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EARTHQUAKE RESPONSE OF ASYMMETRIC FRAME BUILDINGS

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SUMMARY

The earthquake response of torsionally-coupled buildings is presented for a wide range of the system parameters. By comparing these responses with those of corresponding torsionally-uncoupled systems, the effects of lateral-torsional coupling on building forces, arising from lack of symmetry in building plan, are identified.

INTRODUCTION

Buildings subjected to lateral ground motion simultaneously undergo lateral, as well as torsional, motions if their structural plans do not have two axes of mass and stiffness symmetry. The objective of this paper is to investigate the effects of lateral-torsional coupling on the earthquake response of buildings with asymmetrical plan. Because most of the basic research on this problem has been concerned with shear beam idealization of buildings (e.g. 1, 2, 3), this restriction is relaxed in this investigation. In particular, the influence of the beam-to-column stiffness ratio on the response of asymmetric frame buildings is investigated.

SYSTEMS AND DESIGN SPECTRA

Systems Considered The systems analyzed are five-story buildings with all floors having an identical rectangular plan, symmetrical about the X-axis and consisting of three moment-resisting planar frames (Fig. 1a), connected at each story level by a rigid diaphragm. The properties of each frame are uniform over height: constant story height, h, and one bay of width 2h (Fig. 1b); all beams of a frame have the same flexural stiffness, EI_b, and the column stiffness, EI_c, does not vary with height. The mass at each floor is denoted by m, and r is the radius of gyration of each floor about the vertical axis passing through its center of mass. The static eccentricities of all floors are the same, equal to e, and the centers of rigidity of the floors all lie on a vertical line. The idealized buiding, therefore, belongs to the special class of multi-story buildings, described in (4). The damping ratio, ξ, is assumed to be the same in each mode of vibration.

Frame action is measured by the joint rotation index, ρ, which is defined as the sum of EI/L values for all beams divided by the sum of EI/L values for all columns at the mid-height story of the frame. By varying the stiffness ratio ρ, the entire range of behavior of a frame can be covered. For $\rho = 0$, the frame behaves as a flexural column with beams imposing no constraint on joint rotations. For $\rho = \infty$, joint rotations are restrained so that the frame behaves as a shear beam. Intermediate values of ρ, therefore, represent frames with both beam and column deformations and joint rotations. The joint rotation index of frame (1) is denoted by ρ_1, and that of frame (2) by ρ_2. In this study it is assumed that $\rho_1 = \rho_2 = \rho$, a condition which implies that frames (1) and (2) have proportional lateral stiffness matrices.

Response Spectra For earthquake response spectra of arbitrary shape the design forces need not be greater than those for either a hyperbolic or a flat spectrum that constitute upper bounds to the design spectrum in the range of periods less than the fundamental period of the structure (Fig. 2). These two idealized spectra are useful since normalized response of the system does not depend on the system vibrational periods, but only on their ratios (3), and because they are representative of the acceleration- and velocity-controlled regions of smooth design spectra.

EFFECTS OF LATERAL-TORSIONAL COUPLING

The effects of lateral-torsional coupling on building response are investigated by comparing the response to ground motion along the Y-axis of the torsionally-coupled, multistory building of Fig. 1 with that of the corresponding torsionally-uncoupled, multistory system--a system with all properties identical to the torsionally-coupled system except that the centers of mass are coincident with the centers of rigidity. This comparison is presented for flat and hyperbolic pseudo-acceleration spectra. The response quantities selected to study the overall behavior of the building are: the base shear V_B and the base torque T_{BR} at the center of rigidity. These quantities, computed by the analysis procedure developed in (4), are normalized, respectively, by V_{Bo} and eV_{Bo}, where V_{Bo} is the base shear of the corresponding torsionally-uncoupled system. The normalized torque T_{BR}/eV_{Bo} can be interpreted as the ratio of the dynamic eccentricity of the system to its static eccentricity, e_d/e, where the dynamic eccentricity $e_d = T_{BR}/V_{Bo}$ is the distance from the center of rigidity at which static application of V_{Bo} results in the dynamic base torque T_{BR}.

