



Shaking table test of a reduced-scale reinforced concrete structure subjected to near-fault ground motion

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ABSTRACT

A high performance seismic simulation shaking table, which is located in Tainan Laboratory of the National Center for Research on Earthquake Engineering (NCREE), was established to reproduce the near-fault ground motion. The maximum horizontal stroke and velocity capacities of the shaking table are ± 1.0 m, ± 2.0 m/sec, respectively. The 2016 Meinong earthquake caused serious damage in Tainan, especially to several mid- to high-rise mixed-use residential and commercial buildings. Unfortunately, another powerful earthquake with a magnitude of 6.3 struck Taiwan heavily again in 2018. Earthquake reconnaissance investigations show the major causes of damaged structure in the two different earthquake events as follows: (1) soft and weak first story and (2) non-ductile detailing. In order to grasp the dynamic response of this type of building, a three dimensional, half scale, seven-story reinforced concrete (RC) specimen with the above structural characteristics of the complex building in Taiwan in the 1990s was fabricated to perform the tests. The earthquake ground motions which represent the far field and near-fault earthquake record from the 2016 Meinong earthquake were employed as the input motion. In this paper, the design of the specimen, instrumentation layout and the findings from the shaking table test subjected to near-fault ground motion will be introduced and discussed.

1 INTRODUCTION

Taiwan is located on the western Circum-Pacific seismic belt, hence seismic activity is very frequent that earthquake becomes one of the major natural hazards in Taiwan. However, due to the dense population and lack of land resources, many buildings were built near the known fault lines inevitably. As the fault movement occurred, it caused significant damage to buildings. In accordance with the statistics, 2.5 million buildings are located within 10 kilometers of an active fault line, where 5.3 million citizens are threatened by

earthquake. Seismic performance of existing residential building is a very important issue based on the above reasons. Several residential buildings were damaged or even collapsed after a 6.4-magnitude earthquake struck Tainan city on February 6, 2016. The worst of them is a seventeen-story collapsed mixed-use residential and commercial building. Earthquake reconnaissance investigation shows that soft and weak story and non-ductile detailing were the major causes of the above collapsed building. In 2018, a powerful earthquake struck eastern Taiwan, Hualien, on February 6 again. The earthquake caused several buildings to severely damaged or partially collapsed. All the collapsed buildings were 9 to 12 stories high and shared one common characteristic - soft stories. As a result, it is necessary to pay more attention to the issue and to find the solution as soon as possible.

In the past decade, testing of non-ductile RC frame specimens using the shaking table at the NCREE Taipei laboratory have been carried out by researchers (Wu et al. 2005, Kuo et al. 2008 and Lin 2009). However, it is difficult to use the existing experimental facilities to simulate the near-fault ground motions. As a result, a high performance seismic simulation shaking table has established to reproduce near-fault ground motions as shown in Figure 1. It possesses six degrees of freedom to simulate earthquake motions in three axes. The size of the shaking table is 8×8m with a self-weight of 100 ton. Specimens with a maximum weight of 250 ton can be accommodated on the shaking table. The shaking table is driven by eight high performance servo-hydraulic actuators. Four of them are installed horizontally and the other four are mounted vertically. The maximum horizontal stroke and velocity capacities of the shaking table are ± 1.0 m and ± 2.0 m/s, respectively. The maximum horizontal and vertical accelerations for the bare table are ± 2.5 g and ± 3.0 g, correspondingly. The reaction mass is isolated from the fixed foundation by 120 air springs and 192 viscous dampers.

The shaking table specimen was a 1/2-scale model of a prototype building representative of mixed-use residential and commercial structures built in Taiwan in the 1990s. The demonstration test with the three-story specimen has been executed for the grand opening with NCREE Tainan laboratory in 2017 (Shen et al. 2018). Based on the successful experience, the shaking table test was advanced to the seven-story specimen. This paper presents the seven-story specimen accomplished on the shaking table at the NCREE Tainan laboratory. The specimen was exposed to a series of bi-directional far field and near-fault ground motions. This paper presents the experimental program including the design, test setup and testing of the specimen, as well as the test results and the major observations. The test results can offer abundant information of seismic behavior of RC frame for researchers, and they can be used to collaborate the analytical models with better prediction of seismic behavior of RC building.

