FULL-SCALE DYNAMIC COLLAPSE TESTS OF THREE-STORY REINFORCED CONCRETE BUILDINGS ON FLEXIBLE FOUNDATION AT E-DEFENSE

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ABSTRACT:

E-Defense, the world largest three-dimensional earthquake simulator, has been operated and available for shake table tests since 2005. A five-year national project on seismic safety of urban areas has started from 2002, as a part of which seismic performance of existing reinforced concrete (RC) buildings were investigated through the full-scale shake table tests at E-Defense in 2005 and 2006. The second phase tests were conducted for two three-story school buildings with flexible foundation from September to November 2006. One was a bare RC specimen simulating an old and non-ductile school building in Japan and the other was a retrofit specimen strengthened with attached steel braces. The two specimens were tested with the following specific objectives: (1) the simulation of progressive collapse of existing school buildings, (2) verification of strengthening effect by the attached steel frames, and (3) soil-structure interaction with flexible foundation. The observed seismic performances and the measured responses of the two specimens in the shake table test are presented in this paper mainly focused on the failure mechanisms with the effects of the base conditions.

KEYWORDS: Shake table test, sway, input loss, friction coefficient, extreme motion

1. INTRODUCTION

Strong earthquake motions exceeding the current design standard level have been recorded during recent severe earthquakes in Japan and US, such as Northridge 1994, Hyogoken-Nanbu 1995, Tottori-Seibu 2000 and Niigata-Chuetsu 2004 and Niigata-Chuetsu-Oki 2007. However, the damages of existing reinforced concrete building structures estimated from the inelastic time-history analyses using the accelerograms recorded at free-fields generally overestimates the observed damages, especially for the cases with slight or minor damages of low-rise buildings in Japan. The discrepancy between the damage observation and analyses has not yet been interpreted with rational background data because the minor damages or less made no difference as result in the viewpoints of disaster prevention. However, the damage ratios of existing buildings on site should have been correlated quantitatively with the recorded ground motions in scientific or engineering viewpoints, which are essential to rational performance objectives in seismic design and retrofit codes based on realistic behavior of actual structures at present and also in the future.

The reasons for above discrepancy could be estimated as either or combination of: (1) the actual strength of the existing buildings are generally higher than the calculated strength used in the analysis, (2) the residual damages in post-earthquake inspection are generally underestimated than those estimated from the maximum responses in the calculation, and (3) the earthquake intensities input to the buildings are generally smaller than those recorded in the free fields, due to soil-structure interaction or input loss at the foundation. However, rigorous verification by laboratory test or field observation on the problems are very much limited (Kabeyasawa, 2005 and 2006)

E-Defense, the world largest three-dimensional earthquake simulator, has been operated and available for shake table tests since 2005. A five-year national project on seismic safety of urban areas, referred to as DaiDaiToku project, has started from 2002 in Japan. As a part of the project, seismic performance of existing reinforced concrete buildings are investigated through component tests, scaled shake table tests and collapse analyses from 2002 to 2004, and the full-scale shake table tests at E-Defense were planned and conducted in 2005 and 2006. The first full-scale shake table test on reinforced concrete buildings was conducted for a six-story wall-frame building in January 2006(Kabeyasawa, 2005). The second phase tests were conducted for two three-story school buildings with flexible foundation from September to November 2006. The plan and objectives of the shake table tests and the results of the bare reinforced concrete specimen are outlined in this paper. The detailed data and results were reported and are being reported elsewhere(Kabeyasawa, 2007).

2. METHOD OF TESTING

2.1 Plan and Design of the Specimens

Two three-story specimens are designed to be tested with the following specific objectives: (1) the simulation of progressive collapse of existing school buildings, (2) verification of strengthening effect by the attached steel frames, and (3) soil-structure interaction with flexible foundation. Birdseye views of the specimens are shown in Figure 2. The first specimen is a bare reinforced concrete school building designed following 1970' Building code of Japan. The failure mode of the bare specimen under an extreme motion is expected to be shear and axial collapse of columns in the first story starting from flexure to shear failure of the short columns, then inducing progressive structural failure with redistribution of column axial loads. The second one is a specimen originally designed and constructed as identical as the first bare reinforced concrete specimen, but strengthened after the construction with attached steel frames, simulating seismic retrofit of existing buildings. The failure mode of the specimen would change into an overall mechanism of rocking and sway at the foundation. Effectiveness of a conventional detail and a new detail for strengthening is to be verified and compared.

