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EVALUATION OF FACTORS INFLUENCING THE INELASTIC SEISMIC PERFORMANCE OF TORSIONALLY ASYMMETRIC BUILDINGS

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SUMMARY

This paper addresses some fundamentally contradictory conclusions drawn by Tso and Ying[1] and the authors[2] regarding the additional seismic ductility demand in asymmetric building structures and the adequacy of certain code torsional provisions. It also clarifies a number of issues arising from the different approaches employed in the two studies. The Mexico 76 and 87 code torsional provisions are taken as examples. Results show that the structural element at the stiff edge is the more critical and that the Mexico 76 code torsional provisions (among others) are inadequate, substantially underestimating the strength demand of this element. On the other hand, the Mexico 87 code torsional provisions are found to be over-conservative. Recommendations are also given for improving the form and effectiveness of these code torsional provisions.

INTRODUCTION

Significant torsional response of building structures has been observed in major earthquakes. Torsional motion of buildings as a result of the 9 February 1971 San Fernando earthquake was substantial and has been attributed primarily to building asymmetry and torsional ground motion.[3] In the 19 September 1985 Mexico earthquake, 15 per cent of the cases of severe damage or collapse of buildings in Mexico City were caused by pronounced asymmetry in stiffness.[4] Furthermore, it has been reported that many buildings experienced very high torsional response, probably significantly higher than that predicted by the linear theory,[5] and that both stiffness and strength deterioration accentuated the importance of torsion due to non-linear behaviour[4] in this earthquake. In order to provide recommendations for earthquake resistant design to prevent torsional failure and offer effective and consistent control over structural damage to both symmetric and eccentric buildings, concurrent attempts have recently been made by Tso and Ying[1] and the authors[2] to evaluate the major aseismic building code torsional provisions based on inelastic single storey building models. The specification of element strength of these models is based rigorously on the code lateral and torsional provisions.

Tso and Ying[1] have presented a comprehensive report considering seven ways of specifying strength distribution, including the code torsional provisions from four countries. Their results show the variation of total strength and the normalized resistance eccentricity as functions of the normalized stiffness eccentricity, and are useful in examining the strength distribution among resisting elements based on current code provisions. Their finding that the flexible edge displacement can be up to two to three times that of symmetric structures is particularly valuable for urban planning and structural design to avoid pounding between buildings during earthquakes.

However, two fundamentally contradictory conclusions have been reached by Tso and Ying[1] and the authors.[2] One concerns the identity of the critical element in the sense that it is the most susceptible to the

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torsional effect. The other concerns the adequacy of the design eccentricity formulae specified in some building codes for earthquake resistant design in terms of satisfactory control of additional ductility demand due to torsion, in other words, to provide consistent protection for symmetric and eccentric structures against structural damage. These issues are of fundamental importance in preventing torsional failure during strong earthquakes.

Historically, the study of inelastic torsional response of asymmetric structures to strong earthquake motions has been an area where contradictory conclusions have been reached by the various researchers. A comprehensive review of this subject has been given by the authors in Reference 6, where it was demonstrated that the reason for reaching contradictory conclusions is the fundamental differences in approach employed by the researchers. In this respect, a number of issues regarding the varying approaches employed by Tso and Ying[1] and the authors[2] are raised in this paper. They include, firstly, the validity of including the additional torque given by an accidental eccentricity of 0·1 or 0·05 times the building plan dimension b parallel to the direction of eccentricity, in the specification of element strength in the analytical models. This affects the assessment of the results of inelastic dynamic analysis ignoring any uncertainties and torsional ground motion, bearing in mind that the accidental eccentricity is intended to account for these effects. Secondly, the need to employ localized earthquake records or records with dissimilar frequency contents is discussed. Finally, the necessity to carry out inelastic analysis and to present the results over a wide period range is emphasized.

