SEISMIC RESPONSE OF TORSIONALLY COUPLED SINGLE-STOREY STRUCTURES

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SUMMARY

This paper presents a study of the seismic response of single-storey torsionally coupled elastic structural models. A probabilistic ground motion model is used. Stationary responses of one-way and two-way coupled systems to single component white noise ground motion are presented. The effects of realistic frequency content, time-varying intensity and two horizontal components of acceleration in the ground motion model are briefly considered. Simple analytical results are obtained for the maximum reduction in horizontal base shear and the maximum dynamic amplification of eccentricity in one-way coupled systems.

INTRODUCTION

Recent studies (Refs. 1-3) of single-storey elastic systems have provided considerable insight into the general features of torsional coupling. It has been widely recognized that when uncoupled torsional and translational frequencies are nearly equal in a system with stiffness eccentricity, a considerable reduction in response base shear accompanies the induced response torque. Many of the previous studies have employed either smoothed design spectra or actual recorded accelerograms to describe ground motion input, and have concentrated on "one-way" torsional coupling with single component ground motion input. In addition, combination rules for combining modal responses have often been used. Such combination rules may not be accurate enough when structural frequencies are closely spaced and multi-component correlated ground motions act on the structure. In this paper, based on the results of Ref. 4, a probabilistic approach was used which accounts for two components of ground motion input and which does not rely on modal combination rules.

ANALYTICAL MODEL

The general features of the ground motion and structural modeling used in this study are given in the following sections.

Ground Motion Model

The multi-directional ground motion model is probabilistic and is founded on the assumption of the existence of ground motion principal directions (Ref. 5). The ground motion principal directions (X',Y') are rotated by an angle of incidence δ with respect to the principal axes (X,Y) of the floor diaphragm

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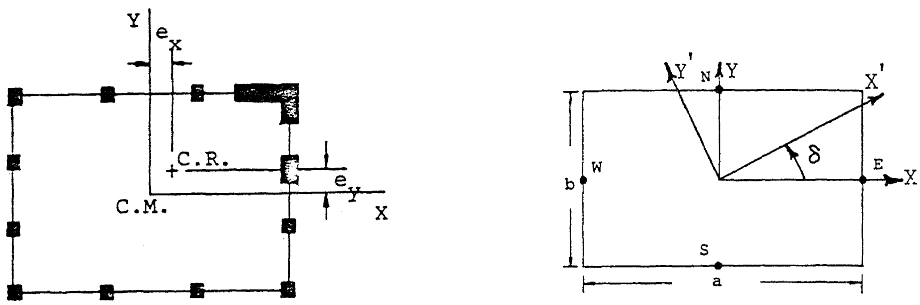
(Fig. 1b). It is assumed that the ground motion inputs in the X',Y' directions are uncorrelated. The ground motion accelerations are modeled as

$$\begin{Bmatrix} a_{X'}(t) \\ a_{Y'}(t) \end{Bmatrix} = \begin{Bmatrix} \bar{a}_{X'} \\ \bar{a}_{Y'} \end{Bmatrix} I(t)\xi(t) \qquad (1)$$

in which $\bar{a}_{X'}, \bar{a}_{Y'}$ are constants which allow different relative strengths of ground acceleration components, I(t) is a deterministic envelope function of double exponential form (Ref. 6), and $\xi(t)$ is a zero mean stationary random process. I(t) accounts for variation of ground motion intensity with time and $\xi(t)$ provides the desired ground motion frequency content as defined by its power spectral density function. In this paper, I(t) is taken as either constant or as a "short-duration" envelope which peaks at t=2.2 sec. $\xi(t)$ is taken as either white noise or as filtered white noise (Ref. 7) with filter parameters (ω_g=15.46 rad/sec, ζ_g=0.623, ω_f=1.636 rad/sec, ζ_f=0.619).



(a) Structural System. Stiffness Eccentricities (e_x,e_y).

(b) Ground Motion Principal Axes (X',Y'). Angle of Incidence (δ).

