SEISMIC RESPONSE OF BASE ISOLATED ASYMMETRIC SHEAR BUILDINGS

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SUMMARY

This paper investigates the effect of three alternative distributions of rigidity and strength among the bearings of bilinear hysteretic base isolation systems on the response of asymmetric low rise multistory buildings to three earthquake records. Changes in response due to shape variations in the bilinear response curve of the bearing and due to viscous damping in the superstructure are studied. It is shown that asymmetry in the response can be appreciably lowered when the centroid of the yield forces in the bearings coincides with the superstructure mass center. Adverse effects of the 1977 Rumanian earthquake are noted.

INTRODUCTION

Base isolation is a technique to protect building structures from the destructive effects of earthquakes by means of a mechanism that limits the forces transmitted from the soil to the building. This approach has become practical in recent years mainly due to developments in rubber technology as applied to elastomeric bearings.

To be effective a base isolation system must combine two basic features: horizontal flexibility and high energy dissipation. The reduced stiffness of the bearings shifts the fundamental frequency of the structure away from the energetic region of the earthquake spectrum, and their elastic-plastic or bilinear hysteretic properties limit the forces transmitted to the superstructure and dissipate energy.

A number of analytical investigations have been carried out on symmetric base isolated structures, and it has been shown that with properly chosen properties, appreciable reduction in shear and bending moments can be achieved without undue increase in lateral displacements. Experimental studies (e.g. Ref. 1) verified the predicted behavior of such structures. A large number of building structures are asymmetric in the sense that the axis of rigidity (CR) of the lateral load resisting system does not coincide with the mass centroidal axis (CM). This asymmetry is usually the result of deliberate design, but small eccentricities can be expected even in nominally symmetric structures due to inhomogeneities of material, inaccuracies in construction and uneven distribution of live loads.

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However, only a limited number of analytical studies were devoted to the effect of base isolation on asymmetric structures (Refs. 2,3,4). In fact, asymmetric structures can benefit from base isolation more than symmetric ones since, in addition to reducing base shear and moment, the base isolation system can be designed to reduce the effective asymmetry in the structure, thereby lowering the torque and the resulting displacements. This idea was apparently first proposed by Crosbie (Ref. 2) and then pursued by Lee (Ref. 3). Crosbie reasoned that by designing the center of yield forces of the base isolation system (CYF) to coincide with the mass center of the superstructure (CM), asymmetry in the post yield response would be substantially lowered. Lee suggested that the rigidity center of the base isolation system (CRB) be designed to coincide with the CM, thereby practically eliminating asymmetry in the elastic range. By keeping the yield stresses of all bearings at the same level, the base isolation system can be made to combine these two properties. This was the case with all the models analyzed by Crosbie and by Lee, so that the distinction between the two strategies was not made apparent.

Using a single story bilinear model, Lee (Ref. 3) found significant reduction in the torsional effects when CRB/CYF coincided with CM, compared with the case when the stiffness distribution in the base isolation system was proportional to the stiffness distribution in the superstructure (CRB at CR). However, Lee's study was restricted to single story structures which were not particularly realistic in the sense that the mass and stiffness were located at the corners of a square deck, leading to very large radii of gyration relative to the plan dimensions of the building. Moreover, no distinction was made between the two alternative design strategies for the reduction of torsional effects.

In an earlier study (Ref. 4) the authors extended Lee's work to multistory asymmetric shear buildings, with one axis of symmetry, rectangular in plan and having more realistic stiffness and mass distributions. Indeed, it was found that base isolation is very effective in lowering base shear as well as torque in asymmetric buildings (up to 10 stories) when excited by the 1940 El Centro earthquake acceleration record. It was also found that locating CRB/CYF at CM leads to better performance in terms of lateral roof displacements, compared with the case of proportional base isolation (CRB at CR). However, several important questions remained: the significance of coincidence of CYF and CRB, the effect of yield stress level and the slope of the post yield stiffness of the base isolation stress-strain diagram (K_2 in Fig. 2), the effect of viscous damping in the superstructure, and finally, the effect of different earthquake time histories on the response. The purpose of the present study is to address these problems.