(a) Bare RC specimen

(b) Strengthened specimen

Figure 1 Overviews of the specimens in the container with backfill soil on the shake table

Both specimens are constructed on a pool-shaped container with backfill soils without fixing at the base. The concrete is placed on the base concrete surface with the construction joint modeling the load-baring foundation so that the shear transfer at the joint would be friction and cohesion of concrete surface. The flexible boundary condition for the shaking table test would be the world first trial simulating the rocking and sway behavior with neighborhood soils, which could be made realistic only by the full-scale test.

2.2 Plan of the test specimens

The structural floor plans, such as 1st floor plan, foundation level, and 2nd floor plan with the base container of the bare reinforced concrete specimen are shown in Figure 2. The structure has three spans in the longitudinal (Y) direction, two spans in the orthogonal (span, X) directions. The span length is 4m in Y-direction, 2m and 6m in X-direction. The specimen models an end part of typical Japanese schools in the longitudinal direction, where irregular location of columns has often been adopted to make a special classroom with wide span. Note that total number of columns is 11 and a column at X2 and Y2 is missing from regular location. Structural walls are located in 6m span of the outer two frames in X-direction, which is also a typical plan.

The elevations of the frame structures are shown in Figure 3. The inter-story height is 2.5m each for the 1st to 3rd story, which is not corresponding to the full-scale but approximately by five-sixth. The scale of the specimen is selected considering the limitation of the crane capacity of 800ton and the area of the shake table 20mx15m. The steel weights of 370 kN were attached on the roof after setup on the table in order to adjust the scaling effect. Both outer frames in the longitudinal direction have spandrel walls or standing walls, which are also typical in Japanese school buildings. The spandrel wall heights in these frames are different as 1.2m in X1-frame, as is typical on the north side, and 0.8m in X3-frame as on the south side. The balcony floors are extended 1.0m from each frame center line in peripherals at the 2nd through roof floors, which is not typical plan for schools, but for convenience of experimental works such as measurement and damage observation.

As for the foundation, the height of the foundation beams and the footings is 0.8m. The backfill soils are infilled into the surrounding area at the base of the specimens, 1.0m width from the footing or 1.4m from the foundation beam to the side face of the container beam. No reinforcement are placed accross the construction joint at the bottom of the footings, while insert for bolts were inbeded at the base of the container for fixing the footings to the container in case of the test with the fixed foundation.

