

A DISPLACEMENT BASED APPROACH TO THE ANALYSIS FOR SEISMICALLY INDUCED TORSION IN BUILDINGS

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ABSTRACT:

The provisions for the torsional response of buildings in contemporary seismic design standards have been based on extensive research investigating the seismic strength and ductility demand of individual lateral resisting elements in buildings with torsionally unbalanced properties. The accuracy with which the element ductility demand is estimated depends essentially on the accuracy with which the element force-displacement behaviour has been modeled. According to research in recent years into the behaviour of reinforced concrete, the yield displacement of the element estimated by conventional methods employing notional EI values could be in significant error depending on the element dimensions. These modeling uncertainties could result in the actual element strength and ductility demand to be mis-represented by observations from case studies that were reported in the literature. Consequently, there are instances in which findings from research on inelastic torsional actions appear to be contradictory.

Actions on elements expressed directly in terms of displacement are unambiguous and easier to interpret than ductility ratios. Thus, seismically induced torsional effects should be better characterized by the instantaneous centers for horizontal rotation along with the displacement of the building at its center of mass (CM). In this paper, a new torsion model employing such displacement-based parameters is introduced. With this new modeling approach, the capacity spectrum method could be extended conveniently to address inelastic torsional actions in buildings.

1. INTRODUCTION

The seismic strength demand on lateral load resisting elements in asymmetrical buildings is controlled partly by the design eccentricities which are based on implicit assumptions in the ductility behaviour of the element. The predicted ductility demand could be in error if unrealistic assumptions have been made of the element displacement at yield. For example, the element yield displacement has often been assumed to be proportional to the element yield strength. Element stiffness has also been assumed to be independent of element yield strength. Problems with the accuracies in these common assumptions have been highlighted by Paulay (2001) and Priestley & Kowalsky (1998) who rightly asserted that the yield strength of a reinforced concrete element is essentially in linear proportion to the element stiffness provided that the gross dimensions of the element and the material properties are held constant.

Uncertainties with the element ductility demand could result in mis-representation of inelastic torsional actions by case studies. Consequently, conclusions reached in different studies reported in the literature appear to be contradictory due to the different modelling assumptions (eg. Tso & Ying, 1990; Chopra & Goel, 1991). The sensitivity of the analysis results to the modelling assumptions was addressed in a recent investigation by Tso & Smith (1999).

The seismic demand on elements expressed directly in terms of displacement is unambiguous and easier to interpret than ductility ratios. Thus, seismically induced torsional effects should be better characterised by the instantaneous centers for horizontal rotation along with the displacement of the building at its center of mass (CM). The use of displacement parameters to represent inelastic torsional actions allows established displacement-based procedures such as the capacity spectrum method to be extended conveniently for 3-D analyses. With the displacement parameters and the building model defined in Sections 2 and 3, results from parametric studies to model static-dynamic modifications for elastic and inelastic systems could then be presented for comparison in the rest of the paper (Sections 4 and 5).

2. DIMENSIONLESS PARAMETERS

The dimensionless parameters associated with the new torsion model that could be adapted to the capacity spectrum method are namely α , λ and ϵ . First, the α parameter is defined as the ratio of the displacement at the center of mass (CM) of a torsionally unbalanced building (*TUB*) and the corresponding torsionally balanced building (*TB*). Thus,

$$\alpha = \frac{\Delta_{CM} (TUB)}{\Delta_{CM} (TB)} \quad (1)$$

where $\Delta_{CM} (TUB)$ and $\Delta_{CM} (TB)$ are the displacements at the CM of a torsionally unbalanced and torsionally balanced buildings respectively.

With the displacement at the centre of mass (CM) defined by α , the maximum displacement of the torsionally responding building can be constructed "on plan" using

the λ parameter which defines the position of the instantaneous centre of rotation (ICR) of the building as shown in Figure 1b. The curve annotated as "DRE" is the envelope of the maximum displacement demand experienced at different positions in a TUB. The λ parameter has been made dimensionless by normalizing it with respect to the radius of gyration (r) of the building.

