Effect of structural period and ground motion parameters on the earthquake response of asymmetric buildings

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The results of a parametric study of torsional coupling effects in the response of asymmetric buildings to a grouped selection of 45 strong motion earthquakes from Europe, North America, the Middle East and Southern Pacific are presented. The period dependency of the key response parameters is studied in relation to the site dependent criteria employed by certain earthquake-resistant design codes for specifying the lateral shear forces to be resisted by the structural frames and/or walls. Unlike lateral forces, the torsional response is relatively insensitive to the ratio of peak ground acceleration to velocity, which has been used in previous studies as a measure of the effect on earthquake ground motions of site soil conditions and epicentral distance. The results show that the effect of torsional coupling on edge displacement response is more pronounced in stiff, short period structures. However, the dynamic shear and torque responses are relatively insensitive to variations in structural period. Codified design provisions for torsional effects specified in the United States, Canadian and European seismic building regulations are assessed, along with alternative proposals, in relation to the analytical results. It is concluded that in some cases special provisions are needed for short period asymmetric systems, a feature which has been neglected by the codes and inadequately accounted for in previous proposals.

Keywords: torsional coupling, earthquake resistant design, period dependent effects

Earthquake building codes[1-4] specify empirical procedures accounting for the modal coupling effect between the lateral and torsional responses of asymmetric structures to seismic loading. These procedures are implemented by means of expressions defining an equivalent static design torque, and are largely based on the results of parametric investigations of the elastic earthquake response of simple single-storey building models[5].

This paper presents results obtained by statistical analysis of the time-history earthquake response of a simplified (but representative) asymmetric building model (*Figure 1*) to a grouped selection of 45 strong motion earthquake records representing a range of site conditions and ground motion parameters. The records include earthquakes from Europe, North America, Mexico, the Middle East and Southern Pacific and include the Spitak (Armenia) 1988 and Loma Prieta (California) 1989 events. The effect of torsional coupling is expressed in terms of the lateral shear and storey torque developed as a result of the earthquake base loading, together with the peak displacement of a lateral

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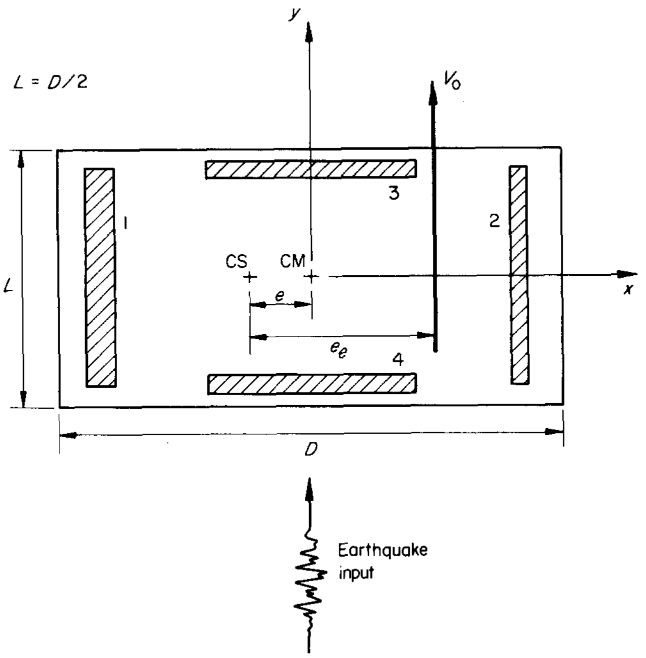

Figure 1 Asymmetric building model subjected to unidirectional earthquake ground motion

load-resisting element situated on the periphery of the building, on the side which is more adversely affected by torsional structural response[6]. The results of this analysis are presented firstly in terms of the effective eccentricity[7], which defines the position at which the design shear must be applied to the floor deck (here assumed rigid) in order to give displacements for the key edge elements which match the results of dynamic analyses. Secondly, results are included for the dynamic amplification of the lateral shear and static eccentricity, which enable direct comparison with building code provisions. This paper represents an extension of a previous time-history parametric study[8] which presented results based on European earthquake records alone. A subsequent study[9] investigated regional variations in seismic torsional coupling effects between Europe and the Western US, and in the appropriate code provisions. It also identified the period dependency of such effects, which is a phenomenon observed in other recent studies based on a statistical combination of the peak time-history responses computed using limited ranges of strong-motion earthquake records[10,11]

Period dependence of torsional coupling effects

Previous studies

In a recent study, Rutenberg and Pekau[11] compared the linear earthquake response of monosymmetric single-storey structures with the expressions for amplifying the static (structural) eccentricity given by the current seismic design codes of the United States[12] and Canada[3]. The analyses were carried out using five ground motion records obtained from four large magnitude Californian earthquakes. It was concluded that the response of short-period systems (uncoupled lateral period $T_0 < 0.5$ s) is different from that of higher period systems, particularly for elements at or near the edge of the floor which is more vulnerable to torsional response effects, that is the side furthest from the centre of stiffness, CS (*Figure 1*). Design eccentricity expressions intended to give an accurate correlation with the mean plus one standard deviation (MSD) dynamic results were also suggested. The proposals made in Reference 11 result in design eccentricities for short period systems with small or moderate static eccentricity (that is, those systems affected significantly by torsional coupling[6–8]) which are smaller than those for equivalent long period systems. The results of the present paper demonstrate that this is contrary to the trend exhibited in the dynamic analysis of such systems, when the response is obtained statistically for a wide range of strong-motion earthquake ground motion inputs.

