Seismic response reduction of a 12-storey reinforced concrete structure using semi-active resettable devices

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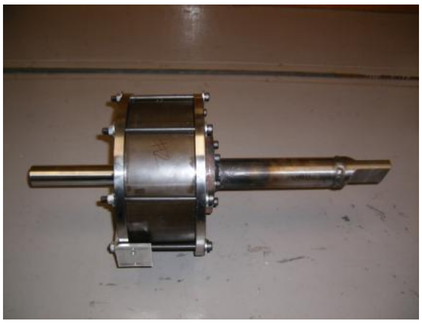
ABSTRACT: Recent analytical and experimental research has demonstrated the potential of semi-active resettable devices for controlling the response of structures subjected to earthquake excitation. Resettable devices manipulate the stiffness characteristics of the structure and are capable of producing large resisting forces. The devices also offer great reliability due to their reliance on standard hydraulic or pneumatic concepts and employ relatively simple mechanisms and control logic. This paper presents an investigation on the use of semi-active resettable devices to reduce the seismic response of multi-storey buildings. Analytical studies are conducted to investigate the performance of a twelve-storey reinforced concrete structure subjected to earthquake ground motion and controlled by resettable devices. Computer simulations are carried out to determine the optimal utilisation of the devices and to evaluate the performance of different control laws used to control the operation of the resettable devices. The effect of the location, number and arrangement of the devices on the seismic response of the structure is discussed.

1 INTRODUCTION

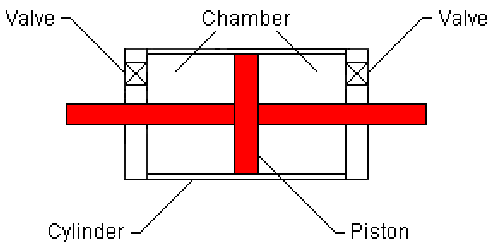
The suppression of excessive vibration in a multi-storey building can be managed, with limited success, in a variety of ways. Additional stiffness can be provided to reduce the vibration period of the building to a less sensitive range. Changes in the mass of the building can be effective in reducing 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 (Taranath 2005). Therefore, to achieve reduction in response, a practical solution is to install energy dissipation devices at discrete locations in the building to supplement its natural energy dissipation and/or absorption capability.

Semi-active resettable devices are an emerging technology that effectively improves the seismic response of structures (Jabbari & Bobrow 2002, Mulligan et al. 2009a). The primary use of resettable energy dissipation devices is to reduce the earthquake-induced displacements of the structure. These 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 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 with semi-active 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 decentralised control logic (Jabbari & Bobrow 2002, Barroso et al. 2003, Chase et al. 2006). The devices mitigate the earthquake excitation of the structure that would otherwise cause higher levels of response and damage to structural components.

An experimentally validated resettable device (Franco-Anaya et al. 2007, Mulligan et al. 2009a, 2009b) is proposed in this research to reduce the seismic response of a twelve-storey reinforced concrete structure. A photograph of a one-fifth scale prototype of the resettable device is shown in Figure 1a. This device has a novel two-chambered design that allows 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. Each device valve can be operated independently allowing independent control of the pressure on each piston side. Therefore, the two-chambered design enables a wider variety of control laws to be implemented. Figure 1b shows a schematic of the two-chambered design of the device. The device also has the ability to sculpt or re-shape structural hysteretic behaviour, because of the possibility to control the device valve and reset times actively (Chase et al. 2006, Rodgers et al. 2007, Mulligan et al. 2009b). In addition, this specific resettable device utilises air as the working fluid for simplicity and can thus make use of the surrounding atmosphere as the fluid reservoir.



(a) Prototype device

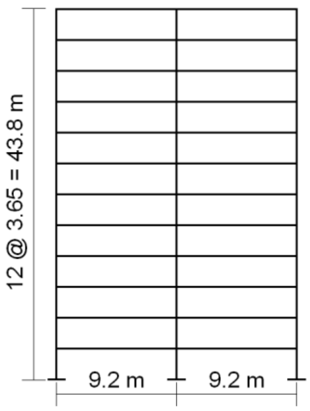


(b) Two-chambered design

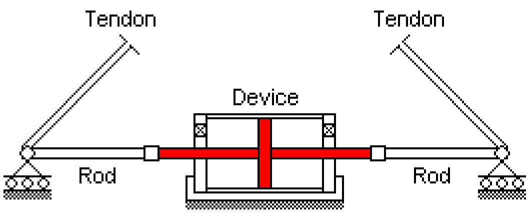
Figure 1. Semi-active resettable device.

