# SEISMIC BEHAVIOR OF INDUSTRIAL FACILITIES WITH ENERGY DISSIPATORS

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## SUMMARY

Numerous theoretical studies and physical experiments on scaled models have demonstrated the effectiveness of passive energy dissipation systems, based on the viscoelastic behavior of special materials, for the reduction of the seismic response of buildings. This paper deals with the potential application of an energy dissipation bracing system for the seismic protection of two existing steel industrial buildings: a molybdenite roaster plant and a copper concentrate storage building. Both buildings are irregular in plan and height, the story heights and the dead and live loads are the main source of irregularity.

For each building three alternative designs are compared: a bare frame structure, a conventional braced structure and a braced structure with cylindrical high-damping rubber dampers. The modal strain energy method is used to predict the damping ratio in the viscoelastic damper design. The damper design is based on seismic forces given by the response spectra acceleration of the Chilean Code Nch2369: Seismic Design of Industrial Buildings, and on the properties of the dampers obtained experimentally on an scale model prototype made in a local factory. The added damping varies between 3- 6 %. The base shear and story drift for the three alternative designs are obtained for Antofagasta 1995 record (Magnitude 7.8) using time history analysis.
Both the maximum accelerations and shears are reduced in the structures with dampers to about half of those for the case of the original braced structures, without increasing story drifts. These results show that the viscoelastic dampers can be used to effectively reduce the overall response of structures at a reasonable cost.

## INTRODUCTION

The use of passive energy dissipation technology represents a feasible alternative to improve seismic behavior of structures by reducing the structural damage resulting from environmental disturbances. Examples of passive supplemental dampers include devices based on yielding of metal, friction, deformation of viscoelastic solid material, viscoelastic fluid deformation, forcing fluid through an orifice and, more recently, the use of shape memory alloys.

In order to be effective, these devices must be exposed to relative displacement or relative velocity as is the case in a braced frame. Some types of dampers can substantially change the force-displacement response of a building by adding strength and stiffness.

In Chile, the usual practice to design steel industrial building is to satisfy strength and drift requirements through the inclusion of a strong bracing system. Columns represent the vertical load bearing system.

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This paper deals with the potential application of an energy dissipation bracing system for the seismic protection of two existing steel industrial buildings, including the characterization of the rubber material and the design and dynamic test of a cylindrical damper prototype. Both buildings, a molybdenite roaster plant and a copper concentrate storage, located at the north of Chile, are irregular in plan and height. The story heights and the dead and live loads distribution are the main sources of irregularity.

## DESIGN OF DAMPER DEVICES

Physical characteristics of the rubber were evaluated by testing shear test samples for sinusoidal excitations at prescribed strains and frequencies. From the shear stress-strain relations, the shear modulus, the storage shear modulus, the loss factor and the equivalent damping ratio were derived. Figure 1 shows the shear modulus and the equivalent damping ratio of the rubber compound as a function of the shear deformation for various frequencies. Both parameters are dependent of shear strain amplitudes and less affected by the frequency variation. The loss factor is rather small compared to different materials used by other authors, [Soong, 1997].

