Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.V)

7-4-1

A COLUMN SAFE DESIGN METHOD OF MULTI-STORY BUILDING STRUCTURES UNDER EARTHQUAKE MOTION

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SUMMARY

In this paper, a method of earthquake response analysis of multi-story space structures is presented to study the effect of multi-axial interaction on the response characteristics. This method is extension of the method presented by Wen, Y.K. et al. by introducing plasticity theory. Some deterministic responses of structures by using curvi-linear hysteretic formulation are also shown in order to clarify the interaction effects on the maximum responses.

INTRODUCTION

In order to resist against severe earthquake motion, multi-story building structures must be designed so as to dissipate most of input energy in ductile members such as beams in flexural yielding. However, it seems very difficult maintain the base of columns in elastic or small plastic region.

There remain some problems to be solved with concerning to the optimum design method of structural members of space structures as follows : 1) Optimum distribution of strength or stiffness of members. 2) Response characteristics of space structures subjected to bi-directional excitation. 3) Deterioration effect of hysteresis on the responses. 4) Effect of dynamic axial forces on the responses of R/C structures. 5) Torsional vibration characteristics of eccentric structures, and so on.

In this paper, one method of earthquake response analysis of multi-story space structures by using the curvi-linear hysteresis rule and by considering dynamic axial forces on the inelastic behavior of reinforced concrete column members are presented. Numerical results of some responses under bi-directional excitation were compared with the results under uni-directional excitation in the case of Ramberg-Osgood type hysteresis (Ref.1) as well as modified curvi-linear hysteresis presented by Park, Y.J., Wen Y.K. and Ang, A.H-S.[Ref.2].

METHOD OF ANALYSIS

<u>Force Deformation Relationship of Curved Hysteresis</u> Considering three dimensional force field, that is, bi-axial bending moments and axial force, the plastic potential function is represented in the form,

$$F(Mx,\ My,\ Mn) = F(W^P) = F \qquad (1)$$

which defined the equivalent force F in one dimension. Deformations of each components Ui are supposed to consist of elastic component and plastic component and the time rates of multi-axial plastic deformation are given by the orthogonality,

$$Ui = Ui^E + Ui^P \quad (2), \qquad \dot{U}i^P = \lambda \frac{\partial F}{\partial Mi} \quad (3), \qquad Mi = Aij\ Uj^E \quad (4)$$

in which Aij is elastic modulas defined by the initial state of the anithotropic structural systems.

The rate of plastic work $\dot{W}^P$ and the incremental relationship between multi-axial forces and deformations are defined by the following equations:

$$\dot{W}^P = Mk\ \dot{U}k^P = \lambda \frac{\partial F}{\partial Mk} Mk = F\dot{U} \quad (5), \qquad U = U^E + U^P \quad (6), \qquad F = A \cdot U^E \quad (7)$$

$$\dot{M}i = Aij\ \dot{U}j^E = Aij\ \dot{U}j - \lambda \frac{\partial F}{\partial Mj} Aij \quad (8)$$

Using eqs. (5) and (8) into the rate of eq.(1) and replacing into eq.(8), the following equation is finally given,

$$\dot{M}i = [Aij - \frac{Aik \frac{\partial F}{\partial Mk} \frac{\partial F}{\partial Ml} Alj}{\frac{\partial F}{\partial Mk} Akl \frac{\partial F}{\partial Ml} + \frac{1}{F} \frac{dF}{dU^P} Mk \frac{\partial F}{\partial Mk}}]\ \dot{U}j \quad (9)$$

in which the term $\frac{1 dF}{F dU^P}$ is defined by giving the equivalent force-deformation relationship such as Ramberg-Osgood Type (Ref.1) or Wen Type (Ref.2).

$$\dot{F} = [A - \{\beta \mathrm{sgn}\ (\ \dot{U}F\ ) + \gamma\} |F|^n\ ]\ \dot{U} \quad (10)$$

$$\frac{1}{F} \frac{dF}{dU^P} = \frac{A}{F} \frac{[A - \{\ \beta \mathrm{sgn}\ (\ \dot{U}F\ ) + \gamma\ \} |F|^n\ ]}{\{\ \beta \mathrm{sgn}\ (\ \dot{U}F\ ) + \gamma\ \}\ |F|^n} \quad (11)$$