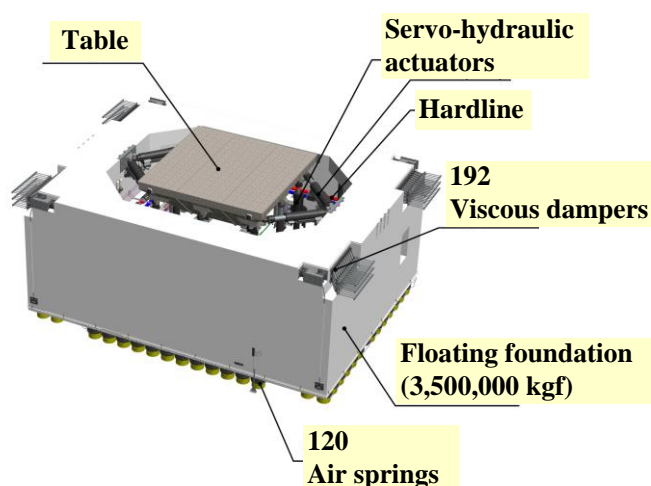


Figure 1: Shaking table at the NCREE Tainan laboratory

2 SPECIMEN DESIGN

2.1 Structural characteristics of prototype structure

Due to the nature of limited land space and overcrowded populations, more and more mid- to high-rise buildings were built in the urban area of Taiwan. The above buildings are usually designed to mixed-use residential and commercial building. The characteristics of the typical mixed-use residential and commercial building in Taiwan are shown as below: (1) lower stories for commercial use or parking lot, upper stories for residential use; (2) fewer wall in the lower stories, more wall in the upper stories. The soft and weak stories were induced due to the fewer wall in the lower stories. Also, the weakness of the structure was observed in the 2016 Meinong earthquake and 2018 Hualien earthquake reconnaissance investigation, respectively.

2.2 Scaling and design of specimen

Testing of a 1/4-scale twenty-story RC specimen has been carried out at the E-Defense shaking table. The reduced-scale specimen was separated into five blocks for shortening the construction period (Sugimoto et al. 2012). Considering the capacity of the overhead crane of the NCREE Tainan laboratory, the concept of modularity was utilized on the specimen design. The shaking table test specimen was fabricated separately in three different parts named Type A, Type B and Type C, and eventually assembled together. Type A can be freely connected with the other two types according to different test requirement. For example, in terms of the seven-story specimen, it is combination of one Type A, two Type B and one Type C. Figure 2 shows the modular design of specimen. On the other hand, the mega steel frame was also fabricated to protect the equipment and prevent the collapse of the specimen during the shaking table test. The seven-story specimen and the collapse prevention system were fixed to the shaking table using all-thread bolts as illustrated in Figure 3.

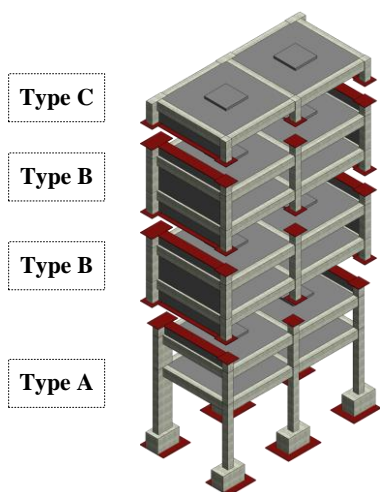


Figure 2: Modular design of specimen



Figure 3: Overview of seven-story specimen and collapse prevention system

The connection between each type of specimen became important since introducing the modular design of specimen. The ends of column in each type were designed to connect each other by using steel plate. The steel plates were locked with several screws, so that it might be not damaged during the shaking table test. The longitudinal rebar in columns or walls were welded on the steel plate. Since the size and the capacity of shaking table are limited, the scale of specimen have been reduced to one-half of the original. The center-to-center distance in longitudinal and lateral directions are 700 and 350 cm, respectively. The total height from

foundation to the top of the column is 1273 cm. Moreover, the 110×110 cm square additional mass was considered on each floor. The plane view, front elevation and side elevation are shown in Figure 4.

