Dynamic Amplification of Eccenticities in Seismic Response of Multistoried Buildings

Pavan Agarwal*, Vinay K. Gupta**

SUMMARY – *A stochastic approach based on the response spectrum superposition technique has been used to investigate the dynamic eccentricity values for different stories of a linear multisoried shear building. It has been shown that for such a building with centres of floor masses lying on a vertical axis, these eccentricity values may be conveniently estimated via the use of an «equivalent» single story model along with the torsionally uncoupled model of the building. In a detailed linear analysis of single story models, parametric dependence of the dynamic amplification of eccentricity has been considered, and it has been shown that the codal provisions for torsional moments may need to be thoroughly revised for more conservatism and rationality in the design of a critical or business-intensive facility.*

1. Introduction

Buildings are usually associated with significant coupling between translational and torsional vibrations due to the centres of mass and stiffness at any floor not coinciding with each other. Quantitatively, this noncoincidence is expressed in terms of the static eccentricity i.e. the distance between the centre of mass and centre of stiffness. The coupling between the translational and torsional modes causes the building to have torsional vibrations even when earthquake excitation is in the form of a uniform base translation, and may be a main cause for damage in buildings [Chandler (1986)]. Several studies in the past have been directed towards linear earthquake analysis of fixed-base, torsionally coupled buildings. These include deterministic studies by Penzien (1969), Gibson et al. (1972), Douglas and Trabert (1973), Kan and Chopra (1977), Rutenberg et al. (1978), Hejal and Chopra (1989), Maheri et al. (1991), and stochastic studies by Kung and Pecknold (1984), Rady (1989), Hutchinson et al. (1991), Agarwal and Gupta (1995). Most of these studies have been based on the response spectrum superposition technique. Since it was shown by Kan and Chopra (1977) that the dynamic response of an asymmetric multistoried building can be obtained by an analysis of the corresponding uncoupled structure together with that of a single-story torsionally coupled system in case of a special class of buildings, most of the subsequent studies were focussed on understanding the behavior of single-story coupled systems under the seismic excitation. Further, for the convenience of design engineers, approaches based on equivalent static load classification were adopted by various codes all over the world. The concept of dynamic eccentricity and associated dynamic amplification of eccentricity for incorporating the torsional effects in buildings thus became popular, and several studies e.g., those by Tso and Dempsey (1980), Tso and Meng (1982), Tsicnias and Hutchinson (1982), Hutchinson and Chandler (1986), Chandler and Hutchinson (1986, 1988), Tso and Zhu (1992), Rutenberg (1992), Duan and Chandler (1993), Correnza et al. (1994) for the inelastic behavior, were carried out to improve the codal provisions on dynamic eccentricity. Most of these studies used the single-story models with the eccentricities (between the centres of mass and stiffness at the floor level) being perpendicular to the direction of the earthquake excitation, assuming that the results of these single-story models could directly be used in case of the multistoried buildings.

In this paper, dynamic amplification of eccentricity in the asymmetrical buildings has been studied by using the stochastic approach proposed by Agarwal and Gupta (1995) for the linear analysis of such structures. This approach can estimate the response peaks of all

* Engineer, Engineers India Limited, New Delhi, India.
** Associate Professor, Dept. of Civil Engineering, Indian Institute of Technology, Kanpur - 208016, India.
Received july 1995. Revised october 1996.

orders i.e. second largest peak, third largest peak, fourth largest peak etc., apart from the largest peak, with the given level of confidence and thus it will be particularly useful in having an idea of the number of excursions a building designed as per the codes may have to undego during the strong ground motion. Using the results of this approach for the expected values of largest response peaks in an example building, it has been seen whether a single-story model can be used to approximate the dependence of dynamic amplification factor on static eccentricity in the case of a typical story of a torsionally coupled multistoried building. Further, critical cases have been identified from a parametric study of this simple model and for these, the code provisions have been critically reviewed, particularly with reference to the dynamic amplification factors corresponding to the higher order peaks.

2. Dynamic Amplification of Eccentricity

Various building codes in the world account for dynamic torsional coupling in the seismic response of asymmetric buildings by considering the design story torque, T_d as

$$T_d = T_e + T_a \tag{1}$$

where, T_e is the story torque due to the static eccentricity, and T_a is the additional torque considered to account for the effects of accidental eccentricity. Thus, even the symmetric buildings are designed for the application of torsional moments, besides the lateral loads, at each story. The design torque, T_d at each story is obtained by multiplying the story shear with a quantity termed as design eccentricity, e where

$$e = e_d + e_a. \tag{2}$$

Here, the first part, e_d, is called dynamic eccentricity and it is defined as the distance measured horizontally from the centre of stiffness to the point at which the shear obtained from the uncoupled dynamic analysis should act in order to give rise to the same torque about the centre of stiffness as that determined by the dynamic analysis for the torsionally coupled system. The dynamic eccentricity is a function of story eccentricity which is defined as the horizontal distance between the centre of stiffness at the story and the resultant of all lateral forces above the story being considered [see Tso (1990), Jiang et al. (1993)]. When the mass distribution is identical at each floor level of the building, the story eccentricity becomes the horizontal distance between the centre of mass at any floor and the centre of stiffness at the story being considered. The second part, e_a, commonly refered to as accidental eccentricity, accounts for other factors such as torsional component of ground motion and the unforeseen differences between the actual and computed static eccentricities. The accidental eccentricity is expressed as a function of the plan dimensions of the building. This has been ignored in the present investigation in order to

