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Experimental Study on Torsional Vibration Behavior of Steel Frame Specimen with Eccentricity

Hiroto Kato and Koichi Kusunoki
Department of Structural Engineering, Building Research Institute, Tsukuba, Japan
Toshibumi Fukuta
International Institute of Seismology and Earthquake Engineering, Building Research Institute, Tsukuba, Japan
Fumitoshi Kumazawa
Faculty of Engineering, Shibaura Institute of Technology, Tokyo, Japan
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Torsional response can destructively effect the seismic capacity of structures. Many damaged buildings due to torsional vibration were observed after sever earthquakes. However, it cannot be said that the mechanism of the damage due to the torsional vibration had been clearly investigated. The main purpose of this paper is to reproduce the torsional response with the pseudo dynamic test technique. One-span, one-bay and two-story steel structures were tested. Three structures that had different eccentric ratios were designed for the pseudo dynamic tests. Furthermore, shaking table tests on three structures were conducted to verify the validity of the pseudo dynamic tests. From the shaking table and the pseudo dynamic tests, it was confirmed that the pseudo dynamic test can adequately reproduce the response of structure with eccentricity; eccentricity was not as effective on the maximum horizontal displacement at center of gravity, but the maximum rotational angle was increased according to its eccentricity.

Keywords: Building structure with eccentricity, steel frame, torsional seismic behaviour, pseudo dynamic test, shaking table test.

1. Introduction

There have been many buildings damaged due to torsional response during severe earthquakes. However, it cannot be said that the mechanism of the damage due to the torsional response has been clearly investigated. One of the main purposes of this study is to reproduce the torsional response of structures with eccentricity by the pseudo dynamic (PSD) test, and to investigate the mechanism of the damage due to the torsional vibration. In order to verify the validity of the PSD test, the shaking table tests were also conducted [1]. This paper presents the outlines of earthquake response tests and the outcomes from the experimental study.

2. Outlines of Specimens

The specimens were one-span, one-bay and two-story steel structures as shown in Fig. 1. Rigid slabs made of reinforced concrete provided the inertia force for the shaking table tests, and were used as the loading beam for the PSD test. The weight of each slab was 76.9kN for the first floor and 78.0kN for the second floor. The eccentricity was provided only on the first story by adjusting column positions as shown in Fig. 1.a. Two of four columns were located closer to the center of the slab than others. The natural period of the specimens need to be nearly the same to neglect the effects of the frequency characteristics of the input motion. However, it is not easy to provide structures with various stiffness eccentricities that have the same natural period. Therefore the method of adjustment of column positions on the first story mentioned above was applied for the test in order to make the natural periods of test structures almost constant.

H-Shaped steel was used for columns (H-125x125x6.5x9 for the first story and H-100x100x6x8 for the second story). The clear height of column between top and bottom base plates was 1,500mm as shown in Fig. 2. Material test results are shown in Table 1. Table 2 shows the strength of column, the story shear and the story shear coefficients. The story shear coefficient for the first story was 1.43 and 1.85 for the second story.

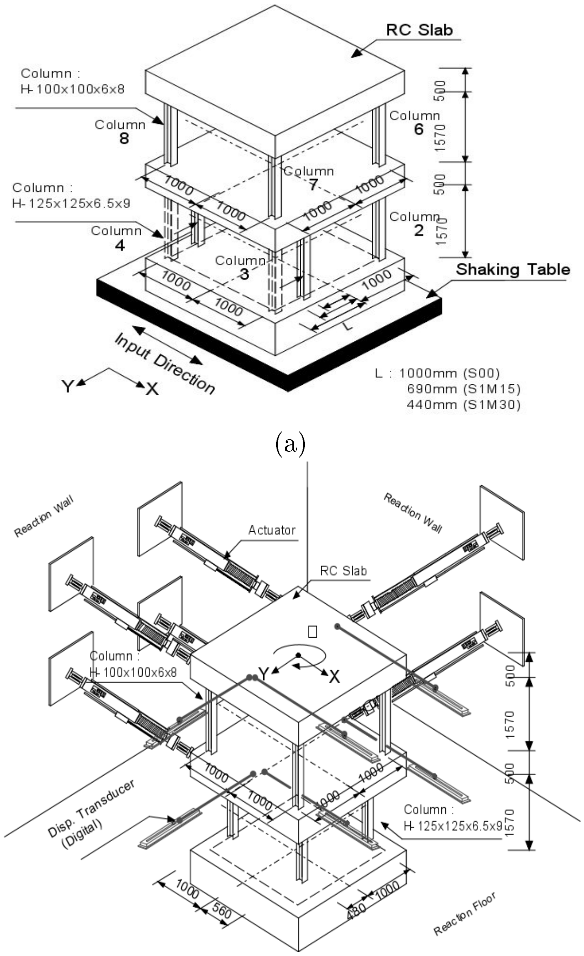


Figure 1. Setup of Specimen (a) shaking table test (b) pseudo dynamic test.

