BIDIRECTIONAL HORIZONTAL BEHAVIOR OF REINFORCED CONCRETE WEAK-BEAM MODEL STRUCTURE

by

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Introduction

It is well accepted in a structural design that seismic forces may be assumed to act independently in the direction of each principal axis of the structure. This assumption is very simple and convenient for the design practice. Actual behavior of structures during earthquakes is, however, very complicated and seismic forces in a transverse direction may have significant effects on seismic performance of structures. It is, hence, of great importance to investigate bidirectional effects of seismic action on structural behavior. Such investigations may serve as a basis for determination of rational design forces with taking account of effects due to responses in a transverse direction. From this point of view, many researchers have carried out experimental and analytical investigations. Most of them are, however, based on laboratory tests or mathematical models, and few investigations due 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 design base shear for existing R/C buildings in Japan. Based on observation results, this report will focus on 1) bidirectional horizontal behavior of the specimens and 2) adequacy of design factor for bidirectional effects which is introduced in "Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept[1]"

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Outline of Model Structures[2]-[4]

Two five-storied R/C frame structures, one is a so called "weak-column strong-beam structure" and the other "weak-beam strong-column structure", have been used for the response observation. Plan- and section-view are shown in Fig. 1. Measurements for inter-story displacements, response accelerations for three directions, and strains of reinforcement etc. are installed and a recording system starts automatically when an accelerometer located -40m below the ground surface catches 1.0 gal. Model structures were designed so that the strength be as low as possible. Each member was designed to fail in a ductile manner. Calculated strength of both structures is shown in Table 1, where the slab system within 10% of the span length from a column surface is assumed to contribute to the beam strength, according to the Japanese standard. It should be noted that the slab-to-beam-depth ratio of weak-beam structure is especially larger than that of existing R/C buildings in Japan, and the contribution of slab system to beam strength may be larger than existing structures. Ultimate strength of the weak-beam structure is estimated about 0.3 in terms of base shear coefficient when all slab system is effective to beam strength.

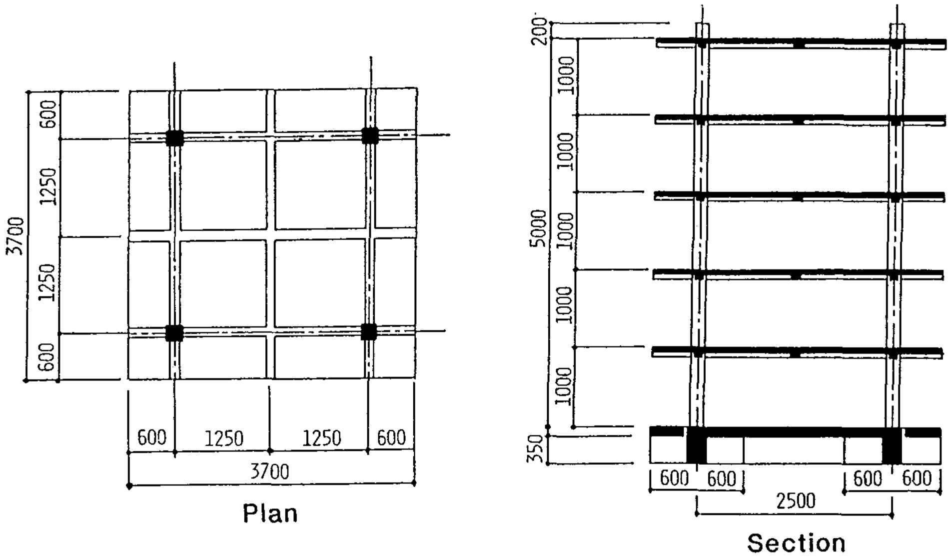
Earthquake Response Results

Since the observation started, more than 150 sets of response records are obtained(as of Jan. 1991). Listed in the following are three major earthquake records and corresponding damages to the specimens. Table 2 summarizes the characteristics of these earthquakes.