This paper is intended to clarify the issues raised above and therefore to provide the basis for rational judgement of the contradictory conclusions reached by Tso and Ying[1] and the authors.[2] The Mexico 76 and 87 codes are taken as examples, and recommendations are given to improve the Mexico 87 code torsional provisions in a form suitable for widespread application. A wider programme of research addressing the general issue of strength distribution for effective inelastic seismic resistance of asymmetric buildings is currently being carried out. This comprises theoretical studies[2,6,7] and a series of small scale experimental tests utilizing the U.K. Science and Engineering Research Council earthquake simulator, which are intended to validate the results of the analytical studies. Currently in preparation[8] is a comprehensive study of codified design provisions for inelastic torsional effects, which includes detailed assessment of the current requirements of Eurocode 8 (see also Reference 2), Canada,[9] the United States (UBC)[10] and New Zealand.[11]

INFLUENTIAL FACTORS IN INELASTIC TORSIONAL RESPONSE

Tso and Ying[1] have concluded that structural asymmetry does not lead to significantly higher ductility demand for any one of the resisting elements if the element strengths are designed based on code provisions for Canada, New Zealand, Mexico and the United States, and that element 3, which is located at the flexible edge of the structure (Figure 1), is the critical element whose displacement can be up to two to three times that of symmetric structures. Their results indicate, however, that in many cases the maximum displacement ductility demand of element 1, which is located at the stiff edge of the structure, is higher than that of

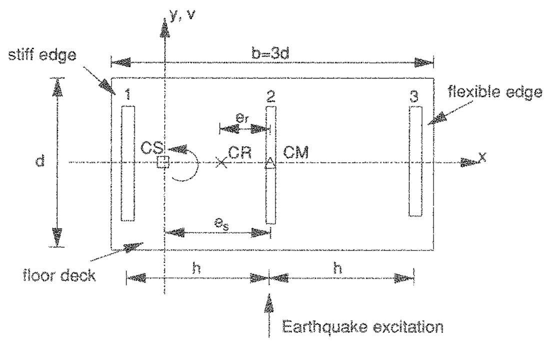

Figure 1. Plan view of the single storey three element stiffness eccentric model

symmetric structures. The authors[2] have emphasized that it is this element at the stiff edge, traditionally considered as favourably affected by torsion, which suffers substantially more severe structural damage than in symmetric structures and that the maximum displacement ductility demand of the element at the flexible edge, traditionally considered to be unfavourably affected by torsion, is always lower than that of symmetric structures. Furthermore, the authors have concluded that when calculating the strength demand of element 1, the code provision specifying the design eccentricity equal to the stiffness eccentricity e_s, if the accidental eccentricity is not included, is inadequate. As a result, the authors have recommended that this design eccentricity be changed to $0{\cdot}5\, e_s$ if excluding accidental eccentricity, which is of the same form as the Canadian code NBCC 1990 provision.[9]

A number of issues, as mentioned above, have contributed to these somewhat contradictory conclusions. In Tso and Ying,[1] the specification of the total strength and the resistance eccentricity is based on observations of the general trends of the variation of these quantities as functions of e_s, as determined by different codes. They defined two models representing the torsional design provisions of Canada, New Zealand or UBC (generic model 1), and those of Mexico 76 (generic model 2). In deriving the total strength and resistance eccentricity of these models, as well as specifying the relation of strength between element 2, the element at the centre and element 3, Tso and Ying[1] have included the accidental eccentricity in the design eccentricity expressions. However, in their inelastic dynamic analysis, there are neither any uncertainties regarding the real values of the stiffness and strength eccentricities nor are there any rotational components of ground motion. Therefore, their results are inevitably non-conservative and tend to mask the effect of torsion on additional element ductility demand.

