INELASTIC RESPONSE OF BUILDING STRUCTURES
BY TRAVELLING EARTHQUAKE WAVE MOTIONS

by

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SYNOPSIS

A strctural model is assumed to be a two-dimensional mass-spring system along the direction of seismic wave propagation. The restoring force function of each vertical member is supposed to have a yield condition defined to the combined story shear force of two horizontal components. Foundations of a model are subjected separately to the horizontal ground motions with a transit time of seismic waves. Ductility factor response to the El Centro earthquake are mainly represented and the necessity of strength in the first story is pointed out.

INTRODUCTION

In earthquake response analysis of building structures, one-dimensional mass-spring systems have been usually supposed for a dynamic model of structures. Earthquake ground motions were assumed to be identical at all points beneath foundations of structures in those analysis. However, for buildings with a comparatively large dimension in one direction, it is supposed that ground motions at both ends along structures will differ from each other. Such a long structure may be caused torsional deformation in addition to two horizontal translations when subjected to seismic input. Recently, some investigations are reported on the effects of propagating seismic waves on the torsional response of foundations and structures[1-4]. The present paper also treats the effects of travelling earthquake wave motions on elasto-plastic responses of multi-story long building structures.

A structural model analyzed is idealyzed as a two-dimensional mass-spring system along the direction of seismic wave propagation. Displacements of masses are supposed in two directions on the horizontal plane. Natural vibration characteristics to two main axes of a model are assumed to differ from each other. Although horizontal members of a structural model are confined to be perfectly elastic, the restoring force function of each vertical member is assumed here to have a yield condition defined by the combination of story shear forces to two horizontal deformation components. And the yield surface to the combined story shear force is supposed to translate proportionally to the plastic deformation according to the plastic flow rule including a strain hardening effect. Horizontal earthquake wave motions, which propagate along the long axis of a structural model, are supposed simultaneously two horizontal components, one in the logitudinal direction and the other in the transverse direction. Structural responses of the story shear deformation and the torsional deformation are analyzed numerically to combinations of horizontal acceleration components corresponding to two different actual earthquake records. The results on distributions of ductility factor of story shear deformation, torsional angle

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of each story level and plastic energy dissipation are shown and compared mainly to the variation of transit time of ground motion between the foundations, the fundamental natural period of structural system and intensity of earthquake excitation.

STRUCTURAL MODEL

In this analysis, a mathematical model of structures is assumed as shown in Fig. 1. The model consists of two sets of three-mass system connected each other with horizontal, elastic members. Points 1 and 2 in Fig. 1 represent foundations, which are excited separately by two-dimensional, horizontal ground motion. Masses of each story are concentrated at Points 3 to 8 and displacement of each mass is assumed to have two horizontal components. Structural members ① to ⑥ represent springs with an elasto-plastic restoring characteristic to the story shear deformation. And horizontal members ⑦ to ⑨ are supposed to be perfectly elastic. Shear deformation of horizontal members is taken into account in the analysis but the axial deformation is neglected.

Natural vibration modes of such a long, multi-story building structure are usually shown as shear rod type in the X-direction and bent beam type in the Y-direction. Models analyzed here have the same vibration characteristics as those of typical long buildings and the natural modes are shown in Fig. 2. Vibration modes by dotted lines in the Y-direction mean alternating displacements at the opposite side in each story, namely torsional deformation, the natural period of which is varied by adjusting shear stiffness of horizontal members. Four types of natural vibration characteristic in the Y-direction corresponding to Models (1) to (4) in Fig. 2 with a common characteristic in the X-direction are supposed here.

The following two types of elasto-plastic restoring force function of members ① to ⑥ are assumed in the analysis:

i) Type (A): Restoring force functions of bilinear hysteretic type are assumed separately for shear deformations in the X- and Y-direction of each member. The restoring force in the X-direction is independent of the deformation in the Y-direction of the member. The stiffness ratio r in the plastic range to the initial stiffness is chosen as r = 0.1 or 0.4 in the analysis.

ii) Type (B): Yield condition of each member is supposed to be of circular type for shear force in the X- and Y-direction expressed by the next equation[5]:

$$f = \left\{ \left(\frac{R_X - \rho_X}{R_{X0}} \right)^2 + \left(\frac{R_Y - \rho_Y}{R_{Y0}} \right)^2 \right\}^{1/2} - K \qquad (1)$$

where, R_X, R_Y: shear force of a member in the X- and Y-direction,
R_{X0}, R_{Y0}: yield level of shear force of a member to the single component in the X- and Y-direction,
ρ_X, ρ_Y: shear force corresponding to transition of origin of yield condition in the X- and Y- direction, respectively.

