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EVALUATION OF DESIGN PROCEDURES FOR PASSIVE SYSTEMS AND APPLICATION TO A CASE STUDY

P. P. Diotallevi[1], L. Landi[2] and S. Orlandi[3]

ABSTRACT

The purpose of this paper is to study the application of metallic, viscoelastic solid and viscous-fluid passive energy dissipation devices for improving the seismic response of buildings. First the principal aspects of the response and the simplified mathematical models of the devices were examined. Then a design procedure was applied to the three types of devices. This procedure, which is well known, is aimed at obtaining a prefixed reduction of one response parameter and it is based on the definition of an equivalent linear system and on the use of response spectrum. A numerical investigation was carried out with the purpose to evaluate the design procedure. Time-history analyses were performed by applying five selected earthquake records to one and multi-story RC frames. The results confirm the effectiveness of the design methodology, especially for structures dominated by the response of first mode. The results also allow a comparison to the performance of the different dissipative systems. Finally, a study for the application of viscous-fluid passive dissipative systems for the seismic retrofit of an existing RC building is presented.

Introduction

The first studies on energy dissipation devices (EDD) for structural application in civil engineering go back to about thirty years ago (Soong and Dargush 1997, Constantinou et al. 1998). The aim of these systems, when incorporated in a structure, is to absorb or to consume a portion of the input energy. The consequence is the reduction of the energy demand to be dissipated from the primary structure and the minimization of its damage. In general the dissipation of energy can be achieved through a transformation of kinetic energy in heat. The hysteretic metallic devices dissipate energy through the steel yielding, in a way that is independent from the rate of application of the load. On the contrary the viscoelastic solid (VES) and viscous-fluid (FV) systems are rate dependent and their dissipation is based on the deformation of a solid or fluid viscoelastic material. In the following a brief summary of properties and models for the three different devices is presented.

The considered metallic hysteretic devices are the added damping and stiffness (ADAS) devices. They are made of a number of x-shaped steel plates in parallel, which undergo deformations at the occurrence

[1]Professor, DISTART, Dept. of Civil Engineering, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy
[2]Assistant Professor, DISTART, Dept. of Civil Engineering, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy
[3]Graduate Research Assistant, DISTART, Dept. of Civil Engineering, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

of inter-story drifts. Their force-displacement response can be idealized by a bilinear curve defined by the following parameters (Whittaker et al. 1989, Martinez and Romero 1993): elastic stiffness K_d, post-elastic to elastic stiffness ratio α and yielding displacement D_{yd}.

The VES devices add both stiffness and damping to the structure, and their behavior is dependent on the vibration frequency, the strain and the ambient temperature. For a given temperature, for a low level of strain and for a sinusoidal loading history they can be modeled with the following simplified force-displacement relationship (Kelvin Model):

$$F(t) = k'(\omega)x(t) + c'(\omega)\dot{x}(t) \tag{1}$$

$$k' = \frac{AG'(\omega)}{\delta}, \quad c' = \frac{AG''(\omega)}{\omega\delta} \tag{2}$$

where A is the total shear area, δ is the total thickness, $G'(\omega)$ is the shear storage modulus of the viscoelastic material, $G''(\omega)$ is the shear loss modulus, ω is the frequency of the load. This model is rigorous only for harmonic excitations, but the approximation for seismic applications may be reasonable. The FV devices considered herein are the orifice fluid dampers, which can be viewed as a particular type of the VES devices in which the added stiffness is zero. For the typical frequencies of application they can be modeled with the purely viscous dashpot model:

$$F(t) = c(\omega)\dot{x}(t) \tag{3}$$

where c is the damping coefficient.

Design Procedure

Aim of the design procedure is to determine iteratively the size of the devices in order to obtain a prefixed value of a response parameter, as the top story displacement, for a structure under seismic action. The assumptions for the structure are: linear elastic behavior, internal damping ratio equal to 5%. Basing on energy criteria the devices are transformed (Fig. 1) in the combination of equivalent linear pure viscous damper and equivalent linear spring (Chopra 1995). The flow-chart of the procedure used here is given in Fig. 2. The advantage of the procedure is to use elastic response spectrum and to avoid expensive non-linear time-history analyses in the preliminary design. Non-linear analyses may be used at the end of the procedure to confirm or to improve the exact design of devices. In the following a brief summary of design equations used for the single degree of freedom systems (SDF) and for the multi-degree of freedom systems (MDF) is reported. In both cases the devices are installed horizontally in the primary structure with a K-brace. The stiffness k_b of the braces is assumed to be large enough to neglect their deformations, that is $k_b = \infty$.