Test parameters are the values of eccentric ratio in the direction of X. The X-axis is the direction of the input motion, as shown in Fig. 1.a. The eccentric ratio of 0.0, 0.15 and 0.30 were applied in the X direction. Here, the eccentric ratio R_e is defined as a function of distance between center of gravity and rigidity Eq. 1, which is prescribed in the Building Standard Low Enforcement Order of Japan, and represents how easily a structure can vibrate torsionaly [2].

$$R_e = \frac{e}{r_e} \quad (1)$$

e : Eccentric Distance. The distance between center of gravity and rigidity,

Table 1
Material Test Results.

	H-125 (First Story)	H-100 (Second Story)
Yield Strength (N/mm^2)	304.4/301.7	347.8/340.1
Tensile Strength (N/mm^2)	431.9/435.5	475.6/473.6
Strain Fracture (%)	26.4/27.3	25.8/25.5

Notes:Left-side value is for flange right-side value for web.

r_e: Radius of Spring Force,

$$r_{ex} = \sqrt{\frac{K_R}{K_x}}, r_{ey} = \sqrt{\frac{K_R}{K_y}}, \quad (2)$$

K_R : Torsional Stiffness
K_x, K_y : Horizontal Stiffness to The Direction of X and Y.

In structural design of building with eccentric ratio R_e larger than 0.15, design external force should be made to increase up to 1.5 times in accordance with the values of eccentric ratio. An eccentric ratio of zero means that the structure has no eccentricity. The test parameters are shown in Table 3. The number of specimens are six, three were prepared for the PSD tests (P00, P1M15 and P1M30).In addition, three specimens (S00, S1M15 and S1M30) were used for the shaking table tests in order to compare the reproduced behaviors between the PSD test and those of the shaking table tests. In order to achieve the specific eccentricity, columns were shifted by the distance shown in Table 3 from the location for the structure without eccentricity.

Table 2
Strength of Specimen.

	Yielding Moment(kN*m)	Story Shear at Yielding(kN)
First Story	41.4/14.3 [2.9]	220.8/76.3 (1.43)
Second story	26.6/9.3 [2.9]	141.9/49.5 (1.85)

Notes:Left-side value is for X Direction, right-side value for Y Direction, [ ] the ratio of yielding moment on X Direction to Y Direction, ( ) Story Shear Coefficient.

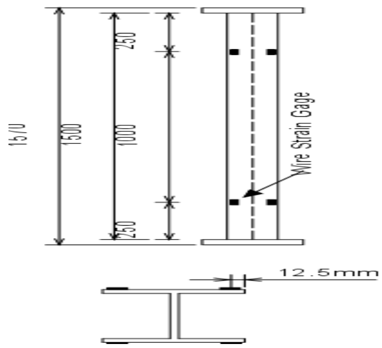


Figure 2. Column size of the specimen.

The test structure was assumed to be 1/2 scaled model of a real size structure. However, no prototype structure in real size was designed because the main purpose of this research was to investigate the basic effect of the torsional response on structural damages, not to observe the response of a specific structure. Because of this, the horizontal strength of column was assumed simply to be proportional to the area of section. Scale factors for each item are listed in Table 4 [3]. Single underlined items are the items that cannot be scaled down, and double underlined items are the items of which scale factor does not have proper relationship with the real size structure.

Strains of steel columns were measured with strain gauges put on the flange at both ends of columns as shown in Fig. 2 (black rectangular marks show strain gauge locations). Four strain gauges were put at one end, eight gauges were used for one column, and totally strains at 64 different points were measured during the PSD and the shaking table tests.