A unique solution for λ could be obtained by introducing an inertia force at the building CM in a static analysis. The rotation resulting from the inertia force causes elements on the "flexible" side of the building to experience the highest displacement demand. Displacement demand on the same elements (and the corresponding λ parameter) could then be re-evaluated by dynamic analyses employing earthquake accelerograms. The effect of dynamic torsional coupling becomes evident when the positions of the ICR, as represented by the λ parameters associated with static and dynamic actions, (denoted herein as λ_{static} and λ_{dynamic} respectively) are compared. This static-dynamic amplification effect can be expressed conveniently by the ratio $\lambda_{\text{dynamic}} / \lambda_{\text{static}}$.

It is as important to note that static analysis shows the building rotating only in one direction (which is defined herein as the "primary rotation"). In contrast, dynamic analysis shows the building responding in both "primary" and "secondary" rotations which are represented by the dual parameters, λ_{primary} and $\lambda_{\text{secondary}}$, as shown in Figure 1c. Thus, static analysis for torsional actions can be described as "biased" since only primary rotation has been modelled. Consequently, the displacement demand experienced by elements positioned on the "stiff" side of the building are understated by the analysis.

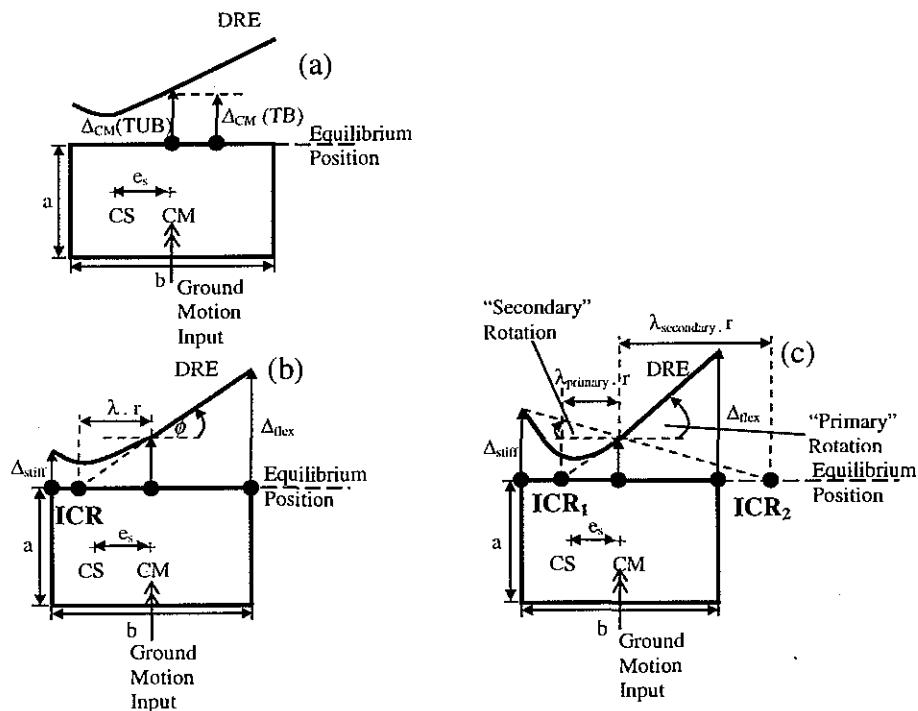


Figure 1. Definition diagrams, (a) Displacement at CM (α parameter), (b) Instantaneous centre of rotation (λ parameter), (c) "Primary" and "secondary" rotations (ϵ parameter).

The dimensionless parameter ϵ is defined as the difference between the primary rotation ($\phi_{primary}$) and the secondary rotation ($\phi_{secondary}$) divided by $\phi_{primary}$ as shown in equation 2a. This equation can also be expressed in terms of the parameter λ as shown in equation 2b.

$$\epsilon = \frac{(\phi_{primary} - \phi_{secondary})}{\phi_{primary}} \quad (2a)$$

$$\epsilon = 1 - \frac{\lambda_{primary}}{\lambda_{secondary}} \quad (2b)$$

The value of ϵ as defined by equation 2 varies from zero to two, with $\epsilon = 0.0$ representing static conditions in which the building responds only in primary rotation, and $\epsilon = 2.0$ representing conditions in which the primary and secondary rotations are of equal magnitude.