Single Degree of Freedom Systems (SDF)

The expressions of the energy W_d dissipated in a complete harmonic cycle at the maximum displacement D_{max}, of the maximum elastic energy W_s and of the effective stiffness K_{eff} of the whole system (devices and primary structure) are summarized in the following Table 1:

Table 1. Expressions of W_d, W_s and K_{eff} for different damping devices (SDF systems).

Device Type	W_d	W_s	K_{eff}
ADAS	$4K_dD_{yd}D_{max}(1-\alpha)(1-(D_{yd}/D_{max}))$	$K_{eff}D_{max}^2/2$	$K_f+K_d(D_{yd}+\alpha(D_{max}-D_{yd}))/D_{max}$
VES	$\pi G''(\omega)r^2_{max}V$	$K_{eff}D_{max}^2/2$	$k'+K_f$
FV	$\pi\omega c(\omega)D_{max}^2$	$K_fD_{max}^2/2$	K_f

In Table 1 K_f is the stiffness of primary structure alone, r^2_{max} and V are the maximum strain and volume of the viscoelastic material. It's worth remarking that the equivalent damping is determined as the ratio:

$$\xi_d = \frac{W_d}{4\pi W_s} \tag{4}$$

For the dissipative devices (VES and ADAS), which change the vibration period of the structure, the procedure is iterative. For the FV devices the procedure is not iterative because they add only damping to the structure. The initial demanded damping is determined by using the displacement response spectra for various level of damping with the purpose to obtain a certain reduction of the control displacement (Fig. 2). From Equation 4 the initial characteristics of devices are determined. If necessary the new vibration period is recalculated. By evaluating the ordinate of the displacement response spectrum associated to the new period, a new demanded damping is determined. The procedure continues until the new value of demanded damping is not significantly different from the previous one. Since the properties of viscoelastic material varies with frequency, they are updated at every iteration step.

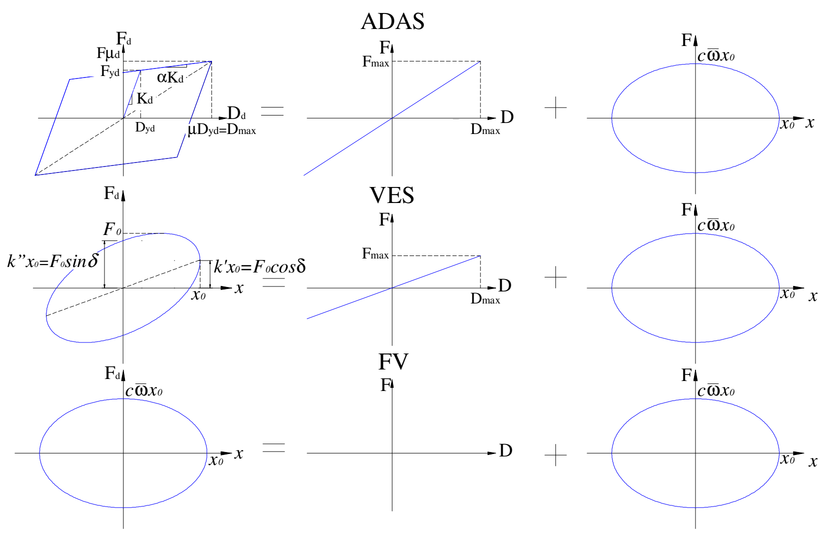

Figure 1. Equivalent linearization.

