BEHAVIORS OF NONSTRUCTURAL COMPONENTS IN SEISMIC RESPONSES OF HIGH-RISE BUILDINGS – E-DEFENSE SHAKING TABLE TEST

**Takuya Nagae [1], Kouich Kajiwara [2], Hideo Fujitani [3], Kunio Fukuyama [4]
Hidenori Kawabe [5] and Masayoshi Nakashima [6]**

[1] *Senior Researcher, National Research Institute for Earth Science and Disaster Prevention, Hyogo, Japan*
[2] *Senior Researcher, National Research Institute for Earth Science and Disaster Prevention, Hyogo, Japan*
[3] *Prof., Kobe Univ., Hyogo, Japan*
[4] *Visiting Researcher, National Research Institute for Earth Science and Disaster Prevention, Hyogo, Japan*
[5] *Assistant Prof., Kyoto Univ., Osaka, Japan*
[6] *Director, National Research Institute for Earth Science and Disaster Prevention, Hyogo, Japan*
Email: nagae@bosai.go.jp

ABSTRACT :

This research focuses on the nonstructural components in high-rise buildings subjected to large seismic responses. A serious of large-scale shaking table tests is conducted by using E-Defense shaking table. For the tests, a partially extracted two-story full scale frame system is adopted to reproduce the seismic responses of high-rise buildings. The two-story frame is 8.6 m x 10.6 m in plan and the story height is 3.4 m. Since the two stories are built on a concrete slab supported by rubber isolators, the system is able to vibrate with the long period of about 2.8 sec and is able to produce long duration events without exceeding the capacity of E-Defense accumulator system. The frame is appropriately designed to generate the drift angle of more than 0.01 rad elastically. The furniture incorporated in the sectioned interior spaces falls down and slides around. The exterior walls installed in the frames show small damage.

KEYWORDS: High-rise building, Long-period ground motion, Shaking table test, Nonstructural Component

1. INTRODUCTION

In the Japan's design for high rise buildings, the seismic performance has been estimated through dynamic response analyses, in which the ground motions were scaled to have the peak ground velocity of 0.5 m/s. However, the peak ground velocity exceeding even 1 m/s was recorded in the 1995 Kobe earthquake. The fact clarified that the intensity of future ground motion can reach more than 2 times design level. Thus, the performance of building and the damage aspect have to be assessed over the range of such design level.

Now, occurrences of large earthquakes having a magnitude over eight are predicted along subduction zones in the southwestern part of Japan. Such earthquakes tend to generate ground motions having long predominant periods, and those ground motions are said to be influential for seismic responses of high-rise buildings [1].

This research focuses on the nonstructural components in high-rise buildings subjected to large seismic responses. Damages of nonstructural components cause functional loss and influence on reparability of the buildings after earthquakes. To obtain physical data for their damage aspects, a serious of shaking table tests is conducted. The engineering parameters, such as the maximum floor velocity and the inter-story drift angle, are associated with the damage level observed in the test. In addition, the video images of the systematically organized rooms can explain the reality of damage aspects including the effect of prevention measures and can be used as powerful educational tools for disaster mitigation.

The response characteristics produced in the test were preliminarily confirmed through seismic response analyses for a standard thirty-story building model. The physical conditions were adopted from the design materials (Figure 1). The natural period of the building is assumed to be 2.8 sec associating with the total height of about 100 m.

