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IMPROVED LINEAR PROCEDURES FOR ANALYSIS OF STRUCTURES WITH PASSIVE ENERGY DISSIPATION DEVICES

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SUMMARY

Passive energy dissipation devices are used to reduce the damaging effects of earthquakes. These devices can absorb a portion of the earthquake-induced energy in structures and thus reduce the energy demand on structural members. Wide acceptance of these devices in structures will depend on the availability of simplified methods for their analysis and design. The objectives of this study are to: 1) investigate the effect of increased viscous damping on the seismic response of structures; 2) assess the accuracy of the linear static and linear dynamic procedures recommended in the NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273) for the design of structures with velocity-dependent passive energy dissipation devices; and 3) propose modifications to the current design procedures to improve their accuracy and reliability. Based on the analysis of single-degree-of-freedom structures under an ensemble of earthquake records, it is shown that the effect of increased damping on the displacement response is more pronounced in structures with intermediate periods. For long-period structures, however, an increase in damping decreases displacements, but increases the absolute accelerations and, consequently, the seismic forces. The study also identifies the following limitations of the FEMA 273 procedures: 1) the use of a constant reduction factor for the displacement response of short-period structures; 2) the assumption of a harmonic response to compute the peak velocity; and 3) the computation of design forces based on the assumption that the structure undergoes a harmonic motion with an amplitude equal to the peak displacement and a frequency equal to that of the fundamental mode. In most cases, these assumptions result in non-conservative estimates of the peak response and design force. Comparisons of the methods proposed in this study and in FEMA 273 indicate that the former produces more reliable results.

INTRODUCTION

Supplemental dampers, also known as passive energy dissipation devices, can absorb a portion of earthquake-induced energy in the structure and reduce the energy demand on the primary structural members such as beams, columns, beam-column joints, and walls. These devices can substantially reduce the inter-story drifts and consequently, non-structural damage. The NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273) categorize these devices according to their mechanical behavior as: 1) displacement-dependent devices where the force-displacement response characteristics are primarily a function of the relative displacement rather than the relative velocity between the ends of the device; 2) velocity-dependent devices where the force-displacement response characteristics are primarily a function of the relative velocity between the ends of the device or the frequency of motion; and 3) other devices that cannot be classified as either displacement- or velocity-dependent.

Wide acceptance of passive energy dissipation devices in structures will depend on the availability of simplified methods for their analysis and design. FEMA 273 guidelines present linear static and dynamic procedures, as well as the more sophisticated nonlinear static and dynamic procedures, for the analysis of rehabilitated structures incorporating these devices. This paper is concerned with investigating the influence of velocity-dependent supplemental dampers on the seismic response of structures, evaluating the accuracy of the linear

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static and dynamic procedures presented in FEMA 273, and proposing modifications to these procedures for the analysis of structures with velocity-dependent dampers.

The paper briefly reviews studies on the influence of supplemental viscous damping on the seismic response of structures, as well as methods of analysis and design presented in recent seismic codes and provisions. Analyses of several single-degree-of-freedom (SDOF) structures with different damping ratios under a large number of earthquake excitations are carried out. The results of the statistical analysis are used in developing linear static and dynamic procedures for the design of structures with linearly elastic behavior and velocity-dependent dampers. The method proposed in this study is compared with that recommended in FEMA 273 and with time history analyses to illustrate the accuracy of the proposed method.

PREVIOUS WORK AND SEISMIC PROVISIONS

The influence of increased viscous damping on the seismic response of structures has been studied by a number of investigators. Newmark and Hall (1982) presented the effect of damping ratio, β, in the range of 0.5 % to 20 % on the median amplification in the three spectral regions (acceleration, velocity, and displacement). Their results indicated reduced amplifications for increased damping. The effect of inherent and supplemental damping on the earthquake spectral displacement, SD, has been studied by Ashour and Hanson (1987) who proposed a relationship describing the decrease in SD with the increase in β. They used SDOF structures with natural periods, T, from 0.5 s to 3.0 s in increments of 0.5 s, and different damping ratios. The computed spectral displacement for each period was normalized to those for zero and 5 % damping ratios for each record. The results of their statistical analysis led to the introduction of a reduction factor that reflects the decaying pattern of the spectral displacement with the increase in the damping ratio. Wu and Hanson (1989) studied the elastic-plastic response of SDOF systems with large damping and different ductilities. They selected structures with two periods in the acceleration region (T = 0.1 s and 0.5 s), one period in the velocity region (between T = 0.5 s and 3.0 s), and two periods in the displacement region (T = 3.0 s and 10.0 s) with different damping and ductility ratios. The study indicated that the effect of damping on the inelastic response is similar to its effect on the elastic response.