MODELING OF STRUCTURE

Simple models of 2, 5 and 10 story asymmetric framed buildings as shown in Fig. 1 were considered. The lateral load resisting system in the direction of excitation consisted of three rigid frames arranged so that CR always lies in the line of action of Frame B. The lateral rigidity was distributed among the three frames so that the rigidity radius of gyration r_k about CR was equal to the mass radius of gyration r_m about CM. For small CR to CM eccentricities this arrangement results in close lateral and torsional frequencies, which is a common situation in tall buildings, and leads to higher response than expected from static considerations. The eccentricity e was varied in the range 0.1 r to 0.5 r by changing the relative lateral rigidities of frames A, B and C while keeping the total lateral and torsional rigidities intact. The uncoupled fundamental vibration periods of the unisolated (i.e. fixed base) structure, T_N^o were chosen as: T_2^o = 0.25 sec., T_5^o = 0.4 sec. and T_{10}^o = 0.8 sec., N denoting the number of stories. The total story weight was approximately 500 ton (1100 kip), and that of the foundation system was about 50 ton (110 kip).

The bearings used for isolating the base of the columns were modeled as bilinear hysteretic springs as shown in Fig. 2, with $K_1 = 5.0$ W/m, W = weight of building, and $K_2 = 0.2\ K_1$, but it was varied within the range $0.02\ K_1 < K_2 < 0.4\ K_1$ to study the effect on the response. Within the linear range this K_1 led to lengthening the fundamental periods to $T_2' = 0.79$ sec., $T_5' = 0.98$ sec. and $T_{10}' = 1.15$ sec. The yield force level F_y was set at 0.05W, which is believed to result in optimum response (e.g. Refs. 1,3). This level was then varied in order to examine the validity of this belief. The applicability of a bilinear model to practical base isolation systems may be questioned. However, among the simple modelling alternatives available to the authors, this model appeared to give acceptable fit to the response of several isolation devices in practical use.

Three design strategies for proportioning the rigidities and yield force levels among the bearings were considered: lateral rigidities of bearings proportional to frame rigidities (CRB at CR); rigidities and yield force levels of bearings arranged so that their rigidity center and yield force center coincide with mass center of superstructure (CRB/CYF at CM); rigidity center of bearings at CR but center of their yield forces at CM (CYF at CM). Locating CRB at CR for the latter case as well, represents just one choice of parameters for the CYF at CM case. It is convenient, since for e=o, this case becomes identical with the other two cases. This design also left the rigidity center of the secondary stiffnesses of the bearings K_2 at CR, since it did not appear practical to vary the K_2/K_1 ratios among the bearings under the three frames. Thus, the last case appears to be inferior in design compared with the CRB/CYF at CM case, but it permitted a separate study of the two cases.

For the purpose of analysis, the lateral displacements of the frames were assumed to be shear dependent. This is a reasonable assumption for non-slender rigid frames, and it permitted applying the axial force -shear force analogy (Ref. 5), in which the shear rigidity of a frame is replaced by an equivalent axial rigidity of a column. With this analogy it was possible to analyze the system by means of a nonlinear plane frame computer program - DRAIN-2D (Ref. 6), rather than by a program having a 3-dimensional capability. The equivalent axial force model is shown in Fig. 3.

For most of the analyses the NS component of the 1940 El Centro earthquake acceleration record was applied. In order to study the effects of different frequency contents on the response, the structures were subjected to the S69E 1952 Taft and the NS 1977 Rumanian earthquake records.