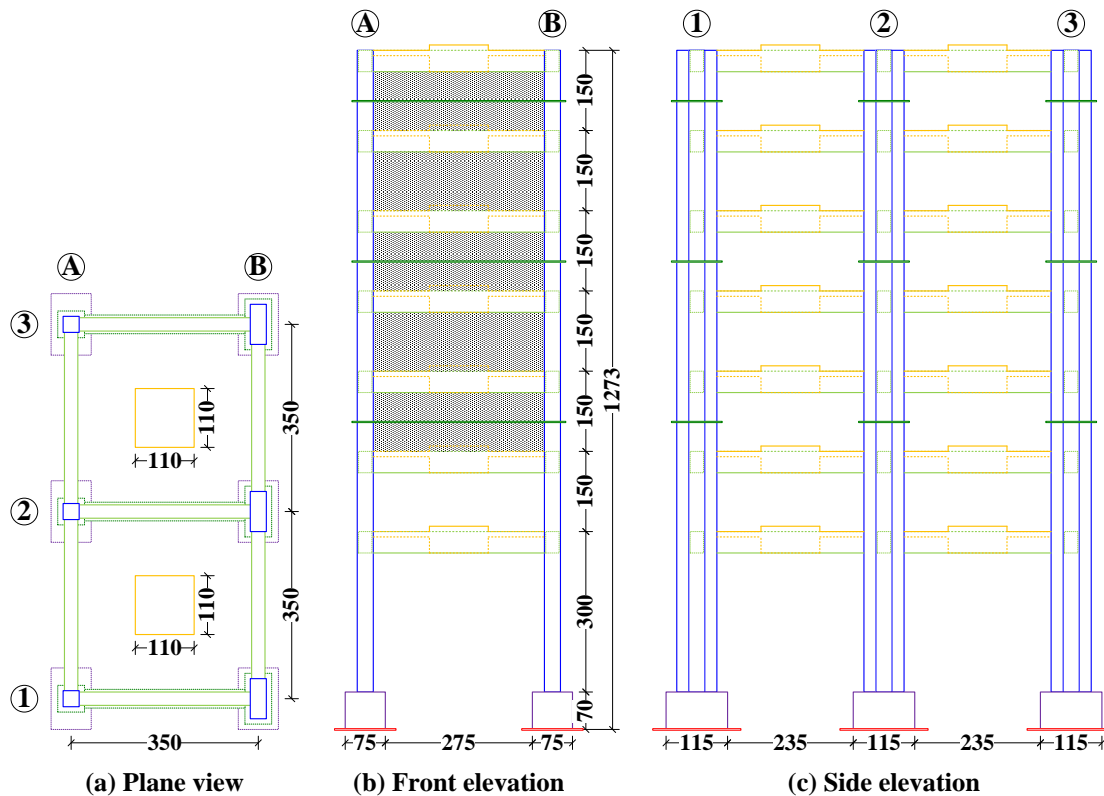


Figure 4: Seven-story specimen (dimensions in cm)

The columns with longitudinal reinforcement ratio of 2.53% which had cross sections of 30×30 cm and 30×75 cm, respectively. The beam with longitudinal reinforcement ratio of 2.85% had cross section of 25×40 cm. As for column and beam elements, the D19 steel with design yielding strength of 4200 kgf/cm² (420 MPa) was used as the longitudinal rebar, and the D10 steel with design yielding strength of 2800 kgf/cm² (280 MPa) were used as the transverse reinforcement. The cross section information is shown in Figure 5. For stirrup hooks, 90-degree bend plus 6 bar diameters extension at the end bar was used. The use of crossies with a 90-degree turn at one end and 135-degree bend at the other end placed so that consecutive crossies had their 90-degree hooks on opposite sides of the columns. The spacing of stirrups and crossies in column elements were designed to be 12 cm and 24 cm, respectively. As for the beam elements, the spacing of stirrups were designed to be 15 cm. It is worth noting that the beam-column joints of the three-story specimen tend to be more vulnerable under high seismic loads because of insufficient transverse reinforcements in the joint region. The weak column-strong beam behavior and strong column-weak beam behavior are expected to appear during the shaking table test due of the two different column dimensions and only one beam dimension.

2.3 Material properties

All material properties were measured by independent laboratory tests prior to the shaking table test. The average measured yield strength and ultimate strength of the longitudinal bars were 4630 kgf/cm² and 6547 kgf/cm², respectively. The average measured yield strength and ultimate strength of the transverse reinforcement were 3569 kgf/cm² and 4833 kgf/cm², respectively. The average measured compressive strength of concrete cylinder was 238 kgf/cm² at 28 day.

