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Rehabilitation of buildings using multiple levels of passive control

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ABSTRACT: A building can be separated into two or more units along its height by passive control elements. A control element is a combination of a base isolation type device and a mechanical damper, or a brace including a mechanical damper. This structural concept has several applications in earthquake resistant design. In particular, this concept can be used in the rehabilitation of existing seismically weak multistory buildings. To illustrate, a six story building with a soft first story is considered. Control elements with optimal mechanical properties are placed in the first story and at one other higher location. It is demonstrated that, compared to conventional techniques, this method results in superior building response during a strong earthquake.

DESCRIPTION OF A BUILDING WITH MULTIPLE LEVELS OF PASSIVE CONTROL

A three story building with multiple levels of passive control is shown in Figure 1. In this two dimensional illustration, the building is divided along its height into four units separated at their interface by means of passive control elements. A control element is similar to currently used base isolators. Lin, Tadjbakhsh, Papageorgiou, and Ahmadi (1990) have described the mechanisms of various isolation systems and conducted a comparative study of their performance in buildings subjected to strong earthquakes. Ideally, a control element should be capable of providing low lateral stiffness, high vertical stiffness, and some degree of damping.

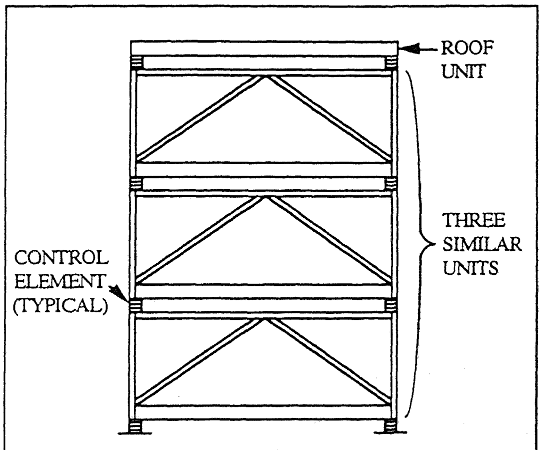

Figure 1. A three story building with multiple levels of passive control.

In the example presented in Figure 1, the control elements are located at all four possible levels. Other models can also be produced by choosing fewer levels of control elements. For instance, Figure 2 shows a model in which the control elements are placed at the base and between the second and third stories. In this case, the first two stories are taken as the lower building unit and the third floor, including the roof, as the upper.

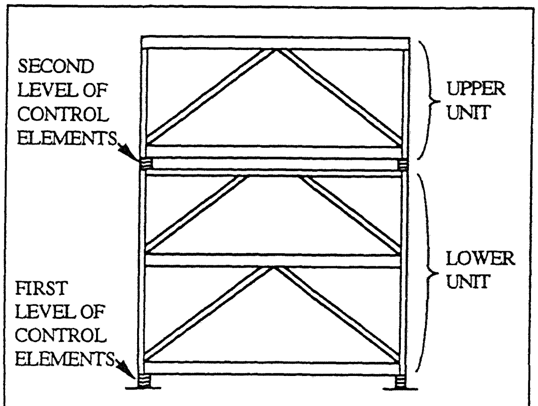

Figure 2. A three story building with two levels of passive control.

It is reasonable to expect that the lateral stiffness of the building units will be much larger than the lateral stiffness of the control elements, so that in a preliminary design cycle the characteristics of the system stiffness can be based solely upon the stiffness of the control elements. Also, ignoring the small inherent damping in the building units, the system damping can be drawn completely from the measurable damping properties of the control elements. These features provide a simple mathematical model for the dynamic behavior of the building. For instance, the three story models in Figures 1 and 2 behave, respectively, like four and two degree of freedom simply coupled systems.

