RING SPRING DAMPERS: PASSIVE CONTROL SYSTEM FOR SEISMIC PROTECTION OF STRUCTURES

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ABSTRACT

When a structure is excited by an earthquake ground motion the input energy may be reduced by inelastic action or by supplemental damping devices. If the seismic energy dissipation can be achieved by means of separate non-load bearing supplementary damping systems, the structure itself can remain elastic providing a continuing serviceability following the design level earthquake.

This paper illustrates the advantages of using added, or supplemental, damping in structures. The control system consists of passive friction dampers installed in the ground floor of the structure using tendons to transmit the damper forces to the other parts of the structure. The damping forces generated by the dampers are transferred to the structure by the tendons and horizontal links that oppose the inertial loads applied to the structure by the earthquake excitation. The dampers are ring spring friction devices consisting of inner and outer ring elements assembled to a form a spring interface. A four storey-two bay steel frame was used in the study.

INTRODUCTION

The damage caused to buildings by earthquake excitation has demonstrated the need for a seismic design methodology that is performance-based whereby the post-earthquake damage state of the structure is considered. Conventional seismic resistant design is based on the ductile design philosophy in which seismic energy is dissipated in predefined plastic hinge zones. This design approach while being attractive for life preservation, suffers from the inability to avoid damage to the structure in strong earthquakes. Even if the damage is modest, the structure may be required to be taken out of service while inspection and/or repairs are undertaken. For structures such as hospitals, fire stations, civil defence centres, schools, etc. this down-time is untenable from a community perspective: such structures should remain functional after a severe earthquake. Therefore, an alternative to ductile deformation is sought to prevent structural damage under large lateral excitation. Passive structural control is an alternative seismic energy dissipation approach that can be achieved by using separate non-load bearing supplementary damping systems.

PASSIVE STRUCTURAL CONTROL

Passive structural control uses mechanisms to reduce the response of the structure where no input energy is required to operate the devices. Passive structural control approaches traditionally utilise two methods: seismic base isolation and supplemental damping. Supplemental damping provides additional damping to augment the damping inherent in a structural system and is beneficial in limiting the maximum response of a structure during a seismic disturbance. This is achieved by incorporating suitable damping devices within a structure.

The advantage of using mechanical energy dissipators in supplemental damping systems are:

1. Supplemental damping, by increasing the system damping, primarily reduces the inertia loads induced in the structural systems; this effect may provide:
    - Increased protection of the structural system since member loads are reduced.
    - A reduction in inelastic deformation sustained by the structure since some of the input energy is dissipated by the mechanical dissipators.
    - Increased capability of the structure to resist subsequent earthquakes as inelastic deformation of the structure’s primary load carrying system is reduced.
    - A reduction in non-structural damage since the maximum response of the structure is reduced.
2. The mechanical dissipators employed in supplemental damping schemes, can be simple, inexpensive, and exhibit reliable and repeatable characteristics.

Passive structural control has four main advantages:

- It requires no external power source in order to operate.
- It is usually relatively inexpensive.
- It is inherently stable
- It works for both major and minor earthquakes

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Passive control systems prevail in engineering practice due to their simplicity and the low cost of installing and maintaining them. A common feature of all passive control systems is that they reduce the dynamic response of the structure by absorbing and dissipating vibrational energy. On the other hand, an active control system is one in which an external power source controls actuators that apply forces to the structure in a prescribed manner. The block diagrams shown in Figures 1 and 2 highlight the simplicity of passive control system in comparing with an active control system.

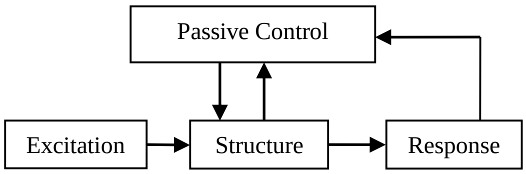

Figure 1: Passive Control System.

