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2015 Three-dimensional Shaking Table Test of a 10-story Reinforced Concrete Building on the E-Defense

Part 3: Base Slip and Base Fixed Test Results

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Abstract

The E-Defense, which is the world's largest three-dimensional (3D) full-scale earthquake shaking table test facility, was built by the National Research Institute for Earth Science and Disaster Resilience (NIED) with the aim of shedding light on the failure mechanisms of full-scale structures during earthquakes and for verifying the effects of seismic retrofitting. Since its start of operations in April 2005, a wide variety of structures have been tested on this facility.

In December 2015, NIED tested a 10-story reinforced concrete building frame on the E-Defense in order to gain building engineering knowledge that will facilitate continued use of damaged buildings after a major earthquake. In this experiment, data were obtained from a structure equipped with a base slip mechanism in order to examine the efficacy of the base slip method. After the base slip construction test, the base of the same specimen was fixed in place to simulate conventional construction conditions and testing was conducted in order to compare fixed-in-place behavior with the base slip response behavior, determine the damage process of each member, and examine damage and response evaluation methods.

This paper discusses the results of the base slip and fixed base tests. In the base slip construction test, the base was observed slipping while base uplift occurred, which may have caused the base to slip with torsional movement. The maximum story drift angle generated in the specimen under 100% amplitude of the JMA-Kobe excitation was 0.0060 rad for the base slip construction test, which is relatively small compared to 0.0305 rad, which was measured during the fixed specimen foundation test. Additionally, for both tests, the story shear force generated at each floor is clearly larger when compared to the story shear force calculated during the specimen design for the same story drift angle. In the fixed base test, the beam and column main reinforcements that were arranged in cross-shaped joints yielded, and damage was concentrated at beam-column joints from the 3rd to 5th floors, where relatively large story drift angles were generated.

Keywords: Earthquake resistance, Damage mitigation, Base slip

1. Introduction

The E-Defense, which is the world's largest three-dimensional (3D) full-scale earthquake shaking table test facility, was built by the National Research Institute for Earth Science and Disaster Resilience (NIED) with the aim of shedding light on the failure mechanisms of full-scale structures during earthquakes and for verifying the effects of seismic retrofitting. Since its start of operations in April 2005, a wide variety of structures have been tested on this facility.

As part of its "Social Infrastructure Research Utilizing the 3D Full-Scale Earthquake Testing Facility" project, NIED conducted shaking table tests on a 10-story reinforced concrete building frame in December 2015. Previously, NIED had also conducted numerous tests on reinforced concrete buildings using the E-Defense. In 2006, two sets of experiments were conducted on reinforced concrete buildings fabricated based on design methods common around 1970[1],[2]. In the experiment using a six-story specimen, the collapse phenomena due to shear failure of the 1st story shear wall and short columns were observed. The experiment using a three-story specimen demonstrated the mitigating effect on ground motion input by the spread foundation slippage and the effectiveness of seismic retrofitting with external frames.

In 2010, tests were carried out on a four-story reinforced concrete building fabricated according to current standards, in which the damage process of each member and failure behavior under seismic motion were observed, and an evaluation of the building frame response during an earthquake was performed[3],[4]. In that experiment, the building was still self-supporting after being subjected to ground motion replicating the Southern Hyogo Prefecture Earthquake, which showed that it had sufficient seismic capacity in terms of being able to avoid building collapse. Based on the damage observed at the shear wall bottom and beam-column joints of the frame, continued use of the building, repair costs, and other economic issues that arise in such conditions were identified. In the 2011 Great East Japan Earthquake, which was centered off the Pacific coast of Tohoku, there were numerous cases of buildings that incurred damage in nonstructural members that made the continued use of those buildings difficult, even though they did not collapse[5].

The aim of the test carried out by NIED in 2015 was to gain building engineering knowledge that will enable continued use of buildings after a major earthquake. Data were obtained from the test on base slip construction in order to examine it as a method of enabling continued use of buildings damaged in earthquakes. Additionally, the building specimen was tested under conventional fixed base conditions in order to compare its response behavior with that from the base slip construction method, determine the damage process of each member, and examine damage and response evaluation methods.

This paper will first describe the ground motion used in the tests for base slip construction and fixed base condition, after which the specimen response acceleration and story drift measured during the tests will be presented and compared with the analysis performed during the design stage. In addition, the base slip behavior will be shown and the base slip accompanied by torsional movement and friction coefficient will be considered. Furthermore, the damaged condition of the specimen will be presented, and the damaged conditions from the base slip construction and fixed base condition tests will be compared. The damage at beam-column joints, which showed pronounced failure, will be discussed as well.

2. Excitation Program

The ground motion observed at JMA's Kobe Marine Meteorological Observatory during the Southern Hyogo Prefecture Earthquake[6] (hereinafter referred to as JMA-Kobe) was used for the excitation waves. The maximum acceleration of the seismic motion was 8.18 m/s^2 in the north-south (NS) direction, 6.17 m/s^2 in the east-west (EW) direction, and 3.32 m/s^2 in the up-down (UD) direction, as shown in Fig. 1. The excitation tests were performed in the program sequence shown in Table 1, with gradually increasing amplitude of vibration for both test cases, that is, the base slip construction test and the base fixed test.