The above mentioned fundamental equations will be simplified by replacing the elastic modulas Aij by the orthotropic structural system as $Aij = Ai\ \delta ij$, and by defining the nondimensional form as $ai = Ai/A$, $bi = Mi/B = Mi/\sqrt{A/(\beta + \gamma)}$.

$$\dot{m}i = A\ [\ \delta ij - \frac{\frac{ai}{bi^2} mimj}{\frac{ak}{bk^2} mkmk + \frac{[A - \{\beta\ \mathrm{sgn}\ (\ \dot{U}F\ ) + \gamma\}\ (mkmk)^{n/2}\ ]}{\{\beta\ \mathrm{sgn}\ (\ \dot{U}F\ ) + \gamma\}\ (mkmk)^{n/2-1}}}]\ \dot{u}j \quad (12)$$

where the potential function is supposed to be

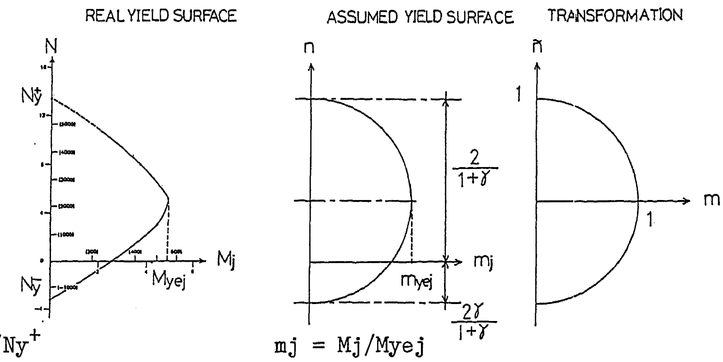
$$F = \mathrm{sgn}\ F(\frac{Mk}{bk} \frac{Mk}{bk})^{1/2} = \mathrm{sgn}\ F\ (mk\ mk)^{1/2} \quad (13)$$

and nondimensional force $mk=Mk/bk$ and the corresponding deformation $uk = Uk/(bk/ak)$ are introduced. Only when $n = 2$ and elastic limit potential energy is equal each other, the above eq.(12) reduces to the equation presented by Park, Y.J. et al. [Ref.2].

$$\dot{m}i = [A\ \delta ij - (mk\ mk)^{n/2-1} \{\beta\ \mathrm{sgn}\ (\ \dot{U}F\ ) + \gamma\}\ mimj]\ \dot{u}j \quad (14)$$

Dynamic Axial Force Typical interaction curve between axial force and bending moment of reinforced concrete column is shown in Fig.1(a). Assuming the interaction curve of such a column like a cubic in equation (11) and transforming the nondimensional axial force n to $\tilde{n}$ in Fig. 1(c), time dependent nondimensional relationship between force and deformation can be given as follows :

$$\begin{Bmatrix} \dot{m}x \\ \dot{m}y \\ \dot{m}n \end{Bmatrix} = \begin{bmatrix} 1 - \Lambda \frac{ax}{bx^2} mx^2 & - \Lambda \frac{ax}{bx^2} mxmy & - \Lambda \frac{ax}{bx^2} mxmn \\ - \Lambda \frac{ay}{by^2} mymx & 1 - \Lambda \frac{ay}{by^2} my^2 & - \Lambda \frac{ay}{by^2} mymn \\ - \Lambda \frac{an}{bn^2} mnmx & - \Lambda \frac{an}{bn^2} mnmy & 1 - \Lambda \frac{an}{bn^2} mn^2 \end{bmatrix} \begin{Bmatrix} \dot{u}x \\ \dot{u}y \\ \dot{u}n \end{Bmatrix} = [k(T)]\{\dot{u}_j\} \tag{15}$$



$\gamma = Ny^-/Ny^+$ $\quad$ $mj = Mj/Myej$

$N_0 = (Ny^+ + Ny^-)/2$ $\quad$ $n = N/N_0$ $\quad$ $\tilde{n} = n - \frac{1-\gamma}{1+\gamma}$