A long-period ground motion assumed at HigashiYuuench in Kobe city is used in this research as an expected ground motion. HigashiYuuench ground motion is one of the synthesized waves assuming Nankai Subduction Earthquake. The ground motion has the time duration of 270 sec and PGA of 2.49 m/s^2 and PGV of 0.73 m/s. The velocity response spectra are shown in Figure 2, and HigashiYuuench ground motion is compared with the typical design ground motion, El Centro NS 1940 scaled at the PGV of 0.5 m/s. Their levels are very deferent in the range of the period of more than 2 sec. Especially at the period of the adopted high-rise building, the amplitude of HigashiYuuenchi ground motion is about 3 times larger than that of the design ground motion. Now it is clear of the high-rise building to suffer much larger floor responses in the long-period ground motion. To make the specific target level of the floor responses and the inter-story drift angle, dynamic response analyses were conducted using a lumped mass-and-spring model with MDOF, as shown in Figure 3. In that model, the lumped mass represented the story mass, and the spring represented the story stiffness. The inelastic behaviors of the springs are assumed referring to some reasonable assumptions and associated stipulations in design codes.

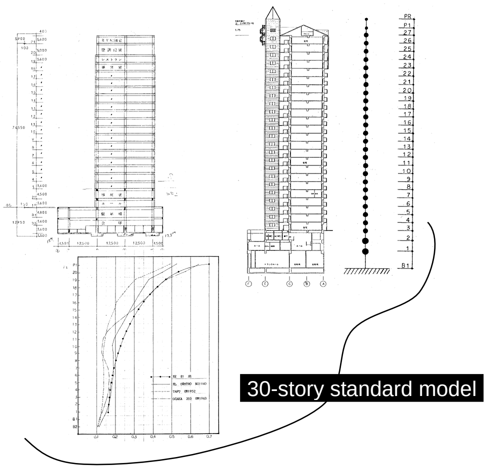


Figure 1 Referred design materials

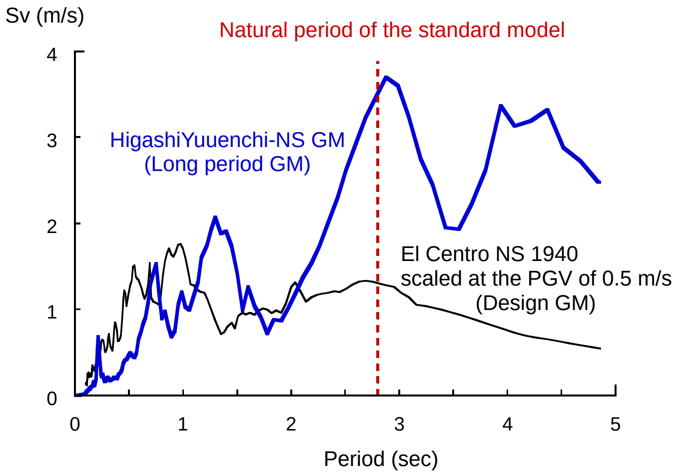


Figure 2 Response velocity spectra h=0.02

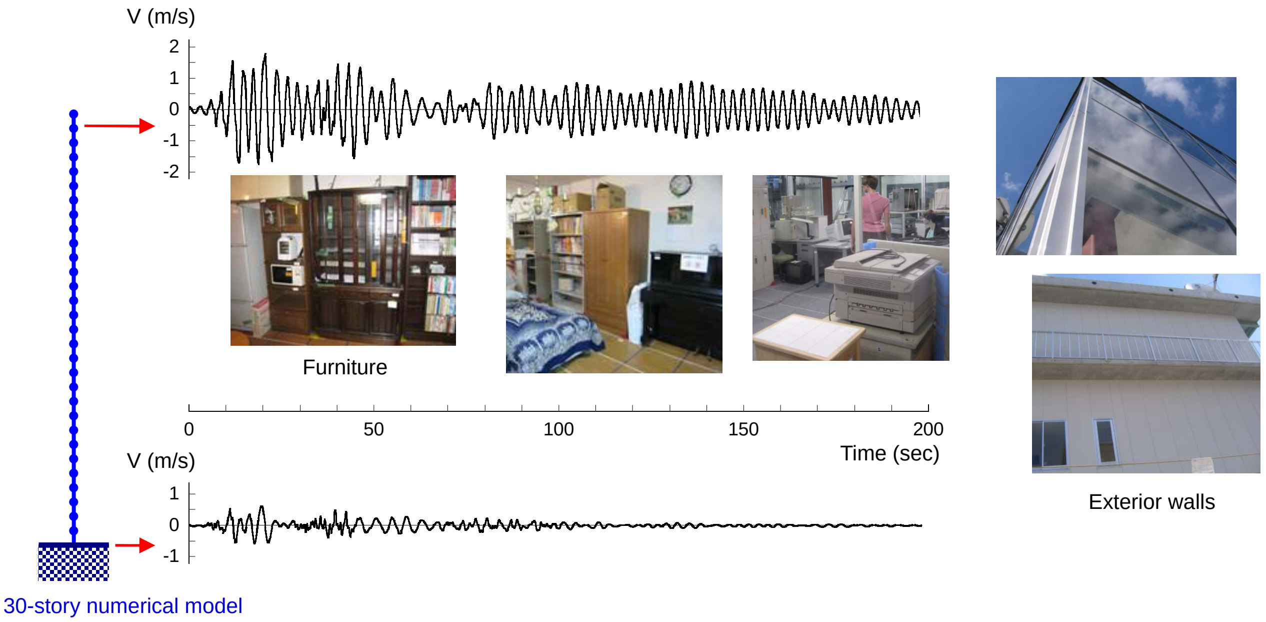


Figure 3 Response of high-rise building by numerical model, Examples of nonstructural components

2. TEST SYSTEM BASED ON E-DEFENSE SHAKING TABLE

