

Implementation Study of Aseismic Roof Isolation System in 13-Story Building

Roberto Villaverde

Professor, Department of Civil Engineering, University of California, Irvine, CA 92697,
USA

ABSTRACT: *An investigation is carried out with an actual 13-story building to assess the viability and effectiveness of a recently proposed roof isolation system that aims at reducing the response of buildings to earthquakes. The roof isolation system entails the insertion of flexible laminated rubber bearings between a building's roof and the columns that support it, and the addition of viscous dampers connected between the roof and the rest of the building. It is based on the concept of a vibration absorber and on the idea of making the roof, flexible bearings, and viscous dampers respectively constitute the mass, spring, and dashpot of such an absorber. The investigation includes a comparison of the building's response under a severe ground motion when it is considered with and without the isolation system, as well as the determination of the properties and size of the required isolation system components. It is found that the proposed isolation system is effective, is constructable, and has the potential to become an attractive way to reduce structural and nonstructural earthquake damage in low and medium-rise buildings.*

Keywords: Passive control; Vibration absorber; Tuned-mass damper; Supplemental damping; Seismic isolation; Protective system

1. INTRODUCTION

Vibration absorbers consisting of a comparatively small mass-spring-dashpot system in resonance with the structure on which they are installed have been proven effective to reduce wind-induced vibrations in high-rise buildings, floor vibrations induced by occupant activity, and the seismic response of buildings. From the practical point of view, these vibration absorbers, first suggested by Frahm in 1909 [1, 2] and often called tuned mass dampers, represent an attractive alternative to protect structures against the detrimental effect of earthquakes. Their attraction stems from the fact that they are capable of significantly reducing the dynamic response of a structure, yet their construction is simple. It only requires putting together a mass, a spring, and a damper at a localized point of the structure, with no need for an external power source or sophisticated hardware.

For the past several years, the author and his co-workers [3-6] have conducted a series of analytical and experimental tests to study the effectiveness of such vibration absorbers in reducing the earthquake response of building and bridge structures. In these studies, it is found that, with an adequate selection of their mass and damping ratios, these devices may indeed be effective to reduce such a response. Unfortunately, it has also been found that they have some disadvantages as well. First of all, they require a relatively large mass and, hence, a large

space for their installation. Secondly, since by design are set in resonance with their supporting structures, they usually undergo large displacements in relation to the points of the structure to which they are attached. As a result, they also need the space and the corresponding clearance to accommodate such large displacements. Lastly, they need to be mounted on a smooth surface to minimize friction forces and facilitate their free motion.

In an effort to overcome these disadvantages, the author has suggested [7-9] to use a portion of a building's mass as the mass of the absorber. Furthermore, instead of conventional springs, he has suggested the use of laminated elastomeric bearings of the type being currently employed in base isolated buildings [10-12]. More specifically, he has proposed to form a vibration absorber using the roof of a building in the way shown in Figure 1. Observe, thus, that under the proposed scheme the roof furnishes the mass of the absorber, the elastomeric bearings its stiffness, and the viscous dampers its damping element.

The advantages of building a vibration absorber this way are many:

1. No burdensome mass is added to the building.
2. The roof space is kept free and may be used for other installations.
3. There is no need for the additional roof space needed

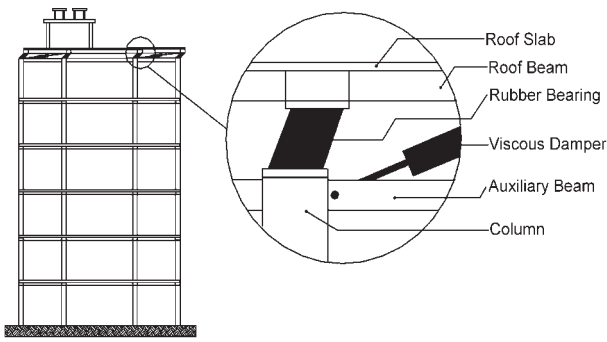


Figure 1. Typical building with proposed roof isolation system.

4. to allow for the free travel of the absorber's mass.
4. There is no need for the use of restraints to avoid an excessive lateral motion of the absorber's mass since the dampers themselves provide such a restraint.
5. It is ideal for retrofitting existing buildings since no significant weight is added to the structure or the foundation and the disruption involved during its construction is restricted to only one story.
6. The components used have properties that are well suited for the intended application. For example, elastomeric bearings are stiff at small strains. Hence, they will only undergo insignificant displacements under small wind and earthquake loads. Similarly, they have a low stiffness and exhibit an almost linear force-deformation behavior under moderately large strains. Furthermore, they harden again at exceptionally large strains, providing thus an additional fail-safe action against extreme seismic loads [11]. Additionally, elastomeric bearings are self-restoring, even after large shear strains.
7. It is relatively easy to implement and has therefore the potential to be cost effective.

The purpose of this paper is to report the details and results of a study that has been carried out with an actual 13-story building to gain an insight as to:

- (a) The size of the bearings and dampers needed to build a vibration absorber in the suggested way in a typical medium-rise building;
- (b) The magnitude of the largest lateral displacements experienced by the isolated roof;
- (c) The design difficulties in implementing a real building with such a scheme; and
- (d) The effectiveness of this scheme in a three-dimensional building with realistic dimensions and under a realistically severe ground motion.

In this study, the aforementioned 13-story building is assumed implemented with the proposed absorber system and its response to a critical ground motion computed and compared to the response obtained when the building is considered with its original configuration. In addition, a selection is made of the characteristics of the

laminated rubber bearings and viscous dampers that are needed to effectively reduce the seismic response of the building and resist, at the same time, the forces and deformations imposed on them when the building is subjected to such a critical ground motion.

In what follows, therefore, a description is made of the building and ground motion selected for the study, the criterion used for the selection of the roof isolation system dynamic characteristics, and the results of the aforementioned comparative analysis. In addition, an account is given of the procedure used to determine the dimensions and properties of the elastomeric bearings and viscous dampers that make the roof isolation system have the desired dynamic characteristics, and of the choices made in regard to these dimensions and properties. Lastly, the conclusions drawn from the results of the study are presented.

