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Roof Isolation System to Reduce the Seismic Response of Buildings: A Preliminary Assessment

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A roof isolation system is proposed as a means to reduce the detrimental effect of earthquakes in buildings. This 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. The properties and dimensions of the rubber bearings and viscous dampers are selected in a way that makes the roof, bearings, and dampers form a highly damped vibration absorber. Presented also is a comparative study with a simple five-story steel building under a strong earthquake ground motion that is carried out to assess the effectiveness of the proposed system. In this comparative study, it is found that the roof isolation scheme reduces the floor displacements and interstory drifts of the analyzed building by as much as 83 percent. On the basis of these results and in view of its simplicity, it is concluded that the proposed roof isolation system has the potential to become a practical and effective way to reduce earthquake damage in buildings.

INTRODUCTION

Throughout the years, vibration absorbers consisting of a relatively small mass, a spring, and a dashpot attached to a point of maximum vibration and in resonance with the structure to which they are attached have been implemented effectively to reduce wind-induced vibrations in high-rise buildings (Engineering News Record 1971, 1975, 1976, 1977); to reduce floor vibrations induced by occupant activity (Thornton et al. 1990, Setareh and Hanson 1992, Webster and Levy 1992); and to reduce the response of buildings to earthquake excitations (Kitamura et al. 1988). From the practical point of view, these vibration absorbers, first suggested by Frahm in 1909 (Frahm 1909, Den Hartog 1956), and often called tuned mass dampers, represent an attractive means to protect structures against the detrimental effects of earthquakes. In comparison with other vibration control techniques, they offer two major advantages. One is that their impact on the design of the structure is only minimal since a structure with this type of device does not require special design procedures. The other is that they are easy to construct. Its construction only requires putting together a mass, a spring, and a dashpot at a localized point of the structure, without the need for sophisticated hardware. Hence, its construction introduces only localized disruption and

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may be performed by non-specialized contractors. Additional advantages are: (a) they do not depend on an external power source for their operation; (b) they do not interfere with the principal vertical and horizontal load paths of the structure; (c) their properties can be adjusted in the field (d) they can be considered in new designs as well as in upgrading work; (e) a single unit can be effective in reducing vibrations induced by different types of dynamic loadings; (f) they require low maintenance; and (g) they can be cost effective.

In the past several years, the author and his co-workers (Villaverde 1985, Villaverde and Koyama 1993, Villaverde 1994, Villaverde and Martin 1995) 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 the adequate selection of their mass and damping ratios, these devices may indeed be effective to reduce such a response. Nonetheless, it is also found that they have some disadvantages too. First of all, to be effective, they require a relatively large mass, and, therefore, a large space for their installation. Secondly, since by design they are set in resonance with the structure, they may undergo large displacements in relation to the points of the structure to which they are attached. Consequently, they also require the additional 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. Thus, vibration absorbers have the potential to become a practical and effective way to protect structures against the effect of earthquakes, but it is necessary to overcome these disadvantages before they can be accepted by designers and widely utilized in actual practice.

PROPOSED ROOF ISOLATION SYSTEM

A possible way whereby one can overcome the aforementioned disadvantages of a vibration absorber is to use a portion of a building's mass as the mass of the absorber. In particular, one possibility is to use the building's roof as the absorber's mass. In this case, one needs to disconnect the roof from the rest of the building, connect it to a spring and a viscous damper, and then connect the spring and the damper to the lower part of the building. More conveniently, however, one can take advantage of recent developments in base isolation technology (Kelly 1993, Skinner et al. 1993) and use elastomeric bearings instead of springs, in the way shown in Figure 1. In this manner, the roof furnishes the mass to construct the vibration absorber, the bearings its stiffness, and the viscous damper its damping element. Elastomeric dampers are now commercially available (Tajirian et al. 1990, Special 1991), and so are, in a large variety of sizes, fluid viscous dampers (Constantinou et al. 1993, Taylor 1993).