Three displacement transducers were used to measure response bi-directional horizontal displacement and rotational angle of each floor as

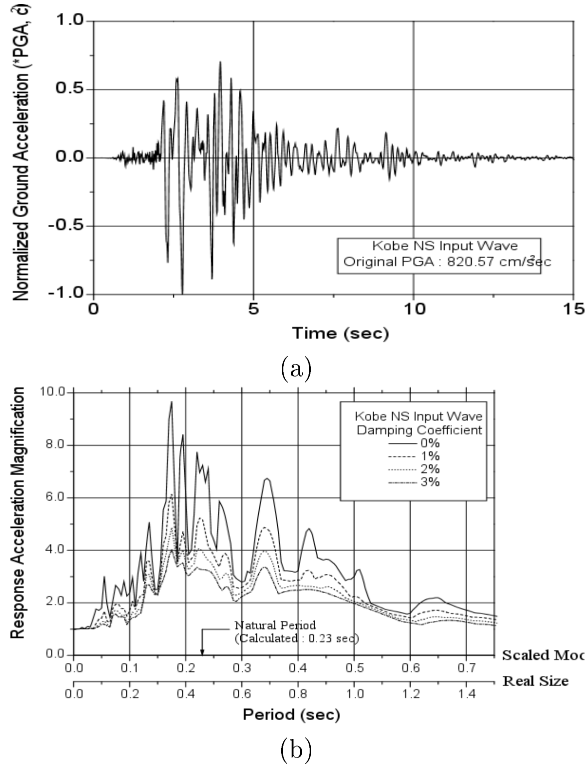


Figure 3. Input Acceleration Wave (a) earthquake acceleration (b) response acceleration magnification.

shown in Fig. 1.b. Two transducers were for X-direction and rotation, and one was for Y-direction. Two additional transducers were used to measure slip displacement at bottom of basement during the shaking table tests. Three accelerometers were used to measure response acceleration during each floor at the shaking table test. Two were for Y-direction and rotation, and one was for X-direction. One accelerometer was placed on the center of the basement to measure actual input motion to a specimen.

Table 3
Names of Specimens and Test Parameters.

Eccentric Ratio in X Direction	Shifted Distance from Uniform Arrange(mm)	Names of Specimens	
		Shaking Table Tests	Pseudo Dynamic Tests
0.00	0	S00	P00
0.15	310	S1M15	P1M15
0.30	560	S1M30	P1M30

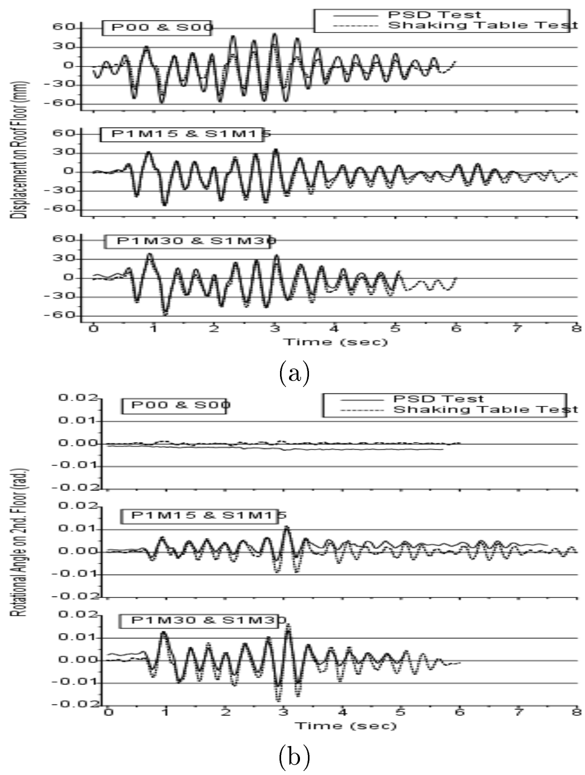


Figure 4. Dynamic Responses of Specimens (1640 cm/sec^2 Input Tests (a) displacement responses (roof floor) (b) rotational angle responses (first story).

3. Input Motions

The North-South component of JMA-Kobe (Kobe Observatory of Japan Meteorological Agency) recorded at the Hyogo-Ken-Nanbu earthquake in 1995 was used for the input motion, of which time axis was scaled down by 1/2 according to the scale factor. The input earthquake wave and the response acceleration magnification with various damping coefficient are shown in Fig. 3. Five different normalized peak acceleration waves of 200, 450, 900, 1640 and 2400 cm/sec^2 were inputted in order of level. Peak accelerations in a real size are 100, 225, 400, 820 and 1200 cm/sec^2 because of scale factors. The shaking table tests were conducted with these input motions prior to the PSD tests, and recorded acceleration at the basement of each specimen was used for the input motion to the PSD tests.