2. BUILDING CHARACTERISTICS

The building selected for the investigation corresponds to an existing commercial building located in Sherman Oaks, California and designed around 1964. The building has 13 stories, 2 basements, a pile foundation, a rectangular plan 22 meters (72 feet) wide and 58 meters (189 feet) long, and is structured with moment-resisting reinforced concrete frames. As shown in Figures 2 and 3, it has seven bays along its longitudinal direction and two along its transverse direction. The dimensions of its beams and columns are listed in Table 1. The floor system consists of a 102mm

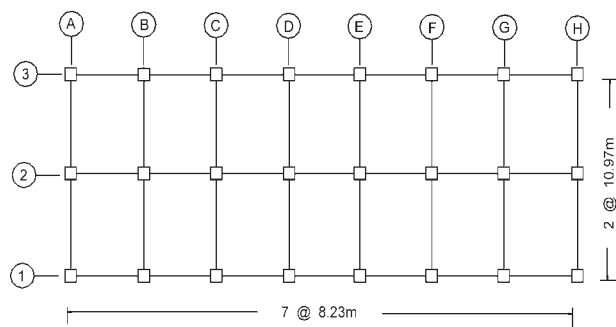


Figure 2. Plan view of studied building structure.

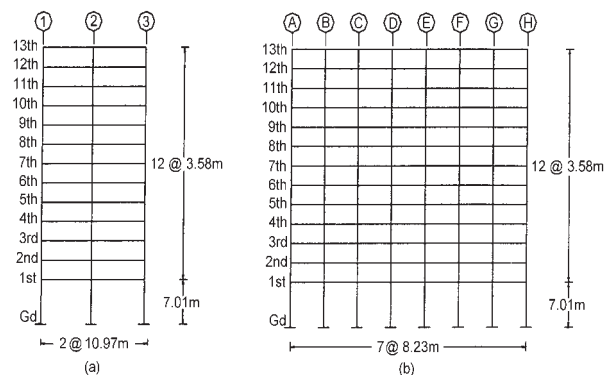


Figure 3. North-south (a) and East-west (b) elevations of studied building structure.

Table 1. Dimensions of beams and columns in studied 13-story building.

Beams			Columns			
Column Line	Floor	Section (m)	Column Line	Location	Story	Section (m)
1&3	1-4	0.46 x 0.99	1&3	Interior	1-4	0.61 x 0.91
	5-8	0.46 x 0.99			5-8	0.61 x 0.91
	9-13	0.46 x 0.99			9-13	0.61 x 0.91
2	1-4	0.61 x 0.81	1&3	Exterior	1-4	0.91 x 0.91
	5-8	0.61 x 0.81			5-8	0.91 x 0.91
	9-13	0.61 x 0.81			9-13	0.91 x 0.91
A&H	1-4	0.46 x 0.99	2	Interior	1-4	0.91 x 0.91
	5-8	0.46 x 0.99			5-8	0.91 x 0.91
	9-13	0.46 x 0.99			9-13	0.91 x 0.91
B-G	1-4	0.61 x 0.81	2	Exterior	1-4	0.61 x 0.91
	5-8	0.61 x 0.81			5-8	0.61 x 0.91
	9-13	0.61 x 0.81			9-13	0.61 x 0.91

(4in) one-way reinforced concrete slab supported by reinforced concrete beams and girders. The concrete and reinforcing steel used in its design have a strength of 27.5MPa (4,000psi) and 412MPa (60,000psi), respectively. As one of the buildings instrumented by the California Division of Mines and Geology, acceleration records were obtained at its base and several other locations during the 1994 Northridge, California earthquake [13].

For the analysis, the building is considered with a gravity load (dead plus live) of 9.1kN/m² (190psf) for the floors and 8.4kN/m² (175psf) for the roof. In addition, all its structural elements are considered with their gross moments of inertia (neglecting the contribution of the slab in the case of the beams) and a modulus of elasticity of 24,000MN/m² (3490ksi). The first five natural frequencies of the building, along its longitudinal and transverse directions and calculated on the basis of such loads and assumptions, are presented in Table 2.

Table 2. Natural frequencies of studied 13-story building.

Mode	Natural Frequency (Hz)	
	Longitudinal Direction	Transverse Direction
1	0.459	0.415
2	1.422	1.294
3	2.531	2.342
4	3.797	3.562
5	5.271	5.028

3. DYNAMIC CHARACTERISTICS OF VIBRATION ABSORBER SYSTEM

It has been shown in previous work [3] that if an appendage with a generalized mass m_a , natural frequency ω_a , and damping ratio ξ_a in one of its modes is attached to a multi-degree-of-freedom structure with a natural frequency $\omega_b = \omega_a$, damping ratio ξ_a , and generalized mass M_b in

one of its modes, then the resulting structure-appendage system possesses two modes of vibration with a natural frequency that is very close to ω_b and a damping ratio that is approximately equal to $(\xi_b + \xi_a)/2$; i.e., the average of the damping ratios of the two independent components. This occurs provided the relationship between the parameters of the structure and the appendage is such that $(\xi_b - \xi_a)^2 \leq \Phi_k^2 m_a / M_b$, where Φ_k denotes the amplitude corresponding to the mass of the structure that supports the appendage in the structural mode shape with frequency ω_b , when Φ_k, m_a , and M_b are computed using a mode shape that has been normalized to have a unit participation factor. Thus, since a vibration absorber is nothing else but a small single-degree-of-freedom appendage in resonance with the structure on which it is installed, it is possible to interpret that the reduction in structural response induced by a vibration absorber comes as a result of the increase in the damping of the structure from its original value ξ_b to a higher value approximately equal to $(\xi_b + \xi_a)/2$, where ξ_a is the damping ratio of the absorber. From this theory, it is also possible to conclude that an effective vibration absorber is one that is attached to the point of the structure that undergoes the largest amplitude when the structure vibrates in its dominant mode, has a natural frequency that is equal to the natural frequency of the structure in such a dominant mode, has a damping ratio that is high in comparison with that of the structure, and has a mass, stiffness, damping ratio and location within the structure that satisfies the relationship $(\xi_b - \xi_a)^2 = \Phi_k^2 m_a / M_b$. Furthermore, one may conclude that if the damping ratio for the vibration absorber is chosen to be a given value ξ_a , then the mass m_a , stiffness constant k_a , and damping coefficient c_a that make it work effectively are given by

$$m_a = \frac{(\xi_b - \xi_a)^2}{\Phi_k^2} M_b; \quad k_a = \omega_b^2 m_a; \quad c_a = 2\xi_a \omega_b m_a \quad (1)$$

where all symbols are as defined before.