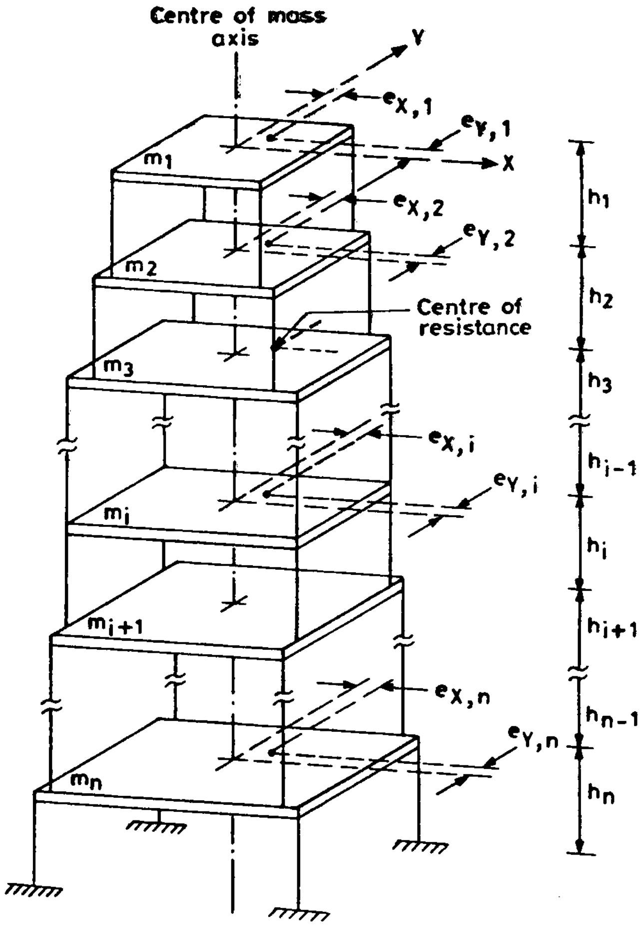

Fig. 1 – Multi-Degree-of-Freedom System for Torsionally Coupled Buildings.

emphasize the parametric variation of dynamic eccentricity alone.

The formulation proposed by Agarwal and Gupta (1995) for the linear stochastic response of a torsionally coupled multistoried building to earthquake excitation in X-direction (see Fig. 1) will be used here to obtain the expected values of the torque response peaks at various story levels. In this approach, the root-mean-square (r.m.s.) value of the response function is evaluated by taking the SRSS (square-root-of-sum-of-squares) combination of the r.m.s. values of the response function in various modes. It is obtained by scaling down the largest peak value of the response function in that mode (as obtained from the response spectrum characterization of the ground motion and appropriately modified for the interaction with other modes) with the help of peak factor in that mode. These peak factors, often assumed to be constant values in stochastic analyses, are estimated from the moments of the energy spectrum of the response function in each mode with the response process being assumed stationary. Once the r.m.s. value of the response function is determined by the SRSS combination, it is then multiplied with the peak factor corresponding to the desired order of peak and desired level of confidence to give the response peak value. The idealized n-story model as shown in Fig. 1 consists of rigid floor decks which are supported on massless, axially inextensible columns and shear walls. The principal axes of resistance for all the story levels are assumed to be parallel to the X and Y-axes. The centres of mass of the floors are assumed to lie on the Z-axis, whereas the centres of stiffness of the stories lie on different vertical axes, with static eccentricities, $e_{X,i}$ and $e_{Y,i}$ respectively along the X and Y-axes for the ith story.

Let the expected value of the largest torque peak, acting about the centre of stiffness, at the ith story be denoted as $T_{R,i}$, $i = 1, 2 \dots n$. If $S_{X0,i}$ is the expected value of the largest story shear, in X-direction, at the ith story obtained by ignoring the torsional coupling (i.e. by taking eccentricities, $e_{X,i} = 0$, $e_{Y,i} = 0$, $i = 1, 2, \dots, n$), the dynamic eccentricity, $e_{d,i}$ at the ith story becomes

$$e_{d,i} = \frac{T_{R,i}}{S_{X0,i}}. \quad (3)$$

The dynamic eccentricity is generally expressed as a dimensionless quantity, called as dynamic eccentricity ratio, $e_{dr,i}$, and is given by

$$e_{dr,i} = \frac{e_{d,i}}{r_i} \quad (4)$$

where, r_i is the radius of gyration of the ith floor about its centre of mass. The dynamic amplification of eccentricity, γ_i (henceforth to be called as amplification factor) at the ith story will thus be given by

$$\gamma_i = \frac{e_{dr,i}}{e_{r,i}} \quad (5)$$

where $e_{r,i} (= e_{Y,i}/r_i)$ is the static eccentricity ratio.

3. «Equivalent» Single Story Model

The concept of «equivalent» single story model used to simplify the coupled analysis of asymmetric buildings [Kan and Chopra (1977)] will be examined here for estimating the stochastic story torque through dynamic amplification factor. To study the variation of this factor in multistoried building, an 8-story, fixed-base building has been considered here. The building of 3.75 m. The critical damping ratio has been assumed equal to 0.05 in all the modes. The mass and stiffness properties of the building are shown in Table 1. The torsional stiffnesses of various stories are computed by neglecting the contributions of the torsional stiffnesses of the various supporting structural elements about their own longitudinal axes. The natural frequencies of the corresponding torsionally uncoupled model in translational and torsional modes are shown in Table 2. It may be observed from this table that the story stiffnesses have been so adjusted that the uncoupled torsional and translational frequencies (along X-axis) are equal in each mode. To provide the base excitation to the building in X-direction. Fourier and response spectra for the recorded ground motion during the Imperial Valley Earthquake, May 18, 1940, at El Centro have been considered with the response duration being assumed to be equal to the stationary time duration of input excitation as given by Trifunac and Brady (1975).