The normalized base shear and base torque are presented in Figs. 3 and 4 (and additional responses in Reference (4)). Also shown in these figures are the normalized responses $\bar{V}$ and $\bar{T}_R$ of the associated torsionally-coupled, one-story system which are independent of ρ; see Part I of Reference (4). This one-story system has the following properties: (a) the static eccentricity ratio e/r for the system is the same as for all floors of the torsionally-coupled, N-story building, and (b) the ratio of the uncoupled torsional and lateral vibration frequencies for the system is the same as $\Omega = \omega_{\theta j}/\omega_{yj}$, where $\omega_{\theta j}$ and ω_{yj} are the jth torsional and lateral frequencies of the corresponding torsionally-coupled, N-story building, and their ratio Ω is independent of j.

It is apparent from Figs. 3 and 4 that the effects of lateral-torsional coupling on structural responses are similar for the multistory and the associated one-story systems. For this reason, the general trends of $\bar{V}$ and $\bar{T}_R$ for the one-story system, which are independent of ρ, are described first, and then the differences that occur for the multistory building, in which case ρ influences the normalized responses, are described next. Lateral-torsional coupling has the effect of reducing $\bar{V}$ and increasing e_d/e. These effects increase as the eccentricity ratio e/r increases, and are dependent on the ratio $\Omega = \omega_{\theta j}/\omega_{yj}$. For systems with smaller e/r values the effect is most pronounced, i.e. $\bar{V}$ reaches its minimum value and e_d/e its maximum value, for values of Ω around unity, i.e. when the uncoupled lateral and torsional frequencies are close to each other. As e/r increases, $\bar{V}$ reaches its minimum values at values of Ω below unity, while e_d/e reaches its maxima for values of Ω above unity. For torsionally-stiff systems ($\Omega > 1$), $\bar{V}$ approaches unity as Ω becomes large, indicating that there is essentially no reduction in the base shear, while e_d/e approaches one, implying no dynamic amplification of eccentricity. For torsionally-flexible systems ($\Omega < 1$) with smaller e/r, there is essentially no reduction in base shear. The dynamic eccentricity ratio, e_d/e, for torsionally-flexible systems approaches zero as Ω tends to zero in the case of a hyperbolic spectrum, implying no torque, but approaches one in the case of a flat spectrum, indicating no dynamic amplification.

These observations on how torsional coupling affects the normalized base shear and torque for the associated torsionally-coupled, one-story system generally carry over to a multistory building. However, unlike the one-story system, the normalized responses of the multistory building depend on ρ, but for e/r up to 0.4 the effects of ρ are generally small. The differences between the normalized responses of the two torsionally-coupled systems--multistory and its associated one-story--are due to the contributions of the terms in the modal combination rule arising from cross-correlation between coupled vibration modes "2j" and "1k" (j = 1 to 4; k = j + 1 to 5) of the multistory building (4). Modes are numbered as "nj" with j = 1, 2, . . . N for an N-story buildilng, and n = 1, 2 for a one-way symmetric building to indicate two DOF per floor. The deviations of the normalized responses of the multistory building from those of the associated one-story system depend on e/r, Ω, ρ, the response quantity, the significance of higher modal-pair contributions, and the response spectrum considered. Since the cross-correlation terms may assume positive or negative values (4), the normalized reponses of the multistory building may be larger or smaller than the corresponding normalized responses of the associated one-story system (Figs. 3 and 4). The deviations between the normalized responses of the two systems are more pronounced in the ranges of Ω where cross-correlation factors $\gamma_{21,12}$ and $\gamma_{21,13}$ are maximum (4). Also, the deviations increase with a decrease in ρ in the case of V_B and T_{BR}, trends which also are related to the importance of the higher modal-pair contributions (4). The deviations increase with increase in e/r and are more significant for the hyperbolic spectrum than the flat spectrum; these trends are related to magnitudes of the cross-correlation terms (4).

