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TESTING AND ANALYSIS OF A STEEL FRAME WITH VISCOELASTIC DAMPERS

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ABSTRACT

Experimental results from a shaking table study of a 2/5 scale three-story steel moment resisting frame with and without VE-dampers are correlated analytically using three different approaches. Analytical methods used to model the effect of the VE-dampers include a global Rayleigh damping model, a local Rayleigh damping model, and a fractional derivative model. The analyses include nonlinear inelastic behavior of the members and correlation of the frame response into the inelastic range. Comparisons between analysis methods are presented. Finally, a redesign of the VE-frame is proposed which uses a stiff damper design concept. The revised damper design reduced frame drifts, damper deformation demand, and significantly reduces the inelastic ductility demand of the structure even when subjected to a catastrophic earthquake.

KEYWORDS

Viscoelastic damper; damping; inelastic response; steel frame; fractional derivative model.

INTRODUCTION

The application of viscoelastic dampers (VE-) to structures has recently attracted interest from the earthquake engineering community (Aiken and Kelly, 1991, Chang *et al.*, 1991, Kasai *et al.*, 1993). This interest stems from the dramatic changes in structural response to dynamically applied forces in structures with VE-dampers. VE-frames, properly designed to minimize temperature sensitivity, can behave elastically and develop small drifts even when subjected to a catastrophic earthquake. As part of the ongoing research in the application of VE-dampers to building structures, a 2/5 scale three-story steel moment resisting frame with and without VE-dampers was recently subjected to shaking table earthquake simulations at the National Taiwan Institute of Technology (NTIT), Taipei, Taiwan (Chou, 1994). Limited analytical correlation of the experimental response was performed, and no analytical correlation was performed for the yielding frame without VE-dampers (Chang *et al.*, 1994). This paper presents analytical correlation of the experimental structural response for both the undamped and VE-damped frame using three approaches to model the effect of the VE-dampers: a global Rayleigh damping model, a local Rayleigh damping model, and a fractional derivative model. The analyses include nonlinear inelastic behavior of the members and correlation of the frame response into the inelastic range. Finally, an improved design for the VE-dampers is proposed which reduces damper deformation demand, frame drift, member strains, and temperature sensitivity.

Two frames were tested at NTIT, a moment resisting frame without VE-dampers (MRF), and an identical MRF with added VE-dampers (VE-frame). The frame was designed to satisfy strength requirements of NEHRP 1988, but largely violates the code specified drift requirements. The frames consisted of a single bay in plan with columns spaced at 2.4 m and story elevations of 1.6 and 1.4 m as illustrated in Fig. 1(a) and 1(b). Section properties for members are shown in Table 1. Steel plates were used to provide lumped mass at each story as shown in Fig. 1(b). Except for the VE-dampers installed at each story, the VE-frame was

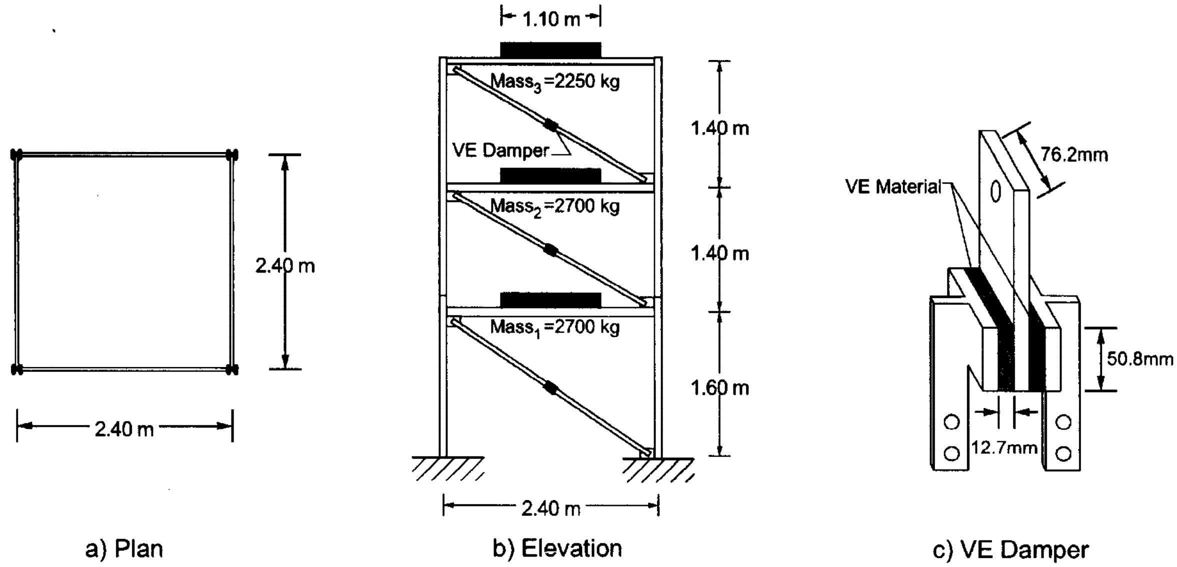

Figure 1. Experimental frame and damper dimensions.