The studies by Newmark and Hall (1982), Ashour and Hanson (1987), and Wu and Hanson (1989) indicate similar conclusions regarding the reductions in earthquake spectral displacements with an increase in viscous damping. No consideration, however, was given to the influence of increased damping on the absolute acceleration response which, as discussed later, is the key parameter for computing the seismic forces and base shears in structures with passive energy dissipation devices.

The NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273) present a method for constructing design spectra for a given damping from the 5 % damped spectra. The procedure is to divide the spectral ordinates in the constant acceleration and constant velocity regions by a factor, B_S and B_1, respectively, corresponding to the specified damping ratio. These factors are based on the recommendations of Newmark and Hall (1982). FEMA 273 also presents the first comprehensive method of analysis and design for structures with passive energy dissipation devices. The guidelines recommend the use of a simplified linear static procedure (LSP) or a linear dynamic procedure (LDP) for structures with linear behavior and with displacement- and velocity-dependent passive energy dissipation devices. In addition, for structures with nonlinear behavior, the guidelines recommend a nonlinear static or a nonlinear dynamic procedure.

The two linear procedures are limited to structures with a framing system, exclusive of the energy dissipation devices, that remains essentially linearly elastic for the expected level of seismic demand. In addition, the effective damping by the energy dissipation devices shall not exceed 30 % of critical in the fundamental mode. The main assumptions of the LSP and LDP can be summarized as follows: 1) use the factors B_S or B_1 to reduce the base shear (LSP) or spectral acceleration (LDP) for 5 % damping; 2) assuming a harmonic response, compute the velocity between the damper ends by multiplying the displacements by the fundamental frequency (LSP) or the modal displacements by the modal frequencies (LDP); and 3) compute design forces as the maximum of the following distinct stages of deformation: at maximum drift, at maximum velocity and zero drift where only the viscous forces in the dampers are applied to the structure, and at maximum floor acceleration where the forces are computed as the sum of the forces at maximum drift times CF_1 and the forces at maximum velocity times CF_2. CF_1 and CF_2 are functions of the effective damping ratio, β_{eff}, such that:

$$CF_1 = cos[tan^{-1}(2\beta_{eff})] \quad \text{and} \quad CF_2 = sin[tan^{-1}(2\beta_{eff})] \tag{1}$$

The procedure presented in FEMA 273 implies that the design forces are computed using the peak restoring forces for displacements that are reduced due to the influence of the supplemental damping. In order to account for the forces in the dampers, a check is performed at the stages of maximum velocity and maximum acceleration where the structure is assumed to undergo a harmonic motion at the fundamental frequency (LSP) or at each modal frequency (LDP) with an amplitude corresponding to the maximum drift.

ANALYSIS

The reduction factors presented by Newmark and Hall (1982), Ashour and Hanson (1987), and Wu and Hanson (1989) can be used to modify the displacement response or drifts of structures with supplemental dampers. They cannot, however, be used to compute the seismic design forces or base shears. The reason is given in the following paragraphs.

For a conventional structure (a structure without supplemental dampers) modeled as a SDOF with mass m, damping c, and stiffness k subjected to an earthquake excitation, the maximum base shear, *V*, is computed as the peak force in the spring which is equal to:

$$V = k|x(t)|_{max} = k\ SD = m\omega^2\ SD = m\ PSA \tag{2}$$

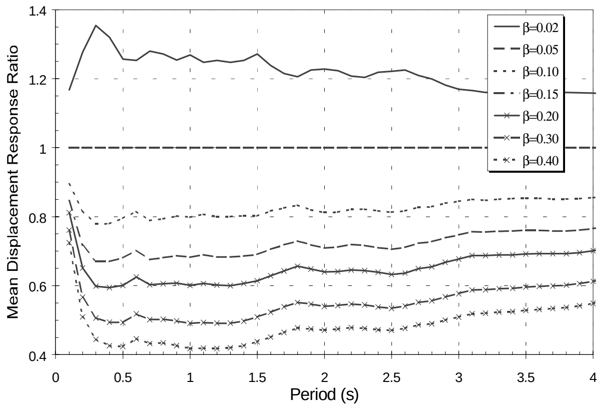
where $x(t)$ is the relative displacement, ω is the natural frequency, and *PSA* is the pseudo-acceleration equal to $\omega^2\ SD$. For the case where the SDOF structure is equipped with a supplemental damper, the base shear is the sum of the forces in the spring and damper. Therefore,