The relation between shear force increment $\{dR\}$ and shear deformation increment $\{dU\}$ in the plastic range is expressed by the next equation according to the plastic flow rule with work-hardening effect[6].

$$\{dR\} = [D^p]\{dU\} \tag{2}$$

$$\{dR\} = \{dR_X \ dR_Y\}^T, \{dU\} = \{dU_X \ dU_Y\}^T \tag{3}$$

$$[D^p] = [D^e] - \frac{[D^e]\{\partial f/\partial R\}\{\partial f/\partial R\}^T[D^e]}{r + \{\partial f/\partial R\}^T[D^e]\{\partial f/\partial R\}} \tag{4}$$

$$\{\partial f/\partial R\} = \{\partial f/\partial R_X \ \ \partial f/\partial R_Y\}^T \tag{5}$$

$$[D^e] = \begin{bmatrix} K_X & 0 \\ 0 & K_Y \end{bmatrix} \tag{6}$$

where, $[D^e]$ and $[D^p]$ represent stiffness matrices of a member in the elastic range and that under the plastic flow, K_X and K_Y are initial stiffnesses of a member in the X- and Y-direction, respectively. And r means the hardening coefficient in the plastic range, and assumed here to be r = 0.1 or 0.4.

Yield level of shear force of a member is determined so as to have an equal amount of the elastic limit potential energy for all members to the restoring force function of both types. Then, the elastic limit deformation is inversely proportional to square root of its initial stiffness. And a model also includes an internal viscous damping, the fraction of which is assumed to be 0.01 for the fundamental mode.

GROUND MOTION

The following combinations of acceleration components corresponding to two different earthquake records are used in the analysis:

El Centro, 1940, N-S and E-W components,
Vernon, 1933, N08E and S82E components.

The N-S component of El Centro earthquake and the N08E component of Vernon earthquake are assumed as the seismic input in the X-direction in each combination. Numerical analysis is made for the first nine seconds in the records as the most severe part of ground motions.

In this study, it is supposed that the ground motion propagates without changing its wave pattern and two foundations, shown as Points 1 and 2 in Fig. 1, of the structural model are subjected to seismic inputs with a time difference T_l. In the case that T_l = 0, the torsional deformation of a model does not occur and responses of two vertical members in the same story exactly coincide with each other. The transit time of seismic waves between the foundations is varied in the range, T_l = 0 to 0.2 sec, in the analysis.

Relating the direction of wave propagation with the difference of dynamic characteristic along two main axes of models, the following two cases concerning with parameter T_l are supposed:

Case (I): the ground motion has equal transit time T_l for both horizontal components,
Case (II): the ground motion in the X-direction is identical at two

foundations based on the neglect of the axial deformation in the X-direction of horizontal members. Consequently, the ground motion has the transit time in the Y-direction only.

Intensity parameter of ground motions or strength parameter of models is expressed by a symbol α, which is defined as a ratio of the maximum ground acceleration to the reference yield level of restoring force per unit volume of mass of models. And the ratio α is determined to unity for intensity of ground motions or strength of models when the maximum restoring force of any member just coincides to its yield level in the case $T_L = 0$.

RESULTS AND CONCLUSIONS

Elasto-plastic responses of a structural model are computed with the Runge-Kutta 4-th order procedure and a time step for numerical integration of the equation of motion is chosen as 0.01 seconds. Since the responses to two combinations of earthquake acceleration are similar to each other, the results are shown here mainly to the El Centro earthquake input.

Figs. 3(a) to 3(d) show examples of relative displacement response to one of foundations (Point 1 in Fig. 1). Displacements in the X-direction are identical for both ends on the same story. In spite of the difference of natural periods of a model in the Y-direction, response of Model (4) is nearly same to that of Model (2). On the other hand, relative displacement responses in the Y-direction are fairly separated from that of the other end in each story because of the torsional deformation of a model. This differences of response is largest at the first story and especially emphasized for Model (4).

The maximum response of elasto-plastic members is represented in terms of the ductility factor. In this paper, the ductility factor μ of a member is expressed by the following equations corresponding to the type of yield condition of its restoring force function:

i) Type (A): $$\mu = max\left(\left|\frac{U_X^m}{U_{X0}}\right|, \left|\frac{U_Y^m}{U_{Y0}}\right| \right) \quad (7)$$

ii) Type (B): $$\mu = \left\{ \left(\frac{U_X^m}{U_{X0}}\right)^2 + \left(\frac{U_Y^m}{U_{Y0}}\right)^2 \right\}^{1/2} \quad (8)$$

where, U_X^m, U_Y^m: maximum shear deformation of a member in the X- and Y-direction,

U_{X0}, U_{Y0}: shear deformation corresponding to the yield level of restoring force function of a member to the single component in the X- and Y-direction, respectively.

