Dynamic Torsional Behavior of Inelastic Systems

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ABSTRACT

This paper evaluates the applicability of the static method for the seismic design of torsionally unbalanced buildings. In evaluating this method it is deemed that the design of a structure with torsion is satisfactory if it leads to the same overall response as the corresponding balanced structure. Specifically, ductility demands and interstory drifts of the vertical elements of a single-story system are used as response parameters for assessing current code static methods, as well as modified static procedures. It is found that the direct distribution of torsional moments stipulated in some codes underpredicts the required strength of some vertical elements, particularly those for which static torsion is favorable. On the other hand, disregarding favorable torsional effects, as required by other codes, can be overly conservative. A modified rule is proposed, which leads to more satisfactory designs.

1 INTRODUCTION

Observations of damaged and undamaged structures during recent earthquakes have provided new opportunities to assess critically the seismic performance of buildings. Post-earthquake studies show that severe damage or complete collapse of engineered structures occurs usually due to one or more unfavorable factors, such as a more intense ground shaking than anticipated; strong discontinuities in stiffness along the height; unbalanced distribution of stiffness or mass, which result in large torsional effects; or inadequate detailing. Examination of structures that did not perform well, including some of recent construction and designed in accordance with modern codes, indicates that in a number of cases the design may not have properly addressed torsional effects. This view is shared widely by reconnaissance teams, researchers, and practitioners. For instance, a recent EERI report (1989) which summarizes the lessons learned from the 1985 Mexico earthquake concludes that torsional effects have been shown to be very important for building response, and that torsional considerations are among the important seismic code issues that require revision.

One lesson from the analysis of distribution of damage to buildings due to torsion in recent earthquakes and to the inherent uncertainty of seismic excitation is that design and construction practices that result in extremely large eccentricities should be avoided, and that performing complex analysis, in the absence of accurate models, does not necessarily lead to satisfactory design of structures with severe torsional problems. It seems preferable, in practice, to employ relatively simple design methods (such as the ones currently in use, with suitable modifications) and to establish quantitative limits of key variables, through experimental and analytical studies, for which torsional seismic provisions remain applicable.

Current building codes consider torsional effects by static or dynamic methods based on elastic behavior. In static procedures, the torsional moment on each story is resolved into horizontal forces applied on the vertical interstory elements according to their relative stiffness and that of the floor diaphragms which connect them. Effects of inelastic behavior, which is implicitly assumed to occur during strong earthquakes, are considered in design by reducing the forces calculated from an elastic analysis by a global factor. This global factor is

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derived from comparisons of the response of simple elastic and inelastic models, and is justified in practice on the basis of observed performance of different types of buildings during actual earthquakes.

However, differences exist in the specific magnitudes of torsional moments specified by different codes for design purposes. The NEHRP (1988) provisions allow the forces produced by torsion to be either added to or subtracted from those resulting from direct shear. The UBC (ICBO, 1988) and the SEAOC (1990) codes, on the other hand, allow no reduction in member forces due to torsion. There are differences also between US codes and those of other countries. Seismic regulations in Mexico, for instance, require that the so-called direct eccentricity effects be amplified by a factor of 1.5 in order to account for the dynamic magnification of the static eccentricity (DDF, 1987). In Canada, a deamplification factor of 0.5 is additionally specified for elements in which torsionally induced forces are favorable (Tso, 1983). On the other hand, the NEHRP, SEAOC, and UBC provisions do not include any dynamic magnification factor. The Commentary to the NEHRP provisions recognizes that this is "partly because its significance is not well understood for buildings designed to deform well beyond the range of linear behavior."

2 ANALYTICAL STUDY

The preceding discussion points out the need for a critical examination of current regulations for including torsion in seismic design, and for an improved understanding of torsional behavior of buildings during destructive earthquakes. This paper presents the results of some initial work in this direction. Our attention is focussed on the static method for including direct torsional moments, aimed at developing more rational code procedures. Accidental torsional effects, such as those due to torsional components of ground motion or to statistical variations of building properties, are not considered here.

To achieve the above objectives, a single-story model with the plan view shown on Figure 1 was analyzed using the El Centro 1940 (NS), Taft 1952 (S69E), and the SCT Mexico City 1985 earthquake records. The deck is rigid with uniformly distributed mass. The location of the vertical elements resisting the seismic forces is symmetric, but their initial stiffnesses are unbalanced, resulting in an asymmetrical position for the center of stiffness (i.e. in a nonzero static eccentricity). Using a nonlinear static analysis, Tso and Bozorgnia (1986) have shown that this distribution of vertical elements leads to the most unfavorable torsional displacements. We have verified that the configuration of Figure 1 is also more unfavorable for simple dynamic loads (Diaz-Molina, 1988).