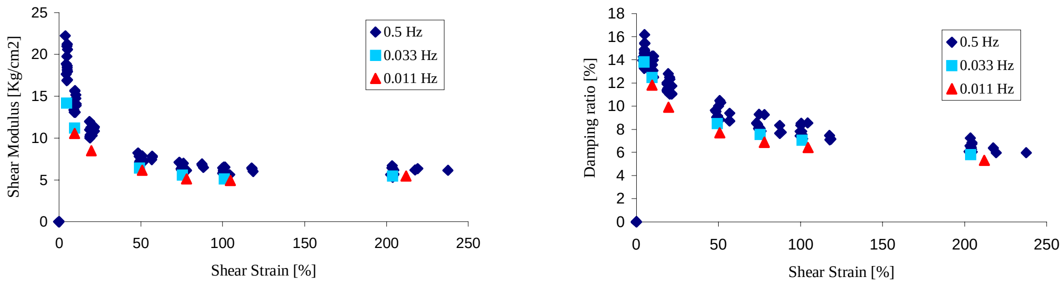


**Figure 1. Rubber Shear Modulus and Damping.**

A prototype cylindrical device consisting of two concentric pipes filled with high damping rubber was designed and tested [Vera, 1999]. The damper device and its connections to the test machine are shown in Figure 2. The outer diameter is 12.7 cm and 3 mm thick, the inner diameter is 7.62 cm and 6 mm thick, and the rubber is 22.4 mm thick.

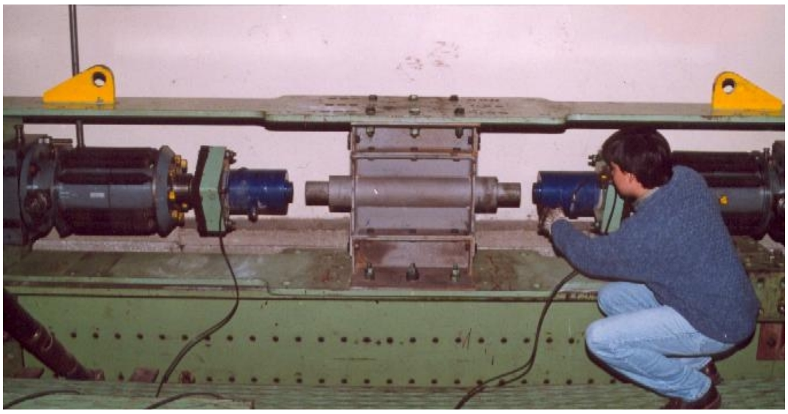

**Figure 2. Damper Testing Device.**

The damper was made in a local rubber factory, using a vulcanization process called “mold by transfer”. It consists on filling an horizontal mold with rubber, by pressuring with a piston, so that the trapped air and the excess of rubber went out at the opposite extreme of the mold.

The damper was subjected to dynamic tests at different frequencies and shear strains. According to [Suizu et al, 1995], the damper stiffness $k_d$, and damping C, of a cylindrical device are given by eq. 1:

$$k_d = \frac{\pi G'(D_e + D_i)L}{2t} \qquad C = \frac{\pi G'\eta(D_e + D_i)L}{2\omega t} \qquad (1)$$

Where $D_e$ = exterior diameter, $D_i$ = interior diameter, t = rubber thickness, G' and $\eta$ are the rubber storage modulus and loss factor, respectively and L is the rubber length.

In this case the target damper stiffness was 63 kN/cm for 50% shear strain deformation. Figure 3 shows the loss factor, and the damper stiffness as a function of shear strain for different frequencies. Figure 4 shows the effect of repeated deformations in the loss factor and damper stiffness for amplitude of 8.3 mm and at a frequency of 1.01 Hz. The target stiffness has been attained, with little margin of error. The rubber equivalent damping ratio was 9% for 50% shear strain, while the damper equivalent ratio was about 6.4-7% for the same shear strains. Repeated deformations cause decrease in the damping coefficient and stiffness and increase in the temperature, but during an earthquake, only a few cycles of large deformations normally occur in the damper, so these effects are limited.