HEIGHT-WISE DISTRIBUTION OF FORCES

The effect of lateral-torsional coupling on the height-wise distribution of forces (story shears and story torques at the centers of rigidity) is summarized in Figs. 5 to 8. It is apparent that for a flat spectrum the height-wise variations of forces are insensitive to the values of e/r or Ω and follow the respective variations in the corresponding uncoupled multistory system (e = 0). This can be explained by noting that the response of torsionally-coupled buildings with T_{y1} in the acceleration-controlled region, or the flat portion of the spectrum, is mainly due to the fundamental vibration modal pair--modes "11" and "21"--and the cross-correlation terms are relatively small, thus ensuring small contributions of higher modal-pairs (4). As a result, the responses of the torsionally-coupled building, normalized by the responses of the corresponding torsionally-uncoupled, multistory system, are very close to the normalized responses of the one-story system, resulting in a very little influence of torsional-coupling on the height-wise distribution of responses. The effect of lateral-torsional coupling on the height-wise distribution of forces is more pronounced for the hyperbolic spectrum, or the velocity-controlled region of the spectrum, with the effect increasing as e/r increases and as ρ decreases, primarily because the cross-correlation terms are more significant in this case, and increase with an increase in e/r and a decrease in ρ (Figs. 3 and 4). For the values of Ω shown in Figs. 5 to 8, the lateral-torsional coupling effects in story shears and story torques are generally most pronounced for systems with closely spaced uncoupled frequencies (Ω close to 1). It appears that the overall effect of lateral-torsional coupling on the height-wise variations of forces is not large.

CONCLUSIONS

This investigation of the effects of lateral-torsional coupling on the earthquake response of multistory buildings has led to the following conclusions:

1. The effects of lateral-torsional coupling on the responses of a multistory building and its associated one-story system are similar. Lateral-torsional coupling causes a decrease in the base shear, the base overturning moment and the top floor lateral displacement at the center of rigidity, but an increase in the base torque; these effects increase as e/r increases and are most pronounced for systems with closely-spaced uncoupled frequencies. However, unlike the one-story system, torsional-coupling effects in the response of multistory buildings depend on ρ, but for e/r up to 0.4 the dependence on ρ is generally small.

2. The differences between the effects of lateral-torsional coupling on the multistory building and its associated one-story system arise due to cross-correlation terms between vibration modes belonging to different modal pairs. These differences increase with an increase in e/r. They are more pronounced for the base shear and base torque than the base overturning moment and the top floor lateral displacement, and are more pronounced for the column moment than the beam moment or column axial force in the base story.

3. The effect of lateral-torsional coupling on the height-wise variations of forces seems not to be very significant (i.e. these force variations are similar for torsionally-coupled and corresponding uncoupled systems), although it is relatively more pronounced for story shears and story torques than story overturning moments. The effect increases as e/r increases and is more pronounced when T_{y1} is in the velocity-controlled region than when it is in the acceleration-controlled region of the spectrum.

ACKNOWLEDGEMENTS

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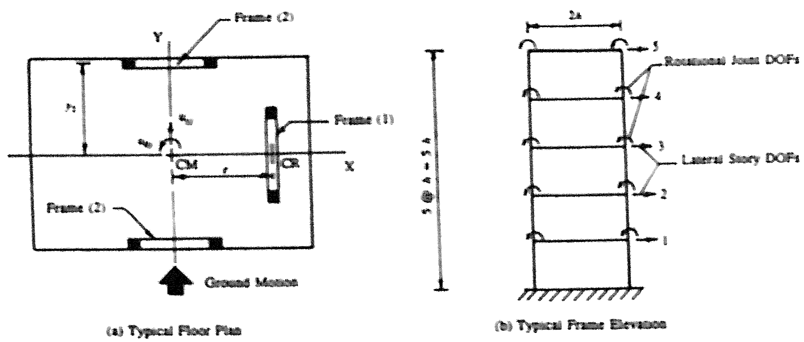