In a previous paper by Cheung and Tso[12] studying the elastic response of multistorey eccentric buildings, the accidental eccentricity of $0{\cdot}1\, b$ was also included in calculating the code static torque and the resulting static shear in resisting elements. Subsequently, Stafford Smith and Vezina[13] have pointed out in the discussion of this paper that much better results showing the discrepancies between the codified static approach and dynamic analysis would have been achieved if only the actual eccentricity had been used and the accidental eccentricity not included in calculating the code static torque, in view of the omission of accidental eccentricities from their dynamic analysis. This point has been clearly proven by the results provided in the reply of Cheung and Tso.[14] Comparing the results in References 12 and 14, it is obvious that including the accidental eccentricity in the design eccentricity expressions is misleading regarding the adequacy of code torsional provisions when neither uncertainties nor torsional ground motion are present in the dynamic analysis. In view of the purpose of specifying accidental eccentricity in the code design eccentricity expressions (as stated explicitly in the commentary of the Canadian code NBCC 1990[9]), if both uncertainties and torsional ground motion are omitted in the dynamic analysis, then a practical approach, as employed by the authors, is not to include the accidental eccentricity in the code design eccentricity expressions for the specification of element strength, and hence to retain the additional torque due to accidental eccentricity for dealing with uncertainties and torsional ground motion. The magnitude of the accidental eccentricity needed to account for the latter effects is an issue to be studied elsewhere. In Tso and Ying,[1] if accidental eccentricity had not been included, the static equilibrium model rather than the generic model 1 would have been the representative model designed in accordance with the New Zealand and UBC code torsional provisions.

The second issue to be addressed is the need to use localized earthquake records or records having dissimilar frequency contents. In order to assess the validity of code provisions in a particular location, localized records should be used, if available. For instance, when evaluating the Mexico 76 and 87 code provisions, which are intended for use in the Federal District of Mexico primarily encompassing Mexico City, use should be made of records obtained from Mexico City in the 1985 earthquake. In order to generalize the applicability of conclusions drawn from dynamic analysis to a wider area, records having dissimilar frequency contents, or shapes of response spectra, and varying peak ground acceleration to velocity (a/v) ratios should be used. However, Tso and Ying[1] have employed eight records, each having intermediate a/v ratio and shape of response spectrum similar to that of the standard Newmark–Hall type design spectrum. This approach limits the generalization of conclusions drawn from their inelastic dynamic analysis.

The third issue discussed here is the necessity to carry out inelastic analysis and present results over the full period range relevant to actual buildings. It has been demonstrated by the authors[2] that when structures are designed based on a Newmark–Hall type design spectrum with total strength capacity substantially lower than elastic strength demand, the inelastic torsional effect is pronounced in different period ranges for ground motions having low, intermediate and high a/v ratios. For instance, if records with intermediate a/v ratios are used as ground motion inputs, the torsional effect on additional displacement ductility demand of element 1 is most pronounced in the very short ($T < 0{\cdot}25$ sec) and short ($0{\cdot}25$ sec $\leqslant T < 0{\cdot}5$ sec) period ranges. It is expected that Tso and Ying would have observed a more pronounced torsional effect on additional ductility demand of element 1 if they had presented results for this element over the whole period range rather than only for one period $T = 0{\cdot}5$ sec.

ACCIDENTAL ECCENTRICITY AND THE MEXICO 76 CODE TORSIONAL PROVISIONS

Inelastic dynamic analysis has been carried out by the authors based on the three element single storey monosymmetric model with stiffness eccentricity shown in Figure 1.

The system's total translational stiffness is $K_y = \Sigma k_i$ and torsional stiffness about the centre of stiffness CS is $K_\theta = \Sigma k_i x_i^2$, where k_i is the translational stiffness of the ith element. The corresponding torsionally uncoupled system is defined as that which has coincident CS and CM ($e_s = 0$) and retains all other properties of the asymmetric system shown in Figure 1.

