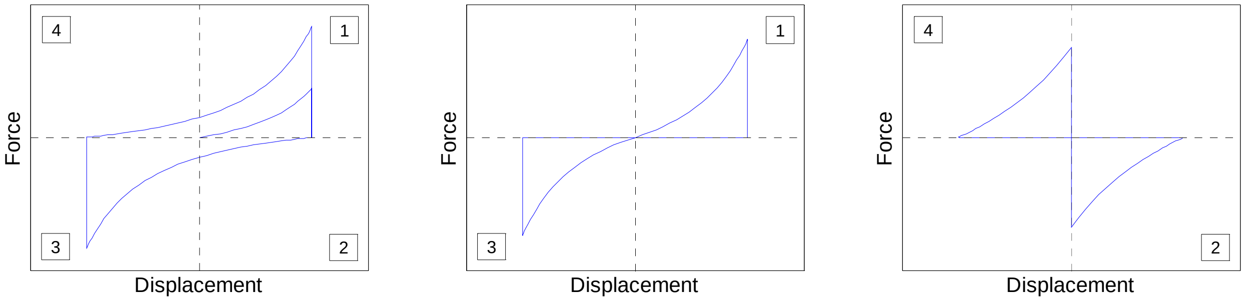
(a) Test structure (b) System implementation

Figure 2. One-fifth scale structure.

Linear potentiometers and accelerometers were used to measure the response of the test structure and the motion of the shake table. A linear potentiometer placed along the axis of each resettable 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 located between the device and the steel tendon. During the shake table tests, responses and loads of the test structure were measured and sent to a control computer. The control computer processed the responses according to a predetermined device control algorithm and sent an appropriate command signal to the device valves. As mentioned before, 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 graph in which the device provides resisting forces (Chase et al. 2006, 2007, Rodgers et al. 2007). Figure 3 shows the main control laws used in this research. The test structure was tested on the shake table using the following control configurations for the resettable tendon, which includes the resettable device and the steel tendon:

- Valves closed. When the valves of the device are closed, the resettable tendon acts as a rigid bracing system in which the stiffness is provided by the bulk modulus of the air in the device cylinder and the steel tendon.
- 1-2-3-4 control law. This control law provides resisting forces in all four quadrants of the force-displacement curve, as shown in Figure 3a.
- 1-3 control law. The 1-3 control law is shown in Figure 3b. This control law provides resisting forces only in the first and third quadrants of the force-displacement graph.
- 2-4 control law. The 2-4 control law provides resisting forces only in the second and fourth quadrants of the force-displacement curve, as shown in Figure 3c.
- 1-2-3-4 to 2-4 control law. For this particular case, the control configuration is switched from the 1-2-3-4 to the 2-4 control law when the relative displacement across the device exceeds 7 mm in both directions.
- Valves open. By opening the device valves, the resettable tendon serves as a flexible bracing system. When the valves of the device are open, the piston is free to move and the air in the cylinder provides only a small amount of damping due to leakage and heat loss. The friction between the moving parts inside the cylinder also contributes to the damping provided by the device.