2 IMPLEMENTATION OF THE CONTROL SYSTEM

The reinforced concrete building shown schematically in Figure 2a is used to analyse the seismic performance of the semi-active resettable devices. The building has twelve storeys and two horizontal bays. The moment-resisting frame structure was designed to examine the seismic load demands on columns of reinforced concrete multi-storey frames (Jury 1978). The building 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. It is assumed that the frame is required to resist the component of the earthquake ground motion in the plane of the frame only. The component in the perpendicular direction is assumed to be taken by other resisting systems (e.g. shear walls). Torsional effects for the building are not considered.



(a) Building model



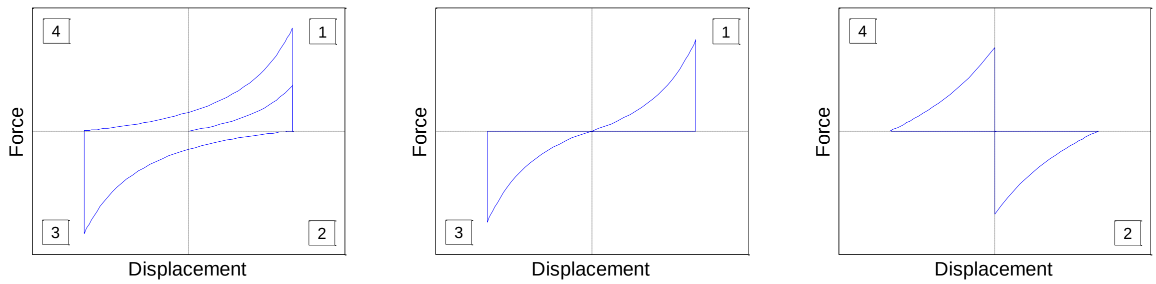
(b) System implementation

Figure 2. Implementation of the control system.

The control system proposed herein utilises 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. Figure 2b shows a schematic of the system implementation. The control forces developed by the resettable device are based on feedback from sensors that measure the excitation and/or the response of the structure.

3 CONTROL LAWS, SYSTEMS AND EARTHQUAKE RECORD

The independent control of the device valves enables the re-shaping of hysteretic behaviour by using different control laws. The 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 (Chase et al. 2006, Rodgers et al. 2007, Mulligan et al. 2009b). Figure 3 shows the control laws studied here. The 1-2-3-4 control law provides resisting forces in all four quadrants of the force-displacement curve (Fig. 3a). The 1-3 control law provides resisting forces only in the first and third quadrants of the force-displacement graph (Fig. 3b). The 2-4 control law provides resisting forces only in the second and fourth quadrants of the force-displacement curve (Fig. 3c).



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

Figure 3. Control laws.

