Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Strength distribution for torsionally unbalanced structures

W.K.Tso
McMaster University, Hamilton, Ont., Canada

T.J.Zhu
Buckland and Taylor Ltd, Vancouver, B.C., Canada

ABSTRACT: Using a three elements single mass model, this paper presents the ductility demands on the elements of torsionally unbalanced systems when subjected to strong earthquake shaking. Torsionally unbalanced systems based on nine structural configurations are considered, ranging from torsionally stiff systems with center of rigidity (CR) centrally located to torsionally flexible systems with CR eccentrically located. The strength of the elements are designed based on the Canadian, New Zealand codes, and the Uniform Building Code (UBC) of the United States. It is shown that all three codes can limit the ductility demands on the elements to that of a similar but torsionally balanced system when the system is torsionally stiff. However, substantial additional ductility demands on element at the stiff edge of the system exist for torsionally flexible systems when the New Zealand code or UBC is used. The large ductility demand is caused by low strength of the stiff edge element permitted by these codes.

1 INTRODUCTION

The problem of seismic inelastic torsional responses of a single mass system is re-examined from a designer's perspective. There are two major differences from previous studies of the same topic, (Tso and Ying 1990, Chandler and Duan 1991, Chopra and Goel 1991). First, the second moment of stiffness distribution as represented by the torsional stiffness of the system is recognised as a key design parameter and taken as an independent system parameter in this study. Second, the reference systems used to normalize the inelastic responses are not required to be symmetric, but only to be torsionally balanced. As a result of this change, a larger class of structural configurations can be covered in this study, and there is no need to make a distinction between stiffness eccentric or mass eccentric systems. The main objective of this study is to evaluate the adequacy of the torsional provisions in three seismic codes to limit the additional ductility demands on the resisting elements of a torsionally unbalanced structural system due to coupled torsional-translational responses.

2 STRUCTURAL MODEL

The structural model consists of a single rectangular rigid slab of size a by b and mass M, supported by three parallel lateral load resisting elements 1, 2, and 3 aligned in the Y direction. Elements 1 and 3 are located at an equal distance of b/2 from, but at the opposite sides of element 2. The structural model is subjected to seismic ground motion along the Y direction as shown in Fig. (1). The three elements have bilinear hysteretic force-deformation characteristics with the strain-hardening stiffness equal to 3% of the initial elastic stiffness. They have in-plane initial elastic stiffness $k_i (i=1,2,3)$ and yield strength $f_i (i=1,2,3)$, whereas their out-of-plane stiffness and strength are negligible.

3 STIFFNESS AND MASS DISTRIBUTION

Nine systems having the same total lateral stiffness K, but different combinations of the first- and second-moment stiffness distributions are considered, as shown in Fig. (2). All systems have uncoupled translation period equal to 0.5 s. For ease of reference, each system will be designated as ζ/λ, where ζ denotes the location of CR relative to element 2, and λ denotes the actual second moment of stiffness distribution. ζ takes on the value of 0.0b, 0.2b, or 0.4b, and λ is given a designation of A, B, or C corresponding to $k_3=10k_2$, $k_3=k_2$, or $k_3=k_2/10$, respectively. Structural configuration A represents a torsionally stiff structure while configuration C represents a torsionally flexible structure in the context that both of them have the same total stiffness and the same first moment of stiffness distribution. Element stiffness $k_i(i=1,2,3)$ (expressed as a percentage of the total lateral stiffness K) is shown for each configuration. The torsional stiffness of the system is represented by the radius of gyration of stiffness about CR normalized to b and is denoted by ρ_k. The computed ρ_k values of the nine configurations are also presented in Fig. (2).

When the center of mass (CM) is located at the same location as CR (zero eccentricity), the nine systems shown in Fig. (2) are designated as the nine torsionally balanced (reference) systems. Torsionally unbalanced systems for this study are developed from each of these nine torsionally balanced systems by shifting CM away from CR toward the right to create different values of eccentricity. With this positioning of CM relative to CR, element 1 will be referred to as the element on the stiff side and element 3 as the element on the flexible side of the structure. In this study, part of the total mass is uniformly distributed over the entire slab, and the rest is uniformly distributed along either the left or the right edge line, depending upon the location of CM relative to the geometric center of the slab for a specified value of eccentricity e. The slab aspect ratio a/b is taken as 0.5.