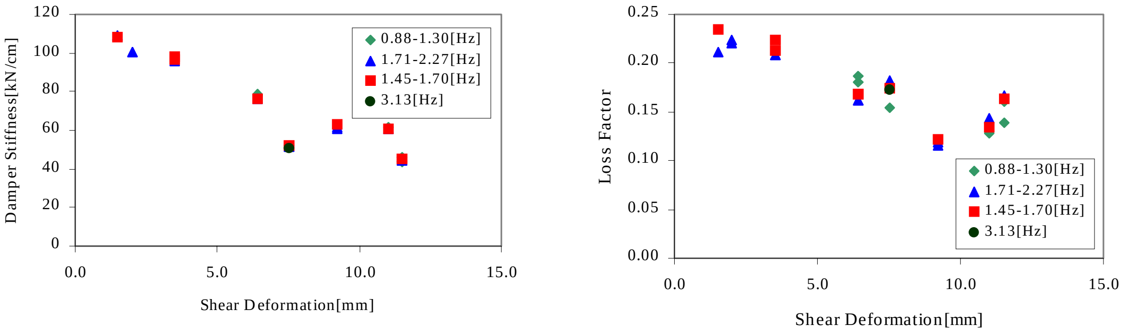


**Figure 3. Damper Stiffness and Loss Factor.**

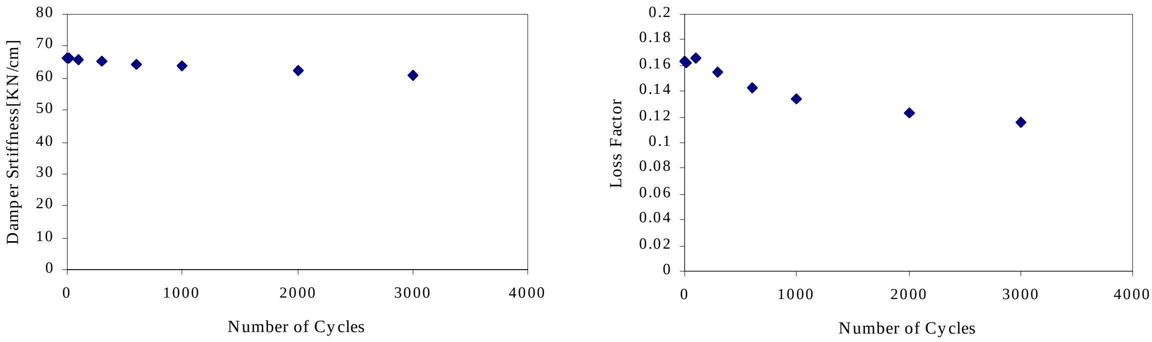


**Figure 4. Number of Cycles Dependency.**

Based on the experimental results, damper devices were designed to be included in two industrial buildings. As an initial trial the dampers were modeled as viscous. Others mathematical models are been tested. The modal strain energy method was employed to predict the added damping to the structures. The damper design procedure contains the following steps:

- Modal analysis of the bare structures. Frequencies and mode shapes were determined.
- Select a target frequency for the damped structure. Choosing the target frequency about twice the frequency of the bare structure may attain optimal damping. With this value the rubber storage shear modulus G' and loss factor $\eta$, were determined.
- Select a desired structure-damping ratio for the first mode, $\xi_1$.
- Select desirable and available damper locations. In both buildings, dampers were located in substitution of the braces of the original structures.
- Design the VE dampers. This consisted on a trial and error process:

Selection of damper stiffness assuming that the added stiffness from the VE dampers was proportional to the story stiffness of the bare structure. This is obtained by modifying the modal strain energy method for each story as

$$K = \frac{2\xi_1}{\eta - 2\xi_1} k_s \qquad (2)$$

where K and $k_s$ are the total horizontal damper stiffness and the structural story stiffness without added dampers at each story, respectively.

- Because the damper is part of a brace system, the brace equivalent stiffness and equivalent damping ratio are
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$$K_{eq} = \frac{k_b k_d (k_d + k_b) + k_b (\eta k_d)^2}{(k_d + k_b)^2 + (\eta k_d)^2} \qquad \eta_{eq} = \eta \frac{(k_d + k_b) k_d - k_d^{\,2}}{(k_d + k_b) k_d + (\eta k_d)^2} \qquad (3)$$

where $k_b$ is the stiffness of the brace that connects the damper to the structure. Both terms increase if the stiffness brace increases.