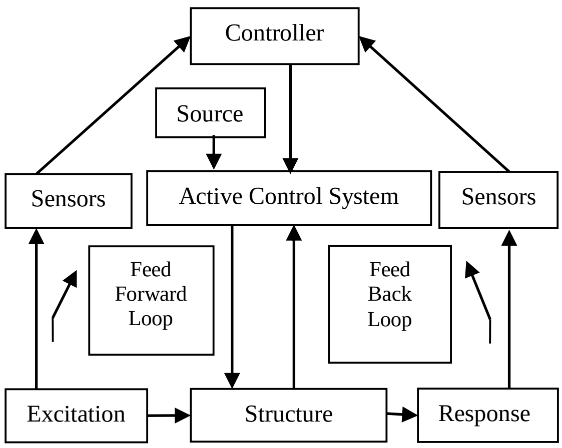

Figure 2: Active Control System.

RING SPRINGS

These are a passive energy dissipator providing a self-centring friction mechanism. Ring springs consist of inner and outer rings that have tapered mating surfaces as shown in Figure 3. As the spring column is loaded in compression, the axial displacement is accompanied by sliding of the rings on the conical friction surfaces. The outer rings are subjected to circumferential tension (hoop stress), and the inner rings experience compression (Figure 4). This study has concentrated on this type of energy dissipater for several reasons:

- Ring springs are totally passive dampers for extreme reliability, no dependence on external power sources to effect the control action which may not be available during major earthquakes.
- Ring spring dampers are constructed of steel materials. No liquid leakage and no refilling or maintenance of any of the parts is needed which are potential problems with viscous dampers.
- Ring spring devices are easy to install in structures thus saving time and materials. They do not require large building preparation to support the devices as in tuned or liquid mass dampers.
- Some of the other ways of adding supplemental damping to structures can be costly and involve major modifications to the structure as in a base isolation system. It is possible to secure a comparable degree of earthquake response mitigation with ring spring dampers located throughout a structure without having to isolate the building.
- Ring springs have powerful friction dampening.
- High spring work combined with low weight and volume.
- High capacity.
- Characteristic independent of loading rate.
- Simple and compact design.

Figure 3: Prototype ring springs [3].

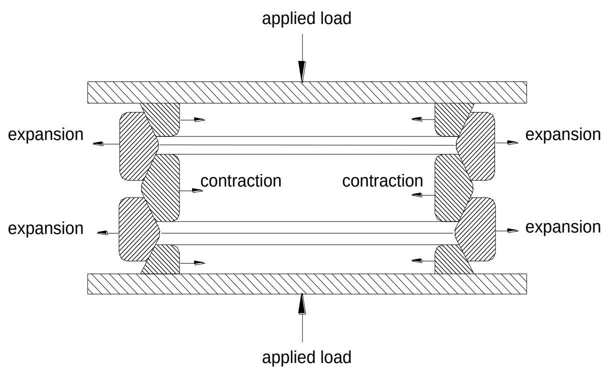

Figure 4: Loaded ring springs fully compacted device.

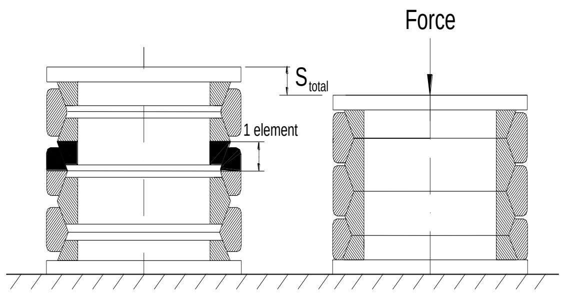

Figure 5: Deflection of a friction spring.

One effective taper face, i.e. one half inner ring and one half outer ring is defined as one element. This example is of a friction spring consisting of four outer rings, three inner rings and two half inner rings. As shown in Figure 5, this consists of eight elements. The figure shows the fully compacted device.

Details of Construction

Ring springs consist of a series of separate inner and outer ring elements with mating taper faces assembled in a columnar form. Under the application of a compressive axial load, the wedge action of the taper faces causes the inner elements to radially contract and the outer elements to radially expand, allowing axial deflection (Figure 5). This sliding action between mating elements results in a large amount of energy being absorbed in overcoming the friction forces.