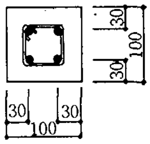
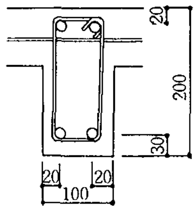
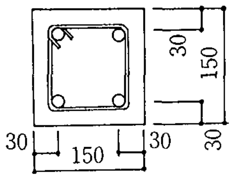
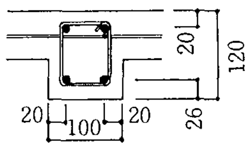
[1] Earthquake on October 4, 1985[3] (referred to as EQ1985 hereafter)
The second largest response acceleration was recorded. The weak-column structure sustained many cracks in columns in the second through fifth story while the weak-beam structure was slightly damaged. The damage level to the weak-column structure was judged "slight" to "moderate" according to the classification generally used in Japan.

[2] Earthquake on June 24, 1986 (referred to as EQ1986 hereafter)
The second largest response displacement was recorded. Propagation of cracks due to prior earthquakes was observed in both specimens.

[3] Earthquake on December 17, 1987[4] (referred to as EQ1987 hereafter)
The largest response was recorded since the observation started in 1983.



(a) Plan- and Section-View (unit:mm)

	Column Section	Beam Section
Weak-Column Structure	 Reinforcement : 4-D6(SD30) Hoop : ϕ2 @30(SR24)	 Reinforcement : 4-D10(SD30) Stirrup : ϕ2 @30(SR24)
Weak-Beam Structure	 Reinforcement : 4-D10(SD30) Hoop : ϕ2 @30(SR24)	 Reinforcement : 4-D6(SD30) Stirrup: ϕ2 @30(SR24)

SD30(deformed bar with nominal yield strength of 3000 kgf/cm^2) is used for longitudinal reinforcement
SR24(round bar with nominal yield strength of 2400 kgf/cm^2) is used for shear reinforcement
●, o : D6 (Deformed Bar with Diameter of 6 mm) and D10, respectively

(b) Section Properties (unit:mm)

Fig. 1 : Dimension of the Model Structure

Table 1 : Strength of Model Structures

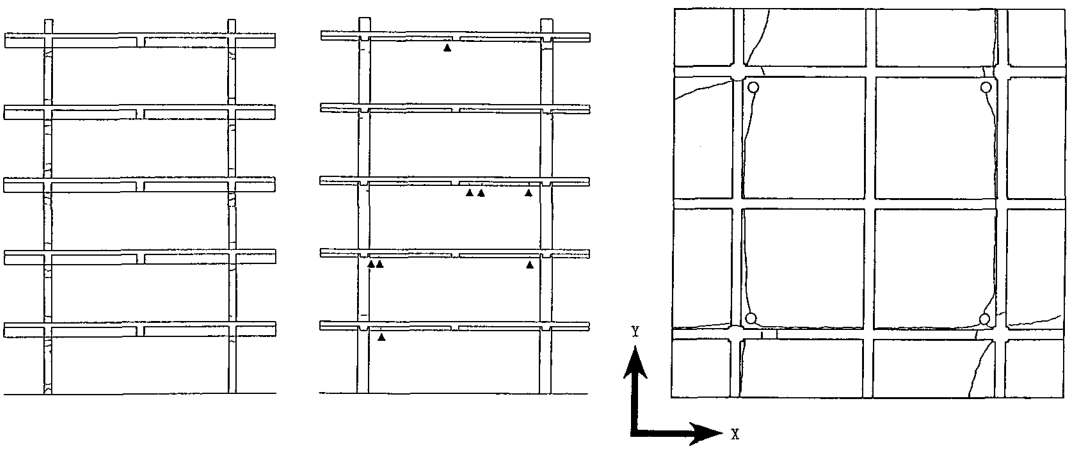
	Weak-Column	Weak-Beam
Base Shear Coefficient*	0.16	0.19
Shear-to-Flexural Strength Ratio**	1.5 - 1.7 1.1	1.2 - 1.3 4.0
Beam-to-Column Strength Ratio***	2.1 - 2.7	1/4.3-1/5.0

