SEISMIC PERFORMANCE OF A MULTI-STOREY BUILDING EQUIPPED WITH SEMI-ACTIVE RESETTABLE DEVICES

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Abstract

Semi-active resettable devices are utilised to reduce earthquake-induced displacements of civil structures. These energy dissipation devices behave as nonlinear springs with adjustable mechanical characteristics. The devices manipulate the stiffness properties of the structure and are capable of developing large resisting forces. Resettable devices offer great reliability due to their reliance on standard hydraulic or pneumatic concepts. In addition, the devices rely on very low power consumption and are subjected to a set of decentralised control logic. This paper will describe an experimentally validated semi-active resettable device to control the earthquake response of multi-storey buildings. An analytical study was carried out to evaluate the seismic performance of a twelve-storey reinforced concrete building. The multi-storey building was subjected to earthquake ground motion and controlled by resettable devices. Different control laws were employed to manipulate the operation of the semi-active devices. A series of computer simulations were conducted to determine the optimal use of the resettable devices. The effects of the location, number and arrangement of the devices on the earthquake response of the building are discussed. The paper also describes some issues that can be important for the implementation of semi-active resettable devices in actual multi-storey buildings.

Keywords: semi-active control; resettable device; energy dissipation; multi-storey building; concrete structure.

1. Introduction

Multi-storey buildings may be prone to large amplitude vibrations due to strong winds and large earthquakes. 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 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 [1]. To achieve reduction in the vibration response of a multi-storey building, 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.

Semi-active resettable devices are an emerging technology that improves the earthquake response of structures effectively [2, 3]. Primary use of resettable energy dissipation devices is to reduce the 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 decentralised control logic [4, 5]. Resettable devices mitigate the seismic excitation of the structure that would otherwise cause higher levels of response and damage to structural components.

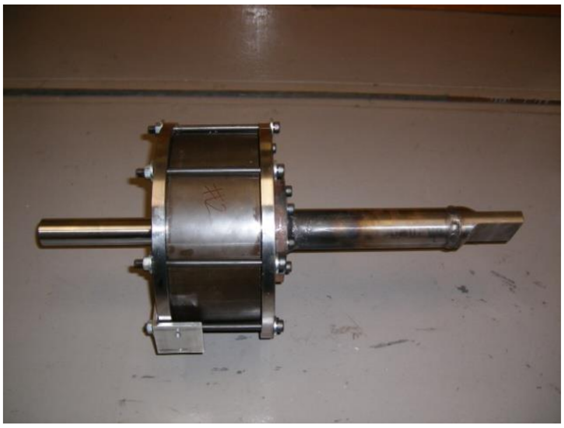
This paper describes various issues relevant to the implementation of semi-active resettable devices in multi-storey building structures. Analytical studies are carried out to investigate the performance of a twelve-storey reinforced concrete building subjected to earthquake excitations and controlled by resettable devices. Several computer simulations are performed to determine the optimal utilization of the resettable devices in the building. The effectiveness of the devices in controlling the seismic response and their location, number, arrangement and connection to the building structure are discussed. The contribution to the seismic response of the pre-stressed tendons and bracings used by the control system is investigated. The effects of variations in the control laws used to control the operation of the device are examined. Reductions in maximum relative displacements, absolute accelerations, inter-storey drift ratios and total base shear are presented to assess the effectiveness of the resettable devices.

2. Semi-Active Resettable Device

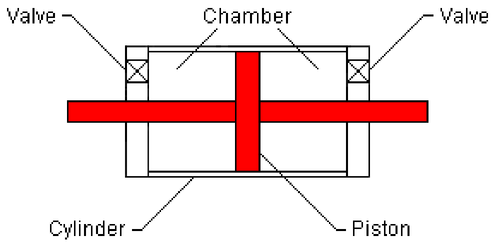
An experimentally validated resettable device [3, 6] is proposed in this research to reduce the earthquake response of a twelve-storey reinforced concrete structure. A photograph of a one-fifth scale prototype of the resettable device is shown in Fig. 1a. This novel device has a two-chambered design that allows the use of each side of the device piston independently. This approach treats each side of the piston as an independent chamber with its own valve and control. Each device valve can be operated independently that allows the independent control of the pressure on each side of the piston. Therefore, the two-chambered design enables a wider variety of control laws to be implemented. Fig. 1b shows a schematic of the two-chambered design of the resettable device.