$$V = |kx(t) + c\dot{x}(t)|_{max} = |m\ddot{x}_t(t)|_{max} = m\ SA \tag{3}$$

where *c* in Equation (3) represents the sum of inherent and supplemental damping coefficients and $\ddot{x}_t(t)$ is the absolute acceleration. For this case, The base shear is equal to the mass times the peak absolute acceleration *SA* rather than the pseudo-acceleration *PSA*. It should be noted that, for zero damping, *PSA* is equal to *SA* and for small damping ratios (up to 10 %), the two are approximately equal and may be used interchangeably. For larger damping ratios, however, the difference between *PSA* and *SA* is significant and the pseudo-acceleration cannot be used as the absolute acceleration. Therefore, when computing the base shear for structures with supplemental dampers with large damping ratios, the absolute acceleration response must be used, and the reduction factors presented earlier which are based on the spectral displacement (or pseudo spectral acceleration) can only be used to reduce drifts but not to compute forces.

To investigate the effect of the damping ratio on the relative displacement and absolute acceleration response of structures, linear SDOF systems with periods ranging from 0.1 s to 4.0 s with increments of 0.1 s and damping ratios of 2 %, 5 %, 10 %, 15 %, 20 %, 30 %, and 40 % of critical were considered in this study. The structures were subjected to a set of 72 horizontal components of accelerograms from 36 stations in the western Unites States. The reader is referred to Sadek et al. (1999) for a complete list of these records. The relative displacement and absolute acceleration response ratios are computed as the ratio of the peak response of the structure with different damping ratios to the peak response with a damping ratio of 5 %. The responses were normalized to those for 5 % damping since design spectra in seismic codes are normally presented for this damping. The mean displacement and acceleration ratios for the 72 records are presented in Figures 1 and 2, respectively. The figures show that increasing the supplemental damping results in a further reduction in the displacement response. The effect of damping is more pronounced in the velocity region (structures with mid-range periods). While larger damping ratios provide further reductions in the displacement response, the additional reductions are not significant, moreover, the increased damping adversely affects the absolute acceleration response and consequently, the seismic forces, especially for long-period (flexible) structures.

Since forces in viscous dampers depend on the relative velocity, it is important to study the effect of increased damping on the relative velocity response of structures. In this study, for each record, the peak relative velocity (or spectral velocity), SV, was computed for different periods and damping ratios and divided by the pseudo-velocity, PSV ($PSV = \omega\ SD$). From the mean values of $SV/\omega\ SD$ for the 72 accelerograms, Figure 3, it may be concluded that assuming the peak relative velocity to be equal to the pseudo-velocity (harmonic response) is valid only for periods in the neighborhood of 0.5 s. For shorter periods, the peak velocity is smaller than the pseudo-velocity while for longer periods, the peak velocity is larger and increases as the period and damping ratio increase.



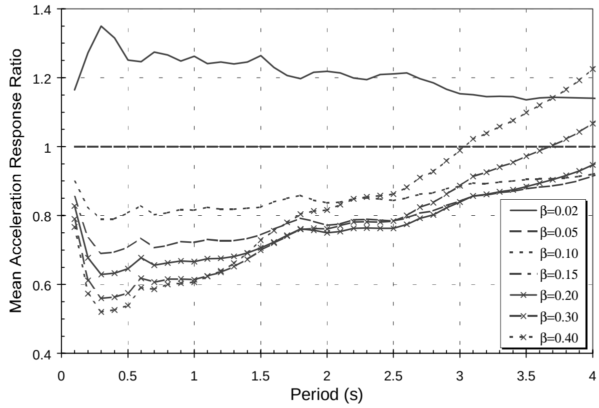
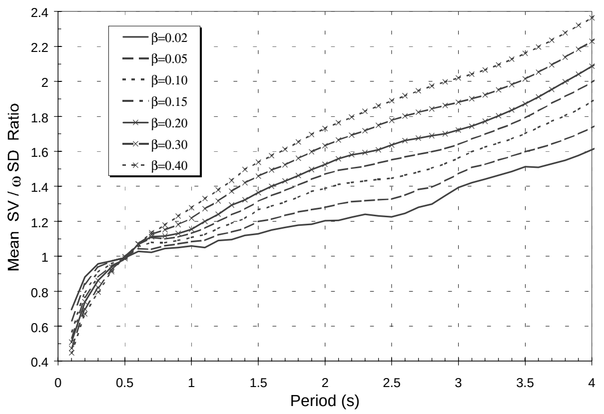