Ring Spring Hysteresis Relationship

The area under the load-deflection diagram in Figure 6 corresponds to the work done or the input energy, while the hatched area within the loop is a measure of the absorbed energy and represents effective damping. The lost energy amounts to 66% of the input work and is dissipated as heat due to friction at the spring interfaces.

These stiffnesses, k_i (ring spring stiffness when an increasing load is applied), k_d (ring spring stiffness when a decreasing load is applied), give rise to the general form of the ring spring hysteresis diagram as shown in Figure 6.

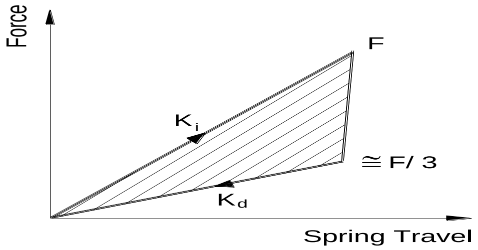

Figure 6: Ring spring hysteresis diagram.

As the axial compression applied to the ring spring is increased, the motion proceeds from the origin up the slope k_i. When the compressive load is reduced, the motion proceeds down the slope k_d. This effect is the result of reversal of frictional force (μ N) acting at the element interfaces.

To ensure that the friction properties of ring springs remain reasonably constant for repeated load-unload cycling, it is essential that the elements be lubricated. Hence grease lubrication is provided during initial spring assembly. Lubricant selection directly affects the coefficient of friction μ. The best compromise between energy absorption capability and the requirement for spring recoil gives rise to practical ring springs with a taper angle, α of between 14° to 15°, and coefficient of friction, μ within the range of 0.09 - 0.12.

Double-Acting Ring Spring

To use the ring spring as a seismic energy dissipating device, it should act to resist the forces induced by earthquake hazard in both the compression and the tension directions. A double acting spring arrangement is shown in its basic form in Figure 8. Under loading in tension, plate (1) remains fixed, and the tensioning cup (2) moves. This is reversed when the damper is in compression. The two parts 1, 2 must be in contact with both the shoulders in the casing and with the rod.

Double-Acting Hysteresis

With reference to Figure 7, the hysteretic behaviour of the ring spring can be characterized by four different physical parameters:

k_o = elastic stiffness (from the origin to point 1).

k_i = ring spring stiffness when an increasing load is applied (point 1 to point 2).

k_1 = ring spring stiffness between k_i and k_d (point 2 to point 3).

k_d = ring spring stiffness when a decreasing load is applied (point 3 to point 4),

where:

$k_i = r\ k_o$

$k_d = r_L\ k_o$ (r_L is the lower unloading stiffness factor)

$k_1 = r_S\ k_o$ (r_S is the steeper unloading stiffness factor).

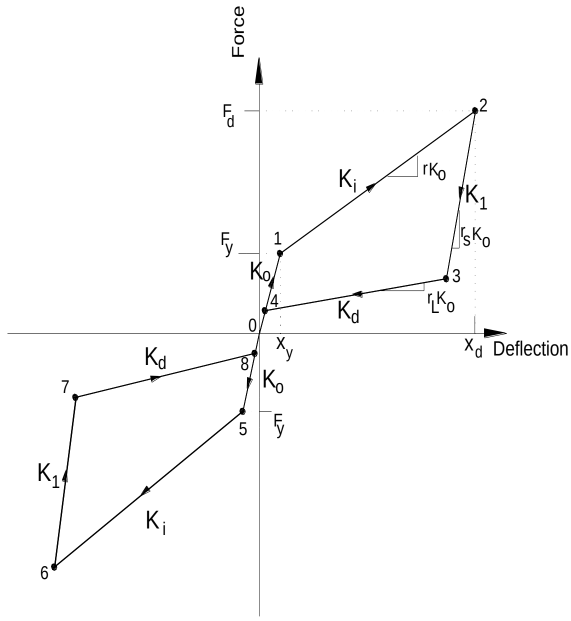

Figure 7: Double acting hysteresis diagram.