To investigate the behavior of furniture and other nonstructural components in high-rise buildings' responses, experimental research activity started in Hyogo Earthquake Engineering Research Center of National Research Institute for Earth Science and Disaster Prevention, where E-Defense shaking table is located. E-Defense shaking table has a dimension of 15 m × 20 m, and the loading capacity of 1200 tf. The capacity of the maximum acceleration, velocity and displacement are, respectively, 9.0 m/s^2, 2.0m/s, 1.0 m. E-Defense shaking table is overviewed in Figure 4.

According to the floor response of the upper part of the high-rise building in figure 3, the maximum velocity is the same level of the capacity of E-Defense. In addition, during the main event, E-Defense accumulator system has to continue to supply the power resource oil to the actuators attached with the shaking table. The calculations of oil amount discharged from the accumulators, assumed that the shaking table directly provides the horizontal two-direction floor responses, are shown in Figure 5. The total oil amount is proportional to the cumulative displacement of the shaking table, and in the case of the top floor response, it reaches even ten times larger than the limit amount.

Thus, the efficient additional test system on the shaking table is necessary for such floor response problem. The proposed test system comprises with two-story frame and a large base concrete slab supported by four rubber isolators. The dimension of specimen is shown in Figure 6. The overview is shown in Figure 7. The two-story frame is 8.6 m x 10.6 m in plan and the story height is.3.4 m. The system adjusted by the balance of concrete slab mass and rubber isolators' stiffness is able to vibrate with the long period and to produce long-duration event with large velocity amplitudes.