Fig. 1 System Considered

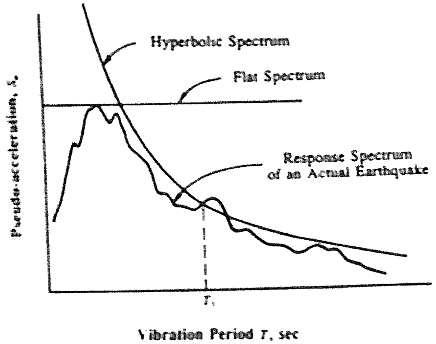

Fig. 2 Flat and Hyperbolic Response Spectra

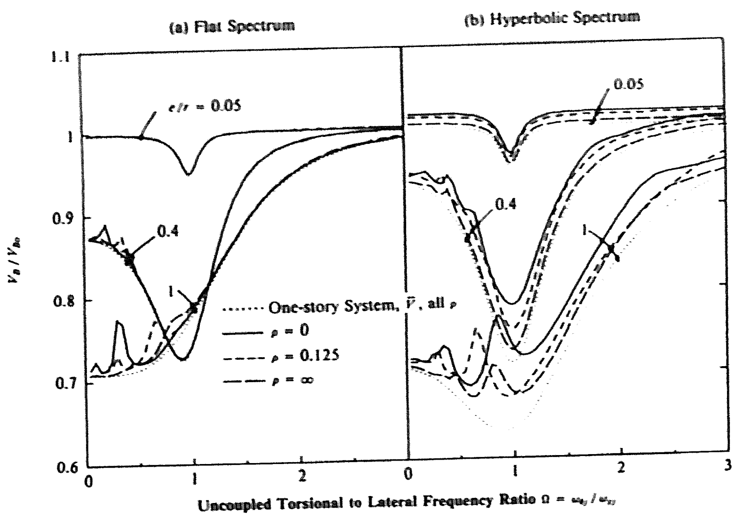

Fig. 3 Normalized Base Shear in Multi-Story Building and Associated One-Story System

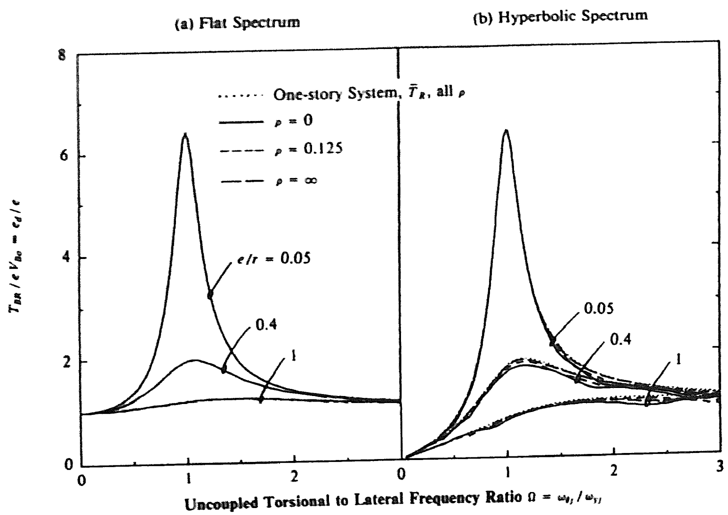

Fig. 4 Normalized Base Torque at C.R. in Multi-Story Building and Associated One-Story System

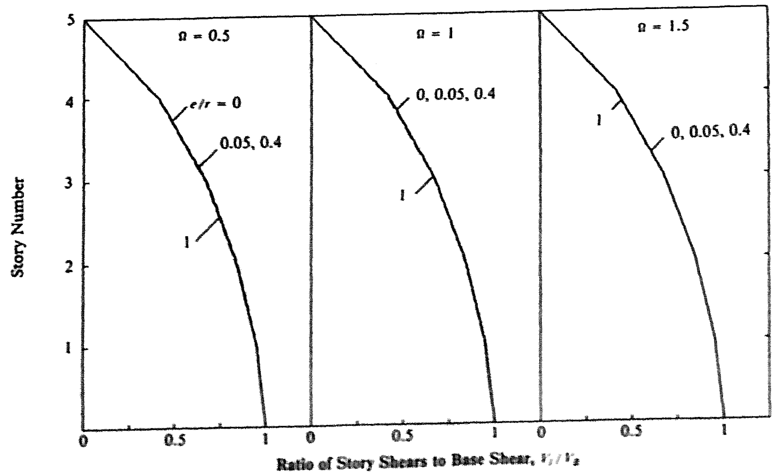

Fig. 5 Comparison of Height-Wise Variation of Story Shears in Torsionally-Uncoupled (e/r = 0) and Torsionally-Coupled (e/r = 0.05, 0.4, and 1) Systems; ρ = 0 for Flat Spectrum