* : f_y = 3900 for D6 and 3500 for D10 (in kgf/cm^2)
f_c' = 210(kgf/cm^2) for concrete strength
10% of slab system is assumed effective
** : upper value indicates columns and lower beams
*** : flexural strength $M = 0.8a_tf_yD + 0.5PD(1-P/BDfc')$
shear strength V = by Arakawa's Min. Equation

Table 2 : Characteristics of Major Earthquakes

		[1] EQ1985	[2] EQ1986	[3] EQ1987
Magnitude		6.1	6.5	6.7
Epicentral Distance		30 km	111 km	45 km
Focal Depth		78 km	73 km	58 km
Intensity*		IV (VII)	IV (VII)	V (VIII)
Max. Ground Acceleration at GL -1m	NS	70 gal	51 gal	400 gal
	EW	83 gal	53 gal	223 gal
	UD	28 gal	--	124 gal
Max. Inter-Story Drift Angle**		1/255(4FL) 1/665(2FL)	1/294(4FL) 1/675(2FL)	1/105(1FL) 1/100(2FL)

* : in JMA Scale (in MM Scale) at the specimen site
** : upper = Weak-Column Structure
lower = Weak-Beam Structure



(a)Weak-Column Structure (b)Weak-Beam Structure (c)Slab of Weak-Beam Structure (in the third story)

Fig. 2 : Crack Patterns due to the Earthquake on Dec. 17 in 1987

Maximum inter-story drift was approximately 1/100 in both structures and reinforcing bars in columns of the weak-column structure and in beams of the weak-beam structure yielded. The specimens sustained many cracks and were classified into "moderate" to "severe" damage level.

In Figs. 2 and 3 are shown crack patterns of the structures due to EQ1987 and response accelerograms recorded at the first- and the roof-floor level during these three earthquakes, respectively.