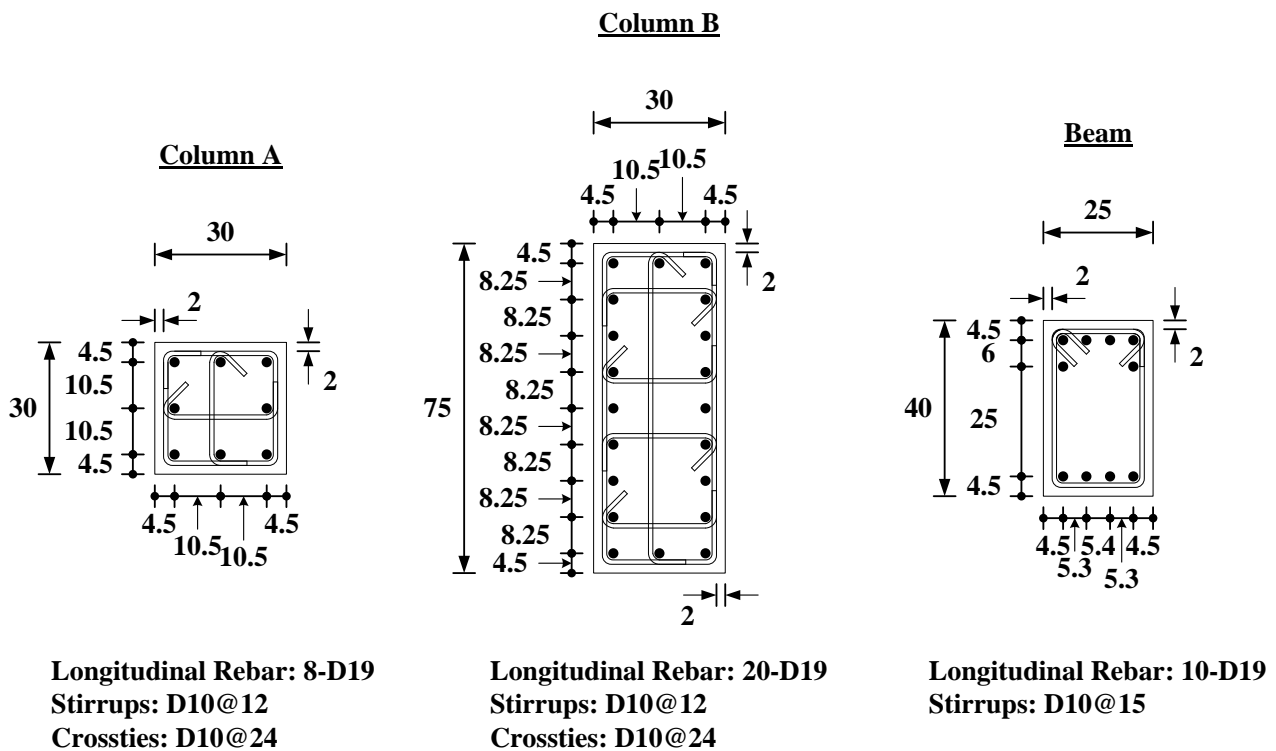


Figure 5: Cross sections of RC members (dimensions in cm)

3 TEST SETUP

The demonstration test with the three-story specimen had been carried out in 2017, however, the longitudinal reinforcement ratios of column and beam elements were over-designed for the low-rise RC building as well as the three-story specimen. After the ground motion excitation, slight damages of three-story specimen were observed. Therefore, the existing Type A of the three-story specimen was utilized to treat as part of the seven-story specimen with new Type B and Type C. On the other hand, the seven-story specimen retrofitting with self-jointing compression brace had been performed prior to the prototype specimen as mentioned in the paper. After test of the retrofitting specimen, the self-jointing compression brace was removed to continue the shaking table test.

3.1 Instrumentation scheme

The motion of the shaking table and the seismic response of the specimen were monitored through a dense network of instrumentation including accelerometer, displacement transducer, string potentiometer, strain gauge, and motion capture system. Among these sensors, 8 triaxial accelerometers were installed on each slab to measure the acceleration. Also, additional accelerometers were used to measure the acceleration of the shaking table.

The measurement of floor displacement in dynamic test is challenging, however, 18 linear displacement transducers were used to record the floor displacement. An external reference frame is installed on the seven-story specimen to measure the relative displacement between the top and bottom slabs of each story with displacement transducers. 9 string potentiometers were mounted vertically on the foundation to measure the displacements along the height of each column in the first floor.