identical to the MRF. The viscoelastic material used in the dampers was ISD 110, manufactured by 3M Corporation. Damper dimensions and configuration are illustrated in Fig. 1(c).

The MRF was subjected to El Centro table accelerations with scaled peak ground accelerations (PGA) from 0.05g to 0.5g. Experimental results from the MRF indicated yielding of some members at 0.1g El Centro and severe damage to the frame after 0.5g El Centro. The VE-frame was subjected to El Centro table accelerations with scaled PGA from 0.05g to 0.8g. Initial temperatures of the VE-dampers were 30 °C ± 1 °C and torsional response of the MRF and VE-frames was negligible.

Table 1. Section properties for frame members.

Location	Area (cm^2)	Ix (cm^4)	Zx (cm^3)
Beam Level 1	7.00	135.3	28.5
Beam Level 2	6.85	121.5	26.8
Beam Level 3	6.10	64.9	18.7
Column Level 0-1	9.10	107.1	29.9
Column Level 1-2	7.60	86.0	24.3
Column Level 2-3	7.60	86.0	24.3

ANALYSIS OF MRF

Before analysis of the VE-frame, an analytical finite element model was developed to calibrate the response of the MRF without dampers to the experimental response. A trilinear stiffness-degrading connection element was used at the column base and each beam-to-column connection to model inelastic moment-rotation behavior of the members. Characteristics of the connection model were selected to provide negligible rotation in the elastic range and moment rotation values compatible with empirical tests of steel moment connections (Kasai and Bleiman, 1996). Elastic free vibration properties of the analytical model were calibrated to the experimentally reported values using static analysis and employing an improved Rayleigh procedure (Clough and Penzien, 1993).

Dynamic analysis of the MRF was conducted using PC-ANSR (Maison, 1992) and NTIT shaking table acceleration records. Table motions corresponding to El Centro with PGA of 0.05g, 0.2g, and 0.5g were selected to correlate structural response when the frame remains elastic (0.05g), exhibits limited yielding (0.2g), and exhibits significant yielding (0.5g). Proportional viscous damping values for the frame were adjusted until the experimental and analytical response were comparable. Damping ratios determined from analysis corresponded well with experimentally reported values. Analytical displacement time histories at the roof elevation are compared with the experimental response in Fig. 2(a), 2(b), and 2(c). Analytical response envelopes are compared with experimental envelopes in Fig. 3. Analytically predicted inelastic rotations are shown in Fig. 4.