The advantages of the proposed roof isolation system are many:

1. Without the need for a burdensome additional mass, a vibration absorber can be added to a building by simply introducing flexible elements and a set of dampers between its roof and the columns that support this roof.
2. Its construction is relatively simple in comparison with other protective systems and has the potential to be cost effective.
3. The roof space is kept free and may be used for any other installations.

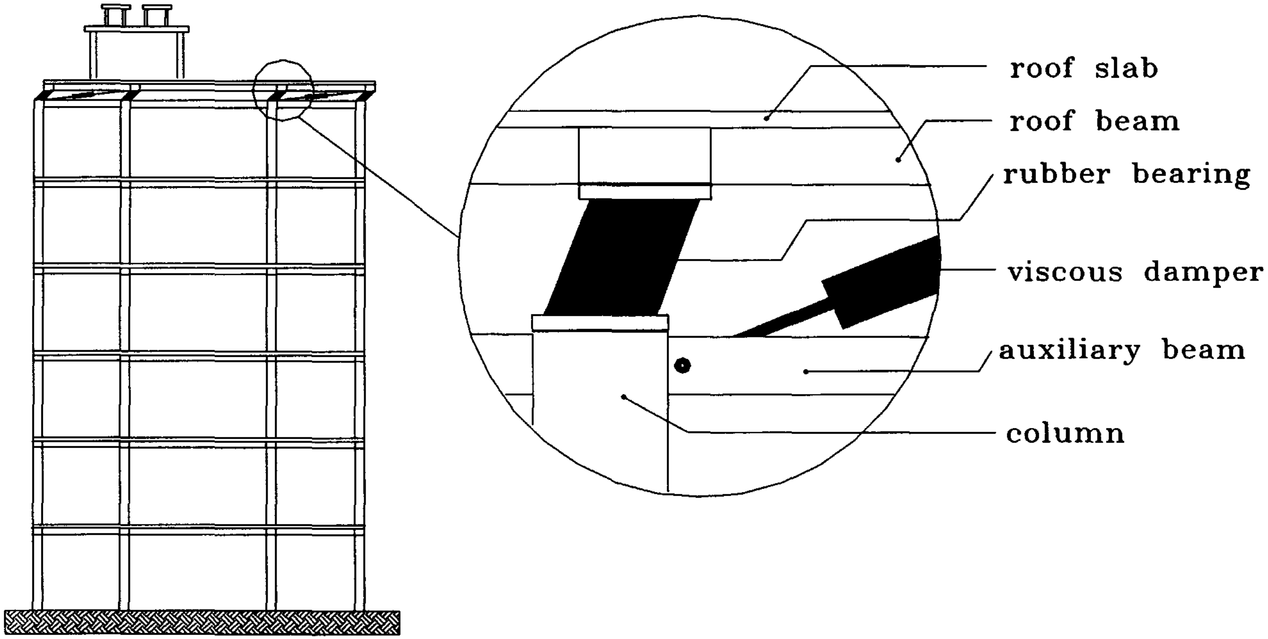

Figure 1. Typical building with proposed roof isolation system

4. There is no need for the additional roof space needed to allow for the free travel of the absorber's mass.
5. 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.
6. It is ideal for retrofitting existing buildings since there is no significant weight added to the structure or the foundation, and there is little disruption involved during its construction.
7. It uses components whose properties are well suited for the intended application. Elastomeric bearings are stiff at small strains, and hence they will only undergo insignificant displacements under small (but frequent) wind and earthquake loads. In contrast, they have a low stiffness at high strains. Consequently, they will possess the desired flexibility during a severe earthquake. Furthermore, for strains greater than 100 percent, their stiffness starts to increase again, providing thus a fail-safe action against extreme seismic loads (Kelly 1993).
8. It is self-restoring, even after large shear strains.

COMPARATIVE STUDY

To assess the effectiveness of the proposed roof isolation system, a comparative study is carried out with the five-story steel structure shown in Figure 2. This structure is 23.7 feet wide and is formed by two longitudinal and two transverse moment-resisting frames. The steel grade used is A36 and the properties of its beams and columns are those listed in Table 1. Its first three natural frequencies, when considered with a conventional configuration, a conventional configuration but no roof (needed for the design of the roof isolation system), and the proposed isolation system (i.e., with the roof mounted on rubber bearings), are given in Table 2. The total weights considered at each of its floors are those indicated in Figure 2.

