

Bidirectional behavior of R/C weak model structure

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ABSTRACT: Since August in 1983, the authors have carried out an earthquake response observation of R/C model structures to natural earthquakes, and more than 150 sets of response records are obtained. This paper describes the bidirectional horizontal behavior of weak-beam model structure and the adequacy of safety factors for simultaneous seismic actions recommended in the seismic design guideline for R/C buildings developed in 1990.

1 INTRODUCTION

In a structural design, seismic forces are usually assumed to act independently in the direction of each principal axis of a structure. This assumption is very simple and convenient for the structural design practice. Actual behavior of structures during earthquakes is, however, very complicated and simultaneous seismic actions may have significant effects on their structural performance. From this point of view, the Architectural Institute of Japan developed the "Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept (referred to as "AIJ Guideline" hereafter)" in 1990, where safety factors to allow for the simultaneous seismic actions are introduced based on the experimental and/or analytical investigations. Most of them are, however, based on laboratory tests or mathematical models, and few investigations to natural earthquakes have been reported.

Since August in 1983, the authors have

carried out an earthquake response observation to natural earthquakes using 1/3 to 1/4 scaled five-storied R/C specimens with approximately half of the design base shear for existing R/C buildings in Japan. Based on observation results, this paper discusses the bidirectional horizontal behavior of the weak-beam model structure and the adequacy of safety factors for simultaneous seismic actions recommended in AIJ Guideline.

2 OUTLINE OF WEAK-BEAM MODEL STRUCTURE

Two five-storied R/C frame structures, one is a so called "weak-column and strong-beam structure" and the other "weak-beam and strong-column structure", have been used for the response observation. The outline of the weak-beam model structure is shown in Fig. 1. Inter-story displacements, response accelerations in three directions, strains of reinforcement etc. are measured. Each member was designed to fail in a ductile manner. The model structures are called "weak model

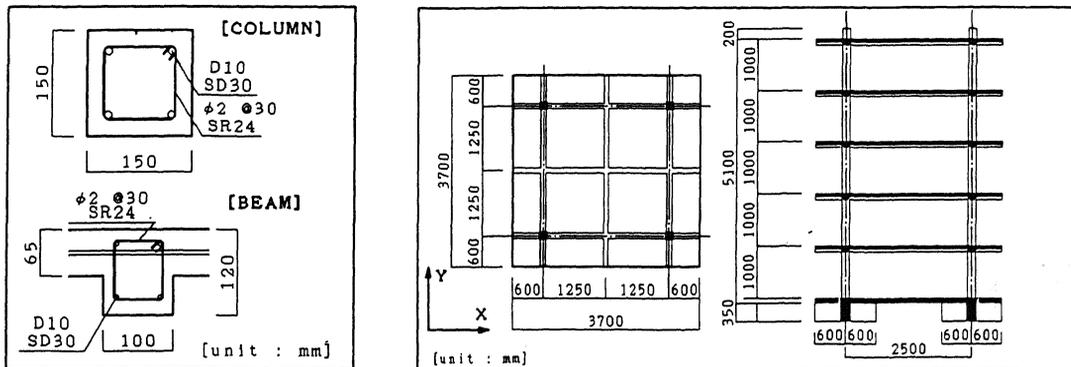


Fig. 1. Outline of weak-beam model structure

structures" because they are designed as weak as possible so that they may sustain damages due to moderate earthquakes. Calculated strength of weak-beam model structure is about 0.19 in terms of base shear coefficient when the slab system within 10% of the span length is assumed effective to beam strength according to the seismic design standard of R/C buildings in Japan, and about 0.30 when all slab system is assumed effective.

3 EARTHQUAKE RESPONSE RESULTS OF WEAK-BEAM MODEL STRUCTURE

Since the observation started in 1983, more than 150 sets of response records are obtained. Listed in the following are three major earthquakes and corresponding damages to the weak-beam model structure. Table 1 summarizes the characteristics of these earthquakes. Fig. 2 shows the observed responses to these three earthquakes.