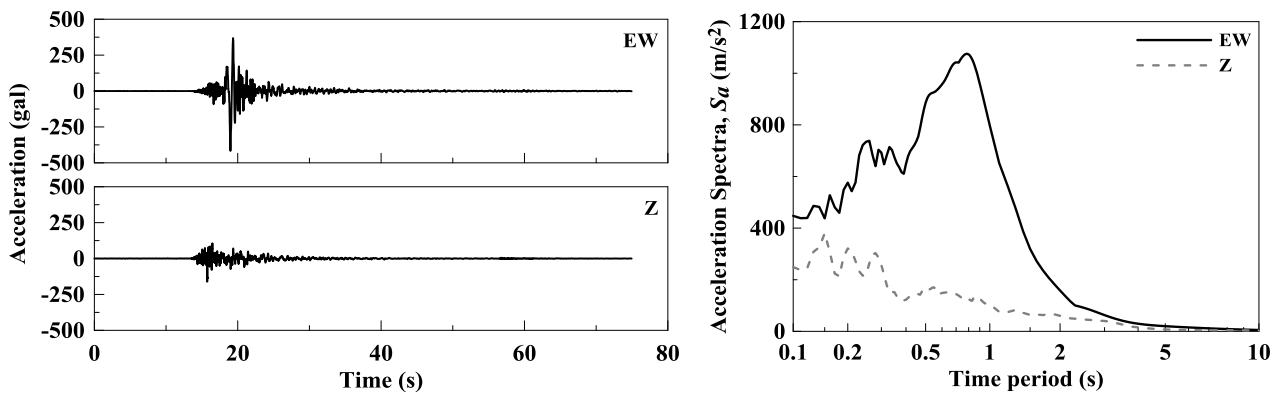
210 strain gauges were attached on the longitudinal and transverse reinforcement close to the top and bottom of five columns excluding the corner mega column near the control room in the bottom and second stories,

additional strain gauges were used to measure the strain of longitudinal and transverse reinforcements of beams in the bottom story.

The motion capture system named OptiTrack (OptiTrack 2017) was adopted to measure the displacements of the whole specimen. The motion of the specimen was detected through reflecting markers glued onto the specimen whose movement is acquired by a high performance camera system. 169 markers were considered to record the reaction during the tests.

3.2 Input ground motion

The selected far field (KAU069 station) and near-fault ground motion (CHY063 station) for the shaking table test are both the strong-motion records of the 2016 Meinong earthquake. Figure 6 shows the acceleration input motions and the acceleration response spectra at 5% critical damping ratio (ζ). The measured maximum peak ground acceleration in the horizontal and vertical directions are 259 gal (~ 0.26 g) and 140 gal (~ 0.14 g) at KAU069 station, respectively. As for the near-fault ground motion, the measured maximum peak ground acceleration in the horizontal and vertical directions are 417 gal and 163 gal at CHY063 station, respectively. The accelerogram were affected in the lateral and vertical direction of the seven-story specimen. Table 1 presents the experimental matrix of the shaking table test with their respective input ground motion.



(a) Acceleration histories

(b) Acceleration response spectra ($\zeta = 5\%$)

Figure 6: Input ground motion (CHY063 station)

Table 1: Test program

Test ID	Earthquake	Ground motion type	Station	Input motion in specimen direction	PGA (gal)	Rate
F01		Far field	KAU069	Lateral / Vertical	259 / 140	100%
N01	Meinong, Taiwan, 2016	Near-fault	CHY063	Lateral / Vertical	208 / 82	50%
N02				Lateral / Vertical	417 / 163	100%
N03				Lateral / Vertical	625 / 245	150%
N04				Lateral / Vertical	834 / 327	200%

4 EXPERIMENT OBSERVATIONS

Figure 7 compares the inter-story drift ratio in the first story after the near-fault ground motion. A significant residual inter-story drift ratio is happened after each test excluding test N01. The response of the seven-story specimen during the 200% near-fault ground motion is demonstrated in terms of the histories of the inter-story drift ratio of first and second floors. The amplitude of the inter-story drift ratio in the first floor is about 11%, but remained close to 6% in the second floor as shown in Figure 8. The strong part of motion during test N04 started at approximately 18.5 seconds and resulted in the residual drift ratio about 6% in the first floor. Also, the residual drift ratio happened in the second floor. The maximum drift ratio recorded during each test are listed in Table 2.

