E-Defense shake table test on retrofitted high-rise buildings subjected to long-period ground motions

1. Background and research outline.

An extremely large earthquake with the magnitude over eight is highly expected on the plate boundary along the east Pacific coast of Japan. Due to such earthquake event, long-period ground motions, which contain high seismic forces in slow shaking components, are transferred to the land, and high-rise buildings are expected to be shaken for a long duration. In this research, quake resistance of a high-rise building is verified through the shake table experiments conducted by E-Defense. The most likely height of high-rise buildings is considered to be about 80 m in Japan. The test specimen is designed to represent seismic responses of a 80 m tall steel building. As shown in Figure 1, a steel frame structure corresponding the lower part of the high-rise building is constructed on the shake table, and the upper part are modeled using concrete-slab weights and laminated rubber bearings. The test specimen has the characteristics to vibrate in a similar way of the supposed high-rise building against a long-period earthquake motion input.

A set of shake table tests were completed in the 2007 fiscal year, supposing a high-rise steel building built before 1980’s. In this first test series, damage aspects of the steel frame were investigated for long-period ground motions. The beam end sustained a number of cyclic deformations, and the beam end with field welding connection details suffered severe damage including fractures due to significant cumulative strains. To avoid such damages, minimizing the frame deformations is essentially needed.

As the second test series, a set of shake table tests on retrofits were conducted in September 2009. Dampers were incorporated into the lower test frame structure and the seismic performance when subjected to long period ground motions was studied. Also as for the beam ends with field weld connection details, the seismic deformability was examined for three kinds of reinforcement methods. In this test system, the seismic floor response of the roof of specimen corresponds to that of 19th floor of the supposed high-rise building. A penthouse, which reproduce office and house interior spaces, were placed on the roof of the specimen, and the dangerous phenomena in large floor response and effects for the prevention methods such as fixing furniture were investigated.

Fig. 1 Test specimen representing a 21-story high-rise building
2. Preparation of test specimen
The outline of test specimen is as follows;
The constitution of test specimen: the lower part of a four story steel frame structure + the upper part consisting of concrete made weights and laminated rubber bearings. (which simulates a 80 m height, 21-story high-rise building)
The size of test specimen: plan of 14 m x 10 m and height of 21 m.
The weight of test specimen: 1200 t.
The adopted dampers for vibration control: steel damper or oil damper

Figure 2 shows the construction scene of the lower part steel frame structure, which had the same configuration as the specimen used in the first test series. But additionally, gusset plates for fixing brace damper were attached, and seismic reinforcements for the beam ends were applied, supposing retrofits conducted in fields, as shown in Figure 3.
3. Test procedure
By setting dampers, the effect of vibration control was investigated.

**Series A**: the case that steel dampers are incorporated in the lower part steel frame structure and the upper modeled part. The retrofitted part corresponds to 2/3 of the total stories of supposed high-rise building.

**Series B**: the case that steel dampers are incorporated in the lower part steel frame structure. The retrofitted part corresponds 1/5 of the total stories of supposed high-rise building.

**Series C**: the case that oil dampers are incorporated in the lower part steel frame structure. The retrofitted part corresponds to 1/5 of the total stories of supposed high-rise building.

**Series D**: the case without dampers.

4. Outline of test series

**Series A**, 2/3 retrofitted case with steel dampers
As for Series A, the setup status of test specimen is shown in Figure 5. The brace-type steel dampers are incorporated in the lower part steel frame structure. In each story, the steel dampers is about twice that of the horizontal stiffness of the steel frame structure. The horizontal strength capacity of the steel dampers is about 0.25 time that of the steel frame structure. In addition, modeled U-shape steel dampers are incorporated in the modeled upper part consisting concrete-made weights and laminated rubber bearings.
Series B, 1/5 retrofitted case with steel dampers
The modeled steel dampers between concrete-made weights used in the test series A were removed. The brace-type steel dampers were remained in the lower part steel frame structure.

Series C, 1/5 retrofitted case with oil dampers
The brace-type steel dampers used in the steel frame structure in the test series B were removed. Then the brace-type oil dampers were set up in the steel frame structure, as shown in Figure 6.

Fig. 6 Series C, 1/5 retrofitted case utilizing oil dampers

5. Seismic response of test specimen when subjected to the Sannomaru motion
The EW-direction wave of Sannomaru motion was input to the Y direction of test specimen. Following are the test results of Y direction.
(1) Equivalent period and input energy
The maximum velocity response spectrum for the EW direction wave of Sannomaru motion is shown in Figure 7. The first mode equivalent periods of test specimen for each test series are added in Figure 7.