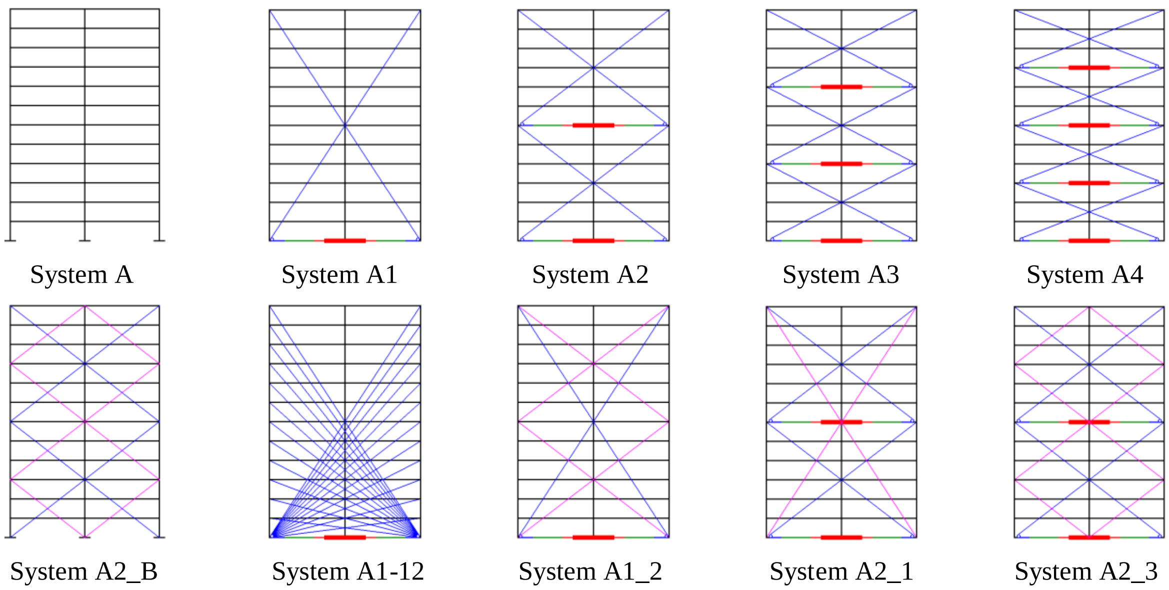


Figure 4. Systems under investigation.

Figure 4 shows the systems used to examine the effectiveness of the semi-active resettable devices in reducing the seismic response of the twelve-storey reinforced concrete structure. Two-dimensional nonlinear time-history analyses are performed using the computer program RUAUMOKO (Carr

2006). The north-south component of the 1940 El Centro earthquake is adopted as the input ground motion in the computer analyses. The seismic performance of the structure is evaluated in terms of reductions in relative displacements, absolute accelerations, inter-storey drift ratios and total base shear, which includes the contribution of the pre-stressed tendons to the seismic response. The results are presented for comparison with the multi-storey structure without resettable devices referred to as the uncontrolled structure or system A.