Displacement demand on elements resulted from elastic and inelastic torsional actions will be presented in terms of α , λ_{static} , $\lambda_{dynamic}$ and ϵ (with $\lambda_{dynamic}$ taken by default as $\lambda_{primary}$) in the rest of the paper.

3. MODELLING CONSIDERATION

Parametric studies reported in this paper were based on static and dynamic analyses of a single-storey building subject to uni-lateral excitations as shown in Figure 2. The floor plan of building shows a uni-axial eccentricity and an aspect ratio (b/a) equal to 2.5. The CM of the building is positioned at the centre of the floor plan due to the uniformity in the distribution of mass. All lateral load resisting elements incorporated into the modelling were assumed to possess a bi-linear hysteretic behaviour with a post-yield stiffness equal to 3 percent of the initial elastic stiffness. The torsional properties are represented by the two dimensionless parameters: e (the eccentricity ratio) and ρ_k (the uncoupled natural period ratio of translation to torsion) both of which have been normalised with respect to the mass radius of gyration of the building (r).

The lateral load resisting elements were designed in accordance with AS1170.4 (1993) with an acceleration coefficient of 0.15g, a site factor of 1.0, 1.5 or 2.0, and structural response factor (R_f) of 3. The building period ranges between 0.2 and 1.2 seconds. The element stiffness and strength were assumed to be in linear proportion. Consequently, the centre of strength (CV) and the centre of stiffness (CS) are coincident in position.

An ensemble of 13 recorded and synthetic accelerograms possessing a range of frequency properties were employed for the analyses (see Table 1 for details). The intensity of each record has been scaled to a PGV in the range 50-100mm/sec to represent seismic conditions for Australia corresponding to a return period of 500-2500 years. The excitations imposed an average ductility demand of about 2 on the lateral load resisting elements.

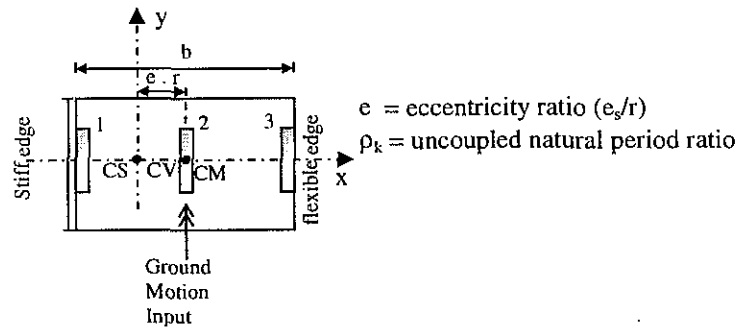


Figure 2. Plan view of the building model.

Table 1. Accelerogram ensemble employed in study.

Corner Period (T_1) (sec)	Earthquake	Direction	Magnitude	Soil
0.1 – 0.3	Parkfield, 1966	E-W	5.6	Stiff
	Friuli, 1976	Trans.	6.4	Rock
	Patras, 1974	Trans.	4.1	Rock
	Ancona-Rocca, 1972	N-S	-	Stiff
0.4 – 0.7	El Centro, 1940	N-S	6.6	Stiff
	Thessaloniki, 1978	Horz. A	5.1	Intermediate
	Gazli, 1976	N-S	7.3	Intermediate
	Leukas, 1973	Long.	5.7	Intermediate
	Kobe, 1995	N-S	6.9	Stiff
	Northridge, 1994	E-W	6.6	Stiff
>1.0	Romanian, 1977	N-S	7.2	Soft
	Synthetic (AS1170.4)	-	-	S = 1
	Synthetic (AS1170.4)	-	-	S = 2

4. ELASTIC STATIC-DYNAMIC AMPLIFICATION

4.1 Parametric studies on α

The displacement demand at the CM of the TUB and TB was analysed for the α ratio which was found to vary between 0.9 and 1.0 for the whole range of modelling parameters (see Figure 3). Thus, the displacement demand at the CM of a TUB could be estimated directly from the analysis of a single-degree-of-freedom system.

