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PLAN-WISE DISTRIBUTION OF SLIP LOAD IN FRICTION DAMPED ECCENTRIC STRUCTURES

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ABSTRACT

Friction damped braces to control the seismic response of framed structures are successfully being deployed in both new construction and for rehabilitation of existing buildings. Past research has confirmed their effectiveness in symmetric structures and to a limited extent also under asymmetric conditions. Reported herein is an investigation to further reduce seismic response by redistribution of the slip load of the friction devices over the plan layout of the building. A parametric study based on a single-story eccentric model and an example application for a multi-story prototype building demonstrate that the proposed redistribution of the slip load results in further reduction of maximum response.

KEYWORDS

Asymmetric buildings; friction damping; slip load redistribution; seismic response.

INTRODUCTION

The concept of friction damping has been introduced in recent years to enhance the seismic performance of structures by dissipating input energy through Coulomb friction in so-called dampers which allow slip to occur at a predetermined load. Originally proposed to be placed in tension cross-bracings (Pall and Marsh, 1982), friction dampers have successfully been implemented in other configurations of the bracing, namely in single diagonal braces and in K-bracing for new construction as well as in retrofit of existing buildings (Wagner *et al.*, 1995).

The effectiveness of these devices as a means of controlling the seismic response of symmetric structures has been the subject of considerable research (Filiatrault and Cherry, 1988; Baktash, 1989) wherein guidelines for determining the optimum ratios of stiffness and strength of the friction damped bracings to that of the unbraced frames were established. Asymmetric structures, on the other hand, pose greater vulnerability to excessive seismic damage and the use of friction dampers for this category of structures is still in need of development. The design approach for symmetric structures involves placing friction damped braces with identical stiffness and strength properties on both sides of a building and this design strategy has previously been demonstrated (Pekau and Guimond, 1991) to be effective also for asymmetric structures.

This paper presents the results of an attempt to further enhance the above performance of friction damping in asymmetric structures by optimizing the distribution of the slip load of these devices over the plan layout of the structure. Distribution of slip load is given by the slip load, or strength, eccentricity e_{pb} of the friction damped braces with respect to the centre of mass CM. Employed first is a single story model subjected to an ensemble of earthquake records for which the effect of slip load redistribution is examined in terms of varying e_{pb}. Based on the results of this parametric study, a 3-D inelastic analysis is performed of a five-story reinforced structure possessing large structural eccentricity between CM and the centre of stiffness CS and equipped with friction dampers. Comparisons are made between the design approach based on $e_{pb} = e_s$ (i.e. identical friction damped braces on both sides of CS as previously (Pekau and Guimond, 1991)) and a proposed design strategy given by $e_{pb} = 0$. In general, it is concluded that the seismic response of both the single-story and the prototype structure can profitably be reduced further by the proposed plan-wise redistribution of the slip load between the friction damped bracings.

PARAMETRIC EVALUATION OF SLIP LOAD REDISTRIBUTION

Figure 1 shows the geometric and structural properties of the single-story asymmetric structure utilized in parametric fashion to investigate the effect of redistributing the slip load between the friction damped braces of an elasto-plastic frame building. Two yielding frames (elements 1 and 2) support a rigid deck of mass m and plan dimensions $D_n = 3\rho$ perpendicular to the applied y-direction excitation and D parallel to the excitation, where ρ is the mass radius of gyration about CM. With symmetry assumed about the x-axis, response is defined by translation in the y-direction and rotation θ about the vertical axis through CM.

Elements 3 and 4 represent friction damped braces of total stiffness $KB = \Sigma KB_i$, $(i = 1,2)$ and total strength (slip load) $RB = \Sigma RB_i$, where KB_i and RB_i denote the stiffness and slip load of individual braces respectively, while KF and RF represent the corresponding total properties of the unbraced structure. With identical stiffness for the two friction damped elements, the centre of stiffness of the braced and the unbraced structure is located at CS with eccentricity e_s from CM. The uncoupled torsional to translational frequency ratio $\Omega_0 = (\omega_{\theta 0}^2 / \omega_y^2)^{1/2}$, where $\omega_y = (KF / m)^{1/2}$ and $\omega_{\theta 0}$ is defined in terms of rotational stiffness about CS and mass moment of inertia about CM. This definition for Ω_0 is chosen because it is independent of eccentricity e_s.