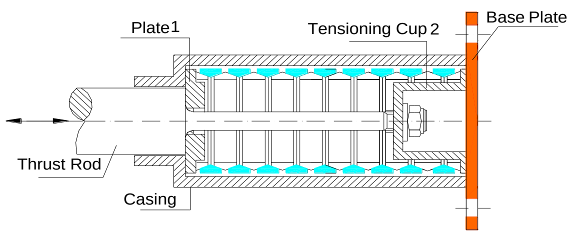

Figure 8: Double acting ring spring.

In applying load to a pre-loaded system, sufficient force must be applied to the ring spring for the motion to proceed along the stiffness path from point 0 to point 1. That force is to overcome frictional resistance before sliding action within the ring spring commences. This gives rise to an elastic stiffness, k_0 active between points 0-1. As load is increased, displacement continues between points 1-2. During the next phase of displacement unloading proceeds between points 2-3 and then continues along stiffness k_d to point 4, returning to the origin along stiffness k_0. This motion is repeated when the direction of the loading/unloading is reversed.

Thus, motion proceeds around points 0-1, 1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, and 8-0 for a complete load/unload cycle. The enclosed area represents the total energy absorbed for one full cycle.

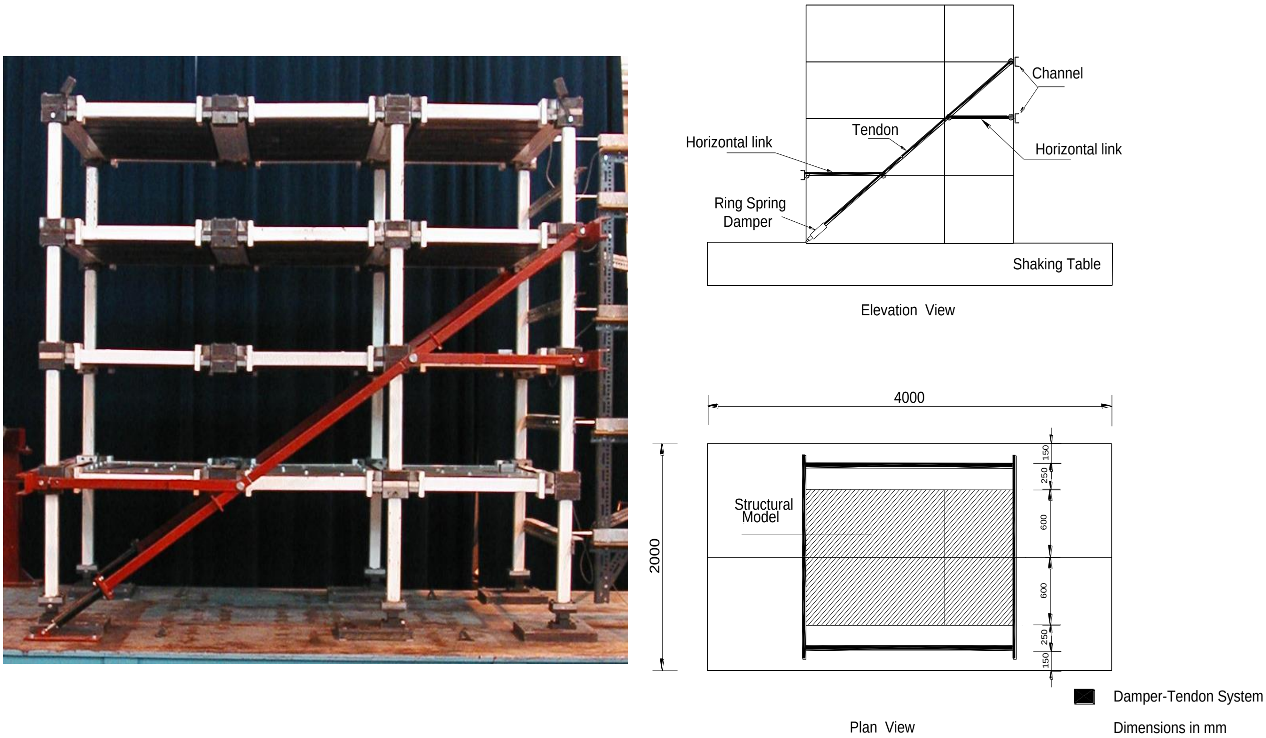

Figure 9: Experimental tests – Damper-Tendon System.