The results of analyses presented in Reference 9 using localized earthquake records to assess regional variations in torsional design regulations gave no justification for the significant differences in the torsional provisions of the US (ATC[1] and NEHRP[2]) and European (Eurocode 8[4]) seismic codes. Regional variations in torsional coupling effects were found to be relatively small when compared with the influence of other parameters such as the static eccentricity ratio, uncoupled torsional to lateral frequency ratio, uncoupled lateral period and plan aspect ratio. The present study aims to quantify the period dependency of torsional coupling effects by analysing the time-history earthquake response of structures with stiffness asymmetry (*Figure 1*) to an ensemble of 45 records from various geographical locations, and with widely varying characteristics (see Tables 1–3 in Reference 12). This study extends the results of previous research and helps to clarify the influence of building period and ground motion characteristics on torsional coupling effects in seismic building response.

Design codes

Several previous studies have shown that the equivalent static design eccentricity provisions of building codes severely underestimate the design forces for structural elements affected adversely by torsional coupling, under some key combinations of the dynamic parameters. Certain of these studies have led to proposals for design code modifications[13,14], but for the majority of the codes the apparent inadequacies have yet to be recognized by appropriate modifications to the design regulations. Partly this is due to the current shortage of consistent data on the effect of inelastic material response on the dynamic behaviour of torsionally asymmetric buildings. Current intensive programmes of research in this area[15,16] are producing results which will greatly assist the process of clarifying these issues.

In view of the objectives of this study, it is significant that none of the major earthquake codes currently allow for period-dependent torsional coupling effects. In most cases the empirical code provisions are based on the simple linear amplification of eccentricity to allow for dynamic modal coupling. Eurocode 8 (Reference 4) is unique in its allowance for the influence of both the uncoupled torsional to lateral frequency ratio R_f and the building's plan aspect ratio D/L (*Figure 1*) on such effects, and generally provides a more consistent and accurate comparison with the results of dynamic analysis[8,10].

Parametric study

Structural model

A simplified but realistic monosymmetric structural model with a rigid rectangular floor deck having a 2:1 aspect ratio has been selected for this study (*Figure 1*). The floor mass is assumed to be distributed uniformly and hence the centre of mass, CM, coincides with the geometric centre of the floor deck. The static eccentricity e between CM and the centre of stiffness, CS, arises due to different elastic stiffness, k, in the lateral load-resisting elements 1 and 2 (*Figure 1*, $k_1 > k_2$), for uni-axial horizontal earthquake ground motion applied in the y-direction. The torque-resisting elements, 3 and 4 in *Figure 1*, provide no lateral resistance in the y-direction but variation of their stiffnesses (k_3, k_4) in the lateral x-direction enables control of the ratio of uncoupled ($e = 0$) torsional to lateral frequency ratio, R_f. Values of $R_f = 0.75$, 1.0 and 1.4 have been chosen to represent buildings with low, intermediate and high torsional stiffness and cover the range in which torsional coupling effects are generally most pronounced. The structural eccentricity, e, has been normalized to the plan dimension D, perpendicular to the earthquake loading (*Figure 1*). The ratio e/D has been assigned the values 0.05, 0.1 and 0.2, representing buildings with small, moderate and large eccentricities, respectively. The damping ratio is taken to be 0.05 (5% of critical damping), typical of buildings of braced frame or frame/shear wall type construction. Finally, the uncoupled lateral period T_0 in the y-direction is taken to be in the range 0.1−5.0 s, representing buildings of up to approximately 50 storeys in height. The simplified single-storey building model analysed in this study has been used extensively in parametric studies of torsional coupling effects[6−11]. It is a sufficiently realistic representation of real buildings and provides useful and accurate information on the performance of equivalent, regularly asymmetric multi-storey buildings[17].

Earthquake records

The ensemble of 45 earthquake records selected for this parametric study has been listed in Table 1 of Reference 12. The records have been subdivided into three sets A, B and C according to the ratio a/v of the peak ground acceleration to velocity of the recorded ground motion. Records with $a/v > 1.2$ g/(m/s) have been classified as set A having high a/v ratios, and usually represent far-field earthquakes on rock or stiff soil sites or near-field earthquakes on rock, stiff soil or intermediate soil sites. The definitions of the US code UBC 1988 (Reference 18) for the four soil types employed in this study are given elsewhere[12]. Records with a/v in the range 0.8−1.2 g/(m/s), designated set B, have stiff to intermediate site soil conditions whereas those records with low a/v ratios [<0.8 g/(m/s)], designated set C, generally arise from intermediate or soft soil sites in the medium to far-field of an earthquake. Reference 12 presents a detailed analysis of the frequency content of the records employed in the present study, and includes comparisons with the elastic spectra recommended by codified design regulations.

