5th Canadian Conf. Earthquake Engineering / Ottawa / 1987 / 5ème Conf. Canadienne Génie Sismique

Approximate decoupling of torsional and translational seismic response considering diaphragm flexibility

A.A.Huckelbridge & Y.H.Lei
Case Western Reserve University, Cleveland, Ohio, USA

ABSTRACT: For as-built structures, complete structural symmetry is rarely, if ever, achieved. Even in nominally symmetric structures, variability in strength and stiffness of the load resisting elements, as well as the non-structural elements, tends to produce accidental asymmetry. Any such asymmetry, even though small in nature, will produce coupling between translational and torsional response, which can have a significant effect on seismic behavior. Problems arise when one attempts to define an appropriate design excitation for the torsional response of such nominally symmetric structures. Furthermore, in instances where significant diaphragm flexibility exists, there are substantial computational advantages in retaining the nominal symmetry of the structure in the analytical model. Approximate decoupling techniques address both of these analysis/design problems by defining appropriate rotational design excitations for a numerically decoupled, antisymmetric, torsional response model. These results are then combined with those from a decoupled, symmetric, translational response model to obtain the total response.

BACKGROUND

It has been demonstrated by a number of investigations (Kan and Chopra, 1977; Tso and Dempsey, 1980) that the coupling associated with even small structural asymmetries can produce significant torsional seismic response, even in the absence of any rotational ground motion components. The extent of coupling of torsional and translational response, for rigid-diaphragm structures, depends both upon the degree of eccentricity present and the degree of separation between torsional and translational natural response frequencies. It has been further demonstrated that rigid-diaphragm structures can be approximately decoupled, both in the linear and nonlinear response ranges, assuming that the analyst appropriately "corrects" the rotational excitation for coupling effects (Chang and Huckelbridge, 1984; Huckelbridge and Lei, 1986).

Structural diaphragms with larger plan aspect ratios, or with significant penetrations, however, may not reasonably satisfy the assumption of rigidity. For structures containing flexible diaphragms, taking advantage of any nominal symmetry, or near-symmetry, becomes particularly advantageous, if not necessary, for an effective seismic analysis. For any such decoupled analysis, however, one must define an appropriately "corrected" rotational excitation for the antisymmetric or torsional, response model.

Previous investigations (Huckelbridge and Kannan, 1984) have demonstrated that in the linear response range, where principles of superposition may be assumed valid, one can indeed perform such an approximately decoupled analysis with quite reasonable accuracy. The objective of this investigation was to ascertain whether similar decoupling techniques could be extended to the nonlinear response range, where principles of superposition are not readily justifiable.

STRUCTURAL MODEL EMPLOYED

To investigate the effectiveness of approximate decoupling techniques for the nonlinear response of flexible diaphragm structures, the simple end-sprung coupled model shown in Figure 1 was utilized. The approximately decoupled symmetric and antisymmetric versions of the model are indicated in Figure 2.