Figure 1. Structural and Ground Motion Models

Structural Model

The structural model consists of a one-storey elastic system with a rigid floor diaphragm which has dimensions a,b in principal axis directions X,Y. Translational degrees-of-freedom u_x, u_y and rotation u_θ are defined at the center of mass (C.M.). The center of resistance (C.R.) has eccentricities (e_x,e_y) with respect to the C.M. The radius of gyration $r=((a^2+b^2)/12)^{1/2}$ of the floor diaphragm is used as a convenient length scale. A "one-way" system has $e_x=0$, $e_y\neq0$ while a "two-way" system has $e_x\neq0$, $e_y\neq0$. Modal damping, with a constant fraction of critical damping in each mode, is assumed. In this paper, attention is restricted to systems with square floor diaphragms (a=b), and equal translational stiffnesses in the X and Y directions. The structural parameters considered are translational frequency f_x(cps), uncoupled torsional-translational frequency ratio ω_θ/ω_x, eccentricities e_x/r and e_y/r, and modal damping ζ. Buildings with a central core, uniformly distributed columns, or peripheral shear walls tend to have, respectively, lower, nearly equal, or higher torsional frequencies than corresponding translational natural frequencies.

RESULTS

A brief summary of results is presented in the following sections. Responses are plotted in terms of normalized mean-square values. Forces and displacements are normalized by mean-square force and displacement responses for an uncoupled system ($e_x=0$, $e_y=0$) subjected to single-component white noise ground motion.

Effect of Ground Motion Duration and Frequency Content

Mean-square displacement responses at the periphery of the square floor diaphragm are shown in Fig. 2. The larger of the values at locations N and S (Fig. 1b) is plotted for a one-way system ($e_y/r=0.15$) with 5 percent modal damping. Systems with uncoupled translational natural frequencies 0.2, 1.0, and 5.0 cps are considered. Figures 2a and 2b compare the responses for white noise input with the responses for the more realistic Clough-Penzien ground motion frequency content. In Fig. 2a a rather rapidly varying ground motion intensity is used, while in Fig. 2b a constant intensity is used. As expected, the white noise model best approximates the more realistic ground

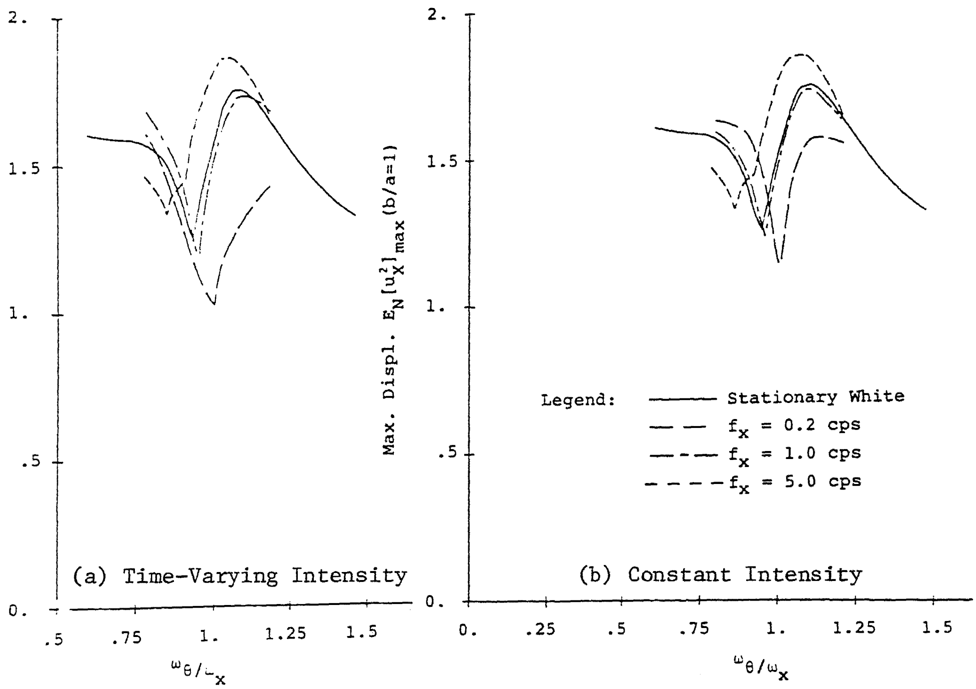


Figure 2. Effect of Ground Motion Duration and Frequency Content. (Clough-Penzien Spectrum. One-Way Eccentricity $e_y/r=0.15$. Modal Damping 5 Percent)

motion model for the medium frequency system (1.0 cps). For the soft system (0.2 cps) the effect of coupling is overestimated by the white noise results, while for the stiff system (5.0 cps) the column response at the periphery is underestimated by the white noise model. These results indicate, however, that the white noise ground motion model is adequate for investigating general response trends in torsionally coupled systems. For white noise input the results are independent of structure frequency f_x.