More recently, however, Sadek et al [14] have obtained by curve fitting numerical results improved formulas to determine the parameters of effective vibration absorbers. These formulas give the absorber-to-structure frequency ratio and absorber damping ratio, and are of the form

$$f = \frac{1}{1 + \Phi_k m_a / M_b} \left[1 - \xi_b \sqrt{\frac{\Phi_k m_a / M_b}{1 + \Phi_k m_a / M_b}} \right] \quad (2)$$

$$\xi_a = \Phi_k \left[\frac{\xi_b}{1 + m_a / M_b} + \sqrt{\frac{m_a / M_b}{1 + m_a / M_b}} \right] \quad (3)$$

where f and ξ_a are such frequency and damping ratios. Thus, the mass and damping constant of the vibration absorber (roof isolation system) for the building under investigation are herein determined by means of the formulas in Eq. (1) but considering that ξ_a is given by Eq. (3). Its stiffness is obtained according to

$$k_a = f^2 \omega_b^2 m_a \quad (4)$$

where f is given Eq. (2).

4. COMPARATIVE STUDY

4.1. Introduction

As mentioned before, the effectiveness of the proposed roof isolation system is assessed by analyzing the building described above under the effect of a critical ground motion and comparing the responses that are obtained when the building is considered with and without the isolation system. For this purpose, two-dimensional analytical models of the building's structure and the roof isolation system are developed first. Then, critical ground motions are selected and defined for each of the two orthogonal directions of the building.

Thereafter, considering the building independently along each of these two directions and alternatively with and without the roof isolation system specifically designed for it, the building's interstory drifts and the ductility demands imposed on its beams and columns are calculated for the case when the base of the building is excited by one of the selected ground motions.

4.2. Structural Model

The beams and columns of the building are modeled with bilinear beams elements with a yield capacity equal to the minimum that is needed to resist the considered ground motion without yielding when the building is implemented with the roof isolation system. A damping ratio of 2 percent is assumed for the fundamental mode of the building. Furthermore, the damping matrix of the building is assumed, when independently considered, proportional to the corresponding stiffness and mass matrices, with proportionality constants equal to $\omega_b \xi_b$ and ξ_b / ω_b , where ω_b and ξ_b respectively denote the natural frequency and damping ratio of the building in its fundamental mode.

In regard to the selection of a beam yield capacity equal to that needed to resist the considered ground motion elastically when the building is implemented with the roof isolation system, it is worthwhile to note that such a selection was made so to emphasize the fact that a roof isolation system may be used effectively to minimize structural damage even in the event of a severe earthquake.

4.3. Roof Isolation System Model

For the case when the building is analyzed with the roof isolation system, the isolation bearings are modeled with shear beam elements that behave linearly up to shear strains of 200 percent. This assumption of elastomeric bearings with a linear behavior is made in accordance with the typical force-deformation relationships reported in the literature (see, for example, the load-deformation relationships for natural rubber shown in Figure 4). In

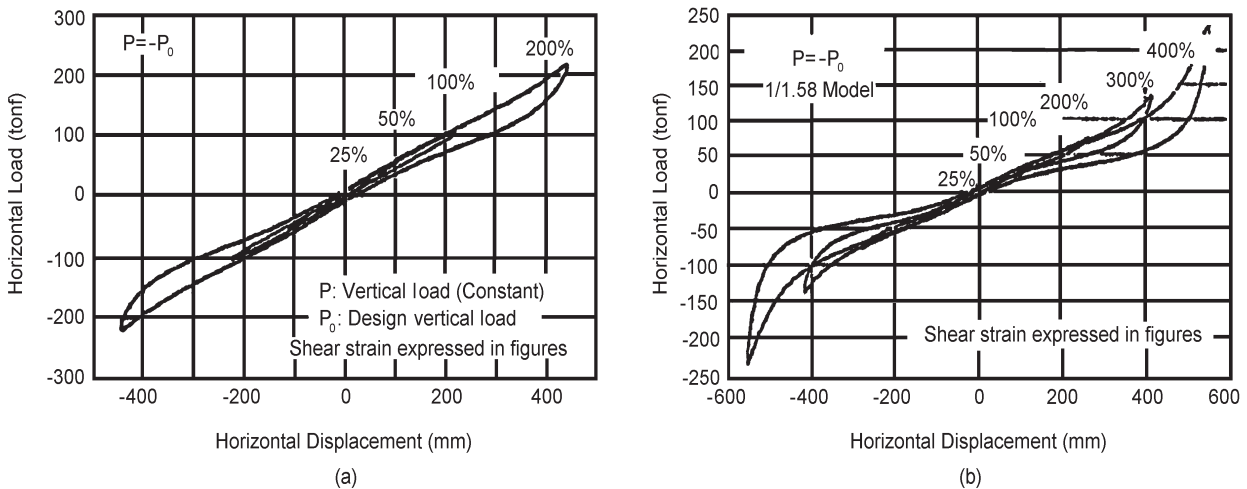


Figure 4. Force-deformation behavior of natural rubber laminated bearings under (a) shear strains below 200 percent, and (b) high shear strains (reproduced with permission from Mazda et al [21]).

addition, a mass of 1,082Mg (74.0kips-s²/ft) is considered to be the mass of the system. This mass is supposed to represent the mass supported by the elastomeric bearings and corresponds to the mass of the 102mm (4in) roof slab, roof beams, parapet, mechanical and electrical equipment, and all other appurtenances commonly found on a building's roof. The stiffnesses of the elastomeric bearings and damping constants of the viscous dampers needed to form an effective roof isolation system are obtained, as indicated earlier, using Eqs. (1, 4), with the damping ratio for the system determined from Eq. (3). Note, however, that because of the different natural frequencies of the building along its longitudinal and transverse directions, different bearing and damping characteristics need to be considered along each of these two directions. In the longitudinal direction and in its fundamental mode, the building without its roof has a fundamental natural frequency of 0.481Hz, a generalized mass of 12,756Mg (827.6kips-s²/ft), and a unit-participation-factor mode shape amplitude at roof level equal to 1.27. Accordingly, the absorber-to-building mass ratio is equal to 0.085, and thus, according to Eqs. (2, 3), the required absorber frequency and damping ratios along that direction are 0.897 and 0.38, respectively. On the basis of this frequency ratio and Eq. (4), the elastomeric bearings need thus to provide a lateral stiffness of 7952kN/m (488.7kips/in), which, by considering that the building has 24 columns, corresponds to a lateral stiffness per bearing of 331kN/m (20.4kips/in). Similarly, since the mass and circular natural frequency of the single oscillator that is formed with the roof mass and the elastomeric bearings are respectively equal to 1082Mg (74.0kips-s²/ft) and 2.711rad/s, the constant of the damping element needed to provide a damping ratio of 38 percent is equal to 2229kN-s/m (152.5kips-s/ft). In the transverse direction, the building without its roof and also in its fundamental mode has a natural frequency equal to 0.435Hz, a generalized mass equal to 12,558Mg (859.0kips-