The resettable 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 [5, 7]. In addition, this 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 characterised, a detailed computer model was created and validated experimentally [8, 9].



(a) Resettable device



(b) Two-chambered design

Fig. 1 Semi-active resettable device

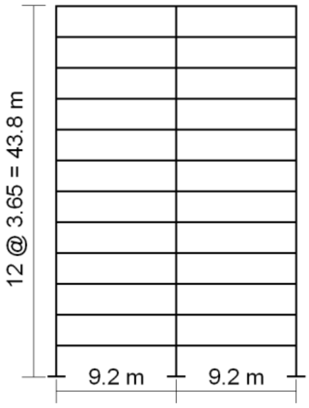
3. Twelve-Storey Reinforced Concrete Building

The reinforced concrete building shown schematically in Fig. 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 investigate the seismic load demands on the columns of reinforced concrete multi-storey frames [10]. The building structure 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 reinforced concrete 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 [10].

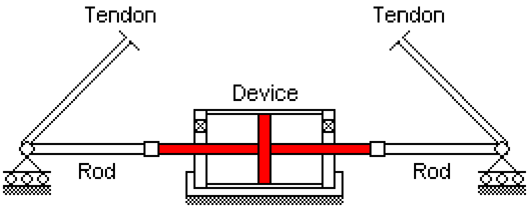
A two-dimensional computer model of the reinforced concrete building was developed for the use of a computer program designed to carry out inelastic dynamic analyses. The model was later modified to take code changes into account and implemented in the computer program RUAUMOKO [11]. The model has 39 nodes and each node has 3 degrees of freedom. All degrees of freedom of the base nodes are restrained for fully fixed boundary condition. To couple the degree of freedom of the horizontal displacement, the nodes of the horizontal elements are slaved at each level. This implies rigid floor slabs. A reduction in the size of the stiffness matrix and hence a large saving in computing time results from this approximation. All degrees of freedom have inertia (including the joint rotations). Thus, rotational mass is assigned to the joints to allow for rotational inertia. Although rotational inertia will influence the behaviour of a real structure during its elastic response, the effect will be minimal after beam hinging has occurred. However, the inclusion of mass for the rotational degree of freedom of a joint, results in a better ordered stiffness matrix, which in turn leads to reductions in computing time.

An elastic modulus of 25 GPa and a shear modulus of 10.4 GPa are adopted for all beam and column members of the concrete building. The Poisson's ratio is taken as 0.2. The shear deformation of the members is considered in the analysis by using the effective shear area of all member sections. The building has a total seismic weight of 19,188 kN [10].

In concordance with the original computer model, initial stiffness Rayleigh damping is adopted herein for the computer analyses. The damping matrix based on the Rayleigh damping model utilises the stiffness of the structure at the beginning of the time-history. The computed damping matrix is constant throughout the time-history analysis and the tangent, secant and elastic damping matrices are identical. This means that the effective damping increases as the structure softens, because the Rayleigh coefficients α and β are computed for the initial natural frequencies of free vibration and some of the frequencies have now decreased [11]. A value of 5% of critical damping is assumed for the first and tenth vibration modes of the structure.



(a) Twelve-storey building



(b) Control system

Fig. 2 Implementation of the control system

The P-Delta effects are included in the dynamic analyses and the constant average acceleration method developed by Newmark (1959) is used to integrate the equation of dynamic equilibrium. A time step of 0.001 seconds is chosen for the nonlinear dynamic analyses.

4. Implementation of the Control System

The purpose of incorporating energy dissipation devices in the design or retrofit of a structure is to reduce its seismic response. Increasing damping in a structure usually reduces the forces and deformations induced by the earthquake ground motion in structural elements. The amount of reduction varies depending on the mass, stiffness and inherent damping characteristics of the structure. It also depends on the amplitude, frequency content and duration of the earthquake ground motion. Therefore, it is not possible to design a supplemental damping system that will be equally effective for all types of structures [12]. Each design problem should be treated on its own merits taking into consideration the suitability of various control systems, the amount of damping required, the type of structural system and the characteristics of the ground motion.

