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

Part 2: Specimen Fabrication and Construction, Test Procedure, and Instrumentation Program

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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 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 performed tests on a 10-story reinforced concrete building frame on the E-Defense in order to gain building engineering knowledge that will enable continued use of buildings after a major earthquake. In this experiment, data was obtained from the structure equipped with a base slip mechanism to examine the efficacy of the base slip construction 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 specimen fabrication and construction, as well as the test preparations. Because of testing facility and specimen transport constraints, the specimen was fabricated in two separate parts at the outdoor grounds of the Hyogo Earthquake Engineering Research Center: one part consisting of the 1st floor to the middle of the 6th floor and another from the middle of the 6th floor to the rooftop. The two separately fabricated parts of the specimen were joined on top of the shaking table to produce a 10-story reinforced concrete building specimen. The base slip construction test was performed first, after which the specimen foundation was fixed to the shaking table and the specimen was tested in that condition.

Finally, we discuss the instrumentation for measuring the specimen response. The floor acceleration and story drift at each story, reinforcement strains, shear wall deformations, and other measurements were taken in a total of 654 channels.

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", 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 first set of experiment using a six-story specimen, collapse phenomena due to shear failure of the first-story shear wall and short columns were observed. The second set of experiments using a three-story specimen demonstrated the mitigating effect on ground motion input by 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 the 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 specimen 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. Apart from this, in the 2011 Great East Japan Earthquake, which occurred off the Pacific coast of Tohoku, there were some 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 experiments carried out by NIED in 2015 was to gain building engineering knowledge that will enable continued use of buildings after a major earthquake. Shaking table tests were performed to obtain basic data on a 10-story reinforced concrete building fabricated with base slip construction in order to gain information on making continued use of a building possible after an earthquake. Furthermore, shaking table tests were likewise performed on the conventional fixed base condition 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 fabrication of the specimen used in the tests, after which the procedure for performing the base slip construction test and fixed base condition test will be discussed. Furthermore, since it is essential that accurate data be obtained for the analysis of test results, this paper also discusses the instrumentation for data acquisition of response acceleration, inter-story drift, and other data used as the basis for analyzing test results.

2. Specimen Fabrication

The specimen used in the shaking table tests was fabricated and constructed at the outdoor yard of NIED's Hyogo Earthquake Engineering Research Center (Fig. 1) from February through October in 2015. Since there was a period of around 300 days from the start of specimen fabrication and construction work until the day of the excitation test, the age of concrete material on each floor frame at the time of the excitation test was 134 to 253 days. Thus, the each material strengths were confirmed by test pieces collected from each floor at the time of the excitation tests. (Table 1).

The concrete quality was confirmed by the air content tests, slump tests, and chloride ions densitometry. Figs. 1(a) to (c) show the placement of concreate form, rebar arrangement, and concrete placing at the site. In principle, the supervision of works for the rebar arrangement and concrete placing followed the Japanese Architectural Standard Specification for Reinforced Concrete Work JASS5 [6]. Figs. 2(a) to (c) show the cast iron bearing surface and its setting at the site. The cast iron bearing surfaces were polished to provide a smooth level surface and the peripheries of the cast iron bearings were chamfered. Studs were placed at the backside of the bearing in order to integrate it with the footing beam.

Because of constraints in lifting and transport of the specimen, the 10-story building specimen was fabricated in two separate parts: from the footing beam to the middle of the 6th floor (hereinafter referred to as the lower specimen) and from the middle of the 6th floor to the rooftop (hereinafter referred to as the upper specimen). The lower and upper specimens were joined at the middle section of the 6th floor columns and walls. Steel plates with 200 mm larger than cross-sectional dimensions of column and wall members were attached at the column and wall connecting surfaces of both specimens (Fig. 3, t = 19 mm at walls, t = 25 mm at columns), which overhang each side of the members by 100 mm.

