ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 11, NO. 4 (2010)
PAGES 509-520

Technical Note

SEISMIC RETROFIT OF EXISTING STRUCTURES USING FRICTION DAMPERS

M.R. Tabeshpour*[a] and H. Ebrahimian[b]
[a]Faculty of Engineering, Sabzevar Tarbiat Moallem University, Sabzevar, Iran
[b]Department of Civil Engineering , Sharif University of Technology, Tehran, Iran

ABSTRACT

Conventional methods of seismic rehabilitation with concrete shear walls or steel bracing are not considered suitable for some buildings as upgrades with these methods would have required expensive and time consuming foundation work. Supplemental damping in conjunction with appropriate stiffness offered an innovative and attractive solution for the seismic rehabilitation of such structures. This paper deals with the use of friction damper as a passive dissipative device in order to seismic retrofit of existing structures and discusses the design criteria and seismic analysis of a building. The structure is modeled using the finite element program Sap2000 and is analysed using both non-linear static pushover analysis and non-linear time history analysis.

Keywords: Friction damper; seismic retrofit; existing building

1. INTRODUCTION

Friction dampers have often been employed as a component of these systems because they present high energy-dissipation potential at relatively low cost and are easy to install and maintain. A friction damper is usually classified as one of the displacement-dependent energy dissipation devices, because its damper force is independent from the velocity and frequency-content of excitations. A friction damper is activated and starts to dissipate energy only if the friction force exerted on its friction interface exceeds the maximum friction force (slip force); otherwise, an inactivated damper is no different from a regular bracing. In this research, a novel friction damper device (FDD), Mualla and Belev [1], which is economical, can be easily manufactured and quickly installed, is presented. It makes use of material that provides very stable performance over many cycles, resists adhesive wear well and does not damage the steel plate surfaces, thus allowing multiple use. This passive control device is designed to dissipate seismic input energy and protect buildings from structural and non-structural damage during

* E-mail address of the corresponding author: tabesh_mreza@yahoo.com (M.R. Tabeshpour)

moderate and severe earthquakes. The effectiveness of the damping system employing such FDDs in 3-story frame is evaluated numerically. Also, a new method for quick design of friction/yielding damping devices is proposed. Then a simplified method for construction of trilinear and bilinrear pushover capacity curves is introduced, in which only the pushover curve of the frame exclusive of damping device is must be determined. So, it make easy for practicing engineers to construct the capacity curve of the building inclusive of damping device and evaluate the performance point of the building by using nonlinear static analysis methods in FEMA 356 [2], or FEMA 440 [3], and also the works of Chopra et. al [4,5]. For a given force and displacement in a damper, the energy dissipation of a friction damper is the largest compared to other damping devices (Figure 1). Therefore, fewer friction dampers are required to provide a given amount of supplemental damping.

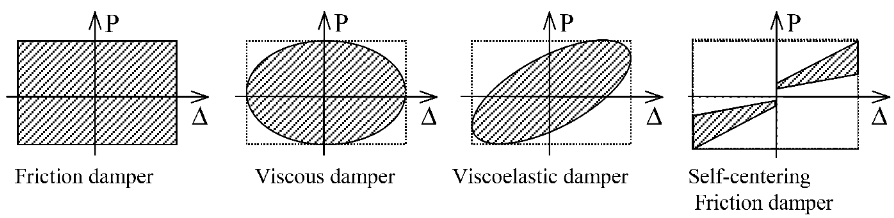

Figure 1. Comparison of hysteresis loops of different dampers

2. DESCRIPTION OF FRICTION DAMPER AND PRINCIPLE OF ACTION

The damper main parts are the central (vertical) plate, two side (horizontal) plates and two circular friction pad discs placed in between the steel. The hinge connection is meant to increase the amount of relative rotation between the central and side plates, which in turn enhances the energy dissipation in the system. The ends of the two side plates are connected to the members of inverted V-brace at a distance r from the FDD centre. The bracing makes use of pretensioned bars in order to avoid compression stresses and subsequent buckling. The bracing bars are pin-connected at both ends to the damper and to the column bases. The combination of two side plates and one central plate increases the frictional surface area and provides symmetry needed for obtaining plane action of the device. When a lateral force excites a frame structure, the girder tends to displace horizontally. The bracing system and the forces of friction developed at the interface of the steel plates and friction pads will resist the horizontal motion. Figure 2 explains the functioning of the FDD under excitation. The device is very simple in its components and can be arranged within different bracing configurations to obtain a complete damping system.