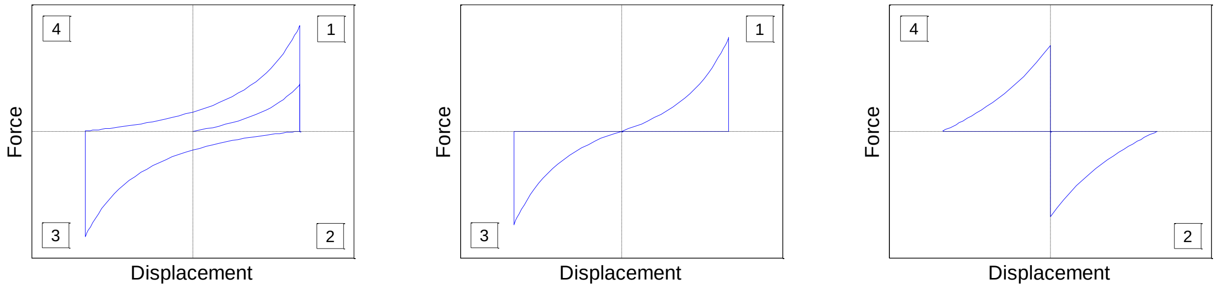
It is common in the design and the retrofit of structures to idealise the actual multi-degree-of-freedom (MDOF) system with an equivalent single-degree-of-freedom (SDOF) system, such that the SDOF system describes the most relevant characteristics of the MDOF system. In the same way, any preliminary attempt to design a control system may be simplified to allow the designer the use of pre-defined response spectra.

The control system proposed in this research utilises rigid rods attached to the two ends of the device piston. The two 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 building at different floor levels. The pre-stressed tendons span the two horizontal bays of the building. The stiffness of the resettable device is based on the maximum force delivered by the device and on the maximum displacement experienced by the building. The control forces developed by the device are based on feedback from sensors that measure the excitation and/or the response of the building. Fig. 2b shows a schematic of the control system.

The rigid rod is required to have a large stiffness to transfer the control forces efficiently and can move in the horizontal direction freely. The rigid rod only represents a link between the device and the pre-stressed tendons and does not add stiffness to the system. The control forces delivered by the device are transferred to the twelve-storey building using a pre-stressed tendon attached to the rigid rod. It is assumed that the tendon works in tension only and its initial pre-stress level is obtained from static analysis of the building.

5. Control Laws and Earthquake Record

The independent control of the two device valves enables the re-shaping of the 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 [5, 7]. Fig. 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

Fig. 3 Control laws

The two-chambered design of the device enables these control laws to be imposed, because each valve can be operated independently, and this allows the 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.

In the following sections, several two-dimensional nonlinear time-history analyses using the computer program RUAUMOKO are performed to examine the effectiveness of the semi-active resettable devices in reducing the seismic response of the twelve-storey reinforced concrete building. The north-south component of the 1940 El Centro earthquake is adopted as the input ground motion in the computer analyses. Overall seismic performance of the building 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 to the building without resettable devices installed and referred to as the uncontrolled structure or system A (Fig. 4).

6. 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 [4]. Four different arrangements are used here to assess the effect of the device distribution on the earthquake 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. Control forces are applied via pre-stressed tendons between the floor where the device is placed on and the respective upper floors. The pre-stressed tendons span the two horizontal bays. Rigid rods attached to the two piston ends are utilised to transfer the control forces from the device to the tendon system. The arrangements of the four systems considered in this analytical study are shown in Fig. 4.

In the system A1, the resettable device is located on the ground level of the building and the device forces are transferred via tendons between the ground level and level 12. For the system A2, one resettable device is placed on the ground level and a second device is located on level 6. In the system A3, the three devices are installed on the ground level, level 4 and level 8, respectively. Four resettable devices located on the ground level, level 3, level 6 and level 9, respectively, are considered for the system A4. These four arrangements are selected primarily to determine whether it is necessary to have devices attached to each floor when controlling the seismic response of tall buildings. It is important to note that the actual control forces applied to the building are reduced by the cosine of the angle of the pre-stressed tendon.