- Modal analysis of the damped structure. Frequencies and modal shapes were determined.
- Estimate the structural damping ratio. The structural total modal damping ratio can be calculated from the structural properties and damper stiffness and loss factor as

$$\xi_i = \beta \frac{\omega_i}{\omega_{si}} + \frac{\eta(\omega_1)}{2} \left( 1 - \frac{\omega_i^2}{\omega_{si}^2} \right) \qquad (4)$$

where $\omega_i$ and $\omega_{si}$ are the *i*th natural frequencies corresponding to the structures without and with added dampers, respectively. This equation assumes that change in mode shapes due to the added dampers can be neglected and that the inherent modal structural damping is proportional to the modal mass.

- Perform dynamic analysis of the structure using the response spectra acceleration given in the Chilean Code NCh2369: Seismic Design of Industrial Buildings, [INN, 1998]:
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$$S_a = ICg \qquad C = \frac{2.75 A_0}{gR} \left( \frac{T'}{T} \right)^n \left( \frac{0.05}{\xi} \right)^{0.4} \qquad (5)$$

Where I is an importance factor, $A_0$ is the effective ground acceleration that depends on the seismic zone, R is a response modification factor, $T'$ and n depends on the soil condition and $\xi$ is the structural damping ratio.

Iterations involving the rubber storage modulus and loss factor must be done in order to adjust the target frequency and the estimated damping ratio. The resulting story drift should represent a damper's deformation of about 50%, in order to insure a rubber shear modulus almost constant. If this does not occur either the rubber thickness or the device length must be modified. The brace elements must resist the seismic forces; if not new sections should be provided. Finally, the invariance in the mode shapes must be verified.

## APPLICATION TO SELECTED BUILDINGS

The first building to be studied is a six-story steel structure [Loyola, 1999]. It weighs 11.000 kN (including 25% live loads), measures 30 by 30 m in plan and is 23,5 m height. It has 6 equally spaced moment resisting frames every 6 m, in each direction. The four exterior frames are braced. All connections are bolted. The brace floor system is different in every story due to functional conditions. Figure 5 shows the plan of the first floor. A concrete silo 6.55m diameter and 20 m height is located on the hollow space but is completely disconnected from the main building. Story heights from bottom to top are 4.57, 3.30, 3.12, 2.95, 3.89 and 5.67 m.

The original structure was designed to resist a base shear force of 6.000 kN mostly by means of the first floor bracing system. A finite element model with 4300 DOF and the SAP2000 computer program were used in the analysis. Table 1 shows the calculated frequencies for the original, bare and damped structure.

**Table 1. Modal Frequencies (Hz)**

| Mode | Original | Bare | Damped |
|---|---|---|---|
| 1 | 2.16 | 0.91 | 1.56 |
| 2 | 2.18 | 0.95 | 1.59 |
| 3 | 2.48 | 1.24 | 2.25 |

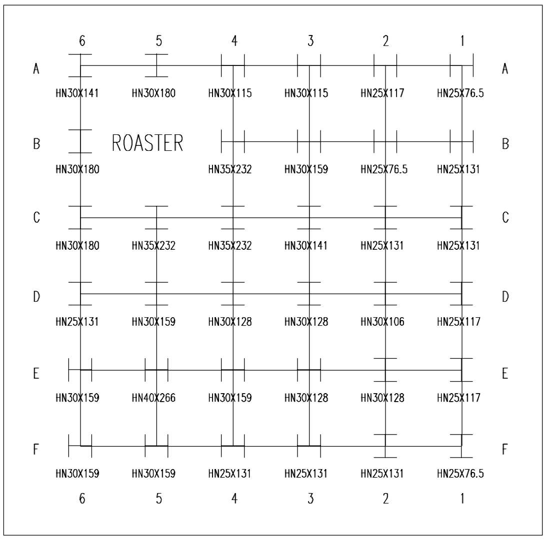


**Figure 5 . Plan View Building 1.**

The parameters have been set to the following values: target structural damping $\xi_1 = 0.05$, importance coefficient I = 1.2; seismic zone 2, $A_0 = 0.3g$; soil type II, T' = 0.35 and n = 1.33; for 50% of shear strain, $\eta\ (\omega_1) = 0.135$; $\beta = 0.03$; and R = 1, which means that the structure behaves elastically.