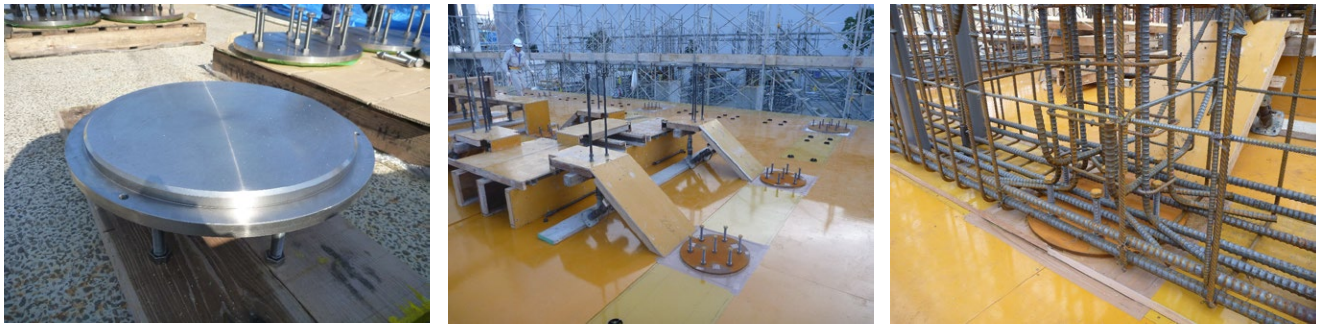
The overhanging parts of the steel plates were provided with 28 mm-diameter holes, and the lower and upper specimens were connected by tightening a total of 184 M20 high strength bolts, thereby joining the steel plates to each other. Blasting was performed at the steel plate connecting surfaces to provide frictional force, and rebar for embedment to the reinforced concrete main frame were stud welded at the backside of the steel plates. The embedment lengths are L = 760 mm at the columns and L = 520 mm at the walls.

Table 1: Concrete strength

Story	1st	2nd	3rd	4th	5th	6th bottom	6th upper	7th	8th	9th	10th
Age [days]	237	211	189	164	143	134	253	227	204	179	153
F_C [N/mm^2]	42	42	33	33	33	27	27	27	27	27	27
σ_B [N/mm^2]	68.7	72.0	57.6	48.1	45.5	42.1	54.6	49.0	51.9	43.9	41.0

(a) Wall and column rebar (b) Beam rebar (c) Concrete placing

Fig. 1: Specimen construction



(a) Surface (b) Setting (c) Cast iron and footing beam rebar

Fig. 2: Cast iron bearings

(a) Joint steel plates (b) Bottom part of 6th floor (c) Upper part of 6th floor

Fig. 3: Specimen joints

3. Test Procedure

The procedure for mounting the specimen to the shaking table and performing the excitation tests were as follows:

(1) Bind the base concrete to the shaking table using prestressing rods.

(2) Mount the lower specimen on top of the base concrete.

(3) Mount the upper specimen on top of the lower specimen, and connect the specimen joint plates to each other by tightening the high-strength bolts.

(4) Perform the excitation test on the base slip construction.

(5) Restore the drift in specimen position due to base slip construction testing to its initial position using hydraulic jacks.

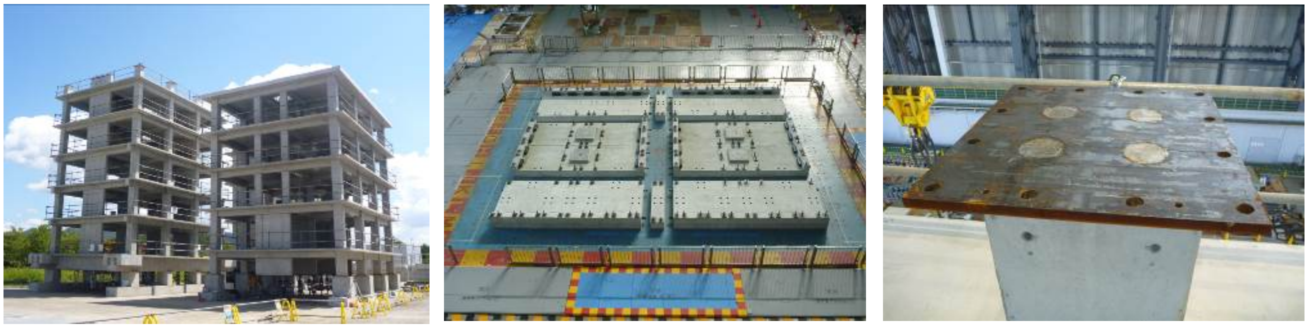
(6) Bind the specimen foundation to the shaking table using prestressing rods and install the collapse protection frame on the specimen exterior.