$F = F(Mx, My, Mn)$ $\quad$ $f' = (mx2 + my2 + (n - \frac{1-\gamma}{1+\gamma})^2)^{1/2}$ $\quad$ $f = (mx2 + my2 + \tilde{n}2)^{1/2}$

Fig.1 Relationship between Axial Force and Bending Moments

Equations of Motion By introducing the above relationship into a constitutive equation of individual members like elasto-plastic joints with finite length of the end of members (Ref.4), earthquake responses of space structures subjected to multi-directional ground motion can be calculated by using following equations :

$$([A]\frac{d^2}{dt^2} + [B]\frac{d}{dt} + [C])\{V\} + [D]\{M\} = -[A]\{F(T)\} \tag{16}$$

$$\{M\} = [F1]\{\theta\} + [F2]\{V\} + [F3]\{U\} \tag{17}$$

$$\{\dot{M}\} = [K(T)]\{\dot{U}\} \quad (18), \qquad [G]\{M\} = \{0\} \quad (19)$$

RESPONSES OF R-O TYPE STRUCTURES

In our previous paper (Ref.5), some responses of space structures subjected to two components of El Centro wave form were shown, where general interaction effects could not be obtained, because of frequency characteristics of input ground motion. Here, average values of maximum displacements and total energy dissipation of space structure with Ramberg-Osgood hysteresis are shown in Fig.2. Nine pairs of wave forms which were produced by three kinds of white noise with the exponential envelope function were used for bi-directional ground motion. When the frequency ratio of X-axis to Y-axis of space structure become large, maximum displacement responses as well as final total dissipated energy become large and displacement responses under bi-directional motion become 1.0 - 2.0 times larger than the responses under uni-directional motion. On the other hand, total dissipated energy is quite similar to the same responses under uni-directional motion.