EXPERIMENTAL TESTS

To mitigate the response of the structure during a seismic event, a damper-tendon system is proposed. The supplemental control system consists of ring spring devices to provide the damping forces and a tendon system to transfer these damping forces to the rest of the building. The aim of the tendon system [4] is to provide a set of damping forces acting on the structure that resist the inertia forces in a way similar to that where a prestressing cable balances the applied loads in a prestressed beam.

The frame used to verify the usefulness of the effect of using ring springs in reducing the seismic response was an existing frame structure in the Structural Laboratory of the Civil Engineering Department, at the University of Canterbury. A view of the assembled frame structure is shown in Figure 9. In this example, in order to simplify the tendon concept a straight tendon was used to connect the damping device at the base of the frame to the third floor of the structure. An alternative to the use of the double acting ring-spring dampers would be to use two tendon systems and one-way ring-springs. This could allow larger displacements within the ring-spring devices, but at the complication of a symmetric tendon layout with twice as many components.

The four storey steel frame is built using square hollow steel sections for the beam and column members. Flat bars are used for the beam-column joints and other connecting joints. The main feature of the structure is the incorporation of replaceable fuses located in the critical regions of the structure, i.e. plastic hinges. The frame models a typical four-storey reinforced concrete ductile frame building. Therefore, the fundamental natural period of free vibration of the frame was required to be within the range of 0.4 to 0.6 seconds to obtain a similar response under earthquake excitation. For reinforced concrete members, the stiffness degrades after cracking especially in and around where the plastic hinges are expected to develop. Therefore, the stiffness of the plastic hinge fuses at the ends of the beams and the base of the ground floor columns were designed to be much smaller than the rest of the frame members but to provide the correct joint to joint flexural stiffness of members and to provide the correct yield moments at these plastic hinge locations.

TEST DEVICES

To determine the size of the dampers which were required for the experimental tests, analyses were carried out on the four storey test structure. The 15% of added damping to the structure was adopted for this research and used in the analyses. The structural analyses were carried out using the four-storey model structure to determine the size of the test

Figure 10: Prototype ring spring devices used in the experimental testing.

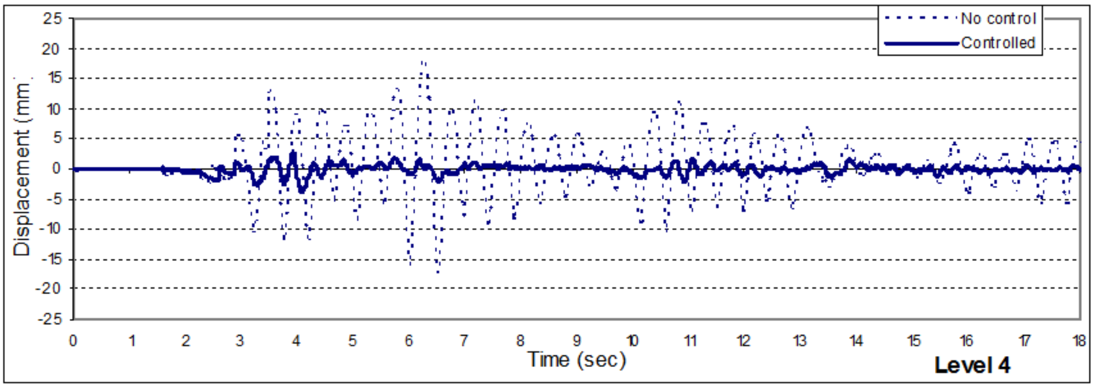

Figure 11: Displacement of the structure with and without the supplemental control system.

