

## Improved Performance of Friction Damped Asymmetric Structures

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### ABSTRACT

In recent years, various studies have confirmed the effectiveness of employing friction damped bracing to control the seismic response of symmetric moment resisting structures. For asymmetric structures, however, additional factors need to be considered to achieve similar benefits from such devices. In this paper, the need to tune the devices with regard to the distribution of their slip load on opposite sides of the structure is examined. Based on the parametric study of a single-storey structural model, it is demonstrated that maximum seismic response can be further reduced. This is achieved by distributing the slip load of the friction damped bracing to create a strength eccentricity for the latter equal in magnitude, but of opposite sign, to that of the elastic stiffness of the structure.

### INTRODUCTION

In 1982, Pall and Marsh introduced a novel approach for the aseismic design of steel framed buildings which comprised the use of friction dampers in tension cross-braces to absorb the seismic energy input. Subsequent studies have demonstrated the good performance of these in symmetric frame structures subjected to strong earthquake excitation (Filiatrault and Cherry 1988, 1989). This comprised the use of friction devices placed in the tension cross-bracings on opposite sides of these structures. For asymmetric structures, Pekau and Guimond (1991) showed that it was necessary to tune the friction damped braces with respect to both the stiffness of the braces as well as the slip load of the devices in order to achieve optimized seismic response. The resulting design approach, therefore, consisted of introducing friction damped braces in direct proportion to the unbraced frames in which they are to be installed.

Since the lateral-torsional coupling of asymmetric structures places severe demands on the edge elements, a structural strategy which further reduces the response of these elements is obviously desirable and is therefore examined in this study. This consists of determining the best plan-wise distribution of the slip load of the friction devices, as well as the effect of a similar redistribution of the stiffness of the braces containing these devices. In a parametric investigation employing a single-storey structural model and an ensemble of earthquake records, determined first is that maximum improvement in seismic performance is achieved when the slip load of the friction dampers is distributed so that the strength eccentricity of these devices equals the negative of the structural stiffness eccentricity; namely  $e_{pb} = -e_s$ . Also determined is the condition that the corresponding stiffness redistribution results in  $e_{sb} = -e_{sf}/2$ , although this produces only marginal improvement over  $e_{sb} = 0$ , where  $e_{sf}$ ,  $e_{sb}$  are the stiffness eccentricities of the unbraced frames and cross-braces, respectively.

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## DESCRIPTION OF PARAMETRIC STUDY

### Structural Modelling

The single-storey structural model of Fig. 1 is similar to that employed by Pekau and Guimond (1991) and consists of a rigid floor deck of mass  $m$  supported by two elasto-plastic planar frames (elements 1,2) equipped with friction dampers (elements 3,4). The deck has dimensions  $D_n = 3\rho$  and  $D = \sqrt{3}\rho$ , where  $D_n$  = dimension perpendicular to the excitation,  $D$  = dimension parallel to the excitation, and  $\rho$  is the mass radius of gyration about the center of mass CM. Symmetry about the  $x$ -axis is assumed so that only two degrees-of-freedom are required to define the structural response to a  $y$ -direction earthquake, namely displacement along  $y$  and rotation  $\theta$  about a vertical axis through CM.

Structural eccentricity  $e_s$  is created between the center of elastic stiffness CS and CM by distributing the total stiffness of the structure between the braced frames, while maintaining CM at the geometric centroid and locating the frames symmetrically about the  $y$ -axis. By definition,  $e_s$  is expressed as

$$e_s = \frac{1}{K_y} \sum_i k_{iy} x_i \quad (1)$$

where  $K_y$  is the total lateral stiffness and  $k_{iy}$  and  $x_i$  are, respectively, the individual stiffnesses and distances from CM of the two resisting braced frames. In generating data employing the model of Fig. 1, the eccentricity  $e_s$  is normalized with respect to  $\rho$  about CM, i.e.