The elastic properties of this single-story system are completely defined by three parameters: the uncoupled translational natural period, T, the ratio of uncoupled torsional to translational frequencies, Ω, and the eccentricity ratio e/r. e is the static (direct) eccentricity and r is the radius of gyration of the rigid deck about it center of mass. Values of T ranging from 0.2 to 3.0 seconds are considered in this study. The values of Ω are 1.0, 1.3 and 1.6. Rather than selecting arbitrarily e/r, we vary the stiffness and location of the vertical elements, thus avoiding unrealistic cases. The resulting values of e/r are 0.72, 0.60 and 0.30. In all cases, element 3 was selected as the stiffer one, shifting the shear center towards it. Therefore, the shear forces resulting from a static distribution of torsional moments will always be additive to direct shear forces for elements 1 and 2, and subtractive for element 3. The inelastic behavior was incorporated considering the nondegrading elastoplastic model, which has been widely used in previous studies. In addition, 5 percent of viscous modal damping was included.

The first step of our evaluation procedure consists in selecting a ground motion and a target ductility demand. A torsionally balanced structure with translational natural period, T, is then selected and the total stiffness of this structure is calculated. The strength, i. e. the yield force, Fy, that produces a ductility demand equal to the target ductility in this structure is calculated by successive dynamic analyses. Then, the properties described in the preceeding paragraph are used to define several torsionally unbalanced systems with the same total stiffness as the balanced system. The relative stiffness of the vertical elements is used to calculate their yield strengths by static distribution of the shear force Fy, which is now eccentric. The eccentricity used in this step is given by: $e_d = \alpha e$; the coefficient α provides a means to incorporate the dynamic nature of seismic torsional response into static calculations. A design criterion is defined by the adoption of particular values for α when considering torsional effects by the static method. In general, modern codes specify two values α_1 and α_2. The first value is to be used for vertical members for which torsional moments are unfavorable, and the second for members that are favorably affected by torsion.

The primary objective of this study is to assess the adequacy of various combinations of α_1 and α_2. For a given pair α_1,α_2, the calculation of the yield strength of the vertical elements completes the definition of the inelastic, torsionally unbalanced, systems. The numerical solution of the equations of motion of these systems provides the ductility demand on the vertical elements, which can then be compared to the target ductility.

3 RESULTS

Figure 2 presents the ductility demands on elements 1 and 3 for $\Omega = 1$ and $e/r = 0.72$, corresponding to the most unfavorable combination of elastic torsional parameters considered in this study. It is immediately seen that the ductility demand in element 3, for which static torsional shear is favorable, consistently exceeds the target ductilities, up to factors near 3. On the other hand, the ductility demands for element 1, for which torsional shear forces are unfavorable, are always below (substantially for most of the periods) than the target value. Ductility demands for element 2 (not shown) are slightly different than those for element 1, and do not exceed the target ductility. Interestingly, the preceding observations hold for the three earthquake records used in th this work, even though they have different duration, intensity and frequency contents.

Figure 3 presents normalized ductility demands on element 3 for two cases in which one of the parameters defining elastic torsional characteristics have been changed with respect to the case of Figure 2. First, the rotational to translational frequency ratio, Ω, was changed from 1 to 1.6, by increasing the torsional stiffness, but keeping the eccentricity ratio e/r equal to 0.72. In the second case Ω was kept equal to 1, and e/r was reduced form 0.72 to 0.3 The ductility demands for element 3 decrease significantly with these changes, but peak values are still above the target ductility. Ductility demands for elements 1 and 2 (not plotted) are again always below the target value. This tendency of the ductility demands for elements 1 and 2 was observed consistently in all the other cases analyzed in this work, indicating that eccentricity amplification factors for elements unfavorably affected by torsion, as prescribed in several codes, may not be justified.