A base isolated structure is a special form of the proposed scheme in which the control elements are placed only at the base. It is also of interest to note that placement of the control elements at the base and at one other location between adjacent stories will create a classic case of vibration isolation. Vibration isolation utilizing a tuned mass damper has been traditionally applied to reduction of wind induced vibrations in tall buildings (McNamara, 1977). The effect of tuned mass dampers on seismic response of structures has been studied by Slasek, Klingner (1983), Kaynia, Veneziano, and Biggs (1981) who concluded that no appreciable reduction in lateral force can be achieved. This conclusion is entirely due to the practical limit that they placed on the mass of the tuned mass damper.

In a two degree of freedom model, such as the one shown in Figure 2, the upper unit and the connecting control elements can be regarded as a tuned mass damper for the lower unit. In this sense the restriction of a practical level of mass for the tuned mass damper does not apply and substantial response improvements can be achieved. Curtis, Boykin (1961), Crandall, and Mark (1963) performed extensive parametric studies of a two degree of freedom system subjected to white noise base excitation. They investigated the vibration absorber action of the upper mass and concluded that vibration isolation exists if the upper to lower mass ratios are sufficiently large. This is practically possible with two levels of passive control.

OPTIMAL DESIGN OF BUILDINGS WITH MULTIPLE LEVELS OF PASSIVE CONTROL

Keshtkar, Hanson, and Scott (1991) have established an optimal design procedure for rigid multistory buildings with one or two levels of passive control. A brief description of their work is presented here to support the proposed rehabilitation technique in the following section.

The optimal design problems were formulated based on the random vibration methodology which requires a knowledge of the power spectral density of the excitation process. Because the statistical characterizations of earthquakes are more widely available in the form of design response spectra, a method was developed to derive power spectral densities from design response spectra. In this effort an existing extreme value probability distribution, which has been shown to apply accurately to earthquake excitation and response processes, was used (Vanmarcke, 1975; Der Kiureghian, 1980).

The design response spectrum used corresponds to acceleration time histories of magnitude 7.5 earthquakes recorded on rock deposits 10 km from the source (Mohraz, 1976; Mohraz and Elghadamsi, 1989). A mean maximum ground acceleration of 0.5g, where g is the gravitational acceleration, and a stationary duration of 25 seconds were adopted to generate the power spectral density of the ground acceleration process.

For both one and two degree of freedom systems the optimal design problems were cast to minimize the base shear over the stiffness and damping coefficients of the control elements. The constraints included upper bounds on the lateral displacement and damping coefficient, and lower bounds on the stiffness of the control elements. The base shear was represented by its mean extreme value; while the displacements were written as the sum of their mean extreme values and a multiple four of the standard deviation of their extreme values. These nonlinear programming problems were solved numerically based on a gradient projection algorithm due to Haug and Arora (1979).

A six story steel building was selected to ascertain the benefits of placing passive control elements at the base and at one other location between adjacent stories. The optimal designs were compared with those of the base isolated version. With the aforementioned excitation process associated with rock sites and the use of laminated rubber bearings as control elements, it was concluded that:

1. For the same base shear , the control elements for the structure with two levels of passive control required less material resource than those for the base isolated structure. The reduction was not however sufficiently radical to offset the costs associated with installation of the second level of control elements.
2. For the same base shear, the control elements at the base of the structure with two levels of passive control required less lateral flexibility than those for the base isolated structure. In this regard, the two level control scheme can be viewed as a method of response improvement without excessive lateral flexibility at the base.
3. In the two level passive control case, the vibration isolation action of the the upper unit significantly reduced the base displacement. This is an important characteristic of the proposed concept which can be used effectively in rehabilitation of existing seismically hazardous buildings. In particular, this idea can be applied to rigid multistory structures with soft first stories. This possibility is discussed in some detail in the following section.

REHABILITATION OF A BUILDING WITH A SOFT FIRST STORY

A building with a soft first story is shown in Figure 3. This is a common example in which, for space and aesthetic requirements, the unbraced columns in the first floor support the relatively rigid structure of the upper levels. In an intense earthquake plastic deformations concentrate in the soft story and ultimately cause the collapse of the entire structure (Arnold, 1989).

