Seismic base isolation of asymmetric shear buildings

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(Received March 1985; revised August 1985)

Effects of alternative designs of bilinear base isolation systems on the seismic response of ten, five and two-storey shear buildings, with one axis of symmetry consisting of three parallel frames, are investigated. Analyses with the El Centro and Taft records predict appreciably lower shear forces and torques compared with the unisolated case, whereas lateral roof displacements are likely to increase for the lower structures. Optimum levels of yield force, and secondary to primary slope ratio of the isolation system hysteretic force displacement relationship, are discussed. Locating the centres of rigidity and the yield forces of the bearings at the mass centre of the superstructure appears to be the best strategy for reducing twist. Other alternatives, however, may reduce base motion and inter-storey shear even more. It is shown that increased shear forces and very large displacements may result when the 1977 Rumanian earthquake record is applied, suggesting that a decision regarding the use of base isolation depends on the earthquake characteristics at the site.

Key words: earthquake resistant design, base isolation, asymmetric structures, shear buildings

Base isolation is used to protect structures from the destructive effects of earthquakes. In many applications, base isolators consist of laterally flexible, yet vertically rigid bearings, which include hysteretic energy absorbers. The response of the superstructure is lowered mainly as a result of two characteristics of the isolation system: the reduced lateral stiffness which shifts the fundamental frequency of the structure away from the energetic region of the earthquake spectrum and the elastic-plastic or bilinear hysteretic behaviour of the isolators, which limits the forces transmitted to the superstructure, and dissipates energy. The reduced level of forces transmitted to the building through the base isolation system practically eliminates the need to design the superstructure for seismic loads. Therein lies the economic advantage of the approach.

Many investigations have been carried out on base isolated structures. Most of this work, however, involved symmetric structures free of torsional effects. It has been shown that, for structures with properly chosen isolation system properties, appreciable reduction in shears and moments can be gained. This reduction could be achieved without significant increase in the lateral displacements. Torsional response of structures is due either to deliberate asymmetric design, or in nominally symmetric structures, to small eccentricities caused by inhomogeneities in material, inaccuracies in construction, and uneven distribution of live loads. For simple buildings, this asymmetry can be modelled as an offset of the axis of rigidity (CR) of the lateral load resisting system, with respect to the mass centroidal axis (CM). For such structures, it is also possible to reduce the effective eccentricity, and as a result, to lower the shears and moments in the structure due to rotation about the vertical axis. Yet, only a small number of studies deal with the effect of base isolation on asymmetric structures.

The idea of using base isolation to reduce torsional effects was apparently first proposed by Crosbie[1] and then pursued by Lee.[2] Crosbie reasoned that by designing the centre of yield forces of the base isolation system (CYF) to coincide with the mass centre of the superstructure (CM), asymmetry in the post-yield response would be substantially lowered. Lee suggested that the rigidity centre of the base isolation system (CRB) be designed to coincide with the CM, thereby practically eliminating asymmetry in the elastic range. For an equal level of yield stresses in all the bearings, the base isolation system combines these two properties. This was the case with all the models analysed by Crosbie and Lee, so that the distinction between the two design strategies was not made apparent.

Lee studied only single storey structures, having four corner columns, and masses concentrated at the corners. He showed that there is a significant reduction in the tor-

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sional effects when CRB/CYF coincides with CM, compared with the case where CRB/CYF coincides with CR of the superstructure. The structures analysed were not particularly realistic in the sense that the radii of gyration, both for the mass and stiffness, were very high compared with the dimensions of the building.

In this work the results of an extensive parametric study on the earthquake response of multi-storey asymmetric shear buildings are presented.[3,4] The model structures have more realistic mass and stiffness distributions than those analysed by Lee. Several parameters affecting the response are studied: (a) CRB location: at CM and at CR; (b) effect of CYF location: at CM and at CR; (c) viscous damping in the superstructure; (d) base isolation characteristics, i.e. yield level and post yield stiffness of the isolators. The latter parametric study is particularly pertinent, in view of the variability in stiffness properties of bearings commonly used in seismic isolation, and the limitations of the commonly used bilinear models in describing the hysteretic behaviour of these bearings.[5] All these factors are investigated using the time histories for three earthquake records: El Centro 1940, Taft 1952, and Rumania 1977.