Fig. 7 Maximum velocity response spectrum and equivalent periods of test specimen for each test series
The equivalent period was found by the transfer function between the base and roof response acceleration records. In the both cases of test series D without dampers and test series C having oil dampers in the steel frame structure, the equivalent periods became 2.6 seconds. As for the test series A and series B, the equivalent periods became shorter due to the presence of steel dampers. The value of test series B having steel dampers in the steel frame structure became 2.0 seconds. The value of test series A having steel dampers in the steel frame structure and the upper modeled part became 1.8 seconds. According to the spectrum shape of Sannomaru motion, the spectrum amplitude tends to be smaller due to the shortening of the period of test specimen.

Figure 8 shows total input energy toward the specimen for each test series. Compared to the test series D, the value of the test series A is about half, and the relationship between spectrum shape and equivalent periods was reflected to the test result of each test series.

![Energy input (kNm)](image)

**Fig. 8** Total energy input from Sannomaru motion

(2) Story drift angle distribution for height direction

Figure 9 shows the maximum story drift distributions for the height direction when subjected to Sannomaru motion. The test series A and B having steel dampers, which are the 2/3 and 1/5 retrofitted cases, are shown compared to the 2007 test without dampers. The modeled upper part was estimated reflecting the assumption that each layer corresponds to five stories of the supposed building. In the 2007 test, the value of the second story of the lower part steel frame structure was 0.018 rad. In case of the test series B, the value of the lower part became 0.3 times that of the 2007 test.

![Drift angle (rad)](image)

**Fig. 9** Maximum drift angle distribution when subjected to Sannomaru motion
However, values of the modeled upper part without dampers was almost the same as the values of 2007 test. A significant difference of the maximum story drift angles between the stories with and without dampers are shown in the test series B. In the case of test series A, the distribution became uniform, indicating that the dampers utilized in 2/3 of the total height reduce the damage of supposed building structure extensively. The maximum value became smaller than 0.005 rad, but in this case, it should be noted that its total input energy of series A was also smaller than that of other test series.

(3) Energy consumption of dampers in steel frame structure
Performance of dampers set in the lower part steel frame structure is assessed in terms of the energy consumption. Energy consumptions of the steel frame structure, the modeled upper part and the dampers are individually estimated. The ratios of such partial energy consumptions to the total input energy are shown in Figure 10. The energy consumption of steel frame structure is 40 % in the 2007 test. On the other hand, the energy consumptions of dampers are 30 % in the Series B with steel dampers and 40 % in the Series C with oil dampers. That means, the dampers covered energy consumption corresponding to damage of the steel frames. The ratio of energy consumption of oil dampers are relatively large because the oil dampers sustained 1.5 times larger deformations than the steel dampers. In the case of oil dampers, the ratio of the modeled upper part is relatively small. This indicates that an efficient energy consumption by dampers might also reduce damage of upper part having no dampers.

(4) Safety issue of rooms subjected to floor responses of high-rise building
A penthouse was placed on the roof of specimen, and damage aspects of a pair of rooms with and without countermeasures were compared. Their video records were acquired for the following rooms in each series.
Series A: Office; meeting room, with/without countermeasures, Sannomaru motion
Series B: Office; meeting room, with/without countermeasures, Sannomaru motion
Series C: Office; workspace, with/without countermeasures, Sannomaru motion
Series D: Apartment; dining kitchen, with/without countermeasures, Sannomaru motion
In each case, two kinds, with/without countermeasures, of rooms, in which furniture was set in the same way, were prepared in order to compare the damage aspects between them. Figure 11 shows layouts of a set of furniture.
Figure 12 and Figure 13 show the roof floor responses. In consequence of the presence of dampers, the floor response of each test series is different. The intensity increases in the order of Series A, Series B, Series C and Series D.

Series A and Series B: Meeting rooms of office

Series C: Workspaces of office

Fig. 11(1) The layout of a pair of rooms prepared in the rooftop penthouse
Fig. 11 (2) The layout of a pair of rooms prepared in the rooftop penthouse.

Fig. 12 (1) Series A, time histories of roof floor response (Y direction).

Fig. 12 (2) Series D, Dining kitchen spaces of apartment.
Fig. 12 (2) Series B, time histories of roof floor response (Y direction)

Fig. 12 (3) Series C, time histories of roof floor response (Y direction)
Fig. 12 (4) Series D, time histories of roof floor response (Y direction)

Fig. 13 Two horizontal movement orbit of roof floor