As an example, consider a six story steel building in which the first floor columns are unbraced but rotationally constrained at both ends. Assume that all other floors are adequately braced and thus comprise a rigid unit supported on the soft columns of the first floor. Under these conditions the building can be treated as a one degree of freedom system. For this model let a typical first floor column have a lateral stiffness equal to 9281.2 kN/m (53 kip/in) and let the total weight of the rigid unit, corresponding to one column, be equal to 1334.4 kN (300 kips).

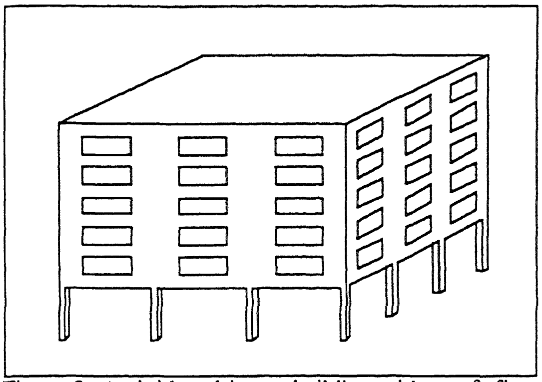

Figure 3. A rigid multistory building with a soft first story.

Based on an elastic design procedure, the allowable relative displacement of the first story columns due to combined action of lateral motion and gravity loads can be readily computed. In the example problem under consideration, a reasonable value for the allowable displacement is 11.4 mm (0.45 in). This value, however, will be far exceeded in the event of a severe ground motion. To illustrate, the ground motion and the probabilistic method of analysis described in the previous section were used. The elastic results with 5% damping, identified as case 1, are summarized in Table 1.

Note that the relative column end displacement (4.68 in =118.9 mm) is excessively large. In order to reduce this displacement to the allowable level of 11.4 mm (0.45 in), the following options can be explored:

1. Provide adequate bracing in the first story.
2. Provide partial bracing with supplemental damping devices in the first story (Bergman and Hanson, 1988).
3. Use the second option together with another level of passive control under the roof or under the floor slab of the top story.

These options can be studied in the context of the optimal design formulations discussed in the previous section. For the first two options the following formulation can be used:

minimize $E[V^e]$
over k, c
such that $y^e \leq 11.4$ mm (0.45 in)
$\xi \leq \xi^u$

in which the objective function $E[V^e]$ is the mean extreme value of the base shear tributary to one column; k and c are, respectively, the lateral stiffness and damping coefficient of the first floor tributary to one column; y^e is the extreme value of the first floor displacement with at most 6% probability of exceedance; ξ is the damping ratio; and ξ^u is the upper bound on ξ. For the first option let ξ^u=5% and for the second option, requiring supplemental mechanical dampers, use ξ^u=20%. The solutions are presented in Table 1 and are respectively identified as case 2 and case 3.

In case 2, large braces have to be used to provide the required lateral stiffness of 205,063 kN/m (1171 kip/in). The acceleration in this case is also excessive (1.2g), requiring strengthening of the upper stories. It should be noted that the results in case 2 are based on an elastic analysis. As such, they do not reflect the forces and accelerations which will be obtained when the structure is retrofitted with braces that are allowed to yield and buckle consistent with a ductile design philosophy. The objective here is to obtain a retrofitting solution which guarantees elastic behavior. In this sense, case 3 provides a better solution because both the required lateral stiffness in the first story (106,647 kN/m = 609 kip/in) and the acceleration of the upper stories (0.66g) are smaller.