Figure 1. Mean Displacement Response Ratios

Figure 2. Mean Acceleration Response Ratios

Figure 4 presents a comparison of the displacement reduction factors computed from this study and those from the studies by Newmark and Hall (1982) and Wu and Hanson (1989) for damping ratios of 10 %, 20 %, and 30 %. The figure indicates that for the three studies, the reduction factors fall within a narrow range in the mid- to long-period region. Similar to the study by Wu and Hanson (1989), this study shows that, for the short period range (periods less than 0.5 s), the reduction factors vary significantly and are larger for shorter periods. The study by Newmark and Hall (1982) which is used to reduce design spectra in FEMA 273 does not reflect this behavior.



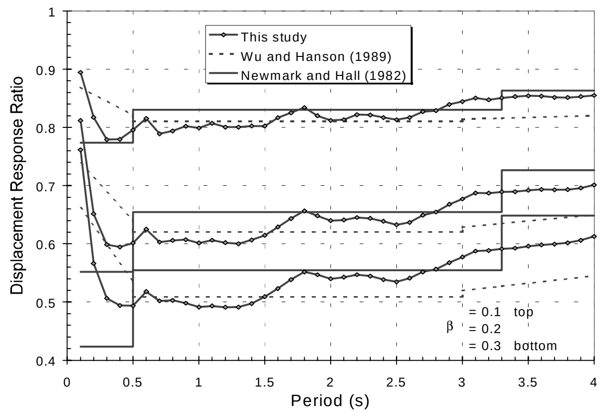


Figure 3. Mean Spectral to Pseudo Velocity Ratios

Figure 4. Comparison between Displacement Reduction Factors Using Different Methods

PROPOSED PROCEDURES

As discussed earlier, computing the story shears from the restoring forces only or assuming the seismic response to be harmonic (i.e. the velocity is equal to the product of natural frequency and displacement) is not accurate, especially for structures with large damping ratios. Based on the analysis presented in the previous section, a more reliable method for design of structures with velocity-dependent supplemental dampers is introduced in this section. The method can be used with the linear static or the linear dynamic procedures.

In the proposed procedure, three damping factors are introduced: a displacement factor, α_d, that can be used to reduce displacements and drifts; a force factor, α_a, that can be used to amplify or attenuate the design forces and base shears; and a velocity factor, α_v, that can be used to compute relative velocities. The displacement, force, and velocity factors, which are based on Figures 1 to 3, can be found in tabular form in Sadek et al. (1999) for selected periods and for the different damping ratios. It should be noted that for small damping ratios (up to 10 %), the displacement factors are very close to the force factors. For large damping ratios, the force factors are larger than the displacement factors. The difference between the two is more pronounced at longer periods. These factors may be used in design as follows: for the structure without supplemental dampers, compute the base shear (LSP) or the spectral acceleration (LDP) from the 5 % damped design spectrum and compute the floor displacements, inter-story drifts, and story shears as usual. Multiply the displacements and drifts by the displacement factor α_d to determine the actual deformations, multiply the story shears by the force factor α_a to compute the actual forces and the base shear, and compute the damper forces as the damping coefficient times the relative velocities which are computed as the product of the relative displacement, natural frequency, and velocity factor α_v.

Although simple, the above method does not explicitly include the contribution of the damper forces in the computation of design forces and base shear. Therefore, erroneous results may be expected especially for multi-story frames with non-uniform distribution of dampers. Consequently, another method is presented in this study. The method is parallel to that in FEMA 273 which includes the influence of the damper forces on the computed design actions directly, thereby accounting for the distribution of the dampers along the height of the building.