Whereas static analyses indicate that torsional shear forces are favorable to element 3, the nonlinear analysis indicates that it could be underdesigned. Therefore, the remainder of our analysis is concentrated on this element. Figure 4 shows normalized ductility demands obtained with the Mexico City 1985 earthquake record for five different combinations of values of α_1 and α_2, i.e. for different design criteria. Figures 5 and 6, present the corresponding results for the El Centro 1940 and the Taft 1952 records. In the first two combinations α_2 was kept equal to 1, i. e., the torsional moments were not modified when calculating the strength of element 3, which is favorably affected by torsion. α_1 was also kept equal to 1 in one case, but in the other was increased to 1.5. Comparing the results for these two cases on Figures 4 to 6 it is observed that the use of an amplification factor for torsional moments reduces only marginally the ductility demands on element 3, and by no means below the target ductility.

A reduction factor α_2 (lower than 1.0) was used for the torsional eccentricity in the other three cases shown on Figures 4 to 6. It can be seen that a significant reduction of ductility demands is achieved when α_2 is taken as 0.5, and, in fact, for most periods the demands are lower than the target value. The simultaneous application of a magnification factor of 1.5 did not produced any appreciable additional benefits. Finally, torsional favorable effects were completely ignored ($\alpha_2 = 0$) resulting in ductility demands smaller than the target value, for periods below 1.5 seconds. For larger periods, there are a few instances where the demands are higher than the target ductility, but they are still lower than those for other combinations of α_1 and α_2, and do not exceed the target value by more than 25 percent. Only in an isolated case (period=2 seconds for the Taft record) does the demand exceed the target value by 50 percent.

4. CONCLUSIONS

The results presented here suggest that the static method can be satisfactorily used for the design of torsionally unbalanced structures provided a reduction factor is applied to the static eccentricity for the calculation of the required shear strength of the vertical elements that are favorably affected by torsion. On the other hand, it appears that the use of an amplification factor for torsional eccentricities is not required, at least from the viewpoint of ductility demand. The appropriate value for the reduction factor seems to be between 0.5 and 0, with larger reductions required for longer translational periods. However, additional studies, with a larger sample of earthquakes, and considering multistory models are needed before definitive rules can be established.

From our analysis one may conclude that codes considering only unfavorable static torsional effects lead to acceptable designs. This is the case of the UBC and SEOAC codes. On the other hand, the complete inclusion of torsional favorable effects, as prescribed for instance by ATC and Mexican codes, might lead to excessive ductility demands in elements whose required strength is reduced because of torsion.

It should be also noted that our results raise some concern on the applicability of three-dimensional modal analysis for unbalanced structures in which significant inelastic behavior is anticipated. In this method, elastic dynamic moments are not modified at all, whether they are favorable or not. Further, it is known that elastic dynamic eccentricities are frequently larger than the static ones, sometimes by factors as large as three. Therefore, favorable torsional effects can be significantly exaggerated, leading to ductility demands that may exceed by far the target value.

ACKNOWLEDGMENT

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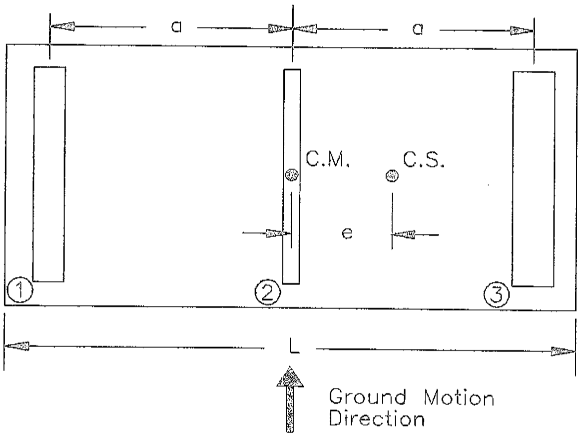

FIGURE 1 PLAN OF THE MODEL

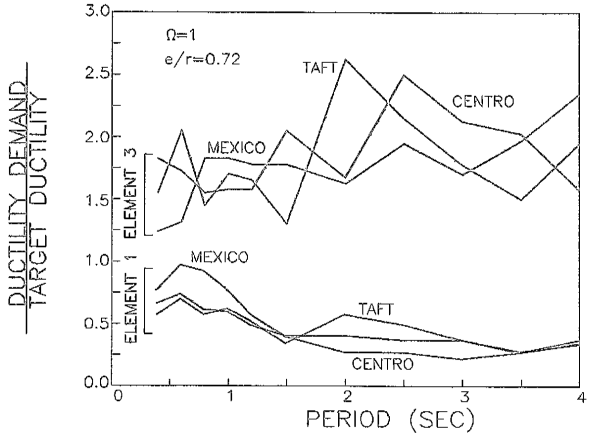

FIGURE 2 NORMALIZED DUCTILITY DEMAND IN ELEMENTS 1 AND 3 UNMODIFIED ECCENTRICITY ($\alpha_1=\alpha_3=1$)