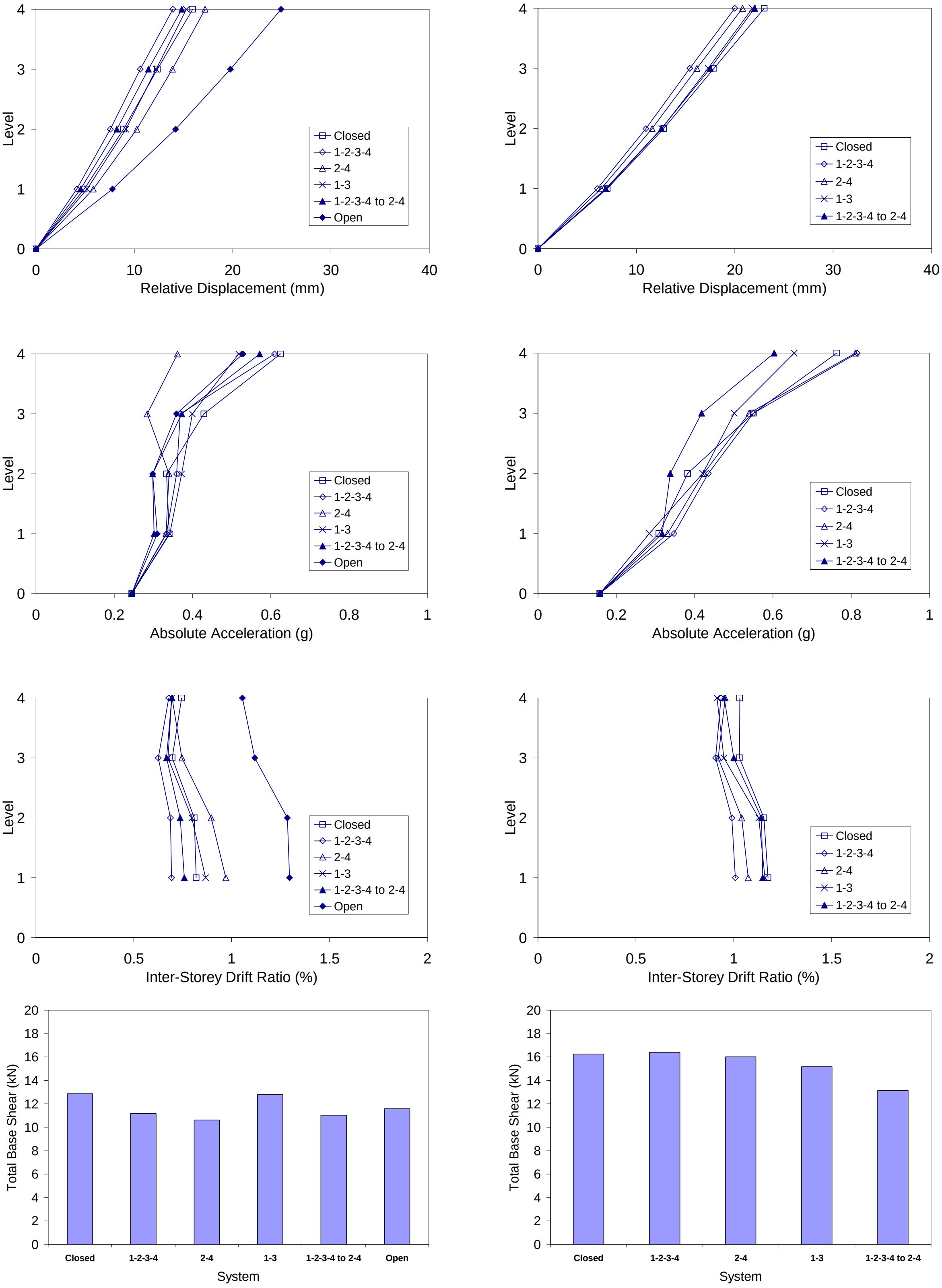
Four different earthquake ground motions were used as input to the shake table, namely El Centro 1940 NS, Taft 1952 S21W, Sylmar County 1994 and Kobe 1995 N00E. El Centro and Taft ground motions are historical earthquake records of vibratory nature, while the Sylmar and Kobe earthquakes are recent earthquake records with pulse-type characteristics. The amplitude of the earthquake records was scaled to excite the test structure with earthquake ground motions of different intensity. Some of the records were also modified in such a way that the earthquake velocity did not exceed the maximum velocity (0.24 m/s) of the shake table (Chase et al. 2005). The modification of the records ensured that unexpected acceleration spikes did not occur during the testing and that the earthquake records were accurately tracked by the shake table (Chase et al. 2005, 2007).



(a) 1-2-3-4 control law (b) 1-3 control law (c) 2-4 control law

Figure 3. Control laws.

