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Technical Note

SEISMIC RESPONSE OF REINFORCED CONCRETE BUILDING WITH VISCOELASTIC DAMPER UNDER NEAR FIELD EARTHQUAKE

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ABSTRACT

Near-field earthquakes are characterized by short duration pulses of long periods with large peak ground velocities and accelerations. Recent studies have shown that the performance of passive energy dissipation systems depends significantly on the characteristics of near-field ground motion pulses. This paper is focused on the viscoelastic (VE) dampers to be used as energy-absorbing devices in buildings. Detailed and systematic investigation on the performance of passive energy dissipation systems during near-field ground motions has been carried. The analytical studies of the model structures exhibiting the structural response reduction due to these VE devices are presented. In order to exhibit the benefits of VE dampers, a nonlinear time history analysis is carried out under strong ground motion records from near-field and far-field earthquakes for all case studies: (a) a 5-story, (b) a 10-story and (c) a 15-story reinforced concrete building. The top story relative displacements as well as the top story absolute accelerations and also the base shear values obtained indicate that these VE dampers when incorporated into the super-structure reduce the earthquake response significantly in proportion to the amount of damping supplied in these devices. Reduction response of structure in 5 and 15 story building is harmonic but in 10 story building, there is no harmony in response of structure. Overall, the highest reduction has been achieved in 5 story building with an average reduction of 100%. Additional viscous damping is suggested as a way to control very large displacements. In order to be effective for mitigating the effects of large near fault motions, large damping values would be required

Keywords: reinforced concete buildings; seismic behavious; viscoelastic damper; near-field ground motions

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1. INTRODUCTION

A challenging research topic in engineering seismology and earthquake engineering is the characterization of near fault seismic motions and their effects on the performance of special structures, such as building with VE damper, tall building and so on. The problem under consideration is twofold: the first aspect of the problem is related to the physical understanding, modeling and simulation of near fault ground motions, while the second one is associated to the characteristics of the structure itself that control its behavior under near fault excitations. While there is a good understanding of the first aspect of the problem, there are still uncertainties and difficulties in understanding, describing and predicting the near fault ground motions.

Following the 1994 Northridge and the 1995 Kobe earthquakes, near fault pulse-type ground motion has attracted the interest of earthquake engineers. These events are characterized by the occurrence of the earthquake under a heavily urbanized area or very close to it. The earthquake ground motion in the region within 15 to 20 km of the fault is characterized by large amplitude pulse with low frequency in both the velocity and displacement time histories. The acceleration record in the near-fault may contain high PGA value that corresponds to a short duration pulse with little or no effect on the structure. On the other hand, a low PGA with long duration pulse may have severe damaging effects on civil engineering structures.

There are two types of structural control provided by the addition of mechanical devices; active and passive control. Active control requires a power supply to activate the dampers and hence may be undependable during seismic events where the power supply could be disrupted. Passive energy dissipation systems have emerged as special devices that are incorporated within the structure to absorb a portion of the input seismic energy.

The idea of utilizing separate passive energy dissipating dampers within a structure to absorb a large portion of the seismic energy began with the conceptual and experimental work of Kelly et al. [1]. Today, there are various types of manufactured passive dampers available in the market which use a variety of materials to obtain different levels of stiffness and damping. These dampers have been reviewed by Constantinou et al. [2], and Sadek et al. [3]. Some of these include VE, viscous fluid, friction and metallic yield dampers. These dampers have different dynamic characteristics and so will affect the seismic response of structures differently. The characteristics of VE dampers are that they dissipate energy at all levels of deformation and over a broad range of excitation frequencies. In order to exhibit the benefits of VE dampers in the reduction of response of structures under the near field earthquake, a nonlinear time history analysis is carried out under strong ground motion records from near-field and far-field earthquakes (for the sake of comparison with the near field earthquake) for three types of structures: (a) a 5-story, (b) a 10-story and (c) a 15-story reinforced concrete building.