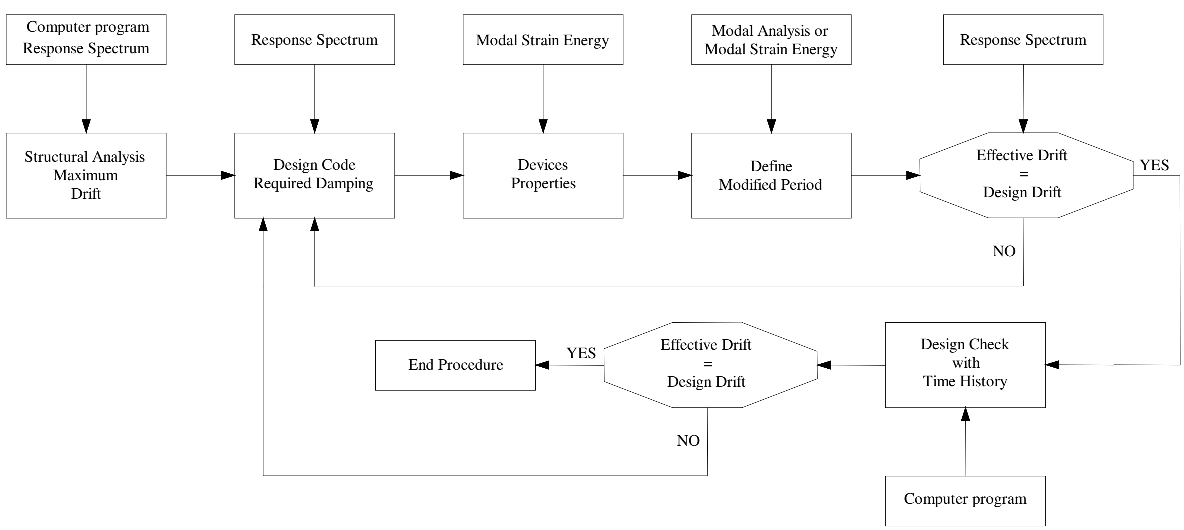

Figure 2. Flow chart of design procedure.

Multi Degree of Freedom Systems (MDF)

Assuming that the structure vibrates harmonically at a frequency ω and that the displacements are proportional to the first mode of vibration, the j-th inter-story displacement at the instant of the maximum top story displacement D_{max} is:

$$x_{r,j} = \left(\phi_j - \phi_{j-1}\right) D_{\max} = \phi_{r,j} D_{\max} \tag{5}$$

where ϕ_j and ϕ_{j-1} are, respectively, the modal displacements at the j-th and the (j-1)-th story of the first mode, normalized to the value at the top of the structure.

Equivalent expression of the maximum elastic and dissipated energy can be found for a MDF system by adding the contributions of each story and considering the inter-story drift between two adjacent story. The total energy dissipated in a complete harmonic cycle $W_{d,TOT}$ and the total maximum elastic energy $W_{s,TOT}$ for the MDF system are obtained by replacing D_{max} in Table 1 with $x_{r,j}$ of Equation 5 and by adding over the height of the structure. These expressions are summarized in the following Table 2, where K_j and m_j are, respectively, stiffness and mass of the j-th story of the primary structure alone.

Table 2. Expressions of $W_{d,TOT}$, $W_{s,TOT}$ and $K_{eff,j}$ for different damping devices (MDF systems).

Device Type	$W_{d,TOT}$	$W_{s,TOT}$	$K_{eff,j}$
ADAS	$\sum_{j=1}^{N} 4K_{d,j} D_{yd} (1\text{-}\alpha)(x_{r,j} - D_{yd})$	$\sum_{j=1}^{N} K_{eff,j}\ x_{r,j}^2/2$	$K_j + K_{d,j}(D_{yd} + \alpha(x_{r,j} - D_{yd}))/x_{r,j}$
VES	$\pi\omega \sum_{j=1}^{N} c'_j\ x_{r,j}{}^2$	$\sum_{j=1}^{N} K_{eff,j}\ x_{r,j}^2/2$	$K_j + K'_j$
FV	$\pi\omega \sum_{j=1}^{N} c_j x_{r,j}{}^2$	$\omega^2 \sum_{j=1}^{N} m_j D_{\max}^2 \phi_j^2 / 2$	K_f

Numerical Examples

Four RC frames with one span and a variable number of story (1, 3, 8, 15 respectively) were considered with and without the three types of devices. They were studied with a group of five selected earthquake records scaled to a peak ground acceleration equal to 0.35g. First the mean value of the top displacement was determined for the structure without the devices (bare) from the average spectrum, then the different devices were sized in order to obtain a certain reduction of the top displacement according to the design procedure described above. The proper sizing of the devices was verified by comparing the target value of top displacement with the results of non-linear time-history analyses. The performance of the different devices was examined in terms of top displacement, inter-story drift, inter-story velocity, story acceleration, shear and bending moment in the columns and axial force in the brace elements.

One story frame

Results regarding the one story frame are shown in Fig. 3. A low difference was obtained between the target displacement of the design procedure and the displacement obtained from time-history analyses. The maximum difference, equal to 5% of the target value, was derived in the case of ADAS devices. For all the response quantities a large reduction was derived for the structure equipped with the devices. In general the performance of the various devices was similar.