Analytical techniques

Time-history response calculations were carried out on the two degrees of freedom structural model illustrated in *Figure 1*, using the frequency domain fast Fourier transform (FFT) algorithm[8]. A statistical approach was adopted for the presentation of the results. For each combination of the structural parameters given above, the response parameters defined in the following section were computed for each of the records in sets A, B and C. The mean response for each set of records and for the complete ensemble was then computed, together with the mean plus one standard deviation (MSD) response and the largest or extreme response. The MSD response is of particular significance because of its common use in earthquake-resistant design[19], where it corresponds to an 84% probability of nonexceedance in the dynamic structural response.

Response parameters

The response parameters used in this study are the effective eccentricity ratio, e_e/D, the shear amplification ratio, A_s, and the eccentricity amplification ratio, A_e. The effective eccentricity ratio has been calculated on the basis that the dynamic displacement of the more flexible lateral load-resisting element (element 2 in *Figure 1*) is matched by the application of the uncoupled lateral shear force V_0 at an eccentricity e_e from CS. The shear force V_0 corresponds to the maximum dynamic lateral shear computed for the equivalent symmetric building with $e = 0$. The amplification of shear due to torsional coupling, A_s, is given by the ratio V/V_0, where V is the total dynamic y-direction storey shear for the asymmetric building. Note that all building codes specify $V = V_0$ and hence $A_s = 1$; this is a conservative approach provided that it is assumed that torsional coupling tends to reduce the lateral shear acting on an asymmetric building compared with the equivalent symmetric case.

The empirical procedures specified by building codes for determining the lateral force V_0 are dependent on the site soil conditions and local seismicity, as well as the type of construction and importance of the designed facility. The provisions account for the varying spectral content of records from sites with different soil profiles, and are related either to the peak ground acceleration[1,2,4] or to the peak ground velocity. The Canadian code NBCC 90 (Reference 3) uses the latter approach, which accounts for the fact that the dynamic response of most structures with periods $T_0 > 0.5$ s (such as medium- to high-rise buildings) is controlled primarily by ground velocity rather than by ground acceleration. For short period structures with $T_0 < 0.5$ s the response is acceleration-controlled and hence in this range NBCC 90 makes a distinction between the design spectra appropriate to ground motions with high, intermediate or low a/v ratios, as defined earlier. Typical design response spectra for normal structures constructed on rock sites in a zone of moderate seismicity with $v = 0.2$ m s^{-1} are shown in *Figure 2*. This code is therefore distinctive in its recognition that the lateral (shear) response of short period structures is strongly affected by the ground motion parameters, and in particular by the ratio a/v.

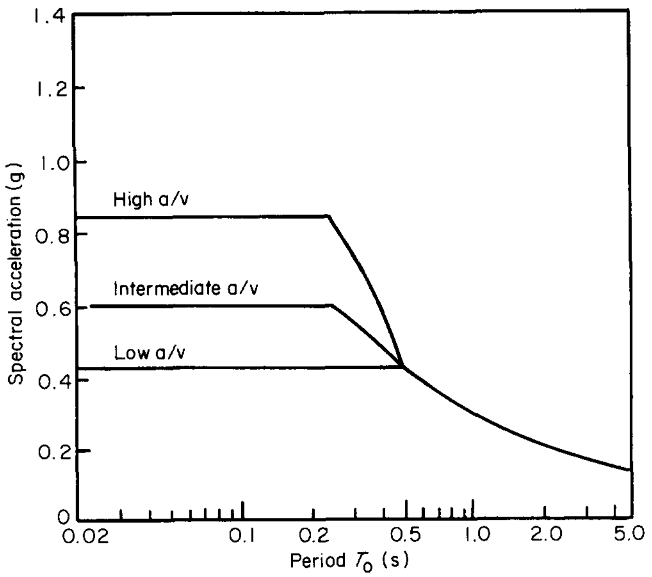

Figure 2 Elastic design spectra for NBCC 90 (Reference 3) corresponding to normal structures built on rock or very stiff soils; peak ground velocity v = 0.2 m/s

The present study aims to determine whether torsional response effects in asymmetric buildings are similarly influenced by the ground motion characteristics, especially in the short period range. These effects are characterized by the effective eccentricity ratio e_e/D defined above, and by the amplification A_e of static eccentricity due to torsional coupling. The latter response parameter is defined as T_d/eV_0, where T_d is the peak dynamic torque acting on the floor diaphragm. This effect is accounted for in building codes by specifying a dynamic eccentricity e_d ($\geq e$), where $e_d = T_d/V_0$.