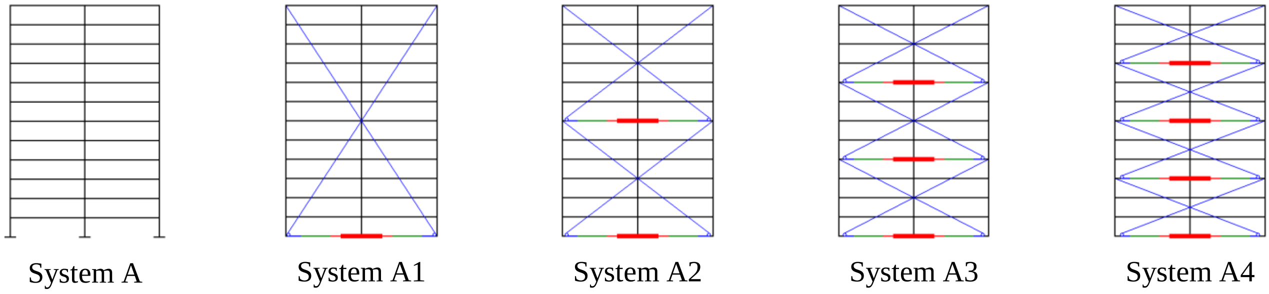


Fig. 4 Distribution of the resettable devices

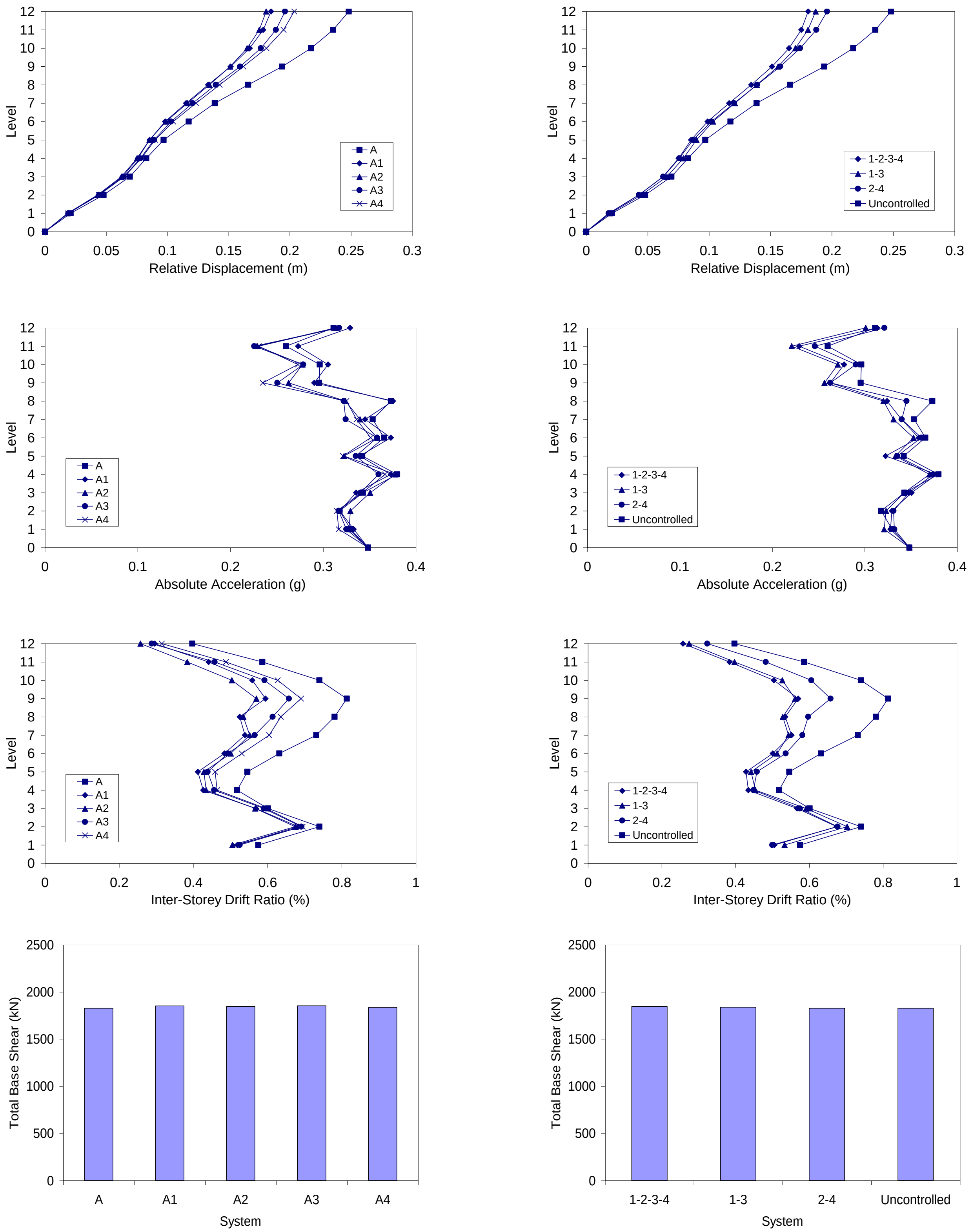
The overall benefits of different distributions of the device in reducing the earthquake response of the twelve-storey reinforced concrete building are shown in Fig. 5a. The 1-2-3-4 device control law is adopted to simulate the hysteretic behaviour of the resettable device. The maximum response envelopes indicate that the earthquake response is reduced by all systems. The systems A1 and A2 show a very similar performance in reducing the maximum relative floor displacements and inter-storey drift ratios. The maximum absolute floor accelerations in some levels are slightly reduced by all systems. All systems increase the maximum total base shear slightly. It can be seen that increasing the number of devices does not improve the seismic performance of the structure very much. For instance, 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 caused by a phenomenon known as actuator-actuator interaction. The actuator-actuator interaction has been properly recognised by similar research studies [4].