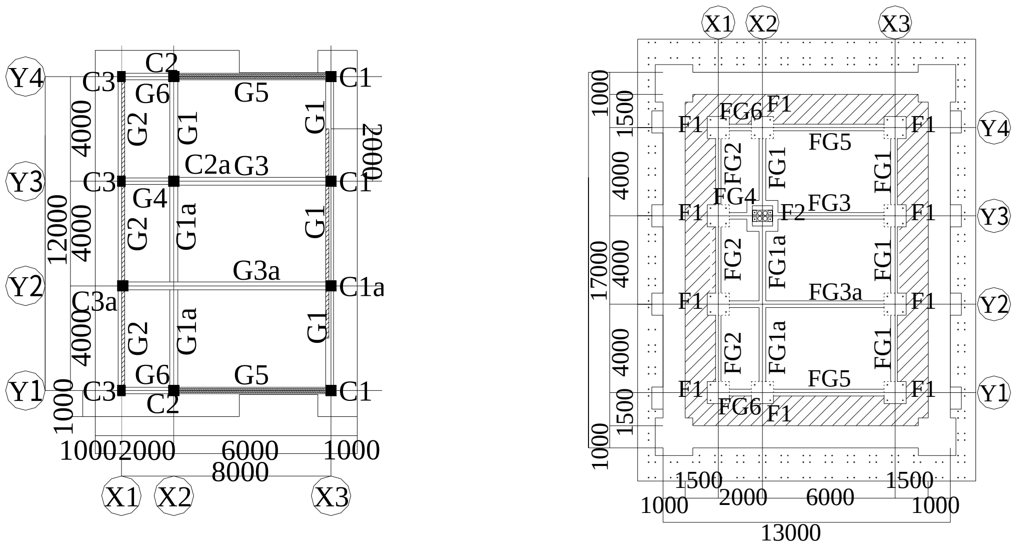

Figure 2 Structural floor plan of the specimens with the container at the base

2.3 Section and Reinforcement Details

The structural calculation was conducted based on the allowable stress method in accordance with the AIJ standard of 1975 edition(AIJ, 1975) and Building Standard Law and the Corresponding Enforcement Order in 1970'. The earthquake lateral loading is rectangular distribution based on uniform seismic coefficient for inertia of 0.2. The calculated weights of the roof, 3rd, 2nd and base level including steel weight on the roof and other instruments are 1103kN(roof) 789kN(3F) and 789kN(2F) and 855kN(base) respectively assuming 2.4 for concrete density.