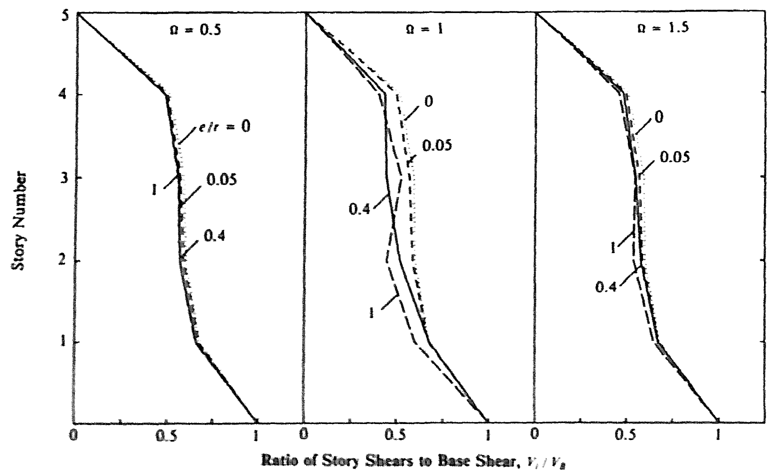

Fig. 6 Comparison of Height-Wise Variation of Story Shears in Torsionally-Uncoupled (e/r = 0) and Torsionally-Coupled (e/r = 0.05, 0.4, and 1) Systems for Hyperbolic Spectrum; ρ = 0

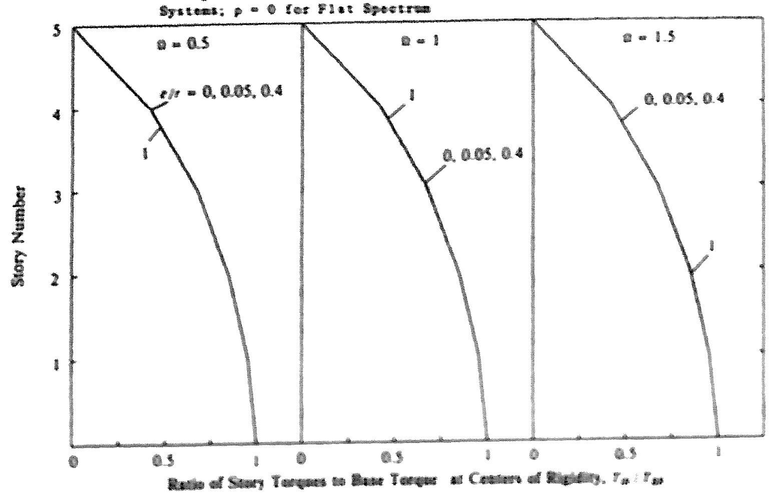

Fig. 7 Comparison of Height-Wise Variation of Story Torques at C.R. in Torsionally-Coupled (e/r = 0.05, 0.4, and 1) Systems and of Story Shears in Torsionally-Uncoupled (e/r = 0) Systems for Flat Spectrum, ρ = 0

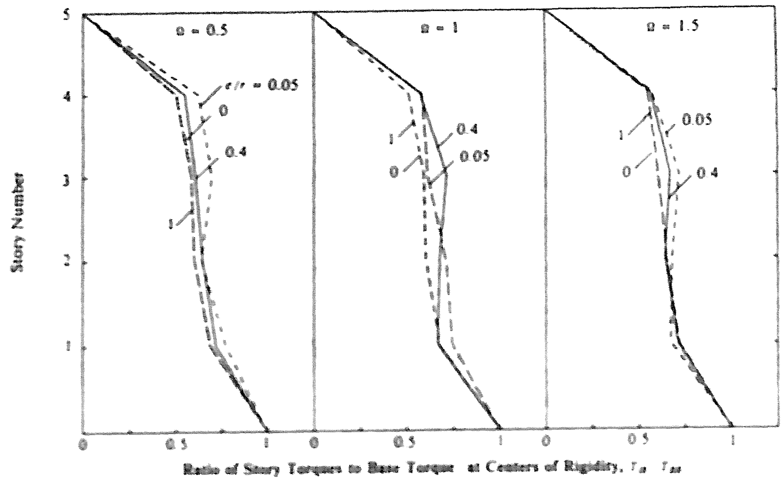

Fig. 8 Comparison of Height-Wise Variations of Story Torques at C.R. in Torsionally-Coupled (e/r = 0.05, 0.4, and 1) Systems and of Story Shears in Torsionally-Uncoupled (e/r = 0) Systems for Hyperbolic Spectrum, ρ = 0