Effective eccentricity

Analytical results

Figure 3 shows the variation of effective eccentricity ratio e_e/D with the uncoupled lateral period T_0, for the complete ensemble of 45 earthquake records. The uncoupled frequency ratio $R_f = 1.0$, and the static eccentricity ratio $e/D = 0.1$.The overall trend demonstrates increasing response at the shorter periods, which correspond to stiffer, shorter buildings. These and other results show that this effect is particularly pronounced for buildings with intermediate and high frequency ratios ($R_f \geq 1.0$). For periods $T_0 > 1.0$ s, the mean effective eccentricity is less than the static value, e. This implies that the design shear should be applied at a position between CS and CM. However, it is considered that the MSD response represents a more appropriate level for most practical cases of earthquake-resistant design[1] and in this case the effective eccentricity e_e is found to be in the order of $1.5e$ for $R_f \geq 1.0$, $T_0 > 1.0$ s. This corresponds to the dynamic eccentricity e_d specified by the Canadian code NBCC 90 (Reference 3). For periods T_0 less than 1.0 s, the effective eccentricity for MSD response is 50–100% greater than the static value, such that for short period structures with $T_0 < 0.5$ s the amplification factor is in the order of 2.0, which corresponds closely to that specified by Eurocode 8 (Reference 4), as evaluated below.

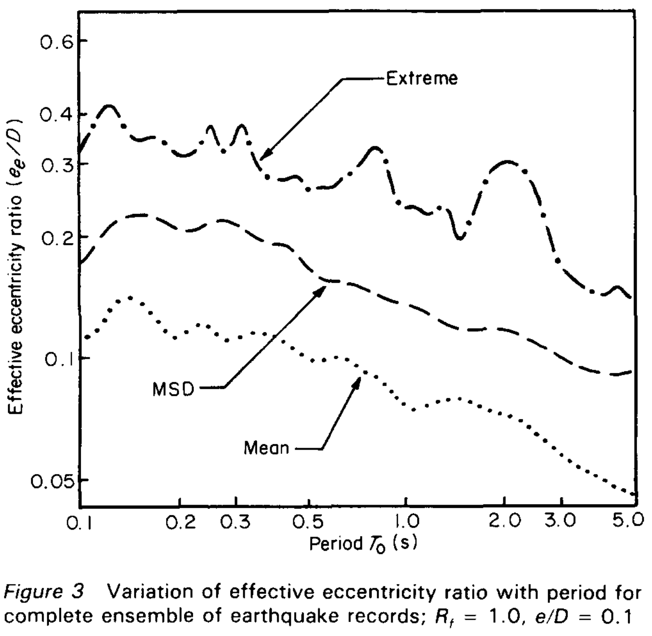

Figure 3 Variation of effective eccentricity ratio with period for complete ensemble of earthquake records; R_f = 1.0, e/D = 0.1

The effect of the peak ground acceleration to velocity ratio, a/v on the MSD effective eccentricity ratio for the cases $e/D = 0.2$, $R_f = 1.0$ and $R_f = 1.4$ is illustrated in *Figure 4(a)* and (*b*), respectively. The results show that records with low a/v ratios (set C) produce a somewhat larger response in the long period range, but that generally the ground motion parameter a/v does not have a particularly significant influence on torsional coupling effects, especially in the most critical period range, $T_0 < 0.5$ s. This is in contrast to the significant effect of a/v on the lateral shear response of planar (symmetric) structures[12]. Similar results have been obtained for structures with small and moderate eccentricity ratios.

Code comparisons

In *Figure 5*, the MSD results for $e/D = 0.2$, $R_f = 1.0$ and 1.4 are compared with the primary torsional design provisions of ATC[1], NEHRP[2], NBCC 90[3] and Eurocode 8[4]. Note that NEHRP is an updated version of ATC3, but retains the same torsional design provisions and hence can be treated identically, for the purpose of code assessments. Although the codified provisions are expressed in terms of dynamic eccentricity, e_d, a direct comparison with effective eccentricity is valid since both methods are used to specify the distance from CS at which the design shear should be applied (*Figure 1*). The ATC3/NEHRP provisions specify $e_d = e$ and hence do not allow for any dynamic amplification of eccentricity due to torsional coupling effects. As stated earlier, the NBCC 90 provisions specify an amplification factor of 1.5 on the static eccentricity e, irrespective of the torsional/lateral frequency ratio and plan shape of the building. These latter factors are taken into account by Eurocode 8, which specifies torsional provisions applicable to asymmetric buildings with $e/D \leq 0.1$. For highly irregular buildings with $e/D > 0.1$ as in *Figure 5*, the code recommends that a full dynamic modal or time history analysis be carried out in order to account for torsional effects (see Reference 5 for a full discussion of the Eurocode 8 torsional provisions). However, extending the Eurocode 8 provisions to the case $e/D = 0.2$