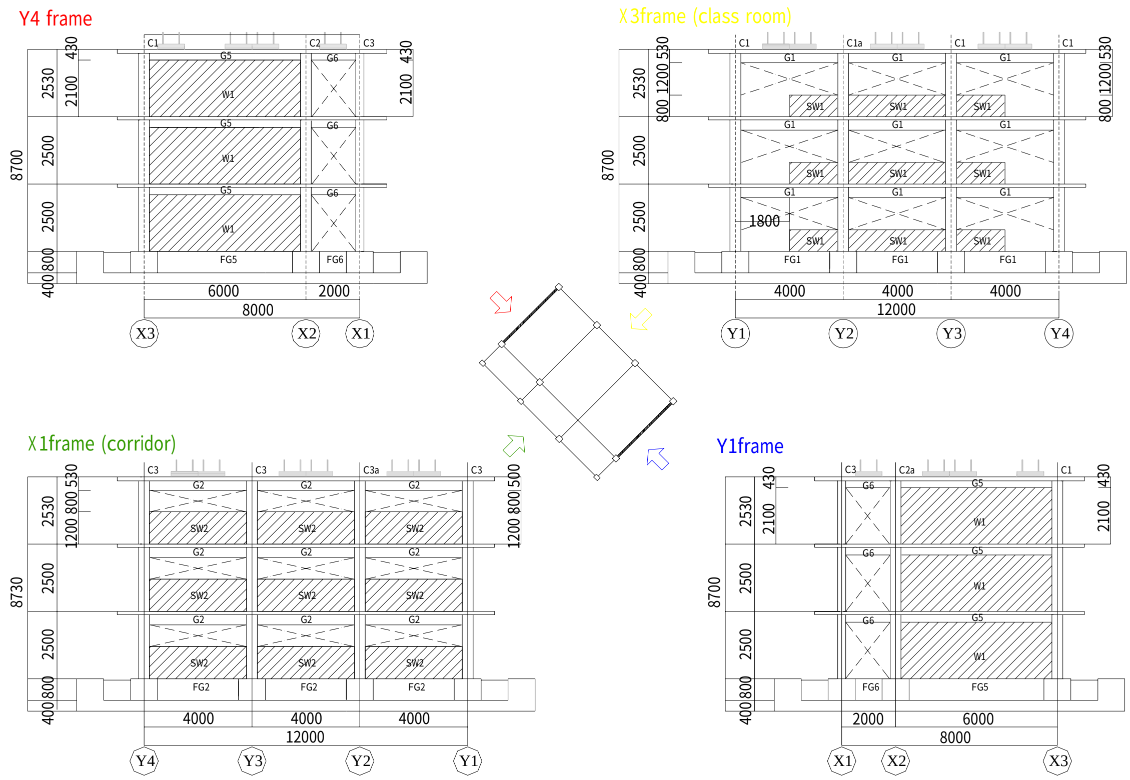

Figure 3 Structural elevation of the bare RC specimen

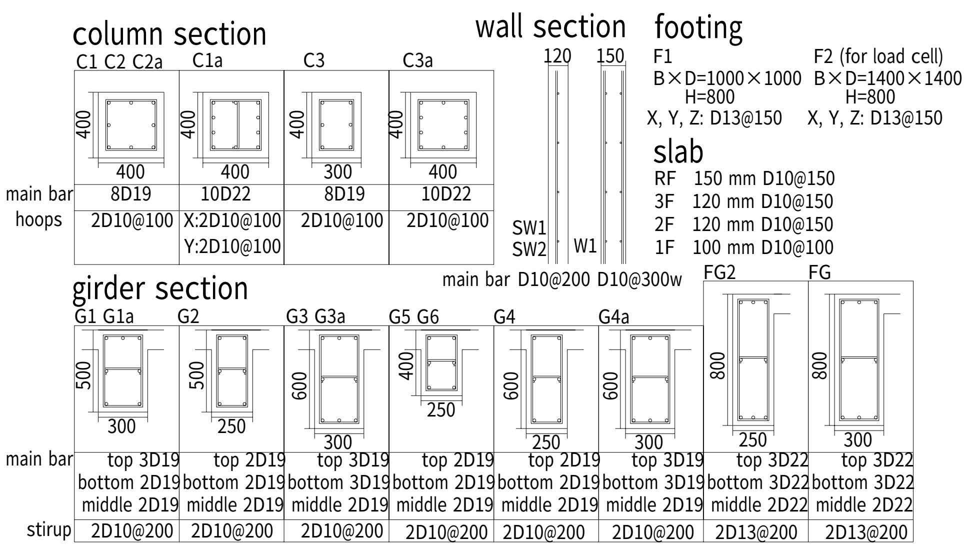

Figure 4 Section size and reinforcement details

The section sizes and the reinforcement details are shown in Figure 4. The slab thickness is 150mm for the roof, 120mm for the 2nd and 3rd floors, and 100mm for the 1st floor. The standard column section is 400×400 mm with 12-D19 (ρy =1.4%, ρw =0.356%), and that of girders is 300×500 mm with 3-D19 at top (ρtop =0.573%) and 2-D19 at bottom ($\rho bottom$ =0.382%). The sections of three short columns in X1 frames are 300×400mm with 8-D19 (ry =1.9 %). The column hoops are D10@100 based on the minimum requirement of spacing, although the ratio (0.35%) is relatively high because of the scaled column section by five-sixth. The thickness of the structural walls is 150 mm with 2-D10 at spacing of 300mm(ρw =0.32%). The concrete strength of the 1st story was estimated from the cylinder test as 31Mpa for the first bare specimen and 28 MPa for the second retrofit specimen. The strength of rebars of D19 was 384MPa.

2.4 Setup and Measurements

Four types of measurement devices were used as: accelerometers(including velocity types), displacement meters, strain gauges, and load cells, the number of channels for which was about 450ch in total. Three-dimensional absolute acceleration meters are distributed on structural nodes in each story and on the container. Relative inter-story displacements in three directions are measured for each story by the condencer displacment meters attached to the steel braced frames at the corners of each floor, which are also designed against the axial collapse of the specimens. Also displacment meters are located between the foundation and the containers at the bases and in the peripheral to measure the horizontal and vertical dislocations of the base from the container. Local deformations of members and strains in the reinforcement are also measured.

2.5 Seismic Evaluation

As a part of preliminary analyses such as with pushover analysis and dynamic analyses, seismic evaluation for existing buildings was conducted based on the Japanese Standard (JBDPA, 2001) during the plan and design of the test specimens. The relations are based on the calculated strengths and deformability of the columns assuming the story mechanism. The cumulative seismic strength coefficient CT is the sum of the ultimate strengths of the first story columns, either major value of shear and flexural strengths, expressed in terms of story shear coefficient. The ductility index is taken as F=0.8 for the short columns in the shear failure, F=1.0 for the shear dominant columns and F=1.27 and more for the flexural columns, which are derived from the ratio of shear strength to flexural strength. In the sum of the strength index, the different yield deformations of the columns are considered with approximate assumption and associated strength contribution factor at the calculated ductility level. The seismic index of the designed specimen is Is=0.51(F=0.8, $C_T S_D$=0.63) due to the short columns in X1-frame on the corridor side, which is less than the standard objective performance levels: Is=0.6 for ordinary buildings and Is=0.7 or 0.75 for school buildings. The bare RC building should be retrofitted in Japanese practice. The calculated maximum base shear coefficient 0.63 at the failure of short columns was made a little less than or equal to the estimated friction coefficient at the base shear.