Table 1 – Properties of Example Multistoried Building

Floor Level, i	Mass m_i	Radius of Gyration, r_i	Story Stiffnesses $K_{X,i}$	$K_{Y,i}$	$K_{\theta,i}$
1	$0.60m$	r	$0.600k$	$0.793k$	$0.600kr^2$
2	$0.66m$	r	$0.657k$	$0.869k$	$0.657kr^2$
3	$0.72m$	r	$0.714k$	$0.944k$	$0.714kr^2$
4	$0.77m$	r	$0.771k$	$1.020k$	$0.771kr^2$
5	$0.83m$	r	$0.821k$	$1.086k$	$0.821kr^2$
6	$0.87m$	r	$0.886k$	$1.171k$	$0.886kr^2$
7	$0.94m$	r	$0.943k$	$1.247k$	$0.943kr^2$
8	$1.00m$	r	$1.000k$	$1.323k$	$1.000kr^2$

$m = .73272 \times 10^5$ kg, $k = 1 \times 10^8$ N/m, $r = 9.242$ m.

Table 2 – Natural Frequencies of Torsionally Uncoupled Model

Mode#	ω_X (rad/sec)	ω_Y (rad/sec)	ω_θ (rad/sec)
1	7.570	8.680	7.570
2	20.17	23.19	20.17
3	32.51	37.39	32.51
4	43.82	50.39	43.82
5	53.67	61.73	53.67
6	61.72	70.97	61.72
7	67.67	77.82	67.67
8	71.35	82.05	71.35

To see how the story to story variation of static eccentricity affects the amplification factors, γ_i in the example building, five different cases have been considered:

Case I: Constant eccentricity ratio, $e_{r,i} = 0.1$ from top to bottom story.

Case II: Step variation with $e_{r,i} = 0.1$ for $i = 1, 2, 3, 4$, and $e_{r,i} = 0.4$ for $i = 5, 6, 7, 8$.

Case III: Step variation with $e_{r,i} = 0.1$ for $i = 1, 2, 3, 4$, and $e_{r,i} = 0.025$ for $i = 5, 6, 7, 8$.

Case IV: Linear variation of $e_{r,i} = 0.1$ at top to 0.025 at the bottom story.

Case V: Linear variation of $e_{r,i}$ from 0.4 at bottom to 0.1 at the top story.

It may be noted that in all the above five cases here, value $e_{r,i}$ has been kept constant at 0.1 for the top story with $i = 1$. Further, the eccentricity in the direction of earthquake excitation, $e_{X,i}$ is taken same as that in the perpendicular direction, $e_{Y,i}$ at all the stories.

Fig. 2 shows the variations of dynamic amplification of eccentricity for the above cases. It is observed that the dynamic amplification of eccentricity at the top story ($i = 1$) is not significantly affected by the patterns of story eccentricity variations in various example cases. Moreover, γ_i consistently decreases or increases with the increase or decrease in $e_{r,i}$ and remains constant in

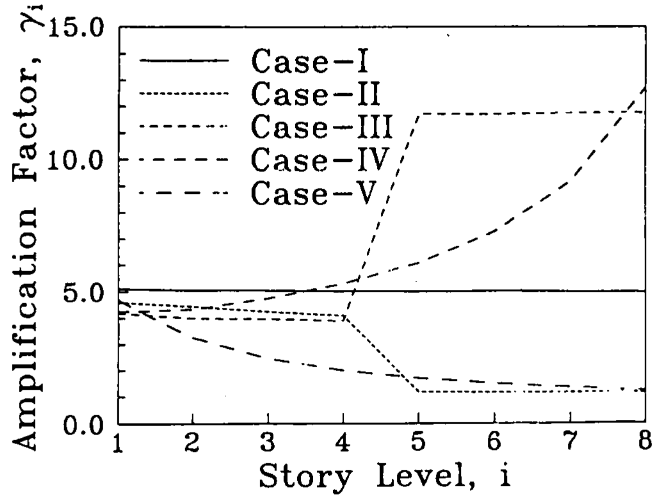

Fig. 2 – Effect of Story Variation of Eccentricity on Amplification Factor.

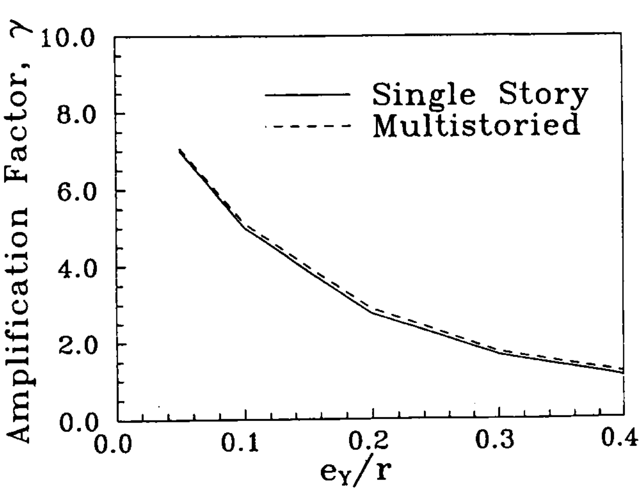

Fig. 3 – Comparison of Amplification Factors for Single Story Model and Multistoried Building.