s²/ft), a unit-participation-factor mode shape amplitude at roof level equal to 1.29, and an absorber-to-building mass ratio equal to 0.086. As a result, the required absorber frequency and damping ratios for the building's transverse direction are equal to 0.894 and 0.39, respectively. In this direction, therefore, the elastomeric bearings need to furnish a total lateral stiffness of 6460kN/m (397.0kips/in), or a lateral stiffness per bearing of 269kN/m (16.5kips/in). Likewise, since the roof mass is equal to 1082Mg (74.0kips-s²/ft) and the circular natural frequency of the roof isolation system in the direction under consideration is equal to 2.443rad/s, the constant of the damping element needed along this direction results equal to 2062kN-s/m (141.0kips-s/ft).

4.4. Selected Ground Motions

The basic ground motion selected for the analysis is the acceleration time history recorded during the 1994 Northridge earthquake at the ground level of the building under investigation and along its transverse direction. This time history, however, is modified to tune its dominant frequency to the fundamental natural frequency of the building. Since the building has different fundamental natural frequencies along its longitudinal and transverse directions, different ground motions are thus considered for the analysis of the building along each of these two directions. The tuning is performed by scaling the time axis of the original ground motion by a factor of 1.453 for the analysis along the building's longitudinal direction and 1.600 for the analysis along its transverse direction. The resulting acceleration time histories and their corresponding displacement and acceleration response spectra are shown in Figures 5 through 7.

The selected ground motion was determined to be suitable for the comparative analysis reported herein because it is a ground motion that induced some structural damage in the building under study during the 1994

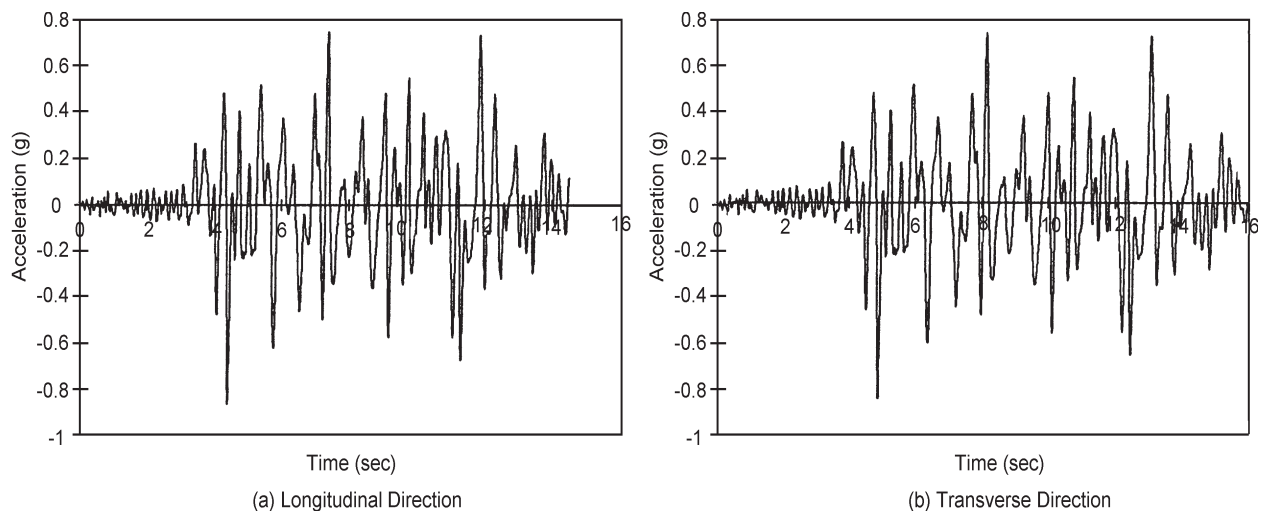


Figure 5. Ground motions considered in comparative study.

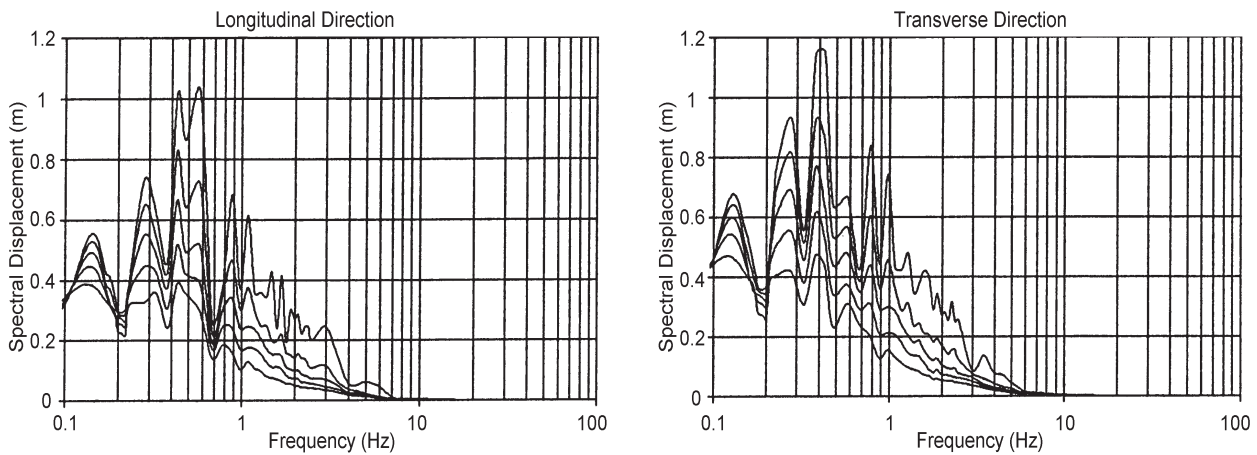


Figure 6. Displacement response spectra of ground motions considered in comparative study for damping ratios of 0, 2, 5, 10, and 20 percent.

