IMPROVED DEPLOYMENT OF FRICTION DAMPERS IN ASYMMETRIC MULTI-STORY BUILDINGS

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SUMMARY

The investigation reported in this paper extends previously reported studies of asymmetric single-story structures equipped with friction dampers to include results for asymmetric multi-story buildings of five and ten-stories subjected also to an ensemble of earthquake records as before, assuming yielding elasto-plastic behavior of the unbraced frames. Typical of the results obtained it is seen that, when the slip loads of the dampers are distributed such that their resultant strength eccentricity e_{pb} is the negative of the structural eccentricity e_s between the centres of stiffness CS and mass CM, the maximum displacement is optimized over a wide range of eccentricity e_s, as previously demonstrated only for single-story structures. In general it is found that, especially for strongly unsymmetric buildings, maximum seismic edge response is markedly reduced if the friction damper slip loads are distributed over the plan layout of multi-story buildings such that $e_{pb} = -e_s$, which yields predictions of similar magnitude of reduction in seismic response as noted for single-story structures. It is also concluded that a slip load distribution given by $e_{pb} = 0$, namely with the centre of damper strength distribution over the plan located at the centre of mass CM provides almost equally good performance.

INTRODUCTION

Since its introduction [Pall and Marsh, 1982], friction damping in moment resisting frames (MRF) as a means of enhancing seismic response has seen many applications in both new and retrofit projects [Elliot et al., 1999]. These include the Concordia University Library in Montreal as one of the earliest to the Boeing Commercial Airplane Factory in Everett as the most recent and now in progress. First envisioned in diagonal tension bracing, these devices have been employed to provide supplemental seismic energy dissipation when variously incorporated also in single as well as K and chevron lateral braces.

For symmetric structures, the desired behavior [Filiatrault and Cherry, 1988] places friction damped braces with identical stiffness and strength properties on both sides of a building and this strategy has previously been demonstrated [Pekau and Guimond, 1991] to be effective also for asymmetric single-story structures. For the latter category, previously reported companion studies [Martin and Pekau, 1995&1996] have demonstrated that it is possible 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 was a single story model structure subjected to an ensemble of earthquake records for which the effect of slip load redistribution was examined in terms of varying e_{pb}. Comparisons were made between the design approach based on $e_{pb} = e_s$ (i.e. identical friction damped braces on both sides of centre of stiffness CS [Pekau and Guimond, 1991]) and a proposed design strategy given by $e_{pb} = 0$. This showed that the seismic response of both the single-story and an example prototype structure can be significantly reduced further by the proposed plan-wise redistribution of the slip load among the friction damped bracing.

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Reported herein are the results from a similar study expanded to include idealized 5- and 10- story multi-story eccentric frame structures. Examined primarily are the above slip load distribution strategies over the plan layout of the eccentric multi-story model structures, including also the necessary stiffness requirements KB for the bracing.

DESCRIPTION OF INVESTIGATION

Properties of Idealized Structures

Figures 1 and 2 show the geometric and structural properties of the one, five and 10-story model building structures. It is assumed that floor slabs and roof deck act as rigid elements, resulting in overall "shear building" behavior. The plan layout of Fig. 1(a) applies to the eccentric building properties at any level of the multi-story structures as well as to the single-story, since plan-wise distribution of properties is constant over the building height. Actual stiffness and strength values vary story-wise as shown in Figs. 2(a-c) with bottom/top ratios of 2.0 and 4.0 for five and 10 stories, respectively. As seen in Fig. 1(a), the geometric and structural properties in any story of the asymmetric structures comprise two elasto-plastic frames (elements 1 and 2) connecting rigid floors above and below of mass m each 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. Symmetry is assumed about the x-axis.

Elements 3 and 4 represent friction damped braces of total stiffness $KB = \Sigma KB_i$, (i = 1,2) and total strength (slip load) $RB = \Sigma RB_i$ per story, 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 per story of the unbraced frame structure. With stiffness for the two friction damped elements proportional to their corresponding frames, the centre of stiffness of the braced and the unbraced structure is located at CS with eccentricity e_s from CM. For the single-story case, the uncoupled torsional to translational frequency ratio $\Omega_0 = (\omega_{\theta 0} / \omega_y^2)^{1/2}$, 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.