However, for the fixed base condition test, a test at 60% amplitude of JMA-Kobe was performed to simulate an aftershock after the 100% amplitude excitation. The tests were conducted with the input seismic wave excitations applied simultaneously in three directions: the NS component of JMA-Kobe in the simple frame direction (hereinafter referred to as the frame direction), the EW component in the direction of the frame with multi-story shear wall (hereinafter referred to as the wall direction), as well as the UD direction, as shown in Figs. 1 and 2. In addition, white noise excitations were applied in each direction, before and after each excitation, to estimate the natural period of the specimen.

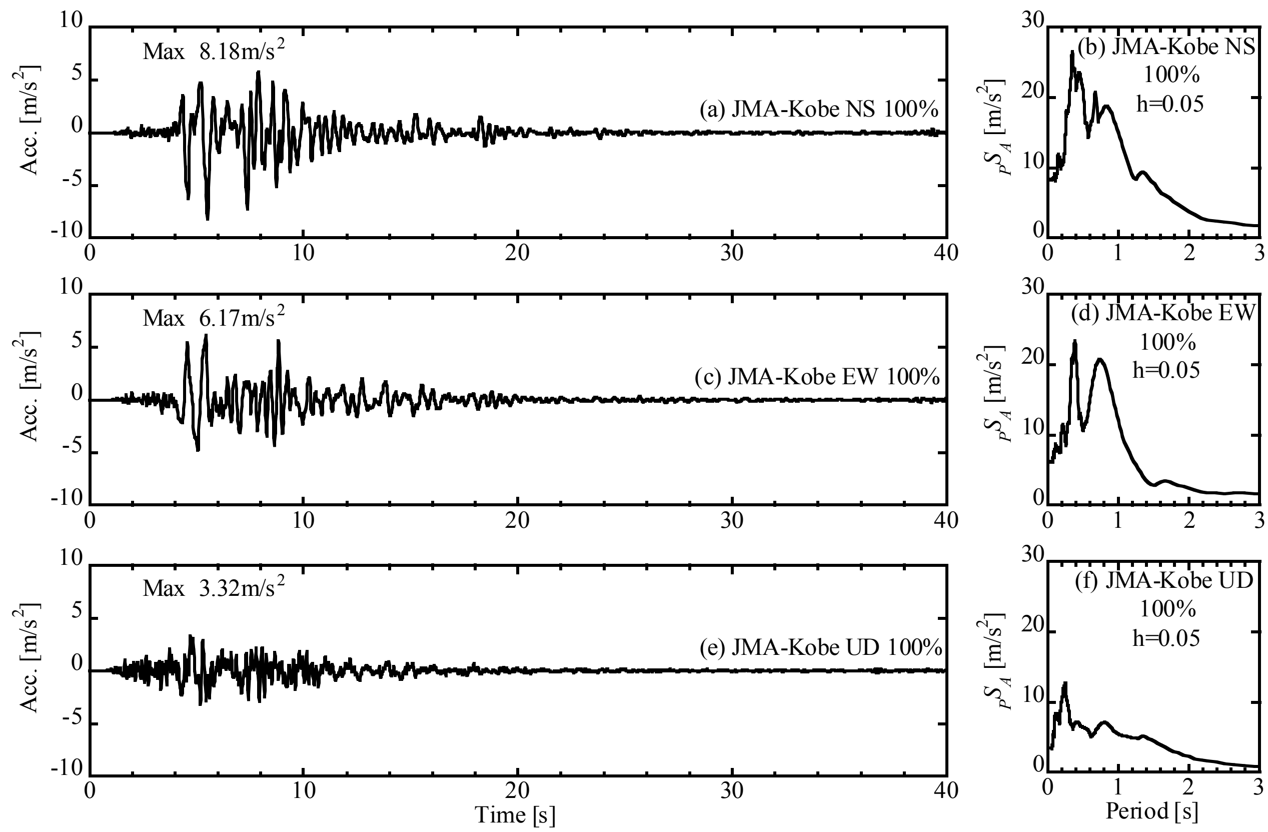


Fig. 1: Input wave time history and response spectrum

Table 1: Test case and input wave

No.	Test case	Input wave	Magnification
1	Base slip	JMA-Kobe	10%
2			25%
3			50%
4			100%
5	Fixed base		10%
6			25%
7			50%
8			100%
9			60%

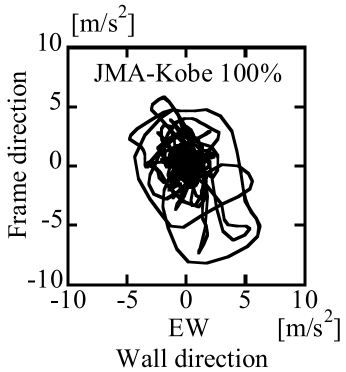


Fig. 2: Orbit of input acceleration

3. Specimen Response

Table 2 shows the natural period based on excitation by white noise after each seismic wave excitation, as well as the maximum story drift angle resulting from each excitation. The natural period before excitation tests of the specimen mounted on the shaking table is 0.57 s in both the frame and wall directions. The maximum response acceleration distributions at each story in the two test cases are shown in Figs. 3 and 4. The maximum acceleration generated at each story in the base slip construction test case where slippage occurred is smaller than the base fixed test of the same amplitude from a few percent to a maximum of about 50%.