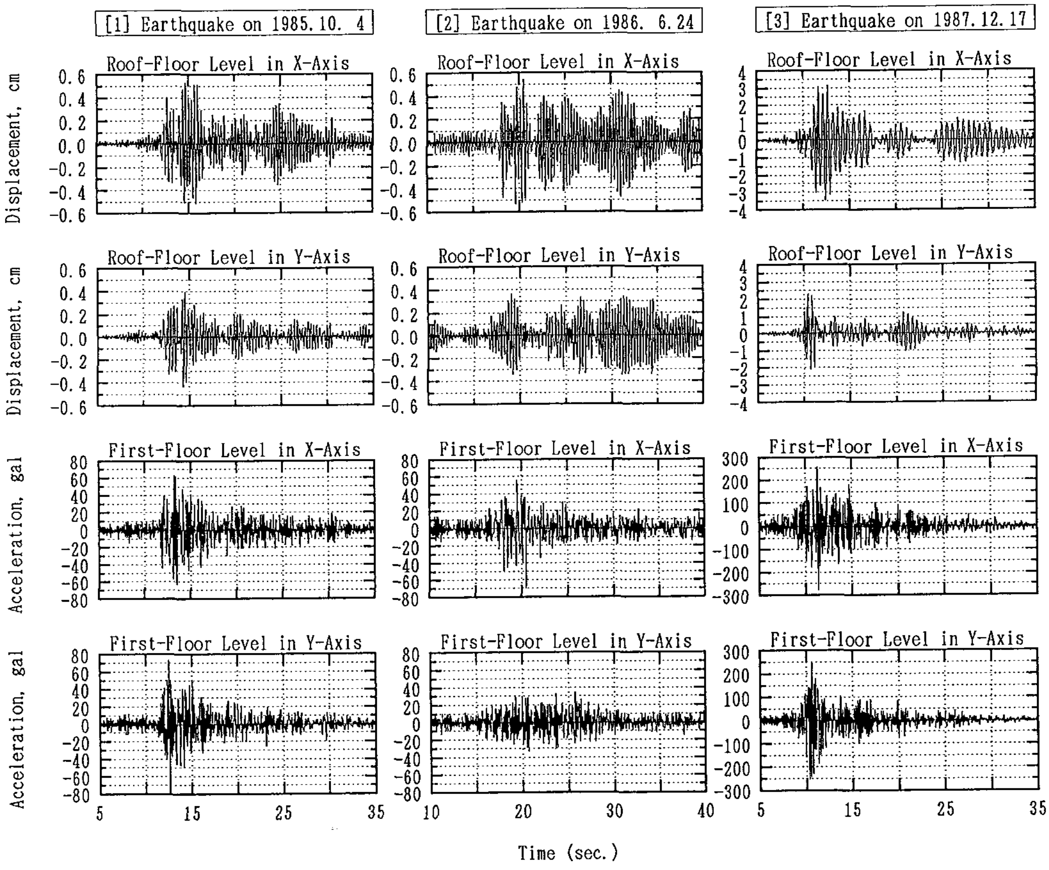


Fig. 3 : Response Records of the Weak-Beam Structure

Bidirectional Response Characteristics of Weak-Beam Structure

Response inter-story displacements, story shear forces, and earthquake induced axial forces of the weak-beam structure due to the prescribed three earthquakes (EQ1985, EQ1986, and EQ1987) are investigated to discuss hereafter bidirectional horizontal effects. Bidirectional response results of the weak-column structure will be discussed elsewhere.

(1)Response Inter-story Displacement

Fig. 4 shows the orbit of response inter-story displacements. Each figure corresponds to the main response for six seconds in a story where the maximum inter-story displacement was recorded. Fig. 4 shows that the bidirectional behavior of the specimen varies depending on the earthquake motion itself, i.e., 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. During the period of 31.0 to 32.0 sec. in EQ1986 record, columns are subjected to circular deformation path which is well recognized unfavorable for columns. In Fig. 5, the relationships between angles of displacement direction from either principal axis, |R|, and the inter-story displacements, $\delta_R(=\sqrt{\delta_x^2+\delta_y^2})$, are plotted. Response displacements δ_R tend to be large in the direction of 45 deg. during EQ1985 and EQ1986, while small during EQ1987. These two figures show that simultaneity of maximum responses of the specimen in each direction is more significant during EQ1985 and EQ1986 than during EQ1987.

(2)Response Shear Force

In Fig. 6 are shown the orbit of response base shear coefficient for the main six seconds. Fig. 7 shows the magnification ratio of bidirectional response base shear forces, V_R, due to EQ1987 to unidirectional story shear forces, V_U, defined by Eq.(1). Design shear force for columns in each story is specified by Eq.(2) in Ref.[1], where factors $\Delta\omega$ and ϕ_2 are introduced to allow for the discrepancy of dynamic actions in columns from static actions(dynamic effects) and simultaneity of 50% of maximum forces in a transverse direction(bidirectional effects, $\phi_2 = 0.1$ is taken in Ref.[1] when a structure is designed to fail in beams, see also Fig. 8), respectively. The value of $(\beta-1.0)$ calculated from Eq.(1) may correspond to ϕ_2 in Eq.(2). Fig. 7 shows that the maximum value of $(\beta-1.0)$ is 0.11 in the third story and