4. Test Results and Discussions

4.1. Fundamental Characteristics of Specimens

In order to measure the natural periods and damping coefficients of specimens, the responses with the white noise input were measured at the shaking table tests. On the other hand, since a stiffness matrix was needed for the PSD tests to assume a damping matrix, unit loading tests, that small amount of force was loaded at each floor and in each direction, were carried out just after setting up each specimen. Then, all responses for each force were measured, and the flexibility matrix was generated. The natural periods were calculated with the flexibility matrix and the mass matrix for each specimen. Measured natural periods were listed in Table 5. The damping coefficients could be assumed as 1% from the shaking table test with the white noise. The damping coefficients of 1% proportional to the initial stiffness were assumed for the PSD tests.

The natural periods of the specimens in both X and Y direction of the shaking table and the PSD tests are almost the same, however, those of torsional response are a little different. Since the natural periods of the shaking table tests were calculated with transfer function at the white noise input, the accuracy of the natural period of the torsional response is not so high because it is higher modes.

4.2. Responses of Specimens

The response displacements at center of gravity on roof floor in the X direction and rotational angles of the first story of which the input level was 1640cm/sec^2, are shown in Fig. 4. In the figure, solid lines show the results of the PSD tests and broken lines are those of the shaking table tests. It can be said that the response displacements of P1M15 and P1M30 agreed very well with those of the shaking table tests, which include maximum response displacements. And the rotational angles of those specimens also show rather well correspondence. However, the response displacement of P00 was evidently larger than that of S00, the behaviors of both did not coincide. From Fig. 4, the maximum response displacements at center of gravity of employed specimens are almost in agreement, in spite of difference of eccentric ratios. Meanwhile the response rotational angles of specimens with eccentricity grow with increasing of eccentric ratio, as against those of

Table 4
Scale Factors.

Physical Phenomena			
Length	1/2	Area	1/4
Volume	1/8	Gravity Acceleration	1.0
Specific Gravity	1.0	Mass	1/8
Rotational Inertia	1/32	Time	1/2
Column			
Young's Modulus	1.0	Axial Strain	1.0
Curvature	2.0	Twisting Strain	2.0
Horizontal Strength	1/4	Horizontal Stiffness	1/2
Yield Deformation	1/2	Rotational Stiffness	1/8
Response of Structure			
Natural Period	1/2	Horizontal Acceleration	2.0
Horizontal Velocity	1.0	Horizontal Deformation	1/2
Rotational Acceleration	1.0	Rotational Velocity	1.0
Rotational Deformation	1.0		

Notes: Single Underlined Item: Item that cannot be scaled down
Double Underlined Item: Item of which scale factor does not have proper relationship with the real size structure.

P00 and S00 are very small. It was observed that the eccentricity of specimen inclined to have an influence on the rotational response.

The relationship between story shear force and inter-story drift in the first story of the PSD test specimens for the same input level are compared with those of the shaking table tests in Fig. 5. Though the behaviors of P1M15 and P1M30 agreed well with those of the shaking table tests, the result of P00 was different from that of S00, especially the initial stiffness of the shaking table test was a little higher than that of the PSD test. Because of the difference of stiffness, the response of the PSD test did not agree with that of the shaking table test. The reason why the stiffness of S00 and P00 were different needs further investigation. From these results, it will be said that the PSD test can adequately reproduce the dynamic response of specimen, if the stiffness of specimens agree with each other.

The orbits at center of gravity in the first story of the PSD test specimens are illustrated in Fig. 6. The results of P1M15 and P1M30 show drifts in Y direction, it is understood that the effects of eccentricity promote the deflection of perpendicular direction where input motions were not given.