4 EFFECT OF THE DEVICE DISTRIBUTION AND CONTROL LAW

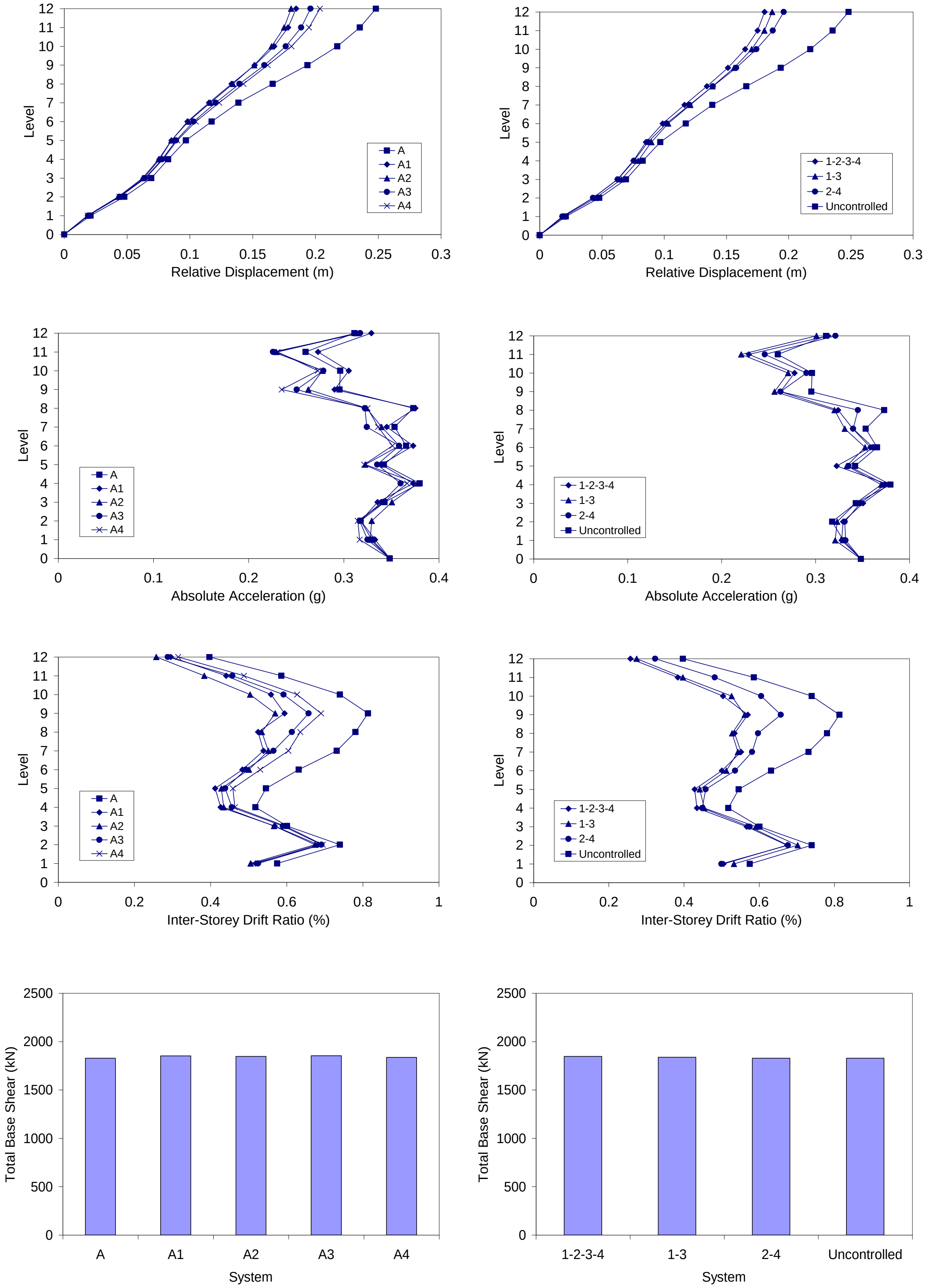
The adequate distribution of energy dissipation devices in tall buildings is essential, since a poor placement of the devices can be detrimental to the dynamic response by changing the balance of structural modes in the response (Barroso et al. 2003). Four different arrangements are used here to assess the effect of the device distribution on the seismic response of the building. Computer simulations are carried out to investigate the effect of 1 to 4 resettable devices distributed through the height of the building. The systems A1, A2, A3 and A4 of Figure 4 are considered in this study.

The overall benefits of the different device distributions in reducing the earthquake response of the twelve-storey reinforced concrete building are shown in Figure 5a. The 1-2-3-4 control law is adopted to simulate the hysteretic behaviour of the resettable device. 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 5a shows that increasing the number of devices does not improve the seismic performance of the structure. For instance, the 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. It reflects the influence of higher modes on the seismic response and requires adjustment of how the control laws are designed and implemented for tall structures (Barroso et al. 2003).

The system A2 is now selected to analyse the performance of the different control laws under seismic excitation. Figure 5b 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 are 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 structure. It was observed that the effect of the control laws was only noticeable by increasing the number of resettable devices or by unrealistically increasing the stiffness of the device.

5 EFFECT OF THE TENDON CONFIGURATION

The systems A1-12, A1_2, A2_1 and A2_3 shown in Figure 4 are adopted to assess the effect of the tendon configuration on the seismic response of the twelve-storey building. The system A1-12 has one resettable device installed on the ground level and the control forces are applied by the pre-stressed tendons at each level of the structure. The system A1_2 utilises one resettable device installed on the ground floor and has two pre-stressed tendons attached that span between the ground and level 12 of the building. The system A1_2 also utilises two pre-stressed bracing systems to minimise the effects of the upper storey whipping (Pekcan 1998). One bracing system is installed on the lower half and the other bracing system is placed on the upper half of the building. The bracing systems are placed along the two bays of the twelve-storey reinforced concrete structure.



(a) Effect of the device distribution

(b) Effect of the control law

Figure 5. Maximum response envelopes for the twelve-storey building.