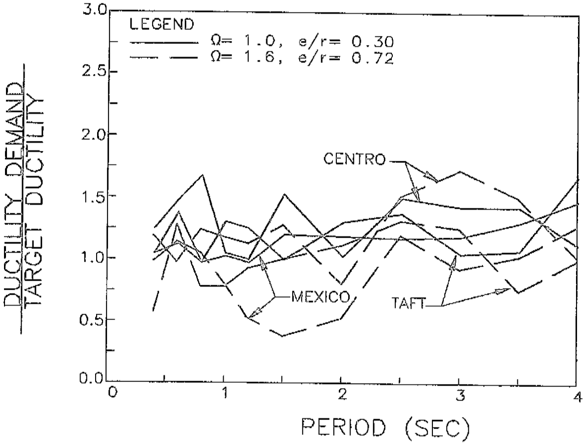

FIGURE 3 NORMALIZED DUCTILITY DEMAND IN ELEMENT 3 UNMODIFIED ECCENTRICITY ($\alpha_1=\alpha_3=1$)

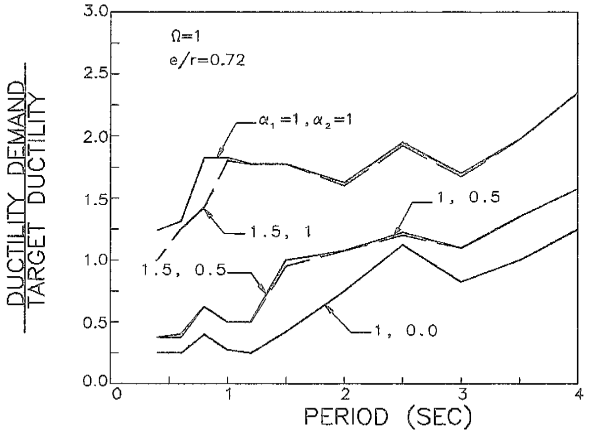

FIGURE 4 NORMALIZED DUCTILITY DEMAND IN ELEMENT 3
MEXICO 1985 EARTHQUAKE RECORD

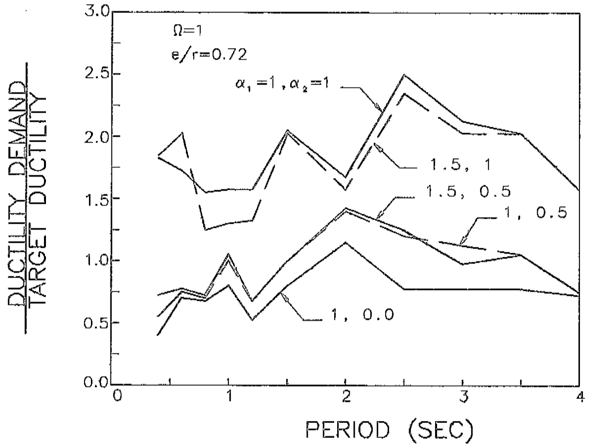

FIGURE 5 NORMALIZED DUCTILITY DEMAND IN ELEMENT 3
EL CENTRO 1940 EARTHQUAKE RECORD

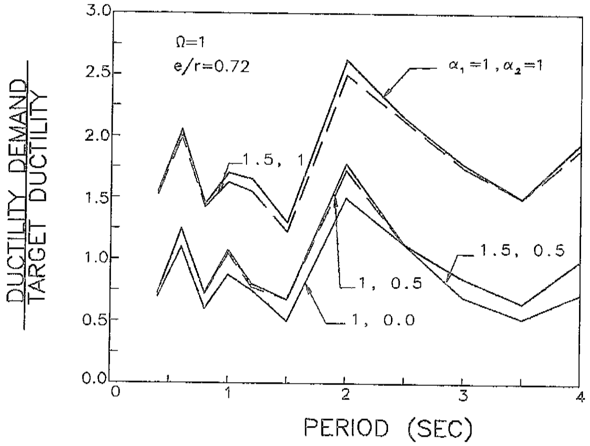

FIGURE 6 NORMALIZED DUCTILITY DEMAND IN ELEMENT 3
TAFT 1952 EARTHQUAKE RECORD