2. VISCOELASTIC DAMPER (VE)

VE dampers have been adopted for several tall buildings to reduce wind induced vibrations. Significant reduction of sway by these dampers has been achieved in these buildings. Recent researchers have proven that they may also be suitable for the seismic hazard mitigation of buildings. Lee et al. [4] compared conventional analysis methods for building structures with added VE dampers, such as direct integration, complex mode superposition, and modal strain energy method, and a procedure based on rigid diaphragm assumption and matrix condensation technique was proposed for application in the preliminary analysis and design stages. According to the eigenvalue analysis, the major vibration modes were mostly preserved after the matrix condensation. It was also found that the matrix condensation technique applied to dynamic analysis of a structure with added VE dampers provided quite accurate results in significantly reduced time, regardless of the plan shape and the location of the VE dampers.

Xu et al. [5] introduced a synthetic optimization analysis method of structures with viscoelastic (VE) dampers, namely the simplex method. The optimal parameters and location of VE dampers can be determined by this method.

Min et al. [6] presented a design process for VE dampers and experimental test results of a 5-storey single bay steel structure with added VE dampers. The mechanical properties of VE dampers and the dynamic characteristics of the model structure were obtained from experiments using harmonic excitation, and the results were used in the design process. The results from experiments using harmonic and band limited random noise indicated that after the dampers were installed the dynamic response of the full-scale model structure reduced as desired in the design process.

Xu et al. [7] presented the simplex method, a synthetic optimization analysis method of structures with VE dampers, which is used to determine the optimal parameters and location of VE dampers. When applied to a shaking table test of the reinforced concrete structure with VE dampers, it was seen that the simplex method can act as the synthetic optimization method of structures with VE dampers.

Hryniewicz [8] developed an analytical method for dynamic analysis of systems with VE dampers. Some aspects concerning the critical damping of structure with elastically supported VE damper were discussed. The considered system was governed by the third order differential equation.

Palmeri [9], in the framework of the random vibration of linear systems, presented alternative frequency- and time-domain approaches to evaluate the correlation coefficients of SDOF oscillators with VE memory, and validated by means of Monte Carlo simulation. In contrast to the usual modal strain energy (MSE) method, the proposed formulations allow the seismic analysis of structures with added VE dampers to be performed in a consistent modal space, where the fading memory arising from these devices is not neglected. The numerical applications show that the inaccuracy associated with the conventional analyses may be unacceptable for engineering purposes.

Garcia et al. [10] investigate the torsional balance of elastic asymmetric structures with VE dampers. It was observed that optimal damper eccentricity values tend to increase linearly as the stiffness or mass eccentricities increase, and that response reduction factors ranging from 1.5 to 3 are possible with a small capacity damper.

In this paper, the influence of VE dampers on the reduction of seismic response of various structures is investigated by analytical studies.

3. PROPERTIES OF VE DAMPERS

These devices contain VE material with certain viscosity characteristics. The most commonly used materials are acrylic copolymers. VE dampers are quite linear in their response and are able to dissipate energy under low levels of shaking. Probably, one drawback of the VE dampers is that their performance is related to the ambient temperature.

The design of VED requires the knowledge of the mechanical properties of VE material. The class of polymer materials is vast and includes families of products such as the natural and synthetic rubbers, the adhesives, and the plastics. The stiffness and damping properties of these polymers vary widely depending on the composition and process employed in their generation.

Rubber is the co-polymer of isobutylene (98%) and a small amount of isoprene (2%) distributed randomly inside the molecular chains. A typical VE damper is shown in Figure 1, which is made up of two VE layers bonded between three steel plates.