Twelve different damper dimensions were selected ranging between 1.15 to 3.4 m in length, 0.4 to 2.1 cm rubber thickness and 322 to 923 kN/cm stiffness, depending on the story location.

The second building [Retamales, 1999], weighs 24770 kN, 1690 kN representing the structure dead load and 23080 kN the weight of 7 silos suspended from the structure at 20 m above the ground. The silos are filled with copper concentrate or limestone. Its overall dimensions are 24 x 15 m in plan and 20.6 m in height. Story heights from bottom to top are 4.08, 2.22, 3.75, 3.77, 3.38 and 3.38m. Four moment resisting frames in the longitudinal direction and 5 equally spaced in the transverse direction constitute the load bearing structure. All exterior frames and one of the interiors in the transverse direction are braced. All connections are bolted. Figure 6 shows a view of the building.

**Figure 6. Building 2**

A finite element model that included the silos stiffness was used for the analysis. Table 2 shows the calculated frequencies for the original, bare and damped structure.

**Table 2. Modal Frequencies (Hz)**

| Mode | Original | Bare | Damped |
|---|---|---|---|
| 1 | 1.78 | 0.38 | 0.88 |
| 2 | 1.85 | 0.44 | 1.17 |
| 3 | 2.63 | 0.58 | 1.69 |

In this case the parameters were set to the following values: target structural total damping $\xi_1 = 0.072$; for 50% shear deformation $\eta(\omega_1) = 0.147$. All the rest are the same than in the previous building. Damper dimensions vary between 0.8 and 3.0 m, in length, 0.47 to 1.91 cm rubber thickness with stiffness ranging between 244 and 2895 kN/cm.

## SEISMIC BEHAVIOR

In order to verify the improvement in seismic behavior, the buildings were subjected to the Antofagasta 1995 record (Magnitude 7.8). This record was chosen because was the closest to the buildings locations registered up to the date and because it represents similar site soil conditions. Time histories analyses were carried out for the original, bare and damped structures. Both horizontal components were applied simultaneously. Maximum peak ground acceleration is 0.28g and 0.22g in the E-W and N-S direction, respectively. Base shear, floor acceleration, lateral displacement, story drift and element forces were calculated for all cases. Table 3 shows the base shear as percentage of the total weight for both buildings.

**Table 3. Base Shear Comparison**

| Structure Type | Building 1 | | Building 2 | |
|---|---|---|---|---|
| | $C_x$ | $C_y$ | $C_x$ | $C_y$ |
| Original | 0.36 | 0.46 | 0.57 | 0.37 |
| Bare | 0.17 | 0.19 | 0.12 | 0.06 |
| Damped | 0.22 | 0.29 | 0.15 | 0.10 |

Figures 7 and 8 show the envelope curves of the lateral displacement for the original buildings and for the cases with and without dampers in both directions. Although the dampers are less stiff than the original braces, the displacements are of the same order of magnitude. In building 1 the story drifts are more evenly distributed in the damped structure. In building 2, the effect of the silo stiffness is apparent.