The results of the shake table tests showed that the addition of the resettable tendon improved the seismic performance of the test structure significantly. The 1-2-3-4 control law and the valves closed case achieved the greatest reduction in maximum floor displacements and inter-storey drift ratios. However, they increased the maximum floor accelerations and thus the total base shear. It should be noted that the total base shear is the base shear associated with the shears in the ground floor columns together with the horizontal reaction required to support the semi-active control device. The response reduction achieved by the 1-3 control law was comparable to that provided by the valves closed case for ground motions of high intensity level. The 2-4 control law was very efficient at reducing the maximum floor accelerations and therefore the total base shear demand. This result is of particular interest for the retrofit of existing buildings where the strength of the foundation is usually limited. The 1-2-3-4 to 2-4 control law showed comparable results to the best performance achieved by the 1-2-3-4 control law. This switching control law further confirms the capability of the resettable devices to manipulate hysteretic behavior and to adapt to changing structural demands. Finally, the valves open case was advantageous over the uncontrolled case due to the resisting forces provided by the flexible bracing system (Mulligan 2007, Franco-Anaya 2008). Figure 4 shows maximum response envelopes for the El Centro and Kobe earthquakes scaled by 70% (0.2451g) and 30% (0.1583g), respectively.



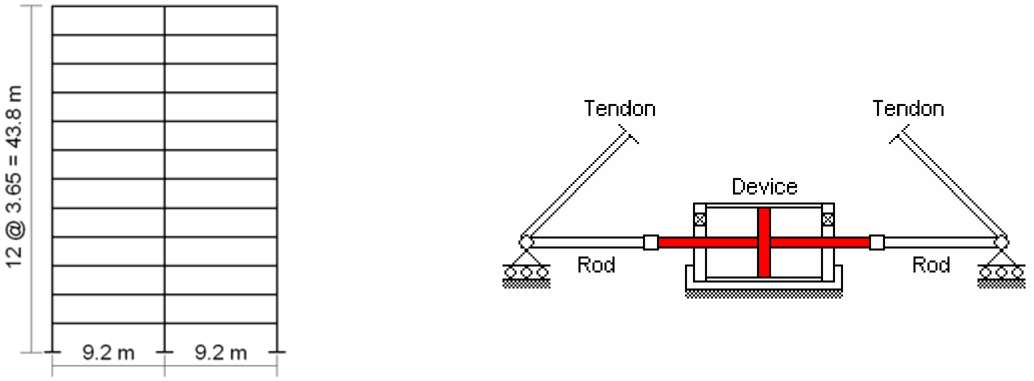
(a) El Centro 70% (Modified)　　(b) Kobe 30% (Modified)

Figure 4. Maximum response envelopes for the one-fifth scale structure.

3. ANALYTICAL STUDIES

Following the experimental validation of the resettable devices, analytical studies were carried out to investigate the potential performance for a twelve-storey reinforced concrete structure subjected to earthquake loading and controlled by similar semi-active resettable devices. The reinforced concrete building used in this research was designed in accordance with the provisions of the New Zealand Loadings Standards NZS 4203 and NZS 3101. The frame is considered to be a typical two-bay interior frame of a building of twelve floors. The moment-resisting frame structure was originally designed to study the seismic load demands on columns of reinforced concrete multi-storey frames (Jury 1978).