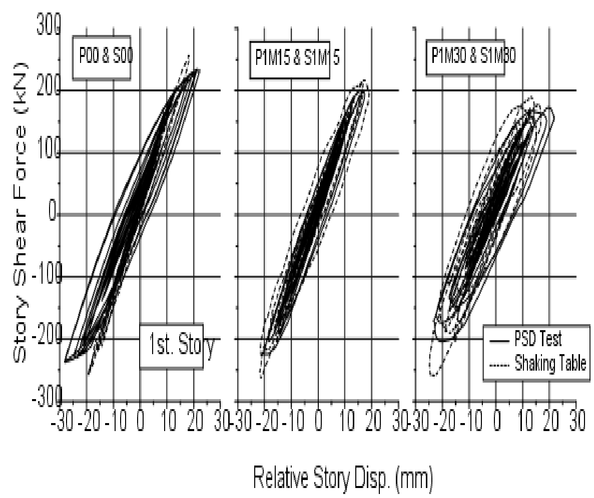


Figure 5. Story Shear Force and Stroy Drift Relationship(1640cm/sec^2 Input Tests).

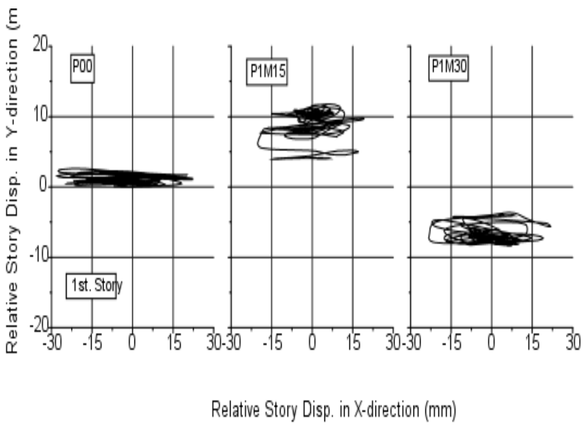


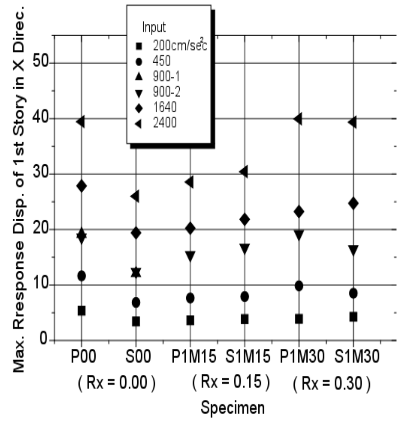
Figure 6. Orbits of Center of Gravity of PSD Specimens (1640 cm/sec^2 Input Test).

4.3. Maximum Responses

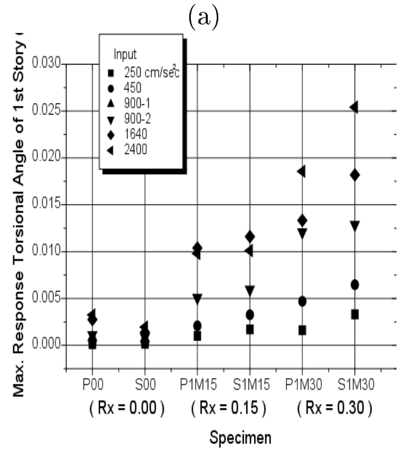
Fig. 7.a shows maximum response displacements at center of gravity of the first story in the X direction for each input level test. As mentioned before, P00 and S00 are quite different especially for relatively large input levels. P1M15 and P1M30 agree well with S1M15 and S1M30 regardless of input level. It can be seen that there is the tendency to slightly increase the maximum response displacement at center of gravity with increasing of the eccentric ratio. Fig. 7.b shows maximum torsional response angle of the first story for each input level test. The maximum torsional response angle of P1M30 at input level of 1640 cm/sec^2 was 28% smaller than that of S1M30. The maximum torsional response angle is the relative angle to the basement and residual torsional angle could be accumulated. The maximum angle of P1M30 at input level of 2400 cm/sec^2 was also 27% smaller than that of S1M30. Maximum torsional response angle increased according to the eccentric ratio. For example, the ratio of maximum angle of P1M30 to that of P1M15 at input level of 1640 cm/sec^2 was 1.15.

Table 5
Natural Periods (sec)

Specimen	X Direction	Y Direction	Torsion
P00	0.264	0.401	0.201
P1M15	0.264	0.390	0.217
P1M30	0.276	0.393	0.226
S00	0.260	0.410	0.220
S1M15	0.280	0.410	0.240
S1M30	0.280	0.410	0.250



(a)



(b)

Figure 7. Comparison of Maximum Responses(a) displacement of First Story (b) torsional angle of first story.