the case of same eccentricity ratio (see the curve for Case I) at different stories. This shows that the dynamic amplification of eccentricity in a given story depends little on the eccentricities in the other stories. It is rather strongly correlated with the static eccentricity ratio at that story level. Further, since the variation of dynamic eccentricity ratio is not linear in Cases IV and V despite the linear variation in the static eccentricity ratio, γ_i appears to vary nonlinearly with the variation in the eccentricity ratio. These observations suggest the possibility of estimating the dynamic eccentricity ratio at any story of a multistoried building from its static eccentricity ratio, once the relationship between the amplification factor and the static eccentricity ratio is known apriori. If this relationship is almost same for all the stories, it may even be sufficient to obtain a single «representative» curve between the amplification factor and the eccentricity ratio for the entire building. We will now consider an «equivalent» single story model to investigate this possibility and see whether the parallel result between γ and e_r for this sample model can adequately represent the relationship between the amplification factor, γ_i and eccentricity ratio, $e_{r,i}$ for all the stories of a multistoried building. Let the multistoried building for this purpose be taken same as the example 8-story building above with same eccentricity ratio, $e_{r,i} = e_r$ in all the stories. In the corresponding torsionally uncoupled multistoried model, let $\omega_{X,1}$ be the fundamental translation frequency of vibration in the X-direction, $\omega_{Y,1}$ be the fundamental frequency in the Y-direction, and $\omega_{\theta,1}$ be the fundamental frequency in torsional vibrations. The single story system is now considered to have the same natural translational and torsional frequencies i.e. $\omega_{X,1}$, $\omega_{Y,1}$ and $\omega_{\theta,1}$ respectively. Thus, this system has the following properties:

i) translational stiffness in X-direction,
$K_X = m\omega_{X,1}{}^2 = 4.2 \times 10^6$ N/m
ii) translational stiffness in Y-direction,
$K_Y = m\omega_{Y,1}{}^2 = 5.52 \times 10^6$ N/m
iii) torsional stiffness about the centre of mass,
$K_\theta = m\omega_{\theta,1}{}^2 r^2 = 358.7 \times 10^6$ N-m/rad

where m and r have arbitrarily been taken as 73272 kg and 9.242 m.

The dynamic amplification of eccentricity, γ in the above single story model is compared with that in the multistoried model, for the static eccentricity ratio, $e_Y/r = e_r$ varying from 0.05 to 0.4 as shown in Fig. 3. The results for the multistoried building in this figure have been obtained by averaging the dynamic amplification factors for all the stories since this factor varies little from story to story in the case of uniform eccentricity ratio. It is seen that the two curves are in excellent agreement over the range of eccentricity ratios considered. Also, these results are in conformity with the observed values of amplification factor, γ_i in Fig. 2 (for different eccentricities at any story level). It may be noted that in the single story model and multistoried building here, the eccentricities in the perpendicular direction have been taken same as those in the direction of the excitation, i.e. $e_Y = e_X$ and $e_{Y,i} = e_{X,i}$, $i = 1, 2, \ldots, n$. If this is not the case, but $e_{X,i} \neq 0$, and $e_{X,i}$ and $e_{Y,i}$ in the multistoried building have the same ratio from story to story, this agreement will be maintained provided e_Y and e_X in the «equivalent» model also have the same ratio. However, if these eccentricities are arbitrarily different from each other, e_X in the «equivalent» model may still be approximated as $\frac{1}{n}\sum_{i=1}^{n}(e_{X,i}/e_{Y,i})$ times e_Y. It will be shown in the parametric dependence of the amplification factor for a single story model that for a given e_Y/r, the amplification factor will depend little on the variation in the ratio of the two eccentricities, particularly for the small to moderate values of e_Y/r, and therefore, the averaging over all the stories as above should cause small errors in the usually found regular buildings. This scheme may not work in the case of mono-symmetric buildings with $e_{X,i} = 0$ for all stories as shown by Chandler et al. (1993). In that case, the single story models may actually give lower estimates of the amplification factors.

It follows from the above discussion that to obtain the «representative» curve (representing the relation between γ and e_r as in Fig. 3) in a multistoried building, it may be sufficient to analyze a single story building with the same fundamental frequencies, $\omega_{X,1}$, $\omega_{Y,1}$, and $\omega_{\theta,1}$, as in the case of the torsionally uncoupled model of the given multistoried building, and with an «averaged» eccentricity in the X-direction. Once an appropriate curve is obtained, it becomes possible to estimate the story torque at the ith story of the given multistoried building by reading γ_i for $e_{Y,i}/r_i$ in that story from the curve and then multiplying this with the X-shear in the uncoupled model of the building. This concept of using an «equivalent» single story model to represent the dynamic amplification of eccentricity in any story of a torsionally coupled building works, without using the higher frequenciens of the uncoupled model, particularly when the ratios of the torsional to X-translational frequencies in all modes of the uncoupled model are almost same. In that case, same γ versus e_Y/r curve is obtained from the «equivalent» story model when its translational and torsional frequencies are taken same as those in a higher mode of the uncoupled model. Such cases are commonly found in the multistoried building, and then this may form a much simpler alternative to using many single story models as suggested by Kan and Chopra (1977) for the analysis of coupled systems. More extensive investigations will however be necessary to verify the validity of this approach in case of a wide range of multistoried buildings.