In each story, 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 per story 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 located at e_{pb} from CM. Thus, redistribution is achieved for given e_{pb} by adjusting brace slip loads RB_i while maintaining total story slip load RB constant. Story-wise 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 RF of the first story of the unbraced multi-story 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 1995 National Building Code of Canada for ductile systems, the total resistance of the frame elements in the bottom story of the asymmetric model is set to $RF = R_{elastic} / 4.0$ Translational period T = 1.0 sec is adopted for all structures 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.

DISCUSSION OF RESULTS

Single-story Structure

Figure 3 summarizes the previously reported performance of the eccentric single-story structure as a friction damped braced frame (FDBF) under the proposed redistribution of the damper slip load given by $e_{pb} = e_s$, $e_{pb} = 0$ and $e_{pb} = - e_s$ over the normalized eccentricity range $e_s^* = e_s / \rho = 0 - 1.1$ for brace to frame stiffness ratio KB/KF = 3.0. Here the maximum eccentricity $e_s^* = 1.1$ represents a large actual eccentricity in the structure of 0.37 times the building dimension D_n. Compared to the symmetric unbraced moment resisting frame (MRF), Fig.

3(a) indicates that $e_{pb} = e_s$ with damper slip load distributed about CS in proportion to the host frame strength and stiffness reduces the maximum edge displacement response for small and moderate eccentricity, i.e. $e_s < 0.6$. For larger eccentricity lateral-torsional coupling increases response above the symmetric unbraced level under slip load distribution $e_{pb} = e_s$. Adopting optimum design slip load strategy $e_{pb} = - e_s$ limits the maximum edge displacement to below that of the unbraced symmetric response over the entire range of e_s. Importantly, the simple approach of arranging slip loads equally about mass centre CM is seen to be a desirable option since it maintains y_{max} to equal or below the symmetric unbraced level of response for eccentricity up to $0.37D_{n.}$.

Improved control of expected damage is examined in Fig. 3(b) in terms of maximum ductility demand μ (i.e. ratio of peak/yield story drift) in the frame elements based on the three redeployment strategies of the damper slip load and stiffness ratio BK/KF = 3.0. The trends for improved performance are similar to those observed for $y_{max.}$ Maintaining slip load centre of resistance at CS by employing $e_{pb} = e_s$ results in excessive ductility demand approaching $\mu = 11$ for maximum eccentricity $e_s^* = 1.1$. Tuning the slip load distribution for optimum (i.e. e_{pb} = - e)$_s$ performance of the dampers reduces the ductility demand to the design level of $\mu = 4$ even for maximum eccentricity. The practical option of slip load distribution given by $e_{pb} = 0$ is seen to be adequate to remove the torsional amplification effect and limit μ to not exceed that of the device free symmetric MRF (i.e. 5.8). Recognizing that stiffness ratio KB/KF is an important parameter in the proper functioning of FDBF structures, the preceding data confirm that introducing braces with stiffness KB/KF = 3.0 is sufficient for single- story structures to achieve the objectives related to the performance criteria discussed above.

Overall Performance of Multi-story Structures

Figures 4 and 5 demonstrate the corresponding effectiveness of slip load redeployment in five and 10-story structures. Here it needs to be noted that increase to KB/KF = 5.0 is required for the brace stiffness in order to obtain results for multi-story FDBF's similar to those for the single-story case. In particular, Fig. 4(a) shows that $e_{pb} = 0$ reduces the maximum edge displacement response y_{max} to below that for the unbraced symmetric MRF structure. Similarly, the ductility demand of Fig. 4(b) is also observed to fall below the symmetric unbraced demand level over the entire eccentricity range. For this 5-story case, optimum slip load deployment of $e_{pb} = - e_s$ succeeds to eliminate the extreme demand of $\mu = 17$ to the desired design level of 4.0.

Corresponding observations are also noted for the 10-story results of Fig. 5, in terms of control of both maximum edge displacement and ductility demand. The same increase in brace stiffness to KB/KF= 5 and e_{pb} = 0 are seen to eliminate concern for the effects of torsion in the normalized response compared to the unbraced symmetric structure. Here also, slip load deployment scheme $e_{pb} = 0$ ensures performance better than the corresponding unbraced MRF, while $e_{pb} = - e_s$ meets design level ductility requirements over the whole range of structural eccentricity e_s.