4 STRENGTH DISTRIBUTION

The nominal lateral design strength F for a system is specified as $F = Ma^*/R$. a^* is chosen as the 5% damped acceleration spectrum of Newmark and Hall. (1982). The strength reduction factor R is taken to be 5, so that all systems will be excited well into the inelastic range in the analysis. Four ways of distributing the strengths among elements 1, 2 and 3 are considered. The first way is to have the strength of each element proportional to its stiffness (stiffness proportioning, or SP for short). This way of strength distribution implies that no torsional provision is allowed for in design. The other three ways of distributing strengths follow the torsional provisions stated in the Canadian code, New Zealand code, and the Uniform Building Code of the United States. They shall be referred to as NBCC, NZC and UBC in the remaining of this paper.

5 INPUT GROUND MOTIONS

An ensemble of 15 strong motion records are used as input ground motions for the systems. They are selected based on the criterion that the shapes of their acceleration response spectra are similar to the shape of the design spectrum in order to minimize the effects of mismatch in frequency content between the input ground motions and the design spectrum as a cause for poor control over ductility demand on the elements. Pertinent information regarding the 15 earthquake records are presented by Tso et al. (1992) where they are referred to as records having intermediate A/V ratio. The Newmark-beta method with beta equal to 1/6 is used to solve the equations of motion. Rayleigh damping giving 5% of critical damping in the two vibrational modes is assumed.

6 INELASTIC RESPONSES

The parameters of interest are the maximum ductility demands on the flexible edge and the stiff edge resisting elements. The ductility demand is normalized with its counterpart in the reference torsionally balanced system, forming quantities referred to as ductility demand ratio. The mean of 15 ductility demand ratios of element i will be denoted as $(r_\mu)_i$, and the inelastic responses of the nine configurations are described via the mean ductility demand ratios of their edge elements.

The mean ductility demand ratios of element 3 (element on the flexible edge) are shown in Fig. (3). r_μ can be very large for the SP systems, particularly when CR is eccentrically located. In other words, one can expect additional ductility demands on the flexible edge element if no torsional provision is used. The ductility ratio curves based on the three codes are essentially the same. All of them have value below unity.

The mean ductility ratio plots for element 1 are shown in Fig. (4). Unlike element 3, the ductility demand ratio for element 1 is very much design code dependent. To appreciate the design implication, it is convenient to discuss the results based on the grouping of A, B, and C structural configurations, and $e=0.4$ shall be considered an upper limit of eccentricity for practical design. For the torsionally stiff A configurations, all ductility ratio curves are either below or in the neighbourhood of unity, indicating there is no additional ductility demand on element 1. For the "B" configuration, substantial ductility demand can be expected for element 1 for the centrally located CR systems (0.0b/B) if the design is based on either NZC or UBC. The range of eccentricities where large additional ductility exists, coincides with the same range in which the design strength of element 1 is allowed to be reduced substantially by these codes. The design strengths of element 1, normalized to their strength based on the corresponding torsionally balanced reference