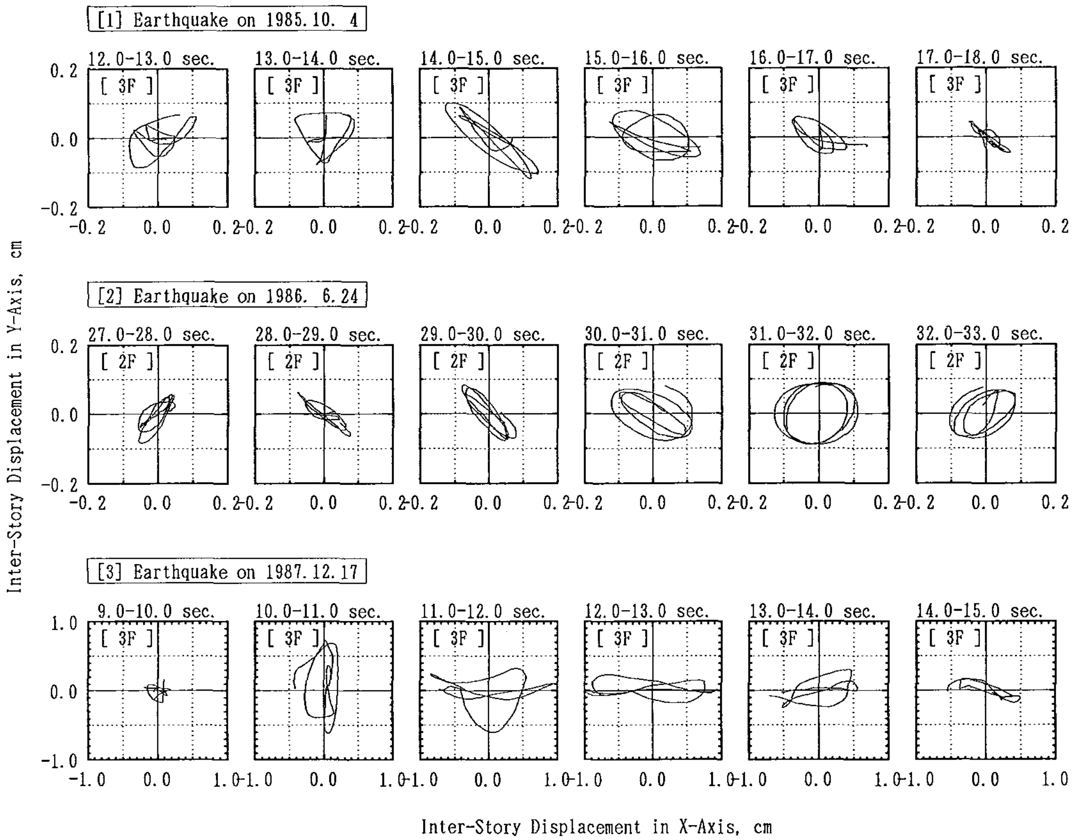


Fig. 4 : Orbit of Response Inter-Story Displacement

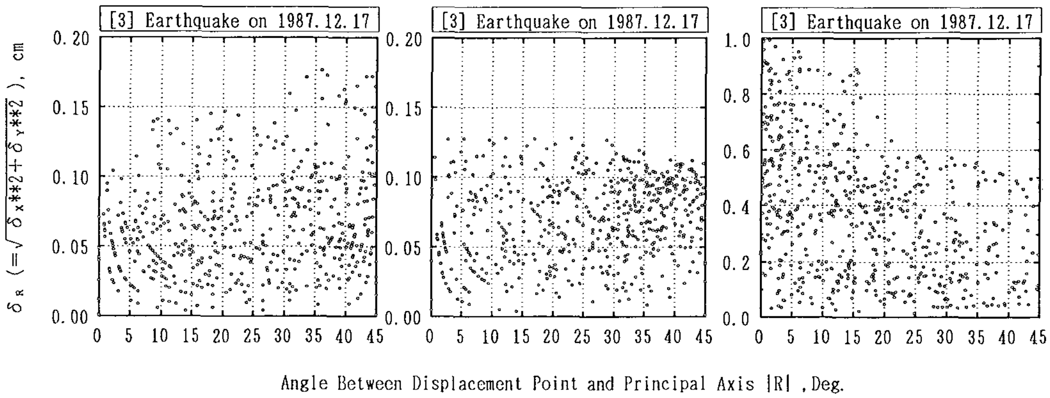


Fig. 5 : Relationship Between Angles of Displacement Point From Either Principal Axis And Inter-Story Displacements