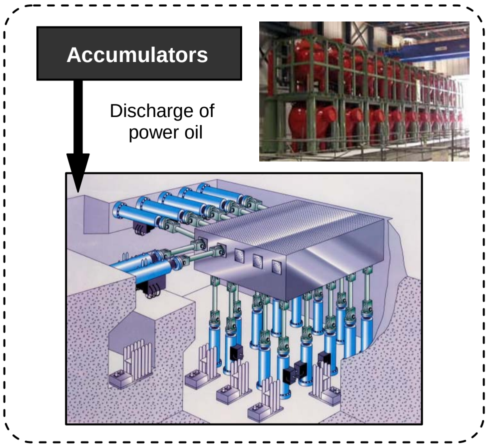


Figure 4 E-Defense Shaking Table

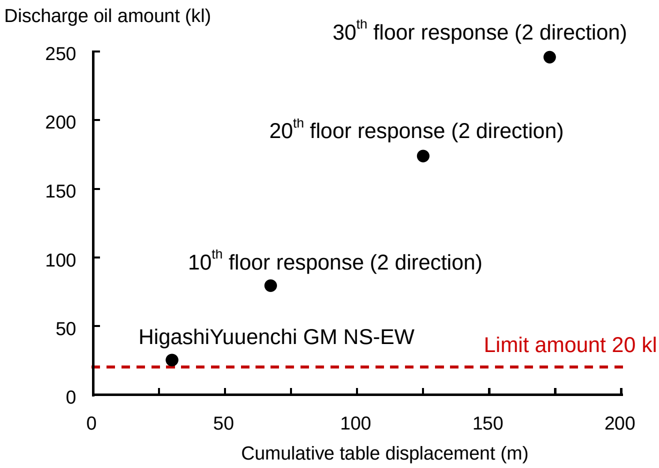


Figure 5 Oil amount demanded by cumulative displacement

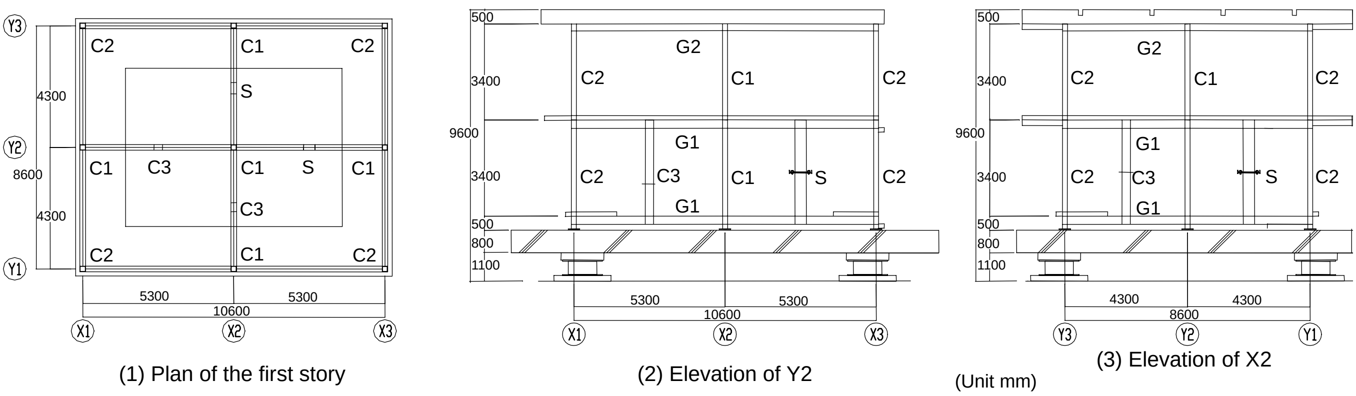


Figure 6 Dimensions of specimen

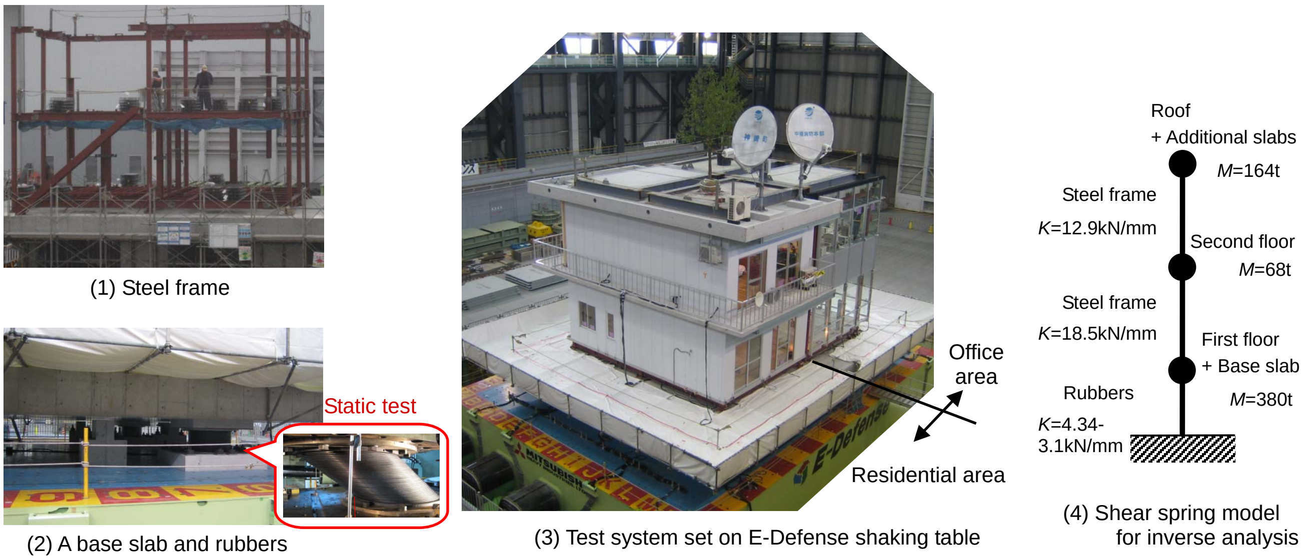


Figure 7 Overview of proposed test system

For this specimen, large rubber isolators with the diameter of 1.0 m were used. The total thickness of rubber is 285 mm in each isolator. According to 85 % of the diameter and 300 % shear strain of rubber, the limit deformation of 0.85m was set for the amplifying base story, which is supported by rubber isolators. The nominal stiffness of rubber (shear strain of 100 %) is 0.3 N/mm^2. Thus, the stiffness of the base story K becomes 3.2 kN/mm. The total weight of specimen W is 612 tf. Here, the total mass M=W/g, and the equivalent natural period T of 2.8 sec is simply given by $T=2\pi(M/K)^{0.5}$.

The upper frame was designed to generate the inter-story drift of 0.017 rad estimated in the standard thirty-story building. Here, thin columns (C1: □-175×175×12, C2: □-175×175×9) were used, which elastically generate most of story drift under the inertia force from the roof and the second floor.