RESULTS

Due to space limitations only partial results pertaining mainly to 10 story buildings are presented. The beneficial effects of base isolation on the total base shear as well as on the horizontal roof displacement, discussed in some detail in Ref. 4, are shown in Figs. 4, 5 and 6, for the three alternative design strategies compared in this study. It is seen that the total base shear is hardly affected by eccentricity and by the distribution of strength and stiffness among the bearings. This is not the case with roof displacements, although the differences between the CYF and CM and the CYF/CRB at CM designs are relatively minor up to the largest eccentricity considered (e = 5.0m = 0.5r). However, the horizontal displacements of frame B at base, representing the movements of flexible connections for utilities (water, gas etc.), are practically unaffected by eccentricity for all design alternatives.

The effect of yield force level F_y of the bearings on the response for e = 3.0m = 0.3r, is shown in Figs. 7 and 8. Marked differences between the CYF at CM or CYF/CRB at CM designs and the CRB at CR design can only be observed in the roof displacements for the lower range of F_y. Variations in the secondary slope of force displacement curve of the bearings are considered in Figs. 9 and 10. The maximum response computed over the five eccentricities (e = 0.1r - 0.5r) is given. It is seen that the maximum base shear is not affected by the design strategy, whereas maximum roof displacements are quite sensitive. The superiority of the CYF/CRB at CM design over the other two alternatives for reducing the roof displacement when K_2/K_1 is large is evident. The minor effect of viscous damping in the superstructure on the displacements of base isolated structures can be seen in Fig. 11. The effect of this damping on base shear is negligible (not shown). However, with increasing damping the CRB at CR design is more strongly affected than the other two alternatives.

Only preliminary results for the 1977 Rumanian earthquake have so far been obtained. The appreciable increase in roof displacements compared with the fixed base case is immediately apparent (Fig. 12). Larger base shears were also obtained for the lower eccentricities (not shown).

DISCUSSION AND CONCLUSIONS

The results reported so far confirm earlier findings that bilinear base isolation can be very effective in reducing base shear and torque in low rise multistory buildings, and also roof displacements for the taller buildings (10 stories). When the centers of rigidity and of yield forces in the base isolation system are both located directly below the mass center of the superstructure (CRB/CYF at CM), rotations are practically eliminated, even for moderate eccentricities (e = 0.5r). This is the case not only for the 1940 El Centro earthquake record (Ref. 4) but also for the 1952 Taft record. Although the base shear is not affected by the variations in strength and stiffness distributions, it is seen that the CRB/CYF at CM design leads to somewhat lower displacements at higher eccentricities than the CYF at CM design, and to appreciably lower response than the CRB at CR alternative. It appears therefore that when CYF is located at CM, displacements are not particularly sensitive to the stiffness distribution. This gives the engineer some latitude in designing the bearings.

This study gave additional confirmation to the belief that the optimum yield force level F_y of the force displacement response curve for controlling base shear and roof displacement is approximately five percent of gravity. The force displacement response of practical base isolation devices cannot usually be predicted with great accuracy. Thus, the effects of varying K_2 can be useful for estimating bounds on the response. It is seen that the base shear is practically proportional to K_2, whereas the displacements are not sensitive to such changes. The minor role played by superstructure viscous damping in base isolated structures is not surprising, although its beneficial effect in reducing displacements, particularly of structures with proportional bearings (CRB at CR), should not be overlooked. It may be concluded that the results presented herein which were derived for undamped structures are also applicable to lightly damped ones.

The response of lower rise base isolated asymmetric buildings to the 1952 Taft earthquake record (not shown) is similar to that described in Ref. 4 for the 1940 El Centro record, i.e., relative to the fixed base response, drastic reductions in base shear and torque, but increasing lateral displacements for the 5 and 2 story structures are predicted. As in the 10 story structures, there is practically no difference in response between the CRB/CYF at CM and the CYF at CM designs.

The preliminary results for the 1977 Rumanian earthquake record are useful reminders that a base isolation system which is effective in shielding a structure from the 1940 El Centro and the 1952 Taft earthquakes, is not necessarily suitable for protecting this structure from an earthquake having different frequency and pulse duration characteristics. The fundamental period of the base isolated 10 story symmetric structure is 1.15 sec., which already is in the high acceleration spectrum range. The bilinear force displacement relationship of the bearings may shift the response of the eccentric structures further into the energetic range of the earthquake, rather than away from it, as is the case with the two California earthquakes. Note, however, the better performance of the CRB/CYF at CR design compared with its two alternatives.