These observations from the base slip and base fixed tests for the same amplitude of excitation confirm that the acceleration produced in the building tends to be reduced by the base slippage. The maximum story drift angle distributions are shown in Figs. 5 and 6. The maximum story drift angle under 100% amplitude of JMA-Kobe excitation for the base slip test is 0.0060 rad in the frame direction, which is a little over the limit of 1/200 (0.0050 rad) in allowable stress design for temporary loading.

For the wall direction, the value is 0.0030 rad, which is only 50% of the maximum deformation in the frame direction. The natural period after testing under the same excitation is 0.87 s in the frame direction and 0.69 s in the wall direction. After the base slip construction test, the natural period of the specimen right after fixing the specimen foundation to the shaking table with prestressing rods is 0.85 s in the frame direction and 0.58 s in the wall direction, which shows that the natural period changes with the change in base fixing condition. The natural period after excitation with 100% amplitude of JMA-Kobe in the fixed base condition test is longer at 2.43 s in the frame direction and 1.13 s in the wall direction. As for the specimen response at this time, the maximum story drift angle generated is 0.0305 rad in the frame direction and 0.0150 rad in the wall direction.

Figure 7 shows the story shear force and story drift angle at the 1st floor under 100% amplitude excitation for each test case, together with results from the pushover analysis. The maximum story shear in the base slip construction test is about 60% in the frame direction and about 40% in the wall direction of those in the fixed base condition. Figure 8 shows the pushover analysis results during the specimen structural design and the maximum response values (when the base was fixed and when it was slipping) during the 100% amplitude excitation test. Note that the pushover analysis results shown in Figs. 7 and 8 were generated using the BRAIN III structural design system[7]. Similar to the usual horizontal load bearing capacity calculation, external forces were assumed based on the Ai distribution. Additionally, reinforcement yield strength were considered as 1.1 times the standard values, and top slab rebar within 1 m on one side was considered in the beam strength calculation. The story shear forces obtained from the tests clearly exceed the results from pushover analysis for the same drift angle in all the stories.

Table 2: Natural period and maximum story drift angle

No.	Input wave		Test case	Natural Period [s]		Maximum story drift angle [rad]	
				Frame direction	Wall direction	Frame direction	Wall direction
-	Initial		Base slip	0.57	0.57	-	-
1	JMA-Kobe	10%		0.61	0.61	0.0011	0.0006
2		25%		0.69	0.63	0.0026	0.0010
3		50%		0.76	0.64	0.0041	0.0017
4		100%		0.87	0.69	0.0060	0.0030
-	Initial		Fixed base	0.85	0.58	-	-
5	JMA-Kobe	10%		0.87	0.58	0.0028	0.0008
6		25%		0.94	0.60	0.0075	0.0022
7		50%		1.24	0.74	0.0171	0.0065
8		100%		2.43	1.13	0.0305	0.0150
9		60%		2.62	1.19	0.0131	0.0122