One-Way Systems with White Noise Input

Systems with one-way stiffness eccentricity subjected to one-dimensional white noise ground acceleration in the X-direction are considered. Figures 3a and 3b show normalized torque about the C.M. and horizontal base shear as a function of frequency ratio ω_θ/ω_x for eccentricities e_y/r=.05,.10,.15 and modal damping equal to 2 percent and 5 percent. Several of the trends have been noted previously by other researchers:

1) One-way systems show an increase in torque and a reduction in horizontal base shear when uncoupled torsional and translational frequencies are nearly equal. Peak torsional response increases as eccentricity increases and as damping decreases.

2) Sum of mean-square normalized torsional and translational forces remains essentially equal to one (Ref. 1) indicating that the torsional coupling merely produces a redistribution of forces.

3) The largest redistribution occurs near $\omega_\theta/\omega_x=1.0$, where the root-mean-square torque (about the C.M.) is approximately equal to $r \cdot F_{x_o} \cdot [(1/2)(e_y/r)^2/((e_y/r)^2+4\zeta^2)]^{1/2}$ in which F_{x_o} is rms base shear in the uncoupled system. The corresponding peak value of rms base shear is approximately $F_{x_o} \cdot [(1/2)((e_y/r)^2+8\zeta^2)/((e_y/r)^2+4\zeta^2)]^{1/2}$. For $\zeta^2 << (e_y/r)^2$, peak rms torque approaches $0.707rF_{x_o}$, and peak rms base shear approaches $0.707F_{x_o}$. Dynamic eccentricity is defined as the eccentricity at which the base shear in the uncoupled system must be applied to produce the dynamic torque. The peak value of rms dynamic eccentricity occurs near $\omega_\theta/\omega_x=1.0$, and is approximately equal to $e_y \cdot [(1/2)/((e_y/r)^2+4\zeta^2)]^{1/2}$. For 2 percent modal damping, and stiffness eccentricity e_y/r=.05, the peak value of rms dynamic eccentricity is approximately 11.0 times the static eccentricity. These simple analytical results for maximum amount of force redistribution in one-way systems are believed to be new.

Figure 3c shows mean square displacement responses at the edge of the square floor diaphragm for eccentricities e_y/r ranging from .05 to .40. These correspond to e_y/b values ranging from .02 to .16. The larger of the responses at locations N and S (Fig. 1b) is plotted against ω_θ/ω_x for modal damping 2 and 5 percent. Additional results are noted as follows:

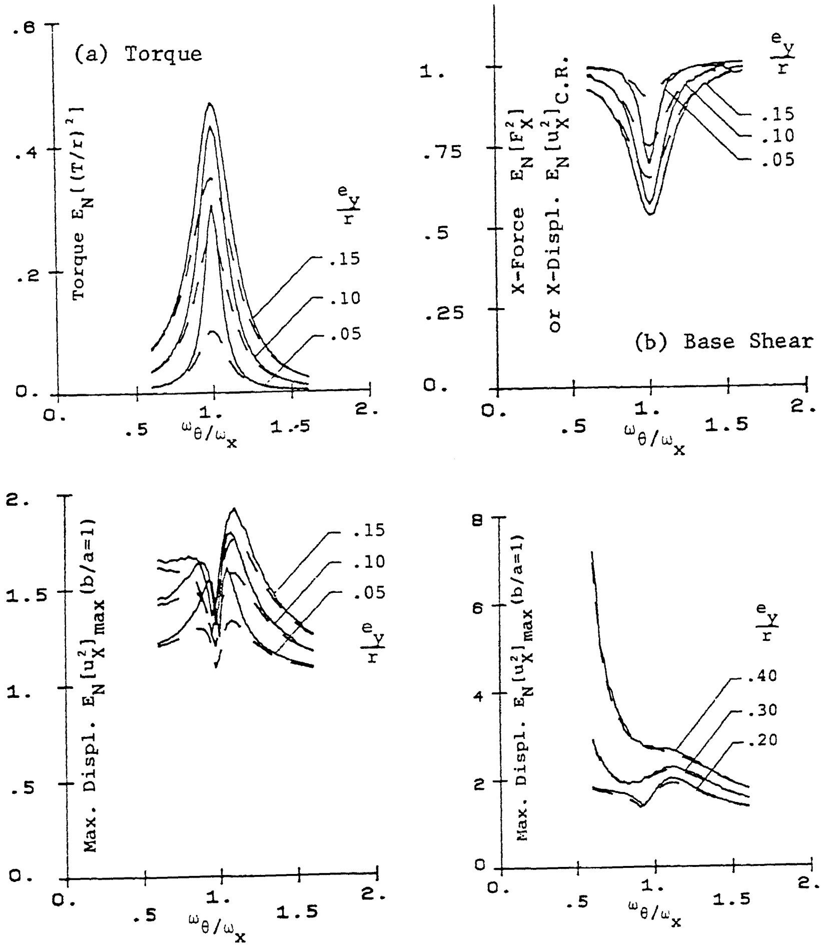
4) For small eccentricities the displacement response at the periphery peaks at ω_θ/ω_x about 1.1, while for larger eccentricities the displacement response grows as ω_θ/ω_x decreases below 1.0. The system becomes unstable when $\omega_\theta/\omega_x < e_y/r$.