The method assumes that the velocity-displacement response in the quadrant having the absolute peak displacement, *SD*, and absolute peak velocity, *SV*, can be approximated by an ellipse. The accuracy of this assumption has been verified using several structures subjected to different earthquake records (see Sadek et al., 1999). The velocity-displacement relationship, thus, can be expressed as:

$$\left(\frac{x(t)}{SD}\right)^2 + \left(\frac{\dot{x}(t)}{SV}\right)^2 = 1 \qquad (4)$$

Maximizing the design force $F(t) = kx(t) + c\dot{x}(t)$ subject to the constraint of Equation (4) will result in the peak forces at the stage of maximum acceleration given as:

$$V = C_1\,k\,SD + C_2\,c\,SV = C_1\,F_d + C_2\,F_v \qquad (5)$$

where F_d and F_v are the forces at maximum drift and velocity, respectively, and C_1 and C_2 are given by:

$$C_1 = \frac{F_d}{\sqrt{F_d^2 + F_v^2}} \qquad \text{and} \qquad C_2 = \frac{F_v}{\sqrt{F_d^2 + F_v^2}} \qquad (6)$$

Thus, the forces at the stage of maximum acceleration will be computed as the sum of the forces at maximum drift times C_1 and the forces at maximum velocity times C_2. Note that when the force at maximum drift has the same direction as the force at maximum velocity, the peak force at maximum acceleration will be equal to $\sqrt{F_d^2 + F_v^2}$.

As Equation (5) indicates, the design forces will include the contributions of the peak restoring forces and peak damping forces. Figure 5 shows the percent contribution of each to the total design forces for damping ratios of 10 %, 20 %, 30 %, and 40 %. The figure indicates that, for small damping ratios, at least 90 % of the design forces are due to restoring forces, while for larger damping ratios, the contribution of damping forces is more significant. This is especially true for long-period structures, due to the effect of increased velocities as indicated by Figure 3.

Proposed Linear Static Procedure (LSP)

Based on the above analyses and discussions, the proposed method for the linear static procedure (LSP) can be summarized in the following steps:

1. Compute the fundamental frequency or period of the structure using any of the methods presented in FEMA 273. Assume an effective damping ratio, β_{eff}, in the fundamental mode and determine the displacement, force, and velocity factors (α_d, α_a, and α_v, respectively) using the computed period and assumed damping ratio.

2. Compute the base shear as the product of the 5 % damped base shear (as given in FEMA 273, Chapter 3) and α_d. Distribute the forces, F_d, along the height of the structure using the method presented in FEMA 273 for conventional structures and compute the design displacements and inter-story drifts.

3. Calculate the effective damping ratio, β_{eff}, using the method outlined in FEMA 273 and iterate on steps 1 through 3 until the desired accuracy is achieved.

4. Compute the velocity between the damper ends as the product of inter-story drift, fundamental frequency, and α_v. Calculate the damper forces as the product of damping coefficient and relative velocity. Estimate the forces acting on the structure at maximum velocity, F_v, due to the damper forces.

5. Compute the design forces at the stage of maximum floor acceleration from Equations (5) and (6). Coefficients C_1 and C_2 will be computed for each story rather than for the whole structure. The final design forces will be selected as the larger of the forces computed at maximum acceleration or at maximum drift (step 2) multiplied by α_a / α_d. This insures that the final design forces are not less than the 5 % damped forces multiplied by the force factors α_a as recommended in the previous section.

Proposed Linear Dynamic Procedure (LDP)

A similar procedure to that of the LSP is recommended for the LDP. The procedure, which uses the response spectrum method, is summarized in the following steps:

1. Perform a modal analysis of the structure with the passive energy dissipation devices to compute the natural frequencies and mode shapes. Select the number of modes to be analyzed and assume an effective damping ratio, β_{eff}, in each mode and determine the displacement, force, and velocity factors (α_d, α_a, and α_v, respectively for each mode.

2. Multiply the 5 % damped spectral acceleration by α_d for each mode and compute the design displacements, inter-story drifts, and story shears.

3. Calculate the effective damping ratio, β_{eff}, using the method outlined in FEMA 273 and iterate on steps 1 through 3 until the desired accuracy is achieved.

4. Compute the velocity between the damper ends as the product of inter-story drift, frequency, and α_v for each mode. Calculate the damper forces as the product of damping coefficient and relative velocity. Estimate the forces acting on the structure at maximum velocity, F_v, due to the damper forces.