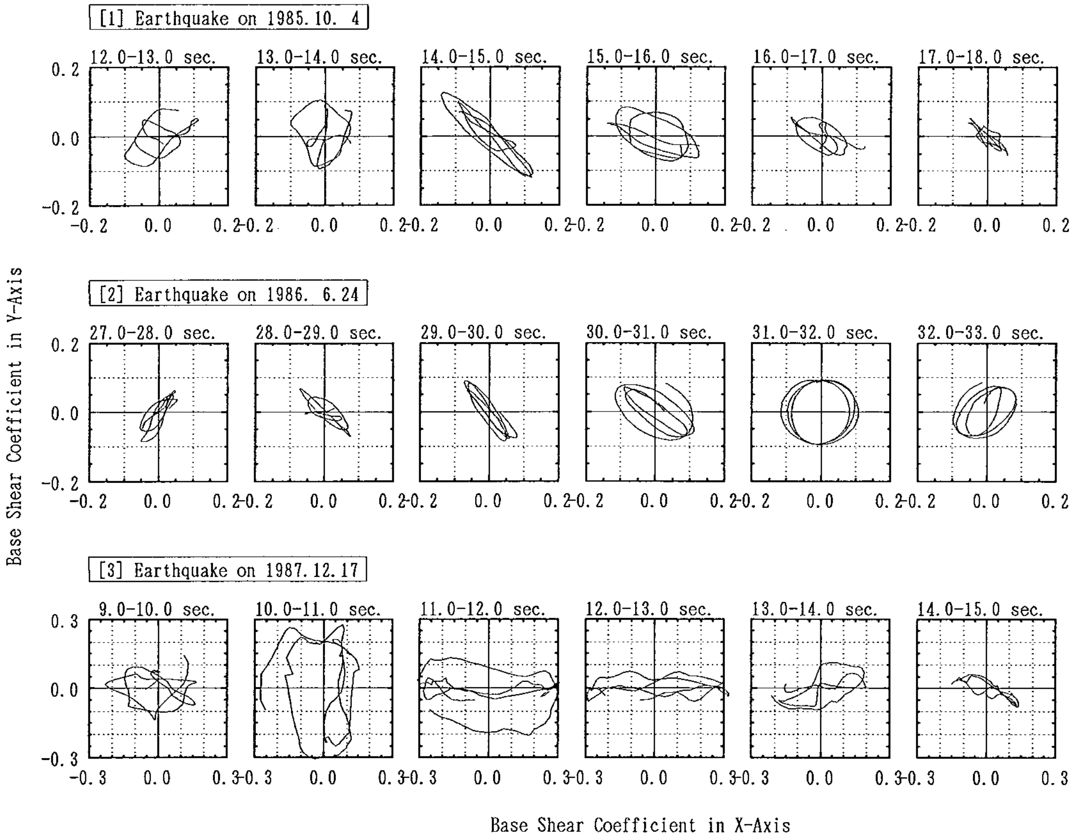


Fig. 6 : Orbit of Base Shear Coefficient

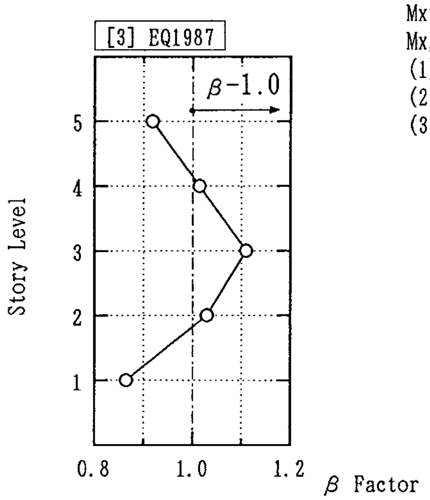


Fig. 7 : Magnification Ratio of Story Shear Force, β

Mxu, Myu : ultimate strength of column in a principal axis
Mx, My : required strength of column to fail in beams
(1) failure surface of column is assumed circular
(2) Y-axis is assumed transverse direction in this figure
(3) when 50% of Myu is attained in Y(transverse)-direction, ϕ_2 is approximately 0.1