5) Compared to uncoupled translational response, the maximum rms displacement response at the edge of the diaphragm is increased by about 40 percent for an eccentricity equal to about 6 percent of the floor span dimension (e_y/r=0.15).

6) Sum of normalized mean square torsional and translational displacement responses is always greater than 1.0 and is independent of damping, indicating that the system is effectively softened by torsional coupling.

Two-Way Systems with White Noise Input

Two-way systems with stiffness eccentricity e_y/r=.10 and 5 percent modal damping subjected to one-dimensional white noise ground acceleration in the

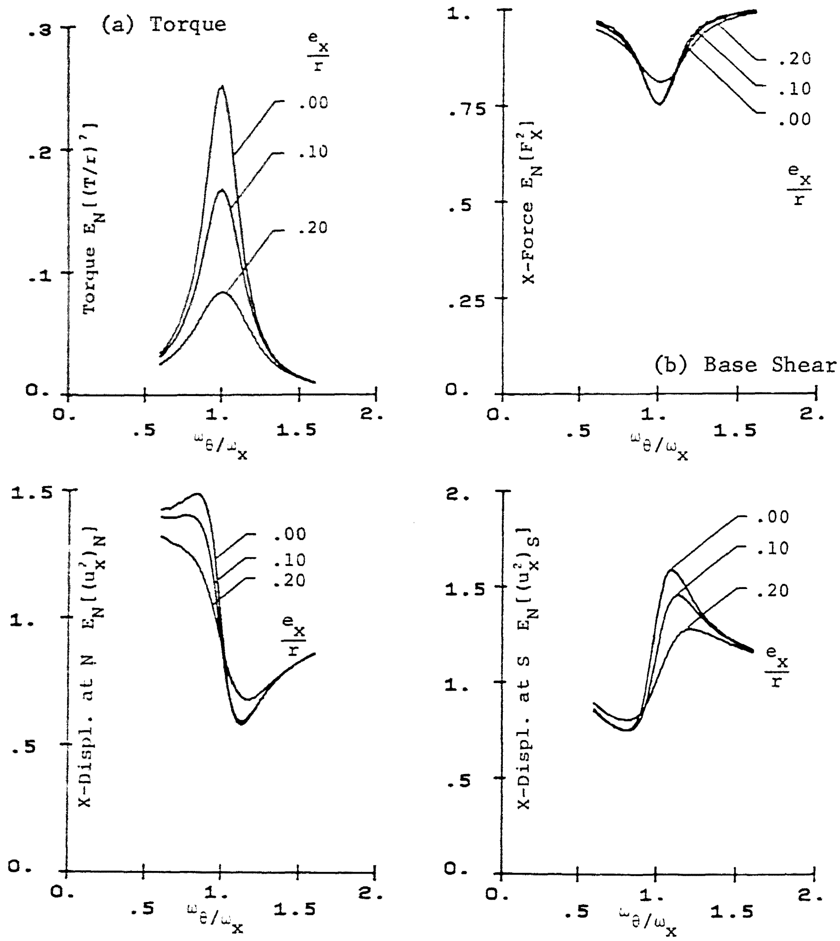


(c) Maximum Displacement at Edge of Floor Diaphragm

Figure 3. One-Way Torsionally Coupled Systems. White Noise Input. (Modal Damping 2 Percent ——, 5 Percent ---)

X-direction are considered. Results are given in Fig. 4 for three values of $e_x/r(0,0.1,0.2)$. Results are noted as follows:

7) For two-way systems subjected to one-directional ground motion, eccentricities in the direction of the ground motion reduce the peak torsional response (Ref. 1). The force interaction relationship (sum of mean square translational and torsional forces=1) remains valid (Ref. 1) so that the appearance of a base shear in the Y-direction must produce a reduction in the other two components of the interaction equation. The base shear F_x in the direction of the ground motion is not, however, as much affected by the second eccentricity e_x as is the torque.