During the earthquake on October 4, 1985 (referred to as "EQ1985" hereafter), the second largest response acceleration was recorded, and the specimen was slightly damaged. During the earthquake on June 24, 1986 (referred to as "EQ1986" hereafter), the second largest response displacement was recorded, and propagation of cracks due to prior earthquakes was observed. During the earthquake on December 17, 1987 (referred to as "EQ1987" hereafter), the largest response

was recorded since the observation started. Maximum inter-story drift was approximately 1%, and yielding of re-bars in beams of the weak-beam model structure was confirmed from the measured strains and base shear

	EQ1985	EQ1986	EQ1987
Magnitude	6.1	6.5	6.7
Epicentral Distance (km)	30	111	45
Focal Depth (km)	78	73	58
Intensity ¹⁾	IV (VII)	IV (VII)	V (VIII)
Max. Ground Acceleration	NS	70	51
EW	83	53	223
at GL -1m (gal)	UD	28	—
Max. Drift Angle ²⁾	1/665(2)	1/675(2)	1/100(2)

1) in JMA Scale (in MM Scale) at the specimen site
2) values in parentheses indicates the recorded story

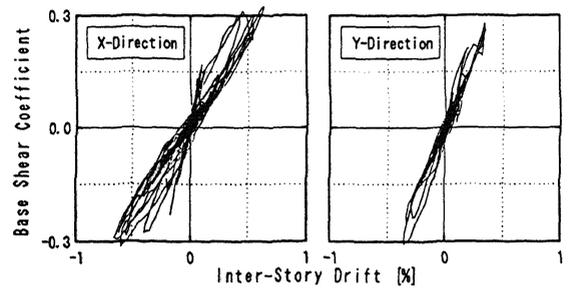


Fig. 3. Response of weak-beam model structure to EQ1987 in the first story

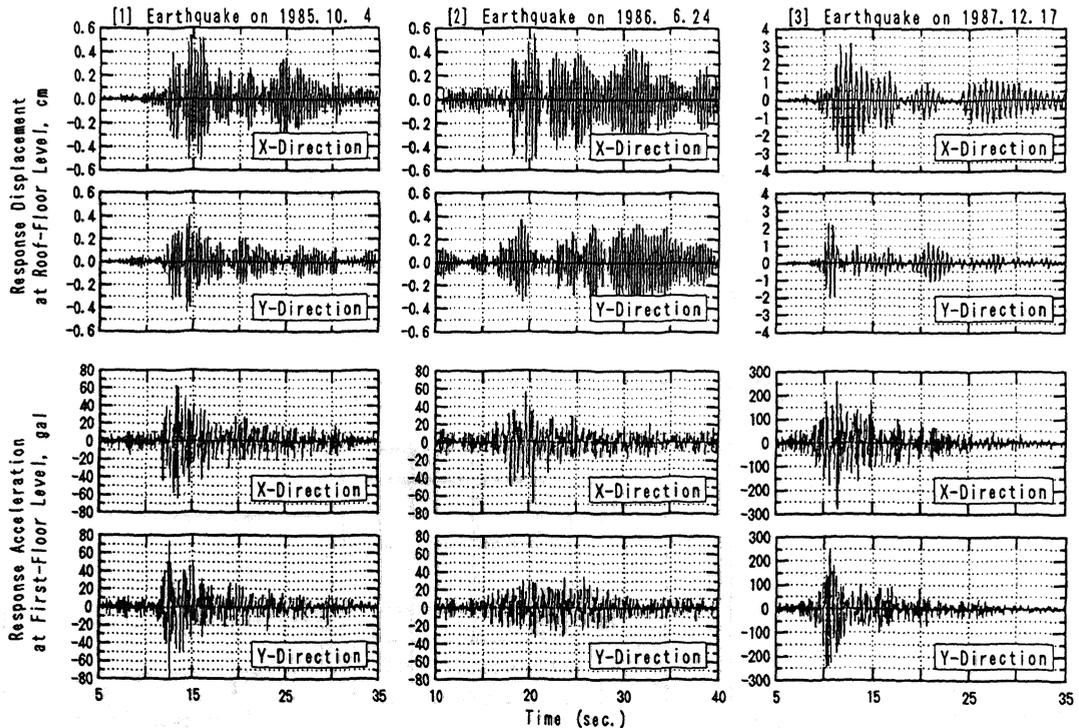


Fig. 2. Response of weak-beam model structure to three major earthquakes

coefficient vs. displacement relationship as shown in Fig. 3. The specimen sustained many cracks and was classified into "moderate" to "severe" damage level according to the damage classification usually used in Japan.

4 BIDIRECTIONAL HORIZONTAL RESPONSE CHARACTERISTICS OF WEAK-BEAM MODEL STRUCTURE

In AIJ Guideline developed in 1990, safety factors to allow for the bidirectional seismic actions were introduced so that a structure subjected to a strong ground motion might fail in a ductile manner as expected in the structural design. The adequacy of the safety factors is discussed hereafter based on the response observation results.