$$e_s^* = \frac{e_s}{\rho} \quad (2)$$

In order to evaluate the lateral-torsional dynamic response of the structure, the static plastic eccentricity is required. Defining the center of resistance CR of a structure as that point along the deck where the application of a load of sufficient magnitude causes simultaneous yielding of all resisting elements, the distance between CR and CM may be defined as the strength eccentricity or plastic eccentricity  $e_p$  given by

$$e_p = \frac{1}{R_y} \sum_i R_{yi} x_i \quad (3)$$

where  $R_y$  represents the total resistance of the structure and  $R_{yi}$  denotes the yield resistance of the individual elements. Yielding of the resisting elements is ensured by restricting the yield capacity of the unbraced structure to a suitable level below the maximum elastic seismic force  $R_{elastic}$ . Based on the corresponding elastic symmetric structure for  $R_{elastic}$  and the force reduction factor  $R$ , resistance  $R_y$  is obtained as

$$R_y = R_{elastic} / R \quad (4)$$

where  $R = 4.0$ , which represents the maximum reduction factor for structures demonstrating a high level of ductility according to the 1990 NBCC.

Analogous to equation (2), static strength eccentricity  $e_p$  is also normalized with respect to  $\rho$  to yield

$$e_p^* = \frac{e_p}{\rho} \quad (5)$$

Note that subscripts 'f' and 'b' will be attached to  $e_s$  and  $e_p$  throughout this study in order to differentiate between eccentricities that apply solely to the frames or braces, respectively, and those of the total system.

The coupled response of the structure is influenced by the uncoupled torsional to lateral frequency ratio defined as

$$\Omega_o^2 = \omega_{\theta o}^2 / \omega_y^2 \quad (6)$$

where

$$\omega_{\theta o} = (K_{\theta s} / m \rho^2)^{1/2}; \quad \omega_y = (K_y / m)^{1/2} \quad (7)$$

in which  $K_{\theta s}$ , is the torsional stiffness about CS.

#### Values of Parameters and Seismic Input

Since friction dampers are deemed to be most beneficial to multi-storey structures of intermediate height, lateral period of vibration of  $T = 1.0$  sec is adopted, with torsional to lateral frequency ratio  $\Omega_o = 1.0$  to represent the critical condition for lateral-torsional coupling in elastic structures. Five percent viscous damping and a time step of  $\Delta t = 0.1$  sec are employed in the dynamic analysis using the computer program DRAIN-2D (Kanaan and Powell, 1973).

Based on existing results from tuning of friction damped bracing in asymmetric structures (Pekau and Guimond, 1991), the ratios of total bracing to total frame stiffness and strength are set to the previously obtained values for optimized response, namely  $KB / KF = 10.0$  and  $RB / RF = 1.0$ , respectively. With these ratios constant, asymmetric structures with six eccentricities over the range  $e_s^* = 0 - 1.2$ , and based on the foregoing structural model, are studied. To incorporate frequency dependence of response, each asymmetric structure is subjected to four earthquake records (1940 El Centro N-S; 1952 Taft S69E; 1977 Romania N90W; and the Newmark-Blume-Kapur artificial excitation). Figure 2 shows the acceleration time histories for this ensemble.

Results demonstrating the improvement in performance achieved by the proposed redistribution of the strength and stiffness of the friction damped bracing are presented in the following. Here, the response is generally presented as maximum edge displacement of the structure normalized with respect to the maximum edge displacement of the corresponding unbraced symmetric structure, i.e. in terms of  $y_{max} / y_{max}(e_s=0, KB=0)$ .

## DISCUSSION OF RESULTS

#### Distribution of Slip Load

With  $RB / RF = 1.0$ , the total slip load required for the braces is therefore determined as the sum of the strengths of the frames. The distribution of this total between the braces is represented by the magnitude of the slip load eccentricity  $e_{pb}$  (or  $e_{pb}^*$  in the data). Variation of this parameter over the range  $-1.5 \leq e_{pb}^* \leq 1.5$  is achieved by increasing the slip load on one side of the structure and simultaneously decreasing it on the other, while maintaining  $RB / RF = 1.0$  for the overall system.