For exterior walls, ALC panels were installed by rocking method in the residential area. Metal curtain wall system was adopted in the office area (reported in associated WCEE paper by Fujitani). The furniture was located on the second floor of the specimen. Residential type of furniture and office type of furniture were, respectively, set up in the sectioned interior spaces. Ceilings were hung from floor slabs.

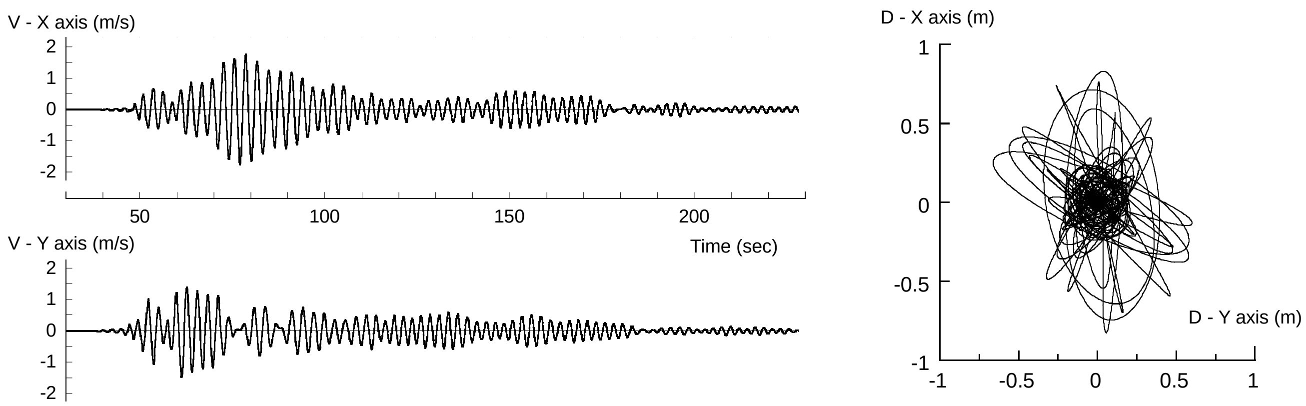
The input wave for the shaking table was identified using inverse analysis. The specimen was treated as a simple stick model based on the result of static analysis using the elastic frame model. The inverse analysis was conducted focusing on the response of the second floor. According to the static test of the rubber isolation, a certain degree of inelastic behavior had been confirmed in advance. In fact, the secant stiffness changed from 4.3 to 3.1 kN/mm depending on the shear deformation level, and the preliminary tests based on the inverse analyses were conducted in the range of the accepted small level of response.