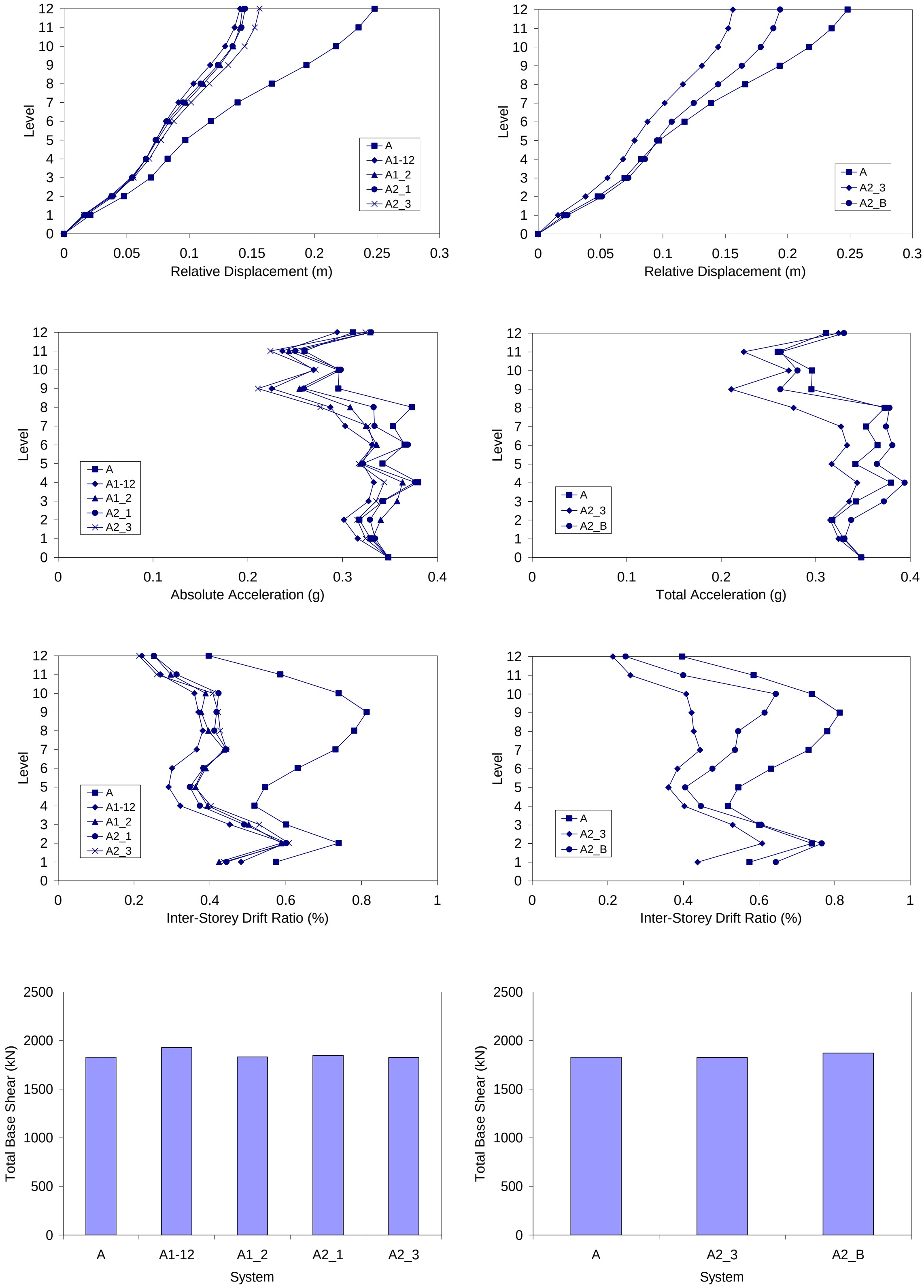
The system A2_1 employs two resettable devices to control the seismic response of the moment-resisting frame structure. One of the devices is installed on the ground with pre-stressed tendons attached to the level 6. The other device is located on the level 6 and has pre-stressed tendons attached to the top of the building. In addition, a large pre-stressed bracing system is installed between the ground floor and the top of the building. The system A2_3 has similar device distribution and tendon configuration to the system A2_1. However, the system A2_3 has three bracing systems distributed along the height of the building. A main bracing system is placed between level 3 and level 9; and two secondary bracing systems are located between the ground and level 3, and between level 9 and level 12, respectively.