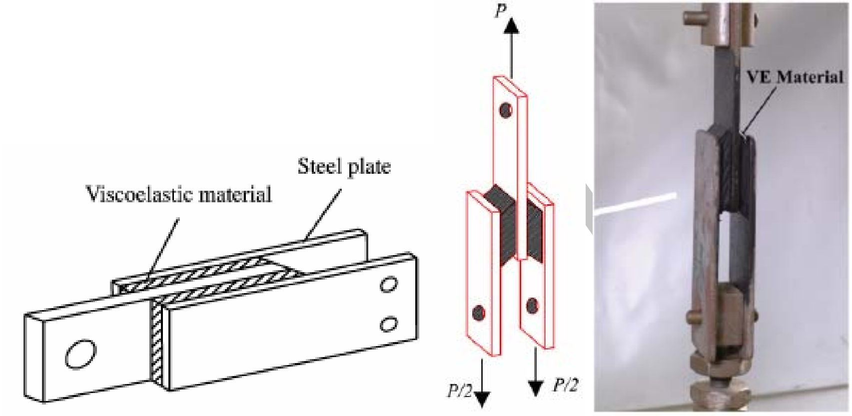

Figure 1. A typical viscoelastic damper [7]

The mechanical properties of VE dampers are rather complex and may vary with environmental temperature and excitation frequency. As shown in Figure 2, each layer 10 mm in thickness and 150cm^2 in area.

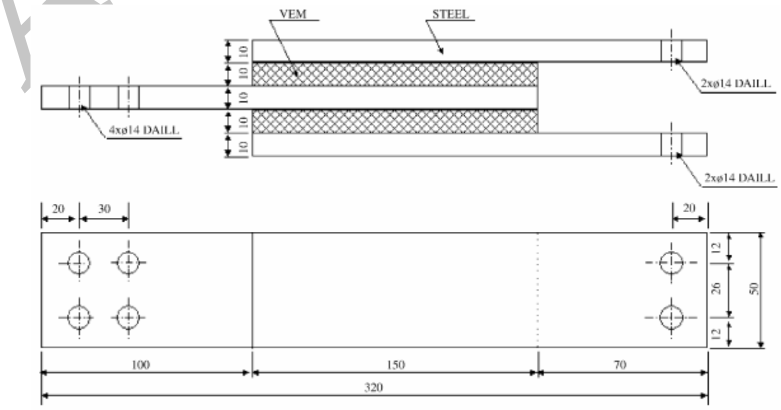

Figure 2. Dimensions of a viscoelastic damper (dimensions in mm)

Ten cyclic tests were conducted on the specimens by using sinusoidal excitation with 0.5 Hz at the temperature of 24^0C with various maximum strains of 20, 25, 50, 75, and 100%. Table 1 presents the test results for storage stiffness and loss factor obtained for different strains, and shows that the loss factor was not sensitive to the maximum strain.

Table 1. Storage stiffness and loss factors for viscoelastic at different displacements

Horizontal displacement (mm)	Storage stiffness (kN/m)	Loss factor
2.0	1260	0.66
2.5	1203	0.67
5.0	1080	0.70
7.5	966	0.72
10.0	926	0.69

Energy dissipation per cycle of VE dampers can be expressed as:

$$E_d = \pi \gamma_0^2 G_1 \eta V \tag{1}$$

where γ_0 is the shear strain amplitude, η is the loss factor ($\eta = G_2/G_1$), G_1 is the storage modulus, G_2 is the loss modulus, V is the volume of VE material ($V = n_v A_v h_v$), n_v is the number of VE layer, A_v and h_v are the area and the thickness of VE layer, respectively. If the storage modulus G_1 and the loss factor η are determined, the stiffness k_d and the damping C_d of VE dampers can be written as

$$\begin{aligned} k_d &= \frac{n_V G_1 A_V}{h_V} \\ C_d &= \frac{n_V G_1 \eta A_V}{\omega h_V} \end{aligned} \tag{2}$$

where ω is the excitation frequency.

4. ANALYTICAL INVESTIGATIONS

4.1 Computer program and earthquake data

Analytical modeling of the VE dampers is achieved by using the SAP2000n package program [11]. The objective of the analysis is to present the amount of reduction in the seismic response of reinforced concrete building under near fault earthquake by the use of VE dampers installed at each story level and were compared with far field earthquake. Three example structures are investigated under the effects of the near fault and far field records. In general, earthquakes have different properties such as peak acceleration, duration of strong motion and different ranges of dominant frequencies and therefore have different influences on the structure. Tow earthquake excitations are used in this study.