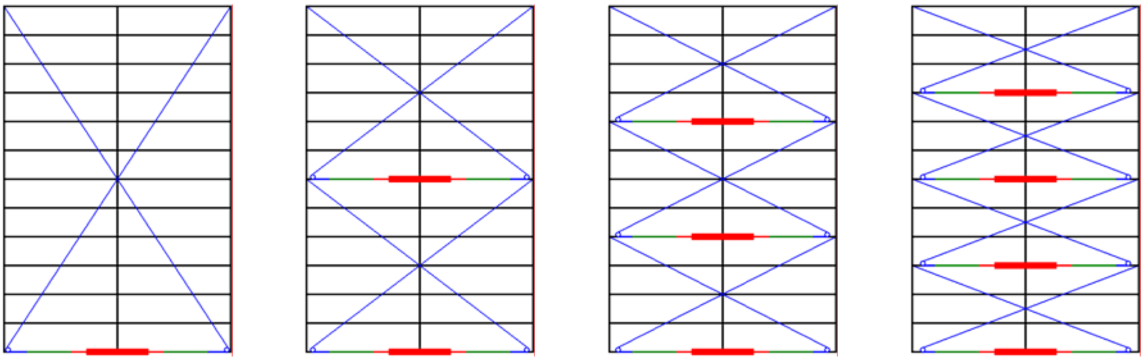
The control system proposed in this research uses rigid rods attached to the two ends of the device piston. The rigid rods transfer the control forces produced by the device to a tendon system. The tendon system consists of pre-stressed tendons that transfer the control forces to the structure at different floor levels. The pre-stressed tendons span the two horizontal bays of the structure. A schematic of the twelve-storey building and the system implementation are shown in Figure 5.



(a) Building model (b) System implementation

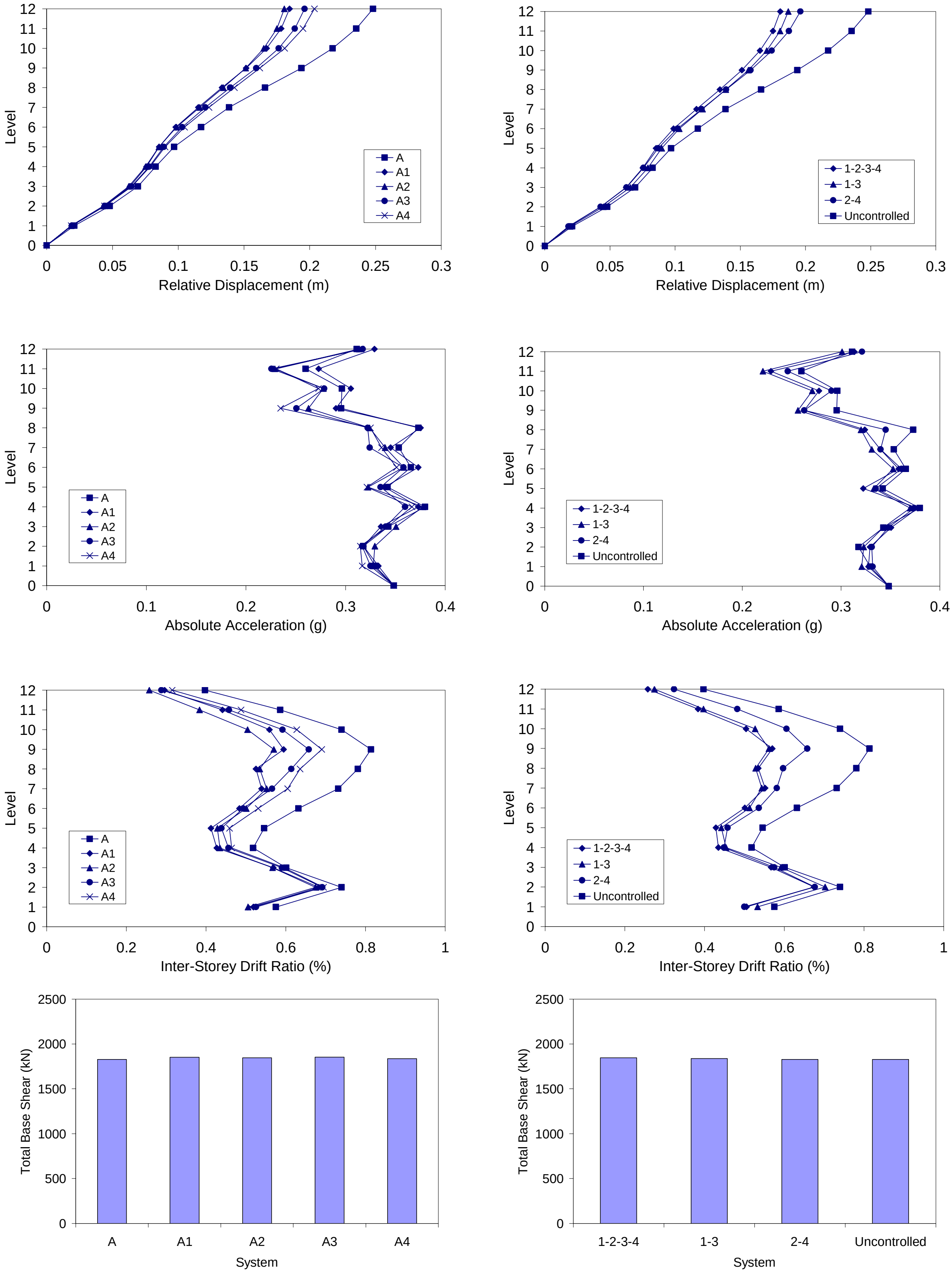
Figure 5. Twelve-storey reinforced concrete building.