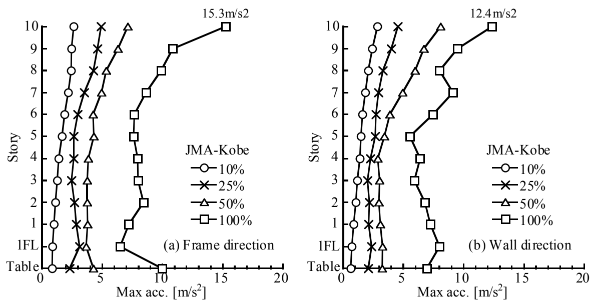


Fig. 3: Maximum acceleration of base slip test

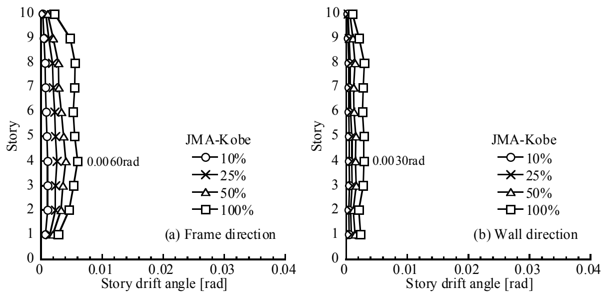


Fig. 5: Maximum story drift angle of base slip test

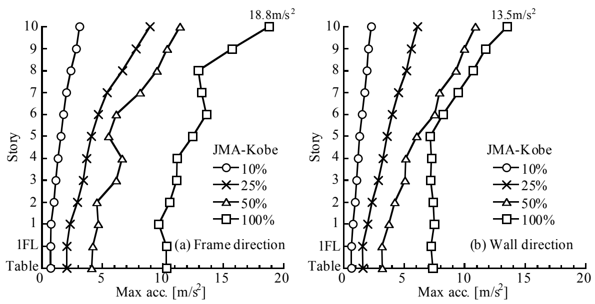


Fig. 4: Maximum acceleration of base fixed test

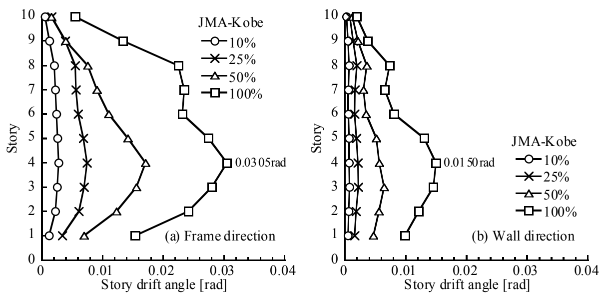


Fig. 6: Maximum story drift angle of base fixed test

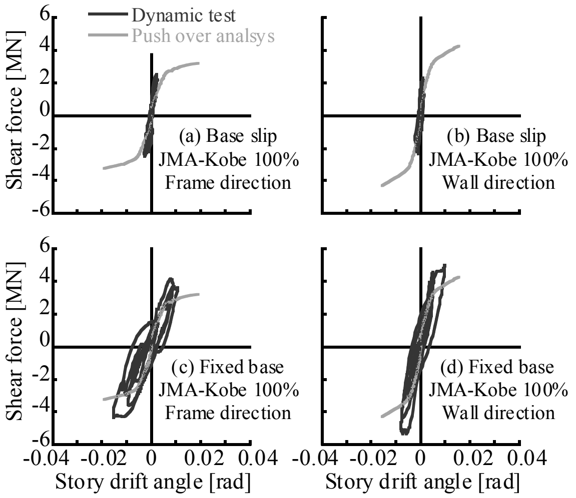


Fig. 7: Shear force and story drift angle at 1st story

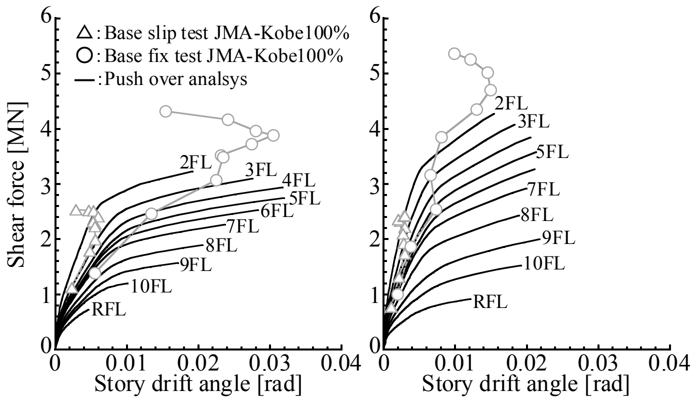


Fig. 8: Shear force and story drift angle

4. Base Slip

Figures 9(a) to (d) show the amount of base slippage from the position shown in Fig. 11(e). The specimen foundation slipped as it twisted such that, after excitation with 50% amplitude of JMA-Kobe, the specimen foundation had rotated about 0.9 degrees counterclockwise. Since an inclination in slip displacement occurred at 25% and 50% amplitude excitations, the phase of the JMA-Kobe waves was reversed before conducting the 100% amplitude excitation test in order to turn the specimen's center of gravity in the direction of its original position. This resulted in the inclination of rotational motion progressing to about 1.8 degrees counterclockwise and resulted in contact with the cushioning, even though the center of gravity did move toward its original position.

In the base slip test, the friction coefficient while the base is slipping is estimated from the acceleration and weight at each story. The horizontal inertial force is obtained by summing the story weights multiplied by the acceleration generated at each story. Figures 10(a) to (c) show the friction force and slip amount of the center of gravity at each base slip direction, and Figs. 10(d) to (f) show the friction coefficient calculated from the combination of the two horizontal components and base slip velocity. The base slip velocity is given as the relative velocity of the 1st floor with respect to the shaking table velocity. Each velocity is obtained by integrating the measured acceleration by the average acceleration method. The friction coefficient μ is estimated as follows

$$\mu = \left(\sum_{Base}^{R} m_i \cdot \alpha_{Hi} \right) \Big/ \left(M \cdot g - M \cdot \alpha_Z \right) \qquad \text{Equation (1)}$$

where m_i is the weigh at each story, α_{Hi} is the horizontal acceleration at each story, M is the total weight of the specimen, g is the gravitational acceleration, and α_Z is the vertical acceleration at the shaking table. The large maximum friction coefficient during the 100% amplitude of JMA-Kobe excitation can be attributed to the collision between the specimen foundation and cushioning. Under the 25% and 50% excitations where collision did not occur, the coefficient of static friction is in the range of 0.21 to 0.23 at the start of base slippage, and the coefficient of kinetic friction is in approximately the range 0.1 to 0.2 while the base is slipping. The friction coefficient fluctuates, which is in contrast to the comparatively stable friction coefficient found in previous studies[8]. The motion of the base during base slippage is shown in Fig. 11. The vertical displacement of 1D shown in Fig. 11(d) has no data after 17 s because of instrumentation damage. In the contour maps in Figs. 11(f) and (g), displacements in locations other than the instrumentation points (12 points in total with 4 points on each side) are interpolated and plotted. Note that base horizontal displacements are shown magnified fivefold. The specimen foundation experienced a maximum of approximately 14 mm uplift under 25% amplitude excitation, 29 mm uplift under 50% amplitude excitation, and 40 mm uplift under 100% excitation, as shown in Fig. 11(c).