Distribution of Response in Multi-story Structures

Figures 6 - 9 examine the effectiveness of slip load redeployment in controlling the asymmetric structural response for the five and 10-story models for selected situations of the normalized CS to CM eccentricity $e_s^* = 0$, 0.3 and 0.9. For the 5-story structure, Fig. 6 shows that in the symmetric case with $e_s^* = 0$, the introduction of friction dampers reduces the displacement envelope dramatically compared to that of the unbraced MRF, indicating a reduction of some 70% at the top. Slip load redeployment beyond $e_{pb} = e_s$ is seen in Fig. 6(b) to produce marginal benefit since $e_{pb} = e_s$ is very effective for small eccentricity as noted earlier. The real benefit of redeploying the slip load beyond $e_{pb} = e_s$ is seen for large eccentricity. As evident in Fig. 6(c), $e_{pb} = e_s$ is less effective for $e_s^* = 0.9$ than it was for $e_s^* = 0$. Distribution scheme $e_{pb} = 0$ is much more significant now. Here, for $e_s^* = 0.9$ top displacement is reduced by approximately 40% for $e_{pb} = e_s$, but by a further 25% for $e_{pb} = 0$.

Correspondingly, in terms of control of potential damage, Fig. 7 confirms that the proposed redistribution of slip load becomes a practical necessity in multi-story structures possessing large eccentricity. For the present 5-story structure, compared to the maximum ductility demand in the bottom story of $\mu = 10.5$ for the MRF of Fig. 7(a), $e_{pb} = e_s$ suffices to reduce maximum μ to the ductile design level of 4.0 for small $e_s^* = 0.3$ in Fig. 7(b). However, for highly asymmetric structures with $e_s^* > 0.9$, Fig. 7(c) shows that redeploying slip load to $e_{pb} = - e_s$ is needed in order to limit maximum demand to the design level $\mu < 4$.

Very similar trends in improved performance over the structure height are noted in Figs. 8 and 9 for the 10-story model structure. For the large eccentricity $e_s^* = 0.9$ of Fig. 8(c), $e_{pb} = e_s$ reduces the unbraced top displacement by about 40%; $e_{pb} = 0$ decreases it additionally by 25% and $e_{pb} = - e_s$ by another some 10%. Thus, the optimum performance is a reduction in top displacement to 25% of that of the unbraced MRF, while an equally acceptable reduction to 35% is achieved with $e_{pb} = 0$.

The corresponding ductility envelopes over height are shown in Fig. 9. The symmetric FDBF structure of Fig. 9(a) exhibits the expected small but quite uniform ductility demand over almost the entire structure, whereas the unbraced MRF experiences plastic action increasing to $\mu = 10.5$ at the base. This concentration of plastic action in the lower portions is seen to be progressively eliminated by slip load redistribution for the eccentric structures of Figs. 9(a,b). For the large $e_s^* = 0.9$ eccentricity structure of Fig. 9(c), the excessive ductility demand over most of the structure for $e_{pb} = e_s$ can be reduced by slip load redeployment to the design level of $\mu = 4$ in nearly uniform fashion over the structure.

CONCLUSIONS

Based on the idealized "shear building" eccentric model structures employed in the present study, the following observations concerning the effectiveness of friction damping in asymmetric multi-story buildings are noted:

(1) As for single-story eccentric structures, the improved deployment of the slip load of the friction dampers over the plan of multi-story buildings results in similar enhanced seismic behavior. Represented herein by their strength eccentricity e_{pb} about CM, the deployment of these devices given by the negative of the symmetric unbraced structure stiffness eccentricity e_s provides the best performance, particularly with regard to peak ductility demands in the frame elements. The more practical approach for design of locating the slip load centre of resistance at the centre of mass CM is sufficient to limit maximum building edge displacement to the magnitude of that for the associated unbraced MRF.

(2) Compared to displacement, control of maximum story ductility demand was seen to be more demanding. Generally, only the optimal distribution of slip load given by $e_{pb} = - e_s$ was found to reduce maximum ductility requirement to the $\mu = 4$ design level.