3. TEST RESULTS

3. 1 Floor Response and Behaviors of Furniture

Figure 8 shows the response on the second floor of the specimen. Since the inelasticity of the rubbers influenced the responses, the results did not show the same time history as the picture in Figure 3. However, the maximum amplitude and the long duration were focused in the test since they are influential for furniture's behaviors [2]. The test results showed the reasonable responses with large amplitude and long duration. The floor moved around in X-Y two directions. The maximum displacement of the floor reached 0.85 m, and the cumulative displacement of the floor reached more than 100 m. Thus, the proposed test system overcame the limit condition of E-Defense shaking table.

When the large amplitude floor response occurred, each room sustains the damage as shown in Figure 9. The behaviors of falling, sliding, and scattering, etc. of many pieces of furniture were seen systematically in realistically arranged rooms. If there were actually residents in those rooms, the physical damages caused by heavy fixtures and fittings jeopardize their lives. It is even guessed that the residents who are deeply feared in such shake that continues for more than 150 sec can not start evacuating right after the event in a panic. On the other hand, the fixtures or fittings constrained from their top parts by the sticks showed no falling or sliding during the long event. That proves the effect of the prevention method.



(1) Time histories of velocity (2) Orbit of displacement

Figure 8 Floor response on the second floor of specimen

(1) Copy machines moved around with casters

(3) Refrigerator flipped over and scattered

(2) Lockers fell and prevented evacuation

(4) Bureau attacked resident

(5) Fall prevention method effected

Figure 9 Aspects of furniture after the test

More detail explanations for Figure 9 are as follows;

(1) Copy machine tables moved around with casters and eventually fell down. According to the observation using the video, the table with casters started moving with the lateral acceleration of about 0.1 g. That means the equivalent coefficient of friction is about 0.1. Referring to the SDOF analyses with rigid plasticity model, the furniture with the friction coefficient of 0.1 moves around with the same level of amplitude as the floor response. That means things with casters are expected to move like the orbit of Figure 9 if they do not fall.

Thus, deadly heavy copy machines can continue attacking workers for long time duration.

(2) Lockers fell down in front of the door. The lockers are so heavy that it is difficult of a few persons to move them away. That means the behaviors of the furniture can prevent resident's evacuation physically after the events.

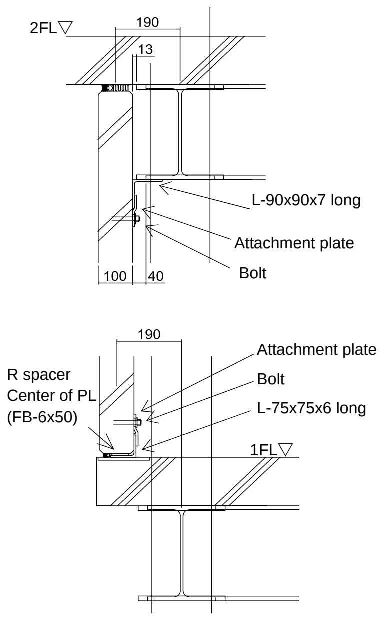
(3) Refrigerator flipped over and scattered its contents. As for kitchen, tableware, hot water, hot oil, and cutlery can be concentrated in the narrow space. Scattered such things attack cooks or other residents, especially long-duration events keep them in the place and continue stirring all of them.

