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Seismic performance of friction damped asymmetric structures

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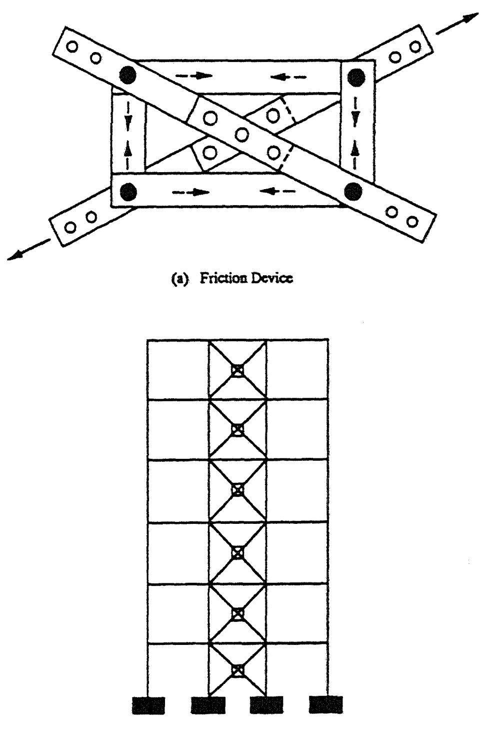
ABSTRACT: Based on the known effectiveness of friction dampers to optimize the seismic response of symmetric frame structures, their use to enhance the performance of eccentric structures is examined. A parametric study is presented employing an idealized single-story structure and five earthquake records. Separate elements of this simple structure model the behaviour of elasto-plastic moment resisting frames and the tension cross-bracing which incorporates the fiction dampers. In addition to the magnitude of the eccentricity between the centres of stiffness and mass, the critical factors examined comprise the optimum slip load of the dampers and the stiffness of the tension braces. The results show that the response of asymmetric structures can be reduced dramactically. Even for structures with large eccentricity, it is shown that it is still possible to reduce the maximum response to that of the corresponding symmetric structure.

1 INTRODUCTION

Various recent studies (Pall and Marsh 1982; Filiatrault and Cherry 1988; Pekau and Guimond 1991) have demonstrated that seismic performance can be optimized for symmetric steel frame buildings by incorporating friction dampers in tension cross-bracing. In this system, each brace in the moment resisting frame is provided with a friction device consisting of heavy duty brake lining pads inserted between sliding stainless steel surfaces. The underlying concept is to dissipate the seismic energy input mechanically through friction rather than by yielding of the structural members. Fig. 1 shows a schematic of the friction device together with a typical arrangement within a multi-story frame.

Although the existing studies have demonstrated the substantial benefit of introducing friction damping, the research is limited primarily to the performance of two-dimensional frames for which the results may also be extrapolated to the seismic response of symmetric three-dimensional structures. However, the lateral-torsional coupling characteristic of asymmetric structures imposes a much more severe demand on these systems during seismic excitation; thus, it is obvious that this category of structures requires special attention.

Examined in this study is the use of friction dampers to improve the seismic performance of the aforementioned more critical category comprising eccentric structures.



(a) Friction Device

(b) Typical Frame with Friction Damped Bracing

Figure 1. Friction damped bracing in frame structures.

2 DETAILS OF STUDY

Fig. 2 shows the idealized single-story structure employed to model asymmetric buildings. It consists of a rigid floor deck of mass m supported laterally by two plane frames (elements 1 and 2) each equipped with friction dampers (elements 3 and 4). For excitation in the y-direction, one-way eccentricity