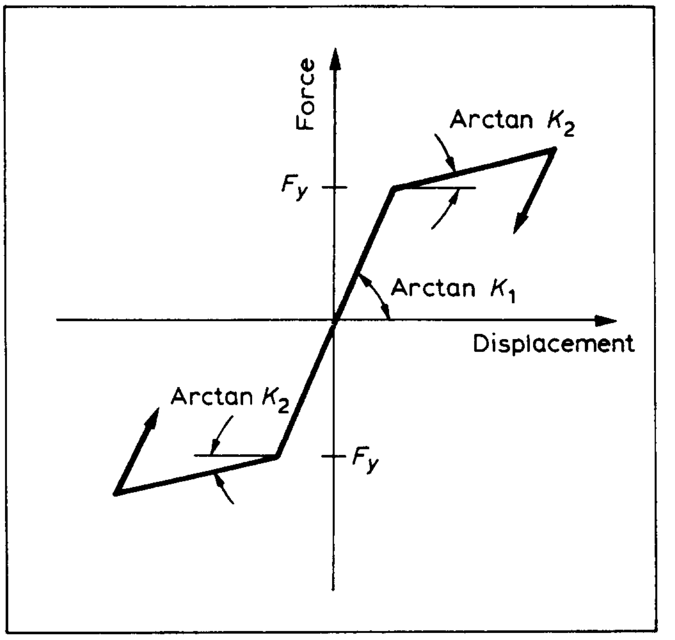

Figure 2 Force displacement relationship for bearings

The model

A typical floor plan of the asymmetric frame structure used for this study is shown in *Figure 1*. Three models with two, five and ten storeys respectively and having this floor plan were studied. The floor slabs were assumed to be rigid in their own plane. The lateral load resisting system in the direction of excitation consisted of three rigid frames arranged such that CR always lay in the line of action of frame B. The lateral rigidity was distributed amongst the three frames, A, B and C, so that the stiffness radius of gyration, r_k, about the CR axis, was equal to the mass radius of gyration, r_m, about the CM axis, assuming uniform distribution of mass on the floor.

This arrangement was adopted since the modal coupling in the linear range causes the dynamic response of structures with close lateral and torsional frequencies to exhibit stronger torsional effects than predicted by static analysis, i.e. when the inertia forces are statically applied at the mass centre.[6] The eccentricity e was varied from zero to one-sixth of the width (i.e. 5.0 m) by altering the relative lateral stiffnesses of frames A, B and C, while keeping their total lateral and torsional stiffnesses intact. The uncoupled

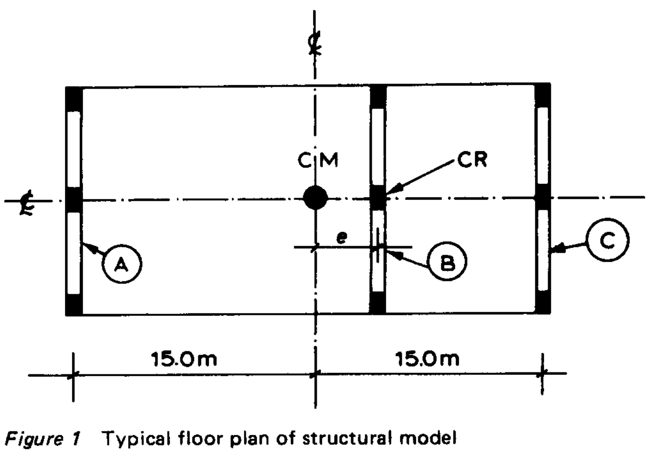

Figure 1 Typical floor plan of structural model

($e = 0$) fundamental periods of vibrations for the unisolated structure (fixed base), T_1 were chosen as 0.25, 0.4 and 0.8 s for the two, five and ten storey buildings respectively. The storey weight was taken as 500 metric tons, and at the base level as 50 metric tons.

The isolation system of each frame was modelled as a bilinear hysteretic spring, with initial lateral stiffness $K = 5.0W/\text{m}$, post yield lateral stiffness $K = 1.0W/\text{m}$, and yield force level $F = 0.05W$, where W is the total weight of the structure[2] (*Figure 2*). The fundamental periods of the three symmetric isolated structures were found to be $T_1 = 0.8$, 0.95 and 1.15 s respectively and were varied in order to study their effects on the structural response. The choice of the strength and stiffness parameters of the bearings in this study is based on earlier experimental and analytical studies. It is important that F_y be set such that the response to wind loading remains in the elastic range. At a level of 5% of weight the yield strength also provides hysteretic damping which reduces the lateral displacements, without unduly increasing the forces transmitted to the superstructure. Indeed this level is considered to be optimal.[7–9]

The most commonly used bearing for seismic isolation, is the lead-rubber bearing.[5] It consists of a laminated elastomeric bearing similar to those used in bridges, with initial stiffness and damping provided by a lead plug inserted through the centre (*Figure 3*). Experimental studies[5] have shown that lead can sustain unlimited cyclic plastic deformations without failure, and that the hysteretic loop can realistically be approximated by a bilinear model with the secondary slope K_2 being approximately parallel to the elastic slope of the bearing without the lead plug, with 40% maximum variations. More problematic, however, is the primary slope K_1. On the basis of his results Robinson suggested that, for the ratio of the cross-sectional areas of the rubber and lead used in the tests, K_1 should lie in the range of $5K_2$ to $15K_2$. Since the actual hysteresis loops, however, are rounded at the corners due to softening, the bilinear model based on these properties may overestimate the energy absorption by 20%.