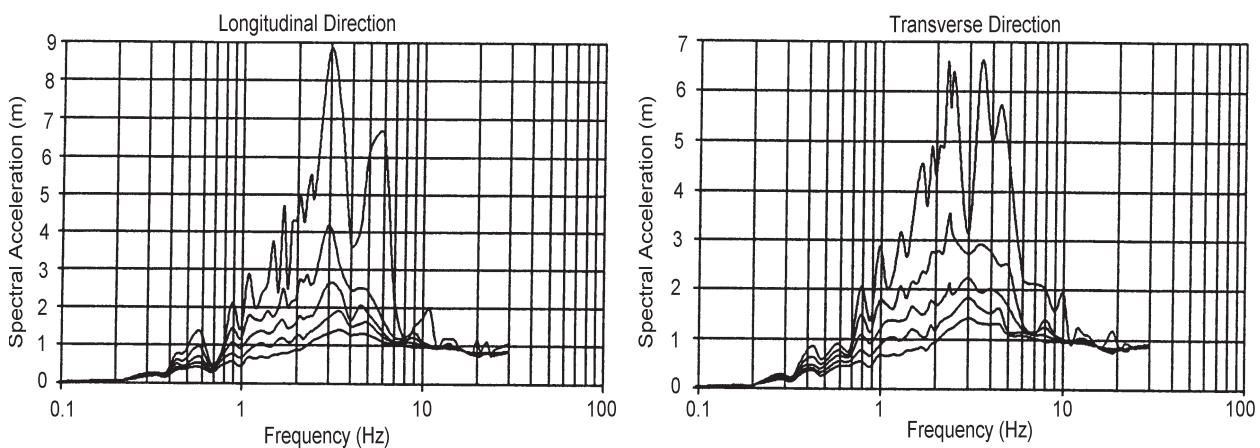


Figure 7. Acceleration response spectra of ground motions considered in comparative study for damping ratios of 0, 2, 5, 10, and 20 percent.

Northridge earthquake [15] and because it was considered thus to be capable of exciting this building well into its nonlinear range of behavior. Its tuning to the fundamental natural frequencies of the building is carried out with the purpose of investigating the demands imposed on the roof isolation system when the building is subjected to a resonant and hence a severe ground excitation. Besides, as shown in previous work [4, 6], the effectiveness of a vibration absorber is more evident when the building is subjected to a damaging ground motion than when it is subjected to a ground motion that only induces an insignificant building response.

Only one ground motion is considered in the investigation since it has been found in previous studies [4, 6] that vibration absorbers are invariably effective to reduce the response of a structure to a resonant ground motion and provide, as a result, protection against damaging ground motions. In other words, the investigation concentrated in testing whether or not the suggested isolation scheme can work effectively as a vibration absorber and not in demonstrating that vibrations absorbers may be effective under different earthquake excitations, which is something that has already been discussed at

length in a previous publication [4].

4.5. Results

The response analyses are carried out using a computer program developed by Hanna [16] for the nonlinear analysis of two-dimensional frames, after its modification to be able to consider damping elements with different damping constants at different structural locations. The obtained results are summarized in Figures 8 through 10. Figures 8 and 9 show the rotational ductility demands in the beams and columns of the building when the building is alternatively considered with and without the proposed roof isolation system. These rotational ductility demands are calculated as the maximum end rotation experienced by a beam or column when the building is subjected to the considered ground motion, divided by the corresponding rotation that makes the beam or column yield. Similarly, Figure 10 shows the interstory drift ratios obtained in each of the two analyzed cases, where these interstory ratios are defined as interstory drift divided by story height. Note that in Figures 8 and 9 a rotational ductility demand of less than unity signifies that the structural member under

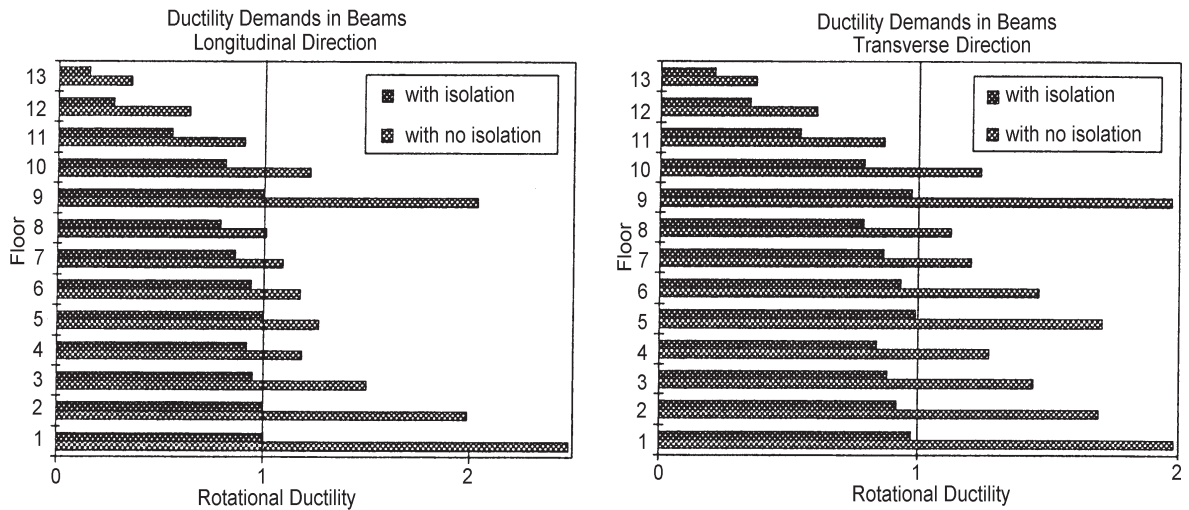


Figure 8. Rotational ductility demands in beams of studied building under selected ground motions.