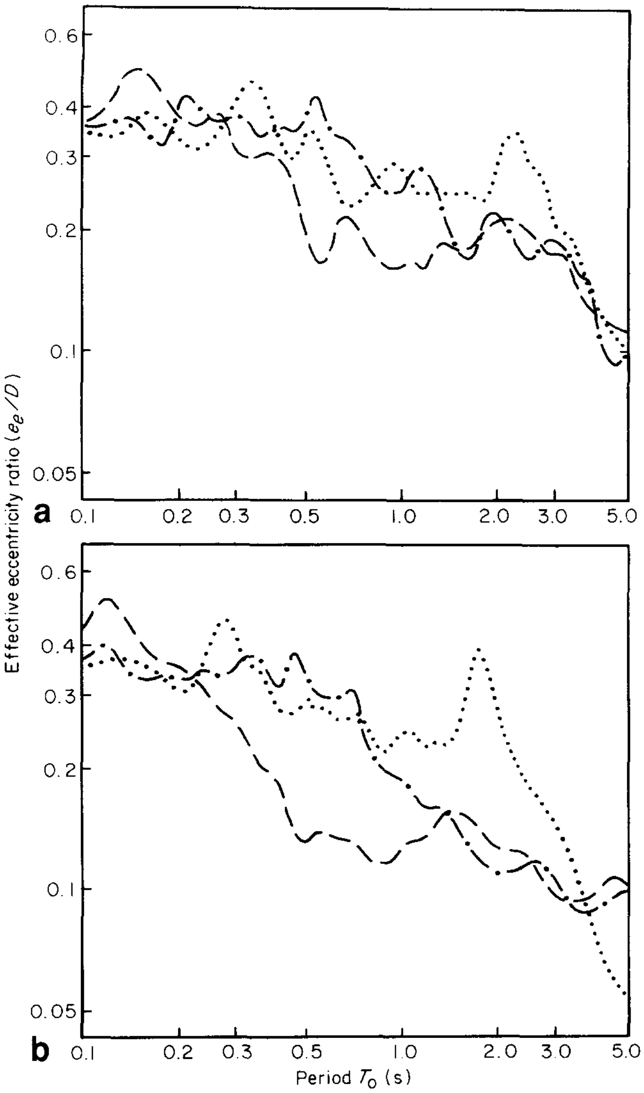

Figure 4 Variation of MSD effective eccentricity ratio with period for sets A, B and C earthquake records having high, intermediate and low *a/v* ratios, respectively; *e/D* = 0.2; (– – –), set A; (— · —), set B; (· · ·), set C; (a), R_f = 1.0; (b), R_f = 1.4

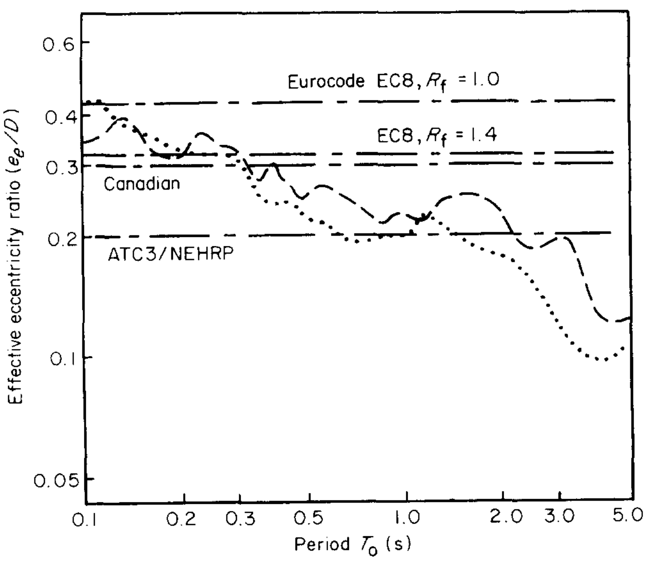

Figure 5 Variation of MSD effective eccentricity ratio with period for complete ensemble of earthquake records, and comparison with building code provisions: *e/D* = 0.2; (— —), R_f = 1.4; (· · ·), R_f = 1.0

gives design (dynamic) eccentricities of $0.412D$ ($R_f = 1.0$) and $0.313D$ ($R_f = 1.4$), corresponding to amplification ratios of 2.06 and 1.57, respectively; (see *Figure 5*).

The ATC3/NEHRP provision gives an adequate estimate of the effective eccentricity only for periods $T_0 > 1.0$ s. Generally the case $R_f = 1.4$ gives somewhat higher effective eccentricities than $R_f = 1.0$ (as observed in earlier studies[7,14]), especially in the mid- to long-period range. The nonconservatism of the ATC3/NEHRP code provisions is by a factor of about 2 for very short period structures ($T_0 < 0.2$ s), and this factor has been found to increase slightly for structures with moderate or small eccentricities.