3. ENGINEERING CHARACTERISTICS OF THE NEW TYPE OF FRICTION DEVICE

The damper properties in terms of the structure properties shown in Figure 3, are defined as follows:

$$SR = \frac{K_{bd}}{K_s} = \text{the ratio of damper stiffness to total structure stiffness} \quad (1)$$

$$FR = \frac{F_h}{F_s} = \text{the ratio of damper yield force to total structure force} \quad (2)$$

The equivalent viscous damping is obtained by:

$$\beta = \frac{E_D}{4\pi E_S} = \frac{2}{\pi}\frac{FR \times (SR - FR)}{(SR + FR^2)}, \quad \frac{FR}{SR} < 1 \quad (3)$$

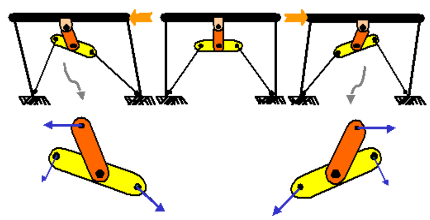

Figure 2. Principle of action of friction damping device

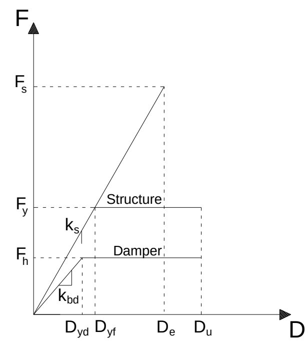

Figure 3. Force deformation for dual system

This formulation facilitates estimating the equivalent viscous damping in a structure based on the various structure and damper parameters that have been described. It is well suited for making a first order estimate of the required damper properties for design.

Because of the nonlinearity inherent in friction devices, it is necessary to perform a nonlinear analysis to verify that the desired response performance of both the structure and device are realized. The relation for β can be used to generate a family of curves as a function of FR and SR as shown in Figure 4. This figure shows some general trends:

The higher the stiffness of the damper relative to the structure, SR, the higher the damping. Practically, it is difficult to achieve values of SR much greater than 1 and so damping of the order of 10% to 15% is a realistic target.

For a realistic value of the stiffness ratio, SR, there is an optimum value of the brace strength to the elastic structure force. This increases causes increasing in stiffness.

For systems with high value of SR ratio, like friction damper systems, the equivalent viscous damping is obtained by:

$$\beta = \frac{E_D}{4\pi E_S} = \frac{2}{\pi}\frac{FR \times \left(1 - \frac{FR}{SR}\right)}{\left(1 + \frac{FR^2}{SR}\right)} \cong \frac{2}{\pi} FR, \quad \frac{FR}{SR} < 1 \quad (4)$$

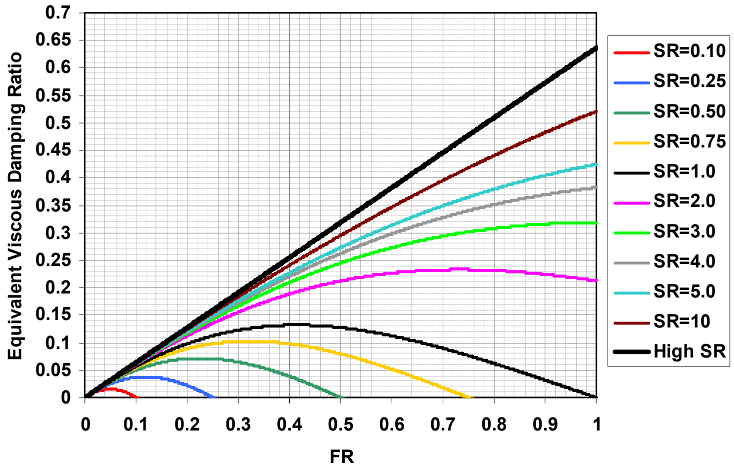

Figure 4. Equivalent viscous damping for dual system

4. REQUIRED STEPS FOR INITIAL DESIGN OF FRICTION DEVICES

The steps for quick estimation of damper properties (slip load and brace section) are described below:

Step 1) Choose desired equivalent additional damping level to be supplied by dissipators, β_{eff} say 15-20%.