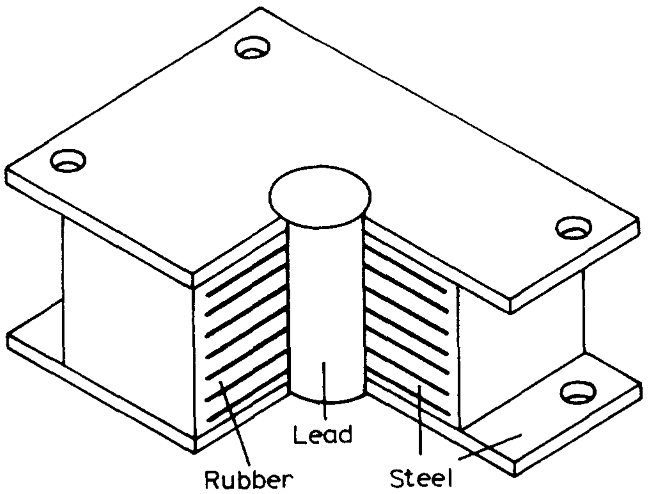

Figure 3 Lead-rubber bearing[5]

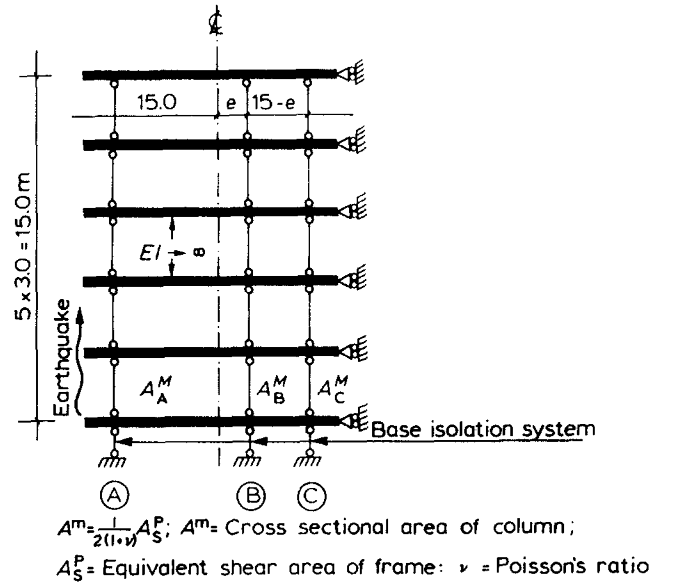

Figure 4 Analysis model for five storey building

Three design strategies for proportioning the rigidities and yield force levels among the bearings were considered: (1) lateral rigidities of bearings proportional to frame rigidities (CRB at CR); (2) rigidities and yield force level of bearings arranged so that the rigidity and yield force centres coincide with the mass centre of the superstructure (CRB/CYF at CM); (3) rigidity centre of bearings at CR but centre of the yield forces at CM (CYF at CM). Locating CRB at CR for the last case as well, represents just one choice of parameters for the CYF at CM case. It is convenient, since for $e = 0$, this case becomes identical with the other two cases. The latter design also left the rigidity centre 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.

The problem of nonlinear dynamic analysis was solved by using the two-dimensional program DRAIN-2D.[10] This was possible because the lateral displacements of the of the frames were assumed to be shear dependent. As is well known, this assumption is reasonable for non-slender rigid frames. Using the shear–axial force analogy[11] it is possible to replace the shear rigidity of a frame with the equivalent axial rigidity of a column. The modified planar model is shown in *Figure 4*. With reference to *Figure 1*, the planar analogy implies that bending of the columns out of the plane of the frames (y direction) due to twist, and the effect of out of plane forces on the yield level of the bearings are ignored. For the problem at hand the errors due to this simplification are believed to be minor and conservative.

Results

(a) *Base and superstructure shear*

In *Figures 5–7* the total base shear (i.e. the sum of the maximum frame shear forces at the base) of the 10 storey structure is plotted against eccentricity, for the three alternative design strategies compared in this study, as well as for the unisolated or fixed base structure. For the two California earthquakes, El Centro and Taft, a very significant reduction in the total base shear is obtained, regardless of the base isolation design strategy adopted. The