The yield strength of the frame elements is assumed proportional to stiffness, resulting in a static plastic centre of resistance CR coincident with CS. Since CR refers to the frames only, the corresponding strength or plastic eccentricity with respect to CM is denoted by e_{pf}. On the other hand, the total strength or slip load RB of elements 3 and 4 representing the friction damped braces is redistributed in parametric fashion with any particular plan-wise configuration represented by the resultant plastic centre of resistance for these elements

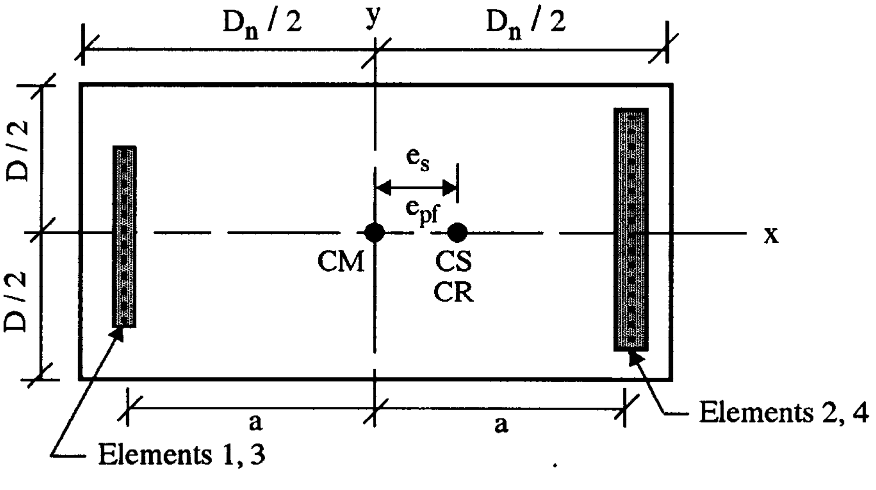

Fig. 1 Asymmetric single-story model

located at e_{pb} from CM. Thus, redistribution is achieved for given e_{pb} by adjusting brace slip loads RB_i while maintaining total slip load RB constant. Slip load eccentricity e_{pb} itself is determined from $e_{pb}= (\Sigma RB_i x_i) / RB$, where x_i denotes the distances of elements 3 and 4 from CM.

The strength level RB of the unbraced structure is derived from the computed elastic response of its symmetric counterpart, for which the induced maximum base shear is $R_{elastic}$. Employing the maximum force reduction factor permitted by the 1990 National Building Code of Canada for ductile systems, the total resistance of the frames of the asymmetric model is set to $RF = R_{elastic} / 4.0$.

Optimization of the bracing to frame stiffness and strength ratios KB/KF and RB/RF has been reported previously (Pekau and Guimond, 1991) based on certain assumptions. These involve assuming that the resisting frames, regardless of their actual plan-wise positions within the structure, are identical in stiffness and strength and that the braces assigned to the frames each also possesses identical slip load and stiffness. Although optimized seismic response was achieved over a range, RB/FB = 1.0 could generally be assumed, whereas KB/KF needs to be greater than seven. Thus, the present results are based on similar values for these parameters, namely RB/RF = 1.0 and KB/KF = 10 and 3. The reduced magnitude of KB/KF = 3 is deemed necessary in order to account for situations where only a few out of all the bays in a multi-story structure can be braced due to architectural restrictions.

Basis for Parametric Data

The primary parameters describing the asymmetric model which were allowed to vary are the strength and stiffness eccentricities normalized with respect to the mass radius of gyration ρ, namely structural eccentricity over the range $0 \leq e^*_s = e_s/\rho \leq 1.2$ and slip load eccentricity over the range $0 \leq e^*_{pb} = e_{pb}/\rho \leq 1.5$. Since the resulting data are meant to pertain to multi-story structures of intermediate height, translational period T = 1.0 sec is adopted together with frequency ratio $\Omega_0 = 1.0$. Parametric response data were generated using the computer code Drain-2D (Kanaan and Powell, 1973) for five percent viscous damping and time step $\Delta t = 0.1$ sec. The seismic input chosen comprises the following four earthquake records: 1940 El Centro N-S; 1952 Taft S69E; 1977 Romania N90W: and the Newmark-Blume-Kapur artificially generated ground motion. Each asymmetric structure and its symmetric counterpart were subjected to this ensemble of ground excitation with the response normalized by that of the unbraced symmetric structure.