3. TEST RESULTS

3.1 Static Pushover Test on Base Slip Behavior

Static tests were also planned and carried out to identify the friction coefficient between the foundation base and the surface of the container slab including the passive resistance of the surrounding infill soils. This is also to replace the dislocation of the foundation, which would occur during the dynamic test with flexible foundation. Therefore the static test was conducted on the table after the test and then the foundation was fixed to the container to conduct the dynamic test in case with the fixed base. Oil jacks were placed on one side of the container at the upper level of the footings and the foundation beams to push the upper structure in the other direction with the reaction of the container beam as shown in Figure 6. Static load versus dislocation relation under the constant vertical load is to be obtained as 0.7 to 0.8 including resistance by backfill soil, which is estimated to be around 0.1, as shown in Figure 6.

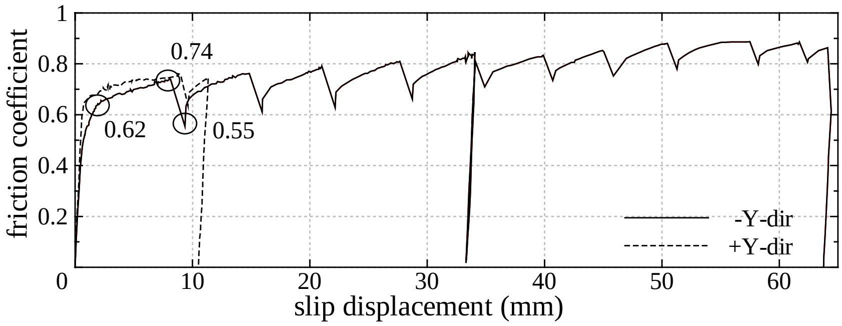

Figure 6 Static tests on base friction and friction coefficient-slip relations from the test

3.2 The Dynamic Test of The Bare RC Specimen

The dynamic tests for the two specimens were conducted at E-Defense from September to November 2006 as listed in Table 1. The test procedure and observed structural damage levels of the bare RC specimen in the first dynamic test are outlined in this section. The first test on the bare specimen was carried out 6 times from Sep 22 to Oct 2. The target earthquake record of all the test runs was the same, JMA_Kobe 1995(JMA, 1995), and the amplitude ratio to the original level was varied as RUN1: 0.1, RUN2: 0.25, RUN3: 0.5, RUN4: 1.0, RUN5: 0.75, and RUN6: 1.0. The base was not fixed but with construction joint to the container through RUN1 to RUN4 allowing sway and rocking mechanism. Although the bolts were used to fix the footings before RUN5, the sway mechanism has occurred because the stiffness and the pretension of the bolts were not enough. In the RUN6, therefore, the steel plates were placed in the backfill soils between the footing and the container to prop the sway movement.

The damage level was evaluated and identified based on the standard (JBDPA, 2001) after each run as listed in Table 1. Representative measured maximum response values are also listed in the table, such as the inter-story displacement in terms of rotation angle and the story shear in terms of shear coefficient. Minor damages were observed in the bare specimen after RUN4 under the 100% of JMA Kobe as shown in Figure 7(a). A story collapse occurred due to shear failure of short columns in RUN6 as shown in Figure 7(b) under almost the same level of input motion as RUN4. The hysteretic relations between the inter-story shear force and the displacement are shown in Figure 8 for RUN4 and RUN6. The response of the building structure remain less than yielding level in RUN4, while the response attained the well inelastic displacement up to near collapse during RUN6.

The obvious different levels of damages and responses between the two runs may be attribute to the sway dislocation at the base in RUN4. The relations between the measured slip displacement and the friction coefficient at the base are shown in Figure 9. The slip started around the level of 0.8 corresponding to the static coefficient in Figure 6, while the slip occurred at lower level around 0.4 in cyclic behavior after. Although the observed behavior need be investigated further in detail, owing to this behavior, the response spectra of the input base motions at the first story became apparently different from those of the motion at the shake table(pool slab) in RUN4, as compared in Figure 10, and also in RUN5, while the motions at the table and the first floor were almost identical in RUN1 to RUN3 under lower levels of input, and in RUN6 under the fixed base, where the slip did not occur. It may be concluded that the damage in RUN4 was minor because the motion was less effective to the upper building structure with the slip behavior of the swaying foundation.