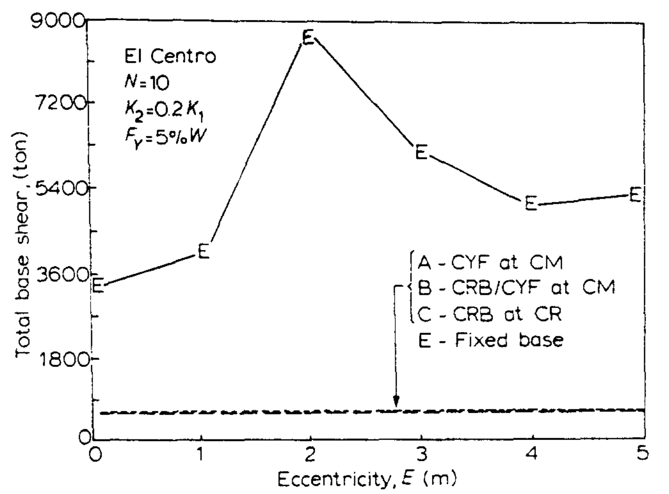

Figure 5 El Centro: total base shear against eccentricity

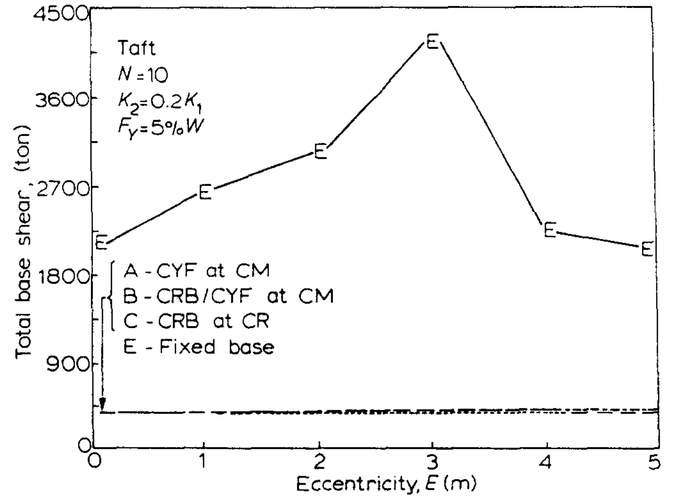

Figure 6 Taft: total base shear against eccentricity

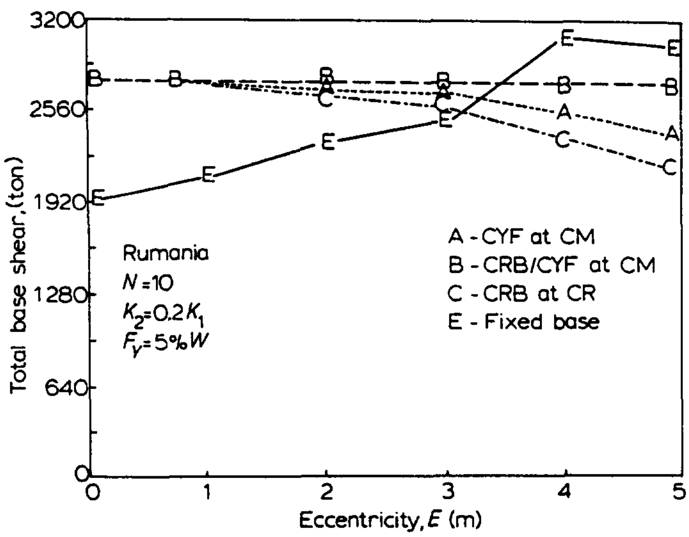

Figure 7 Rumania: total base shear against eccentricity

differences between the three sets of results are minor. This is not the case for the Rumanian earthquake: for low eccentricities there is some increase in the total base shear, and some reduction only for high eccentricities. The values obtained for the three design strategies differ, and the difference is more significant as the eccentricity increases, up to approximately 20% when the CRB at CR option is compared with the CRB/CYF at CM option. The failure of the base isolation to reduce the shear forces resulting from the Bucharest record, and possible remedial measures are discussed in the concluding section of the paper for the California earthquakes.

The results for the two and five storey buildings are similar, although even more dramatic reductions in base shear were noted for some of these structures. Due to space limitations they are not shown here, but some typical results can be found elsewhere.[3]

The variations of the total shear along the height for the two, five and ten storey structures were also computed for the three design strategies using the El Centro earthquake time history. These were compared with the total shears of the corresponding fixed base structures. The results, not presented because of space limitations, show that the shear ratio (isolated/fixed base) was practically constant along the height of the two storey structures for all the design strategies. For the CYF at CM option of the five and ten storey buildings the shear ratio remained practically constant along the height, as did the CRB at CR option. For these buildings, however, the shear ratio of the CRB/CYF at CM option was 40% higher than for the CYF at CM case.

(b) *Maximum roof displacement*

Figures 8–10 show the maximum roof displacements for the 10 storey model. As for the base shear, the results for the Rumanian earthquake are totally different from those for the California earthquakes. Significant reduction of the roof displacements is achieved for these two earthquakes. For the Rumanian earthquake this base isolation system fails to serve its purpose, and as for the base shear, the response increases to much higher values. Amongst the three isolation system design strategies, the CRB/CYF at CM strategy gives lower displacement amplitudes at roof level for almost all the eccentricity range tested. The other two strategies give larger displacements by up to 70%. Note that the values in the figures were obtained for undamped structures and therefore the fixed base results should plot much lower than shown, i.e. the response ratios (isolated/fixed base) are in fact much higher.

For the California earthquakes the displacements of the two and five storey structures were not reduced significantly by base isolation, and in the two storey structures they even increased compared with the unisolated structure.