(7) Perform the excitation test on the fixed base condition.

The specimen was fabricated outdoors and photos for procedures (1), (2), (3), (5), and (6) above are shown in Fig. 4. Fig. 5 shows the base fixing condition for both the base slip and fixed base tests. For the base slip test, only the base concrete was bound to the shaking table, whereas the specimen was merely placed directly on top of the base concrete. In contrast, for the fixed base test, the specimen's footing beam was also bound to the shaking table together with the base concrete, thereby integrating the specimen foundation and shaking table into a single body.

A carrier with a 900 t capacity and two overhead cranes (maximum lift load, 400 t each) were used to transport the specimen from the outdoor yard to the shaking table. To prevent cracks from occurring due to deflection during lifting, the lower specimen's footing beam was prestressed in the longitudinal direction. Figure 6(a) shows the prestressing work being performed. The upper specimen was transported with the self-weight taken up by a steel frame for the lifting.

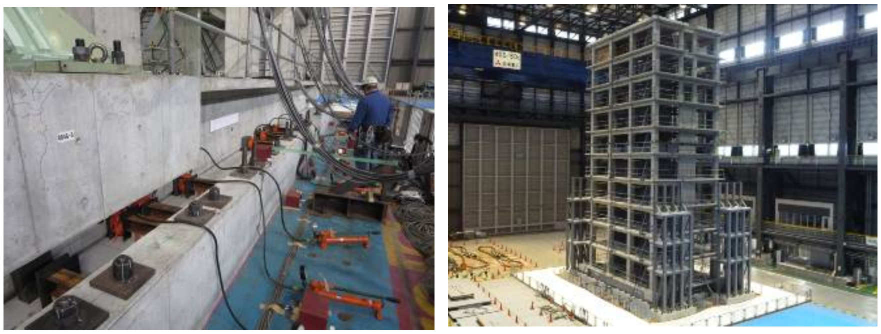
After connecting the upper specimen to the lower specimen, the lifting steel frame was fixed to the 6th floor slab by anchor bolts. When the specimen was removed after completion of the tests, the lifting frame was again used to separate and transport the upper specimen and the lower specimen. The installed steel lifting frame and specimen carrier conveyance are shown in Figs. 6(b) and (c). The carrier was set under the specimen, which was fabricated while elevated on a concrete frame. The specimen was lifted off the concrete frame by raising the carrier platform, after which the specimen was transported inside the test building.