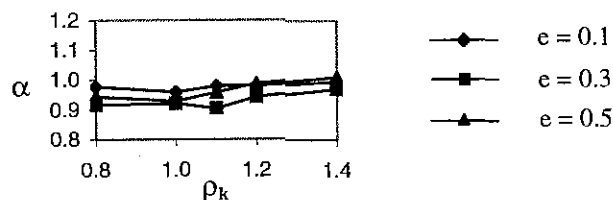


Figure 3. Median values of α parameter from dynamic analyses.

4.2 Parametric studies on λ

The displacement demand at the “flexible” edge of the building associated with primary rotation was studied next. Results from static and dynamic analyses were represented by the λ_{static} and λ_{dynamic} parameters respectively. The values of these parameters and their

ratio $\lambda_{dynamic}/\lambda_{static}$ are presented in Figure 4a and 4b with varying values of ρ_k . A torsionally flexible building (for example, walls orientated in one direction only) will have a low value of ρ_k . It is shown in Figure 4b that increasing the torsional stiffness would result in a higher dynamic amplification of the torsional response (since a smaller ratio of $\lambda_{dynamic}/\lambda_{static}$ indicates a higher static-dynamic amplification). Consequently, the benefits derived from the torsional stiffness are offset partially by the dynamic amplification of the torsional rotation. Similar trends in dynamic amplification have been reported in the literature in terms of the primary effective eccentricity (Chandler & Hutchinson, 1988) which was defined as the distance from the CM of the building at which the static force is applied in order that the maximum displacement from the static and dynamic analyses matches.

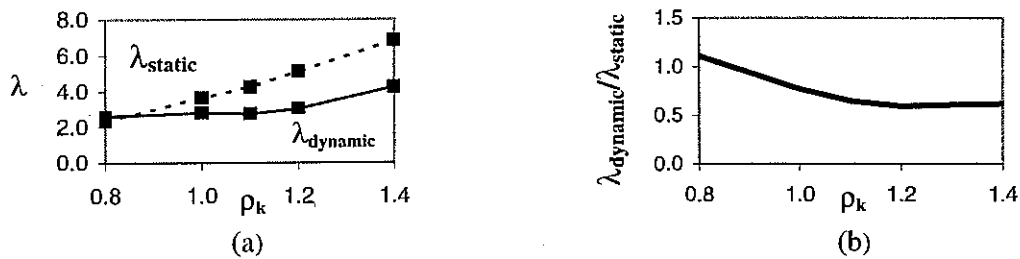


Figure 4. Comparison of λ values from static and dynamic analysis for building models with $e = 0.3$, $\rho_k = 0.8 - 1.4$, (a) λ_{static} versus $\lambda_{dynamic}$, (b) Ratio of $\lambda_{dynamic}/\lambda_{static}$.

4.3. Parametric studies in ϵ

As stated earlier in the paper, the ratio $\lambda_{dynamic}/\lambda_{static}$ only represents the effects of primary rotation which causes elements positioned on the "flexible" side of the building to experience high displacement demand. In contrast, the ϵ parameter was introduced to account for the displacement demand experienced by elements positioned on the "stiff" side of the building. It is shown in Figure 5 that the value of ϵ decreases with increasing value of ρ_k . Thus, for a torsionally flexible building (ie. with low of ρ_k), the ϵ value approaches 2.0 implying that the secondary rotation is in the order of the primary rotation, hence elements on both the "flexible" side and the "stiff" side will be subject to comparable displacement demand. Thus, increasing the torsional stiffness has the desirable effect of suppressing such dynamic phenomenon. Similar trends have been observed in an earlier study in which negative secondary effective eccentricity was used to represent the displacement demand of elements on the "stiff" side of the building. The secondary effective eccentricity was found to be less onerous with high ρ_k values (Chandler and Hutchinson, 1988).

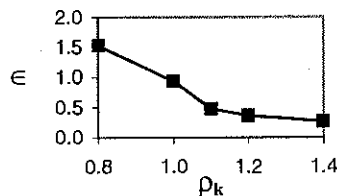


Figure 5. Median values of ϵ parameter from dynamic analysis, $e = 0.3$, $\rho_k = 0.8 - 1.4$.