For all structures, the torsional response was almost eliminated when the first two design strategies (CYF at CM and CRB/CYF at CM) were adopted. For the third strategy some torsional effects still remained, as can be seen from the results for high eccentricities.

(c) *Maximum base displacement*

In base isolated structures, base displacement may control the design because all the utilities connect underground to the base. These often require special flexible connections, which are expensive to install and maintain, and the large gaps between the building and its surroundings require special detailing. *Figures 8–10* show the displacement of the centre frame, frame B, for the three earthquakes. It can be seen that for the California earthquakes the base displacements are almost identical for the three design strategies of the base isolation system, but for the Rumanian earthquake the reduction in base motion, with increasing eccentricity is quite substantial (up to 50%) for CRB at CR and CYF at CM as compared with CRB/CYF at CM.

(d) *Yield level of base isolators*

The effect of the yield force level of the bearings, F_y, is shown in *Figures 11 and 12* for a structure with $e = 0.3r = 3.0$ m excited by the El Centro earthquake. It can be seen that the differences in the base shear between the three strategies are negligible. Lower base shears result when the yield level F_y is 5–10% of the total weight of the structure, W. The horizontal roof displacement varies for the different designs: the CRB at CR option gives higher roof displacements, and the other two alternatives are fairly close. The base displacements are practically the same. Note that in this range the response is practically flat both for the shear and the displacements.