Variations in K_1 are being studied, yet, the practical range of K_1 is probably quite narrow (Ref. 3), since good reduction in shear combined with acceptable displacements (for wind as well) must be provided. The seismic behavior of asymmetric base isolated structures appears to depend on the frequency content of the ground motion. The study of their response to different earthquake records is now in progress.

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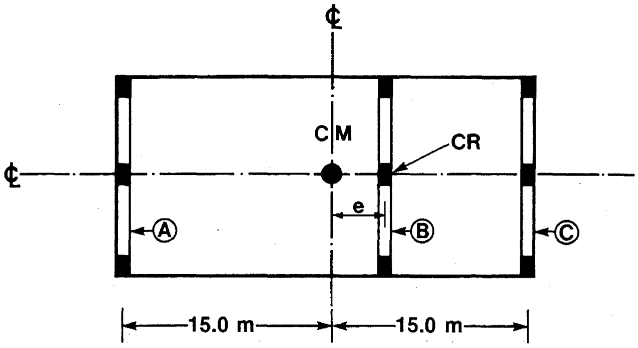

Fig. 1. Typical Floor Plan of Structural Model

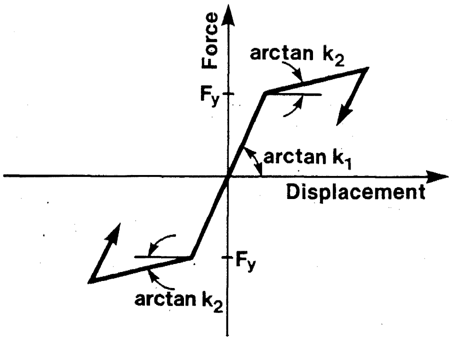

Fig. 2. Force Displacement Relationship for Bearings

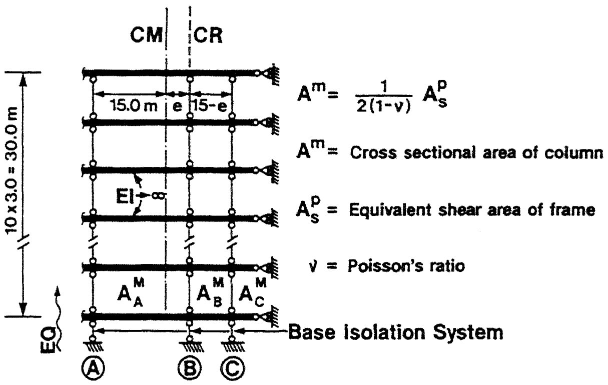

Fig. 3. Analysis Model for 10 Story Building

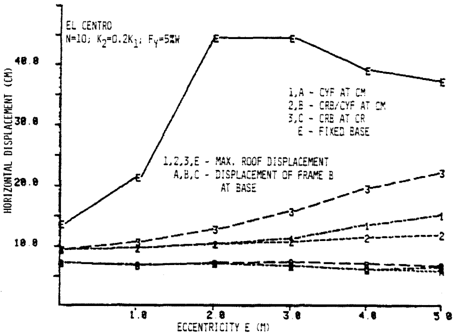

Fig. 4. El Centro: Horizontal Roof Displacement vs. Eccentricity