This effect also reflects the influence of higher modes on the seismic response and requires adjustment of how the control laws are designed and implemented for tall buildings. In building structures with higher modal contributions, devices placed on adjacent floors may in fact have a negative impact due to the equal and opposite reaction forces applied to the floors on which they are placed. When higher modes are present, the velocity of the floors may be slightly out of phase. Therefore, the resettable device may actually apply control forces for which the reaction forces increase the response of some of the floors while attempting to restrict others. Furthermore, with devices installed on each floor, the reaction forces can cancel out the effect of the device below and, therefore, accelerate certain floors away from their equilibrium position.

The effects of three different control laws on the earthquake response of the twelve-storey reinforced concrete building are now examined. The system A2 is selected to analyse the performance of the control laws under seismic excitation. The 1-2-3-4, 1-3 and 2-4 control laws shown in Fig. 3 are used to simulate the hysteretic behaviour of the resettable device.

Fig. 5b shows maximum response profiles for the control laws and the uncontrolled structure (system A). 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 control laws. However, the maximum total base shear is slightly increased by all control laws. 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.

Other tendon systems were also used to investigate the impact of the three control laws. However, the results showed no significant difference in the seismic response reduction provided by the control laws. It was observed that the effect of the control laws was only noticeable by increasing the number of devices in the structure or by unrealistically increasing the stiffness of the device.



(a) Effect of the device distribution

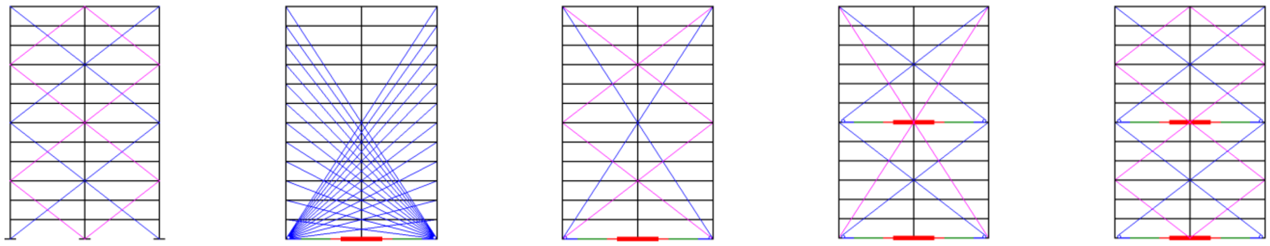
(b) Effect of the control law

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

7. Effect of the Tendon Configuration

The systems A1-12, A1_2, A2_1 and A2_3 shown in Fig. 6 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 [12]. 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 building.