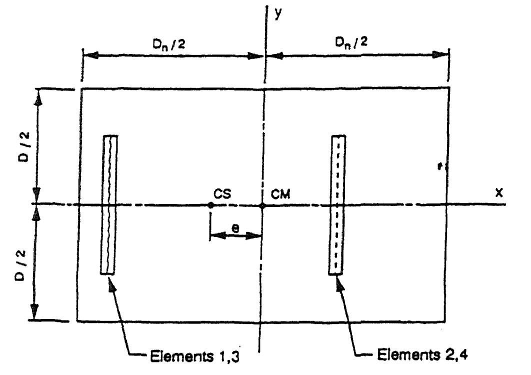


Figure 2. One-story model of friction damped asymmetric structure.

between the centres of mass CM and of stiffness CS is obtained by shifting CS by $e^* = e/\rho$ to a maximum of 1.5, which corresponds the extreme case with CS at the edge of the structure (Note: $D_n = 3.0\rho$), where ρ = mass radius of gyration about CM. The frames are assumed to follow elasto-plastic behaviour with lateral stiffness KF and yield strength RF. In the friction damped cross-bracing, the compression diagonal is assumed to buckle at zero load; however, the rigid links of the device (Fig. 1(a)) keep this member straight and simultaneously cause slip in the friction pads of both members. The combined slip load is denoted by RB, whereas the lateral stiffness of the bracing system is represented by KB.

Time-history analyses were carried out using the computer program DRAIN-2D. To incorporate the frequency characteristics of the ground motion, the results were averaged for the following five earthquake records: 1940 El Centro N-S; 1952 Taft S69E; 1977 Bucharest N-S; 1985 Mexico City E-W; and the artificially generated Newmark-Blume-Kapur excitation. A constant relative intensity for these records was maintained by selecting the yield strengths RF of the unbraced structure for the symmetric condition ($e^* = 0$) based on a force reduction factor Q = 4.0 for each of the records. Viscous damping of 5 per cent and a time step $\Delta t = 0.01$ sec were assumed.

Whereas a similar study was reported previously (Pekau and Guimond 1991), the results presented herein are for an expanded set of earthquake records represented by the inclusion of the 1985 Mexico earthquake. This addition was deemed important due to the special characteristics of the latter.

3 DISCUSSION OF RESULTS

To control effectively the seismic response of eccentric friction damped structures, an optimization or "tuning" process must be performed with regard to the slip load RB of the devices and also with regard to the elastic stiffness KF of the cross-braces.

The response parameters to be optimized are: (i) the maximum edge displacement normalized with respect to either the peak response of the symmetric device-free structure or with respect to the maximum edge displacement of the unbraced eccentric structure, denoted by response ratios y_{max}/y_{max} (e = 0, KB = 0) and y_{max}/y_{max} (KB = 0), respectively; (ii) the displacement ductility ratio for the frame elements; and (iii) the energy dissipated by yielding in the friction damped frames.

Moreover, as is the case for the five earthquake records, the results are further averaged for three categories of eccentricity, namely: (i) symmetric (e^* = 0); (ii) moderate eccentricity (e^* = 0.3, 0.5 and .75); and (iii) large eccentricity (e^* = 0.9, 1.2 and 1.5), for the purpose of generalizing the resulting trends so that they may be applicable to a range of eccentricities within each group and not to a particular eccentricity. The response for each group, therefore, consists of the mean response for the associated range of eccentricity and the 5-earthquake ensemble.

3.1 *Tuning for optimum response to earthquake ensemble*

Fig. 3 shows the results of the optimization process, performed in terms of KB/KF and RB/RF which express the stiffness and strength of the friction damped bracing system with respect to the same properties for the moment resisting frames. Presented is the variation of edge displacement with strength ratio RB/RF for three selected stiffness ratios; namely KB/KF = 1.0, 5.0 and 10.

While these results show the already known effect of the slip load RB of the friction dampers in reducing response, the more significant observation is that stiffness KB of the bracing is equally important. It is seen that response decreases as both the slip load and stiffness of the braces increases and that best performance is achieved when the horizontal shear is shared equally between the braces and the frames, i.e. RB/RF = 1.0. The latter is the optimization criterion used by Pall and Marsh (1982) when they first proposed the devices for symmetric structures. It is also noted that response is not affected greatly for relatively wide variations from this strength level.