As the accumulated value of the whole response history in the duration of ground motion, the transmitted input energy to a model and the hysteretic dissipated energy are also evaluated. But these responses on energy are not represented in this paper.

In Figs. 4(a) to 4(d), the ductility factor responses are shown to the intensity parameter α of ground motion. The largest response appears generally at the first story. Input energy is transmitted first to base story and it causes large plastic deformations in the first story resulting mitigation of excitations to the upper stories. Since the ductility factor response of Models (1) and (2) usually decreases for long transit time, time difference of ground motion seems to have an advantegeous effect on a certain structural model. However, response of the first story of Models (3) and (4) increases considerably as transit time becomes longer. When time difference of ground motion is large enough to be comparable with the fundamental period, the aseismic safety of a model may be reduced by increase of torsional deformation and plastic deformation at the first story.

Figs. 5(a) and 5(b) show mean value $\bar{\mu}$, and coefficient of variation ν, of each ductility factor of members. The effect of transit time on mean of ductility factor is slight except for the case T_ℓ = 0.2 sec, where $\bar{\mu}$ is small for Models (1) and (2) and large for Models (3) and (4). The coefficient of variation shows uniformity of ductility response of members. Relatively small coefficients for Models (1) and (2) represent a desirable distribution. The coefficients for Models (3) and (4) increase exceedingly in the cases of long transit time.

From these response features, it is concluded that members in the first story subjected to most unfavorable excitation are likely to yield into plastic range and that higher strength in the first story is important for a uniform distribution of ductility response. Some additional analyses are made for some models to examine the way to improve these disadvantegeous distribution. Models have increased elastic limit potential energy in restoring force function for the lower story as shown at left column in Figs. 6(a) to (d). To intense ground motions, ductility factor of members becomes to distribute in relatively narrow zone. It is, however, pointed out that a little change of parameter values influences remarkably on these response distribution in a model.

ACKNOWLEDGMENT

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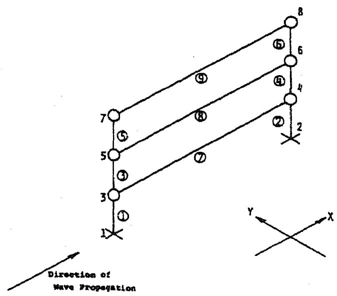
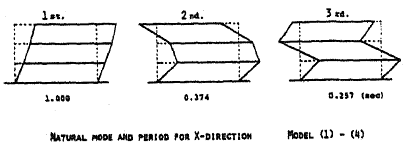
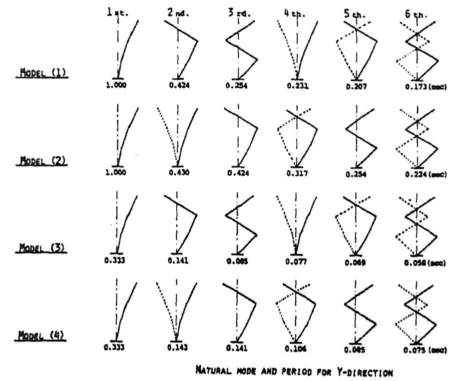


Fig. 1 Structural model

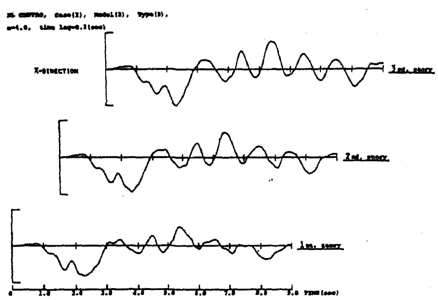


(a)

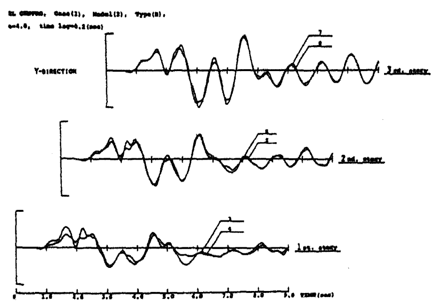


(b)

Fig. 2 Natural vibration characteristic in the X- and Y-direction



(a)