The uncoupled torsional to translational frequency ratio Ω is defined as

$$\Omega^2 = \frac{\omega_\theta^2}{\omega_y^2} = \frac{K_\theta}{K_y r^2} \tag{1}$$

in which ω_θ and ω_y are torsional and translational frequencies of the corresponding torsionally uncoupled system, respectively, and r is the radius of gyration of the floor deck about CM. The translational stiffness of element 2 (k_2) is taken to be the average value of all the three elements. Thus:

$$k_1 = K_y\left(\frac{1}{3} + \frac{1}{2}\frac{e_s}{h}\right) \tag{2}$$

$$k_2 = \frac{1}{3}K_y \tag{3}$$

$$k_3 = K_y\left(\frac{1}{3} - \frac{1}{2}\frac{e_s}{h}\right) \tag{4}$$

$$h = r\left(\frac{3}{2}(\Omega^2 + (e_s/r)^2)\right)^{1/2} \tag{5}$$

The post-yielding force–deformation relationship for each element is taken to be bilinear hysteretic with Bauschinger effect and strain hardening. The post-yielding stiffness is assumed to be 3 per cent of the initial elastic stiffness.

The nominal base shear V_{y0} is détermined according to the Mexico 76 code design spectral acceleration a, expressed as a fraction of the acceleration of gravity, for group B buildings in Zone III with the ductility reduction factor Q equal to 4·0. That is

$$V_{y0} = \frac{Wa}{Q} \tag{6}$$

in which W is the weight of the floor deck, and a/Q equals 0·06 in the period range $0 < T_y \leqslant 3{\cdot}3$ sec.

The element strength is specified in accordance with the Mexico 76 code design eccentricity formulae:

$$e_{d1} = 1{\cdot}5e_s + 0{\cdot}1b \tag{7}$$

$$e_{d2} = 1{\cdot}0e_s - 0{\cdot}1b \tag{8}$$

However, in this study the accidental eccentricity $0{\cdot}1b$ is not included in the element strength specification. Therefore, the yielding strengths of resisting elements are

$$F_{y1} = \frac{V_{y0}}{K_y} k_1 \left(1 - \frac{e_s}{\Omega^2 r^2}(h - e_s)\right) \tag{9}$$

$$F_{y2} = \frac{V_{y0}}{K_y} k_2 \left(1 + \frac{1{\cdot}5e_s}{\Omega^2 r^2} e_s\right) \tag{10}$$

$$F_{y3} = \frac{V_{y0}}{K_y} k_3 \left(1 + \frac{1{\cdot}5e_s}{\Omega^2 r^2}(e_s + h)\right) \tag{11}$$

The uncoupled torsional to translational frequency ratio Ω is taken as unity. The damping value is assumed to be 5 per cent of critical. The east–west component of the record obtained at SCT, Mexico City lake bed, during the 19 September 1985 earthquake is employed as ground motion input.

Figure 2 presents the normalized displacement ductility, which is the maximum displacement ductility demand normalized with the corresponding value of a reference symmetric model, for elements 1 and 3 over the full period range 0·1–2·0 sec. The reference model is a single degree of freedom system having the same lateral period as the uncoupled lateral period of the asymmetric model, and total strength equal to the nominal base shear. The results clearly show that element 1 is the critical element and that the Mexico 76 code torsional provisions are inadequate, substantially underestimating the strength demand of element 1. This finding is in contrast to that of Tso and Ying[1] who have concluded that the Mexico 76 code provision already leads to satisfactory control of additional ductility demand.

The effect on element ductility demand of including accidental eccentricity in the design eccentricity expressions has also been studied. Figure 3 shows the normalized displacement ductility demands of elements 1 and 3, for structures designed again in accordance with Mexico 76 code base shear and torsional provisions but including an accidental eccentricity e_a of zero, $0{\cdot}05b$ and $0{\cdot}1b$ in the design eccentricity expressions. The stiffness eccentricity e_s is taken as $0{\cdot}2b$. Other parameters and the ground motion input are the same as above. It can be seen that including accidental eccentricity strongly affects the normalized ductility of element 1 but only slightly affects that of element 3. Results obtained for structures having e_s equal to $0{\cdot}1b$ and $0{\cdot}3b$ show the same trend. Judging from the dotted curve ($e_a = 0{\cdot}1b$, element 1) in Figure 3, one may arrive at the same conclusion as that of Tso and Ying[1] stated above in relation to the Mexico 76 code. However, for conservative design, allowance should be given to the uncertainties and torsional ground motion not considered in dynamic analysis, and judgement based on the solid curve in Figure 3 ($e_a = 0$, element 1) or the dashed curve ($e_a = 0{\cdot}05b$), which obviously indicate the inadequacy of the Mexico 76 code torsional