Optimum Distribution of Slip Load

For the friction damped model with high stiffness of the braces, the enhanced performance accompanying slip load redistribution has been presented previously (Martin and Pekau, 195). However as aforementioned, such magnitude of KB/KF while desirable may not necessarily be realizable in practice owing to architectural layout requirements which can limit the location of the friction damped braces to only a small number of bays in a building. For this reason the emphasis in the slip load redistribution process below is the evaluation of the effectiveness of the reduced bracing to frame stiffness given by KB/KF = 3.

Figure 2 presents the parametric data showing the maximum edge response for structures with eccentricity up to 40 percent of the building dimension (i.e. $e_s = 0.4D_n$ represented by $e^*_s = 1.2$) for the two stiffness levels of the braces. As is to be expected, KB/KF = 10 provides superior performance compared to KB/K = 3. For both values of this ratio, Fig. 2 shows that redistribution of slip load as represented by variation of the slip load eccentricity e^*_{pb} can lead to remarkable improvement in performance of the friction damped bracing. Noting that before redistribution the slip loads are equal in the two friction damped elements, the performance for this case is represented by response corresponding to data points with $e^*_{pb} = e^*_s$ for each of the six cases of structural eccentricity in Fig.2

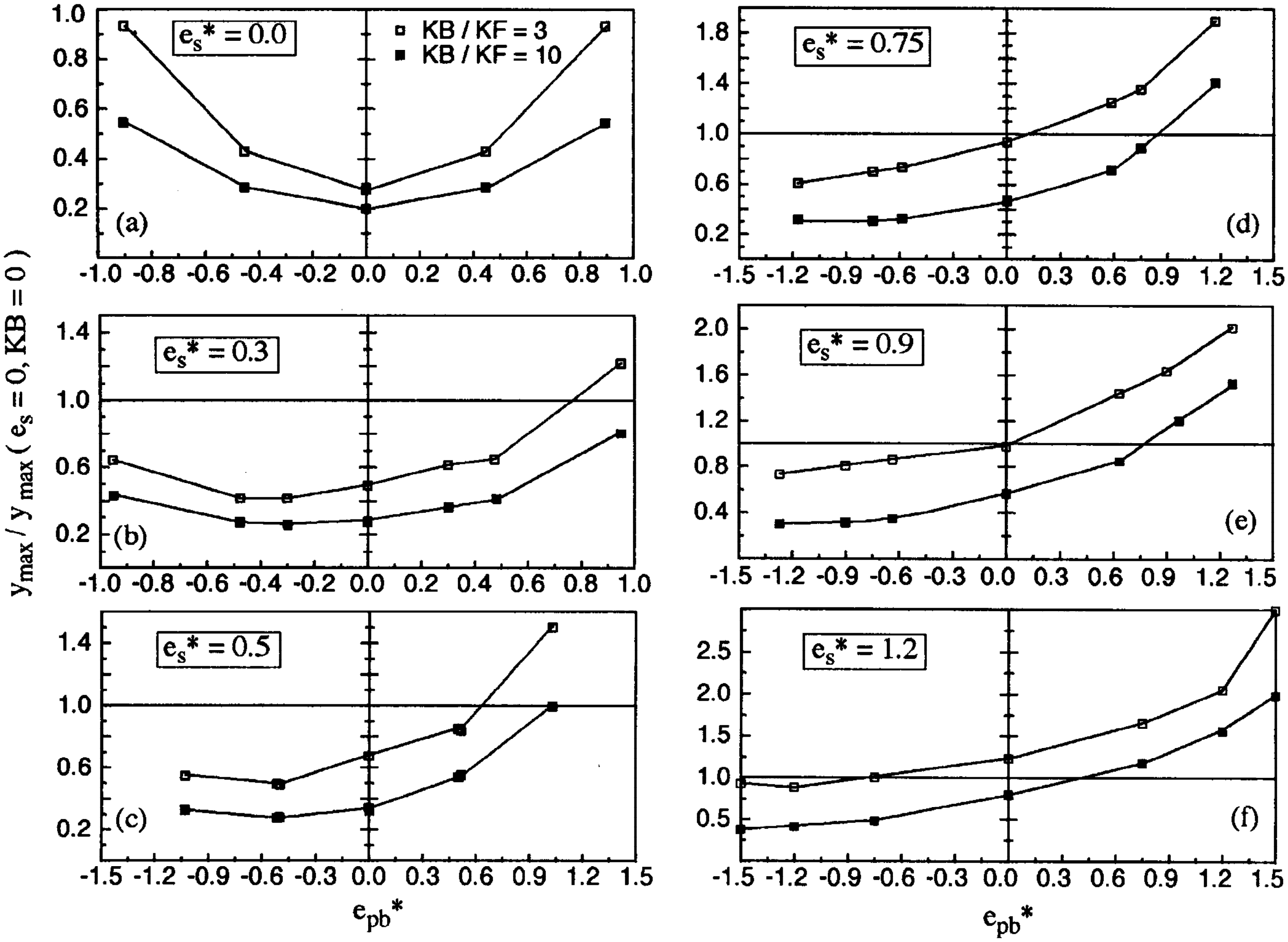

Fig. 2 Single-story structure: maximum normalized displacement with redistribution of slip load