4.1 Response inter-story displacement

Fig. 4 shows the orbit of inter-story displacements of a story where the maximum response was recorded. The bidirectional behavior of the specimen varies depending on the earthquake motion. The maximum displacements in each direction tend to coincide during EQ1985 and EQ1986 while the specimen tends to oscillate along the each principal axis during EQ1987, i.e. the simultaneity of maximum inter-story displacement of the specimen in each direction was less significant during EQ1987 than during the others.

4.2 Response story shear force

The design shear force for columns in each story of the direction considered, V_{Di} , is specified by Eq. (1) in AIJ Guideline, where factors $\Delta\omega_i$ and ϕ_2 are introduced to allow for the discrepancy of dynamic seismic actions in columns from static actions and the effect by simultaneous actions in the transverse direction, respectively. In AIJ Guideline, $\phi_2 = 0.1$ is taken when a structure is designed to fail in beams, based on the assumption that 50% of the seismic actions in the transverse direction may act simultaneously (see Fig. 5(a)). Fig. 5(b) shows the magnification ratios of shear forces, β_i , due to simultaneous actions during EQ1987, defined by Eq. (2). The value of $(\beta_i - 1)$, which may correspond to ϕ_2 in Eq. (1), is 0.11 in the third story and almost equal to the value of 0.1 proposed in AIJ Guideline. It should be noted, however, that the value of 0.1 may be insufficient because the simultaneity of maximum responses in each principal axis was less significant during EQ1987.

$$V_{Di} = (1.0 + \Delta\omega_i + \phi_2) \times V_{Si} \quad (1)$$

$$\beta_i = (V_{Ri} / V_{Ui} - \Delta\omega_i) \quad (2)$$

i : story level

V_{Di} : design shear force of columns

V_{Si} : shear strength of columns required from a static lateral design force in the direction considered

V_{Ri} : time-varying bidirectional response story shear force ($= \sqrt{V_{xi}^2 + V_{yi}^2}$, V_{xi} and V_{yi} are calculated from mass and recorded accelerations in each principal axis)

V_{Ui} : story shear force at the ultimate stage when subjected to a inverted-triangularly distributed lateral force unidirectionally

4.3 Earthquake induced axial force

Fig. 6(a) shows the time history of earthquake induced axial forces in the first

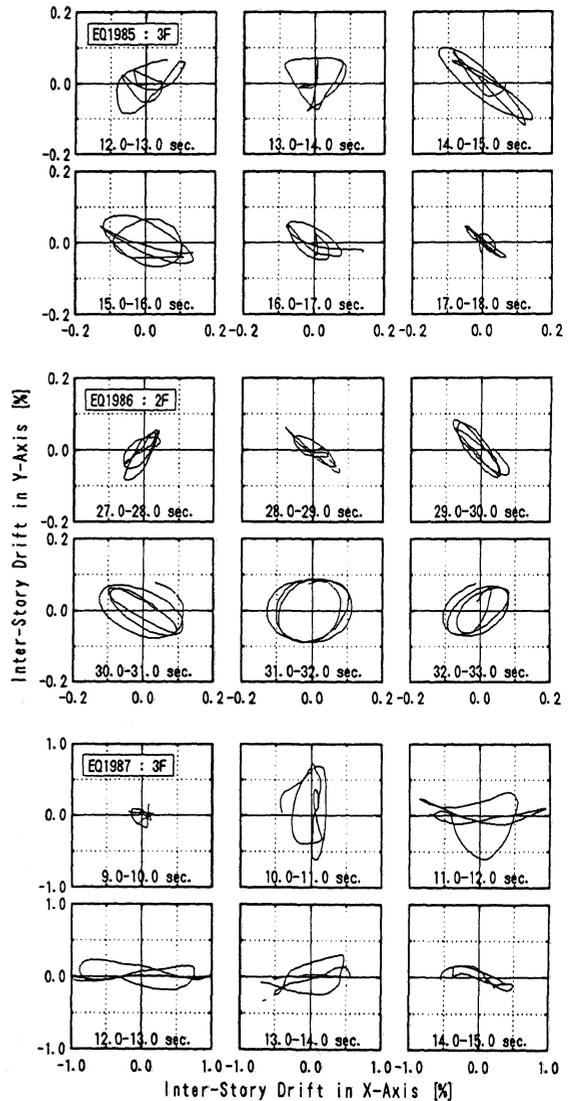


Fig. 4. Orbit of response inter-story displacement

story normalized by $(A_c \times f_c')$, where A_c and f_c' are the column sectional area and nominal strength of concrete, respectively. The discrepancy of earthquake induced axial force level due to these three earthquakes is not significant although the ground acceleration of EQ1987 was much larger than the others. This is because the specimen mainly oscillated along the principal axis during EQ1987.