Step 2) Calculate the corresponding Spectral Reduction due to damping using the following methods. Equivalent linearization procedures applied in practice normally require the use of spectral reduction factors to adjust an initial response spectrum to the appropriate level of effective damping, β_{eff}. These factors are a function of the effective damping and are termed damping coefficients, $B(\beta_{eff})$. They are used to adjust spectral acceleration ordinates as follows:

$$S_a(T,\beta_{eff}) = \frac{S_a(T,5\%)}{B} \tag{5}$$

$$B = \frac{A_{5\%}}{A_{\beta_{eff}}} \tag{6}$$

ATC 40 proposed the value of Newmark and Hall for constant acceleration and velocity regions of median design spectrum as:

$$A_{a,\beta_{eff}} = 3.21 - 0.68\ln\beta_{eff}(\text{in}\,\%) \;\Rightarrow B_S = \frac{2.12}{A_{a,\beta_{eff}}} \tag{7}$$

$$A_{v,\beta_{eff}} = 2.31 - 0.41\ln\beta_{eff}(\text{in}\,\%) \;\Rightarrow B_1 = \frac{1.65}{A_{v,\beta_{eff}}} \tag{8}$$

Note that if the ATC-40 equations are used, then the limits on the reduction should not be applied. NEHRP 2000 proposed the value of Newmark and Hall for constant velocity regions of median design spectrum as:

$$A_{v,\beta_{eff}} = 2.31 - 0.41 \ln \beta_{eff} (\text{in}\,\%) \;\Rightarrow B_1 = \frac{1.65}{A_{v,\beta_{eff}}} \tag{9}$$

FEMA 356 proposed Table 1-6. FEMA utilizes two factors, one for the constant acceleration region of the response spectrum (Bs) and the other for the constant velocity region of the spectrum (B_1). There are two draw backs in the damping coefficient of FEMA 356:

The value for constant average acceleration region of the spectrum (low periods) are higher than those valid in the constant velocity region. This contradicts the fact that there is little or no reduction of displacement with increasing damping in very stiff structures. It also leads to the erroneous impression that damping systems are most effective when used on stiff structures.

When the damping ratio exceeds 50% of critical, the effect of damping in reducing displacements is ignored leading to very conservative estimates in highly damped buildings.

FEMA 440 proposed the following value with no limits:

$$B = \frac{4}{5.60 - \ln \beta_{eff} (\text{in}\,\%)} \tag{10}$$

This simple expression is very close to equations specified in both the NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures and the ATC-40 document.

Damping coefficients, B, as a function of damping, β_{eff}, from various resource documents are compared in the following Figure 5.

Step 3) The effect of period shifting must be considered. Equivalent linearization procedures applied in practice normally require the use of period shift effect with spectral reduction factors to adjust the equivalent linear system. Therefore we have:

$$\frac{S_a(T_{ed}, \xi_{eq})}{S_a(T_e, \xi_0)} = \frac{S_a(T_{ed}, \xi_{eq})}{S_a(T_{ed}, \xi_0)} \times \frac{S_a(T_{ed}, \xi_0)}{S_a(T_e, \xi_0)} \tag{11}$$

Where, T_e = Elastic period of the system without damping devices

T_{ed} = Equivalent Elastic period of the damped system

ξ_0 = 5% damping ratio = β_0

$\xi_{eq} = \beta_{eff}$

In step 2, the ratio $S_a(T, \xi_{eq})/S_a(T, \xi_0)$ has been determined for all range of periods, so the first term on the right hand side of the above equation is determined. The second term can be interpreted by using the basic idea of Newmark-Hall pseudo acceleration design spectrum as:

$$\frac{S_a(T_{ed}, \xi_0)}{S_a(T_e, \xi_0)} = \left(\frac{T_{ed}}{T_e}\right)^p \tag{12}$$