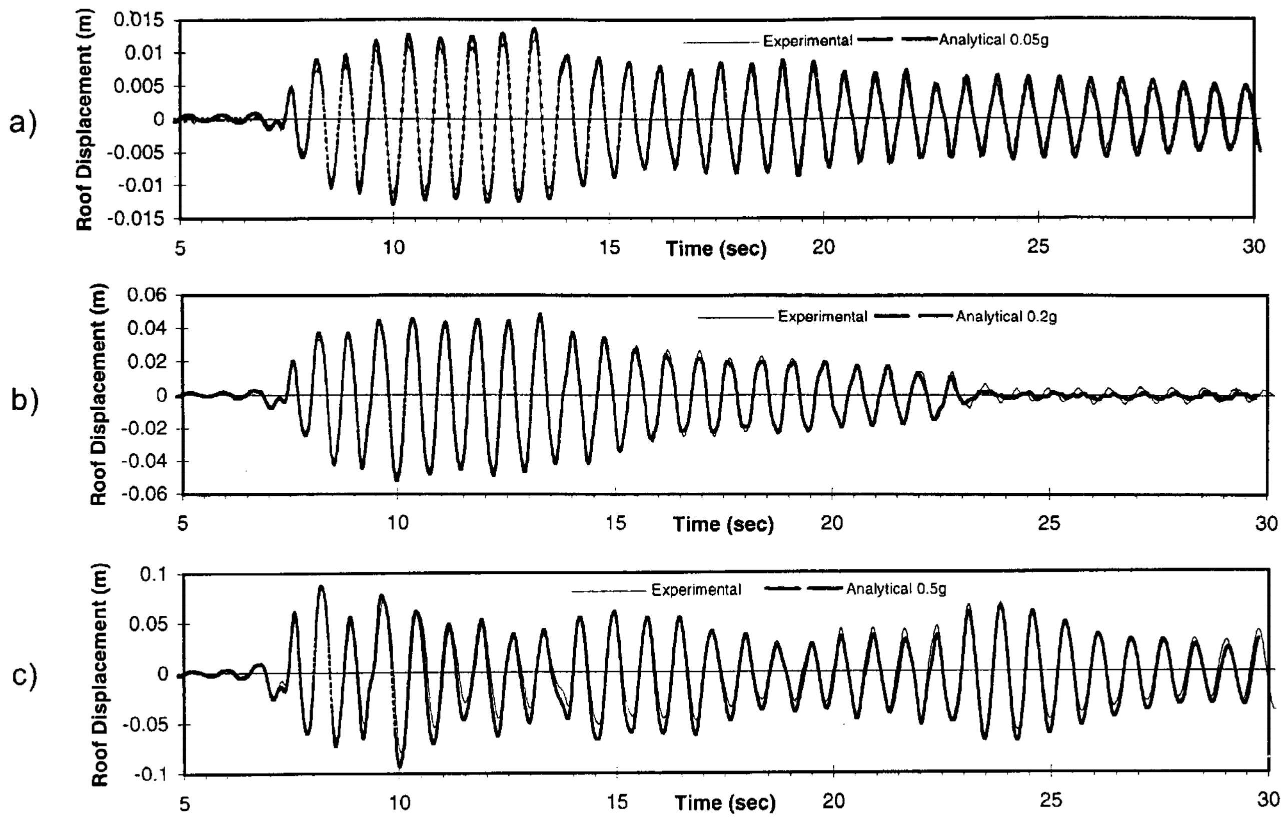

Figure 2. MRF response at roof for (a) 0.05g El Centro, (b) 0.2g El Centro, and (c) 0.5g El Centro.

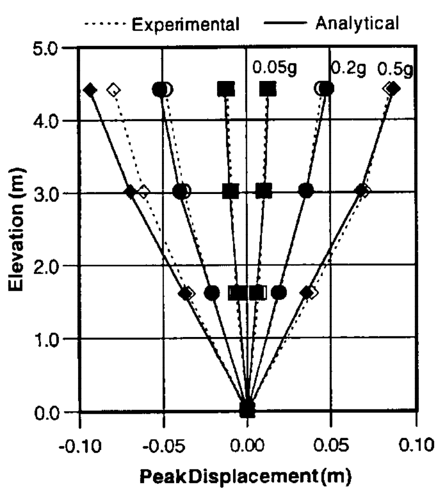

Figure 3. Peak displacement envelopes for MRF.

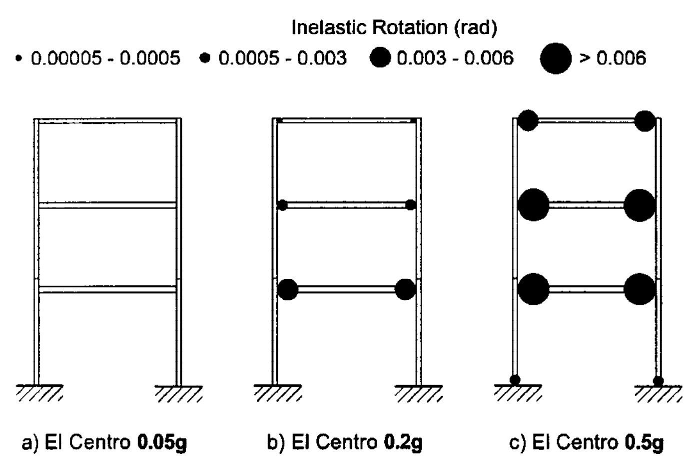

Figure 4. Analytically predicted inelastic rotation.