In order to arrive at the optimum stiffness for friction damped eccentric structures, Fig. 4 shows the variation of edge displacement with stiffness ratio KB/KF at the optimum slip load. These results represent data taken from Fig. 3 at RB/RF = 1.0. Thus, for structures optimized with respect to slip load, it can be seen that a stiffness ratio of 9-10 reduces the response of even highly eccentric structures to the level of the symmetric unbraced structure. This corresponds to a 60 per cent reduction in response, while 68 and 77 per cent reductions are observed for moderately eccentric and symmetric structures, respectively. This KB/KF ratio is, however, sensitive to the ground motion record. For example, the same analyses carried out for the ensemble excluding the Mexico accelerogram (Pekau and Guimond 1991) indicated that a KB/KF ratio of seven was sufficient to optimize response, whereas KB/KF of only approximately three was sufficient for structures subjected to the NBK artificial accelerogram. These results therefore indicate that a strong correlation exists between the optimized response of a structure and the ground motion characteristics expected at a site. Indeed, the sensitivity study carried out by

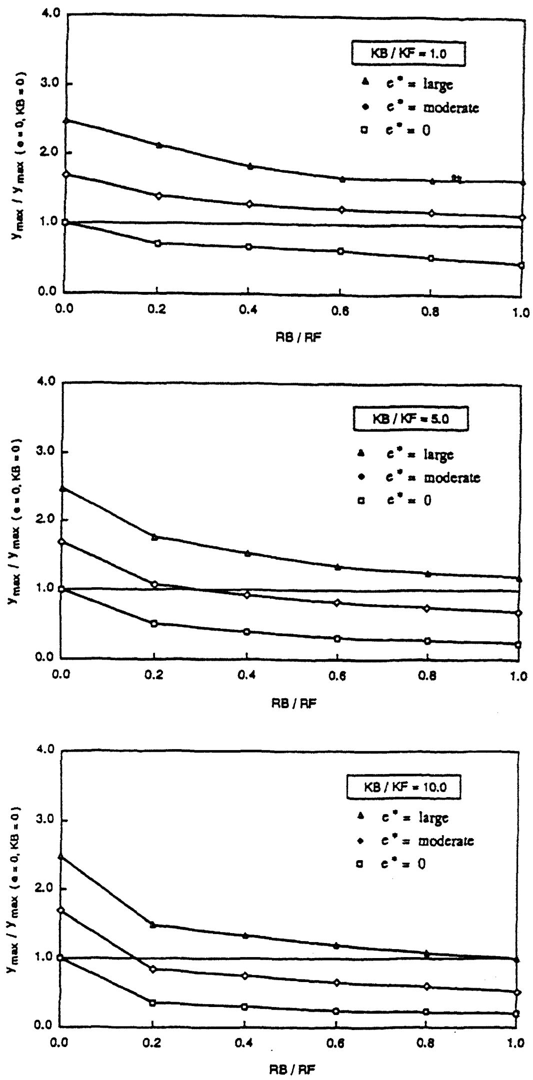


Figure 3. Effect of bracing stiffness KB and slip load RB on eccentric response.

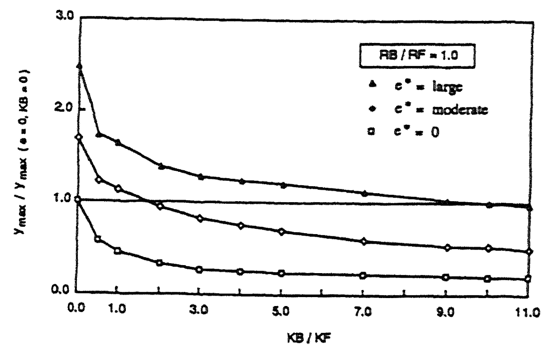


Figure 4. Effect of bracing stiffness KB at optimum slip load.