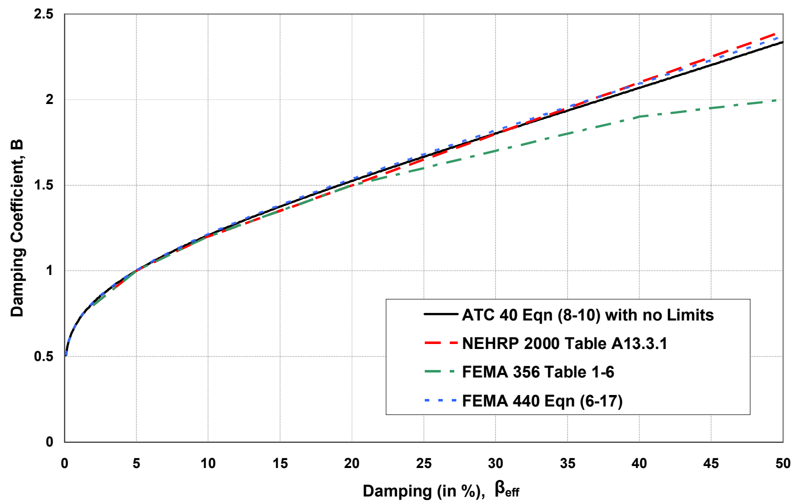

Figure 5. Damping coefficients, b, as a function of damping, β_{eff}, from various resource documents

From the above equation, it can be obtained that the value of index p is larger when the system period is larger and vice versa. Since the equivalent period T_{ed} is always longer than the initial period T_e, the shorter the period, the more significant the increase in spectral acceleration.

A structure without damping would be designed for a code prescribed lateral load equal to:

$$V_y = \frac{W \times S_a(T_e, 5\%)}{R_\mu} \tag{13}$$

For the same structure with equivalent viscous damping system, the actual yield strength will be:

$$V_{yd} = \frac{W \times S_a(T_{ed}, \xi_{eq})}{R_\mu} \tag{14}$$

From step 2 and step 3, it can be concluded that:

$$\frac{S_a(T_{ed}, \xi_{eq})}{S_a(T_e, \xi_0)} = \frac{V_{yd}}{V_y} = \frac{1}{B} \times \left(\frac{T_{ed}}{T_e}\right)^p \tag{15}$$

The damped system elastic period Ted is related to the undamped system (5% damping) on the basis of the following equation:

$$\frac{T_{ed}}{T_e} \approx \left(\frac{I_e}{I_d}\right)^{1/2} \approx \left(\frac{h_e}{h_d}\right)^{3/2} \approx \left(\frac{z_e}{z_d}\right)^{\eta} \approx \left(\frac{V_y}{V_{yd}}\right)^{\eta} \tag{16}$$

Where I_e and I_d are respectively the moment of inertia of the beam and columns of the undamped and damped structures and h and z are section height and section plastic modulus of both structures. η can be taken about 0.45 to 0.65 for wide flange sections and 0.75 for rectangular and 0.66 for square sections. A value of about 0.5 seems to be appropriate.

So, we have:

$$\frac{V_{yd}}{V_y} = \frac{1}{B} \times \left(\frac{V_y}{V_{yd}}\right)^{\frac{p}{2}} \tag{17}$$

For constant acceleration region with p=0, we have:

$$\frac{S_a\left(T_{ed}, \xi_{eq}\right)}{S_a\left(T_e, \xi_0\right)} = \frac{V_{yd}}{V_y} = \frac{1}{B} \tag{18}$$

And for constant velocity region with p=-1, we have:

$$\frac{S_a\left(T_{ed}, \xi_{eq}\right)}{S_a\left(T_e, \xi_0\right)} = \frac{V_{yd}}{V_y} = \frac{1}{B^2} \tag{19}$$

So, we can conclude that:

$$\frac{S_a\left(T_{ed}, \xi_{eq}\right)}{S_a\left(T_e, \xi_0\right)} = \frac{V_{yd}}{V_y} = \begin{cases} \frac{1}{B} & T_e, T_{ed} < T_s \\ \frac{1}{B^2} & T_e, T_{ed} > T_s \end{cases} \tag{20}$$

It must be noted that for an equivalent damping level of about 15% to 20%, the spectral reduction will be about 66% to 72%.in constant acceleration region and about 42% to 52%.in constant velocity region Therefore, as an approximation, the base shear will be reduced from 0.72Vb to 0.65Vb in constant acceleration region and from 0.52Vb to 0.42Vb in constant velocity region by using appropriate damper devices. This can be obtained from Figure 6 in which the base shear reduction as a function of damping is presented.