The system A2_1 employs two resettable devices to control the earthquake 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. In addition, two secondary bracing systems are placed between the ground and level 3, and between level 9 and level 12, respectively.

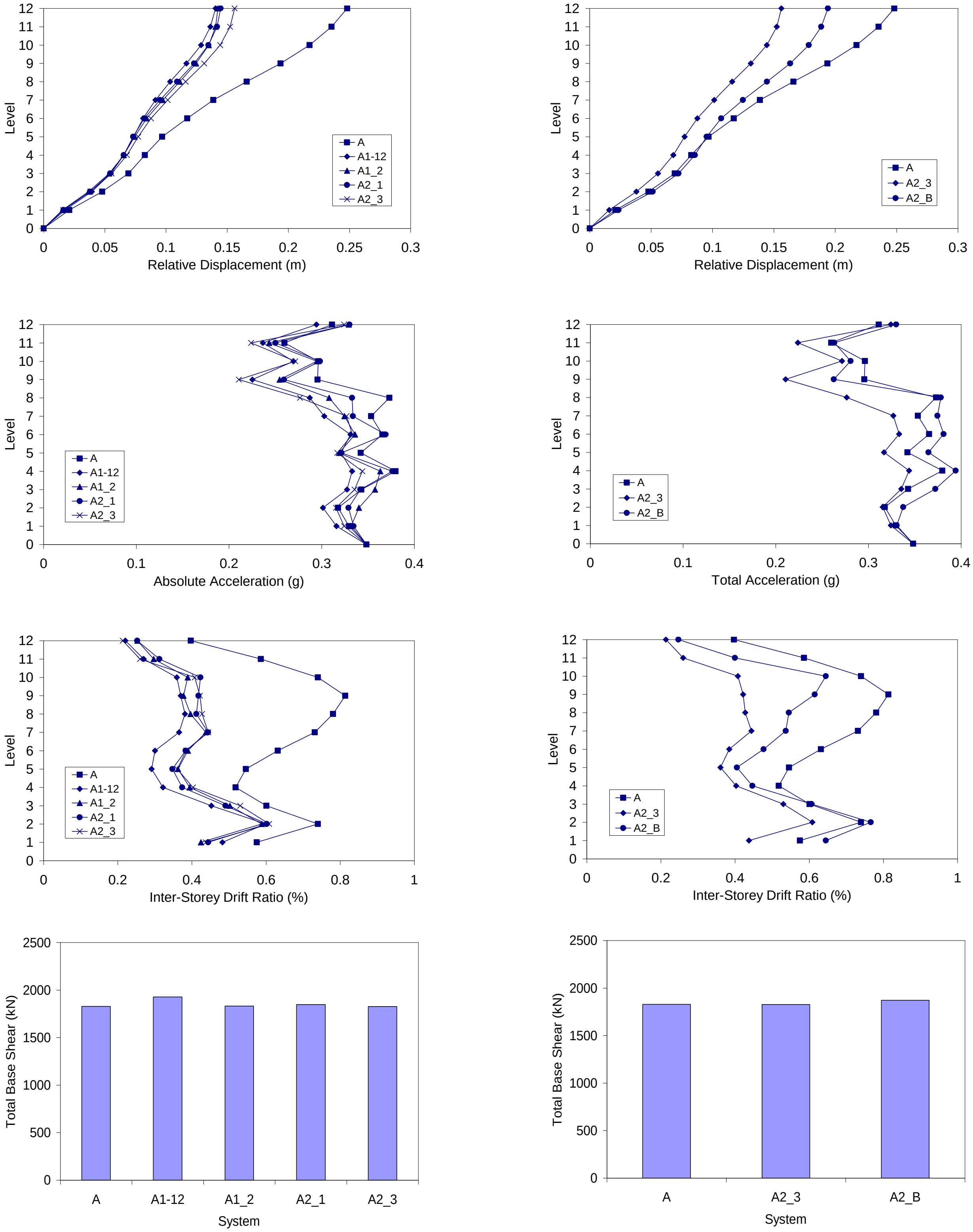


System A2_B System A1-12 System A1_2 System A2_1 System A2_3

Fig. 6 Configuration of the tendon systems

In the systems A1-12 and A1_2, devices are not placed between individual floors in order to avoid the cancelling of control forces due to higher modal contributions. Instead, one resettable device is installed on the ground level and the control forces are applied to the building structure by utilising pre-stressed tendons connected to the device piston. 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 the 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 multi-storey building instead. Reduction of the control forces due to the angle of the pre-stressed tendon is minimised by installing the tendons along the two bays of the reinforced concrete building.