It can be seen from Figs. 11(f) and (g) that during base slippage, uplift occurs at the base on the opposite side of the slip direction, which implies that there are large fluctuations in vertical load supported by each bearing. Since friction coefficients generally tend to decrease as bearing pressure increases[9], the extreme bearing pressure differences between the bearing supports caused various bearings to exhibit different friction coefficients, which may be the reason why stable friction coefficients were not obtained. Moreover, the center of rigidity of friction resistance against base slippage moved away from the specimen's center of gravity due to uplift, which may be a factor in why the occurrence of base slippage was accompanied by rotational movement.

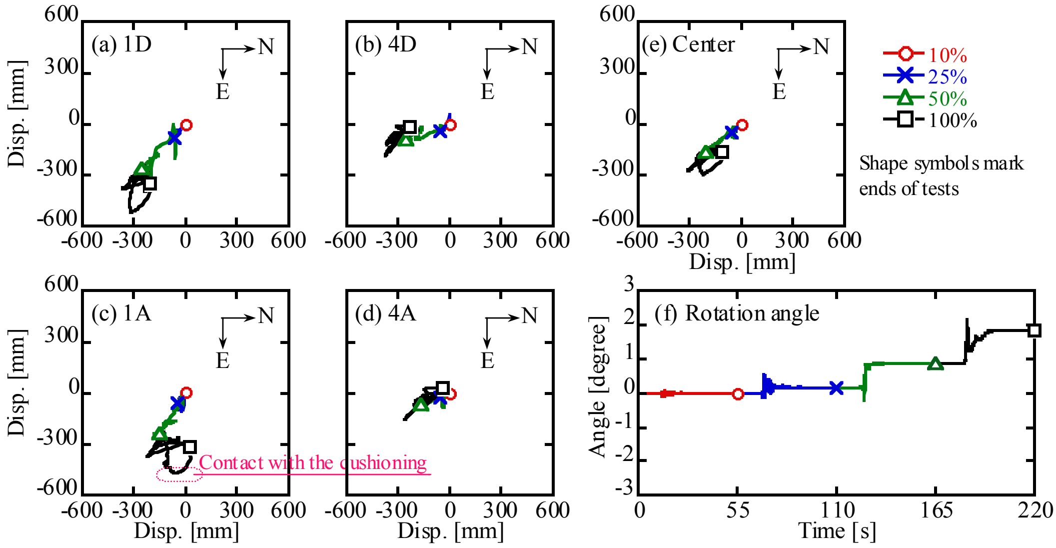


Fig. 9: Base slip displacement

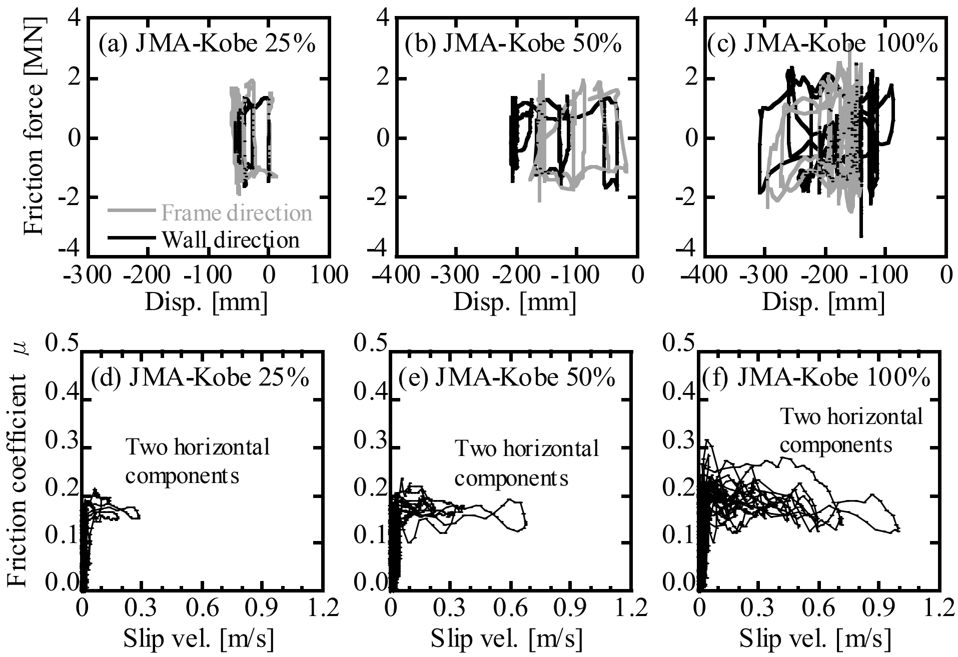


Fig. 10: Friction coefficient

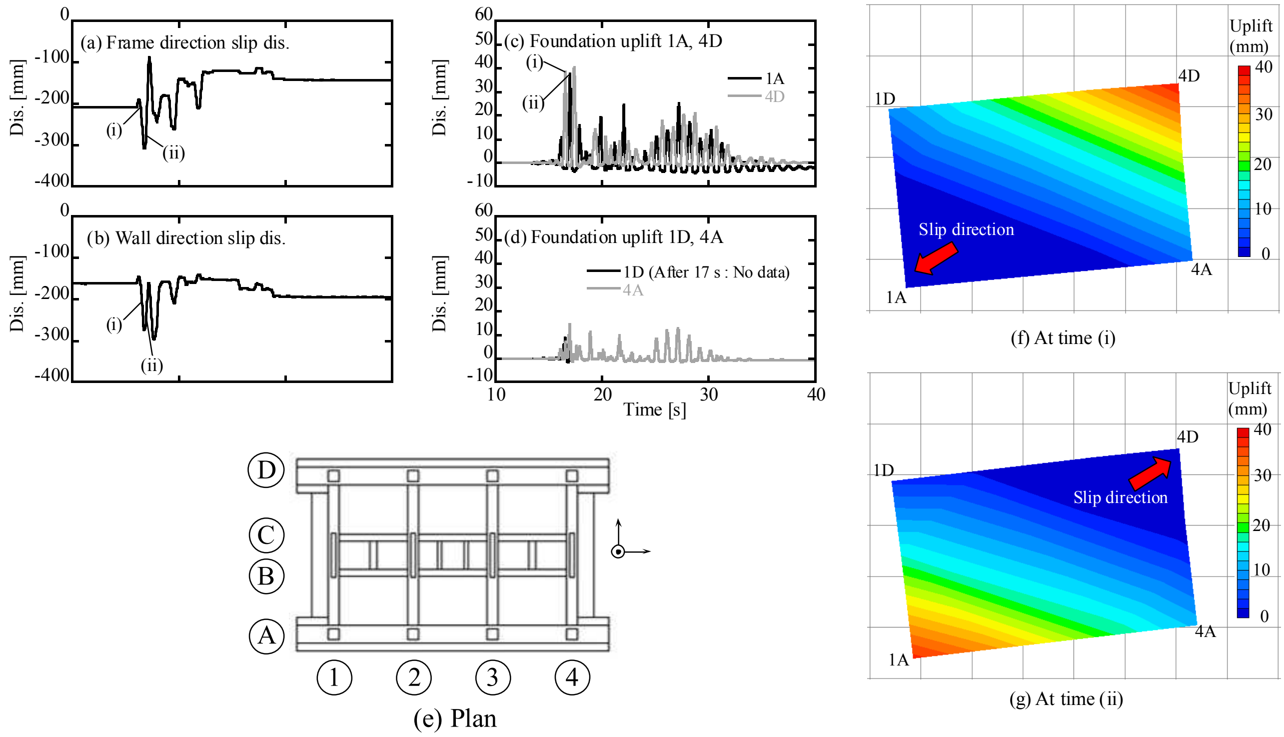


Fig. 11: Base slip motion of JMA-Kobe 100%

5. Specimen Damege

Since the amount of maximum deformation is just a little over 1/200 in the base slip construction test, there were only hairline cracks of 0.05 mm widths or less in the midstory beam ends, floor slabs, and column midsections after excitation. In the base fixed test under 50% amplitude excitation, the interstory drift peaked at 0.0171 rad in the frame direction. From the damage observed after excitation shown in Fig. 12, it can be seen that the number of cracks have increased. Cracks found at beam ends and beam-column joints were up to around 0.15 mm wide.