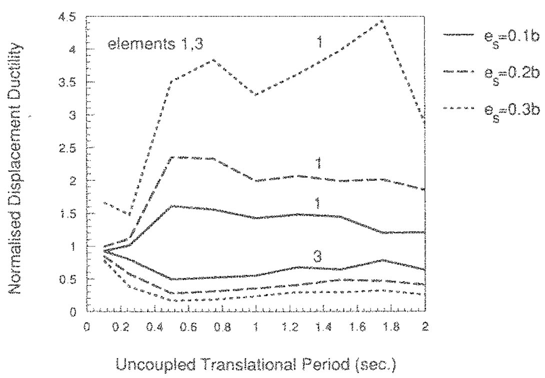

Figure 2. Normalized element displacement ductility of structures based on the Mexico 76 code provisions: element 1, stiff edge; element 3, flexible edge

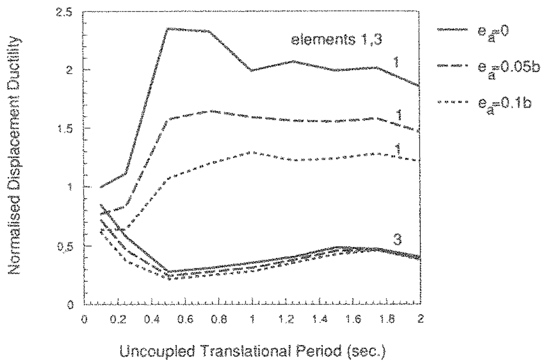

Figure 3. Effect of including accidental eccentricity on normalized element displacement ductility of structures based on the Mexico 76 code provisions: element 1, stiff edge; element 3, flexible edge

provisions. Consequently, the approach of including accidental eccentricity in the design eccentricity expressions and carrying out inelastic dynamic analysis ignoring any uncertainties and torsional ground motion can give misleading results.

EVALUATION OF MEXICO 87 CODE TORSIONAL PROVISIONS

The 1987 edition of the Mexico City building code (see References 15 and 16) has made radical changes to the torsional provisions, as described in detail by Esteva[5] and Gomez and Garcia-Ranz.[15] The new regularity conditions now require that the ductility reduction factor Q be reduced by 20 per cent if e_s exceeds $0{\cdot}1b$. The new requirements added to the torsional provisions now specify that the resistance eccentricity be at least $e_s - 0{\cdot}2b$ if $Q \leqslant 3$ and $e_s - 0{\cdot}1b$ if $Q > 3$, and that the centres of stiffness and resistance be on the same side with respect to the centre of mass. These new requirements are meant to increase the strength capacity of element 1 and therefore provide more protection to this element against structural damage. This is in line with the recommendations of the authors[2] and the results shown in Figures 2 and 3 of this paper.