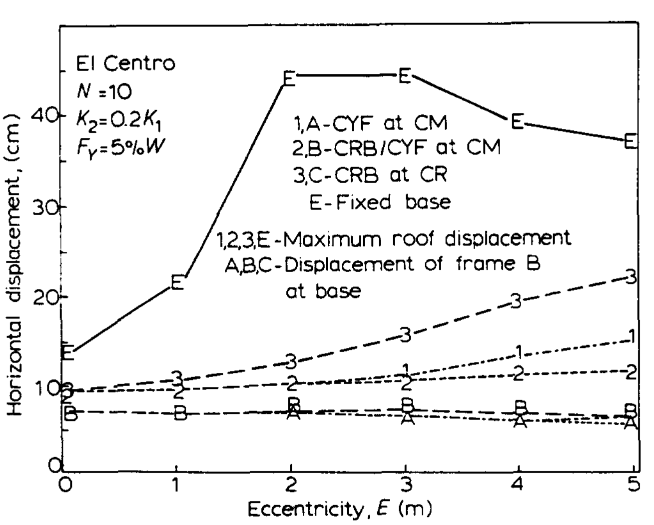

Figure 8 El Centro: horizontal roof and base displacement against eccentricity

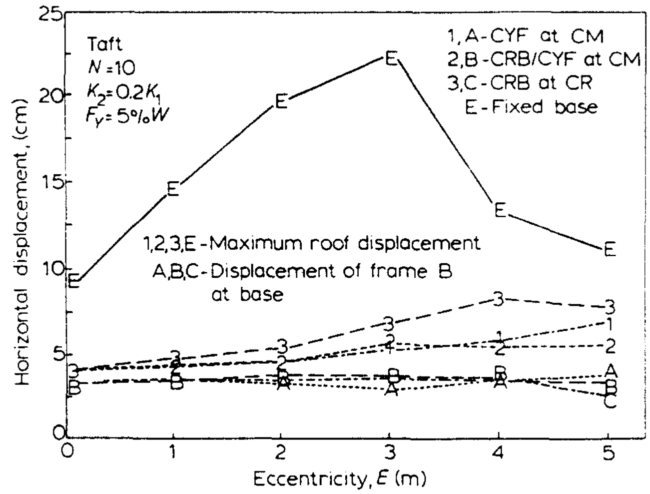

Figure 9 Taft: horizontal roof and base displacement against eccentricity

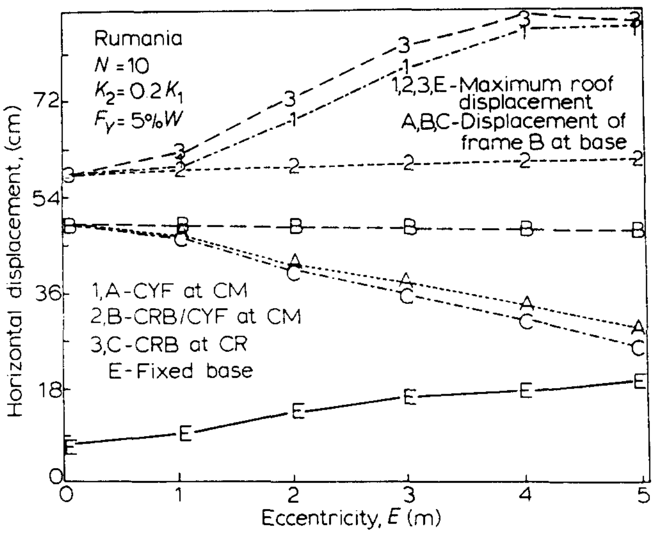

Figure 10 Rumania: horizontal roof and base displacement against eccentricity

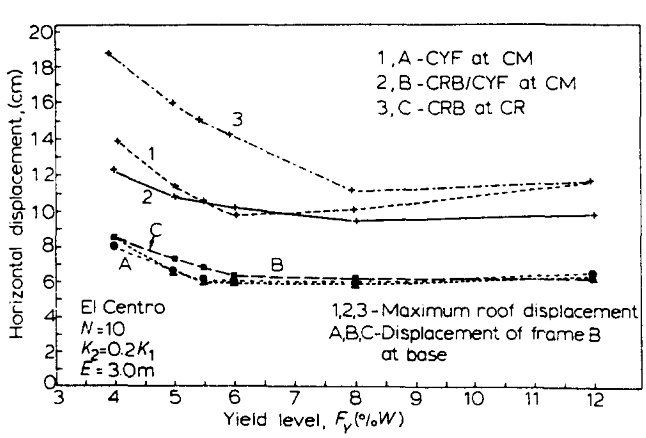

Figure 11 El Centro: horizontal displacement against yield force level (%W)

(e) *Secondary slope*

As noted in an earlier section, it is not possible to predict exactly the secondary slope ratio K_2/K_1 for the lead-rubber bearings, and therefore, it is important to study the effect of varying this parameter within the

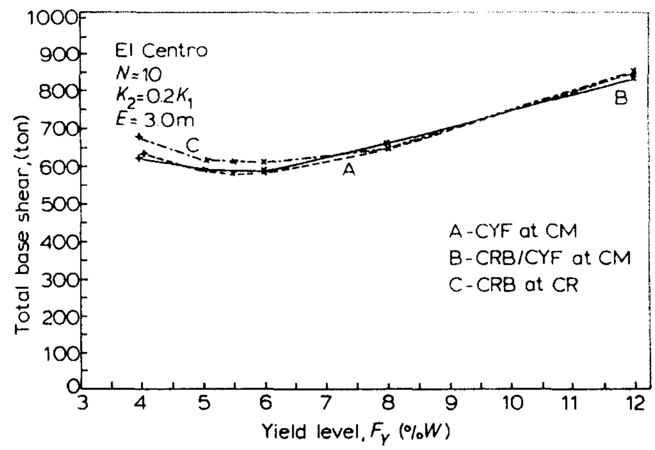

Figure 12 El Centro: total base shear against yield force level (%W)

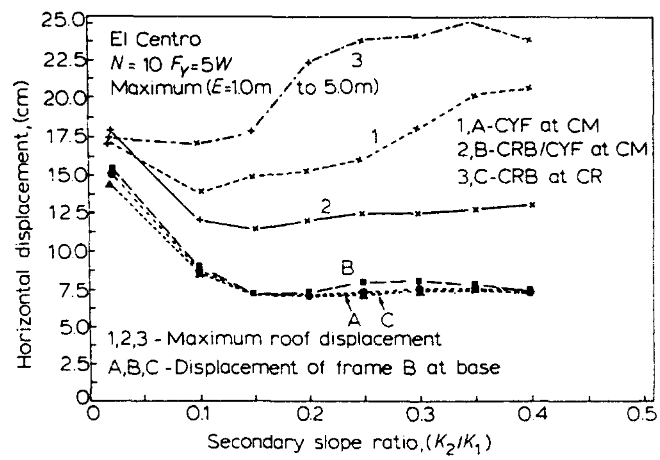

Figure 13 El Centro: horizontal displacement against secondary slope ratio K_2/K_1

expected range. *Figures 13 and 14* show the effect of the ratio K_2/K_1 on the displacements and base shear forces. The values shown are the maximum displacements and maximum total base shear that resulted for the five eccentricities, $0.1r$–$0.5r$. It can be seen that the total base shear is not affected by the design strategy and, as expected, the values of total base shear increase with the secondary slope ratio, since the isolation system becomes more rigid. Base displacements are also not affected by the design strategy. The CRB/CYF at CM strategy is seen to yield lower roof displacements than the other two. From the figures it can be seen that for $K_2/K_1 > 0.1$ the roof and base displacements are practically constant, whereas the base shear forces still increase.

(f) *Viscous damping*

The effect of viscous damping in the superstructure on the response is shown in *Figure 15*, for the El Centro record, and it is seen that this damping has practically no effect on the magnitude of forces and displacements of the base isolated structures, whereas, as is well known, it is quite effective in reducing the response of unisolated structures. It will be recalled that in all the parametric studies reported so far in this study the superstructure was assumed to be free of damping. The present results suggest that for base isolated structures such an assumption is plausible. Since, however, superstructure damping affects