Table 1. Properties of beams and columns of structure in analytical study

Element	Section	Moment of inertia (in^4)	Yield moment (Kip-in)
Columns	W14 X 665	12 400	41 256.9
Beams	W12 X 279	3 110	14 127.4

Table 2. First three natural frequencies in Hz of five-story structure in analytical study

Mode	With conventional configuration	With no roof and no rubber bearings	With roof mounted on rubber bearings
1	2.144	2.608	1.819
2	3.423	4.183	2.206
3	6.866	8.819	3.522

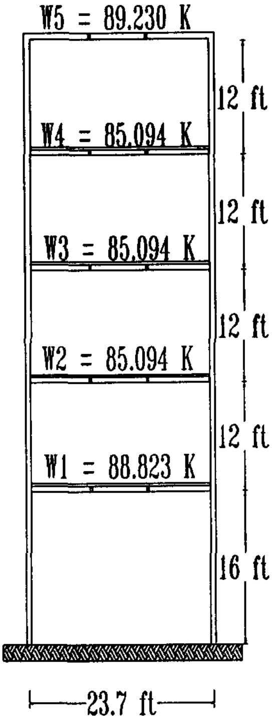

Figure 2. Five-story structure considered in comparative study.

The structure is modeled with beam elements and analyzed first without the proposed roof isolation system and then with it. Bilinear behavior is considered for its beams and columns, with a post-yielding stiffness equal to one percent of their initial, elastic stiffness. In addition, the structure's damping matrix is assumed proportional to its mass and stiffness matrices, with a damping ratio of 2 percent in its fundamental mode. The analysis is carried out using a computer program for the nonlinear analysis of two-dimensional frames (Hanna 1989), after its modification to be able to consider damping elements with different damping constants at different locations within a structure. Peak floor displacements, interstory drifts, and beam rotational ductility demands are determined in each case, when the base of the building is subjected to a strong ground motion. The ground motion considered is a modified version of the accelerogram recorded at Secretaría de Comunicaciones y Transportes (SCT) station during the 1985 Mexico City earthquake, which has a peak ground acceleration of 0.188 g. It is formed by truncating the first 20 seconds from this accelerogram and by considering only the following 20 seconds. In addition, it is multiplied by a time scale factor of 0.233 to produce a ground motion with a dominant period of 2.1 Hz, which is the fundamental natural frequency of the structure in its conventional configuration. Furthermore, the accelerations in this ground motion are scaled by different factors to induce different structural response levels. Scale factors of 0.5, 1.5, 5.0, and 10.0 are used. The elastic response spectra for this ground motion, corresponding to a damping ratio of 2 percent and these scale factors, are shown in Figure 3.

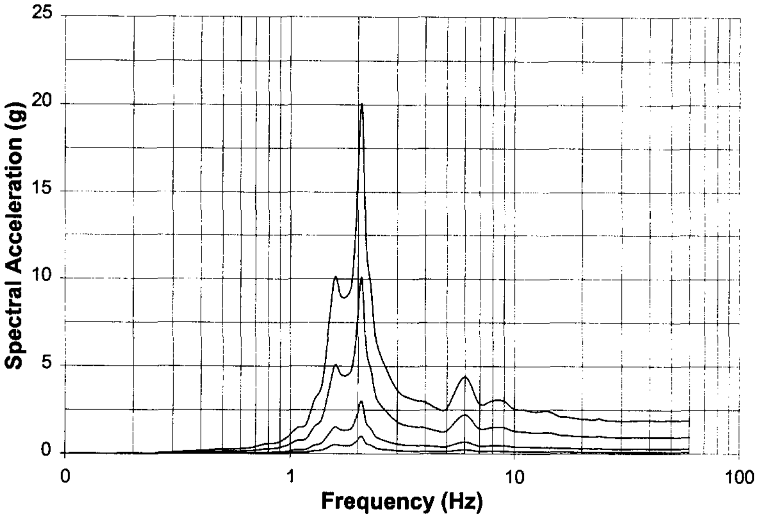

Figure 3. Two-percent damping elastic response spectra for ground motion considered in comparative study corresponding to scale factors of 0.5, 1.5, 5.0 and 10.0.