The reduction of base shear and acceleration resulted slightly larger with FV devices since they do not add stiffness to the structure. In the same figure the effect of a modification of the ambient temperature from 36°C to 24°C for the VES devices is illustrated. The consequence of the temperature reduction was

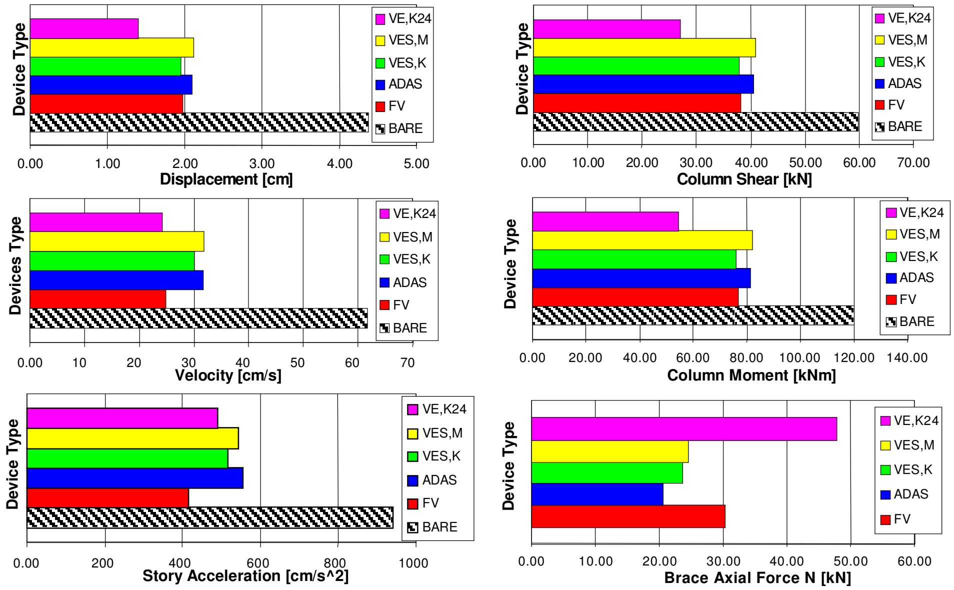

Figure 3. Results for the one story frame.

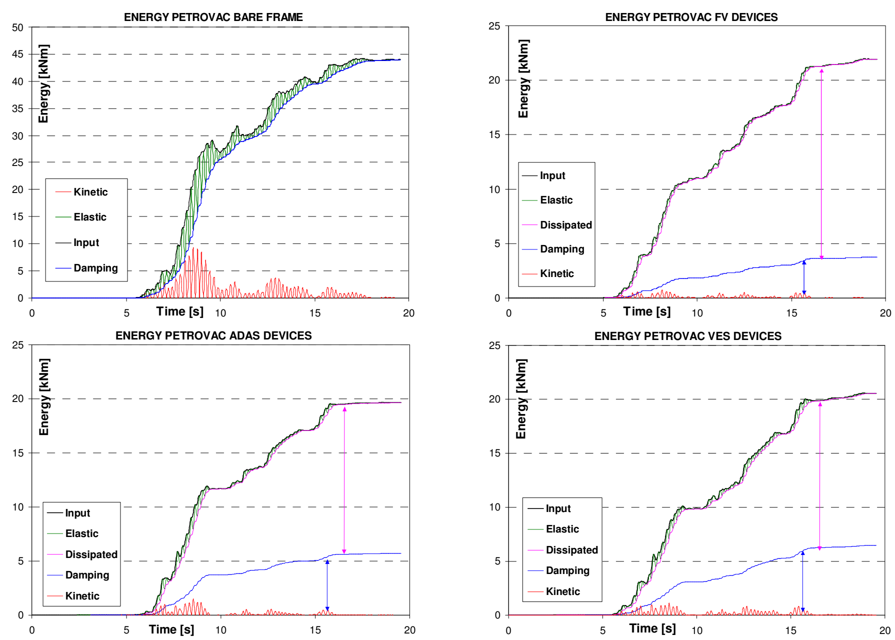

Figure 4. Energy time-histories for the one story frame.

a further reduction of displacement, but also a significant increase of the brace axial force. This larger axial force should be considered in the design of the brace. The VES devices were modeled both with the equivalent Maxwell (VES,M) and Kelvin model (VES,K). The two different models gave similar results. Although not reported in the figure, the variation of the response with the different earthquake records experienced a significant reduction for the structures equipped with the devices. This result points out the effectiveness of the devices in giving a more uniform and reliable seismic behavior of the structure. Fig. 4 shows the time-history of the input energy obtained for the structure without and with the devices in the case of the Petrovac earthquake record, which is the one with the greatest energy content. As expected the devices consumed the larger part of the input energy, thus reducing the damage of RC members.