It must be noted that according to NEHRP 2000, the minimum allowable base shear for design of seismic force resisting system is:

$$V_{\min} = \frac{V}{B} \geq 0.75V \tag{21}$$

The limit 0.75V typically dictates the minimum strength of a building with about 15% damping. From the previous study, it can be obtained that this level of base shear reduction is very conservative. When the design of the seismic force resisting system is based on plastic analysis behavior, the required base shear strength is needed. So, we have:

$$V_y = V_{min} \Omega_0 \frac{C_d}{R} \tag{22}$$

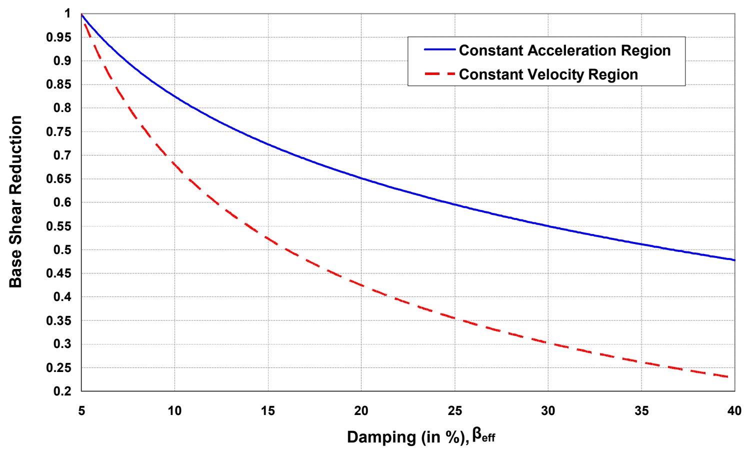

Figure 6. Base shear reduction as a function of damping, β_{eff}

The ratio Cd/R is used because of inconsistency in the values of Cd and R. It is important to note that for special moment resisting frame buildings with Cd=5.5 and R=8, we have:

$$0.75 \times \frac{5.5}{8} = 0.52 \tag{23}$$

Step 4) Calculate corresponding spectral reduction factors using Step 2 and 3. Hence determine equivalent static loads to be applied to structure. Apply these loads to the dual system consisting of frame and braces of damping device. (The stiffness of the damping system is considered here.)

The example special moment resisting frame in section 6, which meets the design criteria of NEHRP 2000, is designed for 0.75 design base shear. The frame exclusive of damping system does not meet the drift criteria and damping system must be added to meet the drift criteria. The pushover curve of the frame without damping device designed for 0.75V is shown in the next section. As indicated, the base shear strength ratio of the frame without damping device designed for 0.75V to the base frame is about 0.5. From the story shear strength of the frame and using Figure 4, the preliminary design of the friction devices consisting of slip load in each story and brace stiffness can be obtained. It must be noted that the brace stiffness can be determined after selecting an appropriate damping device.

A fast and reliable design methodology is presented in the above steps. After the preliminary design of frame with damping devices, the simplified pushover analysis is needed for verification of the design results. A summary of these steps are:

- Choose β_{eff} about 15-20%

- Calculate spectral reduction due to damping
- The effect of period shifting must be considered.
- Design the frame exclusive of damping devices
- Evaluate friction damper slip load for each story
- Choose an appropriate damping device (Friction Damper)
- Evaluate damper stiffness for each story considering that Braces must remain elastic with no Buckling and Dissipated energy in devices to be maximum

5. INITIAL DESIGN OF FRICTION DEVICES FOR EXAMPLE FRAME

Frames with damping systems may be designed in accordance with NEHRP 2000 for a seismic base shear strength not less than $0.75V_{y,min}$ where $V_{y,min}$ is the seismic base shear strength of the frame without a damping system according to the NEHRP 2000 code. The 3 story SMRF has the period of 1.6151 sec and a seismic base shear of 76.94 kips. The frame exclusive of damping system does not meet the drift criteria. So, damping system must be added to meet the drift criteria.