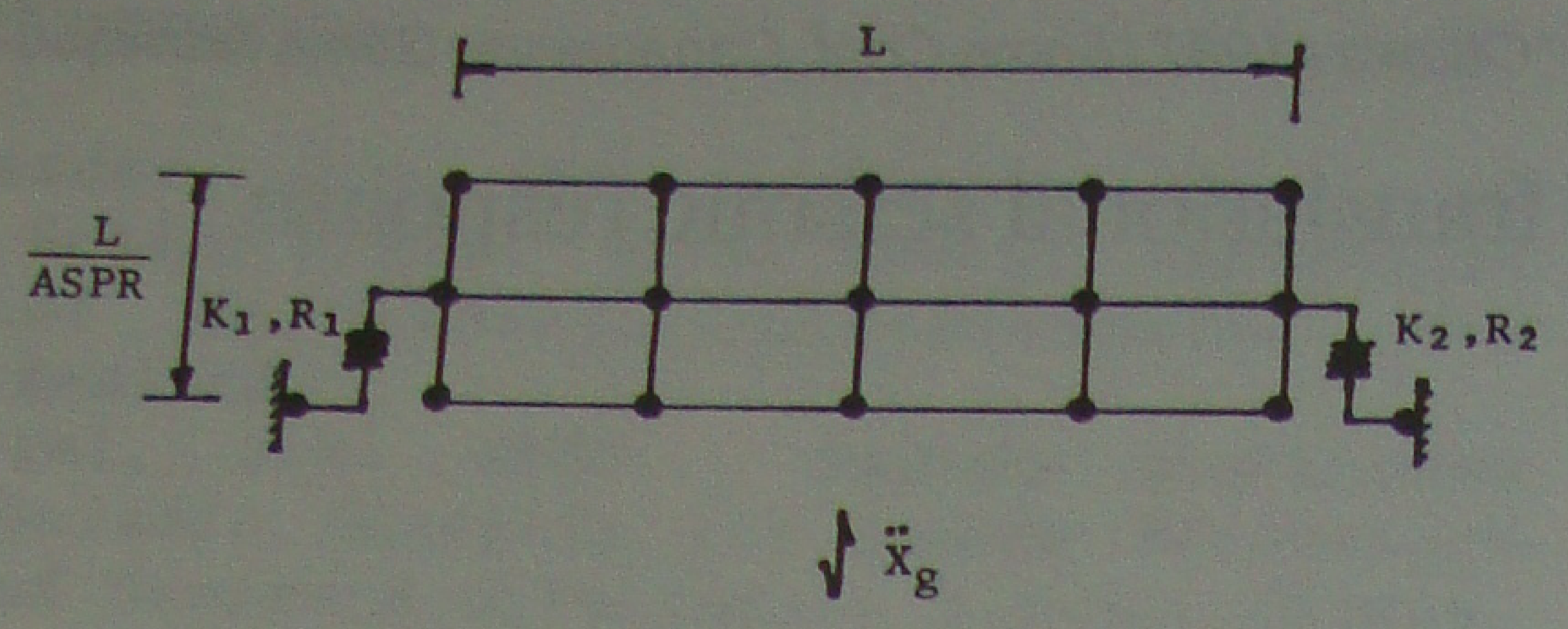

FIGURE 1:Coupled End-Sprung Diaphragm

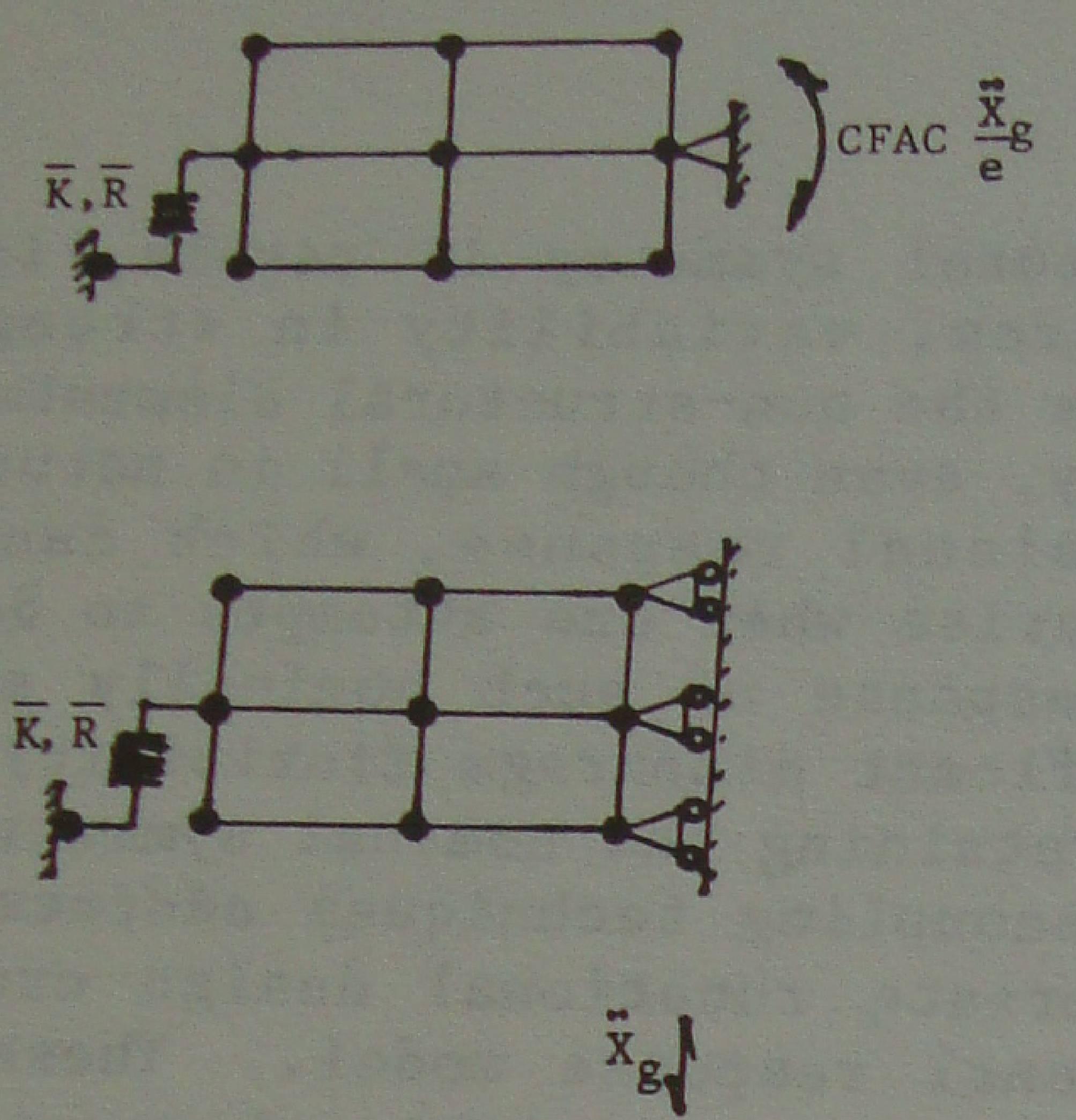

FIGURE 2: Approximately Decoupled End-Sprung Diaphragm

The diaphragm itself, modeled by 2-D quadrilateral membrane finite elements, was assumed to behave linearly. The supporting spring elements were assumed to behave in an elasto-plastic fashion. The 1934 El Centro N-S ground motion was utilized for the study. Supporting element strength (R_1,R_2) and stiffness levels (K_1,K_2), as well as diaphragm flexibility and aspect ratio (ASPR) were varied as discussed in the following sections.

QUANTIFYING DIAPHRAGM FLEXIBILITY

To systematically study the effect of diaphragm flexibility on any sort of structural response, it is first necessary to define some effective measure of that flexibility. One convenient, dimensionless diaphragm flexibility parameter, utilized in previous work (Huckelbridge and Kannan, 1984) is the squared frequency ratio, β, defined as the ratio of the squared natural frequency of the flexible diaphragm on rigid supports to the squared natural frequency of a mass-equivalent rigid diaphragm on the flexible supports. Increasing values of the parameter β thus indicate more nearly rigid diaphragms. It has been previously determined for the linear response range, and verified in this study for the nonlinear response range, that values of β greater than 10 to 20 represent diaphragms which may be reasonably assumed rigid. To get some feel for what might constitute a flexible diaphragm, a solid, normal weight concrete slab, 30 feet (9m) in width, 60 feet (18m) in length and 6 inches (.15m) in thickness, end supported so as to have a "rigid diaphragm" natural period of 0.1 seconds, would correspond approximately to a β value of 10. To be considered flexible, therefore, a diaphragm would need at least some of the following attributes: large plan aspect ratio or significant perforations, stiff supporting elements and substantial self-weight.

CHARACTERIZING ACCIDENTAL ECCENTRICITY