For the case which includes the proposed roof isolation system, the roof is considered supported by four elastomeric bearings, which in turn are assumed connected to the top of the building's fifth floor columns. In addition, it is assumed that two viscous dampers are incorporated between the roof and these columns. The lateral stiffness of the bearings is determined on the basis of the recommendations given by Villaverde and Koyama (1993) for the design of effective vibration absorbers. That is, it is selected as the stiffness that makes the roof and the elastomeric bearings form an oscillator with a natural frequency equal to the fundamental natural frequency of the structure without its roof, i.e., a natural frequency of 2.61 Hz. Considering that 69.91 kips is the roof weight supported by the bearings, each bearing is thus modeled as an elastic shear beam with a lateral stiffness of 12.145 kip/in. Similarly, the dampers' damping constant is obtained in terms of the desired damping ratio for the aforementioned oscillator. Since, a vibration absorber with a damping ratio of 50 percent signifies a damping ratio of approximately 25 percent in the fundamental mode of the structure that houses the absorber (Villaverde and Koyama 1993), 50 percent is considered an adequate value and thus arbitrarily selected for the damping ratio of the roof isolation system. Hence, each of the damping elements in the roof isolation system is modeled as a viscous damper with a damping constant of 1.482 k-s/in. Note that the weight considered in the selection of the roof isolation system components represents about 16 percent of the total weight of the structure.

The results of the study are summarized in Tables 3 through 10. These tables show the peak floor displacements, peak rotational ductility demands at the beams of each floor (i.e., maximum rotation at beam end divided by the rotation that makes the beam yield), and peak interstory drifts that are obtained under the selected ground motion when the structure is considered with and without the proposed roof isolation system. Also shown in these tables are the reduction percentages attained in each case. It may be seen from these results that the addition of the isolation bearings and the damping elements at the top of the structure considerably reduces its seismic response. For example, the peak interstory drifts are reduced, on average, by 83, 76, 51, and 31 percent when the ground motion is scaled by the factors of 0.5, 1.5, 5.0, and 10.0, respectively. In the evaluation of these results, observe that when the ground motion is considered with these scale factors of 0.5, 1.5, 5.0, and 10.0, it respectively induces in the structure without the roof isolation system: (a) purely elastic deformations in all its members; (b) small inelastic deformations in some of its beams; (c) moderately large inelastic deformations in all its beams; and (d) large inelastic deformations in all its beams and at the lower end of its first floor columns. Thus, a significant reduction is attained in the structure's response even when some of its members incur into their nonlinear range of behavior, although this reduction is not as large as when the structure behaves linearly at all times.

Only one ground motion is considered in the investigation reported above. In addition, the dominant frequency of this ground motion is tuned to the fundamental natural frequency of the structure. No other ground motions are used, and only the resonant case is considered, because it has been found in previous studies (Villaverde and Koyama 1993, Villaverde and Martin 1995) that similar results are obtained with different ground motions, provided these ground motions have, or are modified to have, a dominant frequency close to the fundamental natural frequency of the structure. Moreover, it has been found that damped vibration absorbers may significantly reduce the response of a structure to resonant ground motions, but this reduction may be small for ground motions with a dominant frequency that is far apart from the fundamental natural frequency of the structure. It is believed, therefore, that the presented results are representative of the effectiveness of the proposed scheme under ground motions that are capable of inducing a large structural response, and hence, the ground motions that control the design of a structure.