4. Parametric Dependence of Amplification Factor

It has been seen in the preceding section that by analyzing a coupled «equivalent» single story model, it is possible to obtain useful information regarding dynamic eccentricity in any story of the coupled multistoried building. Understanding the bahaviour of various single story systems for various parameters is thus useful for a proper understanding of the effects of coupling on the response of asymmetric buildings. Single story models will now be considered to study the dependence of dynamic amplification of eccentricity i.e. γ on the following parameters: i) earthquake excitation, ii) uncoupled frequency ratio, ω_θ/ω_X and iii) eccentricity ratio in X-direction, e_X/r. The results and inferences obtained in this study will indirectly be applicable to the multistoried buildings.

i) Earthquake Exitation

The variation of γ for the same example single story model as considered above is shown in Fig. 4 for the two additional base excitations (in addition to the Imperial Valley Earthquake): a) N85E Component of California Earthquake, June 27, 1966, recorded at Parkfield; and b) Mexico Earthquake, 1985, synthetically generated for Mexico City Site [see Gupta and Trifunac (1990)]. It is seen from the figure that though the amplification factors for the Imperial Valley earthquake are slightly lower compared to those for the other two earthquakes, in can be assumed that characteristics of

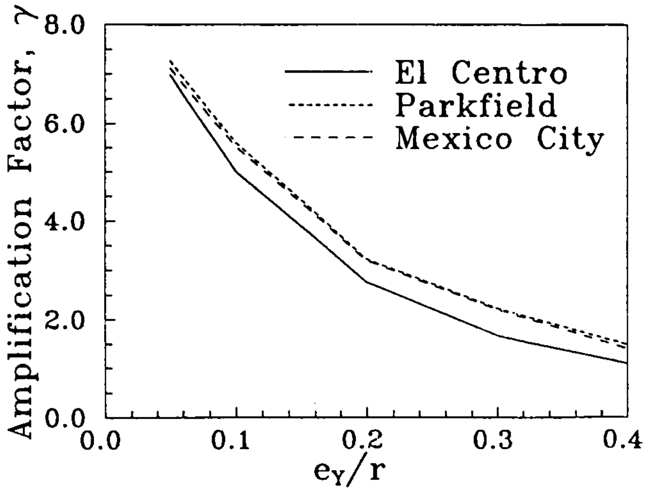

Fig. 4 – Comparison of Amplification Factors for Different Earthquakes in Single Story Model.

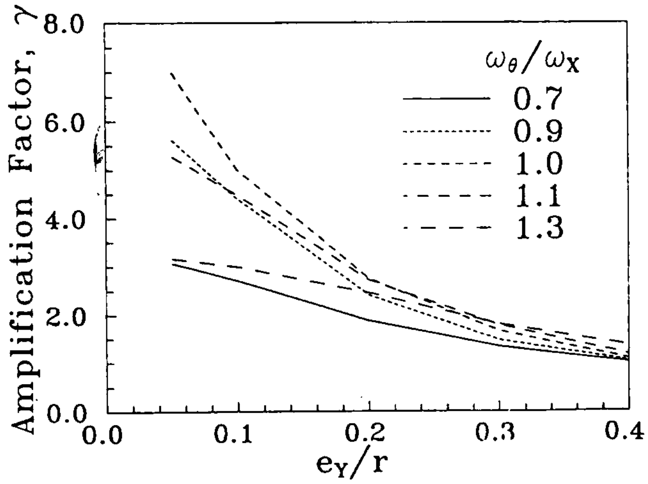

Fig. 5 – Variation of Amplification Factor with Eccentricity Ratio for Different Uncoupled Frequency Ratios in Single Story Model.

the input excitation have negligible effect on the dependence of γ on eccentricity ratio, e_Y/r.

ii) Uncoupled Frequency Ratio

The dependence of amplification factor, γ variation with eccentricity ratio, e_Y/r on ω_θ/ω_X is shown in Fig. 5 by varying the uncoupled frequency ratio, ω_θ/ω_X in the example single story building beyond the already considered value of 1.0, and by also considering $\omega_\theta/\omega_X = 0.7$, 0.9, 1.1, 1.3. It is observed that at small to moderate eccentricity ratios ($e_Y/r \leq 0.18$), the amplification factor is greater for the closer translational and torsional frequencies with the maximum occuring when these are equal. At higher eccentricity ratios, however, amplification factor becomes rather independent of the uncoupled frequency ratio and then, its value is close to 1.0. These observatios are more obvious in Fig. 6 which shows the variation of γ with the uncoupled frequency ratio for different values of eccentricity ratio. It

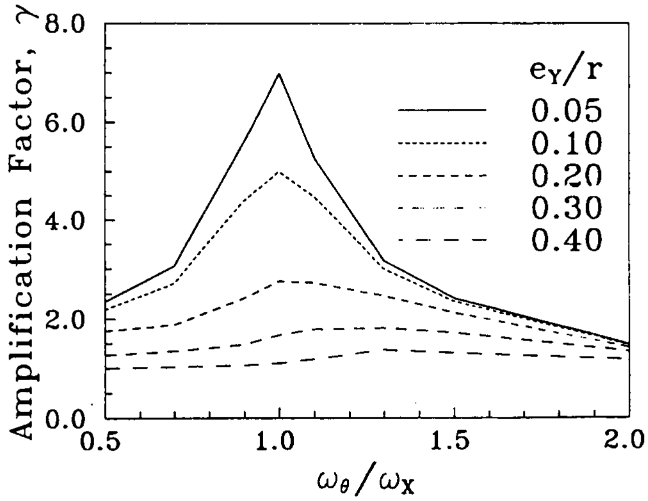

Fig. 6 – Variation of Amplification Factor with Uncoupled Frequency Ratio for Different Eccentricity Ratios in Single Story Model.