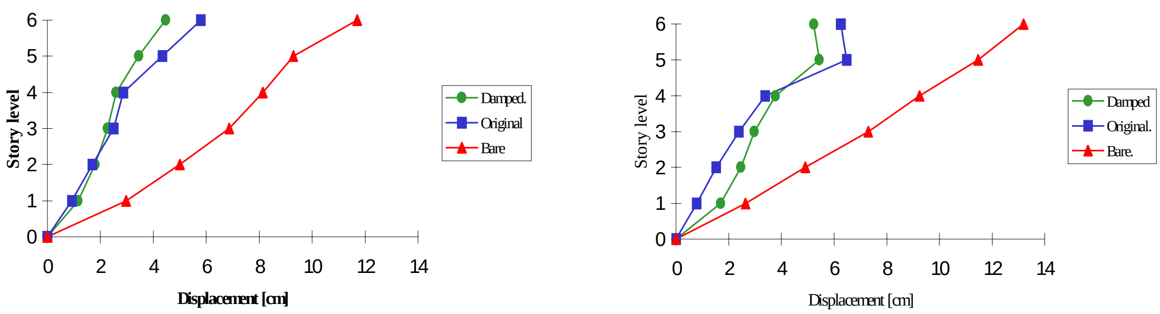


**Figure 7. Building 1, Lateral Displacement.**

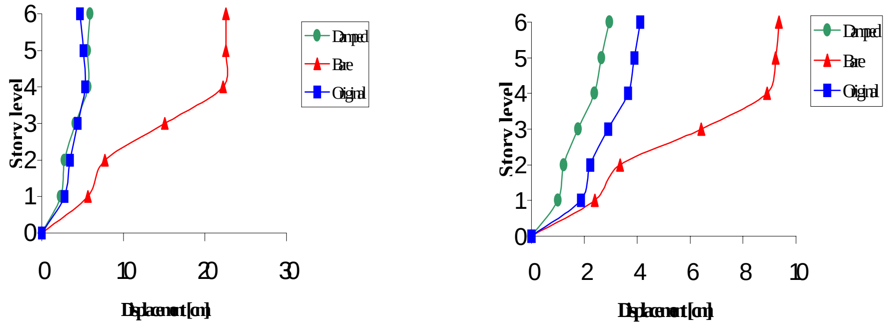


**Figure 8. Building 2, Lateral Displacement.**

With respect to element forces, Table 4 shows the average ratio between the dampers axial force and the original braces axial forces, and the average damper ratio between the maximum axial force due to the Antofagasta record and the spectral design axial force, in each floor.

**Table 4. Maximum Element Forces, Building 1.**

| Story level | $F_{damper}/F_{brace}$ | | $F_{earth}/F_{design}$ | |
|---|---|---|---|---|
| | X | Y | X | Y |
| 1 | 0.6 | 0.5 | 0.6 | 0.81 |
| 2 | 0.51 | 0.45 | 0.6 | 0.81 |
| 3 | 0.5 | 0.39 | 0.63 | 0.75 |
| 4 | 0.51 | 0.41 | 0.68 | 0.83 |
| 5 | 0.52 | 0.49 | 0.77 | 1.1 |
| 6 | 0.74 | 0.75 | 0.89 | 1.34 |

## CONCLUSION

The feasibility of including dampers in two industrial buildings has been studied. The modal strain energy method has been used to estimate the structural damping added by the dampers. The added damping depends mainly on the loss factor of the rubber $\eta$, and the frequency ratio of the structure without and with dampers. Its maximum value is $\eta$ /2; therefore, for the rubber compound used in this study, that value is limited to 6-7 %.

Although the amount of added damping was moderate, its effect was significant. When the buildings including dampers were subjected to the Antofagasta 1995 earthquake, the maximum base shear and peak accelerations were reduced as compared to the conventional braced structures, without increasing the lateral displacement or interstory drifts.

As dampers are made stiffer, the structural damping does increase but also increases the response spectral acceleration, so seismic forces become larger. This represents a trade-off condition.

Cylindrical dampers are difficult to fabricate, because air bubbles can be produced at the interior of the rubber. Furthermore, the rubber thickness depends on the dimensions of the available tube sections, so it is not possible to fit completely the structure requirements. For better optimization and construction, a sandwich type damper should be used.

## ACKNOWLEDGMENT

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