These new requirements are based on the research of Gomez *et al.*,[16] which is also presented in Reference 5. In contrast to this study and that of Tso and Ying,[1] Gomez *et al.* carried out inelastic dynamic analysis based on single storey three element models having symmetric distribution of stiffness but eccentric mass and have concluded that having resistance eccentricity much smaller than the stiffness eccentricity leads to excessive ductility demand. Therefore, it was recommended that the resistance centre be close to the stiffness centre, in accordance with the regulations given above. Tso and Ying[1] stated that this is in contrast to the finding of Sadek and Tso,[17] who concluded that the inelastic torsional response decreases with a system's decreasing resistance eccentricity. This issue could be clarified by the observation that Sadek and Tso were referring to the element at the flexible edge whilst Gomez *et al.* were referring to the element at the stiff edge. Furthermore, systems based on the recommendations of Gomez *et al.* are different from the stiffness proportional models employed by Tso and Ying in Reference 1. The approach employed by Gomez *et al.* requires the element strength be first specified according to code design eccentricity expressions and then the strength of element 1 be increased to shift the resistance centre sufficiently close to the stiffness centre. In contrast, the element strength in stiffness proportional models as studied by Tso and Ying[1] is determined simply by applying the nominal base shear through the stiffness centre, which ignores the torsional shear and therefore obviously underestimates the strength and leads to excessive ductility demand of element 1.

In view of the radical changes introduced in the Mexico 87 code, a key issue arises. This concerns the effectiveness of the new provisions to provide satisfactory control over additional structural damage due to uneven distribution of stiffness. Evaluation of the Mexico 87 code torsional provisions is carried out in this paper based on the same three element model described in Reference 2 and illustrated in Figure 1. The calculation of the nominal base shear is in accordance with the modified design spectrum for group B

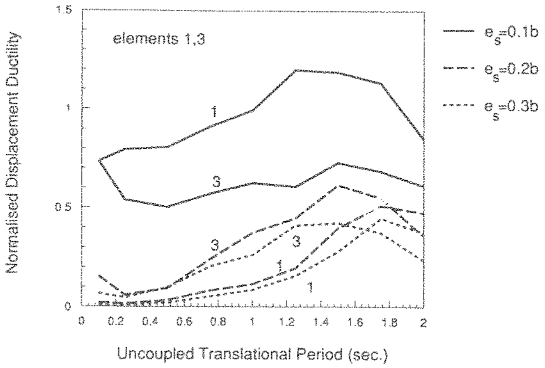

Figure 4. Normalized element displacement ductility of structures based on the Mexico 87 code provisions: element 1, stiff edge; element 3, flexible edge

buildings in Zone III and the appropriate regularity conditions. The specification of element strength is achieved first by applying the nominal base shear at distances from the centre of stiffness equal to the design eccentricity expressions specified in the Mexico 87 code [which are the same as those in the Mexico 76 code, see equations (7), (8)] but excluding accidental eccentricity, and then increasing the strength of element 1 to shift the resistance centre towards element 1 to satisfy the new requirements. Here, the Q factor is taken as 4·0 and the requirement that the resistance eccentricity should be at least $e_s - 0{\cdot}1b$ is interpreted as in Reference 1 to be equal to $e_s - 0{\cdot}1b$. Other parameters and the ground motion input are the same as given above. Figure 4 shows the normalized displacement ductility demands of elements 1 and 3 over the full period range. The normalized displacement ductility of element 1 decreases rapidly with the increase of stiffness eccentricity but the corresponding decrease of the normalized displacement ductility of element 3 is only marginal. These findings agree with those shown in Figure 6 of Reference 1. Because of the additional requirements, there is a large increase in the strength of element 1 and hence a large increase in the overall strength, as shown in Table II of Reference 1. This leads to an unnecessarily conservative normalized displacement ductility for element 1. As a result, unlike the Mexico 76 code the torsional provisions in Mexico 87 are overly conservative.

IMPROVEMENTS TO CODE TORSIONAL PROVISIONS

A study has been carried out by the authors to provide recommendations to improve the Mexico 87 code torsional provisions. The aim is to change the code design expression pertaining to element 1 and therefore to delete the requirements supplementary to the 76 code. The authors have already recommended[2] that the secondary design eccentricity expression of Eurocode 8 be changed from $1{\cdot}0e_s - 0{\cdot}05b$ to $0{\cdot}5e_s - 0{\cdot}05b$. Here, this approach is again employed and the authors recommend that the primary and secondary design eccentricity expressions be specified respectively as $1{\cdot}5e_s + 0{\cdot}1b$ and $0{\cdot}5e_s - 0{\cdot}1b$, as in the Canadian code NBCC 1990,[9] without the need for the new requirements.