(4) Bureau fell down on the resident who lay down on the bed. In such case, it is dark in the room. The panicked resident, who is injured and choked, can not remove that bureau.

(5) Furniture fastened by instruments proved the effect of the fall prevention method. The diagonal bands were fixed on the top portion of furniture in one side and on the wall in another side. The vertical sticks initially pushed the top portion of furniture having reaction from ceiling. They can constrain the furniture's overturning and sliding. In addition, the doors were locked and the openings are guarded by lateral bars in the furniture. <u>Thus, the risk scenarios mentioned above can be mitigated with prevention measures practically taken by residents.</u>

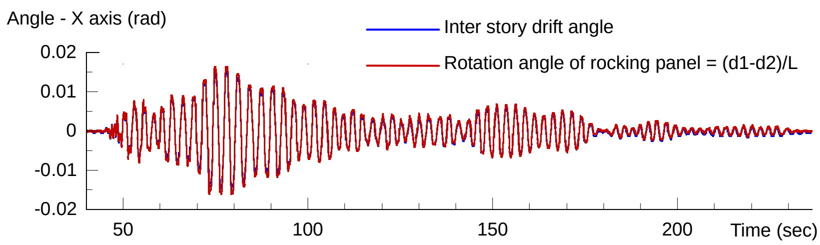
3. 2 Inter-Story Drift Angle and Exterior Wall Fastened by Rocking Method

By rocking method, the exterior wall panels can rotate and follow the inter-story drift in the building. ALC (Autoclaved Lightweight aerated Concrete) panel is used as nonstructural wall. The strength is more than 3 N/mm^2 (it is provided in JIS). The details are shown in Figure 10.

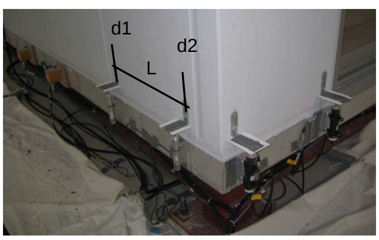


(1) Rocking method of ALC panel

(2) Process of attachment



(4) Rocking panel's performance (flexibility)



(3) Measuring condition of rocking angle

(5) Damage aspect

Figure 10 Exterior wall fastened by rocking method

In this case, assuming to be used in RC residential building, the ALC panels were placed between the RC veranda and the projected RC slab. The standard ALC panel used in the test has the thickness of 100 mm, width of 600 mm and length of 3220 mm. In the process of the installation of ALC panel, a bolt is used, whose one end is inserted and connected with the reinforcement in the panel and another end is set with an attachment plate and screwed by a nut. The attachment plate is weld to the long steel angle which is welded to the main frame. Since the bottom part of the ALC panel is placed on the R spacer plate with the thickness of 6 mm in the center, the panel can rotate around the R spacer plate. When the ALC panel rotates, the panel and the attachment plate slip around the bolt.