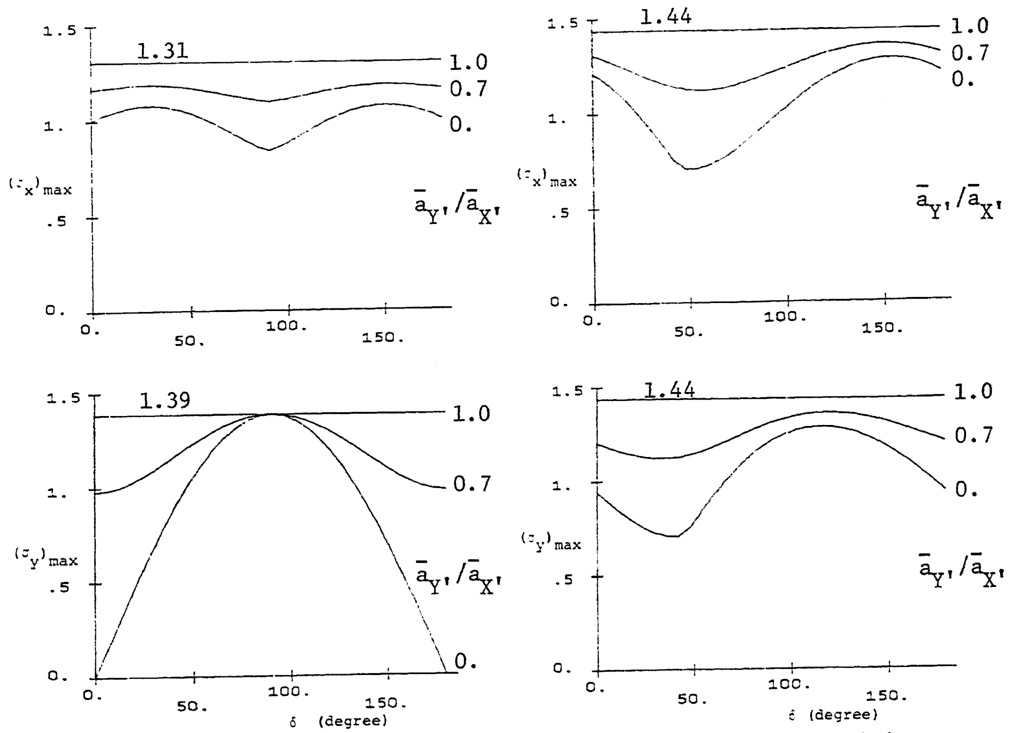
(c) Maximum Displacement at Edge of Floor Diaphragm

Figure 4. Two-Way Torsionally Coupled Systems. White Noise Input. (Eccentricity e_y/r=0.1, Modal Damping 5 Percent)

8) Figure 4c shows the displacement responses at two locations on the periphery of the floor diaphragm. Stiffness eccentricity in the direction of the ground motion acts to reduce the peak displacement responses in comparison with the one-way torsionally coupled systems. This conclusion is valid only for one-dimensional input (see Fig. 5).

Effect of Ground Motion Directionality

The effect on structural response of ground motion directionality was studied by varying the incidence angle δ (Fig. 1b). Three different relative strengths $\bar{a}_{Y'}/\bar{a}_{X'}$ (0,0.707,1.) of the two ground acceleration components were considered. A one-way system (e_x/r=0.2,e_y/r=0.) and a two-way system (e_x/r=0.2,e_y/r=0.2) with square floor diaphragms and 5 percent modal damping were studied. At each ground motion incidence angle, the largest of the rms displacement responses at locations N,S,E,W in Fig. 1b was determined over the full range of ω_θ/ω_x values of interest. Figure 5 shows the normalized displacement responses in the X-direction and in the Y-direction as a function of incidence angle δ. The following conclusion can be drawn:



(a) One-Way Eccentricity (e_x/r=.2, e_y/r=0.)

(b) Two-Way Eccentricity (e_x/r=.2, e_y/r=.2)

Figure 5. Effect of Ground Motion Directionality on Maximum Displacement at Edge of Floor Diaphragm. White Noise Input. Modal Damping 5 Percent.

9) When the governing incidence angle is taken into account (the incidence angle at which peak response occurs) the maximum displacement at the periphery of the floor diaphragm is relatively insensitive to the relative strengths of the two ground motion components. The "worst case", that of two equal-intensity ground motion components is not grossly overconservative. The procedure recommended by the recent ATC-3 Code (Ref. 8) for recognizing orthogonal effects produces quite reasonable results when applied to the simple structural model considered in this paper.

ACKNOWLEDGMENTS

The results reported in this paper were obtained as part of a research program supported by the National Science Foundation under Grants ENV 77-07190 and PFR 80-02582. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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