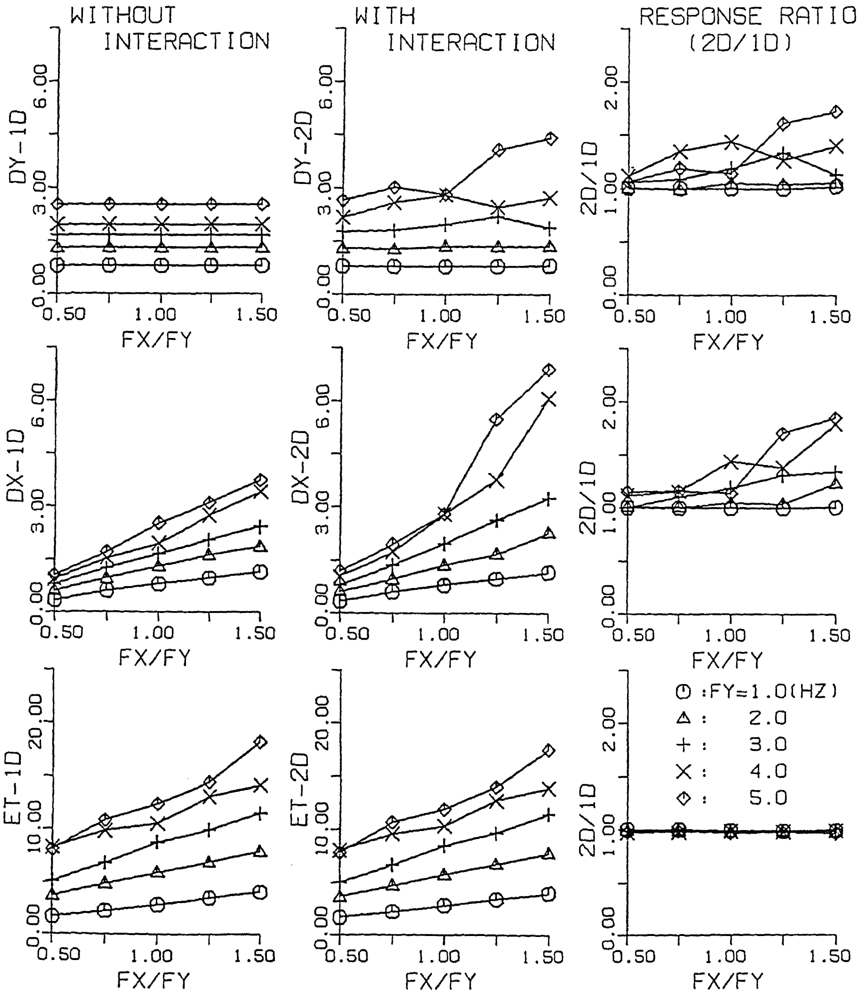


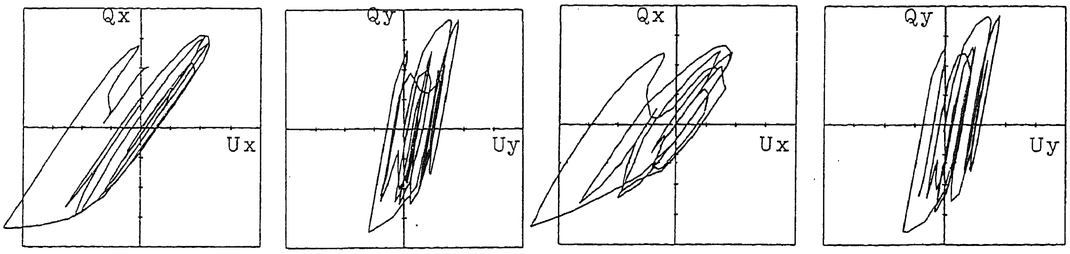
Fig.2 Average Responses of Space Structures by Using Ramberg-Osgood Model

RESPONSES OF WEN TYPE STRUCTURES

Two types of the hysteretic characteristics are used here. One is the hysteresis introducing from the plasticity theory presented here and the other is the hysteresis presented by Park et al., that is, the hysteresis corresponding to the same elastic limit potential energy in both axes.

The model structures considered here have same strength and different frequency in each direction of single story space frame. Other parameters of structures are constant, that is, $h = 0.02$, $\alpha = 0.1$, $\beta = \gamma = 0.5$, $n=2$ and $\delta_A = 0$ or 0.03, which designates a parameter of deterioration due to energy dissipation (Ref.2). Nine pairs of bi-directional ground motion are considered here, the predominant frequency of which are assumed to be same as the fundamental frequency of X-axis of the structure.

Figure 3 shows two types of typical restoring force characteristics in both axes; modified Wen type and Wen type hysteresis. As shown in Fig.3, restoring force characteristics resemble to each other in global sense in spite of small difference between two types of hysteresis in detail. Average values of displacement responses of space structures with/without interaction subjected to filtered white noise are shown in Fig.4. Average responses of structures having two types of hysteresis are similar in this deterministic analysis. Interaction