The adequate distribution of energy dissipation devices in tall buildings is essential, since a poor placement of the devices can be detrimental to the dynamic response by changing the balance of structural modes in the response (Barroso et al. 2003). Four different arrangements were used to assess the impact of the device distribution on the seismic response of the building. Computer simulations were carried out to investigate the effect of 1 to 4 resettable devices distributed through the height of the building. Figure 6 shows the systems considered in this investigation.



(a) System A1 (b) System A2 (c) System A3 (d) System A4

Figure 6. Distribution of 1 to 4 resettable devices in the structure.



(a) Impact of the device distribution (b) Impact of the control law

Figure 7. Maximum response envelopes for the twelve-storey building.

Two-dimensional inelastic dynamic analyses using the computer program RUAUMOKO (Carr 2006) were performed to evaluate the effectiveness of the systems. The seismic response of the systems was examined for the north-south component of the 1940 El Centro ground motion. The 1-2-3-4 control law was adopted to simulate the hysteretic behavior of the device.

The overall benefits of the different device distributions in reducing the earthquake response of the twelve-storey reinforced concrete building are shown in Figure 7a. The results are presented for comparison to the uncontrolled structure (system A) shown in Figure 5a. Maximum response envelopes indicate that the seismic response is reduced by all of the systems. The systems A1 and A2 show a very similar performance in reducing the maximum relative displacements and inter-storey drift ratios. The maximum absolute accelerations in some levels are slightly reduced by all of the systems. All of the systems increase the maximum total base shear slightly. Figure 7a shows that increasing the number of devices does not improve the seismic performance of the structure. It can be seen that response reductions achieved by the system A4 with four devices installed are less significant than those obtained by the system A1 that only uses one resettable device. This effect is due to actuator-actuator interaction and reflects the influence of higher modes on the seismic response, requiring adjustment of how the control laws are designed and implemented for tall structures (Barroso et al. 2003).

The system A2 shown in Figure 6b was adopted to analyze the performance of the control laws under seismic excitation. The 1-2-3-4, 1-3 and 2-4 control laws shown in Figure 3 were utilized to simulate the hysteretic behavior of the resettable device. Nonlinear dynamic analyses using RUAUMOKO were performed to evaluate the performance of the control laws to reduce the seismic response of the system A2. The seismic response was examined for the north-south component of the 1940 El Centro ground motion.

Figure 7b shows maximum response profiles for the control laws and the uncontrolled structure. All control laws reduce the maximum relative displacements and inter-storey drift ratios efficiently. The maximum absolute accelerations are reduced in some levels of the structure by all of the control laws. However, the maximum total base shear is increased by all control laws slightly. The simulation results show that the response reductions achieved by each of the control laws is very similar. The differences in the response reduction delivered by all three control laws are not significant. This result complicates the selection of an appropriate control law to reduce the seismic response of this particular structure. It was observed that the effect of the control laws was only noticeable by increasing the number of devices or by unrealistically increasing the device stiffness. Hence, an optimal solution will be a function of device capacity, control architecture and control law.

