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

7-4-9

SEISMIC DESIGN FOR MULTISTORY BUILDINGS WITH ECCENTRICITY SUBJECTED TO TWO-DIRECTIONAL GROUND MOTIONS

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SUMMARY

A practical seismic design method for multistory buildings with eccentricity is proposed based on linear and non-linear dynamic analysis for building models subjected to ground motions in the x- and y-directions, simultaneously.

Damage prediction is evaluated based on the proposed shear and torsional capacity and the design shear force and torsional moment for each story of the buildings.

INTRODUCTION

The practical seismic design method for multistory buildings with eccentricity is not established because of the complexity of linear and non-linear response analysis.

This paper deals with a practical design method for multistory buildings with eccentricity subjected to ground motions in the x- and y-directions considering the damage prediction for each story of the buildings.

STRONG EARTHQUAKE GROUND MOTIONS

Modified ground motions have the predominant period T_G=0.4 sec. and the stationary duration T_D=20 sec. in average. The linear response spectrum for single-degree-of-freedom systems with damping ratio ξ=0.05 is shown in Fig. 1, which is the average computed by a step-by-step time integration response analysis using 20 artificial earthquake ground motions. The response values are approximately proportional to 1/T, when the fundamental natural period T of the system is longer than the predominant period T_G of ground motions.

In seismic response analysis, linear and non-linear building models with eccentricity are investigated by using 20 pairs of the different combination of the above-mentioned artificial earthquake ground motions in the x- and y-directions, simultaneously.

$$
\left[\begin{array}{ccc|ccc|ccc}
M_n & & & & & & & & \\
 & M_n & & & & & & & \\
 & & I_n & & & & & & \\
\hline
 & & & M_i & & & & & \\
 & & & & M_i & & & & \\
 & & & & & I_i & & & \\
\hline
 & & & & & & M_1 & & \\
 & & & & & & & M_1 & \\
 & & & & & & & & I_1
\end{array}\right]
\left\{\begin{array}{c}
\ddot{x}_n \\ \ddot{y}_n \\ \ddot{\theta}_n \\ \ddot{x}_i \\ \ddot{y}_i \\ \ddot{\theta}_i \\ \ddot{x}_1 \\ \ddot{y}_1 \\ \ddot{\theta}_1
\end{array}\right\}
+
\left[\begin{array}{c|c|c}
K_A & K_B & K_C \\
\hline
K_B^T & K_D & K_E \\
\hline
K_C^T & K_E^T & K_F
\end{array}\right]
\left\{\begin{array}{c}
x_n \\ y_n \\ \theta_n \\ x_i \\ y_i \\ \theta_i \\ x_1 \\ y_1 \\ \theta_1
\end{array}\right\}
= 0 \qquad \cdots\cdots (1)
$$

where

$$
K_A = \begin{bmatrix} K_{xn} & 0 & -K_{xn} f_{yn} \\ & K_{yn} & K_{yn} f_{xn} \\ S_{ym.} & & K_{xn} f^2_{yn} + K_{yn} f^2_{xn} + K\theta_n \end{bmatrix}, \quad
K_B = \begin{bmatrix} -K_{xn} & 0 & K_{xn} f^{yn-1} \\ 0 & -K_{yn} & -K_{yn} f^{xn-1} \\ K_{xn} f_{yn} & -K_{yn} f_{xn} & -K_{xn} f_{yn} f^{yn-1} - K_{yn} f_{xn} f^{xn-1} - K\theta_n \end{bmatrix}
$$

$$
K_C = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad
K_D = \begin{bmatrix} K_{xi+1} + K_{xi} & 0 & -K_{xi+1} f^{yi} - K_{xi} f_{yi} \\ & K_{yi+1} + K_{yi} & K_{yi+1} f^{xi} + K_{yi} f_{xi} \\ S_{ym.} & & K_{xi+1} (f^{yi})^2 + K_{yi+1} (f^{xi})^2 + K\theta_{i+1} + K_{xi} (f_{yi})^2 + K_{yi} (f_{xi})^2 + K\theta_i \end{bmatrix}
$$