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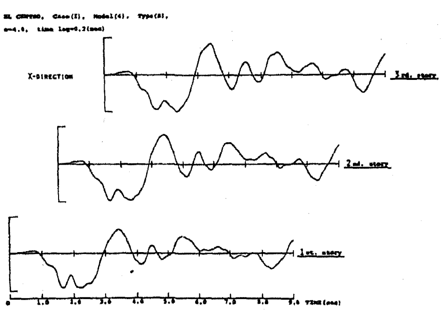
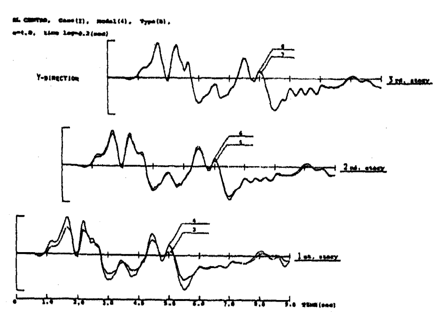


(c)



(d)

Fig. 3 Relative displacement response to the foundation

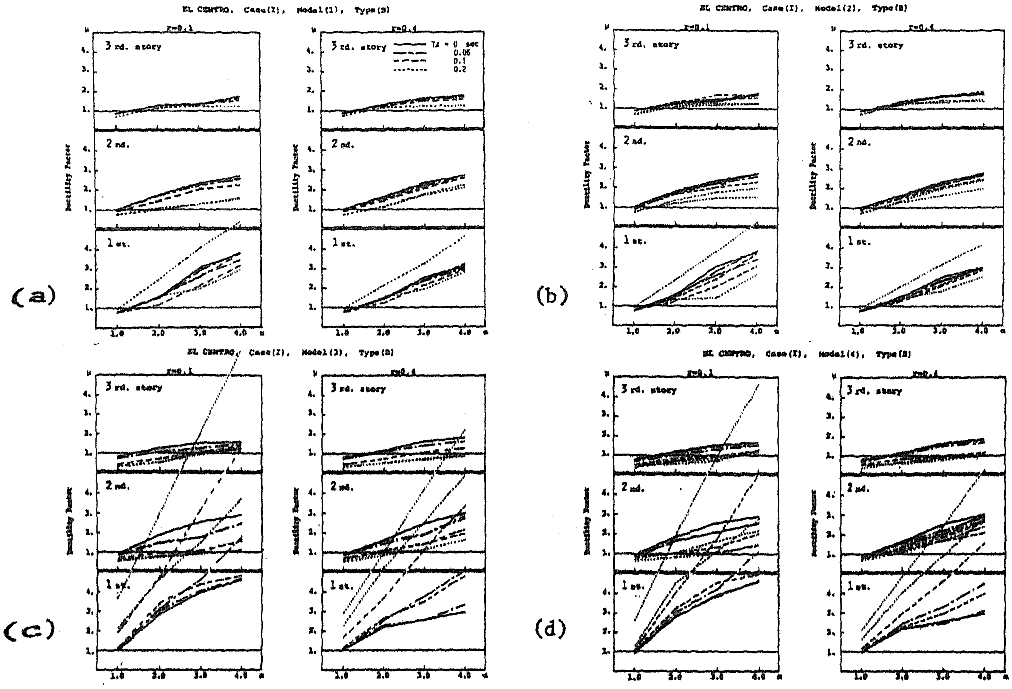
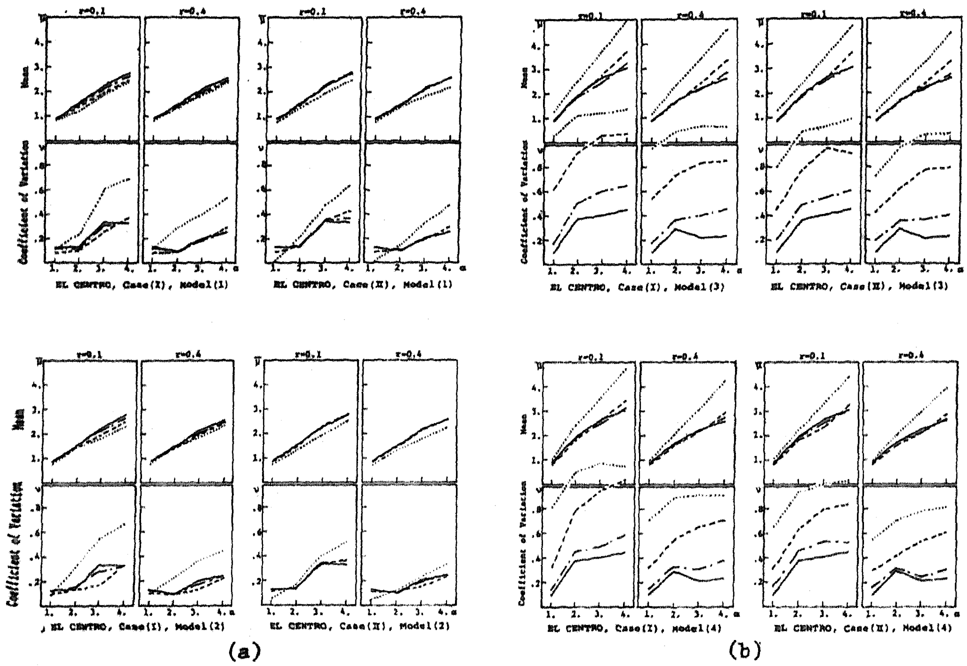