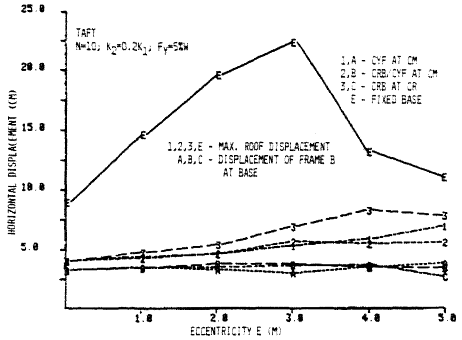

Fig. 5. Taft: Horizontal Roof Displacement vs. Eccentricity

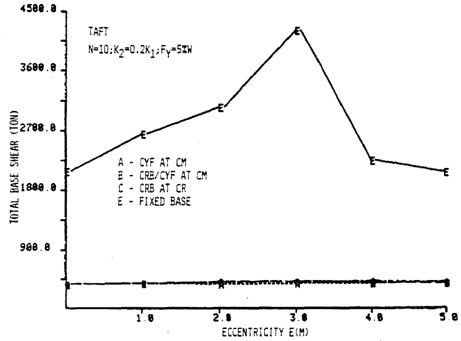

Fig. 6. Taft: Total Base Shear vs. Eccentricity

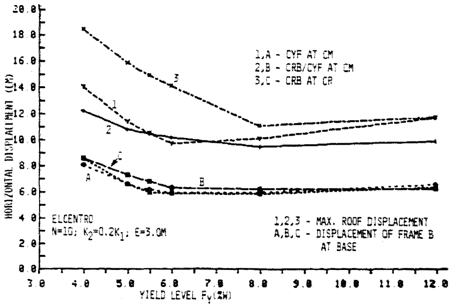

Fig. 7. El Centro: Horizontal Roof Displacement vs. Yield Force Level (%W)

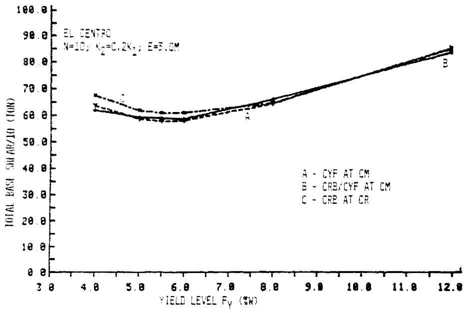

Fig. 8. El Centro: Total Base Shear vs. Yield Force Level (%W)

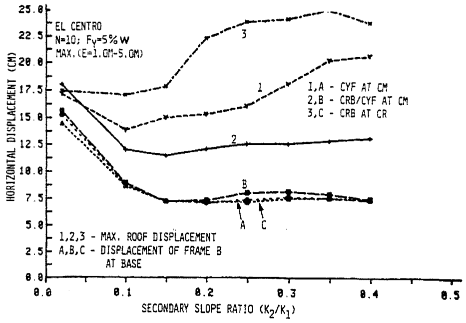

Fig. 9. El Centro: Horizontal Roof Displacement vs. Secondary Slope Ratio K_2/K_1

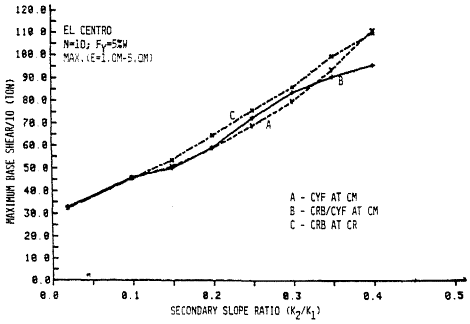

Fig. 10. El Centro: Maximum Base Shear vs. Secondary Slope Ratio K_2/K_1

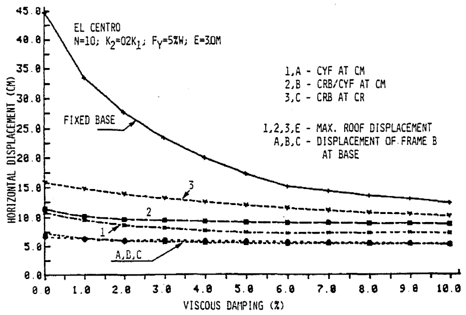

Fig. 11. El Centro: Horizontal Roof Displacement vs. Viscous Damping Ratio(%)

Fig. 12. Rumania: Horizontal Roof Displacement vs. Eccentricity