$$
K_E = \begin{bmatrix} -K_{xi} & 0 & K_{xi} f^{yi-1} \\ 0 & -K_{yi} & -K_{yi} f^{xi-1} \\ K_{xi} f_{yi} & -K_{yi} f_{xi} & -K_{xi} f_{yi} f^{yi-1} - K_{yi} f_{xi} f^{xi-1} - K\theta_i \end{bmatrix}, \quad
K_F = \begin{bmatrix} K_{x2} + K_{x1} & 0 & -K_{x2} f^{y1} - K_{x1} f_{y1} \\ & K_{y2} + K_{y1} & K_{y2} f^{x1} + K_{y1} f_{x1} \\ S_{ym.} & & K_{x2}(f^{y1})^2 + K_{y2}(f^{x1})^2 + K\theta_2 + K_{x1}(f_{y1})^2 + K_{y1}(f_{x1})^2 + K\theta_1 \end{bmatrix}
$$

$$\cdots\cdots (2)$$

Gi : Center of gravity in i story
Ci : Center of rigidity in i story
Kxi: Rigidity in x-direction in i story
Kyi: Rigidity in y-direction in i story
$K_{\theta i}$: Torsional rigidity in i story
Mi : Mass in i story
Ii : Moment of inertia in i story

f_{xi}, f_{yi}: Eccentric distance in x- or y-direction in i story
f^{xi}, f^{yi}: Distance in x- or y-direction between center of gravity in i story and center of rigidity in i+1 story

RESPONSE ANALYSIS FOR BUILDING MODELS

For the reason of simplicity, the following assumptions are used for the earthquake response analysis of building models with eccentricity.

1) Buildings with eccentricity are represented by shear-type multistory building models with a rigid floor diaphragm in each story.

2) Horizontal rigidity and strength of each vertical member of the building models are independent in the x- and y-directions, respectively, regardless of

the intensity and direction of the external horizontal forces acting on the models, because of the limilation of computer capacity.

3) Each vertical member has sufficient ductility and deformation capacity with origin-oriented and elasto-plastic restoring force characteristics with 5% damping as shown in Fig. 2 and Fig. 3, respectively.

Fig. 4 illustrates a building model with two-axes eccentricity. The equation of motion (undamped free vibration) and the elastic stiffness matrix K are shown in Eqs. (1) and (2). For the response analysis of building models, a step-by-step integration method (linear acceleration method) is used.

STORY STRENGTH RATIOS eRx AND eRy FOR BUILDING MODELS WITH ECCENTRICITY

For multistory buildings, story strength ratios Rx and Ry to reasonable linear design story shear forces in the x- and y-directions are the reasonable and approximate measurement to predict the damage concentration when they are subjected to severe earthquake motions.

$$R_x = \frac{Q_{Px}}{Q_{Lx}}, \quad R_y = \frac{Q_{Py}}{Q_{Ly}} \tag{3}$$

where Q_{Px} and Q_{Py} are the strength of each story in the x- and y-directions, and Q_{Lx} and Q_{Ly} are the linear design shear forces of the corresponding story in the x- and y-directions, respectively, when such buildings are assumed to be elastic without yielding.

The above-mentioned concepts can be extended to multistory buildings with eccentricity by using story strength ratios eRx and eRy with torsional effect corresponding to each story of the buildings.

Fig. 5 shows an m x n frame floor plan of a multistory building with two-axes eccentricity in the x- and y-directions and the replaced 2 x 2 frame building model considering the story structural properties of the building with eccentricity. In the replacement of m x n frame model to 2 x 2 frame model, the consideration for torsional rigidity of the models is not included. The torsional effect due to torsional rigidity is considered as additional eccentricity in design of building models.

In Fig. 5,

Q: Center of design shear force G: Center of gravity
S: Center of story strength

$$Q_{Px1}\cdot l_{y1} = Q_{Px2}\cdot l_{y2}, \quad Q_{Py1}\cdot l_{x1} = Q_{Py2}\cdot l_{x2} \tag{4}$$

fx, fy: Distances between the center of design shear force Q and the center of story strength S in the x- and y-directions, respectively.
lx, ly: Plan dimensions of the replaced 2 x 2 frame buildings in the x- and y-directions, respectively.
Q_{Pxi}, Q_{Pyi}: Shear strength of xi and yi shear resisting frames in the 2 x 2 frame building, respectively (i = 1, 2)