Fig. 7a shows the 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 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 the inter-storey drift ratios. A very similar performance is shown by the systems A1_2 and A2_1 in reducing the maximum relative floor displacements and inter-storey drift ratios. All 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 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.



(a) Effect of the tendon configuration

(b) Contribution of the tendon system

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

Since the pre-stressed tendons and the bracing systems provide additional stiffness and damping to the system, it is of great interest to investigate their overall contribution to the seismic response reduction of the twelve-storey reinforced concrete structure. The system A2_B shown in Fig. 6 is utilised here 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 Fig. 7b for the 1-2-3-4 control law. The comparisons show that the average contributions of the pre-stressed tendons and the 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 floor displacements and inter-storey drifts but also the floor accelerations and the total base shear.

8. Recommendations for Device Implementation

Some recommendations for the implementation of resettable devices in multi-storey buildings can be drawn from the studies presented in the previous sections. The recommendations include the following:

- The stiffness of the resettable devices is based on the maximum force delivered by the device and on the maximum displacement experienced by the building during severe earthquake loading. Thus, preliminary nonlinear dynamic analyses of the structure without supplemental devices can provide an indication of the maximum structural demand expected to select the appropriate device stiffness.
- The placement of resettable devices on each storey of the multi-storey building should be avoided due to the negative effects of any actuator-actuator interaction.
- Selection of the appropriate control law to manipulate the behaviour of the resettable device should take into consideration the type of structural system, the amount of damping required and the characteristics of the earthquake ground motion.
- The low level of the forces produced by the resettable devices is a limiting factor for devices that use air as the working fluid. However, the use of a high-pressure air source can be an effective means to increase the resisting forces of the resettable devices provided that the addition of air pressure does not destabilise the structural system.
- Additional techniques such as lever-like systems can be utilised to increase the piston displacement of the resettable device and thus amplify the control force transmitted to the structure.
- Since the resettable devices offer high response adaptability, the use of these devices together with other passive or active control techniques can improve the overall performance of the resettable devices.
- Pre-stressed tendons should be used to transfer the control forces of the resettable device to the building structure. The maximum pre-stressed forces given by the static analysis of the structure provides a good indication of the level of pre-stress required by the tendons.
- The use of resettable devices in combination with pre-stressed tendons and bracings should be preferred over the use of pre-stressed tendons and bracings alone to reduce the floor displacements and inter-storey drifts of multi-storey buildings. The use of pre-stressed tendons and bracings without resettable devices increases the floor accelerations and total base shear. The addition of the resettable devices enables the reduction of the structural displacements and inter-storey drifts without increasing the floor accelerations and the base shear demand significantly.

9. Conclusions

This paper presented a description of a number of relevant aspects related to the implementation of a novel semi-active resettable device in multi-storey buildings. Analytical studies were performed to investigate the performance of a twelve-storey reinforced concrete building subjected to earthquake ground motion. The seismic response of the building was manipulated by using various control strategies based on the resettable device. Computer simulations were performed to determine the optimal utilisation of the resettable device in the moment-resisting frame building.

The analytical results showed that increasing the number of resettable devices in the building did not reduce its 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 buildings. The reduction of the seismic response achieved by the 1-2-3-4, 1-3 and 2-4 control laws was very similar. The difference in the seismic 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 building. In contrast, the use of resettable devices combined with pre-stressed tendons and bracings effectively reduced the floor displacements and inter-storey drifts, but without increasing the floor accelerations and the base shear demand significantly.

The paper also highlighted some issues that can become important for the implementation of semi-active resettable devices in multi-storey buildings. However, eventual implementation of resettable devices must also consider 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.

10. Acknowledgement

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