5. Compute the design forces for each mode at the stage of maximum floor acceleration from Equations (5) and (6). Coefficients C_1 and C_2 should be computed for each story and for each mode. For each mode, the final design forces are selected as the larger of the forces computed at maximum acceleration or at maximum drift (step 2) multiplied by α_a / α_d.

COMPARISONS

In this section, the analysis procedure proposed in this study is compared with that presented in FEMA 273 using several SDOF structures. Both procedures are compared with the average results of time history analyses using the 72 accelerograms to assess their accuracy and reliability. The three key parameters in the design of a structure with supplemental dampers are the design displacement, design velocity, and design force. For a SDOF structure with period *T*, effective weight *W*, and no supplemental damping, the design base shear is given as (FEMA 273):

$$V_{uncontrolled} = \overline{C}_1 \overline{C}_2 \overline{C}_3 S_a W = aW \tag{7}$$

where $a = \overline{C}_1\overline{C}_2\overline{C}_3 S_a$; S_a is the response spectrum acceleration at the effective fundamental period and damping ratio; and $\overline{C}_1$, $\overline{C}_2$, and $\overline{C}_3$ are modification factors that can be found in Section 3.3.1.3 of FEMA 273. The reader is referred to Sadek et al. (1999) for the details of the derivations of the three design parameters using the LSP (same as LDP for SDOF structures) recommended in this study and in FEMA 273.

Figures 6 - 8 present comparisons between the methods proposed herein and in FEMA 273 for the design displacement, velocity, and base shear, respectively, for structures with periods ranging from 0.1 s to 4.0 s with effective damping ratios of 10 %, 20 %, and 30 %. The figures also show the average results from the time-history analyses. The three figures show the discrepancy between the two design methods (FEMA 273 and this study), especially for larger damping ratios, and indicate the accuracy of the proposed method compared to that in FEMA 273. Figure 6 shows that the two methods give displacements close to each other for periods greater than 0.5 s. For periods shorter than 0.5 s, however, the method presented in FEMA 273 significantly underestimates the displacements. Figure 7 shows that the two methods yield velocities close to each other for periods less than 1.0 s. For periods longer than 1.0 s, the FEMA 273 method gives non-conservative velocities and consequently, non-conservative damper forces. Figure 8 shows that the method presented in FEMA 273 gives erroneous design forces and it does not capture the increase in design forces for structures with long-periods and large damping ratios.