Three, eight and fifteen story frames

The response for the three story frame is illustrated in Fig. 5. The reduction of the fundamental period due to the addition of the dissipative devices was quite low for the VES and more significant for the ADAS. The required damping was maximum for the FV, while it was very low for the ADAS, since they mostly stiffen the structure. From the top diagram of Fig. 5 it is possible to notice that the design procedure was effective also for the three story frame, since the difference between the target value of top displacement and the value obtained from time-history analyses was very low, always smaller than 4.5% of the target value. As observed for the one story frame, a reduction of the variation of the response due to the different earthquake records was derived for the structures with the devices. In Fig. 5 the comparison between the performance of the various types of devices is illustrated. For all the frames with a number of story larger than one two different distributions of the damping properties of the devices were considered: one is characterized by a uniform distribution of the device properties along the height, the other is characterized by a distribution proportional to the inter-story drift of the structure without devices. In terms of displacements the two distributions gave similar results for FV and VES devices, while the proportional distribution improved the results for the ADAS devices.

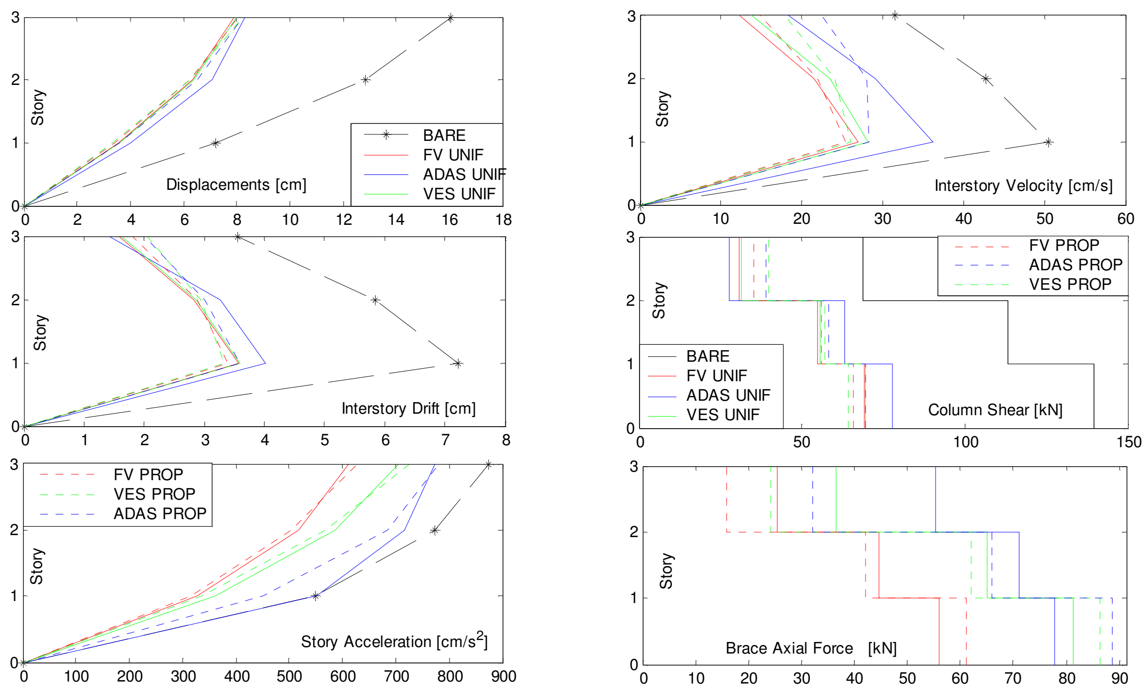

Figure 5. Results for the three story frame.

The reduction of the maximum inter-story drift at the first story due to the presence of dissipative devices was equal about 50% of the value obtained without the devices for the structures with FV and VES, and 44% for the structure with ADAS. The reduction of the maximum inter-story velocity at the first story was about 45% with FV and VED, and 30% with ADAS, while the reduction of the maximum acceleration was about 31% with FV, 20% with VES and 12% with ADAS. The reduction of bending moments and shear forces in each column was about 45% with all devices. In general the additional axial loads in the columns and in the diagonal braces caused by the devices were larger with the uniform distribution of the device properties than with the proportional distribution. From these results it comes that the performance in terms of maximum drift and internal actions in columns was similar with all devices, while the performance in terms of inter-story acceleration and velocity was better with FV and VES than with ADAS devices. Similar results (Fig. 6 and 7) were obtained for the structures with eight and fifteen story.