(3) The magnitude of the stiffness KB of the braces in eccentric FDBF structures which is needed to achieve the reported improved performance is larger for multi-story structures. Compared to KB/KF = 3 for single-story structures, increased stiffness ratio KB/KF = 5 was found necessary for the five and 10-story models.

(4) Although not presented herein, damper slip strength falling within the range RB/RF = 0.5 - 1.0 was observed to provide optimized reduction in the seismic response of both single and multi-story asymmetric buildings.

ACKNOWLEDGEMENT

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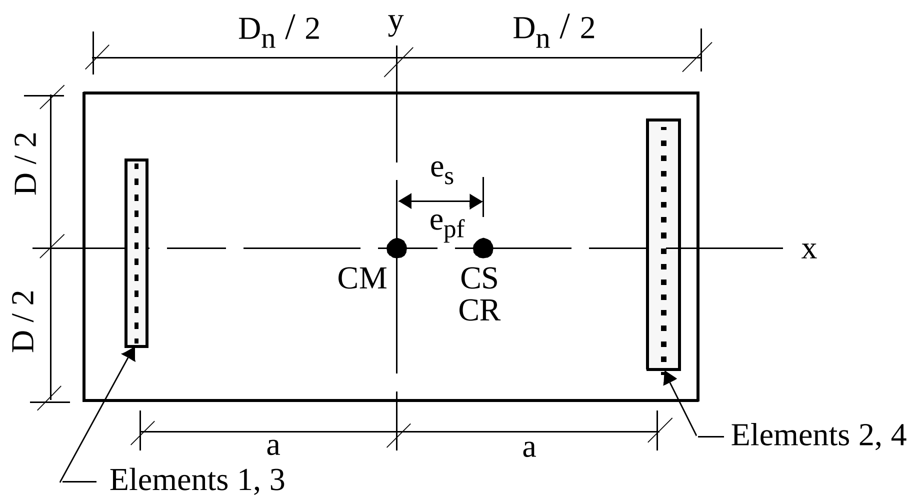

Figure. 1: Plan layout in typical story for single and multi-story asymmetric structures.

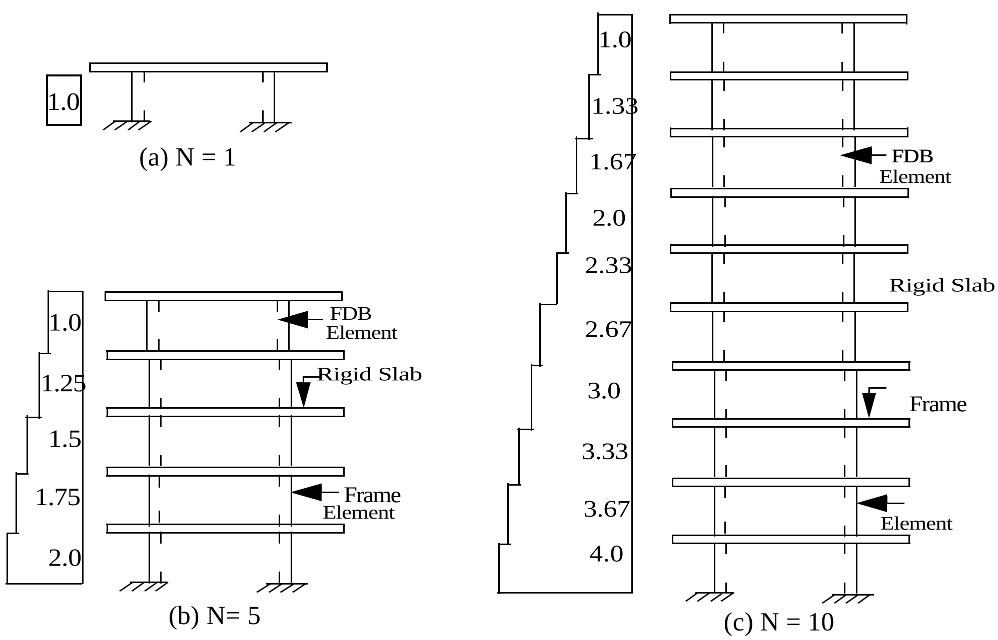

Figure 2: Height-wise stiffness and strength variations in N = 1, 5 and 10-story structures.