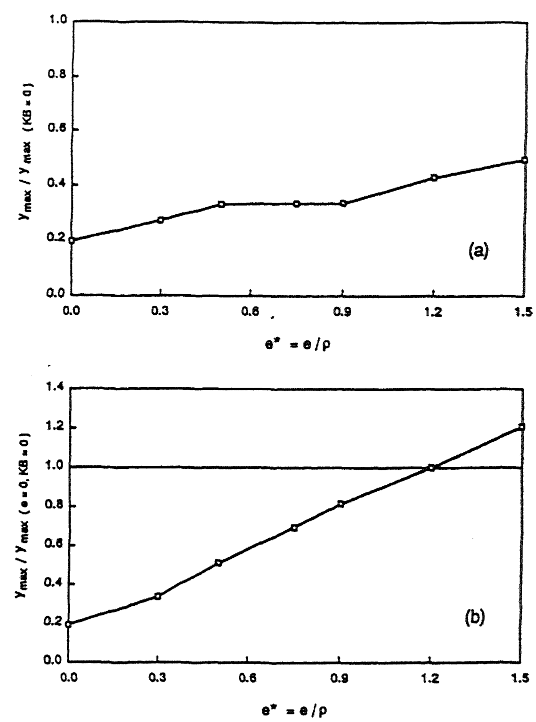


Figure 5. Displacement of optimized friction damped structures normalized with respect to corresponding: (a) unbraced eccentric structure; (b) unbraced symmetric structure.

Filiatrault and Cherry (1988) on symmetric structures also demonstrated this correlation.

3.2 *Optimized response of friction damped structures*

Based on the optimum response parameters obtained above, i.e. RB/RF = 1.0 and KB/KF = 10.0, a detailed investigation of the response of eccentric structures is presented in Figs. 5-7. Compared to the response of eccentric structures without friction dampers, Fig. 5(a) shows that the optimized friction damped bracing provides an almost uniform reduction in response over the whole range of eccentricities. This reduction ranges from 50 per cent for extreme eccentricity to 80 per cent for symmetric structures.

Comparing the response to that of the symmetric unbraced structure, Fig.5(b) shows that the optimized friction damped bracing is capable of controlling the effects of lateral-torsional coupling for normalized eccentricities up to 1.2,which corresponds to 40 per cent of the plan dimension of the structure.

In terms of reducing the structural damage incurred in the structure, Figs. 6 and 7 show the inelastic response of the frame elements in terms of ductility ratio and energy dissipation, respectively. The

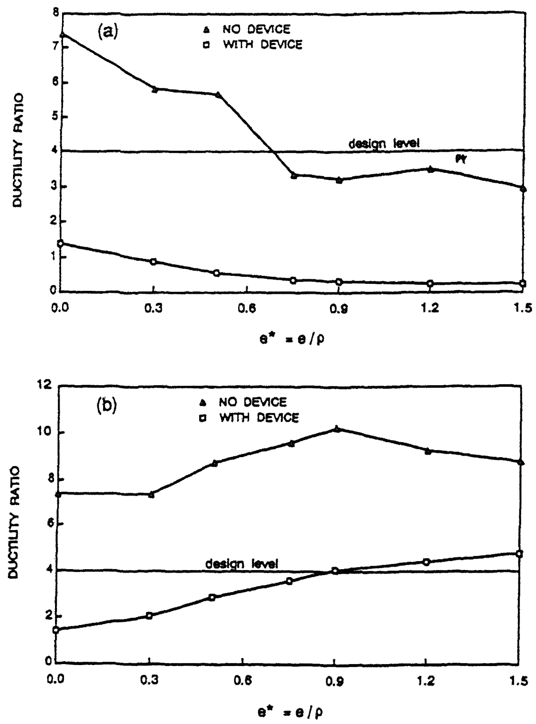


Figure 6. Effect of friction devices on ductility demand for frames on: (a) stiff side; (b) flexible side.