Unintended asymmetry may arise due to unavoidable variability in either the mass, stiffness or strength distribution in the as-built structure. For this study two eccentricity sources were considered: unbalanced stiffness and unbalanced strength in the supporting elements. Obviously the latter effect is not a factor unless the structure exceeds the linear response range. The discrepancy between the stiffnesses or strengths of the two supporting springs was assumed to be 30% (i.e. $K_2 = 1.3K_1$ or $R_2 = 1.3R_1$), which was felt to be a reasonable upper bound on accidental asymmetry. This assumption produces an actual eccentricity,e, (distance between center of resistance and center of mass) equal to 6.5% of the diaphragm length. Earlier studies (Huckelbridge and Lei, 1986) indicate that if significant inelastic excursions occur, strength eccentricity becomes the more important factor in torsional response due to translational ground motion.

SCOPE OF THIS INVESTIGATION

For this study, values of the squared frequency ratio, β , between 1 and 16 where selected. (Values of β greater than 16 would essentially correspond to rigid diaphragm behavior.) Supporting element stiffnesses were selected so as to produce a fundamental translational frequency of 10 hz, assuming rigid diaphragm behavior. Aspect ratios of 2,4, and 6 were examined, producing rigid diaphragm ratios of fundamental torsional frequency to fundamental translational frequency of 1.55, 1.63 and 1.71, respectively. Supporting element strength levels were selected so as to achieve a wide range of displacement ductility demand in the supporting elements. Corrected rotational excitations for decoupled antisymmetric models were determined by matching total response results with those from coupled analyses, for both sources of eccentricity. The response parameters matched were peak displacement in the linear response range and peak displacement ductility demand in the nonlinear response range. The appropriate decoupled rotational excitation was defined as a dimensionless correction factor, CFAC, multiplied by the ratio of translational excitation to eccentricity, $\ddot{x}_g/e$.