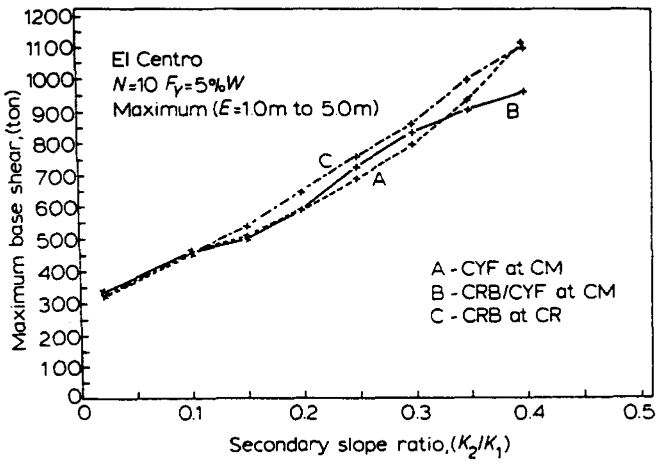

Figure 14 El Centro: maximum base shear against secondary slope ratio K_2/K_1

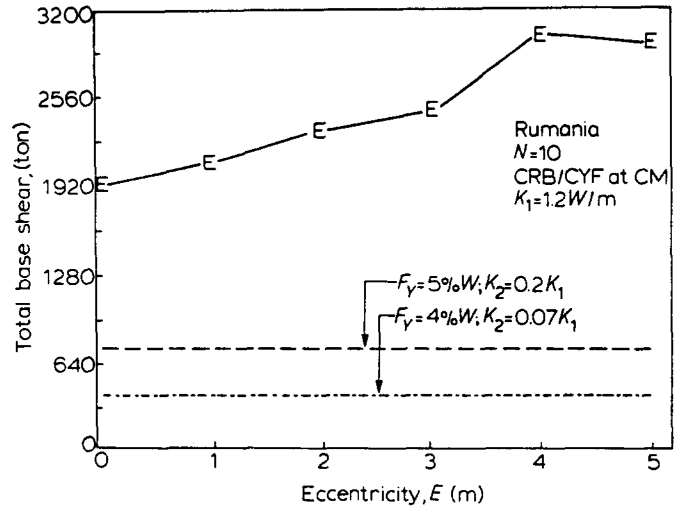

Figure 16 Rumania: total base shear against eccentricity (softer isolation system)

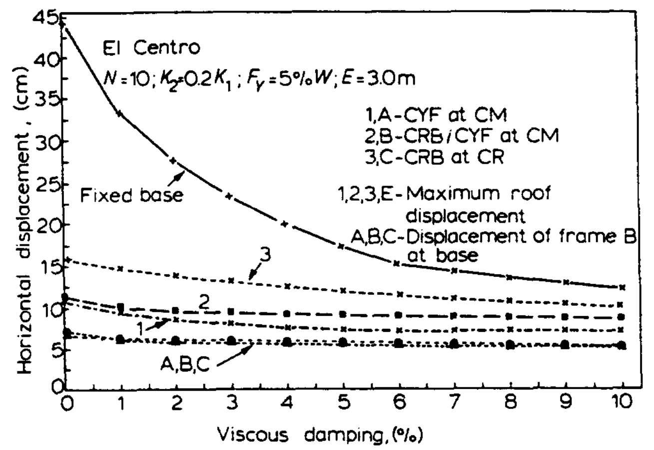

Figure 15 El Centro: horizontal displacement against viscous damping ratio (%)

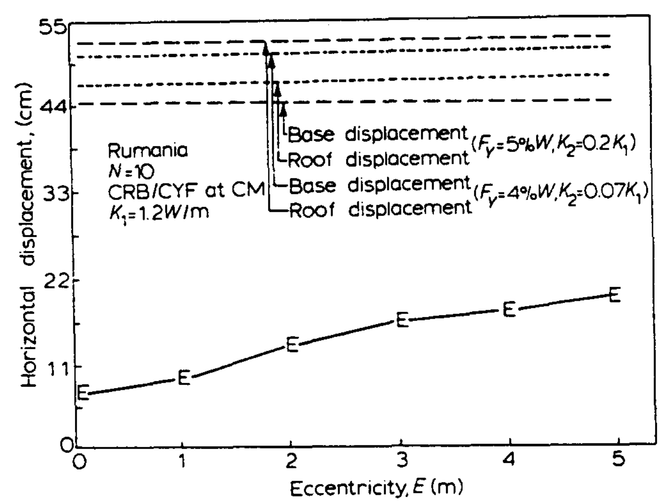

Figure 17 Rumania: horizontal roof and base displacement against eccentricity (softer isolation system)

the response of unisolated structures quite strongly, it has to be allowed for when comparing the responses of the two systems.

Discussion and conclusions

The results of an extensive parametric study on the effect of a bilinear hysteretic base isolation system, on the seismic response of two, five and ten storey shear buildings have been reported. The main design and base isolation parameters have been varied within their practical range, and three alternative design strategies for the distribution of strength and stiffness among the base isolating bearings have been compared.