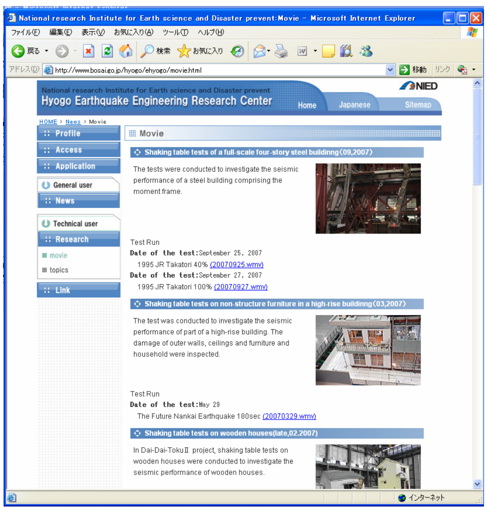
The drift angle time history of the first story in the specimen is shown in Figure 10. That shows the feature similar to the floor response time history in Figure 8. The cyclic response occurred with the assumed natural period of about 2.8 sec. The maximum inter-story drift angle is 0.015 rad that is 1.5 times larger than the standard design criteria of 0.01 rad. The frame is designed to generate such level of drift angle elastically, and that was successfully produced with the long time duration.

In the same figure, the rotation angle time history of the ALC panel in the first story is shown. The rotation angle of the panel is slightly larger than the story drift angle. The difference is only 5%, and it is confirmed that the rocking method keeps the exterior wall very flexible. According to the observation, small cracks were found in one panel right under the opening and at bottom corners of four panels in total forty panels of the first story. Thus, the damage of the wall system is said to be reparable and even negligible under the drift angle of 1.5 times larger than the standard design criteria. As for the ALC panel around the opening, the rotation tends to be restrained by the opening's reinforcement (steel angles). Some additional stress would be caused between adjacent ALC panels and the reinforcement.

4. EDUCATIONAL TOOL FOR DISASTER MITIGATION

The value of this test is extremely high in terms of educational materials. There has been no image opened to the public that reproduces the scene of devastation in office or house subjected to intense floor response. In this test, many video cameras were installed in the specimen, and much data was acquired successfully. In the materials, the effect of fall prevention methods for furniture was verified through the simple comparisons in the scene. Seismic response of high-rise building is focused on, in this activity, however the methods applicable to the low-rise building were also included as for the fall prevention methods for furniture.

The video images are delivered through the Internet as shown in Figure 11. The strategies of enlightening activity can be built based on the materials in world wide. Now in Japan, disaster mitigation measures are expected to spread through the familiar points such as public organizations, schools and municipalities.



(1) http://www.bosai.go.jp/hyogo/ehyogo/movie.html

(2) Powerful tool for disaster mitigation education

Figure 11 Realistic movies reproducing response of high-rise building

5. CONCLUSIONS

The efficient additional test system on E-Defense shaking table was needed for floor response reproduction of high-rise buildings. The proposed test system comprises with two-story frame and a large concrete slab supported by rubber isolators. The two-story frame is 8.6 m x 10.6 m in plan and the story height is 3.4 m.

The test results showed the responses with large amplitude of velocity and with the natural period of about 2.8 sec. That time duration reached more than 150 sec. The floor moved around in X-Y two directions and the maximum displacement reached 0.85 m. The cumulative displacement of the floor reached more than 100 m. The drift angle time history had the feature similar to the floor response, and the maximum inter-story drift angle of 0.015 rad was generated from the soft elastic frame.

Once the large amplitude floor response occurred, the rooms were fallen at risk by the furniture’s behaviors, such as falling, sliding, and scattering. If there were actually residents in those rooms, the attacks given by heavy furniture jeopardizes their lives. On the other hand, the fixtures or fittings constrained from their top parts by the sticks or bands showed no falling or sliding. That proves the effect of the prevention.

As for exterior walls, it was confirmed that ALC panels installed by the rocking method is very flexible. The rotation angle of the ALC panes is slightly larger than the story drift angle. The difference is only 5%. With the maximum angle of 0.015 rad, small cracks are seen in one panel right under the opening and at bottom corners of four panels in total forty panels. The damage of the wall system is said to be reparable and even negligible.

Many video cameras installed in the specimen provided much data successfully. In the materials, the effect of fall prevention methods for furniture can be understood easily. Now, the animations can be down loaded through the Internet. Wide enlightening activities started, and disaster mitigation measures are expected to spread through the familiar points such as public organizations, schools and municipalities.

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