Under 100% amplitude excitation, the beam-column joint failure progressed further until the concrete cover spalled, whereas in the wall direction, the compression side concrete at the base of the multi-story shear wall started to crush. Moreover, concrete cover spalling was observed at the base of the 1st floor corner column (Figs. 13(a) to (c)).

In Table 3, row (a) shows the shear verification ratio, which is defined as the ratio of shear force to shear strength of beam-column joints based on material strengths assumed in the design, and row (b) shows the ratio calculated using concrete strengths during the test and reinforcement yield strengths based on materials testing. Similar to the specimen design, the shear strengths of beam-column joints were calculated based on the Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Inelastic Displacement Concept[10]. Additionally, the shear forces acting on beam-column joints were calculated assuming plastic hinges formed at the beam ends.

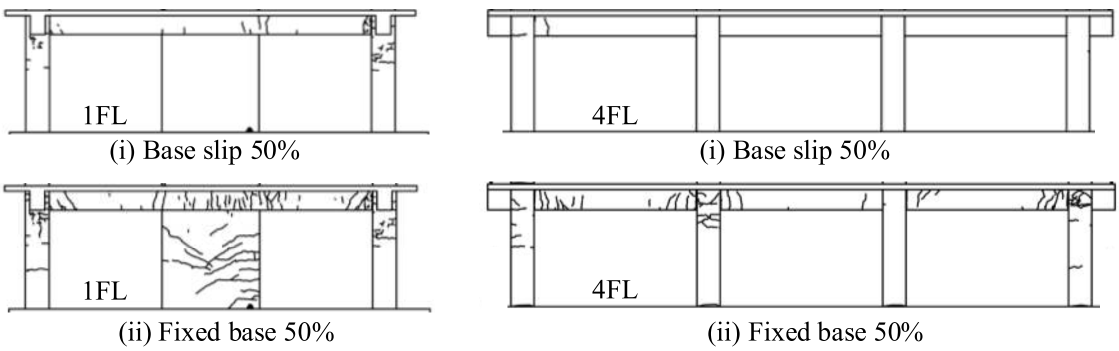
Compared to row (a), larger margins were evaluated for row (b), which reflects the material properties during the test. However, damage was concentrated in the beam-column joints in the test. Furthermore, column main reinforcements and joint hoops were partly exposed due to concrete cover spalling. This degree of damage in beam-column joints is thought to fall under damage level III or IV in the frame damage level classification used in the Japan Institute of Architects (JIA) Post-Earthquake Temporary Risk Evaluation of Damaged Buildings, where the building itself is not leaning but the level of damage can be assessed as moderate or heavy.