SUMMARY OF RESULTS

In the linear response range, where superposition of results from decoupled models is valid as long as the coupling effects are accounted for, there is a relatively small amount of scatter in the comparative response data from coupled and decoupled analyses (Kannan, 1984). The resulting rotational excitation correction factors, CFAC, which approximately match coupled and decoupled responses in the linear range for a stiffness-produced eccentricity of .065L are shown in Table 1.

In the nonlinear response range there is substantially more scatter in the rotational excitation correction factors required to match peak displacement ductility demand with the corresponding coupled analysis. This result is hardly surprising given the lack of rigorous justification for superposing results in this range of response. For a wide range of displacement ductility demand values, however, it does appear possible to establish reasonable upper bounds on the required rotational excitation correction factor such that observed coupled ductility demand values are bracketed, given the specific values of the pertinent response parameters (eccentricity, aspect ratio, flexibility, etc.). A typical ensemble of observed values for a specific parameter set is shown in Figure 3.

TABLE 1. Rotational excitation correction factors; linear response with eccentricity = .065L

Aspect Ratio (ASPR)	Diaphragm Flexibility Parameter(β)	Rotational Excitation Correction Factor (CFAC)
2	1	.021
2	6	.035
2	11	.037
2	16	.039
2	∞	.041
4	1	.019
4	6	.032
4	11	.033
4	16	.035
4	∞	.037
6	1	.018
6	6	.031
6	11	.033
6	16	.034
6	∞	.037