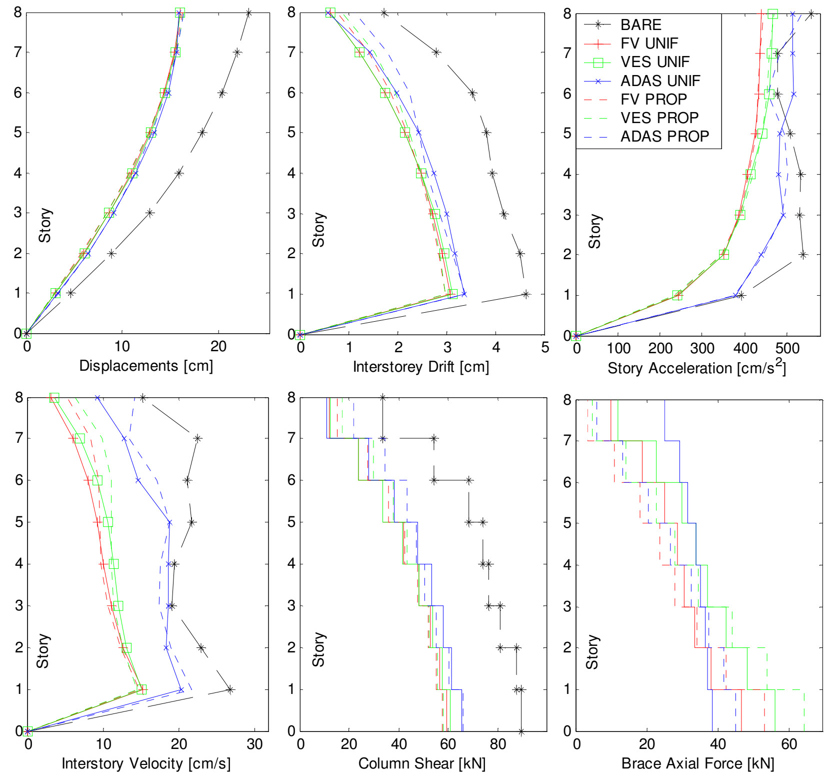

Figure 6. Results for the eight story frame.

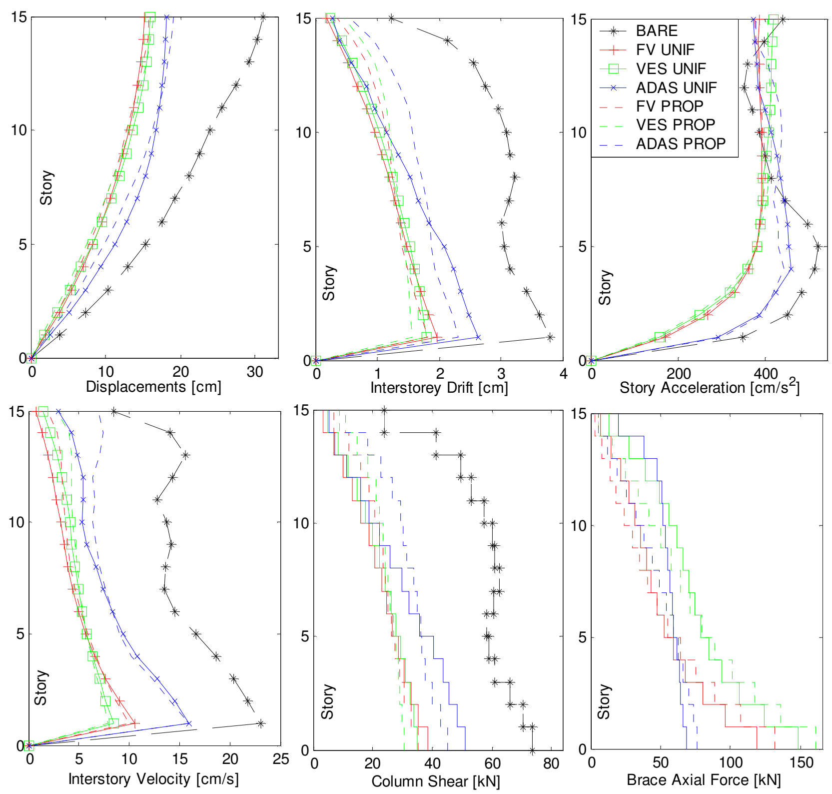

Figure 7. Results for the fifteen story frame.

For the case with fifteen stories, the difference between the target value of drift and the value obtained from time-history analyses was larger than for other structures This difference was also depending on the type of device. With FV it was below 1% in the case of uniform distribution of device properties and 6% in the case of proportional distribution. With VES it was about 10% in both cases. With ADAS it was 19% in the case of uniform distribution and 27% in the case of proportional distribution. This large difference is probably correlated to the difference between the inter-story drift profiles calculated using the secant stiffness of the devices and the real stiffness. Another reason is that the design procedure for MDF systems accounts for only the first mode of vibration and the increase of the number of degrees of freedom is usually correlated with an increase of the higher mode effect. Moreover the modification of the mode shape due to the added devices is not considered accurately in the design procedure.