For the entire range of normalized structural eccentricity e^*_s the optimum distribution of slip load is seen to occur when $e^*_{pb} = -e^*_s$, although for very large eccentricity (i.e. $e^*_s \geq 0.75$) there exists a tendency for the optimum point to be somewhat less well defined. Nonetheless, with slip load distributed such that $e^*_{pb} = -e^*_s$ the response of even highly eccentric structures is reduced to a level below that of their corresponding unbraced symmetric counterparts. For KB/KF = 3, this is noted in Figs.2(d) - 2(f) where the optimized response falls to 70 - 90 percent of the associated unbraced symmetric response. Increased stiffness ratio KB/KF = 10 is seen to result in further lowering the normalized response to 30 - 40 percent. By comparison, before redistribution the corresponding friction damped eccentric to symmetric unbraced responses are approximately 135 - 200 percent for KB/KF = 3 and 90 - 150 percent for KB/KF = 10. For the KB/KF = 3 case of interest herein, it is important to note that slip load equally distributed about CM (i.e. $e^*_{pb} = 0$) reduces eccentric response down to or below that of the unbraced symmetric structure for $e^*_s \leq 0.9$ (Figs. 2(a) - 2(e)) and only some 25 percent above for the extreme case of $e^*_s = 1.2$ (Fig. 2(f)).

The foregoing performance for $e^*_{pb} = 0$ indicates that this distribution of the slip load can serve as a suitable criterion in design. Indeed, adoption of $e^*_{pb} = 0$ is also attractive for practical reasons since it requires only the location of CM, which is readily determined. The performance of $e^*_{pb} = 0$ as the design rule for the plan-wise distribution of the slip load in the friction devices is presented in Fig. 3 for KB/KF = 3. Compared to $e^*_{pb} = e^*_s$, Fig. 3(a) shows that slip load distribution based on $e^*_{pb} = 0$ improves the effectiveness of the friction damped bracing considerably over the complete range of the normalized structural eccentricity e^*_s. As noted previously, it also limits the eccentric response to below, or for extreme eccentricity e^*_s close to, that of the symmetric unbraced structure.