The main findings of the study are that base isolation through bilinear bearings can be very effective in reducing shear, and in practically eliminating torque and twist in low rise multistorey buildings, without unduly increasing the horizontal displacements. These conclusions, however, are valid for the California type earthquakes, such as the 1940 El Centro and the Taft acceleration time histories, which are characterized by relatively high spectral ordinates at low natural periods.

Results for the Bucharest record of the 1977 Rumanian earthquake, with peak spectral acceleration at 1.7 s[12] show quite clearly that base isolation systems, with properties effective in reducing the response to California type earthquakes, are not necessarily applicable to 'low frequency' earthquakes. One may argue that this is because the base isolation system was not designed to be sufficiently soft so as to shift the response beyond the high energy range of the spectrum. For this purpose, the stiffness of the base isolation system was lowered to obtain $T_1 = 2.0$ s for the ten storey symmetric structure. Two alternative designs were analysed: (1) $K_1 = 1.2W$/m; $K_2/K_1 = 0.2$ and $F_y = 0.05W$; (2) $K_1 = 1.2W$/m; $K_2/K_1 = 0.07$ and $F_y = 0.04W$. The results are given in *Figures 16 and 17*. It is seen that although base shear has been appreciably reduced, the displacements are still very large. Further lowering of K_1 and F_y is not practicable because of the limitation imposed by wind design requirements, unless special wind restraints are installed. Note that with such modifications the predicted displacements due to the El Centro record are doubled (not shown).

The following observations are therefore pertinent only to base isolated structures excited by 'high frequency' earthquakes. Base and interstorey shear always appear to be lowered by base isolation, and torque is practically eliminated, even for moderate eccentricities ($e = 1/6$ of width), irrespective of the design strategy adopted for the isolation system. The effect on roof displacements is quite different. Base isolation appears to increase these displacements for the lower buildings (two storeys), compared with the unisolated case, but base isolated ten storey structures may displace less than similar unisolated ones. The distribution of strength and stiffness between the bearings does, however, affect the response, and this effect is summarized below.

The lateral displacements at base level which are important for the design of utilities and gaps, have also been studied, and it is concluded that these can be reduced to a manageable level.

This study confirmed earlier findings[7,8] that a yield force near 5% of weight is indeed an optimum level for the bearings of a bilinear base isolation system. The optimum secondary to primary slope ratio of the bilinear force displacement relationship has been found to lie in the range of 10-20%. Indeed, the properties of lead-rubber bearings in present use are in this range.[5] It is also important to note that the important response quantities – base shear and roof displacement – were not found to be particularly sensitive to small variations in K_2/K_1, and in F_y near their optimum levels. Therefore, the fact that the properties of standard lead-rubber bearings can only be predicted within a relatively wide range has little significance for design.

The effect of superstructure damping (assumed to be viscous) on the response of base isolated structures has been found to be quite small. This follows from the fact that, due to the high flexibility of the bearings, the superstructure moves practically as a rigid body. Thus, superstructure damping is not an important design parameter for base isolated structures.

The design of base isolation systems for asymmetric structures offers much more scope to the engineer than design for symmetric ones. It appears that the force response is affected by the relative locations of the mass axis, centre of rigidity (elastic centre) of the superstructure and of the bearings, as well as their yield force centre. Whereas the properties pertaining to the superstructure cannot easily be modified, this is not the case with those of the isolators. By designing the centre of rigidity as well as the yield force centre of the base isolation system to coincide with the mass axis of the structure, torque can effectively be eliminated for the whole range of eccentricities likely to be encountered in practice (up to 1/6 of width). This particular choice of parameters, however, does not necessarily ensure that interstorey shear or base displacements would be the lowest. In fact, it was shown that locating the centre of yield forces at the mass axis, but leaving the centre of rigidity of the bearings at the centre of rigidity of the superstructure, does not alter the results appreciably, and may even lower the interstorey shear. Designing the base isolation system, however, to be proportional in strength and stiffness to the superstructure tends to increase the roof displacements. On the other hand, this design may lower the base displacements for the larger eccentricities.

The present paper focused on the effect of base isolation on the seismic response of asymmetric shear buildings. This choice was basically a matter of convenience because the shear-axial force analogy permits planar modelling of asymmetric shear buildings with one axis of symmetry. The out of plane effects, including yielding with interaction of the bearings, which are likely to lower the response somewhat, were not modelled. Although planar modelling of these effects is possible,[13] it is outside the scope of the present paper. It is believed, however, that the conclusions drawn from the parametric study are also relevant to other types of structural configurations such as flexural walls and wall-frame systems.

The response to vertical ground acceleration has not been addressed in this paper but, since the vertical stiffness of rubber bearings is very high, no amplification of the vertical response above the level predicted for the fixed base structure should be expected.

It is thus seen that properly designed asymmetric buildings can in the right circumstances benefit from base isolation perhaps even more than symmetric ones, and it is hoped that this paper will contribute to a better understanding of their behaviour.

Acknowledgments

The authors are indebted to the reviewers for constructive criticism. This research was supported by the Israel Electric Corporation.

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