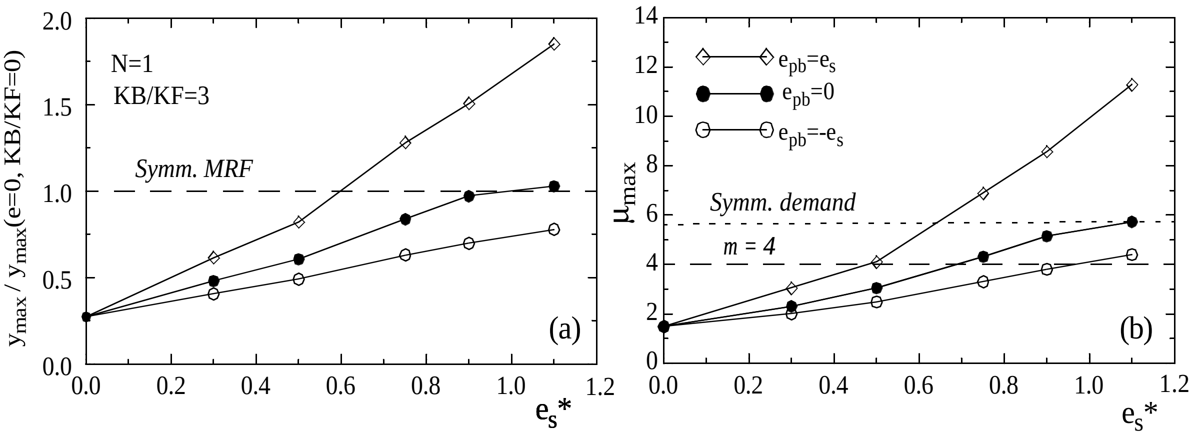

Figure 3: Slip load redistribution for single-story (N=1) structure.

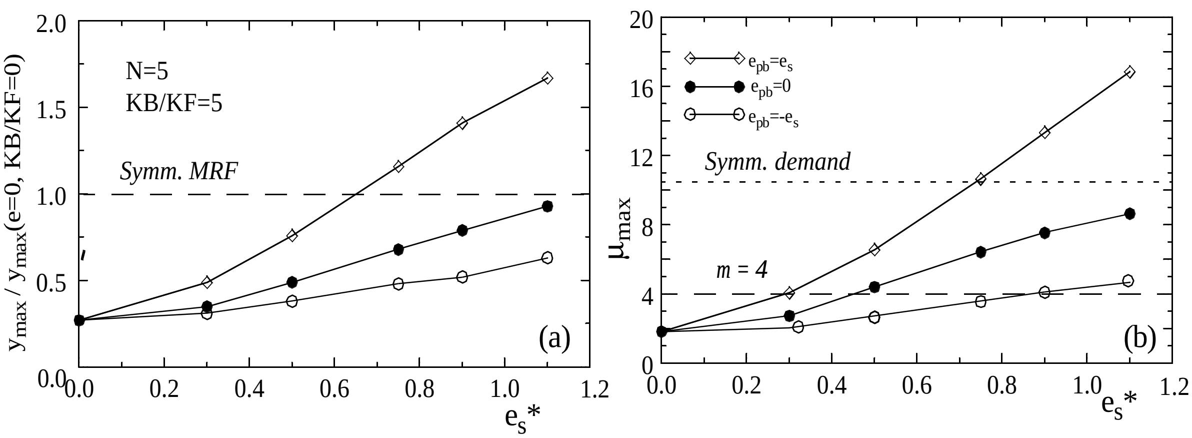

Figure 4: Slip load redistribution for 5-story (N=5) structure.