El Centro with duration of strong motion in the range of 1.5–5.5 s and dominant frequencies in the range 0.39–6.39 Hz (Figure 3). Takatori record from the 17 January 1995, Kobe earthquake (*M*w = 6.9) with duration of strong motion in the range of 7.5–12.5 s and dominant frequencies in the range 0.29–1.12 Hz (Figure 4). Kobe earthquake is near fault records with a distance to source of less than 5 km. For the Takatori record, the near fault pulse has a period of about 2 s with peak velocity amplitude of 150 cm.s^{-1}, and peak displacement amplitude of about 50 cm. The peak ground acceleration is 0.64 g for Kobe. El Centro earthquake was selected to illustrate far-field ground motion characteristics and Kobe earthquake was selected to illustrate near-field ground motion characteristics.

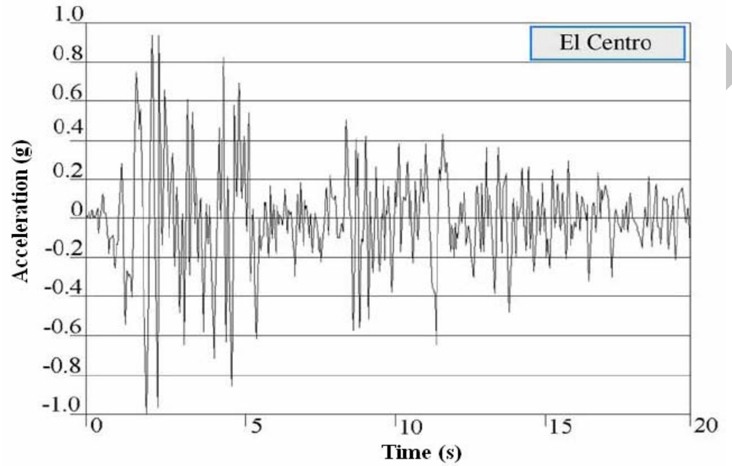

Figure 3. El Centro earthquake record

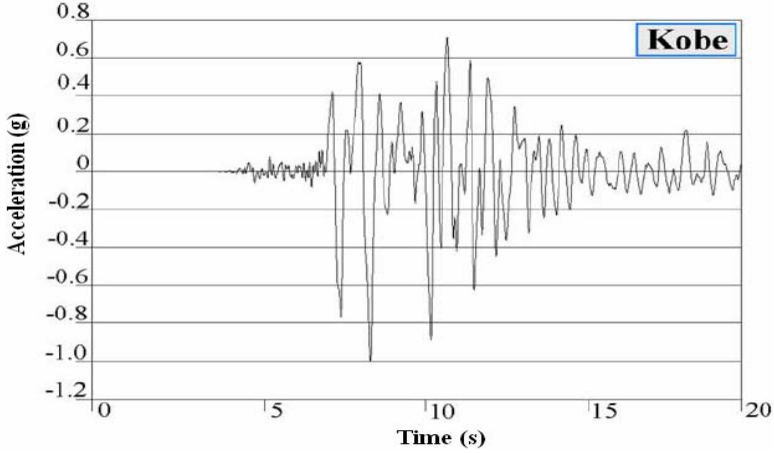

Figure 4. Kobe earthquake record

4.2 Modelling of the viscoelastic dampers

The VE dampers have been modelled by the NLPROP and NLLINK data blocks of the SAP2000n program. For each deformational degree of freedom, independent damping properties may be specified. The damping properties are based on the Maxwell model of viscoelasticity having a linear or nonlinear damper in series with a spring. If nonlinear properties are not specified for a degree of freedom, that degree of freedom is linear using the effective stiffness, which may be zero. The nonlinear force *f* is given by