Table 1 List of the shake test runs: input motions, base conditions, damages and responses

Run	Date	Motion	Base	Damage	Shear	Displacement
1	Sep25	Kobe 10	N	No	0.13	1/5000
2	Sep25	Kobe 25	N	Slight	0.28	1/2000
3	Sep27	Kobe 50	N	Minor	0.60	1/700
4	Sep29	Kobe 100	N	Minor	0.96	1/250
5	Oct2	Kobe* 75	FB	Moderate	1.08	1/180
6	Oct2	Kobe**100	FBP	Collapse	1.30	1/20

(Note on Table 1)
Motion: Input records and amplitudes in terms of the percentage ratio to the original intensity,
*: The target amplitude was 100% while the input in the test was 75% due to mistake,
**: The target amplitude was 130% while the effective input in the test was equivalent to 100%
Base condition: N:Free, FB:Fixed with bolts, FBP:Fixed with bolts and prop against sway,
FCP:Fixed with bolts at the corners and prop against sway (Figure 14)
Damage: Observed damage level identified after each run based on the standard by JBDPA[2001]
Shear: Measured maximum response of the 1st story shear in Y-direction in terms of story shear coefficient
Displacement: Measured maximum response of the 1st story displacement in Y-direction in terms of inter-story rotation angle (rad.).

(a) After Run 4 (Sway Foundation) (b) After Run 6 (Fixed foundation)