Figures 3-5 depict the improvement in seismic performance to be expected by optimizing the distribution of the slip load for unbraced structures with coincident centers of elastic stiffness and strength (i.e.  $e_{pf} = e_s$ ). Figure 3 shows a reduction in maximum edge displacement as the center of resistance of the braces moves from the stiff to the flexible side of the structure. In general, minimum edge displacement is achieved when the slip load eccentricity  $e_{pb}$  equals  $-e_s$ . Thus, the optimum response occurs when the eccentricity in slip load distribution equals that of the elastic stiffness of the structure, but on the opposite side of the structure. Closer examination of the data of Fig. 3, however, indicates that an acceptable distribution for design is one in which equal slip loads are assigned to the friction braces (i.e.  $e_{pb} = 0$ ), regardless of the eccentricity  $e_s$ . This approach is seen to yield displacements that are not

much above the lowest response for  $e_s^* < 0.75$ , while for  $e_s^* > 0.75$  it still limits the maximum response to below that of the corresponding symmetric structure.

Figure 4 examines the above increase in structural performance by comparing with the response obtained for an asymmetric structure if designed according to the practice for symmetric structures. The latter consists of setting the slip load of the friction damper equal to the strength of the frame in which it is located. This corresponds to the case  $e_{pb} = e_s$  of Fig. 4. It is seen that dramatic reductions in the edge response of the single storey model are achieved with the proposed redistribution of the slip load. Compared to that for  $e_{pb} = e_s$ , the response for  $e_{pb} = -e_s$  is reduced over the entire range of stiffness eccentricity  $e_s^*$ , with a maximum reduction of over 70 percent for  $e_s^* = 1.2$  (i.e.  $e_s = 0.4 D_n$ ). For the 'practical design' distribution of  $e_{pb} = 0$ , the corresponding maximum reduction in response is approximately 45 percent.

Plotting the ductility demand reveals a similar trend as the above for this response parameter with redistribution of slip load (ductility demand is defined as the ratio of maximum displacement to yield displacement). Figure 5 shows the ductility demand for the frames on the stiff and flexible sides of the model. As is seen, the ductility demand decreases with increase in  $e_s$  on the stiff side, and increases with increase in  $e_s$  on the flexible side. More importantly, however, the ductility demand with variation of slip load distribution shows that the best results are obtained when  $e_{pb} = -e_s$ . In general, both the  $e_{pb} = -e_s$  and the  $e_{pb} = 0$  distributions perform well in maintaining the ductility demand either well below that of  $e_{pb} = e_s$  on the flexible side and either less than, or close to, unity on the stiff side (when ductility demand is below unity, the element remains elastic).

It is interesting to note that similar results for yielding unbraced systems have been obtained previously by others. Ayala, Garcia and Escobar (1992), Tso and Ying (1990), and Sadek and Tso (1989) studied the effect of strength distribution on the overall displacement of structures consisting of ductile moment resisting frames. Their results, analogous to the above, also demonstrated that structures having strength eccentricity negative that of the stiffness eccentricity generally performed better during severe earthquakes.

#### Distribution of Stiffness

In the preceding results, the overall bracing to frame stiffness ratio  $KB / KF$  was maintained constant at a value of 10.0 and the braced system had the same elastic stiffness eccentricity  $e_s$  as the corresponding unbraced system. Recognizing that modification of the stiffness distribution of the braces affects the eccentricity  $e_s$  of the overall system (i.e. braces and frames), it is useful to examine the elastic stiffness  $e_s$  as due to  $e_{sb}$ , the elastic stiffness eccentricity of the friction damped braces and  $e_{sf}$ , the eccentricity of the unbraced structure. For the preceding slip load analysis,  $e_s$  was unaffected by the presence of the braces and  $e_{sf}$  was equal to  $e_s$ . Also, given the large  $KB / KF$  ratio considered, it is expected that the elastic stiffness eccentricity  $e_s$  will be dominated by the distribution of the brace stiffnesses.