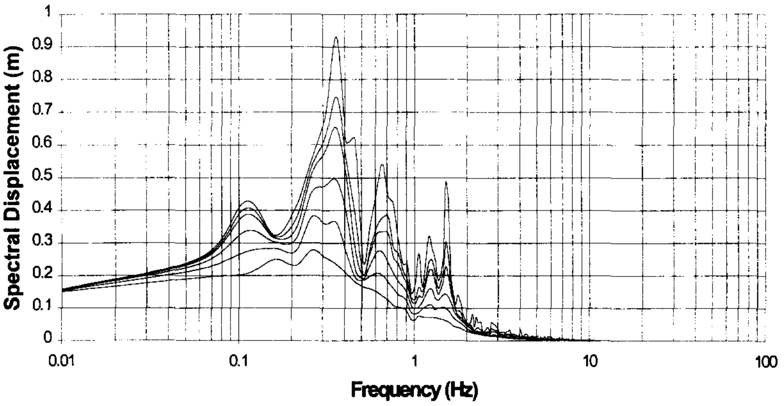

Figure 4. Displacement response spectra for 0, 1, 2, 5, 10, and 20 percent damping of E-W component of Foster City accelerogram recorded during the 1989 Loma Prieta earthquake.

The fact that a damped vibration absorber, and hence the proposed roof isolation system, does not lead to a significant response reduction under nonresonant ground motions should not be interpreted as a failure of the system to provide protection against earthquake damage. Since the effect of a damped vibration absorber is to augment the damping ratio in the fundamental mode of a structure (Villaverde 1985), and since damping is effective in reducing the response of a structure when there is a significant ground motion amplification, it should be considered instead that damped vibration absorbers are capable of providing protection against damaging ground motions in much the same way as an increase in the damping of a structure does. In support of this argument, consider, for example, the response spectra shown in Figure 4, which corresponds to the East-West component of the accelerogram recorded at Foster City during the 1989 Loma Prieta earthquake. It may be observed from these spectra that an increase in the damping ratio from 2 to 20 percent significantly reduces the response of structures with a fundamental natural frequency of about 0.35 Hz, but not so much the response of structures with a fundamental natural frequency of, say, 2 Hz. This is not to say that damping is not an effective mechanism to reduce structural response. It simply means that it is a mechanism that provides protection against the sharp resonant ground motions that can cause significant structural damage.

Table 3. Peak floor displacements and beam rotational ductility demands in five-story structure under selected ground motion scaled by a factor of 0.5

Floor	Floor displacement (in)			Beam rotational ductility demand		
	Conventional configuration	Configuration with roof bearings	Reduction (%)	Conventional configuration	Configuration with roof bearings	Reduction (%)
1	0.498	0.086	83	0.53	0.09	84
2	1.120	0.190	83	0.58	0.10	83
3	1.730	0.289	83	0.52	0.08	84
4	2.240	0.369	84	0.40	0.07	84
5	2.610	0.429	84	0.29	0.05	81

Table 4. Peak interstory drifts in five-story structure under selected ground motion scaled by a factor of 0.5

Story	Interstory drift (in)		
	Conventional configuration	Configuration with roof bearings	Reduction (%)
1	0.498	0.086	83
2	0.625	0.105	83
3	0.611	0.100	84
4	0.505	0.083	84
5	0.371	0.065	82

Table 5. Peak floor displacements and beam rotational ductility demands in five-story structure under selected ground motion scaled by a factor of 1.5

	Floor displacement (in)			Beam rotational ductility demand		
Floor	Conventional configuration	Configuration with roof bearings	Reduction (%)	Conventional configuration	Configuration with roof bearings	Reduction (%)
1	1.040	0.258	75	1.16	0.27	77
2	2.390	0.571	76	1.30	0.29	78
3	3.720	0.868	77	1.09	0.25	77
4	4.790	1.110	77	0.82	0.20	76
5	5.550	1.290	77	0.59	0.16	72

Table 6. Peak interstory drifts in five-story structure under selected ground motion scaled by a factor of 1.5

	Interstory drift (in)		
Story	Conventional configuration	Configuration with roof bearings	Reduction (%)
1	1.040	0.258	75
2	1.360	0.314	77
3	1.340	0.300	78
4	1.070	0.249	77
5	0.763	0.195	74