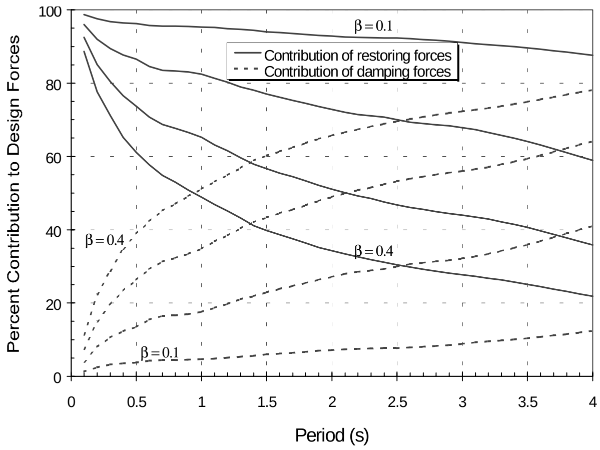


Figure 5. Contribution of Restoring and Damping Forces to Total Design Forces

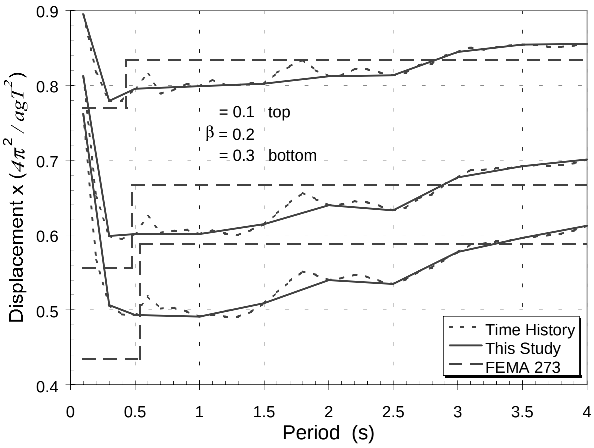


Figure 6. Design Displacement for SDOF Structures

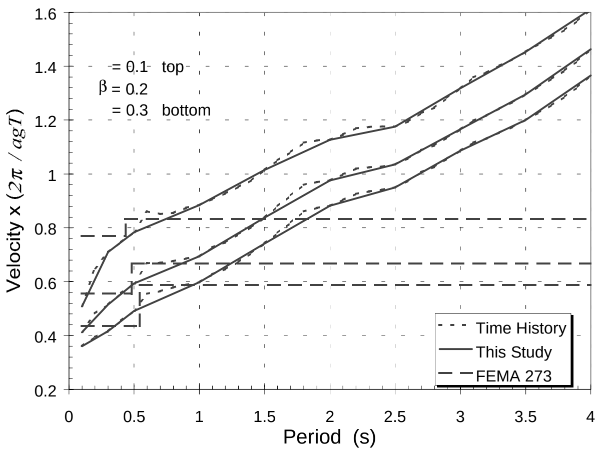


Figure 7. Design Velocity for SDOF Structures

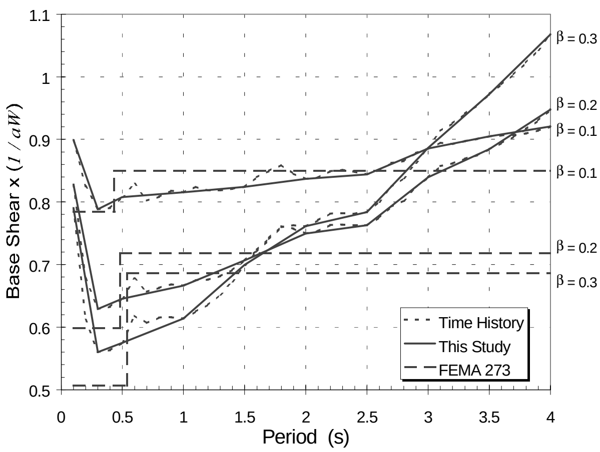


Figure 8. Design Base Shear for SDOF Structures

CONCLUSIONS

The overall objectives of this study were: 1) to investigate the effect of increased viscous damping on the seismic response of structures, 2) to assess the accuracy of the linear static (LSP) and linear dynamic (LDP) procedures recommended by FEMA 273 for designing structures with velocity-dependent passive energy dissipation devices, and 3) to propose modifications to the current design procedures to achieve better accuracy and reliability. The findings of the study can be summarized as follows:

- Increasing damping in structures allows more input seismic energy to be dissipated, which generally reduces the response of structures. The reduction, however, depends on the structural period and the amount of supplemental damping. For example, the effect of damping on the displacement response is more pronounced in the velocity region (structures with periods in the range of 0.3 s to 0.5 s). For long-period structures, an increase in damping further decreases the displacement response, but increases the absolute acceleration response and consequently seismic forces.

- Design forces should include the contributions of the peak restoring forces and peak damping forces. The study indicates that for small damping ratios, approximately 90 % of the design forces are due to the restoring forces, while for larger damping ratios, the contribution of damping forces is more significant. This is especially true for long-period structures, due to the effect of increased velocities.

- The LSP and LDP recommended by FEMA 273 have the following limitations: 1) they use a constant reduction factor for the displacement response in the acceleration region of the spectrum. This assumption can result in a non-conservative design in short-period structures, 2) they assume a harmonic response to compute the peak velocity, i.e., the peak velocity is equal to the pseudo-velocity. This assumption results in accurate velocities, and consequently damper forces, only for structures with periods close to 0.5 s. This study, however, shows that for structures with other periods, the pseudo-velocity should be multiplied by a factor that depends on the structural period and the damping ratio, and 3) they assume that the structure undergoes a harmonic motion with an amplitude equal to the peak displacement and a frequency equal to that of the fundamental (or a given) mode. Consequently, the same coefficients are used in each story to compute the design forces. This study shows that assuming an elliptical peak displacement-velocity response and using different coefficients for each story to compute the design forces is more accurate.

Based on the analysis of SDOF structures subjected to 72 earthquake records, modifications to the LSP and LDP presented in FEMA 273 are recommended. Comparisons between the methods proposed in this study and in FEMA 273 show that the method presented herein is more accurate when compared with the time-history analysis of several structures.

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