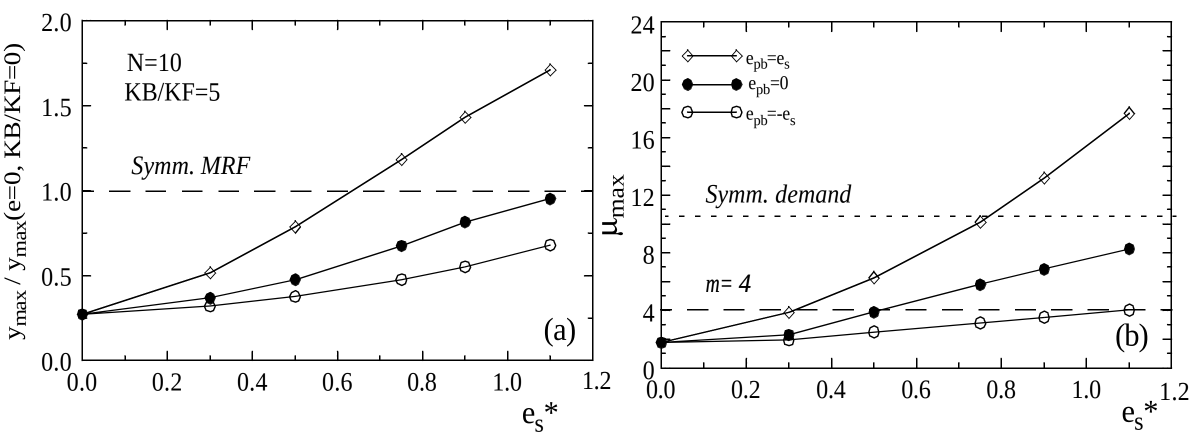

Figure 5: Slip load redistribution for 10-story (N=10) structure.

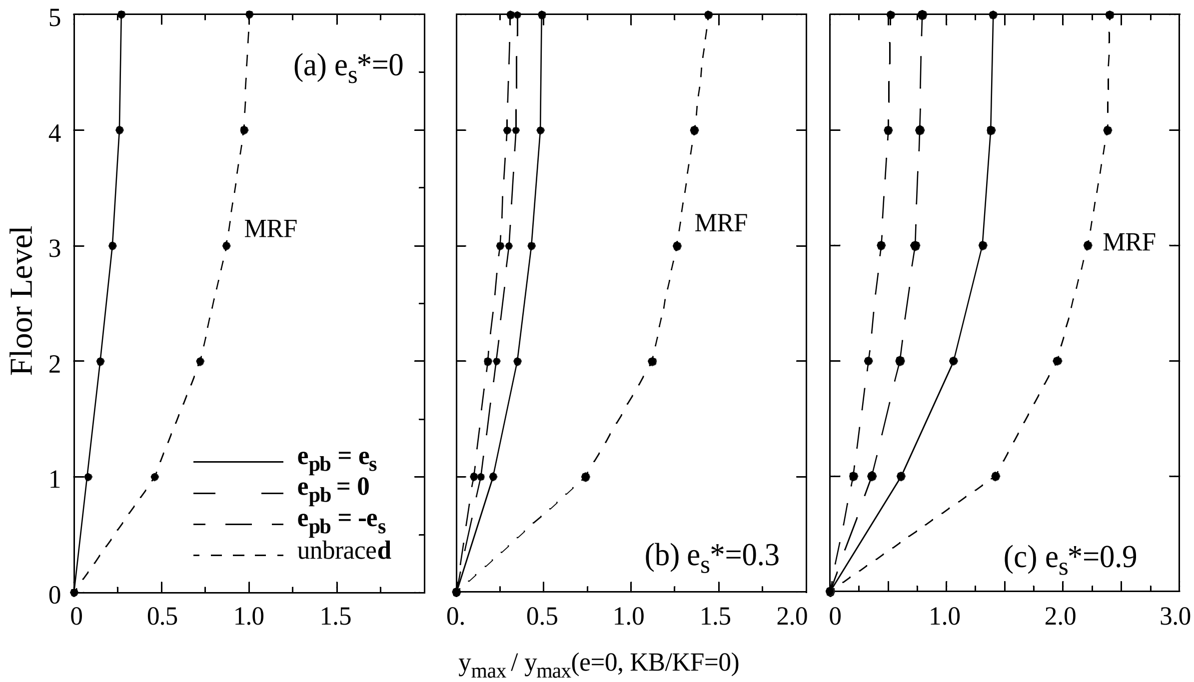

Figure 6: Five story structure - displacement envelopes for slip load redistribution (KB/KF = 5).