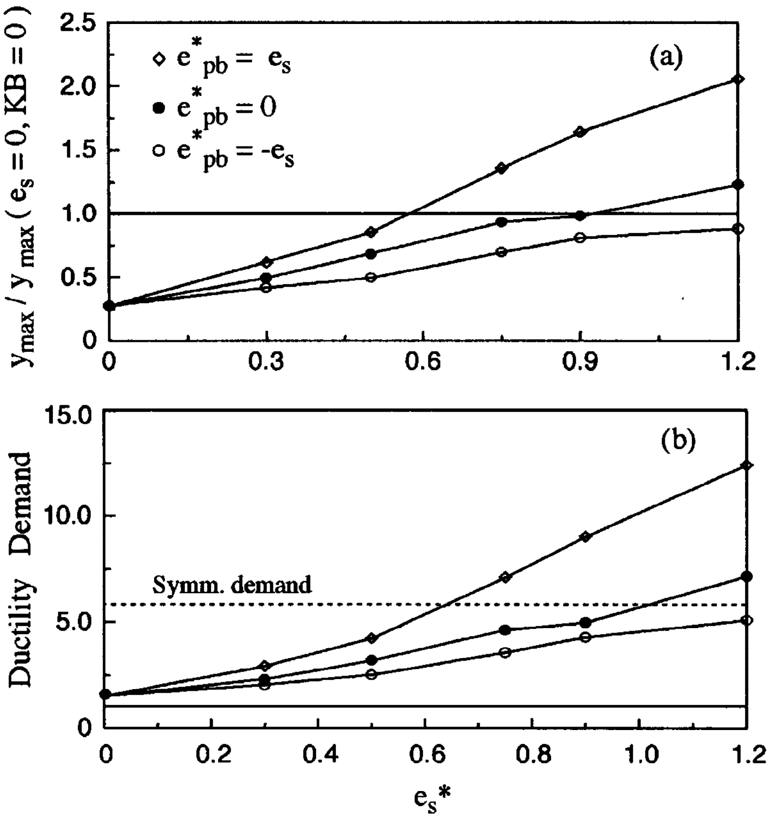

Fig. 3 Performance of proposed slip load redistribution for single-story structure with KB/KF = 3: (a) displacement; (b) ductility demand

For the maximum ductility demand in the frame elements, Fig. 3(b) demonstrates similar effectiveness of the proposed plan-wise slip load configuration given by $e^*_{pb} = 0$. Here ductility demand for the whole range of structural eccentricity is also kept to below, or close to, that of the symmetric unbraced structure (i.e. 5.8 as represented by the dashed reference line). For the extreme case $e^*_s = 1.2$, the ductility demand is 12.4 before redistribution and reduced to 7.1 after redistribution of the slip load.

Figure 3 shows also that the optimum slip load distribution represented by $e^*_{pb} = - e^*_s$ improves performance over $e^*_{pb} = 0$, which is to be expected. However, it is seen that the additional benefit to reduced seismic response may not warrant the task of determining e^*_s in practice, especially since the structural eccentricity usually varies from floor to floor in a multi-story building.

EXAMPLE APPLICATION IN PROTOTYPE BUILDING

As a preliminary demonstration of implementing slip load redistribution in a multi-story structure equipped with friction dampers, the prototype five-story structure studied previously (Pekau and Guimond,1991) was employed. The plan layout of this reinforced concrete building is shown in Fig.4 and represents an early version of the Concordia University Library complex which was eventually constructed as a twelve-story friction damped structure.

Details of Structure and Analysis

The example building was designed as a reinforced concrete flat slab system with drop panels. For the y-direction of interest herein, seismic loading acting on the unbraced structure is resisted by six effective frames in this direction, namely frames I - IV. In both its braced and unbraced forms, centre of stiffness CS lies within

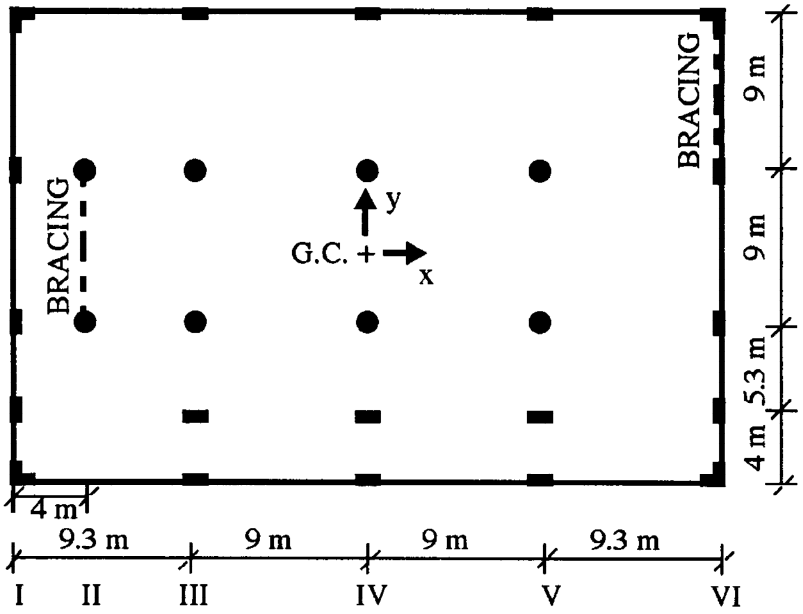

Fig. 4 Plan of prototype structure

eccentricity of two percent from the geometric centroid G.C. The pertinent structural and material properties are available from the earlier study (Pekau and Guimond, 1991) which employed this building to investigate friction damped bracing in frames II and VI as shown in Fig. 4. Whereas equal slip loads resulting in strength eccentricity $e_{pb} = e_s$ from centre of mass CM were employed, the present results examine the effect of the proposed redistribution $e_{pb} = 0$. To create a structure possessing large eccentricity, CM is assumed to be located at $x = 0.35D_n$, where $D_n = 36.6$m.