ANALYSIS OF VE-DAMPED FRAME

Dynamic analyses of the VE-frame were conducted using table motions corresponding to El Centro with PGA of 0.05g, 0.2g, 0.5g, and 0.8g. Analysis of the VE-damped frame was performed utilizing the material, stiffness, and frame damping properties determined from the earlier analytical correlation of the MRF. No modifications were made to the frame members or connections after completion of the MRF analyses. The only changes were to introduce VE-dampers to the MRF model. Analytical VE-frame response was determined using three methods to model the VE-dampers: a global Rayleigh damping model, a local Rayleigh damping model, and a fractional derivative model. These models are illustrated in Fig. 5.

VE-dampers, like those used in this study, are typically attached to a steel brace and the interaction between the brace and damper affects the behavior of the VE system. The combined damper and brace will be termed

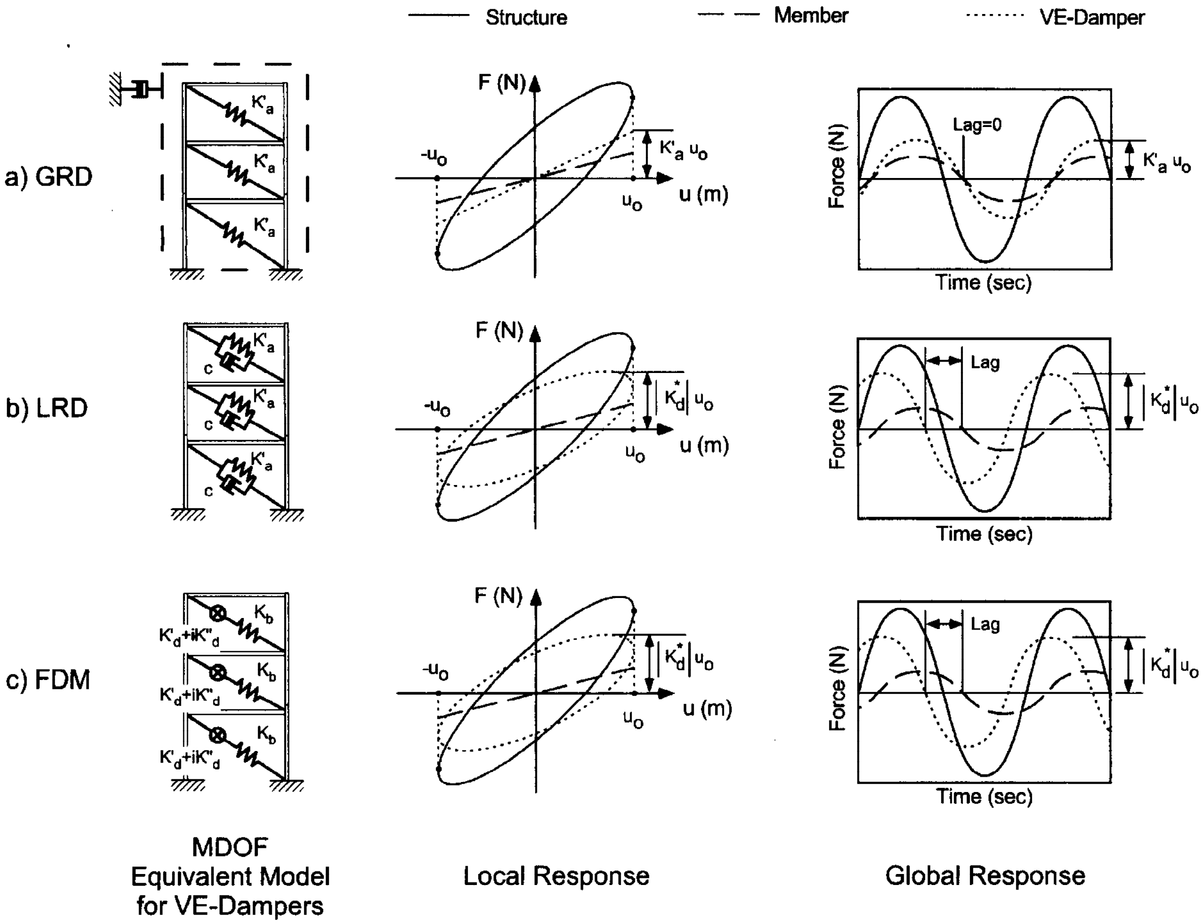

Figure 5. Equivalent models and examples of response for three methods used to model VE-dampers.