The torsional story strength ratios eRx and eRy which correspond to the values of story strength/linear design shear forces in the x- and y-directions can be defined as follows, by using shear and torsional capacity and design shear force and torsional moment surface as illustrated in Fig. 6.

$$eR_x = OA/OA' \sim OC/OC', \quad eR_y = OC/OC' \sim OE/OE'$$

In Fig. 6,

$$\left.\begin{aligned} Q_{Px} &= Q_{Px1} + Q_{Px2} \\ Q_{Py} &= Q_{Py1} + Q_{Py2} \end{aligned}\right\} \text{Shear capacity}$$

$$T_{P\theta} = Q_{Py1} \cdot l_x + Q_{Px1} \cdot l_y \cdots\cdots \text{Torsional capacity}$$

$$\left.\begin{aligned} Q_{Lx} &= Q_{Lx1} + Q_{Lx2} \\ Q_{Ly} &= Q_{ly1} + Q_{Ly2} \end{aligned}\right\} \text{Design shear forces}$$

$$\left.\begin{aligned} T_{Lx} &= Q_{Lx} \cdot f_y \\ T_{Ly} &= Q_{Ly} \cdot f_x \end{aligned}\right\} \text{Design torsional moments} \qquad (5)$$

If the shear strength Q_{Px} and Q_{Py} of the x and y shear resisting frames are independent, regardless of two directional non-linear response due to two directional ground motions, the torsional story strength ratios e_{Rx} and e_{Ry} can be approximated as follows,

$$e_{Rx} = \frac{1}{2}\left\{ \frac{1}{\frac{|T_{Lx} - 0.5\ T_{Ly}|}{T_{P\theta}} + \frac{Q_{Lx}}{Q_{Px}}} + \frac{1}{\frac{T_{Lx} + 0.5\ T_{Ly}}{T_{P\theta}} + \frac{Q_{Lx}}{Q_{Px}}} \right\}$$

$$e_{Ry} = \frac{1}{2}\left\{ \frac{1}{\frac{|T_{Ly} - 0.5\ T_{Lx}|}{T_{P\theta}} + \frac{Q_{Ly}}{Q_{Py}}} + \frac{1}{\frac{T_{Ly} + 0.5\ T_{Lx}}{T_{P\theta}} + \frac{Q_{Ly}}{Q_{Py}}} \right\} \qquad (6)$$

ADDITIONAL ECCENTRICITY DUE TO TORSIONAL EFFECT

Additional eccentricity due to torsional effect is examined by linear response analysis using single story building models with one-axix eccentricity.

Fig. 7 shows additional eccentricity f_x' for various values of j',

where $j' = \frac{j}{i}$, $j = \sqrt{\frac{K_\theta}{K_x}}$, $i = \sqrt{\frac{I}{M}}$, when $j' > 1.0$, max. $\frac{f_x'}{i} \fallingdotseq 0.4$ (7)

For this reason, ten percent (10%) times the maximum x and y plan dimensions in each story are used as the additional eccentricity, regardless of the direction of applied design shear forces for multistory building models as well as single-story building models with eccentricity, considering safe side approximation.

NON-LINEAR RESPONSE OF BUILDING MODELS WITH ECCENTRICITY

Non-linear response analysis is carried out to compare response values of two story building models with one-axis eccentricity with the corresponding values of two story building models without eccentricity.

The two story standard building model without eccentricity is shown in Table 1. Two story building models with eccentricity are divided into two types of models as follows.

Type 1 1st story with eccentricity, 2nd one without eccentricity
Type 2 1st story without eccentricity, 2nd one with eccentricity

Story plan with various arrangements of eccentricity with respect to the story rigidity as well as the story strength is shown in Table 2.

The maximum plastic deformation of the weak frame in each story of the building models with eccentricity having the story strength ratios eRx and eRy are compared with the corresponding values in the building models without eccentricity having the same elastic story rigidities Kx and Ky and the same story strength ratios Rx and Ry in Fig. 8 and Fig. 9, respectively.

CONCLUSION

It is confirmed that severe damage is observed in a particular story with the minimum strength ratio based on the shear and torsional capacity and the linear design shear force and torsional moment surface for each story of the buildings with eccentricity.