Figure 5 illustrates the normalized displacement ductility demands of elements 1 and 3 of structures designed according to the base shear provisions and regularity conditions of Mexico 87 code and the above recommended design eccentricity expressions, but excluding accidental eccentricity. It can be seen that the overall performance of these structures is satisfactory. In most cases, the normalized displacement ductility demand of element 1 is less than or around unity. Only for large stiffness eccentricity and periods longer than about 1·5 sec does this demand exceed unity, indicating displacement ductilities greater than those of the reference symmetric structures. Furthermore, as shown by Tso and Ying,[1] the above recommended design eccentricity expressions automatically satisfy the requirement that the resistance and the stiffness eccentricities have the same sign, which is also the case for mass eccentric systems.

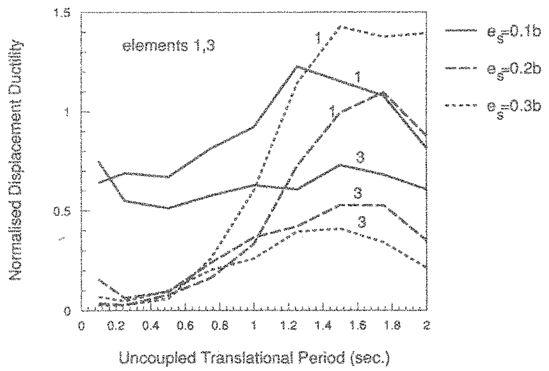

Figure 5. Normalized element displacement ductility of structures based on the Mexico 87 code base shear and the torsional provisions recommended in this study: element 1, stiff edge; element 3, flexible edge

CONCLUDING REMARKS

1. When element strength is specified according to code design eccentricity expressions, the element at the stiff edge is the critical element which suffers significantly more severe damage than corresponding symmetric structures. The peak displacement ductility demand of the element at the flexible edge is always lower than that of corresponding symmetric structures.
2. The Mexico 76 code torsional provisions, together with those specifying $1{\cdot}0e_s - 0{\cdot}1b$ or $1{\cdot}0e_s - 0{\cdot}05b$ as the design eccentricity for the element at the stiff edge, are inadequate, substantially underestimating the strength demand of this element.
3. The approach of including accidental eccentricity in the code design eccentricity expressions but ignoring uncertainties and torsional ground motion in inelastic dynamic analysis is misleading.
4. Localized earthquake records and records having dissimilar frequency contents should be employed for inelastic dynamic analysis, and results should be presented over a wide period range.
5. The Mexico 87 code torsional provisions have included additional requirements which correctly increase the strength capacity of the element at the stiff edge. However, in view of the large increase in the overall strength, they are overly conservative.
6. The authors recommend that the design eccentricity expressions of the Mexico 87 code be changed to $1{\cdot}5e_s + 0{\cdot}1b$ and $0{\cdot}5e_s - 0{\cdot}1b$ and that the new requirements added to the torsional provisions be deleted. These provisions should be interpreted as leading to minimum design strengths in resisting elements, according to the objectives of earthquake resistant design regulations. However, it is recognized that, because of architectural restrictions and the detailing provisions for different construction materials, the strengths of some elements may be higher than those resulting from the structural design. This results in non-uniformly distributed ductility demand. Further research is needed to evaluate this effect and to incorporate design provisions which deal appropriately with such uncertainties. In view of the fact that the above recommendations lead to satisfactory results, and that they are the same as those in the current Canadian code NBCC 1990 and also applicable to Eurocode 8 (see Reference 2), these recommended design eccentricity expressions could be regarded as general guidelines for the specification of element strength capacity in asymmetric structures, as described in Reference 8.

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