Figure 6 shows the effect of varying the distribution of stiffness between the resisting braces. For each of the stiffness eccentricities  $e_{sf}^*$  considered, the normalized response for the ensemble of four earthquakes is plotted against the stiffness eccentricity of the friction damped braces  $e_{sb}^*$ . Except for the extreme points where the bracing stiffness is concentrated solely on either the stiff or solely on the flexible side of the structure, the response obtained is relatively uniform over  $e_{sb}^*$ . As in the foregoing analysis, two reasonable brace stiffness distributions are detected. In this case, however, there is less difference between the optimum distribution and the practical distribution than observed for the slip load analysis. Here, the optimum response is obtained at  $e_{sb} = -e_{sf}/2$ , while the more practical approach is represented by  $e_{sb} = 0$ , which is as expected for stiffness. However, the difference between the results at

these two points is less than five percent for the entire range of  $e_{sf}^*$  considered, thus indicating that redistribution of the stiffness of the braces does not result in significant improvement in the seismic performance.

### CONCLUSION

While previous investigators have demonstrated the effectiveness of friction bracing in improving the seismic performance of both symmetric and asymmetric structures, the results presented herein demonstrate that additional improvement in performance may be obtained by properly tuning the devices with respect to the slip load distribution between the resisting braces. For varying slip load distribution in asymmetric structures, optimum responses have been obtained when the slip load eccentricity is opposite that of the structure's stiffness eccentricity (i.e.  $e_{pb} = -e_s$ ). For practical purposes, distributing the slip load according to  $e_{pb} = 0$  provides generally acceptable results.

Once the slip load distribution has been accounted for, stiffness redistribution between the braces has little effect on the response of the structure, due primarily to the large KB / KF ratio required for proper functioning of the friction devices.

It is concluded that, in the overall design of friction damped braced frames, three factors are of importance; namely, the overall bracing to frame strength ratio RB / RF, the bracing to frame stiffness ratio KB / KF, and the optimum distribution of the slip load between the braces. For the latter  $e_{pb} = 0$  is the practical approach, while the optimum is given by  $e_{pb} = -e_s$ .

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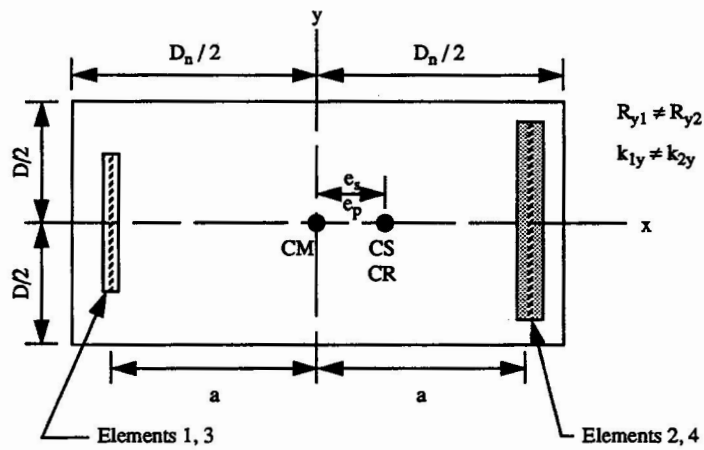


Figure 1. Idealized structural model.