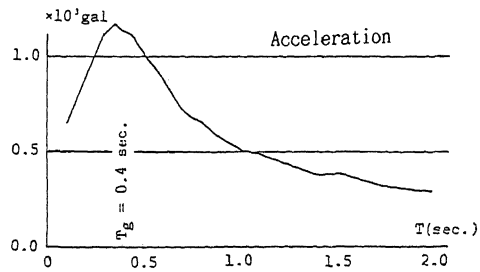


Fig. 1 Response spectrum

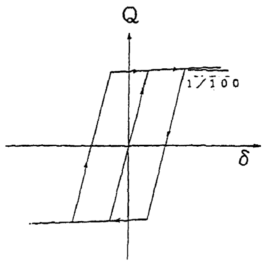


Fig.2 Elasto-plastic

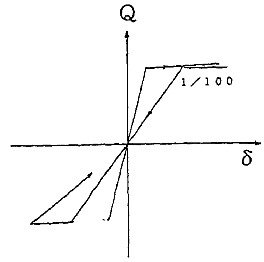


Fig.3 Origin-oriented

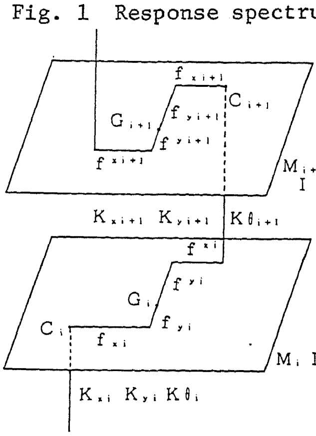


Fig. 4 Building model

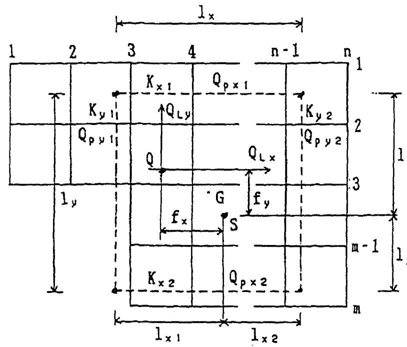


Fig. 5 Floor plan

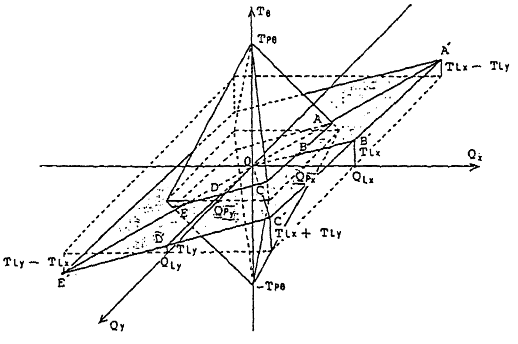


Fig. 6 Shear and torsional capacity and design force surface

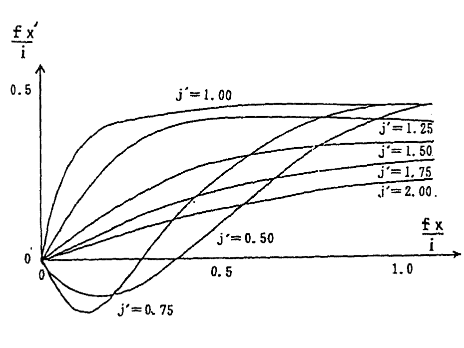
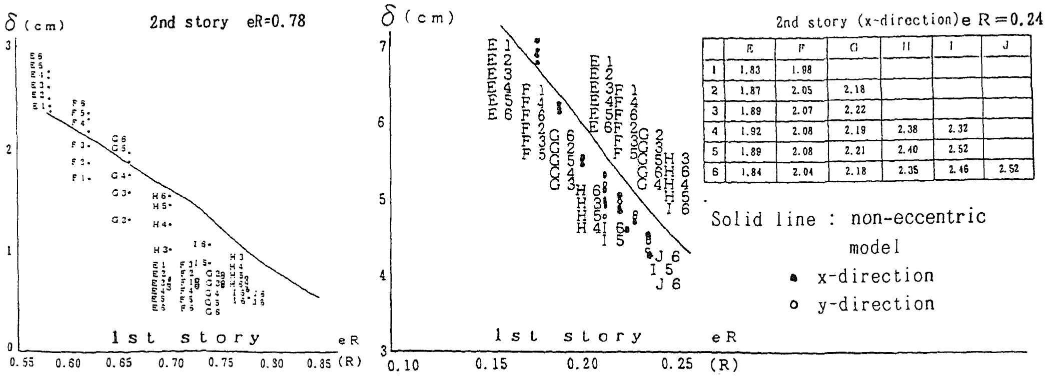