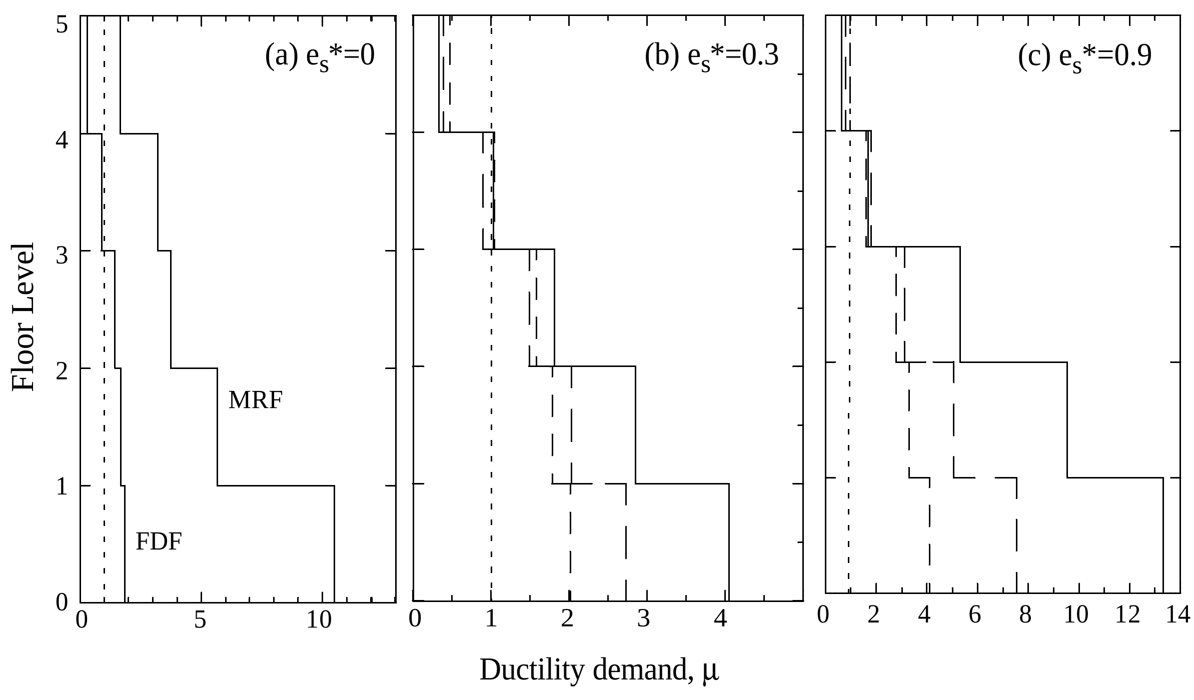

Figure 7: Five story structure - ductility demand envelopes for slip load redistribution.