By using the chart and the formulas in section 4, for A_b, and assuming the bar material $E=29000Ksi$ and $F_y=50Ksi$, we have design procedure indicated as follows:

SR is in most of real cases equal or greater than 1.0. According to Figure 4, a value of FR equal to 0.30 seems to be sufficient to have an equivalent viscous damping of about 15% to 20%. With reference to Table 1, we have:

Table 1: Story shear strength and damper slip loads

Parameter	**1st Story**	**2nd Story**	**3rd Story**	**Total Structure**
V_y (Kips)	270.08	173.19	80.44	234.44
$0.30V_y$ (Kips)	81.02	51.96	24.13	70.33

The slip load of dampers in each story will be as follow:

$$V_{d1} = F_{h1} = 70\,\text{Kips} \tag{24}$$

$$V_{d2} = F_{h2} = 50\,\text{Kips} \tag{25}$$

$$V_{d3} = F_{h3} = 25\,\text{Kips} \tag{26}$$

Equations (27) and (28) give values for A_b. The larger of these two (typically the latter) must be used. These two equations are:

$$A_{b1} = \frac{M_f}{\sigma_y h_a \cos v} \tag{27}$$

$$A_{b2} = \frac{M_f l}{h_a E D_u \cos^2 v} \tag{28}$$

The values for Ab1 and Ab2 are shown in Table 3.

From the yield point of each story listed in Table A4-1, and using the brace stiffness of each story, the SR ratio can be obtained by using the following Table 4:

Now, we can construct the SR-FR-βeff diagram for the values of SR equal to 1.50 and 2.0 as shown in Figure 7.

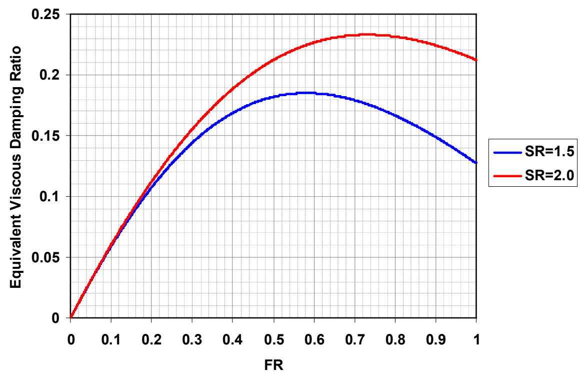

Figure 7. Equivalent viscous damping for 3 story frame

6. SIMPLIFIED METHOD FOR CONSTRUCTION OF PUSHOVER CURVE FOR BUILDING WITH FRICTION DEVICES

The following methodology is used to construct the pushover curve of buildings with friction devices. The frame in section 6 is reanalyzed be considering the new type of friction devices. The slip load and brace area are determined previously and the total system will be modeled in SAP2000. Figure 8 shows a schematic view of the 3 story frame building.

The pushover curve of the frame with and without damping system are shown Figure 9.

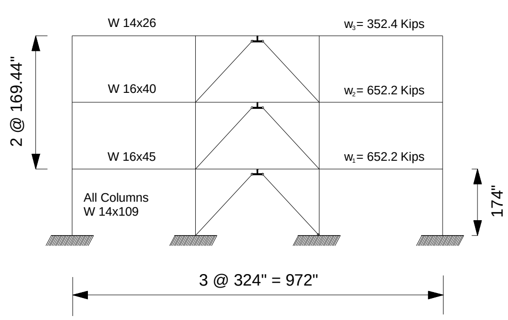

Figure 8. Three-story frame with damping device

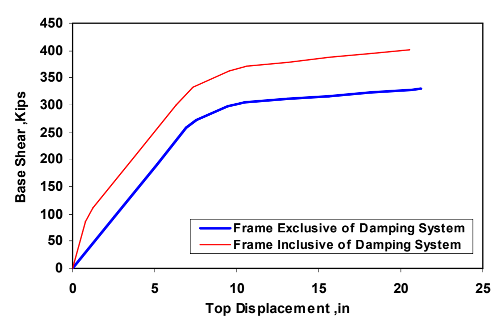

Figure 9. Pushover curve of the frame with and without damping system

7. DISPLACEMENT MODIFICATION METHOD FOR ANALYSIS AND DESIGN OF BUILDING WITH FRICTION DEVICES

A summary of target displacement method in details extracted from FEMA 356 is shown on the next pages. Modification factor to relate the expected maximum displacements of an inelastic SDOF oscillator with EPP hysteretic properties to displacements calculated for the linear elastic response is introduced in FEMA as coefficient C1. The large NLRH analysis for structures with damping systems permitted as re-evaluation of coefficient C1.