$$f = kd_k = cv^{c\,exp} \qquad (3)$$

where *k* is the spring constant, *C* is the damping coefficient, *c* exp is the damping exponent, d_k is the deformation across the spring and *v* is the velocity across the damper. The damping exponent must be positive. The practical range is between *c* exp = 0.2 and 2.0. In the numerical data of this study *c* exp is taken as unity. The total internal deformation *d*, of the diagonal link element is the sum of the spring deformation d_k and the damper deformation d_c. If pure damping behavior is desired, the effect of spring deformation can be made negligible by defining *k* sufficiently stiff. The spring stiffness *k* should be large enough so that the characteristic time of the spring-dashpot system, given by t = *c*/ *k*, is an order of magnitude smaller than the size of the time steps. In the numerical investigations, an appropriate *k* is selected which makes t smaller than 0.02, then for these predetermined values of *t* and *k*, the damping coefficient *C* is varied to observe purely the influence of damping.

The damping ratio supplied by the VE devices is obtained by an analogy to the logarithmic decrement curve for one degree freedom system. The displacement amplitude versus time curve of one degree freedom system is a decreasing sine curve from which the damping ratio is calculated by

$$Ln(u_1 / u_2) = 2\pi\beta / \sqrt{1-\beta^2} \qquad (4)$$

where u_1 and u_2 are the peak displacements at two consecutive time periods, and b is the effective damping ratio. In the same manner, if u_1 and u_2 are the maximum horizontal displacements of the top story at any time *t* for the undamped and the damped system, respectively, the average effective damping ratio β supplied by the devices is obtained from the above formula. By changing the viscosity coefficient *c*, in the program, the effective damping ratio β is changed likewise. According to the layers thickness in the VE damper, relationships between β (in percent) and *c* (kN.s/m) values for each example building are given in Table 2.

Table 2. Viscosity c and corresponding β values

5 story		10 story		15 story	
c	*β*	*c*	*β*	*c*	*β*

500	7.6	500	4	2000	5
1000	11.6	5000	15	7000	10
5000	27.4	10000	30	15000	15

5. EXAMPLE BUILDINGS

The buildings are 5-story, 10 story and 15 story reinforced concrete building with six frames in each direction (Figure 5) and with a typical story mass of 315 ton. The buildings equipped with the VE damping devices in frames 2 and 5 at each story level as shown in Figure 6. Equal structural bracings having the same stiffness coefficient *k* = 250000 kN/m have been used for both the undamped and damped frames in order to detect the sole influence of VE dampers. Modal properties of the first three modes are given in Table 3.