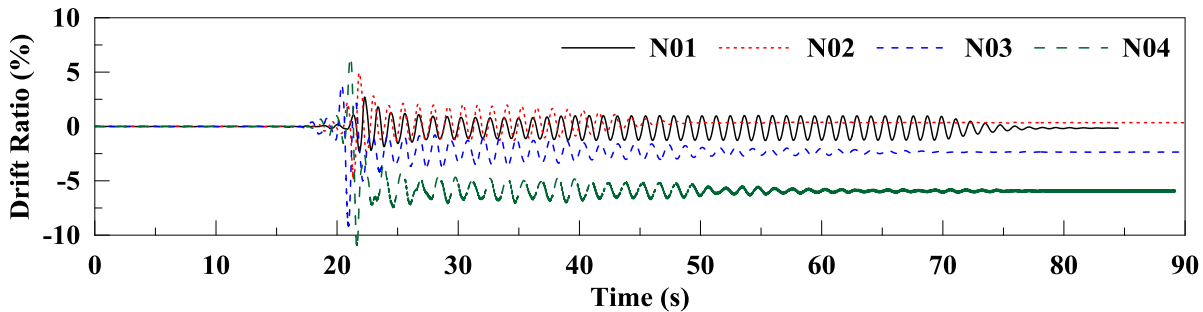


Figure 7: Comparison of inter-story drift ratio in the first story during near-fault ground motions

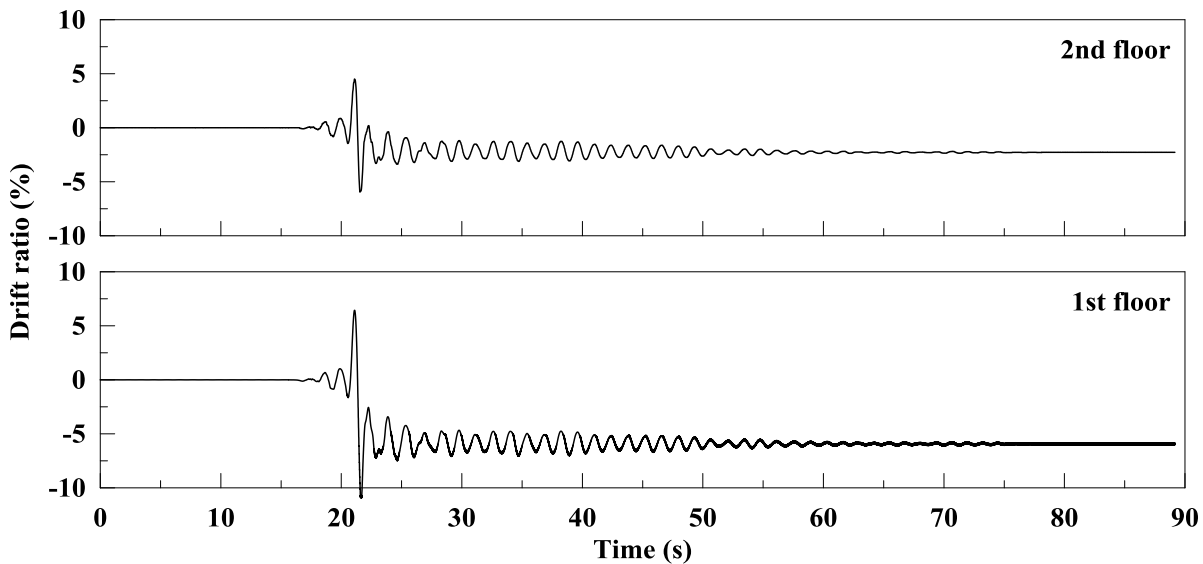


Figure 8: Inter-story drift ratio during 200% near-fault excitation (N04)

Table 2: Maximum inter-story drift ratio (%) of each test

Test ID Level	F01	N01	N02	N03	N04
2nd floor	0.00	1.97	3.61	6.46	5.96
1st floor	0.01	2.70	4.93	9.20	10.92

No significant damage was observed in the seven-story specimen after the first two tests F01 and N01. After test N02, slight spalling of concrete occurred in bottom of the square corner column. More concrete was spalling or crushing after test N03. Figure 8 shows the damage of specimen after test N04. Concrete crushing

and reinforcement buckling were observed at each column end in the first story. Moreover, the significant cracks developed on the beam-column joint due to the poor detailing of reinforcement.



(a) Corner column

(b) Interior column

(c) Beam-column joint

Figure 8: Damage of specimen after test N04

5 CONCLUSIONS

The paper presents the shaking table test performed to understand the dynamic response of a half scale RC building whose structural characteristics were representative of those in the mixed-use residential and commercial building in Taiwan in the 1990s. Also, the high performance of the novel shaking table was demonstrated via the seven-story specimen test. The measured displacements of the shaking table showed satisfactory results when compared with the displacement-time histories of the input file during the 90-second shaking. The results showed that specimen experienced different responses, strongly dependant on the rate of the input motions. In addition, the concept of modular design was successfully employed on the specimen.

6 REFERENCES

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