The same ensemble of four earthquake records as in the preceding parametric study are adopted, with results averaged for a common normalized intensity corresponding to 0.36g of the Newmark-Blume Kapur record. The normalization comprised scaling the ground motion to produce equal computed base shears in the braced and unbraced structures. The dynamic computations were carried out through the computer program Drain-Tabs (Guendelman-Israel and Powell, 1997) for zero viscous damping and time step $\Delta t = 0.01$ sec.

Since only a preliminary demonstration of the benefit of slip load redistribution is involved herein, the slip load itself of the braces was not optimized either before or after redistribution for the current ensemble of excitation and intensity. Instead, total story slip loads varying from 700kN at the base to 75kN at the top obtained in the abovementioned study for different intensity of excitation and only the Newmark-Blume-Kapur record were utilized for convenience.

Discussion of Results

Figure 5 depicts the performance of the two chosen slip load distributions compared to that of the unbraced moment resisting frame (MRF) under the earthquake ensemble. For the rotations of Fig.5(a), equal slip loads in the two braced bays given $e_{pb} = e_s$ reduces the 0.0058 top floor rotation of the unbraced building by 25 percent. Redistribution according to $e_{pb} = 0$ results in a corresponding decrease of 35 percent. Similarly, for frame VI located on the flexible edge, Fig. 5(b) shows that slip load redistribution leads to a 30 percent improvement from the 166mm top displacement experienced by the unbraced structure, compared to 20 percent for $e_{pb} = e_s$.

More significant evidence for slip load redistribution in this structure under the Newmark-Blume-Kapur record is presented in Fig. 6 with regard to controlling predicted damage as indicated by plastic hinge forma-

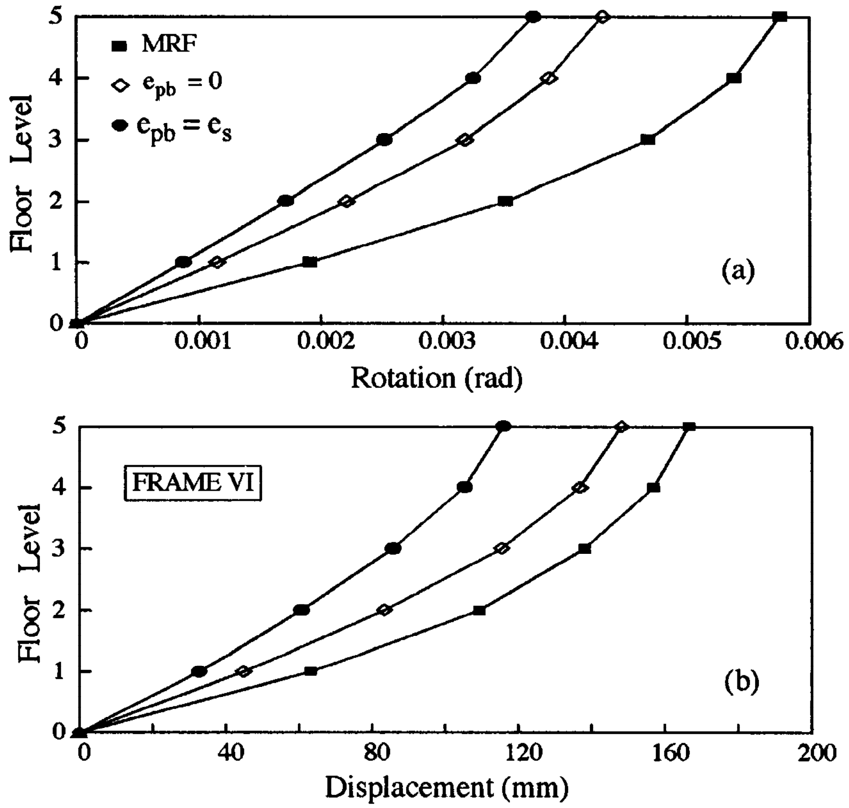

Fig. 5 Effect of proposed slip load redistribution $e_{pb} = 0$ on: (a) rotation; (b) displacement of prototype structure