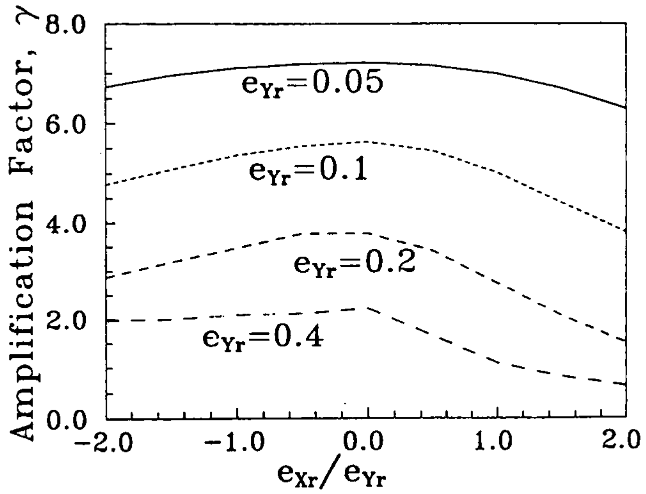

Fig. 7 – Effects of Eccentricity Ratio, e_{X_r} on Amplification Factor for Different e_{Y_r} Values in Single Story Model.

can be seen that the curves for small eccentricity ratios i.e. $e_Y/r = 0.05$ and 0.1, have distinct peaks in the vicinity of $\omega_\theta/\omega_X = 1.0$, and for larger eccentricities, there is little effect of the uncoupled frequency ratio. Moreover, for all the eccentricity ratios, the effect of uncoupled frequency ratio on γ becomes negligible as these frequencies grow apart. Then it may be possible to approximate γ by functions of e_Y/r only. These results are in agreement with those of the earlier works, e.g., those by Tsicnias and Hutchinson (1981), Kung and Pecknold (1984), Chandler and Hutchinson (1986) and Rady and Hutchinson (1988).

iii) Eccentricity Ratio in X-direction

The effects of eccentricity ratio, $e_{X_r}(= e_X/r)$, on the amplification factor have been shown in Fig. 7 by considering the example single story building for the eccentricity ratio $e_{Y_r}(= e_Y/r) = 0.05$, 0.1, 0.2 and 0.4. Each curve shows the variation of dynamic amplification of eccentricity with the eccentricity ratio e_{X_r} as a fraction of e_{Y_r}. It appears that the amplification factor, γ varies little with the eccentricity in the direction of excitation, particularly for the small to moderate values of e_{Y_r}. Also, it becomes maximum in the case of zero value of e_{X_r} for all the considered values of e_{Y_r}. This is the reason why the earlier researchers, e.g. Chandler et al. (1993), focussed on the study of amplification factors in case of mono-symmetric buildings.

5. Comparison with Code Provisions

As shown above, the amplification factor is maximum when the static eccentricity occurs only in the perpendicular direction of excitation and its component in the direction of excitation is zero. To critically examine the seismic code provisions, therefore, the example single story model has been considered with eccentricity only in the perpendicular direction of excitation,

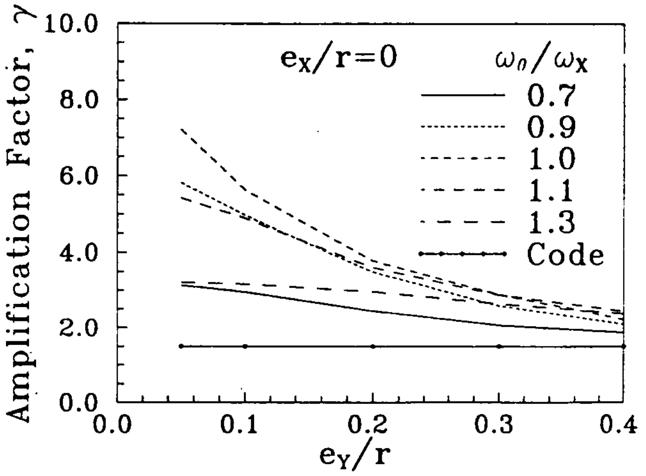

Fig. 8 – Comparison of Amplification Factors for Different Uncoupled Frequency Ratios with the Code Values in Single Story Model.

and its results on the dynamic amplification factor for different ω_θ/ω_X ratios have been compared with those recommended by the Indian Standard code (IS: 1893-1894) as shown in Fig. 8. The code uniformly recommends the dynamic eccentricity as 1.5 times the computed static eccentricity, irrespective of the uncoupled frequency ratio and eccentricity ratio level in the building. The figure clearly indicates that for all the values of ω_θ/ω_X considered in the range of 0.7-1.3, the codal provisions of the dynamic amplification of eccentricity are much smaller particularly for the low eccentricity ratios. In fact, if the torsional frequencies are very close to the translational frequencies in a multistoried building, the dynamic eccentricity ratios may be as much as five times those recommended by the code. For large values of the eccentricity ratios, however, the codal provisions are only slightly on the unsafe side.

The underestimation of dynamic amplification as implied in the codal provisions is considered acceptable because the codal provisions are usually aimed at preventing the total collapse of the most critical earthquake.

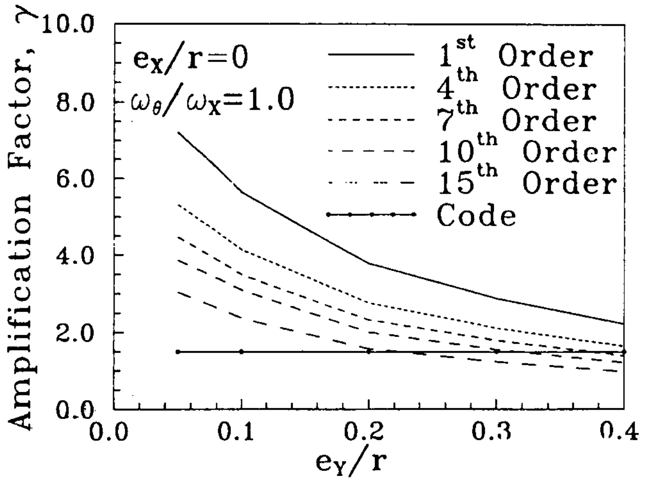

Fig. 9 – Comparison of Amplification Factors for Higher Orders of Torque Peaks with the Code Values in Single Story Model.