The torsional provision of NBCC 90 is reasonably conservative for $T_0 > 0.5$ s, but is slightly inadequate for short period structures. The Eurocode 8 provisions for $R_f = 1.0$ and 1.4 (for a building with 2:1 aspect ratio as in this study, see *Figure 1*) are also compared in *Figure 5* with the dynamic results for the MSD response. The provision for $R_f = 1.0$ which is assumed to produce the greatest coupled response (generally contrary to the trend of the dynamic results, as commented above) is conservative throughout the full period range, and is overconservative for highly asymmetric long period systems. The Eurocode 8 provision for $R_f = 1.4$ is slightly nonconservative for short period systems with $e/D = 0.2$, but has been found to compare well with the dynamic results for $e/D = 0.05$ and 0.1.

Design recommendation

The results of the comparisons with code design provisions shown in *Figure 5* are generally in agreement with those of earlier studies[8,10,14], but in addition incorporate the important effect of building period on the coupled torsional response. Further comparisons of the dynamic results with design proposals have been made in *Figure 6*, which illustrates the effective eccentricity provision proposed by the authors in a previous study[6]. This recommendation consists of the parabolic relationship:

$$e_e = e[2.6 - 3.6(e/s)] \tag{1}$$

where s is the characteristic or maximum plan dimension, which for a rectangular building (*Figure 1*) is given by $s = (D^2 + L^2)^{1/2}$. For a building with 2:1 aspect ratio as in this study, $s = 1.118D$ and hence equation (1) becomes

$$e_e/D = e/D[2.6 - 3.22(e/D)] \tag{2}$$

Equation (2) is then modified by the application of a factor $C_r (\leq 1.0)$ to allow for the effect of the uncoupled frequency ratio R_f, where

$$C_r = 0.1 + R_f, \quad R_f \leq 0.9 \tag{3a}$$

$$C_r = 1.0, \quad 0.9 < R_f \leq 1.3 \tag{3b}$$

$$C_r = 1.26 - 0.2R_f, \quad 1.3 < R_f \tag{3c}$$

In *Figure 6* the dynamic results have been presented for $R_f = 1.0$ and 1.4, for which $C_r = 1.0$ and 0.98, respectively. Hence for this critical range of R_f the design effective eccentricity given in equation (2) has been employed in an unmodified form in comparison with the dynamic results, taking the selected value of the static eccentricity ratio, $e/D = 0.2$. This yields an eccentricity amplification factor of 1.96, and gives good comparisons with the dynamic results for short period systems ($T_0 < 0.5$ s). The provisions are conservative for moderate to long period systems, and it is proposed therefore to modify the design effective eccentricity of equation (2) using a second factor $C_p(\leq 1.0)$ as in equation (4), which accounts for the reduction of torsional coupling effects for systems with periods $T_0 > 0.5$ s:

$$C_p = 1.0 \qquad T_0 \leq 0.5 \text{ s} \quad (4a)$$

$$C_p = 1.0 - 3.5(e/D)(T_0^{1/3} - 0.8) \quad T_0 > 0.5 \text{ s} \quad (4b)$$

The combination of equations (2) and (4) is shown by the solid curve in *Figure 6*, which demonstrates that good agreement is achieved with the presented dynamic results, over the full period range. Further results show that equally good agreement is obtained for buildings with small and moderate static eccentricities.

Rutenberg and Pekau[11,14] have also made proposals for modified seismic code provisions for asymmetric structures, which for elements on the critical flexible edge of the building (furthest from CS, see *Figure 1*) take the form

$$e_e/D = \left[\frac{3.0\rho}{1.5\rho + e}\right](e/D), \; T_0 \geq 0.5 \text{ s} \quad (5a)$$

$$e_e/D = 1.5(e/D) \quad T_0 < 0.5 \text{ s} \quad (5b)$$

where ρ is the mass radius of gyration about CM. In this study, $\rho^2 = (D^2 + L^2)/12$ which for $L = D/2$ gives $\rho = 0.323D$. Hence D is approximately 3ρ as in Rutenberg and Pekau's later study[11], which aimed to incorporate period-dependent torsional coupling effects in the codified design regulations. The provisions given in equation (5) have been plotted in *Figure 6* in comparison with dynamic results and the recommendations of the present study. It is evident that the Rutenberg–Pekau provisions are nonconservative for $T_0 < 0.5$ s. This is a serious discrepancy, given that equation (5*a*) is intended to account specifically for the effects of torsional coupling in low period systems. For buildings with small and moderate static eccentricity, the provisions of equation (5) result in a small increase in the design provision for periods $T_0 > 0.5$ s; this trend is contrary to that observed in the dynamic results and hence gives misleading guidance to designers.