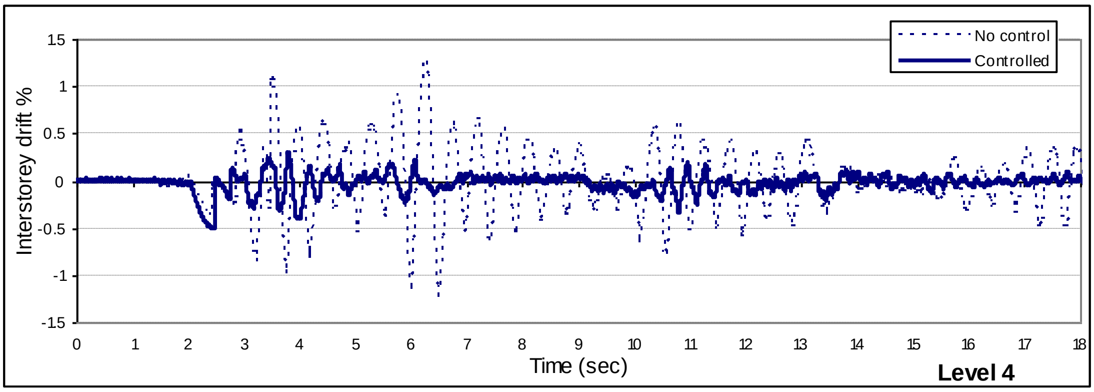

Figure 12: Inter-storey drifts of the structure with and without the supplemental control system.

devices. The analyses are based on comparing the roof displacement of the frame with a constant damping model to the roof displacement of the frame with a ring spring damper. By investigating the roof displacement, the size of the damper can be found so as to give the same roof deflection as that obtained when using the constant damping model.

The damping device used in the experimental tests in this research is a double acting ring spring device shown in Figure 10. They contain 84 ring spring elements (42 outer ring, 41 inner rings and 2 half inner rings). The blocking force capacity of the device is 5 kN, the height of each element h_e is 2.2 mm and the spring travel for one element is 0.4 mm.

EXPERIMENTAL INVESTIGATION

Dynamic testing of the test structure was performed on the shaking table in the Structures Laboratory at The University of Canterbury. Linear potentiometers and accelerometers were used to measure the frame response. Several tests were carried out during the testing. The tests could be categorized into free vibration and different levels of earthquake shaking tests. The free vibration tests were conducted to obtain the fundamental period and the critical damping ratio of the structure with and without the supplemental control system. The different levels of the shaking tests were carried out to obtain the effect of the supplement control. Figures 11 and 12 show the responses with and without the supplemental damping using 50% of the El Centro, May 1940 North-South earthquake as the table excitation.

Displacement and Inter-storey Drift Ratios

The relative displacement and inter-storey drift time histories for the structure with and without the supplemental damping system have been compared. The effectiveness of the ring spring dampers was obvious as they reduced the response by up to 40-80% of the unrestrained response. The maximum response envelopes for the four storey test structure with and without the supplemental control system are been presented in the various figures. As can be seen, the overall response of the structure up to 40-80% is significantly reduced by the addition of the dampers. Adding damping and increase in the stiffness of the structure by using the ring spring dampers was sufficient to protect the structure from undergoing severe inelastic deformation in the test. It must be mentioned, that the contribution of the beam-column connections and column base fuses did not affect the response of the structure as they were designed to give the appropriate flexibility to the structure in the plastic hinge regions so that the combination of the hinge members and the stiff interconnecting beam members model the flexibility of a normal frame members.

The ring-spring damper system added considerably to the stiffness of the frame and a large part of the displacement response reduction is associated with this increase in stiffness. Such an increase in stiffness would normally markedly reduce the natural period of free-vibration and increase the accelerations within the structure. However, the accelerations within the structure were no higher than those observed in the frame without the supplemental control system showing that the energy dissipated by the ring-springs restrained the, otherwise, expected increase in the acceleration response.