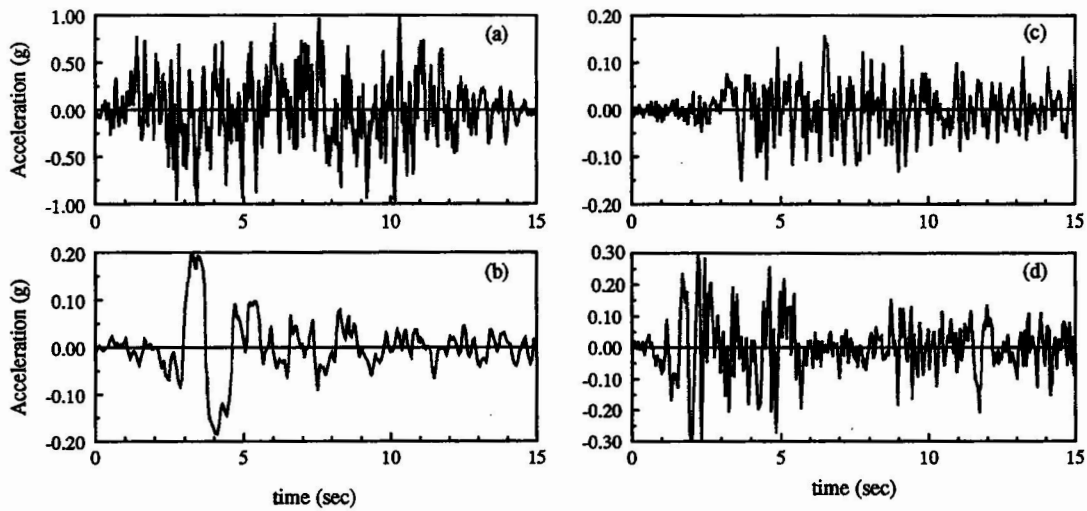


Figure 2. Acceleration time histories for earthquake ensemble: (a) Newmark-Blume-Kapur artificial excitation; (b) 1977 Bucharest N-S; (c) 1952 Taft S69E; (d) 1940 El Centro N-S.

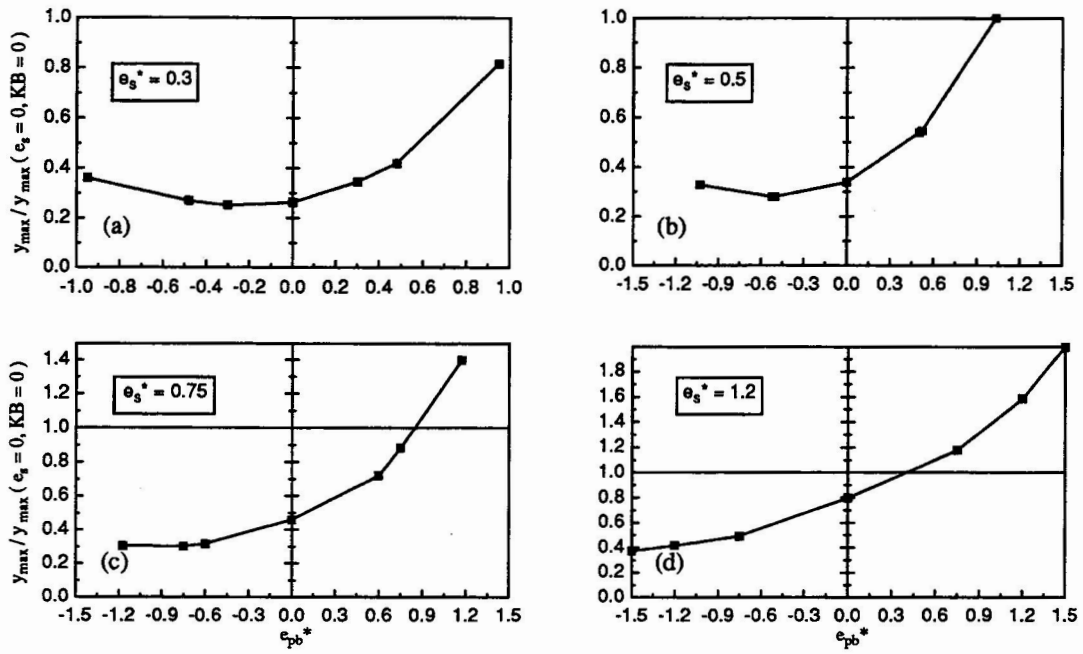


Figure 3. Response with variation in slip load eccentricity  $e_{pb}^*$  of the braces.