'added component' for this study. The complex stiffness of the added component K^*_a contains in-phase stiffness K'_a and out-of-phase stiffness $\eta_a K'_a$ where η_a is the loss factor of the added component. K'_a and η_a are determined according to Eqs. 1(a) and 1(b) respectively (Kasai and Fu, 1995).

$$K'_a = \frac{K_b K'_d}{(K_b/\Gamma) + K'_d}, \quad \eta_a = \frac{\eta_d}{\left[1 + (1+\eta_d^2) K'_d/K_b\right]} \quad \text{where } \Gamma = 1 + \frac{\eta_d^2}{(1 + K_b/K'_d)} \qquad (1(a), 1(b), 1(c))$$

Global Rayleigh Damping Model (GRD)

The global Rayleigh damping model is a practical analysis procedure currently being applied to the analysis of VE-frames (Chang *et al.,* 1991). The amount of global damping is based on the modal strain energy method (MSE), originally developed in the aerospace/mechanical engineering field. The GRD approximates the VE-damper as a member having in-phase stiffness only, and the damping provided by the VE-dampers is applied to the entire structure as equivalent viscous damping as illustrated in Fig. 5(a). In-phase stiffness of the added component was determined applying Eqs. 1(a) and 1(b). The brace connected to the VE-damper is relatively stiff compared to K'_d and as a result K'_a is approximately equal to K'_d. The loss factor and K'_d were determined from experimental data for the VE-dampers tested under sinusoidal loading. Equivalent viscous damping ξ_{tot} for the VE-frame was calculated using an energy approach and static analysis (Kasai *et al.*, 1994, Sause *et al.*, 1994) as follows:

$$\xi_{tot} = \frac{\sum \eta_a \cdot F_a \cdot u_a}{2 \sum F \cdot u} \qquad (2)$$

Using Eq. 2, with $\eta_a = 0.93$, ξ_{tot} was calculated to be 12.5%. Dynamic analysis was performed using the MRF finite element model with added braces possessing stiffness K'_a=2.77 KN/cm and applying proportional equivalent viscous damping to the structure. Displacement time history at the roof elevation is compared with the experimental response for El Centro 0.5g in Fig. 6(a). Analytical response envelopes are compared with experimental envelopes in Fig. 7(a).

Local Rayleigh Damping Model (LRD)

Some dynamic analysis programs, such as PC-ANSR, permit stiffness proportional equivalent viscous damping to be applied at the element level. The local Rayleigh damping model (LRD) utilizes this feature to approximate both in-phase and out-of-phase stiffness of the VE-damper as illustrated in Fig. 5(b). In-phase stiffness of the added component was determined by the procedure described above. Out-of-phase stiffness as well as high local damping of the added component are approximated by applying element level stiffness proportional damping to a brace element in the finite element model. The damping coefficient c for a brace element is established proportional to the added component stiffness. The damping coefficient can also be estimated as the out-of-phase stiffness $\eta_a K'_a$ divided by the damped natural frequency ω. Solving for α provides the stiffness proportional damping coefficient:

$$\alpha = \frac{\eta_a}{\omega} \tag{3}$$

Using only the first mode for ω and η_a=.93, α=0.0891. Dynamic analysis was performed using the MRF finite element model with added braces possessing stiffness K'_a=2.77 KN/cm and applying stiffness proportional equivalent viscous damping at the brace element level. Displacement time history at the roof elevation is compared with the experimental response for El Centro 0.5g in Fig. 6(b). Analytical response envelopes are compared with experimental envelopes in Fig. 7(b).

Fractional Derivative Model (FDM)

Actual VE material behavior is very complex and includes frequency, amplitude, and temperature dependent properties. An analytical model which represents nonlinear VE behavior has been developed using a fractional derivative model for the stress-strain relationship (Kasai *et al.*, 1994). Parameters used in the constitutive rule are obtained using experimentally determined values for the material storage modulus and loss factor. The material constitutive rule is integrated in a step-by-step analysis procedure to determine the dynamic response of the VE-damper. At each time step, the amount of energy dissipated and the temperature rise are calculated using thermo-mechanics principles and heat transfer theory. Based on the temperature rise and satisfying the VE temperature-frequency equivalence property, parameters for the constitutive rule are updated at each time step. Continuous updating of the parameters results in a nonlinear constitutive rule. These features have been incorporated into a finite element which can accurately simulate the nonlinear cyclic behavior of a VE-damper, including temperature and excitation frequency effects (Kasai *et al.*, 1994). Linear aspects of this model are illustrated in Fig. 5(c).

Dynamic analysis was performed using the MRF finite element model with added VE elements at each story. Element parameters were determined using the VE material properties from experimental damper response under sinusoidal loading at 28 °C. Displacement time history at the roof elevation is compared with the experimental response for El Centro 0.5g in Fig. 6(c). Analytical response envelopes for the VE-frame are compared with experimental envelopes in Fig. 7(c).