Accordingly, the damage in beam-column joints is discussed here. Figure 14 shows the ratio of column to beam moment capacity calculated based on the conditions during pushover analysis in the specimen design, while Fig. 15 shows the bar arrangement details at the 4th story beam-column joint where damage was significant. The joint hoops are 2, 2-D10@150. Figure 16 shows the main reinforcement of beam 5G1 and the maximum tensile strains in the 5th floor slab reinforcement. The bottom rebar yielded in beam 5G1. Assuming that the reinforcement yield strain is 0.2%, the top beam rebar and slab reinforcement adjacent to beam 5G1 (both top and bottom) exceed the yield strain. Strains close to yielding were generated in the other slab reinforcements as well. Furthermore, roughly equal strains were produced between the pairs of top and bottom slab reinforcement.

Previous studies have shown that bottom slab rebar embedded in the transverse beam can also contribute to beam strength[11]. Hence, ratios of column to beam moment capacity during the test were thought to be actually closer to unity because of the effect of slab reinforcements. In rows (a) and (b) of Table 3, the strengths of the beam's main reinforcement and the top slab rebar within 1 m of the beam side were taken into account in calculating the shear acting on the beam-column joint. On the other hand, in row (c) of Table 3, the shear margin was calculated while assuming that slab reinforcements, both top and bottom rebar, up to the center of span and within the cantilever slab, contribute to the shear acting on the beam-column joint. Under this condition, the ratios of shear force to shear strength of cross-shaped joints from the 3rd to 5th stories, which showed particularly significant damage, are 0.66 to 0.77. Even with this conditional assumption, the verification ratios are less than unity.

The hysteretic behavior of the 4th story, where the maximum story drift angle is large, and which showed pronounced beam-column joint damage, is shown in Figs. 17(b) to (d). In the 100% amplitude excitation in Fig. 17(c), the hysteresis loop going toward point b or point c is spindle-shaped, with a story drift angle of 0.028 rad (point b) and a beam-column joint shear deformation angle of 0.008 rad (Fig. 17(a)). Thereafter, the succeeding cycles shifted into a slip hysteresis.

In addition, the main reinforcements yielded at beams and columns attached to the cross-shaped joints from the 3rd to 5th stories, where damage was concentrated. Based on these conditions, the damage in beam-column joints from this experiment may be considered as falling under the beam-column joint yielding condition shown by Kusuhara et al.[12].