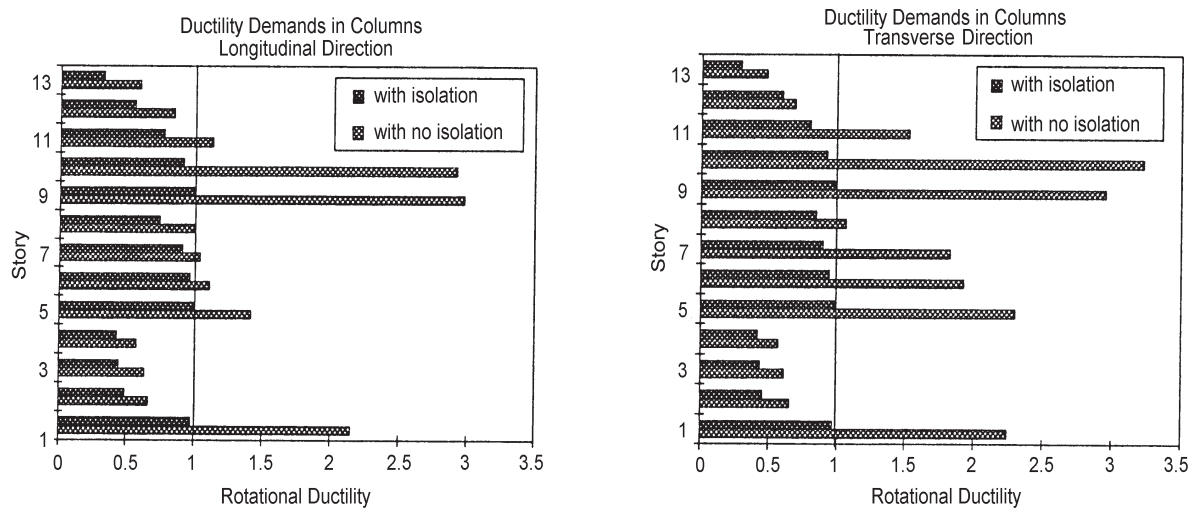


Figure 9. Rotational ductility demands in columns of studied building under selected ground motions.

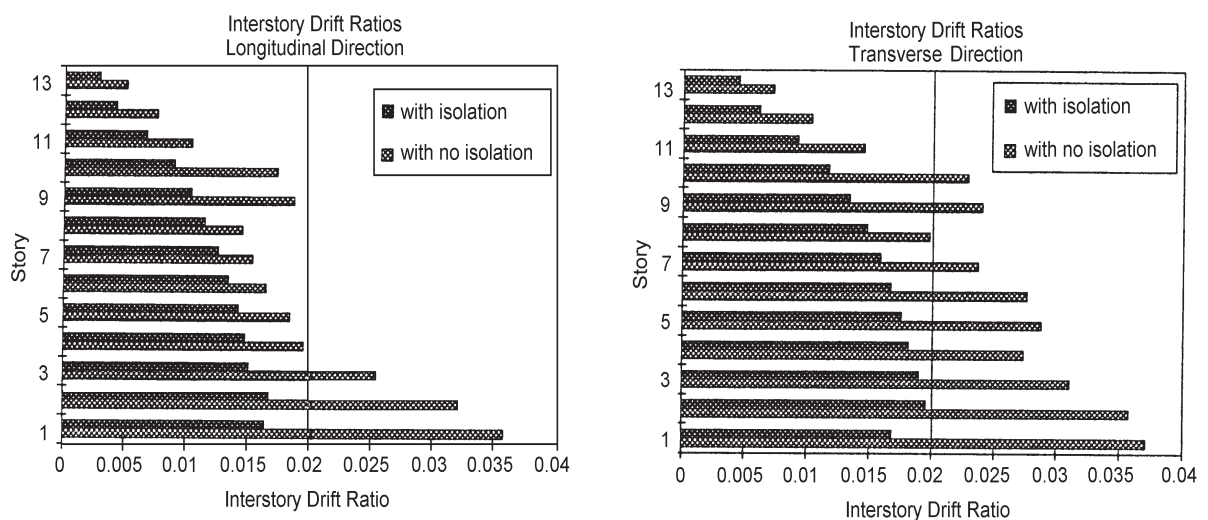


Figure 10. Interstory drift ratios in studied building under selected ground motions.

consideration remained in its elastic range during the entire excitation. Similarly, note that in Figure 10 an interstory drift ratio of less than 0.02 means that this ratio is less than the limit imposed by the 1997 version of the

Uniform Building Code [17] for a building with the characteristics of the one herein being studied. It may be seen, thus, that the effect of the roof isolation system is to significantly reduce the rotational ductility demand in the

structural members of the building as well as its interstory drifts. Furthermore, it may be seen that the roof isolation system keeps all members within their linear elastic range of behavior (as expected since their yield capacity was established with this objective in mind) and all interstory drifts within the allowable limit. On average the roof isolation system reduces the interstory drifts of the building by 35.7 percent in the longitudinal direction and 39.8 percent in the transverse direction.

In regard to the response of the roof isolation system itself, it is found that under the considered ground motions the elastomeric bearings deform 0.59m (23.2in) in the longitudinal direction and 0.75m (19.5in) in the transverse direction. In like fashion, it is observed that the maximum velocity of the roof relative to that of the 12th floor is equal to 2.22m/s (7.28ft/s) in the longitudinal direction and 2.53m/s (8.30ft/s) in the transverse direction.

5. DESIGN OF ISOLATION SYSTEM COMPONENTS

5.1. Design of Elastomeric Bearings

The dimensions and characteristics of the laminated rubber bearings are determined following guidelines for the design of bridge bearing pads [18] and some of the recommendations given by Kelly [11]. Natural rubber with a hardness of 50 and a shear modulus of elasticity of 759kPa (110psi) at 21°C (70°F) is selected for their construction. The constraints considered in their design are:

1. The bearings have to support a total weight of 10,614kN (2,386kips), with the bearings on the interior columns supporting 4 times the axial load supported by the bearings on the corner columns and 2 times that supported by the bearings on the exterior columns.
2. The bearings plan area can not exceed the cross section area of the roof columns; that is, 0.61 × 0.91m (24 × 36in) for the exterior columns and 0.91 × 0.91m (36 × 36in) for the corner and interior columns.
3. The maximum vertical stress cannot exceed 6900kPa (1000psi) [11] and the maximum vertical deflection cannot exceed 15 percent of the bearings' initial thickness.
4. The bearings have to accommodate a maximum lateral displacement of 0.59m (23.2in) in the longitudinal direction and 0.75m (29.5in) in the transverse one with a shear strain of less than 200 percent.
5. The bearings have to provide a total lateral stiffness of 7952kN/m (488.7kips/in) in the longitudinal direction and 6460kN/m (397.0kips/in) in the transverse one.