Table 7. Peak floor displacements and beam rotational ductility demands in five-story structure under selected ground motion scaled by a factor of 5.0

	Floor displacement (in)			Beam rotational ductility demand		
Floor	Conventional configuration	Configuration with roof bearings	Reduction (%)	Conventional configuration	Configuration with roof bearings	Reduction (%)
1	1.460	0.861	41	1.66	0.90	46
2	3.450	1.900	45	2.08	0.96	54
3	5.580	2.890	48	2.01	0.84	58
4	7.460	3.690	50	1.51	0.67	56
5	8.820	4.290	51	1.09	0.54	51

Table 8. Peak interstory drifts in five-story structure under selected ground motion scaled by a factor of 5.0

Story	Interstory drift (in)		
	Conventional configuration	Configuration with roof bearings	Reduction (%)
1	1.460	0.861	41
2	2.020	1.050	48
3	2.200	1.000	55
4	1.900	0.829	56
5	1.390	0.651	53

Table 9. Peak floor displacements and beam rotational ductility demands in five-story structure under selected ground motion scaled by a factor of 10.0

Floor	Floor displacement (in)			Beam rotational ductility demand		
	Conventional configuration	Configuration with roof bearings	Reduction (%)	Conventional configuration	Configuration with roof bearings	Reduction (%)
1	2.150	1.540	28	2.22	1.66	25
2	4.780	3.480	27	2.65	1.87	29
3	7.540	5.380	29	2.50	1.73	31
4	9.920	6.900	30	2.08	1.30	37
5	11.70	8.020	31	1.58	0.96	39

Table 10. Peak interstory drifts in five-story structure under selected ground motion scaled by a factor of 10.0

Story	Interstory drift (in)		
	Conventional configuration	Configuration with roof bearings	Reduction (%)
1	2.150	1.540	28
2	2.640	1.960	26
3	2.770	1.950	30
4	2.420	1.620	33
5	1.930	1.210	37

SUMMARY AND CONCLUSIONS

A roof isolation system has been proposed as a means to reduce the response of building structures to earthquake excitations. The system entails the insertion of flexible laminated rubber bearings between a building's roof and the columns that support this roof, and the addition of high-damping 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. Presented also are the details and results of a comparative study that has been conducted to assess the feasibility and effectiveness of such an isolation system. From the results of this comparative study, it is found that the proposed scheme may significantly reduce the seismic response of a structure, even when the structure incurs into its nonlinear range of behavior. In view of these findings and the fact that it is relatively easy to construct and the needed components are commercially available, it is concluded that the proposed roof isolation system has the potential to become a practical and effective way to reduce earthquake damage in buildings. It is concluded too that the system merits further studies to examine thoroughly its advantages and disadvantages and to find solutions to overcome some of the practical problems associated with it.

The study reported herein represents the first part of a comprehensive investigation that is underway to assess the effectiveness and drawbacks of the proposed isolation system. Included in this investigation are (a) an experimental study with a small-scale model which will serve to test the system without the assumptions and uncertainties involved in an analytical study; and (b) an analytical study with an actual 13-story building which will help to gain an insight as to the size of the bearings and dampers needed to build an effective roof isolation system in real buildings, the space required to accommodate the dampers, the order of magnitude of the deformations experienced by the bearings, and the difficulties involved in the design and implementation of such a technique. In addition, planned future work includes experimental tests with a mid- or full-scale model and an investigation to analyze the impact that the system might have on the architectural features of a building such as its water proofing, pipes and ducts, and stairways and elevators. Although this impact is unquestionably a disadvantage of the system, it is believed, judging from the experience with base isolated buildings, that it is possible to overcome it in a practical and cost-effective way.

ACKNOWLEDGMENTS

The work herein reported is part of a project funded by the National Science Foundation through Grant CMS-9503200. The author gratefully acknowledges this support. The author's gratitude is also extended to one of the anonymous reviewers of the paper, who discovered an error in the computer results reported in the paper's original version. Without this reviewer's insight and critical review of the manuscript, the error would have gone undetected.

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