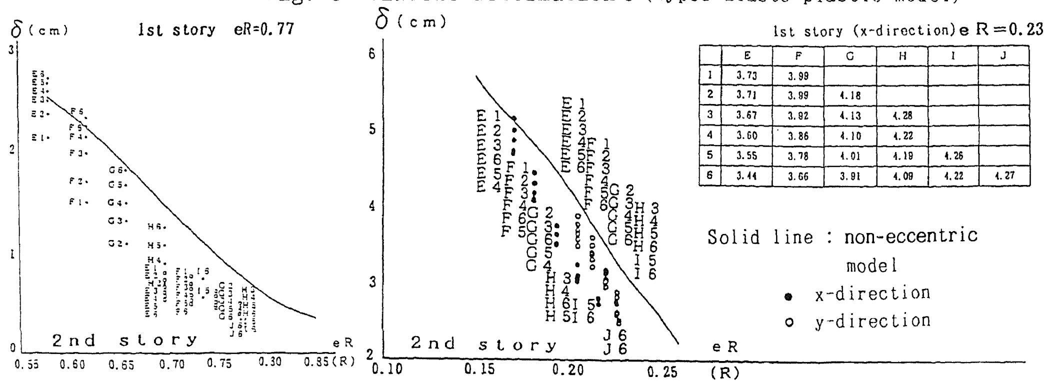
Fig. 7 Additional eccentricity f'x



2nd story (x-direction) eR=0.24

	E	F	G	H	I	J
1	1.83	1.98				
2	1.87	2.05	2.18			
3	1.89	2.07	2.22			
4	1.92	2.08	2.19	2.38	2.32	
5	1.89	2.08	2.21	2.40	2.52	
6	1.84	2.04	2.18	2.35	2.46	2.52

Fig. 8 Plastic deformation δ (Type1 Elasto-plastic model)



1st story (x-direction) eR=0.23

	E	F	G	H	I	J
1	3.73	3.99				
2	3.71	3.99	4.18			
3	3.67	3.92	4.13	4.28		
4	3.60	3.86	4.10	4.22		
5	3.55	3.78	4.01	4.19	4.26	
6	3.44	3.66	3.91	4.09	4.22	4.27

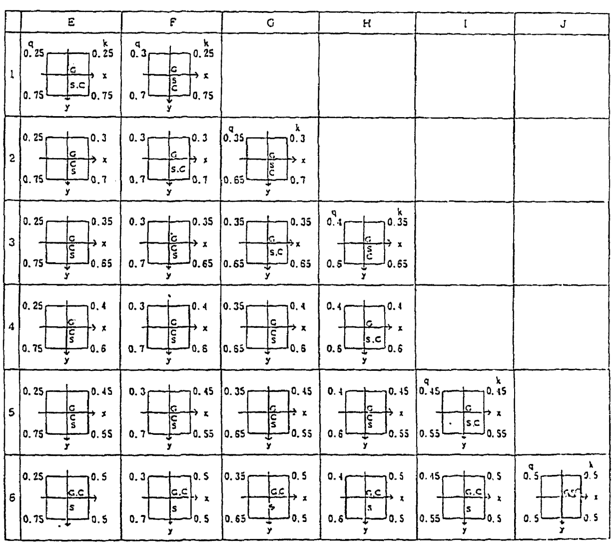
Fig. 9 Plastic deformation δ (Type2 Elasto-plastic model)

Table 1 Standard model

	Lx=Ly (cm)	M ($t \cdot sec^2/cm$)	I ($t \cdot sec^2/cm$)	Kx=Ky (t/cm)	$Q_{Lx}=Q_{Ly}$ (t)
2	800.0	0.1	10667	41.34	118.55
1	800.0	0.1	10667	41.34	191.19

Natural period of model T_n = 0.5 sec.

Table 2 Arrangements of rigidity and strength



G : Center of gravity
C : Center of rigidity
S : Center of strength
q : Normalized frame capacity
k : Normalized frame rigidity