Also for the structures with eight and fifteen story the performance with FV and VES resulted similar for all the response quantities, except for the column axial force, which was slightly larger with VES. The ADAS devices, instead, showed the tendency to a lower performance in terms of response reduction with the increase of the number of story.

Example of a Design Application

A RC building built in the sixties and designed for only gravity load was considered in this study. According to new zoning of the territory the building is now located in a seismic zone which corresponds to a second category, associated to a peak ground acceleration equal to 0.25 g. The assessment and the design of the seismic upgrading were performed according to the new Italian Seismic Code (OPCM 2003).

Current state

The building is made of a rectangular body, whose dimensions in plan are equal to 54.5 and 12.3 m. It has nine floors for a total height of 28.7 m. The structure is made of three longitudinal RC moment resisting frames, with a standard dimension of the bay equal to 3.9m. The inter-story height varies from 4.55 m of the ground floor to 3.56 m of the last floor. The frame on the side of the stairs body has fifteen bays, one more in comparison with the other two, due to the connection between the building and the stairs. The three frames are connected together in the transversal direction only by the floor diaphragms, some internal beams and the external girders. The columns are oriented in the transversal direction and they show a gradual narrowing of the transversal section along the height of the building. All the floors have a thickness of 27.5cm. There are also two internal elevators characterized by RC nucleus. For design purpose a linear model of the structure was realized and a response spectrum analysis was carried out. The period of the first vibration mode resulted about 2 sec. All the RC elements were checked with the internal actions obtained from the response spectrum analysis. About 60% of the columns did not satisfy the strength requirements for the Ultimate Limit State. Moreover also the base sections of the three bodies of the stairs and the elevators did not satisfy the strength requirements.

Retrofit design

The seismic upgrade was designed by adopting both traditional and innovative techniques. As traditional techniques the addition of RC walls and the reinforcing of weak elements, not described here, were considered. For completing the retrofit, the addition of a passive energy dissipation system was considered. Among the various dissipative systems studied previously the linear viscous-fluid FV device was selected. The choice of FV was due to several reasons: they do not add stiffness to the structure, the reduction of response parameters resulted better than with other systems, the performance is more reliable regarding the ambient condition, the design procedure is simpler and it does not require iterative procedures. For the addition of FV devices diagonal braces were adopted. An additional damping of 30% in both X direction (longitudinal) and Y direction (transversal) was given. It was assumed to set along the height 36 devices in X direction for each of the external frame (Fig. 8) and 9 devices in Y direction for each of the external frame (Fig. 8). Following the previously described procedure, the coefficients of damping of the devices were determined considering two distributions along the height: the first uniform, the second proportional to the inter-story drift in the first mode.

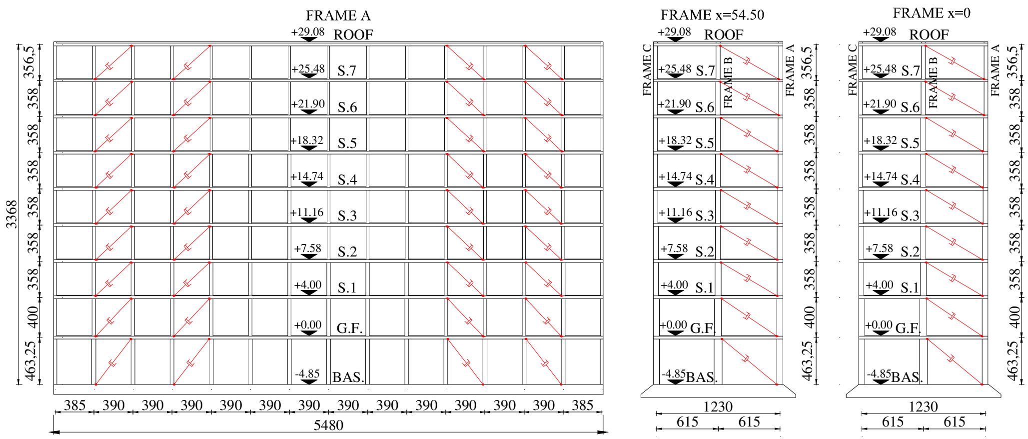

Figure 8. View of typical FV installations.