In the systems A1-12 and A1_2, the reduction of the control forces due to the angle of the tendon is minimised by installing the tendons along the two bays of the structure. Both systems eliminate the possibility of actuator-actuator interaction, since all response measurements and reaction forces are relative to the ground floor. In the systems A2_1 and A2_3, the bracing systems and pre-stressed tendons span through the entire width of the building. The two systems avoid the use of a huge device needed to provide large control forces by having two smaller devices evenly distributed through the height of the structure instead.

Figure 6a shows maximum response envelopes for the tendon systems obtained from the computer simulations. The hysteretic behaviour of the resettable device follows the 1-2-3-4 control law. It can be seen that all of the systems considered reduce the seismic response of the twelve-storey frame structure. System A1-12 shows the best performance in reducing the maximum relative displacements and inter-storey drift ratios. A very similar performance is shown by systems A1_2 and A2_1 in reducing the maximum relative displacements and inter-storey drift ratios. All of the systems reduce the maximum absolute accelerations in some levels of the structure. Systems A1-12, A1_2 and A2_1 increase the maximum total base shear. System A2_3 slightly reduces the maximum total base shear. It should be noted that although the response reductions achieved by the system A1-12 are very significant, the additional stiffness provided by the pre-stressed tendons greatly contributes to the improvement of the seismic response.

Since the pre-stressed tendons and the bracing systems provide additional stiffness and damping to the system, it is of interest to investigate their overall contribution to the seismic response reduction of the twelve-storey reinforced concrete structure. The system A2_B shown in Figure 4 is used to evaluate the contribution of the pre-stressed tendons and the bracing systems to the reduction of the earthquake response. The arrangement of the pre-stressed tendons and the bracing systems used by system A2_B is similar to that of the system A2_3. However, system A2_B has neither resettable devices nor rigid rods installed.

Maximum response envelopes of the systems A, A2_3 and A2_B are compared in Figure 6b for the 1-2-3-4 control law. The comparisons show that the average contributions of the pre-stressed tendons and bracing systems to the reduction of the maximum relative displacements and inter-storey drift ratios are 43% and 61%, respectively. However, the maximum absolute accelerations are increased by up to 4% on average and the maximum total base shear is increased by up to 2%. These results show the significant contribution of the pre-stressed tendons and bracing systems to the reduction of the seismic response, especially to the reduction of the inter-storey drifts. However, the use of the pre-stressed tendons and bracing systems without resettable devices increases the accelerations and the total base shear. In contrast, the system A2_3 with two resettable devices installed not only reduces the displacements and inter-storey drifts but also the accelerations and the total base shear.



(a) Effect of the tendon configuration (b) Contribution to the seismic response

Figure 6. Maximum response envelopes for the twelve-storey building.

6 CONCLUSIONS

In this paper, a novel semi-active resettable device was proposed to reduce the seismic response of a twelve-storey reinforced concrete building. The analytical results showed that increasing the number of resettable devices in the structure did not reduce the seismic response. On the contrary, the response of the structure was slightly amplified. This effect is caused by actuator-actuator interaction and reflects the influence of higher modes on the seismic response of tall structures. The reduction of the seismic response achieved by the 1-2-3-4, 1-3 and 2-4 control laws was very similar. Besides, the difference in response reduction delivered by the three control laws was not significant. However, all control laws effectively reduced the seismic response of the structure. The use of pre-stressed tendons and bracings without resettable devices increased the floor accelerations and the total base shear of the structure. In contrast, the use of resettable devices combined with pre-stressed tendons and bracings reduced the floor displacements and inter-storey drifts, but without increasing the floor accelerations and the base shear demand significantly.

The paper highlighted a few issues that may become important for the implementation of semi-active resettable devices in multi-storey structures. However, eventual implementation of resettable devices must also take into account other issues such as technological considerations, software and hardware developments, structural integration, etc. Above all, the cost-effectiveness of resettable devices must be carefully assessed especially when compared with conventional energy dissipation devices.

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