(a) Construction site (b) (1) Concrete base (c) Joint steel plate

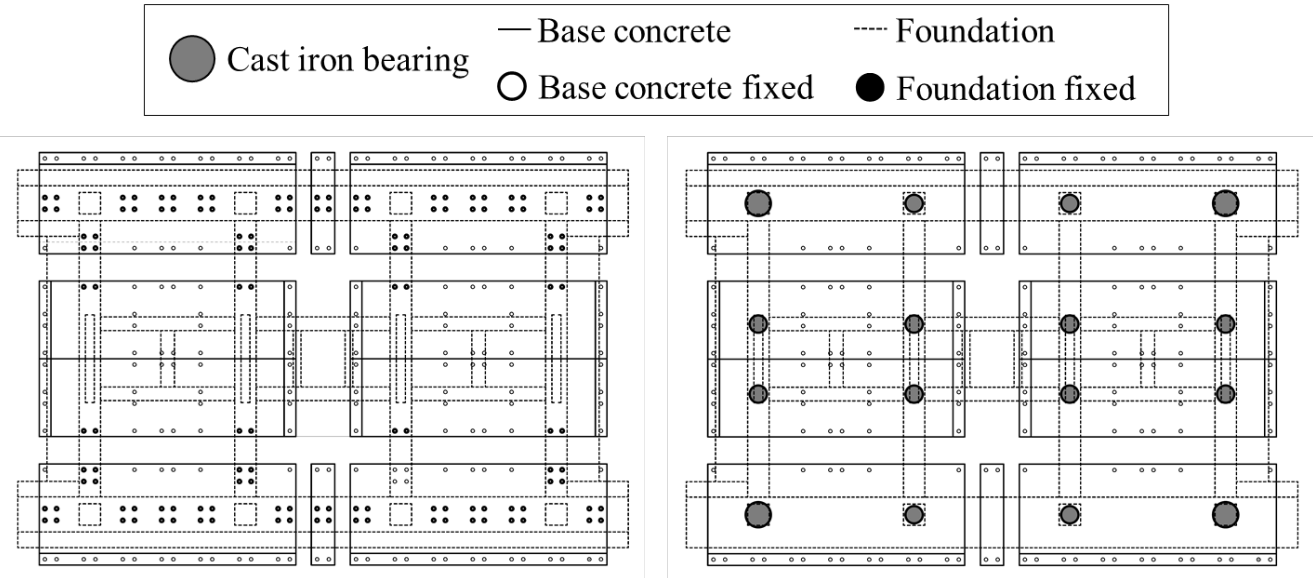
Fig. 4: Shaking test procedure

(d) (2) Lower specimen (e) (3) Upper specimen (f) (3) Specimen joint



(g) (5) Specimen return (h) (6) Base fixed specimen

Fig. 4: Shaking test procedure



(a) Base slip test (b) Fixed base test

Fig. 5: Base-fixing condition

(a) Prestressing (b) Steel frame for conveyance (c) Specimen conveyance by carrier

Fig. 6: Specimen conveyance procedure

4. Instrumentation

To determine the response behavior of the specimen and its damage process, the floor acceleration and story drift at each story, deformation of members, reinforcement strains, and so on were measured. Each floor acceleration at each story was measured by triaxial accelerometers installed on the floor slab at two locations on each floor (Fig. 7(a)).

Inter-story drifts were measured as the relative displacement between the steel frame fixed on top of the floor slab at each floor and the rectangular steel pipe fixed to the bottom of the upper floor slab (Fig. 7(b)). Base slip displacements were measured by laser displacement sensors installed on top of the base concrete bound to the shaking table and in the steel frame bound directly to the shaking table. Displacement sensors for measuring base slip were installed at two locations on each of the four sides of the specimen's outer circumference, for a total of eight locations.

In addition, displacement sensors were installed at 10 locations on the sides of the footing beam to measure base uplift as well (Figs. 7(c) and (d)). Bending and shear deformations were measured at shear walls on lower floors, where deformations are expected to become large (Fig. 7(e)). Furthermore, shear deformations on cross-shaped beam-column joints were also measured from the lower through middle floor levels, where the margin of shear strength is relatively small (Fig. 7(f)). As a result, there were 654 measurement points. The data sampling frequency was 1,000 Hz. In addition, videos were taken at 52 locations to record the overall behavior of the specimen and the damage process at members, beam-column joints, and other areas.

After the test, sketches and photos of cracks were taken to record the damaged condition of the specimen.

5. CONCLUSIONS

The specimen fabrication, test procedure, and measurement of specimen response were presented for the shaking table tests conducted by NIED on a 10-story reinforced concrete building in December 2015.

- The specimen was fabricated in two separate parts: one from the 1st floor to the middle of the 6th floor and another from the middle of the 6th floor to the rooftop.
- The separately fabricated parts of the specimen were individually transported to the shaking table and assembled into a 10-story building on top of the shaking table.
- To record the response and damage in the specimen from the excitation tests, measurements at 654 channels and videos at 52 locations were taken.

(a) Acceleration (b) Story drift angle (c) Base slip

(d) Base liftup (e) Wall deformation (f) Beam-column joint deformation

Fig. 7: Instrumentation

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