Note that according to these design constraints the lateral bearing stiffness needed for the longitudinal

direction differs from the one needed for the transverse direction. Since a bearing's rigidity depends on its plan area and thickness alone, the rigidity of a bearing of given dimensions will provide the same rigidity along its two orthogonal directions. Therefore, the dimensions and properties of the needed bearings are selected on the basis of the smallest of these two lateral stiffnesses, with the understanding that the additional stiffness needed for the other direction will be furnished with supplementary linear springs. This type of isolator has been used before in actual practice [19], so using it for the purpose herein intended is not considered a problem. Note too that the thickness of the bearings is governed by the requirement of a shear strain of less than 200 percent. Accordingly, a bearing's thickness of at least 0.375m (14.8in) is needed to comply with this requirement. Since under the assumption of linear elastic behavior and a deformation in pure shear, the lateral stiffness of a rubber pad is given by

$$K_y = \frac{GA}{t} \quad (5)$$

where K_y denotes pad's lateral stiffness, A its plan area, t its thickness, and G the rubber's shear modulus of elasticity, the total bearing area needed to satisfy the requirement of a lateral stiffness of 6460kN/m (397.0kips/in) is thus equal to 3.19m² (34.3ft²). Or since the building has 24 columns, the plan area required for each bearing results equal to 0.133m² (206in²), which can be obtained with a width of 0.35m (13.8in) and a length of 0.38m (15.0in). Observe that with these dimensions each bearing would be subjected to a maximum vertical stress of 5,699 kPa (826psi), which is less than the allowable one of 6,900kPa (1,000psi).

To comply with the requirement of a maximum vertical deformation of no more than 15 percent of their thickness, the bearings will be constructed with several thin rubber pieces, each placed between two steel shims or plates. According to the charts presented in Reference 18, the shape factor needed to keep the vertical deformation of a rectangular rubber pad within 15 percent of its thickness when subjected to a vertical pressure of 5,699kPa (826psi) is approximately equal to 3.5, where this shape factor is defined as

$$s = \frac{BD}{2(B+D)t_r} \quad (6)$$

where B , D , and t_r respectively represent the width, length, and thickness of the rubber pad. Therefore, the maximum thickness the rubber pieces may have to satisfy such a requirement is 0.026m (1.02in). Using rubber pieces 25mm (0.98in) thick, the bearings may be thus constructed using 15 rubber pieces, joined to 14 reinforcing steel shims, and two end steel plates. Following the recommendations by Kelly [11], a thickness of 3mm (1.8in) is selected for the interior steel shims and 19mm (3/4in) for the end steel plates. In summary, the laminated rubber bearings for the roof isolation system under consideration need to be composed

of 15 rubber pieces 2.5mm (0.98in) thick, and 14 steel shims 3.0mm (3/8in) thick. All together, they will have a total thickness of 0.42m (16.5in) and, under the maximum displacement of 0.75m (29.5in), will be subjected to a maximum shear strain of 183 percent, which is less than the specified one of 200 percent.

It may be observed that as a result of the small vertical pressure and low natural frequency, the required bearings result rather slender and may therefore be susceptible to buckling. To prevent buckling, bearings are customarily built with a thickness that does not exceed 1/5 of their smallest dimension in plan. However, this cannot be done in the case under consideration because the bearings' thickness is controlled by the rigidity that is needed to form a roof isolation system with the specified natural frequency. Consequently, it is recommended to use instead a multi-column configuration, such as that shown in Figure 11. Because of the larger radius of gyration involved, a multi-column configuration will insure that the bearings will resist without buckling the large displacements they may be subjected to during an extreme seismic event. The separation between columns in this multi-column configuration is a parameter that can be determined from a stability analysis of the bearings and will depend on the desired safety margin. The determination of such a separation is, however, beyond the scope of this study.

The final recommendations in regard to the size, form, and dimensions of the laminated rubber bearings needed for the roof isolation system under investigation are summarized in Figure 11.

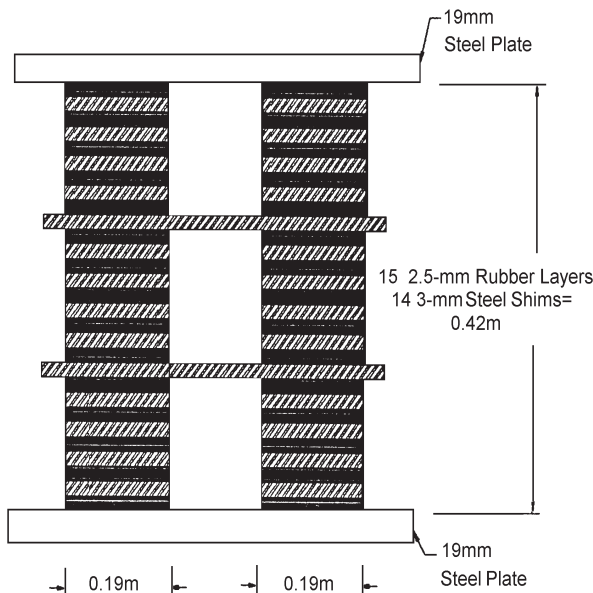


Figure 11. Dimensions and configuration of laminated rubber bearings.

5.2. Design of Viscous Dampers

Linear viscous dampers of the type produced by Taylor Devices, Inc. [20] are considered for the selection of the

roof dampers. These dampers are particularly convenient for this application because they exhibit a truly linear behavior, are insensitive to temperature changes, and are small in size in comparison with their stroke and output force. The size of the units needed is selected on the basis of the level of the maximum forces they are supposed to resist, which in turn are determined from the required damper constants and the maximum roof relative velocities obtained in the preceding section. Proceeding accordingly and considering that for the longitudinal direction of the building such damper constant and maximum roof velocity are respectively equal to 2229kN-s/m (152.5kips-s/ft) and 2.22m/s (7.28ft/s), it is found thus that the expected maximum level of the roof damping forces along this direction is equal to 4,948kN (1,112kips). Similarly, by considering that the corresponding parameters along the building's transverse direction are equal to 2062kN-s/m (141.0kips-s/ft) and 2.53m/s (8.30ft/s), respectively, the expected maximum level of the roof damping forces in that direction results equal to 5,217kN (1,173kips). On the basis of these calculations and recalling that the roof's maximum displacements along its longitudinal and transverse directions are equal to 0.59 and 0.75m (23.2 and 29.5in), respectively, four 1,335kN (300kips) high capacity hydraulic dampers with a total stroke of 1.83m (72in) from Taylor Devices, Inc., are therefore specified for installation below the roof along each of these directions.