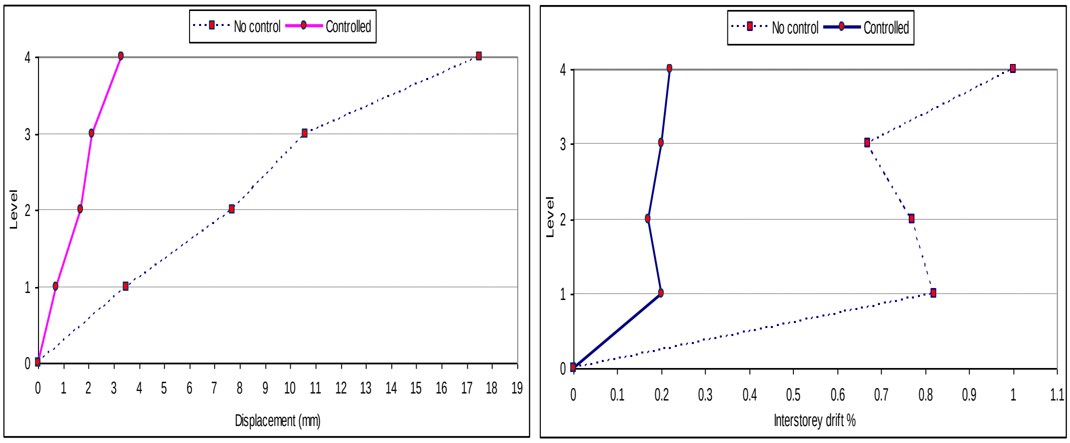

Figure 13: Displacement and inter-storey drifts of the structure with and without the supplemental control system.

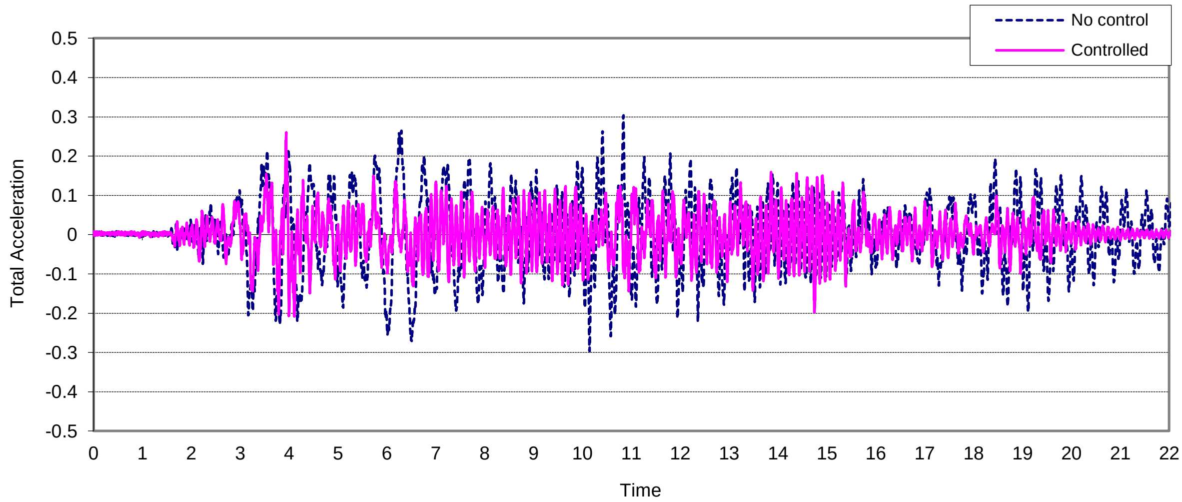

Figure 14: Experimental total acceleration of the top floor with 50% floor acceleration, with and without supplemental control system.

Figure 15: New construction of the Salt Lake City Public Safety Building, a post-disaster performance level steel moment building frame using fluid viscous dampers (Holmes Culley, San Francisco) [5].

GENERAL COMPARISON BETWEEN RING SPRING AND VISCOUS FLUID DAMPERS

Ring spring dampers have some features and characteristics that make them very useful as seismic control devices. Ring spring dampers are constructed of steel materials in which no possible leakage of liquid and no refilling or maintenance of any of the parts is needed which are potential problem in the viscous fluid dampers. Ring spring dampers absorb large amount of the input energy with low weight and small size which is in contrast to viscous fluid dampers. However, viscous fluid dampers do not increase the stiffness of the structure and consequently the accelerations of the structure and its contents.