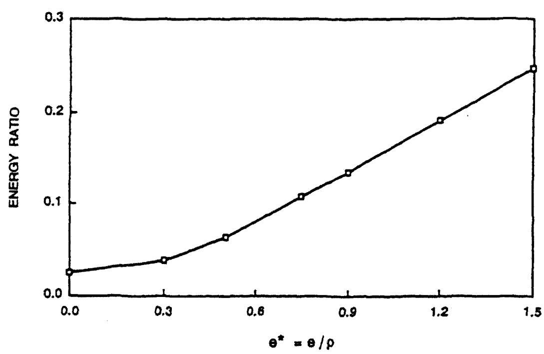


Figure 7. Energy dissipated by yielding in friction damped frames with respect to unbraced frames.

ductility ratio represents the ratio of maximum displacement to the displacement at first yield.

Fig. 6 shows the ductility ratio for the frame elements on the "stiff" and "flexible" sides of the structure, the stiff frame being the one closest to the centre of stiffness CS. For the less severe case of frames on this side it can be seen from Fig. 6(a) that, except for the symmetric structure, the devices are capable of providing elastic behaviour over the entire range of eccenticities. Although these frames experience less damage than those on the flexible side, the improved performance of the optimized structures corresponds to reductions of 80 and 90 per cent, respectively, for the symmetric and highly eccentric structures. For the more critical elements on the flexible side Fig. 6(b) shows that, although large reductions in ductility ratio are achieved, the devices are unable to maintain the ductility ratio below that of the design level represented by Q = 4.0 over the entire range of eccentricities. Nevertheless, structures with eccentricities up to 30 per cent of the plan dimension have ductility ratios less than 4.0 while highly eccentric structures exceed this value by only 20 per cent.

An alternate method of measuring structural damage is the energy absorbed by inelastic deformation of the structural elements. Fig. 7 plots the energy dissipated by yielding of the moment resisting elements when equipped with devices normalized by that consumed without the devices. For the optimized friction damped symmetric structure, the energy absorbed by inelastic action in the frame elements is reduced by 97 per cent, whereas an equally impressive 75 per cent reduction is obtained for the extreme case of e* = 1.5.

4 CONCLUSIONS

Based on a simplified one-story structural model, results have been presented which show that friction damped bracing is an effective strategy to control the seismic response of asymmetric structures. For a 5-earthquake ensemble that includes the 1977 Bucharest and the 1985 Mexico earthquakes, it is found that the design of the friction damped bracing for optimum performance should satisfy the slip load criterion RB/RF ≈ 1.0, which is similar to what has previously been determined for symmetric structures. In terms of the optimum bracing to frame stiffness (see Fig. 4), KB/KF ≈ 2.0 suffices to assure optimum response for symmetric structures. For eccentric structures, on the other hand, KB/KF ≈ 2.0 is also adequate for moderately eccentric structures to reduce peak eccentric response to the symmetric level. For highly eccentric structures, however, a much larger KB/KF ≈ 9-10 is needed to achieve reduction to the level of the associated symmetric response.

REFERENCES

Filiatrault, A. and Cherry, S. 1988. Comparative performance of friction damped systems and base isolation systems for earthquake retrofit and aseismic design. *Earthquake Engineering and Structural Dynamics* 16:389-416.

Filiatrault, A. and Cherry, S. 1988. Seismic design of friction damped braced steel plane frames by energy methods. *Report No. UBC-EERL-88-01.* Vancouver: University of British Columbia.

Pall, A.S. and Marsh, C. 1982. Response of friction damped braced frames. *Journal of the Structural Division, ASCE* 108:1313-1323.

Pekau, O.A. and Guimond, R. 1991. Controlling seismic response of eccentric structures. *Earthquake Engineering and Structural Dynamics* 20:505-521.