Fig. 4 Comparison of ductility factor response



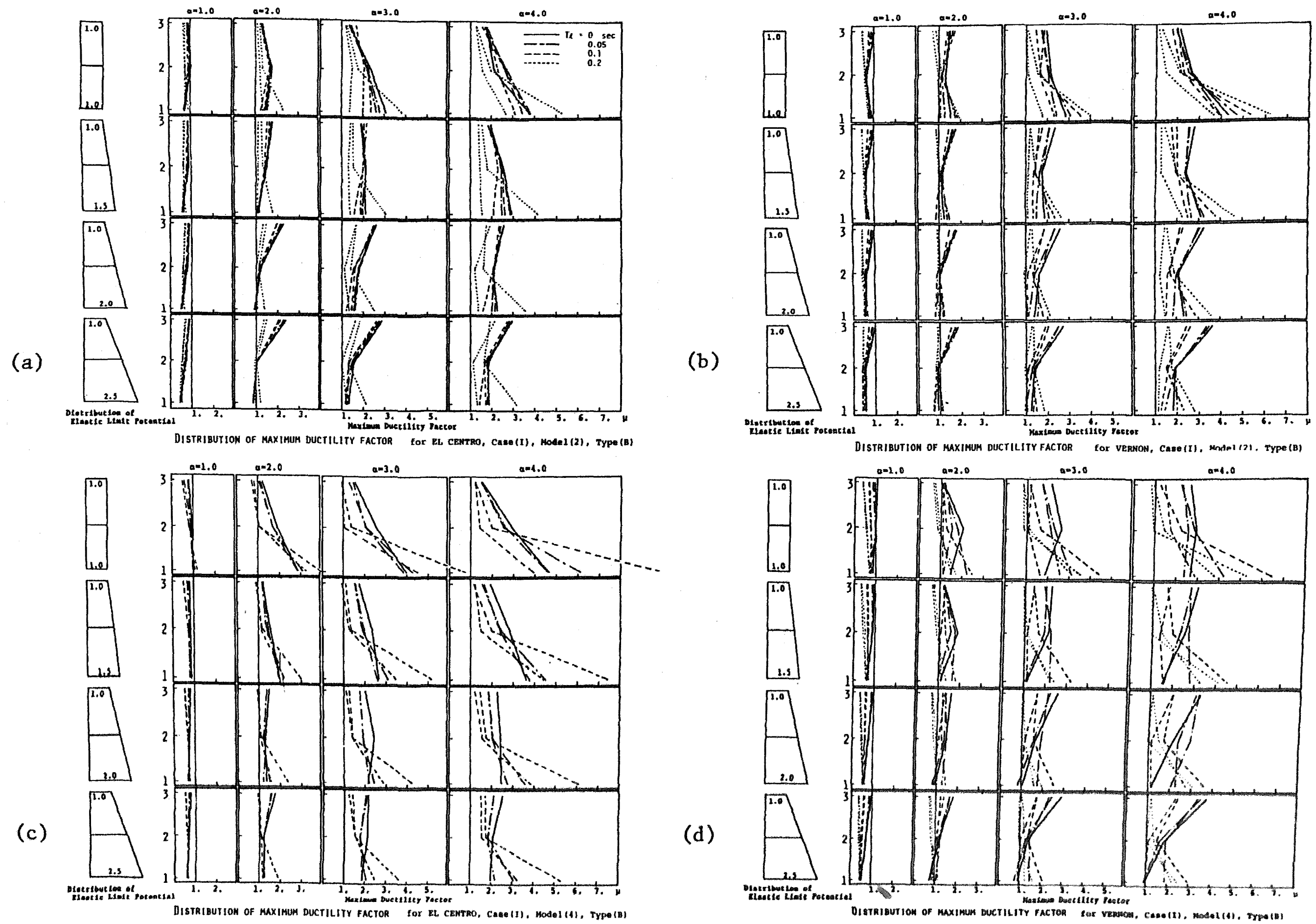


Fig. 6 Distribution of ductility factor