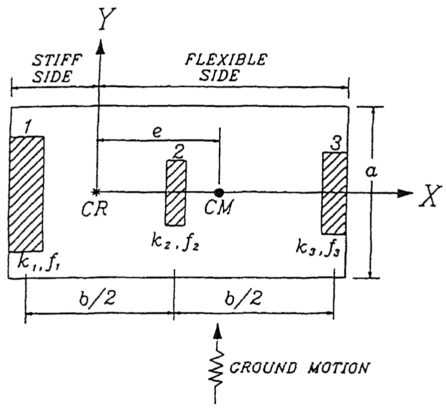

Fig. (1) Structural Model

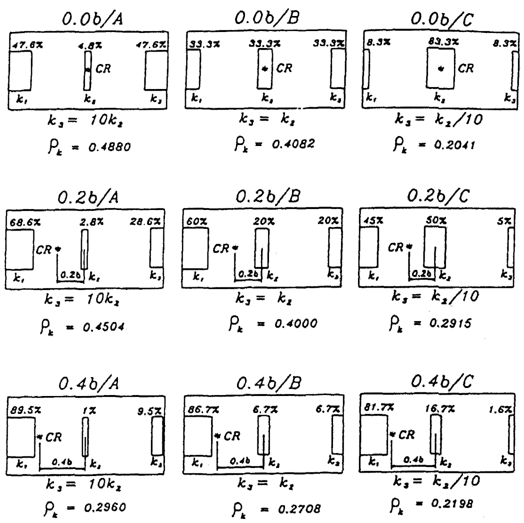

Fig. (2) Nine Basic Structural Configurations

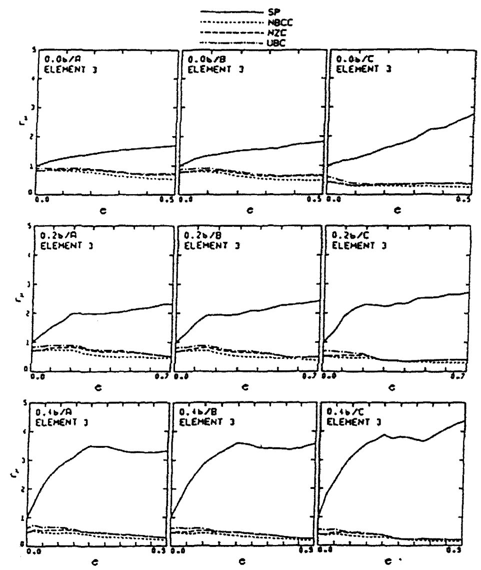

Fig. (3) Mean Ductility Ratio (Element 3)

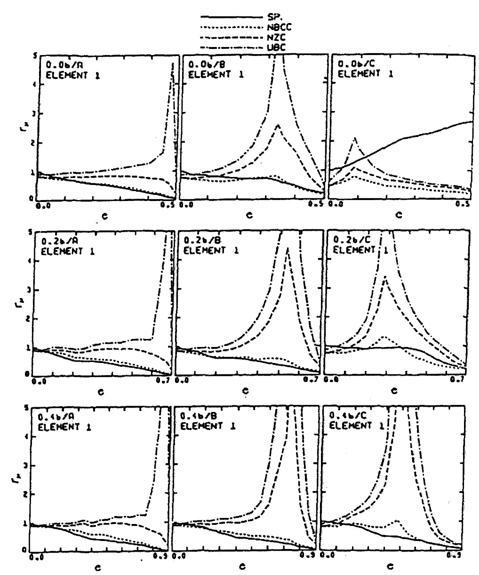

Fig. (4) Mean Ductility Ratio (Element 1)

systems are shown in Fig. (5). The reduction of element strength based on NBCC is limited. As a result, the NBCC ductility ratio curve remains below unity. A discussion on the correspondence between high ductility demand and low design strength of element 1 has been given. (Tso and Zhu, 1992). For the 0.0b/C configuration, the UBC ductility curve reaches a peak value of two at fairly low eccentricity ($e \approx 0.1b$). Larger values of r_μ are also exhibited by the UBC and NZC curves for the torsionally flexible system with eccentrically located CR (0.02b/C and 0.04b/C).

7 CONCLUSIONS

Denoting systems having $e \leq 0.1b$, $0.1b < e \leq 0.3b$, and $0.3b < e$ as systems having small, moderate and large eccentricities respectively, the following conclusions can be made on systems designed to different code provisions.

(1) Systems designed not incorporating torsional provisions will have large additional ductility demand on elements at the flexible side of the structure.

(2) Systems designed based on NBCC exhibit good control over ductility demand on elements at both the flexible and stiff side of the structure. Any additional ductility

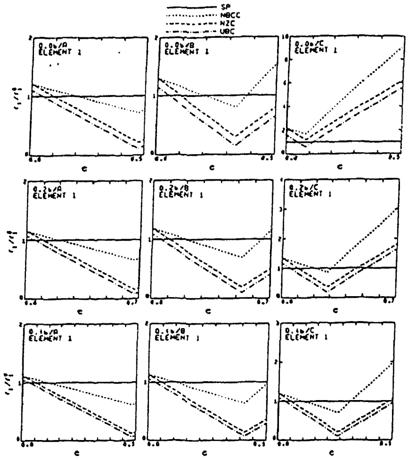

Fig. (5) Design Strenght (Element 1)

demand (on the stiff side element) is minimal. This is the result that the Canadian code does not allow a drastic reduction of strength on the stiff side element. (Zhu and Tso, 1992).

(3) Systems designed based on NZC show no additional ductility demand on element at the flexible side, but some additional demand on element at the stiff side. This will occur for torsionally flexible configurations having moderate and large eccentricities (0.2b/C and 0.4b/C configurations) and in torsionally moderately stiff configuration having large eccentricity (0.0b/B configuration).

(4) Systems designed based on UBC also exhibit no additional ductility demand on element at the flexible side of the structure. However, there is substantial additional ductility demand on the element at the stiff side on a number of configurations. Torsionally flexible structures (0.0b/C, 0.2b/C and 0.4b/C configurations) having small, moderate or large eccentricities are susceptible to high additional demand. This is caused by the low design strength of the stiff edge element.

8 ACKNOWLEDGEMENT

The writers wish to acknowledge the support of Natural Sciences and Engineering Research Council of Canada (NSERC) for the work presented.

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