(i) Base slip 50% (i) Base slip 50%

(ii) Fixed base 50% (ii) Fixed base 50%

(a) 1F 4A-4D West side (b) 4F 1A-4A North side

Fig. 12: Damage observation results

(a) 4th story beam-column joint

(b) 1st floor column base

(c) 1st floor wall base

Fig. 13: Specimen damage

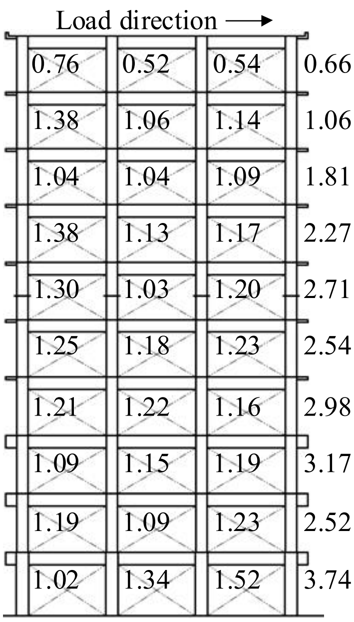


Fig. 14: Ratio of column to beam moment capacity

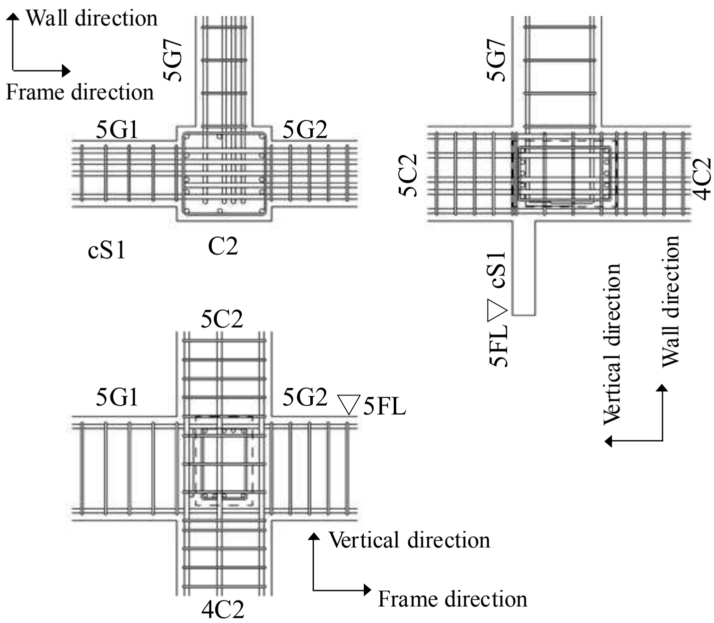


Fig. 15: Detailed view of beam-column joint

Table 3: Shear force / Shear strength of beam-column joint

Story	1		2		3		4		5	
Location	C1	C2	C1	C2	C1	C2	C1	C2	C1	C2
(a)	0.74	0.60	0.85	0.69	0.87	0.82	0.87	0.82	0.87	0.82
(b)	0.54	0.44	0.60	0.49	0.61	0.57	0.69	0.65	0.72	0.67
(c)	0.66	0.50	0.74	0.56	0.77	0.66	0.87	0.74	0.90	0.77
Story	6		7		8		9		10	
Location	C1	C2	C1	C2	C1	C2	C1	C2	C1	C2
(a)	0.84	0.77	0.84	0.77	0.73	0.65	0.73	0.65	0.48	0.42
(b)	0.53	0.49	0.57	0.52	0.47	0.42	0.53	0.47	0.36	0.31
(c)	0.70	0.58	0.76	0.62	0.65	0.51	0.73	0.57	0.53	0.39

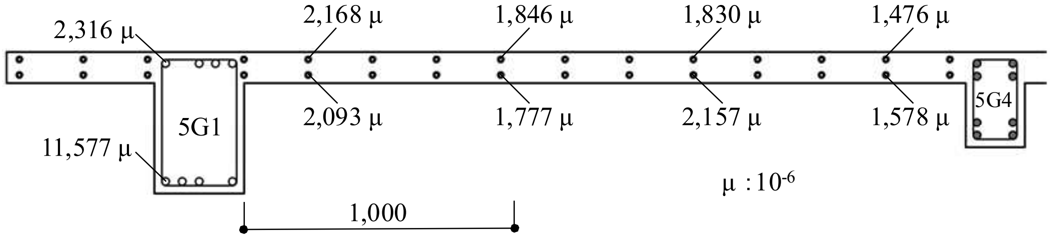


Fig. 16: Maximum strain of JMA-Kobe 100%

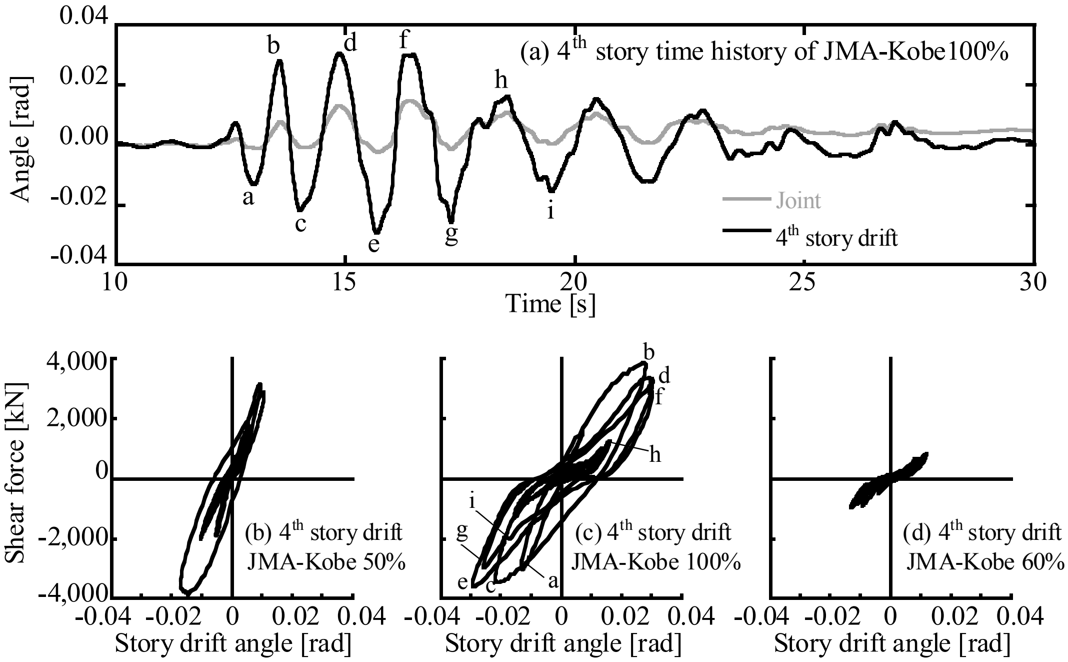


Fig. 17: Hysteretic behavior of 4th story

6. CONCLUSIONS

The following can be concluded from the data obtained from shaking table tests on a 10-story reinforced concrete building:

- In this experiment, base slippage caused the external forces acting on the specimen to be smaller, thereby making the story drift angles smaller and reducing damage to the frame.
- base slippage occurred together with base uplift, seismic forces acted on the specimen when the slip resistance center of rigidity had moved away from the specimen's center of gravity, thereby causing the foundation to move rotationally.
- The story shear force generated at each floor when the base was fixed was larger compared to the story shear force calculated during the specimen design for the same deformation.
- Damage was concentrated in the cross-shaped beam-column joints where column-to-beam flexural strength ratios are slightly greater than unity.

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