# STRUCTURAL RESPONSE ARISING FROM TRAVELING SEISMIC WAVES

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## ABSTRACT

The results of studies of the dynamic response of a simple structural system with coupled translational and rotational degrees of freedom subjected to ground motion containing both translational and rotational components are presented.

Earlier studies dealt only with symmetrical structures, used superposition of the two effects to arrive at the combined response. In this paper the response of a coupled system to the average translational and induced torsional ground motion is investigated.

Comparisons of the results of the calculations with results obtained using current code approaches for buildings are presented.

## INTRODUCTION

Observations of earthquake damage indicate that buildings undergo rotational as well as translational motion, and that structures on large foundations respond with less intensity to ground shaking than do structures on smaller foundations. In 1969 Newmark (Ref. 1) developed a basis for determining torsional earthquake effects in symmetrical buildings, and in 1970 Yamahara (Ref. 2) offered an explanation of observed reductions in translational response of buildings as compared with free field behavior. More recently, Newmark, Hall, and Morgan (Ref. 3) have presented numerical techniques for computing the averaged translational and induced torsional motion in a rigid foundation.

The intent of this investigation was to study to some limited extent a number of parameters believed to be important in assessing the translational and torsional responses arising from wave passage by a structure. These parameters were the eccentricity between centers of mass and stiffness as a percent of the building dimension along the axis of symmetry, the ratio of torsional to translational frequency for the structure, the aspect ratio of the building (i.e., the ratio of the horizontal dimensions of the building), and the ratio of stiffnesses in the two translational coordinate directions. Also, comparisons are made between the results obtained in this study and those obtained using current seismic building code procedures. A common approach employed by U.S. building codes is to include so-called accidental torsion arising from numerous effects, including ground rotation, by computing response from the free field ground motion, positioning the resulting inertial force five percent of the building dimension away from the mass center, and computing the additional response arising from the equivalent static moment.

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## COUPLED MODEL AND MOTION PARAMETERS

A single story three degree-of-freedom model with one axis of symmetry and some finite eccentricity between centers of mass and stiffness is a logical progression from the symmetrical building studied previously. For the sake of simplicity the mass is treated as a rigid thin plate with coordinate origin at the center of stiffness as shown in Fig. 1.

The ground motion input at the coordinate origin from the $\tau$-averaged time histories obtained using Eq. 1 and Eq. 2 presented in earlier work (Refs. 3) is as follows:

$$\ddot{\Phi} = \frac{1}{\tau}\{\dot{\rho}(B) - \dot{\rho}(A)\} \tag{1}$$

$$\ddot{\alpha} = \frac{6}{\tau^2}\{\dot{\rho}(B) + \dot{\rho}(A)\} - \frac{12}{\tau^3}\{\rho(B) - \rho(A)\} \tag{2}$$

Since $\ddot{\alpha}$ is in units of length/time$^3$ and the coordinate is in radians one must first convert to angular acceleration (radian/time$^2$); this can be done easily by dividing $\ddot{\alpha}$ by the wave velocity C. Also, because the average translational time history is applied to the center of mass rather than the coordinate center, the ground motion input for the y direction must be modified such that $\ddot{y}_{cs} = \ddot{\Phi} - e\ddot{\alpha}/C$ as shown in Fig. 1. The details of this theory modelling and results of the study summarized herein are contained in Ref. 4.

## SUMMARY OF FINDINGS

Several assumptions have been made throughout the study which warrant additional comment

> Only systematic motions over the base are taken into account. The true motions are in large part random, and therefore cause much lower torsional responses, but about the same translational reduction.
>
> Only horizontally propagated plane waves with vertical wave fronts of motion are considered. Since only part of the motions in an earthquake is of this type, the torsional responses may well be exaggerated, but the translational reductions are not greatly affected.
>
> Only rigid foundation systems are considered. This assumption tends to exaggerate both the induced torsional responses and the translational reductions computed.

### Superposition model

Briefly, the conclusions to be drawn from the results of the superposition model are as follows:

> Translational averaging leads to significant response reductions depending on (width/wave velocity) when compared to response computed from free-field records, at frequencies above 1 Hz with little change in response for lower frequencies.

The response arising from rotation induced by a traveling wave passing a foundation is most important at frequencies above 1 Hz and tends to offset reductions arising from translation averaging.

The use of frequency ratios greater than unity more closely simulates real buildings and leads to response in the regions of greatest interest which is less than that observed for a frequency ratio of unity.

Coupled model

In general, the coupling of translational and rotational response leads to increased scatter in the computed responses obtained and less certainty in the types of trends noted for the superposition model. Briefly, the following observations can be made.

The coupling of Y and $\theta$ coordinates no longer allows the separation of translational and rotational effects noted previously.

Although the trend is not conclusive, it was observed that an increase in torsional to translational frequency ratio ($f_\theta/f_x$ or $f_\theta/f_y$) generally leads to lower computed edge responses.

There is a trend toward the behavior that would be expected with respect to eccentricities; however, coupling of translational and torsional responses and phasing between Y and $\theta$ ground motions do not allow exact predictions of response.

The results of the study clearly suggest that symmetry is desirable if possible. In such cases it is easier to predict the motions and they are in general more uniform throughout the structure.

As a result of the various approaches for computing effects involving phasing of ground motion and/or phasing of response components, one observes that the techniques involving summation of maxima without respect to time in all cases studied gave motions that were larger than if they were summed with respect to time. This observation suggests that the code approaches (i.e., no allowance for time phasing) are of a conservative type.

## COMPARISONS WITH BUILDING CODE PROCEDURES

For the most part the results obtained in this study fall (averaging thirty percent) below those computed using a five percent accidental eccentricity approach; however, there is a great deal of scatter in the results ranging from an 80 percent reduction to a 31 percent increase of response computed over the building code approach.

It should be noted that the code approach intent is to include accidental torsion from all sources, of which ground rotation is only one item. Based on the results of this limited study, the 5 percent code value for accidental eccentricity appears reasonable; however, additional study of this complex topic appears desirable.

## ACKNOWLEDGEMENTS

This study was supported by the National Science Foundation under Grants AEN 75-08456 and ENV 77-07190. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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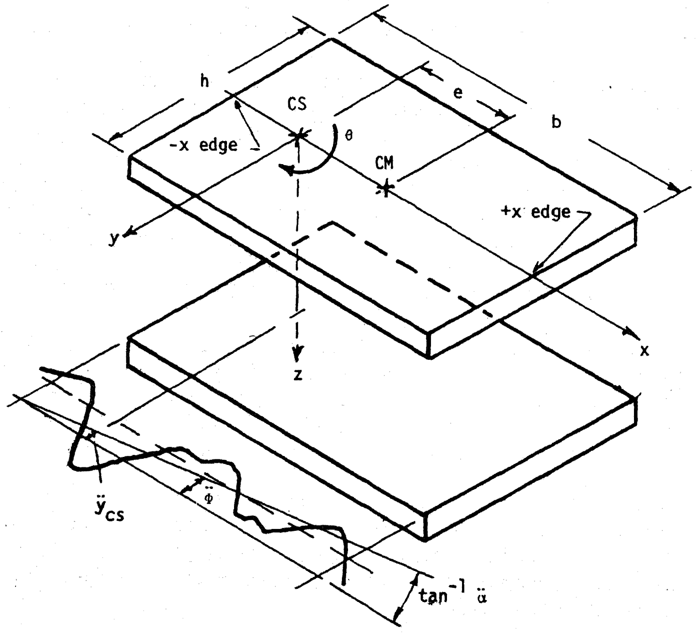

FIG. 1 MODEL AND GROUND INPUT