Table 1. Elastic solutions to the soft first story building example using one degree of freedom models.
(1 kip-mass=0.453 ton; 1 in=25.4 mm; 1 kip/in =175.118 kN/m; 1 kip=4.448 kN)

Quantity	Units	Case 1 (original structure)	Case 2 (braces only)	Case 3 (braces and dampers)
m	kip-mass	300	300	300
k	kip/in	53	1171	609
c	kip-sec/in	0.59	3.02	8.7
ω	rad/sec	8.26	38.82	28.00
ξ	-	0.05	0.05	0.20
$E[V^e]$	kips	151.7	361.0	199.1
$E[a^e]$	g	0.51	1.20	0.66
y^e	in	4.68	0.45	0.45

m=mass of the building tributary to one column; k=lateral stiffness of the first floor tributary to one column; c=damping coefficient of the first floor tributary to one column; ω=frequency; ξ=damping ratio; $E[V^e]$=mean extreme value of the base shear tributary to one column; $E[a^e]$=mean extreme value of the acceleration of the rigid unit; y^e=relative elastic column end displacement in the first story with an exceedance probability of at most 6%.

Next consider the third option using the following minimization problem:

minimize $E[V_1^e]$
over k_1, k_2, c_1, c_2
such that $y_1^e \leq 11.4$ mm (0.45 in)
$c_1 \leq 1523.5$ kN-sec/m (8.7 kip-sec/in)

in which the objective function $E[V_1^e]$ is the mean extreme value of the base shear tributary to one column; k_1 and c_1 are, respectively, the stiffness and damping coefficient of the supplemental braces and dampers in the first story tributary to one column; k_2 and c_2 are, respectively, the stiffness and damping coefficients of the control elements under the roof or under the floor slab of the top story; and y_1^e is the extreme value of the first floor lateral displacement with at most 6% probability of exceedance.

In this two degree of freedom formulation, the upper bound on the first floor damping has been set equal to the damping required for the second option (case 3, Table 1). The solutions, for two different mass ratios, are provided in Table 2. Case 1 requires placement of the control elements under the roof while in case 2 the control elements are placed under the floor slab of the top story. With respect to the base shear, accelerations, and the lateral stiffness requirements in the first floor, both solutions in Table 2 indicate substantial advantages over those considered previously (Table 1).

Table 2. Elastic solutions to the soft first story building example using two levels of passive control.
(1 kip-mass=0.453 ton; 1 in=25.4 mm; 1 kip/in =175.118 kN/m; 1 kip=4.448 kN)

Quantity	Units	Case 1	Case 2
m_1	kip-mass	250	200
m_2	kip-mass	50	100
m_1+m_2	kip-mass	300	300
k_1	kip/in	402	259
k_2	kip/in	16.2	9.4
c_1	kip-sec/in	8.7	8.7
c_2	kip-sec/in	1.1	1.5
ω_1	rad/sec	25.3	22.5
ω_2	rad/sec	11.0	6.0
ξ_1	-	0.31	0.44
ξ_2	-	0.36	0.46
$E[V_1^e]$	kips	119.2	84.7
$E[a_1^e]$	g	0.53	0.45
$E[a_2^e]$	g	0.41	0.22
y_1^e	in	0.45	0.45
y_2^e	in	1.37	1.46

m_1=mass of the lower unit ; m_2=mass of the upper unit ; ω_1 and ω_2=approximate modal frequencies; ξ_1 and ξ_2=approximate modal damping ratios; $E[a_1^e]$=mean extreme value of the acceleration of the lower unit; $E[a_2^e]$=mean extreme value of the acceleration of the upper unit; y_2^e=lateral displacement of the control elements between the lower and upper units with an exceedance probability of at most 6%.

CONCLUSION

An optimal arrangement of multiple levels of passive control within the framework of seismically weak buildings enhances their seismic performance in strong earthquakes. This structural concept was applied to rehabilitation of a six story building with a weak and flexible first story. It was shown that installation of passive control devices in the first floor and in one other location, such as under the roof or under the floor slab of the top story, ensures elastic behavior of the entire building in a strong earthquake.

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