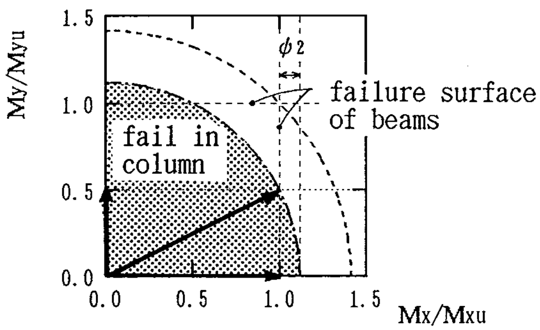


Fig. 8 : Safety Factor ϕ_2

almost equal to the proposed value of 0.1 in Ref.[1]. It should be noted, however, that the value of 0.1 may not be sufficient because the simultaneity of maximum responses in each principal axis was not significant during EQ1987.

$$\beta = (V_R / V_U - \Delta\omega) \quad \cdots\cdots (1)$$

where, V_R : time-varying bidirectional response story shear force in i-th story ($= \sqrt{V_x^2 + V_y^2}$, V_x and V_y are calculated from mass and recorded accelerations)

V_U : story shear force in i-th story at the ultimate stage when unidirectionally subjected to a reversed-triangularly distributed lateral force

$\Delta\omega$: higher-order vibration mode factor in i-th story to take account of dynamic effects[1]

$$V_D = V_S \cdot (1.0 + \Delta\omega + \phi_2) \quad \cdots\cdots (2)$$

where, V_D : design shear force for columns in i-th story with consideration of dynamic and bidirectional effects

V_S : column shear strength in i-th story required from a static lateral force in a direction considered

$\Delta\omega$: higher-order vibration mode factor in i-th story to take account of dynamic effects[1]

ϕ_2 : safety factor to allow for the magnification of shear force in columns due to the bidirectional effects ($\phi_2 = 0.1$ is proposed in Ref.[1], see also Fig. 8)

(3)Earthquake Induced Axial Force

Earthquake induced axial forces, ΔP, of the first story in the direction of each principal axis which are imposed due to shear forces in beams can be calculated from Eq.(3), given the point of contraflexure in the first story. Fig. 9(a) shows the time history of earthquake induced axial forces normalized by ($A_c \cdot f_c'$) where A_c and f_c' refers to the column sectional area(15cm x 15cm) and nominal strength of concrete(210 kgf/cm^2), respectively. The discrepancy of axial force level is not so significant although the ground acceleration level of EQ1987 was three to four times larger than that of EQ1985 and EQ1986. This is because the specimen oscillated mainly along the principal axis during EQ1987.