$$C_1 = \frac{D_u}{D_{elastic}} = \frac{\mu \cdot D_y}{D_{elastic}} = \frac{\mu}{R_\mu} \tag{29}$$

The Mander et al. (1984) relationship has been implemented in FEMA 356 as described below:

$$C_1 = \begin{cases} \frac{1}{R_\mu}\left[1 + (R_\mu - 1)\left(\frac{T_S}{T_e}\right)\right] & T_e < T_S \\ 1 & T_e \geq T_S \end{cases} \tag{30}$$

FEMA 440 has modifications on this coefficient. The FEMA 356 guidelines for target displacement method and its improvement from FEMA 440 are given in the following pages.

Coefficient C1 relates to the ductility based portion of the R-factor and the elastic period. Of interest is a relation for the coefficient C1 , which has the form:

$$C_1 = \psi(\alpha, T_e, T_S, \beta_{eff}, R_\mu) \tag{31}$$

Now, according to the above explanations, for the 3 story frame building with friction dampers, the performance point will be evaluated as follows:

By using FEMA 356:

$$C_0 \cong 1.4 \ , \ C_1 = 1.0 \ , \ C_2 = 1.0 \ , \ C_3 = 1.0 \ , \ T_e = T_{11} = 1.346\,\text{sec} \tag{32}$$

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g = 1.40 \times \frac{0.6}{1.346} \times \frac{1.346^2}{4\pi^2} g = 11.0'' \tag{33}$$

By using FEMA 440:

$$R = \frac{S_a W}{V} = \frac{\frac{0.6}{1.346} \times 0.8 \times 1656.8}{356.12} = 1.66 \tag{34}$$

$$C_1 = 1 + \frac{1.66 - 1}{60 \times 1.346^2} = 1.0 \ , \ C_2 = 1 + \frac{1}{800}\left(\frac{2.074 - 1}{1.346}\right)^2 = 1.0$$

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g = 1.00 \times \frac{0.6}{1.346} \times \frac{1.346^2}{4\pi^2} g = 8.0'' \tag{35}$$

8. CONCLUSION

In this paper a conceptual view on retrofit design on existing buildings using an innovative friction damper (proposed by Mualla IH) is presented. A simple design procedure can be used in seismic design of friction dampers based on the structural desired performance. As an example a 3-story steel structure that its strength and stiffness is not sufficient for desired performance is considered. The simple performance based method presented in FEMA is used to determine the slip load and bracing stiffness.

REFERENCES

1. Mualla IH, Belev B. Performance of steel frames with a new friction damper device under earthquake excitation, *Engineering Structure*, **24**(2002) 365-71.
2. FEMA 356, Prestandard and commentary for the seismic rehabilitation of buildings. Report FEMA 356, Federal Emergency Management Agency, Washington DC, 2000.
3. FEMA 440, Improvement of nonlinear static seismic analysis procedures. Report FEMA 356, Federal emergency management agency, Washington DC, 2005.
4. Goel RK, Chopra AK. Evaluation of modal and FEMA pushover analyses: SAC buildings, *Earthquake Spectra,* No. 1, **20**(2004) 225–54.
5. Chopra AK, Goel RK, Chintanapakdee C. Evaluation of a modified MPA procedure assuming higher modes as elastic to estimate seismic demands, *Earthquake Spectra,* No. 3, **20**(2004) 757–78.
6. Applied Technology Council (ATC). Seismic evaluation and retrofit of concrete buildings. Volumes 1 and 2. Report no. ATC-40, Redwood City (CA), 1996.
7. Soong TT, Spencer BF. Supplemental energy dissipation: state-of-the-art and stateof-the-practice, *Engineering Structures*, **24**(2002) 243-59.
8. NEHRP, Recommended provisions for seismic regulations for new buildings and other structures. Federal Emergency Management Agency, Washington DC, 2000.