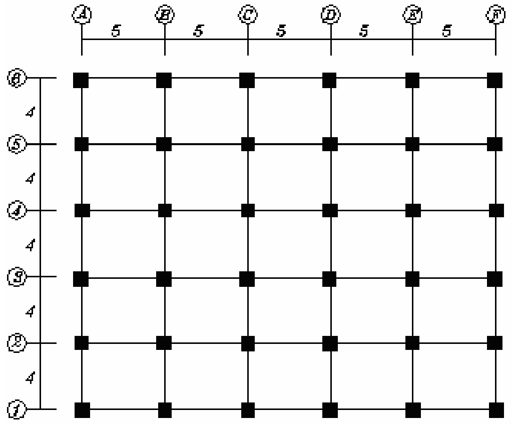

Figure 5. The plan of example buildings

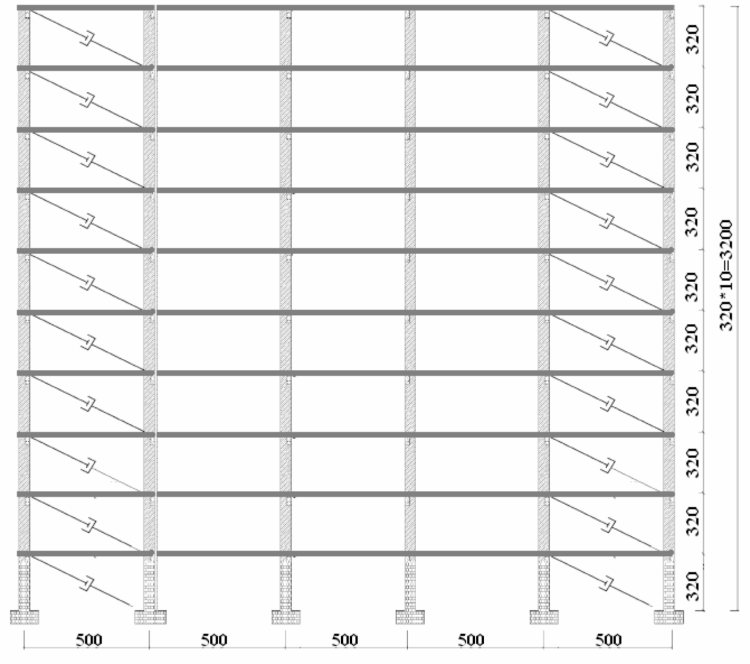

Figure 6. Elevation of example buildings

Table 3. Modal properties of the first three modes

Building	**Mode 1 (sec)**	**Mode 2 (sec)**	**Mode 3 (sec)**
5 story	0.95	0.32	0.17
10 story	1.64	0.53	0.3
15 story	2.1	0.74	0.41

6. REDUCTION OF RESPONSE BY VE DAMPERS

All three example buildings have been subjected to near fault ground motions for both the undamped and damped cases. The time history responses including horizontal displacements, velocities, accelerations and internal forces at all joints and members in all degrees of freedom have been computed. For the purpose of illustration, however, the time history of relative horizontal displacements at the top level of the 5-, 10- and 15-story buildings is shown in Figures. 7–9 for undamped and also three different effective damping values. Similarly, the time history of the base shear of the 15-story building is shown in Figure 10 again for various effective damping values. In addition to the effective damping supplied by the viscous dampers, in all examples, an inherent critical structural damping ratio of 5% is assumed.

It is seen that, as the total damping ratio increases, the response values decrease significantly, thereby proving the favorable roles of the VE dampers.

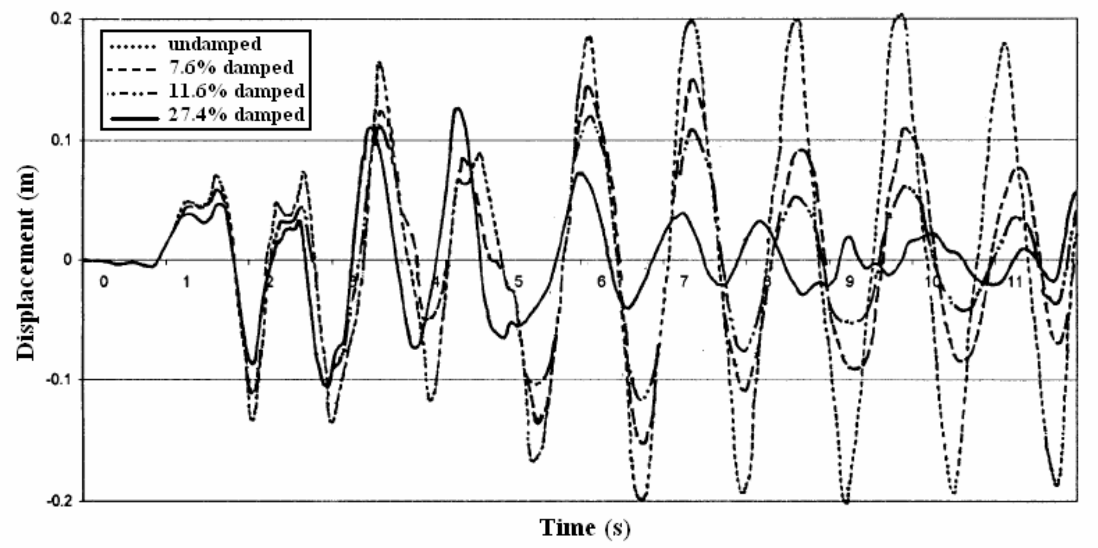

Figure 7. Top story relative horizontal displacements (5-story building).