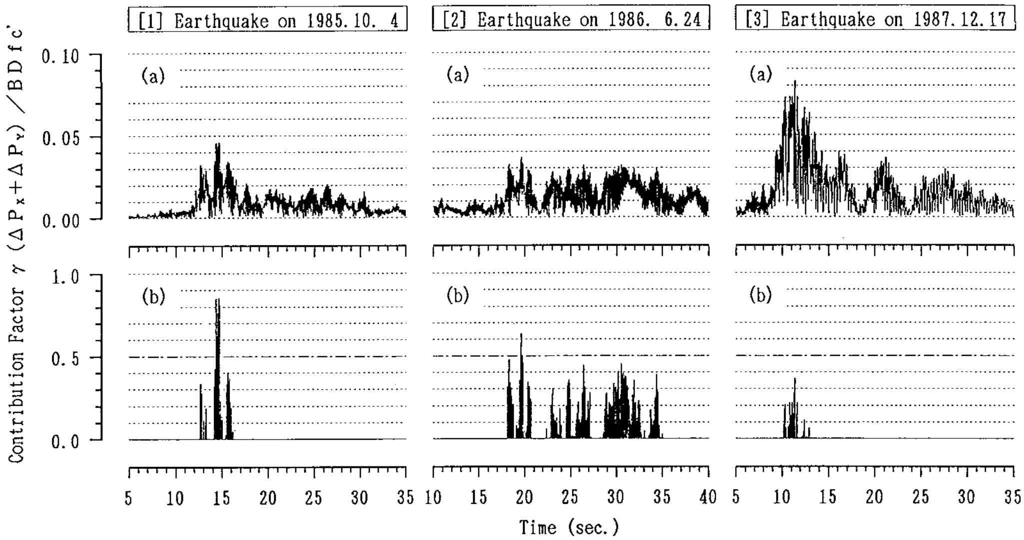


Fig. 9 : Simultaneity of Earthquake Induced Axial Force

$$\Delta P = \left| \sum_{i=2}^{5} (V_i H / L) + V_1 H (1.0-\alpha) / L \right| / 2 \cdots\cdots\cdots\cdots (3)$$

where, V_i : story shear force in i-th story (calculated from mass and response acceleration)

H: inter-story height (=100 cm)

L: span length (=250 cm)

αH: location of the point of contraflexure from the bottom end of columns in the first story (α=2/3 is assumed herein)

Fig. 9(b) shows the contribution of the axial force in a transverse direction, γ, calculated from Eq.(4). As previously stated, a design axial force is specified in Ref.[1] to consider half of the maximum earthquake induced axial force in a transverse direction in addition to that in a direction considered (Eq.(5)), based on the assumption that both axial forces due to seismic excitation is unlikely to attain their maximum values simultaneously. Fig. 9(b) shows that the factor γ in Eq.(4) which signifies simultaneity of maximum axis forces in each direction exceeds 0.5 due to EQ1985 and EQ1986 and the value of 0.5 adopted in Ref.[1] may not be conservative. However, it should be noted that this factor should be determined considering not only the simultaneity but also the axial force level and the combination with effects of higher-order-mode vibration, and further investigations are necessary.

$$\gamma = (\Delta P_x + \Delta P_y - \Delta P_{max}) / \Delta P_{Tmax} \quad \cdots \quad (4)$$

where, ΔP_x, ΔP_y : time-varying axial forces in X- and Y-axis defined in Eq.(3), respectively

$\Delta P_{max}, \Delta P_{Tmax}$: maximum axial force in a principal axis and in a transverse axis, respectively

$(\Delta P_{max}, \Delta P_{Tmax}) = (\Delta P_{xmax}, \Delta P_{ymax})$ when $\Delta P_{xmax} \geq \Delta P_{ymax}$

$= (\Delta P_{ymax}, \Delta P_{xmax})$ when $\Delta P_{xmax} < \Delta P_{ymax}$

γ : contribution factor of axial force in a transverse direction

$$P_D = P_{DL} + \Delta P + 0.5 \, \Delta P_T \quad \cdots \quad (5)$$

where, P_D : design axial force

P_{DL} : axial force due to dead load

ΔP : earthquake induced axial force in a direction considered

ΔP_T : earthquake induced axial force in a transverse direction

Concluding Remarks

Bidirectional response characteristics of the weak-beam model structure due to major three earthquakes which caused damages to the specimens were investigated. Adequacy of the safety factors specified in Ref.[1] were also examined based on the observation results. Conclusions are summarized as follows.

1)Characteristics of bidirectional horizontal response displacements varied widely depending on the earthquake motion, and simultaneity of maximum responses in each principal axis due to EQ1985 and EQ1986 was more significant than due to EQ1987.

2)The contribution factor ϕ_2 for bidirectional story shear force due to EQ1987 was almost equal to the value of 0.1 specified in Ref.[1]. However, this may not be conservative if the lower simultaneity of bidirectional response due to EQ1987 than due to EQ1985 and EQ1986 are taken into account.

3)The contribution factor γ for bidirectional earthquake induced axial forces due to EQ1985 and EQ1986 exceeded 0.5 which is adopted in Ref.[1]. However, it should be noted that this factor should be determined considering not only the simultaneity but also the axial force level and the combination with effects of higher-order-mode vibration, and further investigation is necessary for a rational safety factor.

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