4.4. Responses of Individual Columns

Since the tendency of promoting torsional vibration by eccentricity of specimen was observed as mentioned above, the responses of individual columns are indicated below. Fig. 8 shows the response displacement of eccentric and non-eccentric bays with those at center of gravity of P1M30 at input level of 1640 cm/sec^2. The displacement of eccentric bay are larger than that of center of gravity, on the other hand the one of

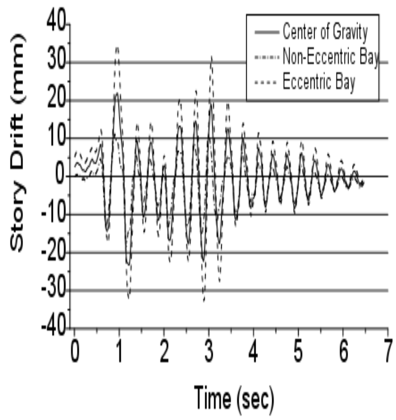


Figure 8. Comparison of Displacement Response in Each Street of Specimen (1st story of P1M30, $1640 cm/sec^2$ Input Test).

non-eccentric bay show opposite trend. The ratio of maximum response of eccentric bay to that at center of gravity was about 1.4; the one of non-eccentric bay was 0.6. These outcomes make clear that the eccentric bay is forced to be deformed largely, in spite of the displacements at center of gravity of each specimens were not so different as shown in Fig. 4.a.

The restoring characteristics of individual columns in the first story of specimens with eccentricity are illustrated in Fig. 9. Here Column2 is in non-eccentric bay and Column 3 is in eccentric bay as shown in Fig. 1.a. The abscissa of the graph is deformation of column and the ordinate shows shear force obtained from measured strain of column. The restoring characteristics of the PSD and the shaking table tests adequately agreed with each other, it is confirmed that the both results correspond in the level of structural elements. The Columns 3 have a spindle-shaped hysteresis loops, it means that the columns had been yielded and reached in plastic range. On the other hand, the Columns 2 show elastic restoring characteristics, those had remained in elastic range. The phenomena which areas of hysteresis loops of P1M30 and S1M30 are larger than those of P1M15 and S1M15, show the possibility that structural element in eccentric bay will be suffered heavy damage in large earthquake excitations.

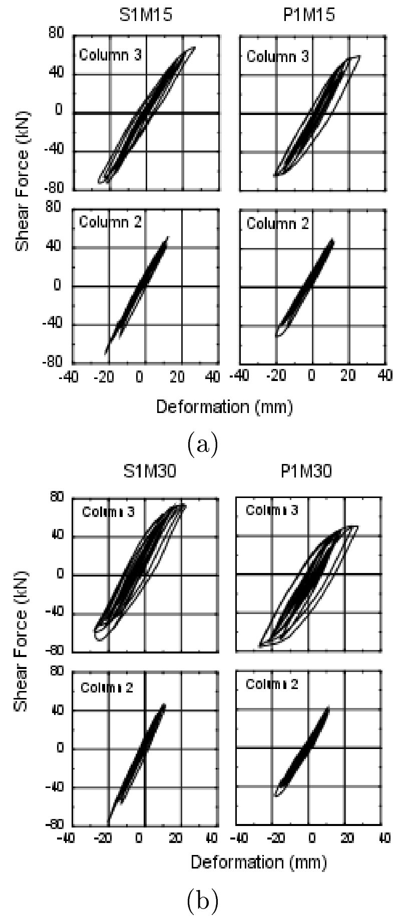


Figure 9. Restoring Characteristics of Individual Columns ($1640 cm/sec^2$ Input Test) (a) eccentric Ratio 0.15 (b) eccentric Ratio 0.30.

5. Conclusions

In order to investigate the mechanism of damage due to torsional response, a series of PSD tests on the specimens with various eccentricities were conducted. Furthermore, in order to verify the validity of the PSD test, the shaking table tests on the same specimens were conducted. The outcomes from these experimental studies are summarized as follows; 1. The pseudo dynamic test technique with torsional response was newly developed. If the stiffness of specimen can be given properly, the pseudo dynamic test can reproduce the dynamic response of eccentric specimen with sufficient accuracy. 2. The displacement response at center of gravity of specimens was not so influenced by the values of eccentric ratio. 3. Torsional response angle increases evidently according to the eccentric ratio. 4. There is the possibility that structural elements in eccentric bay will be suffered heavy damage in large earthquake excitations.

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