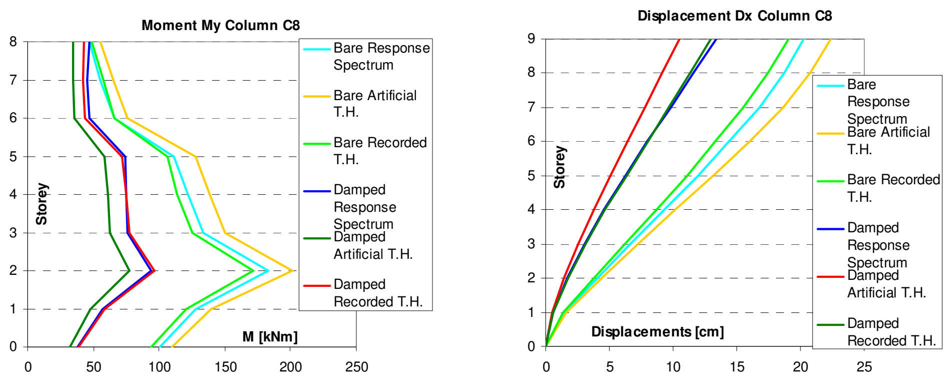

Figure 9. Bending moment in columns and displacements along the height.

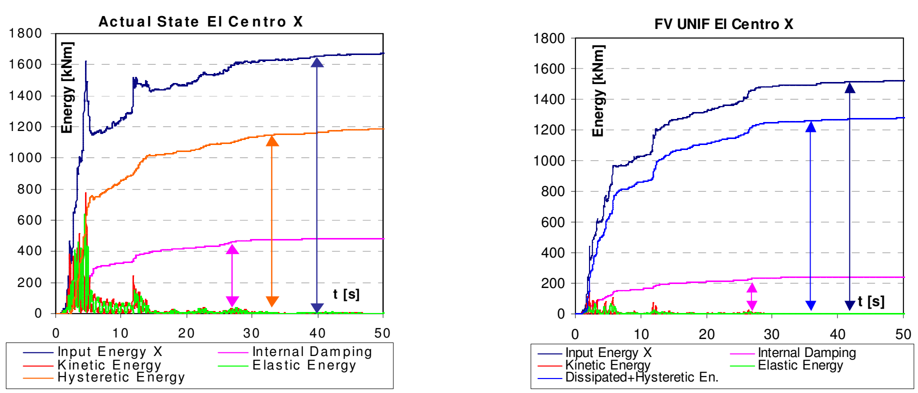

Figure 10. Energy time-histories for existing and upgraded building.

The effectiveness of the dissipative system was verified through time-history analyses. A group of twelve artificial earthquake motions, generated with the SIMQKE software (Gasparini and Vanmarcke 1976), and a group of nine real records scaled to design PGA were considered. The earthquake records were selected in order to give an average response spectrum compatible with the code spectrum. The Fig. 9 shows the results obtained for a typical column in terms of bending moment and displacement. It is possible to notice a reduction equal about to 50% of these response quantities. It is possible to observe also that the response predicted by the design procedure is substantially confirmed by the time-history analyses. Finally, Fig. 10 shows the energy plot for the initial and upgraded structure with the uniform distribution in the case of the El Centro record. This figure confirms the fundamental objective of the FV devices, which is to dissipate the largest quantity of input energy so to decrease the dissipation of energy in the structural members.

Conclusions

In the present work some of the principal passive energy dissipation systems were examined. In the first part some simplified models were introduced for their implementation in most common structural software. Then numerical analyses were performed in order to study the behavior of different types of devices. Structures with an increasing number of stories were considered. The following conclusions can be drawn from the obtained results.

• The difference between the target value of drift and the value obtained from time-history analyses was not so significant for the structures with one, three and eight story and with all types of devices. The maximum values in these cases resulted about 5%. The larger difference obtained for the fifteen story frame (for example about 10% with VES and 20% with ADAS) was due to various reasons correlated to the approximations adopted in the design procedure. In this procedure, in fact, only the first mode of vibration is considered and the modified period of the structure with the devices is not calculated accurately.

• The reduction of the response quantities, as bending moments and shear forces in columns, inter-story drifts, velocities and accelerations, were similar with FV and VES devices for any number of stories. With ADAS the response reduction resulted lower especially for the frames with the larger number of story.

• Two distribution of device properties were considered along the height: one uniform, the other proportional to the first mode. In terms of displacements and inter-story drift the proportional distribution improved the results, especially for structures with ADAS.

• The seismic retrofit of an existing RC building with FV devices was studied. The seismic upgrade was designed by adopting both traditional techniques and dissipative devices. The FV produced a general reduction of internal forces in columns and of displacement, equal in most elements to 50% of the values of the existing structures. Also the reduction of energy to be dissipated by RC structure was noticeable.

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