The dimensions of the selected dampers are shown in Figure 12. It may be seen from the inspection of these dimensions and the dimensions of the building itself that the selected dampers are of a size that fits well within the available space below the building's roof and between the building's columns. Accordingly, the final recommendation is to install two of such dampers along each of the four sides of the building.

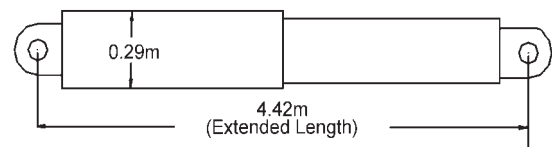


Figure 12. Dimensions of viscous dampers.

6. CONCLUSIONS

The main conclusions drawn from this study may be summarized as follows:

- ❖ The proposed roof isolation system may effectively reduce the response of a building and keep it from experiencing structural damage in the event of a severe earthquake.
- ❖ The rubber bearings and viscous dampers required to build such a roof isolation system are of a reasonable size and may therefore be accommodated

- within the available space.
- ❖ The lateral displacements of an isolated roof may be significantly large when the building is subjected to a strong earthquake, but these large displacements seem not to be a serious problem as far as the rubber bearings are concerned.
- ❖ The required bearings are rather slender and susceptible to buckling, although this susceptible to buckling can be avoided by using rubber bearings with a multi-column configuration.

Overall, it is found that the proposed scheme to build a vibration absorber with a building's roof is effective, is constructible and has the potential to become an attractive way to reduce structural and non-structural earthquake damage in those buildings for which their roof weight is a significant percentage of their total weight; that is, low and medium-rise buildings.

ACKNOWLEDGMENTS

The work reported herein is part of a project funded by the National Science Foundation through Grant CMS-9503200. Access to the structural drawings of the studied building was facilitated by the Strong Motion Instrumentation Program of the California Division of Mines and Geology. The author wishes to express his gratitude to these two institutions for their support.

REFERENCES

1. Frahm, H. (1909). "Device for Damping Vibration of Bodies", *U.S. Patent No. 989958*.
2. Den Hartong, J.P. (1956). "Mechanical Vibration", 4th Edition, McGraw-Hill, New York, 436pp.
3. Villaverde, R. (1985). "Reduction in Seismic Response with Heavily-Damped Vibration Absorbers", *Earthquake Engineering and Structural Dynamics*, **13**(1), 33-42.
4. Villaverde, R., and Koyama, L.A. (1993). "Damped Resonant Appendages to Increase Inherent Damping in Buildings", *Earthquake Engineering and Structural Dynamics*, **22**(6), 491-507.
5. Villaverde, R. (1994). "Seismic Control of Structures with Resonant Appendages", *Proc. 1st World Conference on Structural Control*, Pasadena, Calif., **1**, WP4, 113-122,
6. Villaverde, R., and Martin, S.C. (1995). "Passive Seismic Control of Cable-Stayed Bridges with Damped Resonant Appendages", *Earthquake Engineering and Structural Dynamics*, **24**(2), 233-246.
7. Villaverde, R. (1998). "Roof Isolation System to Reduce the Seismic Response of Buildings: A Preliminary Assessment", *Earthquake Spectra*, **14**(3), 521-532.
8. Villaverde, R., and Mosqueda, G. (1998). "Architectural Detail to Increase the Seismic Resistance of Buildings", *Paper T204-2 in Structural Engineering World Wide 1998*, N.K. Srivastava, Editor.
9. Villaverde, R., and Mosqueda, G. (1999). "Aseismic Roof Isolation System: Analytic and Shake Table Studies", *Earthquake Engineering and Structural Dynamics*, **28**(3), 217-234.
10. Tajirian, F.F., Kelly, J.M., and Aiken, I.D. (1990). "Seismic Isolation for Advanced Nuclear Power Stations", *Earthquake Spectra*, **6**(2), 371-401.
11. Kelly, J.M. (1993). "Earthquake-Resistant Design with Rubber", Springer-Verlag, London, 134pp.
12. Skinner, R.I., Robinson, W.H., and McVerry, G.H. (1993). "An Introduction to Seismic Isolation", John Wiley & Sons, New York, 354pp.
13. Shakal, A.F., and Huang, M.J. (1995). "Recorded Ground and Structure Motions", Chapter 2 in Northridge Earthquake Reconnaissance Report, **1**, *Earthquake Spectra*, Supplement C to Vol. 11.
14. Sadek, B., Mohraz, A.W. Taylor, and Chung, R.M. (1997). "A Method of Estimating the Parameters of Tuned Mass Dampers for Seismic Applications", *Earthquake Engineering and Structural Dynamics*, **26**(6), 617-835.
15. Hall, J.F., Tech. Ed. (1994). "Preliminary Reconnaissance Report, Northridge Earthquake", Earthquake Engineering Research Institute.
16. Hanna, M.M. (1989). "An Efficient Mode Superposition Method for the Numerical Dynamic Analysis of Bilinear Systems", Ph.D. Thesis, University of California, Irvine, California.
17. International Conference of Building Officials (1997). "Uniform Building Code", **2**, Whittier, California.
18. E.I. Du Pont de Nemours, Inc. (1959). "Design of Neoprene Bridge Bearing Pads", Elastomer Chemicals Department, Wilmington, Del.
19. Watson, R.J. (1998). "Current State of the Art in the Testing of Isolation Bearing Systems for Bridges in the USA", Paper No. 443, *Proc. 6th U.S. National Conference on Earthquake Engineering*, Seattle, Wash.
20. Taylor Devices, Inc. (1993). "General Product

Specifications”, North Tonawanda, N.Y.

21. Mazda, T., Shiojiri, H., Oka, Y., Fujita, T., and Seki, M. (1989). “Test on Large Seismic Isolation Elements”, *Trans. 10th International Conference on Structural Mechanics in Reactor Technology*, **K2**, 679-684.