Fig. 6(b) shows the contribution of the axial force in the first story in the transverse direction to that in the direction considered, γ , calculated from Eq. (3). The design axial force due to seismic forces ΔP_D is proposed in AIJ Guideline to consider 50% of the maximum earthquake induced axial force in the transverse direction in addition to that in the direction considered, as shown in Eq. (4). The factor γ is 85% to EQ1985 and 65% to EQ1986 and larger than 50% recommended in AIJ Guideline. This result reveals that the assumption in AIJ Guideline may not be conservative. It should be noted, however, that γ should be determined considering not only the simultaneity but also the axial force level and the effects by higher-order-mode vibration, and further investigations are necessary for a rational safety factor γ .

$$\gamma = (\Delta P_x + \Delta P_y - \Delta P_{max}) / \Delta P_{Tmax} \quad (3)$$

$$\Delta P_D = \Delta P + 0.5 \times \Delta P_T \quad (4)$$

$\Delta P_x, \Delta P_y$: earthquake induced axial forces in X- and Y-axis, respectively

$\Delta P_{max}, \Delta P_{Tmax}$: maximum value of ΔP and ΔP_T , respectively

$\Delta P, \Delta P_T$: earthquake induced axial force in the direction considered and in the transverse direction, respectively

5 CONCLUDING REMARKS

Bidirectional horizontal response character-

istics varied depending on the ground motion, and the simultaneity of maximum responses in each principal axis due to EQ1987 was less significant than due to the others.

The maximum value of $(\beta-1)$ due to simultaneous story shear force during EQ1987 was almost equal to the value of $\phi_2 = 0.1$ recommended in AIJ Guideline. However, this value may not be conservative because the simultaneous responses during EQ1987 was less significant than those during the others.

The contribution factor γ of earthquake induced axial forces in the transverse direction due to EQ1985 and EQ1986 exceeded 50% recommended in AIJ Guideline. However, it should be noted that γ should be determined considering not only the simultaneity but also the axial force level and the effects by higher-order-mode vibration, and further investigations are necessary for a rational safety factor γ .

REFERENCE

Architectural Institute of Japan 1990. Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept (AIJ Guideline).

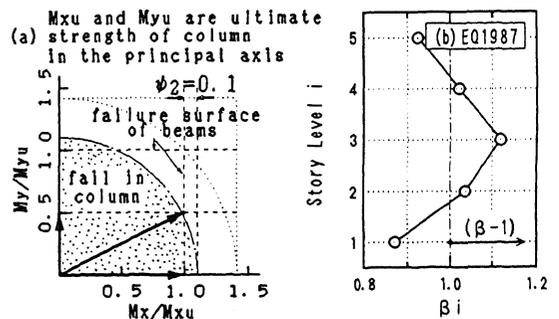


Fig. 5. Safety factor ϕ_2 and magnification ratio of story shear force, β_i , due to EQ1987

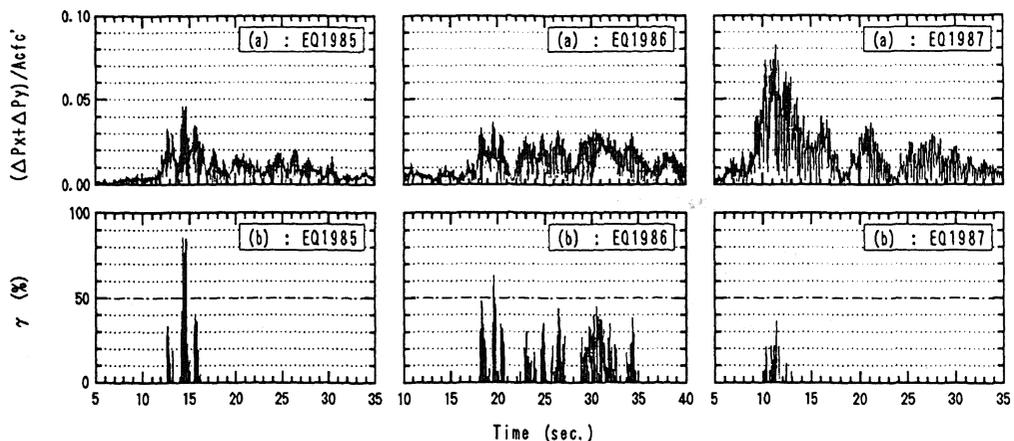


Fig. 6. Simultaneity of earthquake induced axial force in the first story