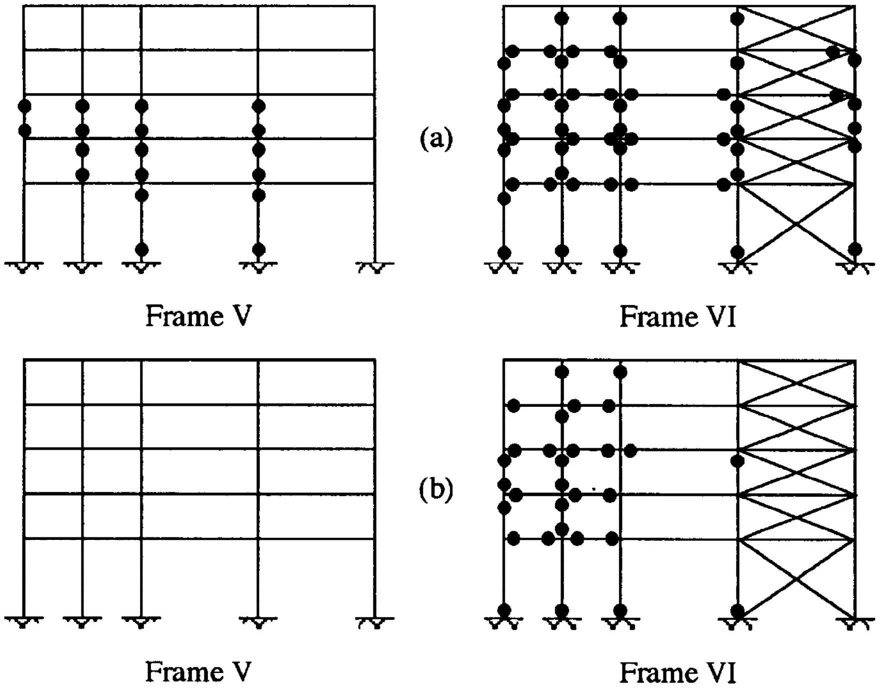

Fig. 6 Plastic hinge formation in prototype structure for: (a) $e_{pb} = e_s$; (b) $e_{pb} = 0$

tion. In this highly asymmetric structure yielding is expected to occur primarily in the in the frames located on the flexible CM side. Accordingly, for $e_{pb} = e_s$ Fig. 6(a) indicates that 72 hinges are induced in frames V and VI, with three others in frame IV not shown. By comparison, the hinge formation pattern for $e_{pb} = 0$ of Fig. 6(b) shows a reduction of 58 percent, with only 30 hinges occurring in frame VI.

Noting that the aforementioned optimization of the magnitude of the slip load itself was not performed, it is of interest to examine the possible maximum benefit to be expected from this effort. For normalized structural eccentricity $e^*_s \approx 1.0$ for this prototype structure, Fig. 3 of the preceding single-story results predicts approximately 45 percent reduction in both displacement and ductility demand. Thus, further tuning with regard to the RB/RF ratio of this structure for the current group of earthquake records and level of intensity can be expected to produce a doubling of the effectiveness in the slip load redistribution identified in Figs. 4 - 6.

CONCLUDING REMARKS

A parametric study of slip load redistribution in single-story friction damped structures has produced results indicating major reductions in maximum seismic response of asymmetric structures with redistribution of the slip load. Of particular interest is that the predicted benefit increases with increasing eccentricity. For redistribution represented by slip load eccentricity $e_{pb} = - e_s$, maximum response of edge elements is reduced to below that in the corresponding unbraced symmetric structure. A practical design approach with similar benefit consists of $e_{pb} = 0$, which places the plastic centre of resistance of the friction damped braces at the centre of mass CM.

Preliminary results for an example prototype multi-story building have confirmed the potential usefulness of slip load redistribution. Because complete optimization was not undertaken, related in particular to the magnitude of the slip load itself, the true benefit to be derived awaits future evaluation. The concept of redistributing the slip load is attractive because it is relatively easy to achieve in practice. This is because it involves only simple adjustment of the pretension in the bolts of the friction dampers which reside in slotted holes.

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