Shear and eccentricity amplification ratios

The dynamic amplification of shear (A_s) due to torsional coupling is plotted as a function of natural period T_0 in *Figure 7*, which compares the MSD dynamic response for structures with $e/D = 0.2$ and $R_f = 1.0$ with the code design recommendation ($A_s = 1.0$). The structures have been subjected to earthquake ground motions in sets A, B and C having high, intermediate and low a/v ratios, respectively. As with the effective eccentricity shown in *Figure 4*, there is no consistent trend in the effects of torsional coupling on lateral shear associated with the parameter a/v, and furthermore unlike the results obtained for effective eccentricity there is no clearly defined trend for variation of the shear amplification A_s with the period T_0. Similar comments apply to equivalent results obtained for the dynamic amplification of eccentricity, A_e.

It is concluded that period-dependent effects in the shear and torque responses of asymmetric buildings are less marked than for the results for effective eccentricity (which is a measure of edge displacement response). The results of a previous study[9] have also shown that there is no justification for the significant regional differences in torsional design provisions evidenced in the present study by examples taken from the United States, Canada and Europe. The comments made herein are also applicable to the primary torsional design provisions of

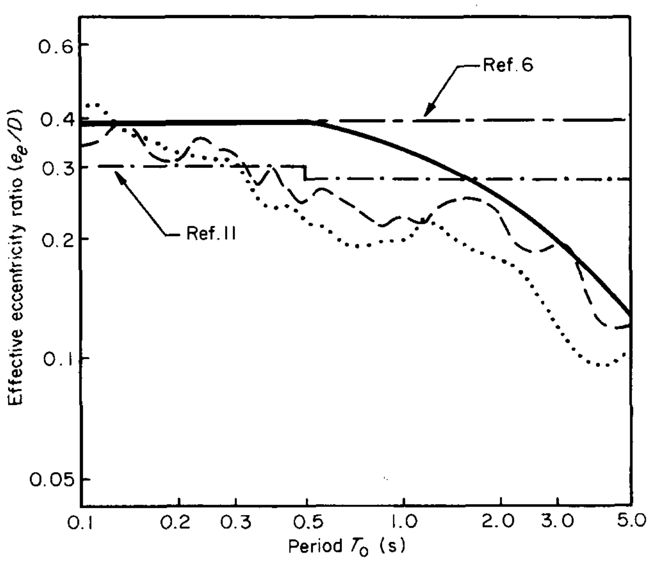

Figure 6 Variation of MSD effective eccentricity ratio with period for complete ensemble of earthquake records, and comparison with various design recommendations; $e/D = 0.2$; (——), equations (2) and (4); (– – –), $R_f = 1.4$; (· · · ·), $R_f = 1.0$

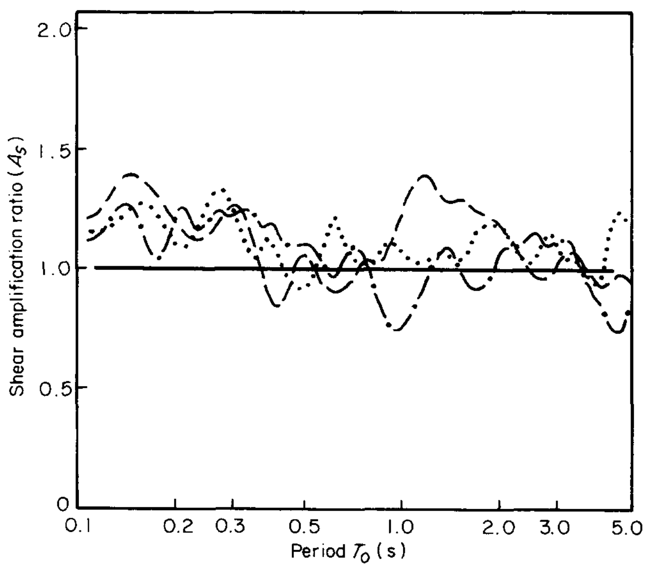

Figure 7 Variation of MSD shear amplification ratio with period for sets A, B and C earthquake records having high, intermediate and low a/v ratios respectively; $e/D = 0.2$; (– – –), set A; (– · –), set B; (· · · ·), set C; (——), building codes

the New Zealand and Mexican codes, which are identical (apart from the supplementary provision for accidental eccentricity) to the provisions of ATC3/NEHRP and NBCC 90, respectively.

Conclusions

Torsional coupling effects in monosymmetric buildings subjected to earthquake loading have been found to be dependent on the fundamental uncoupled natural period of the structure. In general, short period systems exhibit greater coupling of lateral and torsional response components than buildings with intermediate or long natural periods. This results in greater increases for short period systems of the edge displacement response affecting the design of lateral load-resisting elements situated on the more flexible side of the building.

The trend identified above is more pronounced for highly eccentric structures than for those with small or intermediate eccentricity. The period dependence of the design effective eccentricity, as determined from dynamic analysis, shows a more consistent trend than the other response parameters considered in this study, namely the dynamic amplification of lateral shear and static eccentricity.

Torsional coupling effects have been found to be relatively insensitive to the ratio of peak ground acceleration to velocity, which in previous studies has been shown to influence strongly the lateral shear response of buildings in the short period range.