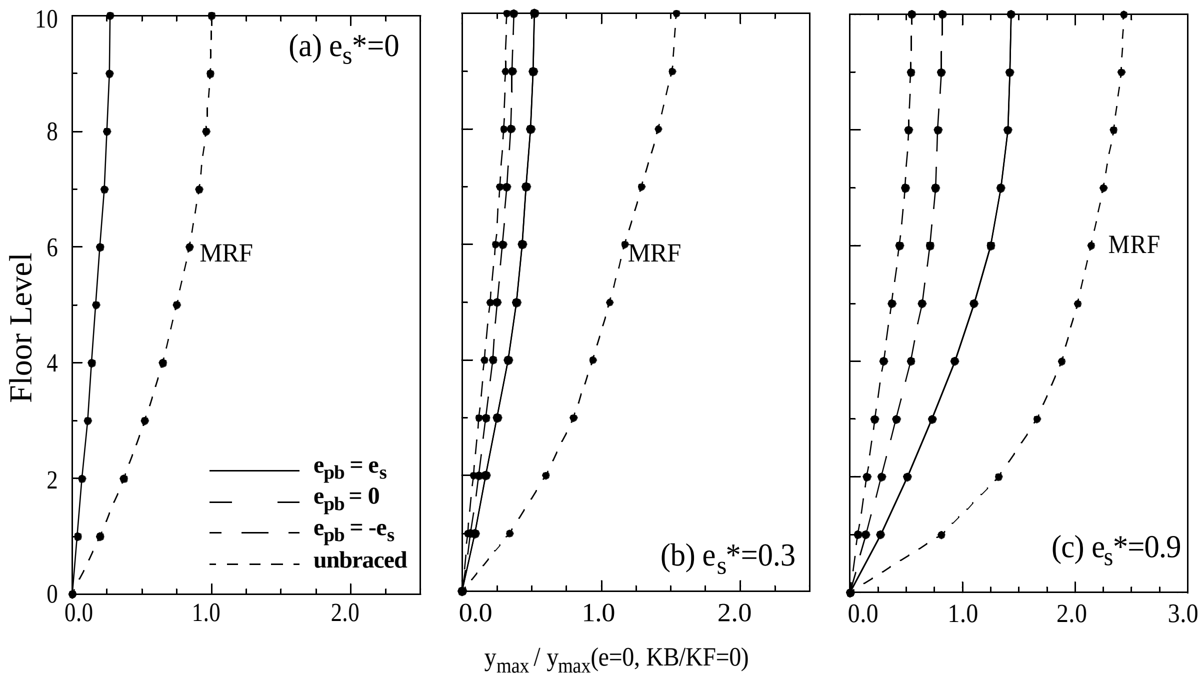

Figure 8: Ten story structure - displacement envelopes for slip load redistribution (KB/KF = 5).

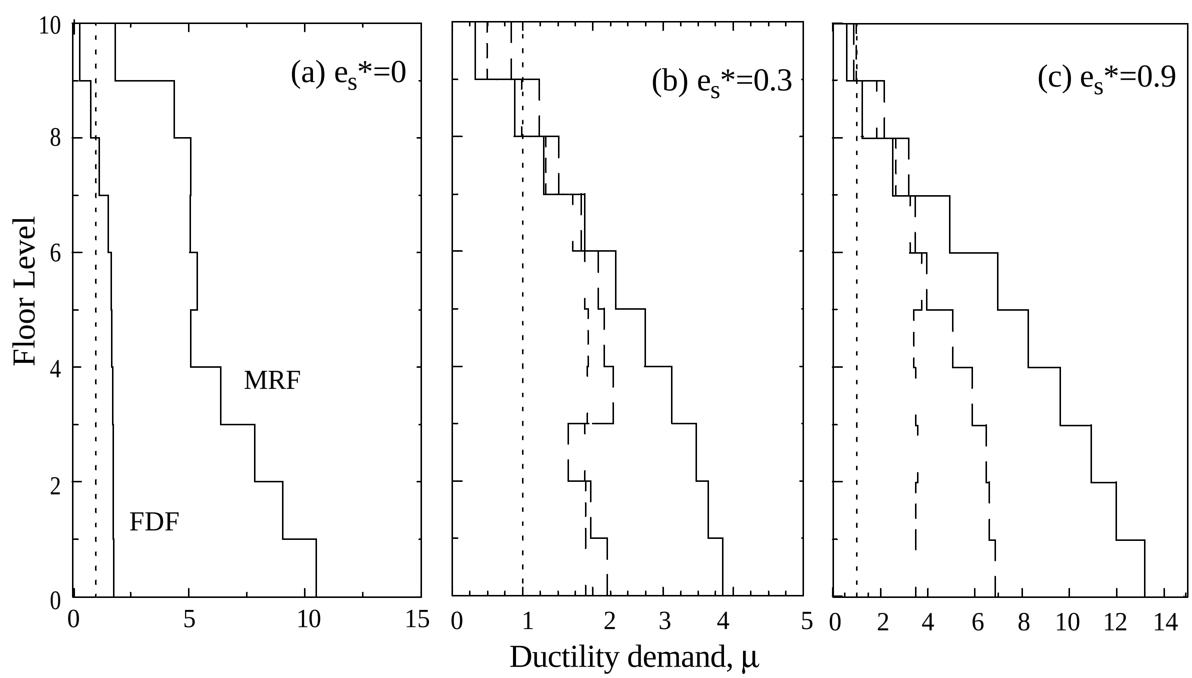

Figure 9: Ten story structure - ductility demand envelopes for slip load redistribution.