(a) MODIFIED WEN TYPE HYSTERESIS (b) WEN TYPE HYSTERESIS

Fig.3 Hysteresis of Modified Wen's Formulation and Wen's Formulation

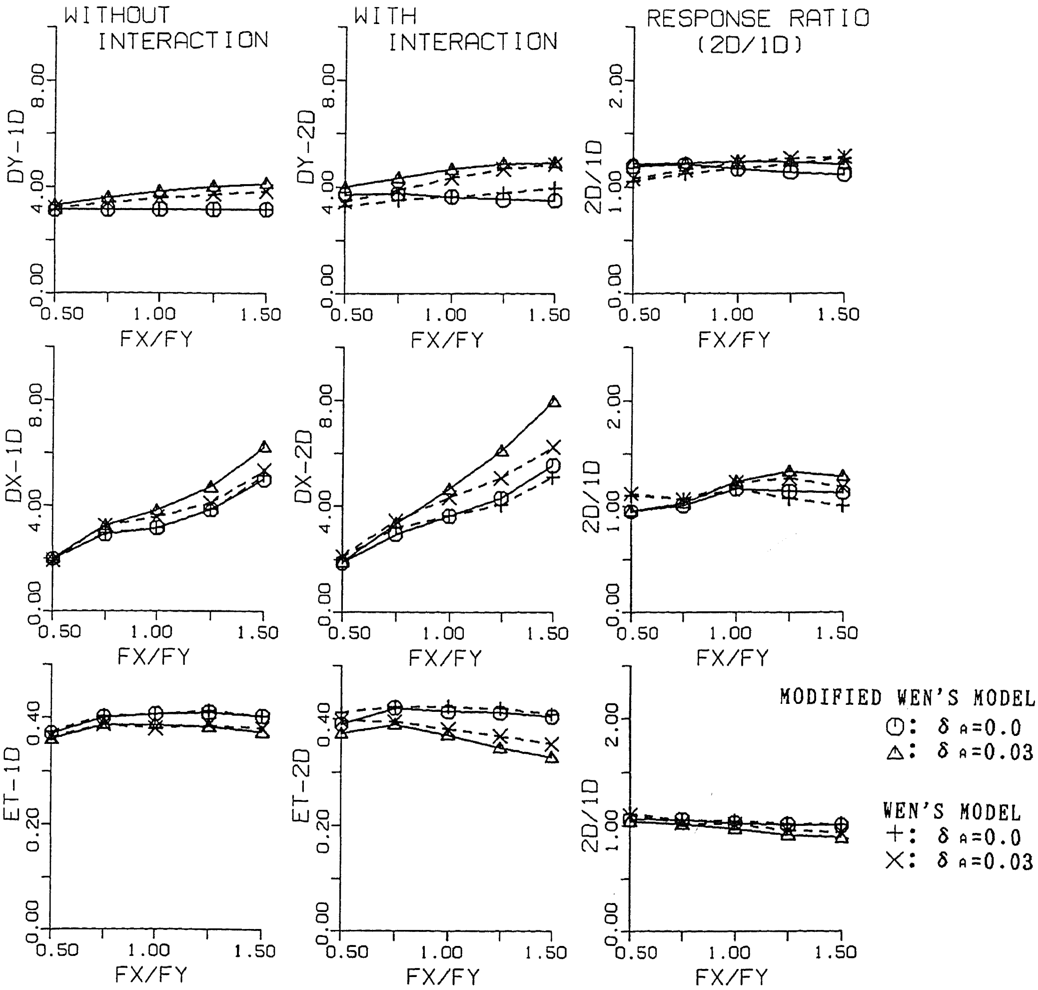


Fig.4 Average Responses of Space Structure by Using Wen's Model

effect is supposed to depend on the strength ratio of structures to input motion and on the stiffness ratio of both axes. In this case, maximum response considering interaction becomes 1.2 - 1.4 times greater than the response without interaction. And effect of frequency ratio is not so remarkable but has a tendency to increase the response in weak stiffness axis. Deterioration of hysteresis affects on the maximum response, considerably. It is noted that such members must possess enough deformation capacity. General remarks of the interaction effect are represented in the reference 7, where random responses are obtained by using Wen type hysteresis.

GENERAL DISCUSSIONS AND CONCLUDING REMARKS

As shown in previous paper (Refs.8,9), it is necessary to design column strengths 1.2 - 1.4 times larger than beam strength for maintaining column response of plane frame structures in elastic region. It depends on the higher mode frequency of structures as well as frequency characteristics of ground motion. When considering the interaction of multi-axial forces, the above mentioned strength ratio is supposed to become more larger in the case of space structures.

Interaction effects on the displacement responses of space structures subjected to not only oblique motion but bi-directional ground motion (Ref.3) are very remarkable, especially in the direction of weak stiffness or strong strength where the responses under uni-directional motion are smaller than that of the perpendicular direction. It is noted that such members subjected to multi-axial forces as base columns have to possess appropriate deformation capacity. On the other hand, hysteretic energy dissipation with or without interaction is quite similar each other. It may be effective to use this fact on the structural design. Deterioration of hysteresis is also taken care of designing the structural members. The responses become larger according to the repetition of plastic behavior. The effect of the dynamic axial force may be also important for the aseismic safety of R/C column members and to be discussed in near future.

ACKNOWLEDGEMENTS

We express our sincere thanks to Prof. Wen, Y.K., Univ. of Illinois, Minai, R. and Suzuki, Y., D.P.R.I. Kyoto Univ. for their valuable suggestions and discussions. Contributions of Mr. Yu, D.M. and Miss Hosotani, M. for preparing this manuscript are also appreciated.

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