The torsional design recommendations of ATC3[1] NEHRP[2] are nonconservative for buildings with small and moderate static eccentricity, but are adequate for buildings with large eccentricity except in the short period range ($T_0 < 0.5$ s).

The torsional design provision of the Canadian code NBCC 90[3] is nonconservative for buildings with small eccentricity, and for buildings with moderate eccentricity and natural periods $T_0 < 1.0$ s. The provision fails to account (as do other earthquake building codes) for the marked period dependence of torsional coupling effects for systems with large eccentricity, for which it is over-conservative for periods $T_0 > 0.5$ s.

The torsional design provisions in the draft Eurocode EC8 1989[4] give a reasonably conservative prediction of dynamic response for structures with small eccentricity, and are slightly over-conservative for structures with moderate eccentricity. The provisions are over-conservative for highly asymmetric buildings except for very short periods ($T_0 < 0.3$ s).

The results of analyses presented in this study using 45 strong-motion earthquake records with varying frequency content and other key characteristics have been used to formulate a straightforward procedure for extending earlier recommendations[6] for the primary design eccentricity. These were based on the influence on torsional coupling of static (structural) eccentricity and uncoupled torsional/lateral frequency ratio. The provisions recommended here include, by means of an empirical modification factor, the significant effect of the uncoupled lateral period (T_0) on torsional coupling effects.

References

1 Applied Technology Council. 'Tentative provisions for the development of seismic regulations for buildings', Structural Engineers' Association of California, ATC3-06, US. Department of Commerce, Washington D.C. 1978

2 Federal Emergency Management Agency (FEMA). 'NEHRP recommended provisions for the development of seismic regulations for new buildings, 1988 edition', Earthquake Hazards Reduction Series 17, Building Seismic Safety Council, Washington D.C. Part 1: Provisions, 1988

3 Associate Committee on the National Building Code. 'National Building Code of Canada 1990', National Research Council of Canada, Ottawa, Ontario, 1990

4 Commission of the European Communities. 'Eurocode EC8: Structures in seismic regions; Part 1, General design and building', Report EUR 12266 EN, Brussels, 1989

5 Chandler, A. M. 'Aseismic code design provisions for torsion in asymmetric buildings', *Struc. Engng Rev.*, 1988, **1**, 63–73

6 Chandler, A. M. and Hutchinson, G. L. 'A modified approach to earthquake resistant design of torsionally coupled buildings', *Bull. N.Z. Nat. Soc. Earthquake Engng* 1988, **21**, (2), 140–153

7 Dempsey, K. M. and Tso, W. K. 'An alternative path to seismic torsional provisions', *Soil Dyn. Earthquake*, 1982, **1**, (1), 3–10

8 Chandler, A. M. and Hutchinson, G. L. 'Evaluation of code torsional provisions by a time history approach', *Earthquake Engng Struct. Dyn.*, 1987, **15**, (4), 491–516

9 Hutchinson, G. L. and Chandler, A. M. 'Regional variations in aseismic design requirements for torsionally coupled buildings', *Proc. 9th Eur. Conf. on Earthquake Engineering*, Moscow, 1990, Vol. 7B 171–180

10 Rady, M. A. and Hutchinson, G. L. 'Evaluation of dynamic eccentricities obtained using a probabilistic approach, response spectrum methods and modern building codes', *Earthquake Engng Struct. Dyn.*, 1988, **16**, (2), 275–291

11 Rutenberg, A. and Pekau, O. A. 'Seismic code provisions for asymmetric structures: low period systems', *Engng Struct.*, 1989, **11**, 92–96

12 Chandler, A. M. 'Evaluation of site-dependent spectra for earthquake-resistent design of structures in Europe and North America', *Proc. Instn Civ. Engrs*, London, 1991, **90**, Part 1, 605–626

13 Tso, W. K. 'A proposal to improve the static torsional provisions for the National Building code of Canada', *Can J of Civ. Engng*, 1983, **10**, Part 4, 561–565.

14 Rutenberg, A. and Pekau, O. A. 'Seismic code provisions for asymmetric structures: a re-evaluation', *Eng. Struct*, 1987, **9**, 255–264

15 Chandler, A. M. and Duan, X. N. Inelastic torsional behaviour of asymmetric buildings under severe earthquake shaking', *Struct. Engng Rev.*, 1990, **2**, 141–159

16 Tso, W. K. and Ying, H. 'Additional seismic inelastic deformation caused by structural asymmetry', *Earthquake Engng Struct. Dyn.*, 1990, **19**, 243–258

17 Hejal, R. and Chopra, A. K. 'Earthquake analysis of a class of torsionally coupled buildings', *Earthquake Engng Struct. Dyn.*, 1989, **18**, 305–323

18 Uniform Building Code of America, 'Earthquake regulations (Section 2313)', International Conference of Building Officials, Whittier, California, 1988

19 Newmark, N. M. and Hall, W. J. 'Earthquake spectra and design', EERI Monograph Series, Earthquake Engineering Research Institute, El Cerrito, California, 1982