Comparison of Analysis Methods

Each of the methods used to account for the effect of VE-dampers was able to correlate the global experimental response of the structure. One of the characteristics of VE-damped systems is the out-of-phase stiffness contributed by the VE-dampers (Fig. 5). This out-of-phase stiffness results in peak member forces occurring out-of-phase with the peak displacements of the structure. The GRD approximation can not account for this effect, and while the global structural response may be captured, out-of-phase forces and deformations of members and dampers can not be accurately determined because they are assumed to all be in-phase. Corrections for peak member forces are provided by Kasai and Fu (1995). This model has no way of compensating for the temperature rise within the VE-damper and the subsequent effect on the damper performance. Accuracy of the GRD approach is dependent on the estimation of the equivalent viscous damping ratio provided by the dampers.

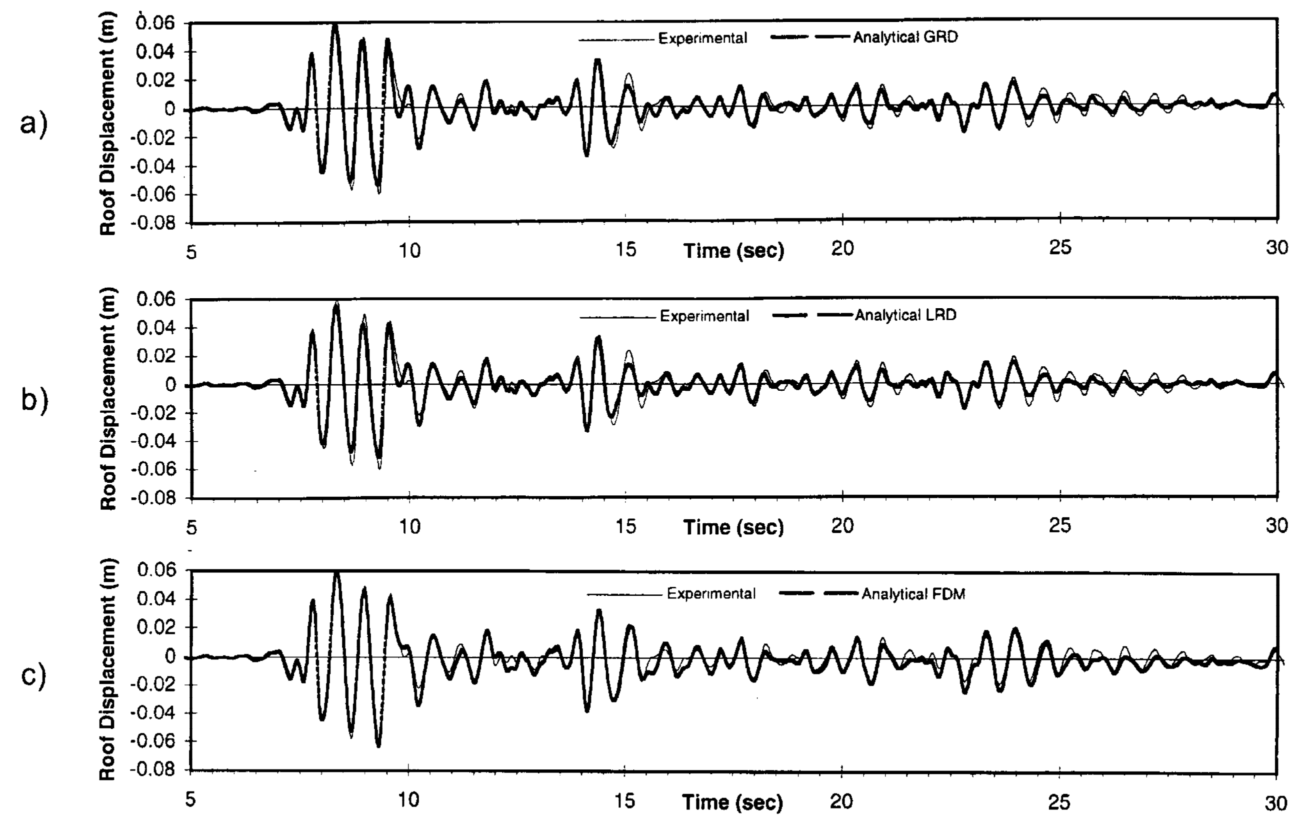

Figure 6. Response at roof of VE-damped frame for 0.5g El Centro, (a) GRD, (b) LRD, and (c) FDM damper models.