Figure 7 Damages to the bare RC specimen after dynamic tests

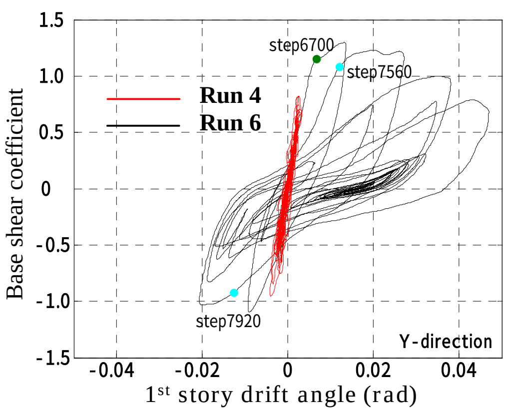

Figure 8 Hysteretic relations of the RC specimen

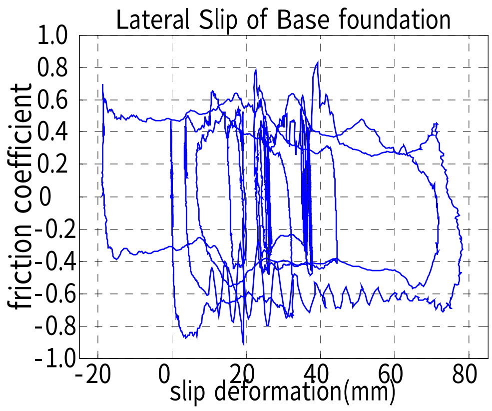

Figure 9 Hysteretic relations of slip deformation at base

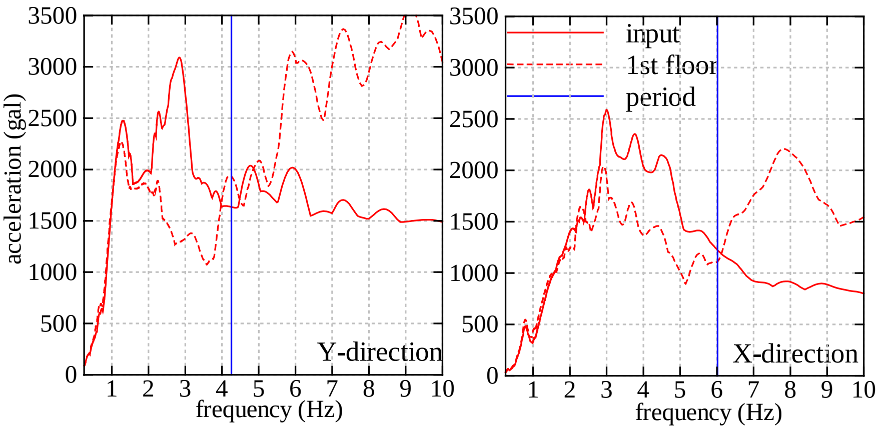

Figure 10 Response spectra of input motion at 1st floor

It might be still controversial whether the obvious slip behavior observed at the base of the specimen would occur or not at the foundation base in real building structures existing in site with soil and foundation. However, the base detail with construction joint with concrete surface could easily be designed and constructed similarly to the specimen, especially in case of spread foundation without piles. If we take into account the elastic stiffness of underneath soil in addition, the effect of input loss would be much more even with the lower level of acceleration. Therefore, the behavior could be positively taken into account as a fail-safe design against the extreme earthquake motion exceeding the design level, which are frequently observed at recent earthquakes such as near source, especially for low-rise or medium-rise typical reinforced concrete structures with relatively high strength and limited ductility.

4. CONCLUSIONS

The full-scale three-dimensional earthquake simulation tests on three-story reinforced concrete school building structures were conducted at E-Defense. The plan, specimens and results of the test are outlined. The damage observed in the bare reinforced concrete specimen was obviously minor under the extreme motion owing to the input loss with the slip behavior at the base. The observed behavior could be applied to the fail-safe seismic design of the RC building with higher strength and limited ductility.

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REFERENCES

Kabeyasawa, Toshimi, Kabeyasawa, Toshikazu, et al. (2005). Observation of aftershocks and damages in buildings after 2004 Niigata-Chuuetsu Earthquake(in Japanese). Proceedings of AIJ Annual Convention, Vol. IV, No. 2C, pp. 719-720.

Kabeyasawa, Toshikazu, Kabeyasawa, Toshimi, et al. (2006). Identification of input loss in base motion based on observation of aftershocks and damages to buildings after Niigata-Chuuetsu Earthquake(in Japanese). Collected Papers of Structural Engineering, Vol. 52B, 8pp.

Toshimi Kabeyasawa, Taizo Matsumori, Hideo Katsumata, and Kazutaka Shirai. (2005). Design of the Full-Scale Six-Story Reinforced Concrete Wall-Frame Building for Testing at E-Defense, The First NEES/E-Defense Workshop on Collapse Simulation of Reinforced Concrete Building Structure, Berkeley, July 6-8, NIED and PEER, 23-46.

Toshimi Kabeyasawa, Toshikazu Kabeyasawa, Taizo Matsumori, Kim YouSok, and Toshinori Kabeyasawa. (2007). Plan of 3-D dynamic collapse tests on three-story reinforced concrete buildings on flexible foundation. 2007 Structures Congress, SEI, ASCE, 16pp.

Toshikazu Kabeyasawa, Toshimi Kabeyasawa, Taizo Matsumori, Toshinori Kabeyasawa, and Kim YouSok. (2007). 3-D collapse test and analyses of the three-story reinforced concrete buildings on flexible foundation. 2007 Structures Congress, SEI, ASCE, 14pp.

Toshimi Kabeyasawa, Taizo Matsumori, Toshikazu Kabeyasawa, Toshinori Kabeyasawa, and Yousok Kim. (2007). Design of The Three-Story Reinforced Concrete Buildings with Flexible Foundations for Testing at E-Defense. Proceedings of The Second NEES/E-Defense Workshop on Collapse Simulation of Reinforced Concrete Building Structure, March 2007, pp. 225-242.

Toshikazu Kabeyasawa, Toshimi Kabeyasawa, Taizo Matsumori, Toshinori Kabeyasawa and Yousok Kim. (2007). Shake Table Tests on The Three-Story Reinforced Concrete Buildings with Flexible Foundations. Proceedings of The Second NEES/E-Defense Workshop on Collapse Simulation of Reinforced Concrete Building Structure, 243-254.

AIJ. (1975) *AIJ Standard for Structural Calculation on Reinforced Concrete Structures(1975 and Japanese version).* AIJ(Architectural Institute of Japan).

JBDPA. (2001). *Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings (2001 Japanese version and 2004 English version)* JBDPA(Japan Building Disaster Prevention Association).

JMA. (1995). An earthquake record in the south part of Hyogo-prefecture Jan.17. JMA(Japan Meteorological observatory Agency).

JBDPA. (2001). *Standard for Damage Level Evaluation and Guidelines for Recovery Technologies of Buildings Damaged by Earthquake.* JBDPA(Japan Building Disaster Prevention Association).