5. EFFECTS OF DUCTILE YIELDING

The effect that ductile yielding has upon the dynamic torsional response behaviour of buildings has been the subject of intensive research over two decades. In this section, the sensitivity of the dimensionless parameters (α , λ and ϵ) to changes in the ductility ratio, from $\mu = 1$ (elastic behaviour) to $\mu = 2$ (limited ductile behaviour), were studied.

The value of α was found to be insensitive to the ductility ratio. Thus, limited ductile behaviour was found to have insignificant effect on the displacement of the building at the CM.

The behaviour of the other parameters namely λ_{dynamic} , the ratio $\lambda_{\text{dynamic}} / \lambda_{\text{static}}$, and ϵ have also been studied. It is shown in Figure 6a that primary rotation resulting from torsional actions could be amplified by ductile yielding particularly for buildings possessing high values of ρ_k . However, the effects of ductile yielding could be overstated by a quasi-static analysis which is an interesting contrast to the dynamic amplification behaviour that has been identified with the elastic response. The $\lambda_{\text{dynamic}} / \lambda_{\text{static}}$ ratio associated with elastic and inelastic behaviour are shown in Figure 6b to reveal this trend (note, a lower ratio infers a higher amplification). It is inferred from the comparison that recent studies by Paulay (1997) based on quasi-static simulations could have overstated the effects of inelastic torsional actions in buildings.

Favourable trends associated with ductile yielding were also observed with the ϵ parameter which represents the effects of secondary rotation. The mitigating effects of ductile yielding on "secondary" rotation as shown in Figure 6c contradict the conclusions reached by Chandler and Duan (1997) in which the accentuation of secondary rotation by ductile yielding was highlighted. The high ductility demand observed from this latter study is considered by the author to be the result of very low yield strength (hence very low yield displacement) being assigned to elements positioned on the "stiff" side of the building. This comparison demonstrates the need for extreme caution in interpreting results reported in the literature.

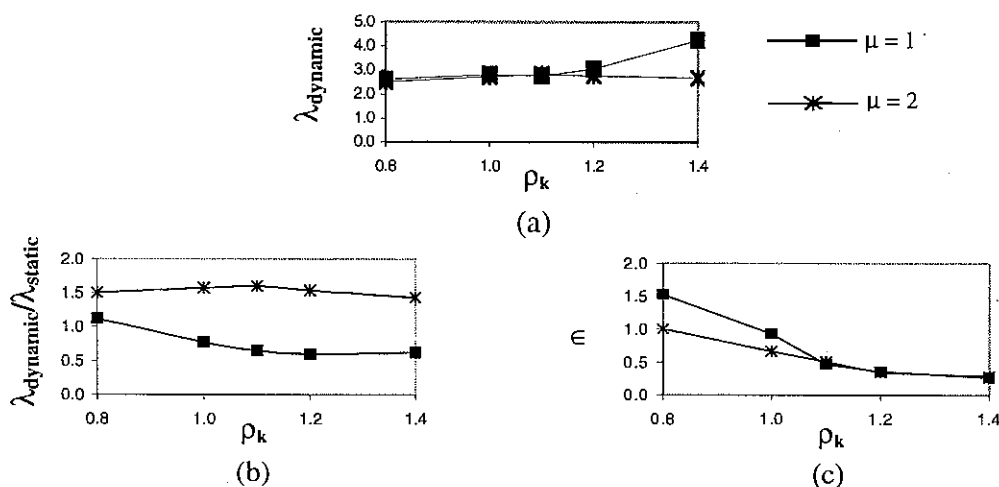


Figure 6. Effect of ductile yielding on dynamic torsion, $e = 0.3$, $\rho_k = 0.8 - 1.4$, (a) Median values of λ_{dynamic} , (b) Ratio of $\lambda_{\text{dynamic}} / \lambda_{\text{static}}$, (c) Median values of ϵ parameter.

6. CLOSING REMARKS

A new model is introduced in this paper to address the effects of elastic and inelastic torsional actions in buildings using dimensionless parameters. This new model could be used to enhance the displacement-based methodology which was primarily developed for pure translation response, such as in the capacity spectrum method.

Using this new model, limited analyses were carried out for comparison with previous studies reported in the literature. The trends observed in this study and in previous studies with elastic responses are generally consistent. However, certain trends observed with inelastic response contradict observations previously reported in the literature.

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