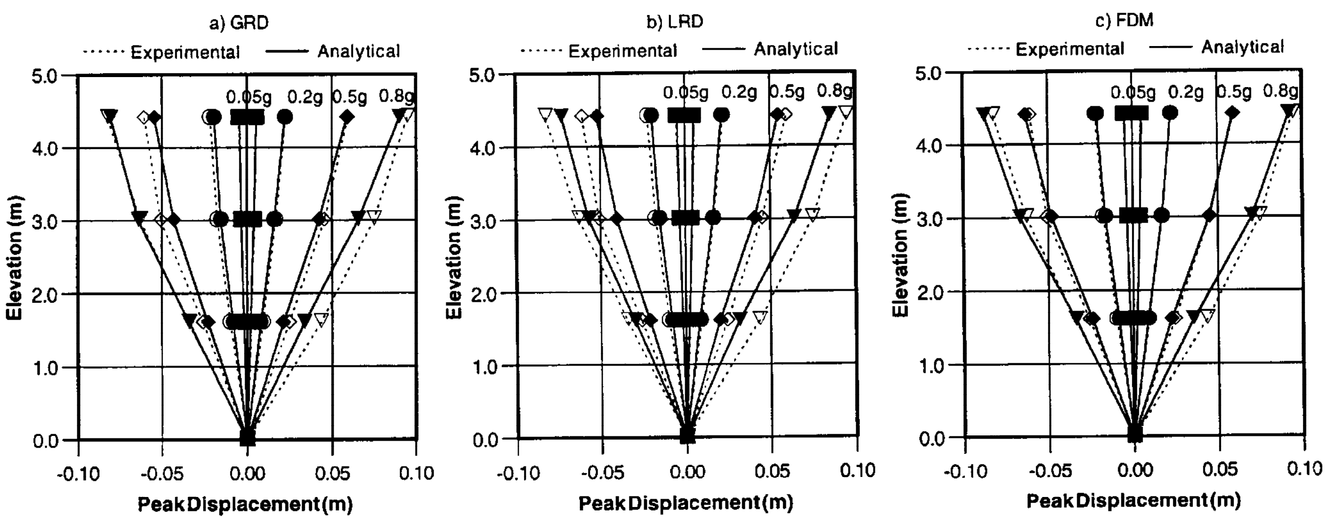

Figure 7. Peak displacement envelopes for (a) GRD, (b), LRD, and (c) FDM VE-damper models.

The local Rayleigh damping model is able to capture the global response of the structure and predict out-of-phase forces and deformations of members and dampers. Applying stiffness proportional damping to brace elements enables modeling of the out-of-phase stiffness response of the VE-dampers. This model also has no way of compensating for the temperature rise within the VE-damper. Accuracy of the LRD approach is dependent on the estimation of the local equivalent viscous damping ratio. The limitations of the GRD and LRD methods resulted in more significant errors in global response and member force estimates at larger excitations.

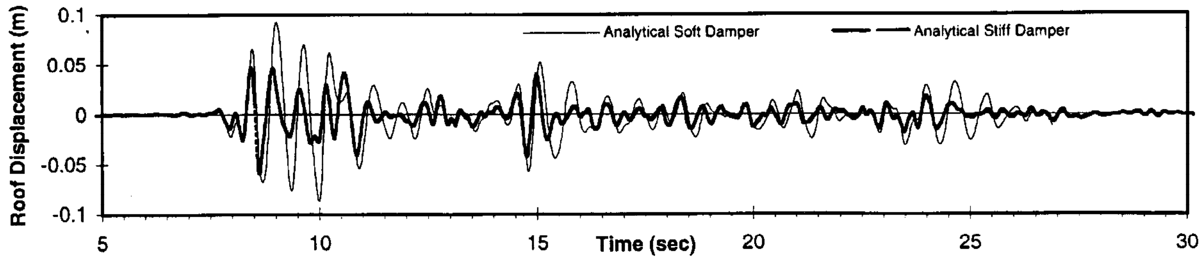

Figure 8. Analytically predicted response at roof for VE-frame with soft and stiff dampers at 0.8g El Centro.