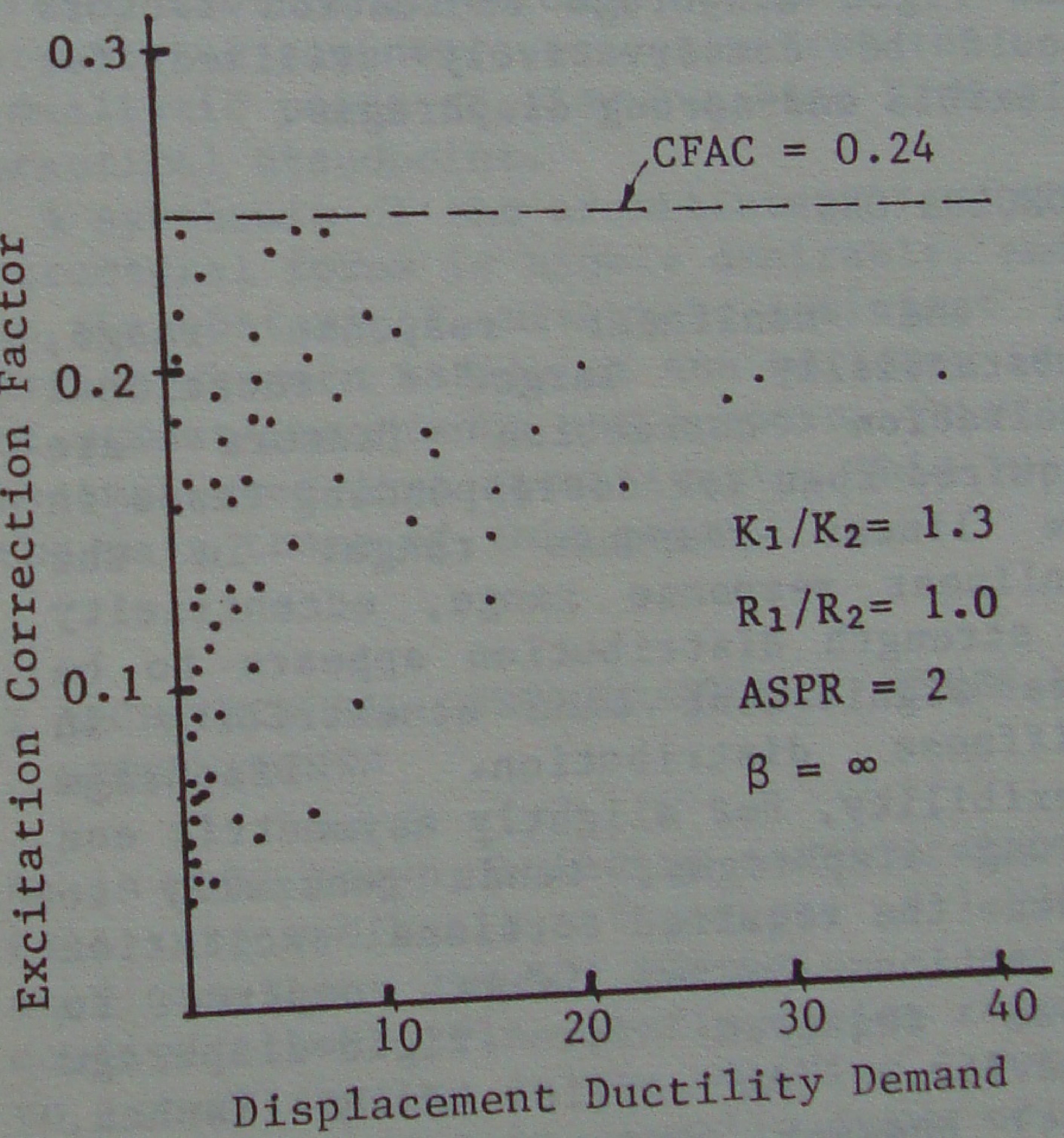

FIGURE 3: Typical ensemble of CFAC values for a given set of response parameters.

Based upon this technique of bracketing observed coupled ductility demand values for all observed levels of ductility, the required rotational excitation correction factors, CFAC, for rigid diaphragm behavior shown in Table 2 were obtained.

TABLE 2: Rotational excitation correction factors: nonlinear response range with rigid diaphragm behavior

ASPR	K_1/K_2	R_1/R_2	CFAC
2	1.3	1.0	.241
4	1.3	1.0	.274
6	1.3	1.0	.274
2	1.0	1.3	.372
4	1.0	1.3	.463
6	1.0	1.3	.522
2	1.3	1.3	.387
4	1.3	1.3	.505
6	1.3	1.3	.558

The influence of diaphragm flexibility, for the end-sprung diaphragms studied, did not appear to be significant. No substantial increases in excitation correction factors were observed as compared to the rigid diaphragm cases, and observed decreases did not exceed 20%. There was no consistently decreasing tendency in required correction factors as the flexibility increased, as had been the case in the linear response range. It would appear, therefore, based upon this study, that the rigid diaphragm excitation factors could be conservatively utilized for flexible end-sprung diaphragms.

CONCLUSIONS

In the nonlinear response range, substantially larger rotational excitation correction factors are required than for corresponding cases in the linear response range. In the nonlinear response range, eccentricity in strength distribution appears to be more significant than eccentricity in stiffness distribution. Diaphragm flexibility, for slightly asymmetric end sprung diaphragms, tends generally to reduce the required torsional excitation correction factors when compared to those required for rigid-diaphragm behavior. (An earlier study (Kannan, 1984) however, indicated the opposite trend for center-sprung or core-supported diaphragms, at least in the linear response range.) For end sprung diaphragms, which tend to have torsional response modes higher in frequency than the corresponding translational response modes, the reduction in required excitation correction factors due to diaphragm flexibility is not very great, and can justifiably be neglected in defining appropriate decoupled antisymmetric excitation. This does not imply, however, that the effect of diaphragm flexibility is not ultimately significant in determining the actual seismic response; this response effect itself can only be estimated by the subsequent approximately decoupled analysis performed.

ACKNOWLEDGEMENTS

This research has been supported by the U.S. National Science Foundation under grant No. CEE-8415590. This support is gratefully acknowledged. The opinions and findings are those of the authors.

REFERENCES

Chang, W.C. and Huckelbridge, A. 1984. "Modeling and Computational Techniques for Torsional Response in Numerically Symmetric Structures," Proceedings 4th International Conference on Applied Numerical Modeling, Taiwan, R.O.C.

Huckelbridge, A. and Kannan, R. 1984. "Seismic Analysis of Slightly Asymmetric Structures," Proceedings 5th ASCE Specialty Conference, University of Wyoming.

Huckelbridge, A. and Lei, Y. H. 1986. "Torsional Seismic Load Effects in Nearly Symmetric Structures," Proceedings, 8th European Earthquake Engineering Conference, Lisbon, Portugal.

Kan, C.L. and Chopra, L.K. 1977. "Effects of Torsional Coupling on Earthquake Forces in Building," ASCE Journal of the Structural Division, v. 103.

Kannan, R. 1984. "Seismic Analysis of Asymmetric Structures Considering the Effects of Diaphragm Flexibility," M.S. Thesis, Case Western Reserve University.

Tso, W.K. and Dempsey, K.M. 1980. "Seismic Torsional Provisions for Dynamic Eccentricity," Earthquake Engineering and Structural Dynamics, v. 8.