The code-designed buildings are expected to posess sufficient ductility so as to undergo large inelastic deformations without collapse. Several studies e.g., those by Chandler and Duan (1991), Chopra and Goel (1991), Tso and Zhu (1992), Rutenberg (1992), Duan and Chandler (1993), Correnza et al. (1994) etc. have extensively studied the inelastic response of code-designed asymmetric buildings and have shown the adequacy of lower dynamic amplification factors that those obtained from the linear analyses. However, in modern technologically developed societies, the indirect losses due to loss of working space and interruption of work may far exceed the direct losses due to structural and non-structural damage during a severe earthquake. In fact, the indirect losses can exceed many times the replacement value of the whole building [Jordanovski et al. (1992)]. Hence, in the long run, it is considered cheaper to invest in higher strength than the code-specified levels at the time of constructing a new building. Keeping these considerations in view, it may be preferred to allow «not too far» inelastic excursions of the response beyond the linear levels. For such cases of limited inelastic action, it has been shown by Goel and Chopra (1991) that the dynamic amplification factors are likely to be close to those based on the linear analyses. Also, the dependence of these factors on the uncoupled frequency ratio and eccentricity ratio may be almost as strong as in the case of linear systems. Thus, for the design of a business-intensive or critical facility by using the codal provision, the underestimation of dynamic amplification as discussed above may not be acceptable.

To appreciate the underestimation of dynamic amplification by the code more clearly in case of buildings with limited inelastic action, the variation of amplification factor with e_Y/r, has been shown in Fig. 9 for the 1st, 4th, 7th, 10th and 15th order peaks of torsional moment response in the example single story model (with $\omega_\theta/\omega_X = 1$). The curves for the higher orders of the respective orders with the «largest» peak amplitude of the story shear in the uncoupled model, and not with the peak shear values of respective orders. It is seen in the figure that for the small to moderate eccentricity ratios, even the 15th order peak of the amplification factor is larger than the values recommended by the code. This points to the possibility of «too many excursions» of the response of a building designed as per the code beyond the design level. Even greater number of these excursions may be experienced in case of long duration ground motions and stiff structures, and thus, the damage may be much higher than what is suggested by the extent to which the design level is exceeded by the largest response peak [Basu and Gupta (1995)]. Thus, the codal provisions for the buildings of critical importance should also account for the number of nonlinear excursions, apart from the largest to the yield response ratio, for acceptable damage during each seismic event.

The above conclusions have been obtained for the Indian code but these are qualitatively true for all the other seismic codes in the world also. These also indicate the need of correlating the codal recommendations with the number of inelastic excursions, apart from the usually provided levels of ductility, in case of the buildings designed to undergo substantial inelastic deformations. Therefore, inelastic analyses should be carried out to give more detailed and realistic information on this aspect of the code-based design procedures.

6. Conclusions

A stochastic approach has been used to study the dynamic amplification of eccentricity due to torsional coupling by determining the dynamic eccentricities based on the expected first order peak amplitudes of story torques and shears. On the basis of this, it has been found that the dynamic amplification values of eccentricity may be estimated at different story levels of a torsionally coupled multistoried building by analyzing an «equivalent» single story model, in addition to the torsionally uncoupled multistoried model of the given building. As also shown earlier by several researchers, these amplification factors are shown to be strongly dependent on the ratio of uncoupled torsional frequency to the translational frequency and the eccentricity ratio.

A comparison of the single story results with the seismic code provisions has shown that the code severly underestimates the torsional moment in case of buildings with limited inelastic action, particularly when the eccentricity ratios of the building are small and when the uncoupled frequency ratio of the building is close to unity. Buildings may be designed to have little inelastic deformations for limiting the indirect losses after the critical earthquake. In such cases, when the eccentricity ratio is moderate, say 0.2, the code estimates may be as low as the 15th order peak of the torsional response. These many exursions may lead to substantial damages in violation of the «limited indirect losses» philosophy. Hence, the codal provisions should not only incorporate the dependence on the uncoupled frequency ratio and eccentricity ratio, but should also take the correlation between the damage and the number of inelastic excursions into account.

References

Agarwal, P. and V.K. Gupta (1995). A stochastic approach to the response of torsionally coupled multistoried buildings, *European Earthq. Eng.*, **IX (2)**, 44-45.

Basu, B. and V.K. Gupta (1995). A probabilistic assessment of seismic damage in ductile structures, *Earthq. Eng. Struct. Dyn.*, **24**, 1333-1342.

Chandler, A.M. (1986). Building damage in Mexico City earthquake, Nature, **320 (6062)**, 497-501.

Chandler, A.M. and X.N. Duan (1991). Evaluation of factors influencing the inelastic seismic performance of torsionally asymmetric buildings, *Earthq. Eng. Struct. Dyn.*, **20**, 87-95.

Chandler, A.M. and G.L. Hutchinson (1986). Seismic design eccentricity for torsionally culpled building, *Proc. Eighth Eur. Conf. Earthq. Eng., Lisbon*, **6 (7)**, 33-40.

Chandler, A.M. and G.L. Hutchinson (1988). Evaluation of the secondary torsional design provisions of earthquake building codes, *Proc. Instn. Civ. Engrs., London*, **Part 2 (85)**, 587-607.

Chandler, A.M., G.L. Hutchinson, and M.A. Rady (1993). Torsional coupling in multistorey buildings with vertical irregularities: parametric study, *Struct. Eng. Review*, **5 (1)**, 39-51.