Using viscous fluid dampers to improve the response of a building without adding significant structural stiffness is shown in reference [5]. Fluid viscous dampers are often used in seismic upgrade projects because they can be used to improve the response of a building without adding significant structural stiffness (and therefore increasing accelerations). This can be a particular advantage where additional foundation demands are to be avoided due to poor soil conditions or where budget constraints limit the scope for foundation or superstructure strengthening. In new construction they have been found to offer similar levels of performance benefits as base isolation, and provide an economical option that avoids a number of the construction and finishing issues inherent with isolation schemes. The example in Figure 15 is the Utah Public Safety Building, which is close to finishing construction. This steel moment-frame structure using fluid viscous dampers was chosen over base isolation as it offered post-disaster performance, flexibility in the usage of floor space and met the budget targets. The big size of the viscous fluid dampers can be observed from Figure 15.

RECENT USE OF RING SPRING DAMPERS IN BUILDINGS

One of the recent projects from the New Zealand consulting practice, Aurecon, which implements low damage design technologies in a 15 Storey Rocking Steel Framed Building, is located in Wellington, New Zealand. The design complexities, philosophies and detailing are described in the reference [6]. The primary bracing includes rocking concentrically braced frames (CBFs) across the building, and moment resisting frames (MRFs) with sliding hinge joints along the building. Ring springs are provided at the base of the CBF columns to allow the building to uplift and rock during design level earthquakes. Allowing the building to uplift limits the earthquake forces in the structure and provides protection to the seismic resisting elements.

The structure comprises two dis-similar lateral load resisting systems, Steel moment frames, with sliding hinge joints, in one direction and concentrically braced steel frames, with ring springs to provide controlled tension hold down, in the other.

The ring springs enable the connection to be preloaded so as to set the performance criteria at which “lift off” occurs. The friction sliding connection has two functions, firstly it provides additional resistance to uplift which reduces the size of the ring springs, and secondly it provides resistance during the downward motion of the column, reducing impact loads from the column.

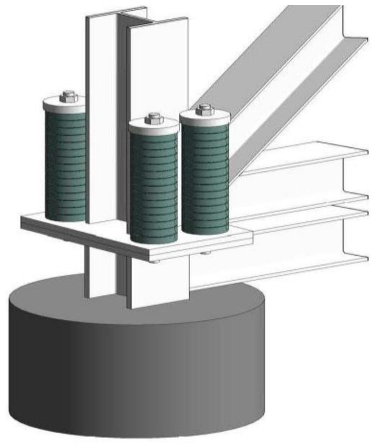

Figure 16: 3D view of CBF column base connection [6].

Under a design level seismic event, the tension columns of the CBFs are designed to uplift. Uplift will occur once the spring pre-stress, sliding friction connection and gravity loads are overcome. As the column begins to uplift the ring spring is compressed between the baseplate and a cover plate.

The building’s transverse bracing system consists of CBFs with tension limiting base connections. The base hinge consists of ring springs and a vertically orientated sliding friction connection. This system allows controlled hold down of the CBFs which limit the lateral loads to be resisted by the structure. This makes the base connection of the CBF the strength limiting element, preventing damage from occurring in the primary structural elements. This has advantages over a traditional CBF which relies on yielding of the braces to impart ductility into the structure, resulting in inelastic deformation of the structural system, requiring significant repairs post-earthquake.

CONCLUSION

This paper has focused on added damping in structures by using a passive control system. The seismic response of a four storey, two bay steel frame structure with and without the supplemental damping system has been investigated. This frame was used to verify the application of supplemental damping in reducing the seismic response of the structure under earthquake loading. Dynamic tests of the structure were carried out on the shaking table. The effectiveness of the ring springs dampers was obvious in reducing the response of the structure under earthquake excitations.

Structural control using such a supplemental damping system provides a cost-effective way of controlling structural deformation and damage under earthquake excitations. Such a system can be easily incorporated into a structure, either during its initial design or as a retrofit strategy. The supplemental system can be readily replaced, if necessary, after a major earthquake without interfering with the primary structural system. The displacements and deformations of the structure can be greatly reduced without the need for increasing the stiffness (member sizes) of the primary structure. This type of structural control is also suitable for retrofitting a non-ductile structure and also provides a good alternative solution when designing new building structures to resist earthquake excitations.

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