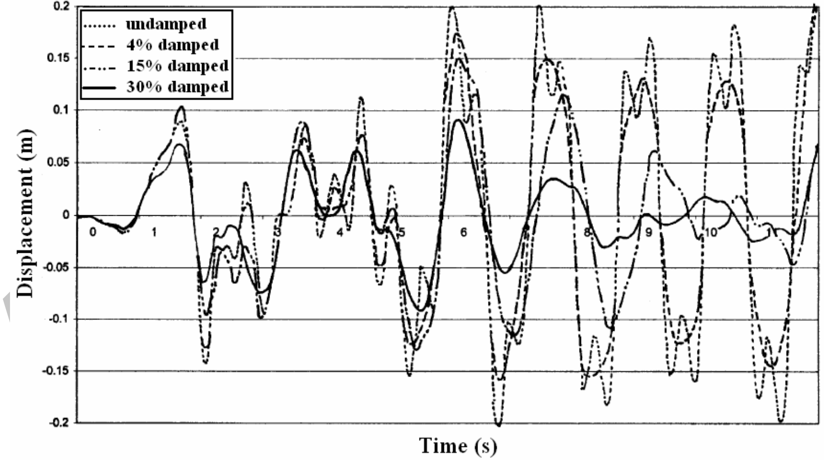

Figure 8. Top story relative horizontal displacements (10-story building)

The time displacement responses of all three types of damping ratio compared with that of undamped system clearly demonstrate that incorporation of dampers reduces the peak displacement of the structure, under seismic loads.

The results show that in 5 story building, maximum value of displacement occurs in last third part of earthquake duration but in 10 and 15 story buildings, maximum displacement occurs in nearly middle of time duration. In 5 and 15 story buildings, we have normal trend but in 10 story building in the time of 4s there is a discontinuity in harmonic response of structure. For a same time among mentioned structures, effect of VE damper in 5 story building is larger than 10 and 15 story buildings. Reduction response of structure in 5 and 15 story building is harmonic but in 10 story building, there is no harmony in response of structure. Overall, the highest reduction has been achieved in 5 story building with an average reduction of 100%.

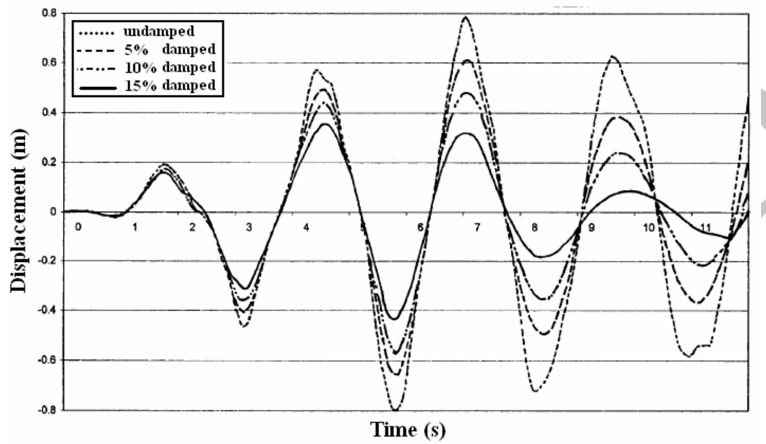

Figure 9. Top story relative horizontal displacements (15-story building).