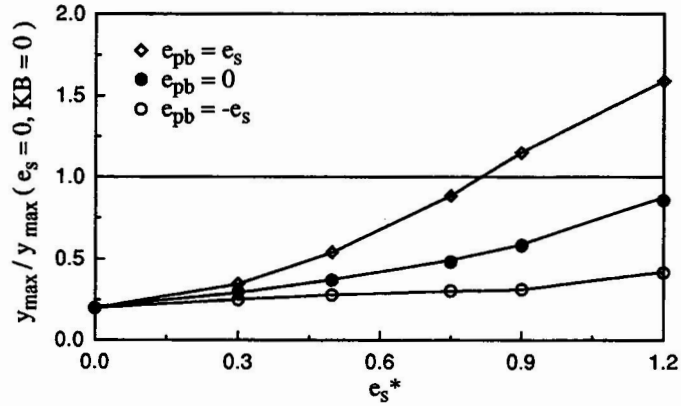


Figure 4. Comparison of response for different distributions of slip load represented by  $e_{pb}$ .

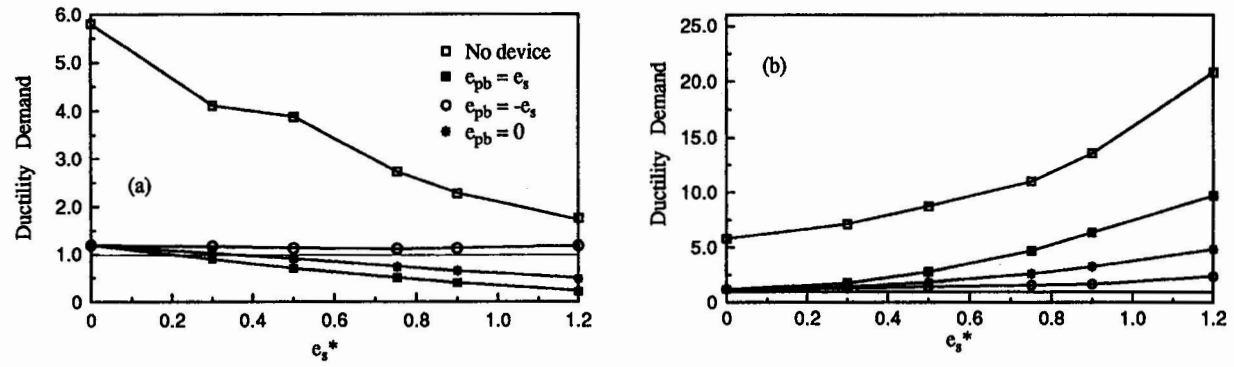


Figure 5. Effect of slip load eccentricity  $e_{pb}$  on ductility demand for: (a) stiff side; (b) flexible side.

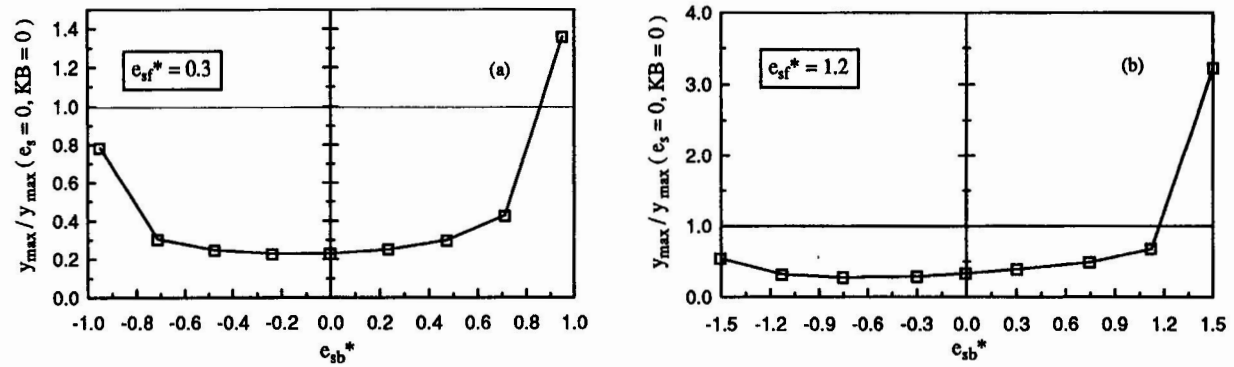


Figure 6. Response with variation in stiffness distribution  $e_{sb}^*$  of the braces.