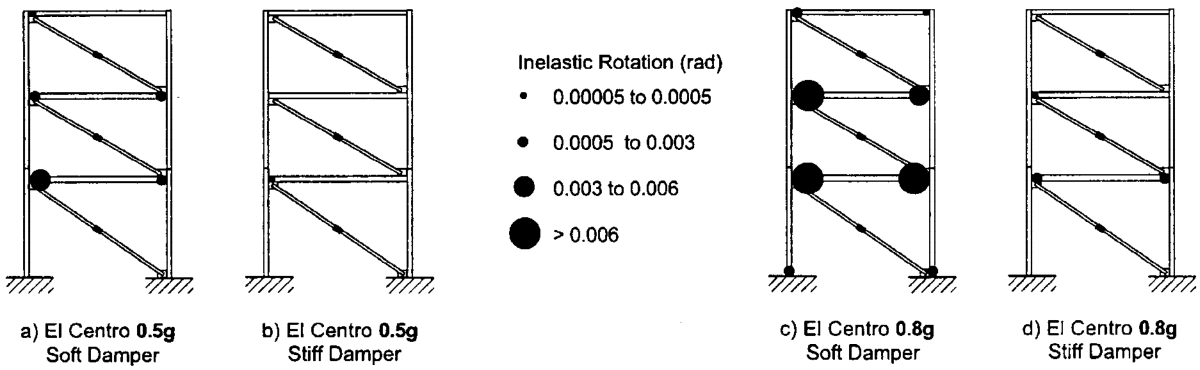

Figure 9. Analytically predicted inelastic rotations for VE-frame with soft and stiff damper subjected to 0.5g and 0.8g El Centro.

The fractional derivative model was the most sophisticated and computationally intensive model used to correlate the response of the VE-frame. The advantage of this model is the ability to account for temperature rise within the dampers in addition to both the in-phase and out-of-phase stiffness characteristics. Damper response predicted by the FDM is dependent on sinusoidal loading response of the VE-material at varying frequency, temperature, and amplitude. This information is generally available from the manufacturer of the VE-material.

PROPOSED REDESIGN OF VE-FRAME UTILIZING STIFF DAMPER

The soft damper design used in the shaking table experiments resulted in significant reductions in building drift and inelastic ductility demand at large excitations compared to the MRF without dampers, however, damper deformations became quite large. Application of a stiff damper design concept can result in even smaller drifts, reduce member forces, reduce damper deformation demand, and keep the structure elastic until larger excitations.

Following the procedure outlined by Kasai and Fu (1995), the VE-frame is redesigned utilizing a stiff damper design. The new dampers are three times as stiff compared to the original soft dampers and provide an equivalent viscous damping ratio of 21%. Dynamic analysis was performed using the MRF finite element model with the new stiff VE-damper elements at each story. Displacement time history at the roof elevation of the redesigned VE-frame is compared with the analytical response for the soft damper VE-frame subjected to El Centro 0.8g in Fig. 8. The stiff dampers reduced the positive drift by 49%, negative drift by 32%, damper demand up to 52%, and resulted in only limited damage to the frame. Figure 9 compares the effect of soft and stiff VE-dampers on the inelastic ductility demand of the VE-frame.

CONCLUSIONS

Experimental results from a shaking table study of a 2/5 scale three-story steel moment resisting frame with and without VE-dampers were correlated analytically using three different approaches. Analytical methods used to model the effect of the VE-dampers included a global Rayleigh damping model, a local Rayleigh damping model, and a fractional derivative model. The analyses included nonlinear inelastic behavior of the members and correlation of the frame response into the inelastic range.

Results indicated all three methods are capable of capturing the global displacement response of the VE-frame. Only the LRD and FDM are able to model the out-of-phase stiffness of the dampers. As a result, the GRD method requires correction for local member forces. Only the FDM is able to model the temperature rise of the dampers. Limitations of the LRD and GRD methods resulted in more significant errors for the larger earthquake ground motions.

The soft VE-dampers used in the experiment provided significant reductions in building drift for all levels of excitation compared to the MRF without dampers. VE-dampers were also effective in reducing the inelastic ductility demand at larger excitations. While the soft dampers resulted in significant reduction in response, application of a stiff damper resulted in even better seismic performance. The proposed redesign using a stiff damper significantly reduced frame drifts, damper deformation demand, and inelastic ductility demand of the structure even when subjected to a catastrophic earthquake (El Centro PGA 0.8g).

Additional work is currently under way at Lehigh University to test the bottom 3-story portion of a 10 story full-scale VE-damped steel frame. The purpose of this full-scale experiment is to provide test data to verify various analytical conclusions as well as design concepts recently developed at Lehigh University.

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