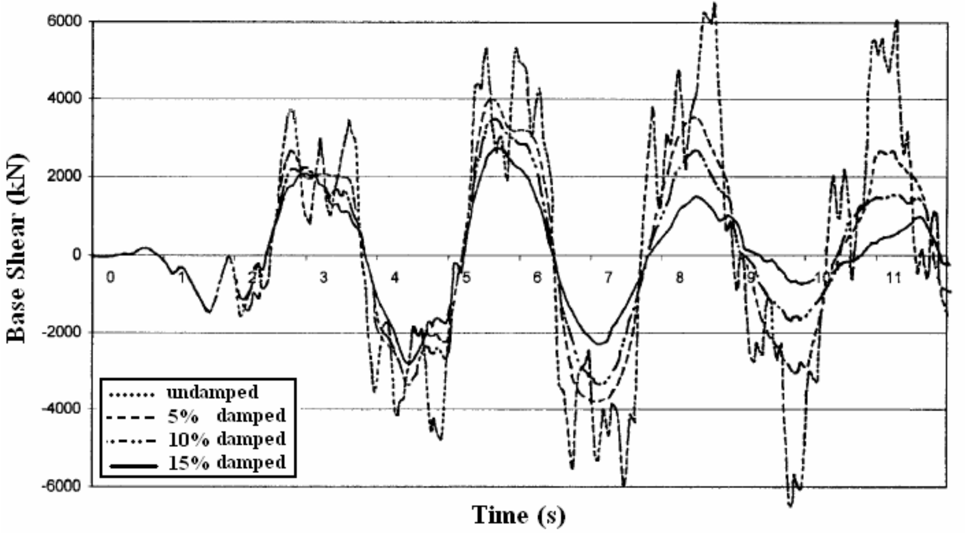

Figure 10. Base shear (15-story building).

The results for 15 story building under each of the near field and far field earthquakes records are presented in Figure 11. This figure illustrates the typical time history responses of the tip displacement of the building.

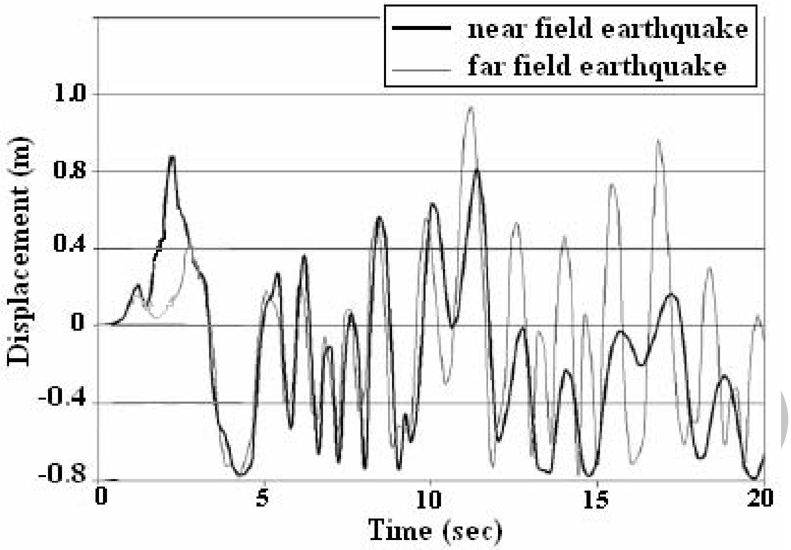

Figure 11. Top displacement of 15 story building under near and far field earthquakes

While comparing models with VE damper under near field and far field earthquakes, VE dampers performed better in early time of far field earthquake and last third part of near field. Due to impulsive nature of the highly directed near field earthquake energy, increase in viscous damping are not as effective in reducing response displacements as would be expected for a harmonic excitation. Additional viscous damping is suggested as a way to control very large displacements. In order to be effective for mitigating the effects of large near fault motions, large damping values would be required. However, this would also transfer more force into building.

7. CONCLUSIONS

(1) The computer package SAP2000n is ideally suitable for conducting a time history analysis of structures with linearly or nonlinearly varying VE dampers.

(2) The numerical results on three example buildings clearly indicate that the VE dampers reduce the seismic response of structures in an extremely efficient way. Reduction response of structure in 5 and 15 story building is harmonic but in 10 story building, there is no harmony in response of structure. Overall, the highest reduction has been achieved in 5 story building with an average reduction of 100%.

(3) A frame without any energy dissipaters itself absorbs most of the input energy and is subjected to large displacements and inter story drifts. On the contrary, a protected frame is kept in the elastic range and the plastic deformations are concentrated in the dissipaters, which can be easily replaced after an earthquake. This system could be a solution to avoid story mechanism.

(4) Additional viscous damping is suggested as a way to control very large displacements. In order to be effective for mitigating the effects of large near fault motions, large damping

values would be required. However, this would also transfer more force into building.

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