4. CONCLUSIONS

This paper has examined the seismic performance of a four-storey one-fifth scale structure equipped with semi-active resettable devices. Two novel resettable devices were installed in the lateral bracing of the structure. Shake table tests were performed on the structure to assess the effectiveness of the devices in reducing the seismic response. The devices modified the structural stiffness by following a control algorithm that took into account the measured responses of the structure and the deformations of the devices. The test structure was subjected to different simulated earthquake ground motions at various peak ground accelerations. Different control laws were used to manipulate the hysteretic behavior of the resettable devices during the seismic testing. The results of the shake table tests confirmed that the resettable devices were quite effective in reducing the structural response over a wide range of earthquake excitations and demonstrated the significant potential of these devices for the seismic protection of civil engineering structures.

The paper has also investigated the effectiveness of the resettable devices to reduce the seismic response of a twelve-storey reinforced concrete building. Nonlinear dynamic analyses were used to determine the optimal utilization of the devices in the structure. Different device distributions and control laws were used to examine the effects on the seismic response resulting from the addition of the devices to the moment-resisting frame building. The analytical results highlighted two important aspects related to the potential implementation of the resettable devices in actual buildings, namely the device distribution and the control law.

REFERENCES

Barroso, L.R., Chase, J.G. and Hunt, S. (2003). Resettable smart dampers for multi-level seismic hazard mitigation of steel moment frames. *Journal of Structural Control*, **10:1**, 41-58.

Carr, A.J. (2006). RUAUMOKO-Inelastic dynamic analysis program. Computer Program Library, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

Chase, J.G., Hudson, N.H., Lin, J., Elliot, R. and Sim, A. (2005). Nonlinear shake table identification and control for near-field earthquake testing. *Journal of Earthquake Engineering*, **9:4**, 461-482.

Chase, J.G., Mulligan, K.J., Gue, A., Alnot, T., Rodgers, G., Mander, J.B., Elliott, R., Deam, B., Cleeve, L. and Heaton, D. (2006). Re-shaping hysteretic behaviour using semi-active resettable device dampers. *Engineering Structures*, **28:10**, 1418-1429.

Chase, J.G., Mulligan, K.J., Elliott, R.B., Rodgers, G.W., Mander, J.B., Carr, A.J. and Franco-Anaya, R. (2007). Re-shaping hysteresis: Seismic semi-active control experiments for a 1/5th scale structure. *Proc., 8th Pacific Conference on Earthquake Engineering*, Singapore.

Franco-Anaya, R., Carr, A.J., Mander, J.B., Chase, J.G., Mulligan, K.J. and Rodgers, G.W. (2007). Seismic testing of a model structure with semi-active resetable devices. *Proc., NZSEE Conference 2007, Performance by design: Can we predict it?*, Palmerston North, New Zealand, G. Beattie, ed., (CD-ROM), New Zealand Society for Earthquake Engineering Incorporated, Wellington.

Franco-Anaya, R. (2008). Seismic performance of semi-active control systems. PhD Thesis, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.

Jabbari, F. and Bobrow, J.E. (2002). Vibration suppression with resettable device. *Journal of Engineering Mechanics*, **128:9**, 916-924.

Jury, R.D. (1978). Seismic load demands on columns of reinforced concrete multi-storey frames. ME Thesis, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

Mulligan, K. (2007). Experimental and analytical studies of semi-active and passive structural control of buildings. PhD Thesis, Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand.

Rodgers, G.W., Mander, J.B., Chase, J.G., Mulligan, K.J., Deam, B.L. and Carr, A. (2007). Re-shaping hysteretic behaviour-Spectral analysis and design equations for semi-active structures. *Earthquake Engineering and Structural Dynamics*, **36:1**, 77-100.

Rodríguez, M.E., Restrepo, J.I. and Blandón, J.J. (2006). Shaking table tests of a four-story miniature steel building-Model validation. *Earthquake Spectra*, **22:3**, 755-780.