Chopra, A.K. and R.K. Goel (1991). Evaluation of torsional provisions in seismic codes, *J. Struct. Eng. (ASCE)*, **117 (12)**, 3762-3782.

Correnza, J.C., G.L. Hutchinson, and A.M. Chandler (1994). Effect of transverse loadresisting elements on inelastic earthquake response of eccentric-plan buildings, *Earthq. Eng. Struct. Dyn.*, **23**, 75-89.

Douglas, B.M. and T.E. Trabert (1973). Coupled torsional dynamic analysis of a multistory building, *Bull. Seism. Soc. Amer.*, **63 (3)**, 1025-1039.

Duan, X.N. and A.M. Chandler (1993). Inelastic seismic response of code-designed multistorey frame buildings with regular asymmetry, *Earthq. Eng. Struct. Dyn.*, **22**, 431-445.

Gibson, R.E., M.L. Moody and R.S. Ayre (1972). Response spectrum solution for earthquake analysis of unsymmetrical multistoried building, *Bull. Seism. Soc. Amer.*, **62**, 215-229.

Goel, R.K. and A.K. Chopra (1991). Effects of plan asymmetry in inelastic seismic response of one-story systems, *J. Struct. Eng. (ASCE)*, **117 (5)**, 1492-1513.

Gupta, V.K. and M.D. Trifunac (1990). Response of multistoried buildings to ground translation and rocking during earthquakes, *J. Prob. Eng. Mech.*, **5 (3)**, 138-145.

Hejal, R. and A.K. Chopra (1989). Earthquake response of torsionally coupled, frame buildings, *J. Struct. Eng. (ASCE)*, **115 (4)**, 834-851.

Hutchinson, G.L. and A.M. Chandler (1986). Parametric earthquake response of torsionally coupled buildings and comparison with building codes, *Proc. Eighth Eur. Conf. Earthq. Eng., Lisbon*, **6 (7)**, 25-32.

Hutchinson, G.L., A.M. Chandler and M.A. Rady (1991). Effect of vertical distributions of mass and translational stiffness on dynamic eccentricities for a special class of multistorey buildings, *Pacific. Conf. Earthq. Eng., New Zealand*, **1**, 61-69.

IS: 1893-1894. Criteria for earthquake resistant design of structures, *Bureau of Indian Standards, New Delhi.*

Jiang, W., G.L. Hutchinson, and A.M. Chandler (1993). Definitions of static eccentricity for design of asymmetric shear buildings, *Eng. Struct.*, **15 (3)**, 167-178.

Jordanovski, L.R., M.I. Todorovska, and M.D. Trifunac (1992). The total loss in a building exposed to earthquake hazard, part I: the model, *European Earthq. Eng.*, **VI (3)**, 14-25.

Kan, C.L. and A.K. Chopra (1977). Elastic earthquake analysis of torsionally coupled multistorey buildings, *Earthq. Eng. Struct. Dyn.*, **5**, 395-412.

Kung, S.Y. and D.A. Pecknold (1984). Seismic response of torsionally coupled single-storey structures, *Proc. Eighth Wid Conf. Earthq. Eng., San Francisco, California*, 235-242.

Maheri, M.R., A.M. Chandler and R.H. Bassett (1991). Coupled lateral-torsional behaviour of frame structures under earthquake loading, *Earthq. Eng. Struct. Dyn.*, **20**, 61-85.

Penzien, J. (1969). Earthquake response of irregularly shaped buildings, *Proc. Fourth Wld Conf. Earthq. Eng., Santiago, Cile*, **II (A-3)**, 75-89.

Rady, M.A. (1989). A new refined approach to the formulation of the earthquake-resistant design regulations for torsionally coupled multistorey buildings, *Ph. D. Thesis, The University of Melbourne, Australia.*

Rady, M.A. and G.L. Hutchinson (1988). Evaluation of dynamic eccentricities obtained using a probabilistic approach, response spectrum methods and modern building codes, *Earthq. Eng. Struct. Dyn.*, **16**, 275-291.

Rutenberg, A. (1992). Nonlinear response of asymmetric building structures and seismic codes: a state of the art review, *European Earthq. Eng.*, **VI (2)**, 3-19.

Rutenberg, A., T.I. Hus and W.K. Tso (1978). Response spectrum techniques for asymmetric buildings, *Earthq. Eng. Struct. Dyn.*, **6**, 427-435.

Trifunac, M.D. and A.G. Brady (1975). A study on the duration of strong earthquake ground motion, *Bull. Seism. Soc. Amer.*, **65 (3)**, 581-626.

Tsicnias, T.G. and G.L: Hutchinson (1981). Evaluation of code requirements for the earthquake resistant design of torsionally coupled buildings, *Proc. Instn. Civ. Engrs.* **Part 2 (71)**, 821-843.

Tsicnias, T.G. and G.L. Hutchinson (1982). Evaluation of code torsional-provisions for earthquake resistant design of single storey buildings with two eccentricity components, *Proc. Instn. Civ. Engrs.*, **Part 2 (73)**, 455-464.

Tso, W.K. (1990), Static eccentricity concept for torsional moment estimations, *J. Struct. Eng.* (ASCE), **116 (5)**, 1199-1212.

Tso, W.K. and K.M. Dempsey (1980). Seismic torsion-

al provisions for dynamic eccentricity, *Earthq. Eng. Struct. Dyn.*, **8**, 275-289.
Tso, W.K. and V. Meng (1982). Torsional provisions in building codes, *Can. J. Civ. Eng.*, **9**, 38-46.
Tso, W.K. and T.J. Zhu (1992). Design of torsionally unbalanced structural systems based on code provisions I: ductility demand, *Earthq. Eng. Struct. Dyn.*, **21**, 609-627.