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Structural Design of Base-Isolation system for Tall Building in Japan

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Abstract

The high-rise buildings with the base isolation system have been realized by studying the practical applicability of this system, that is, by extracting and resolving the several problems in the actual design. Sendai MT building is the first base-isolated building with over 60 m height in Japan, and Thousand Tower was the tallest base-isolated residential Tower in Japan when completed. With the base isolation system, it is possible for the high-rise buildings to possess not only the high seismic performance, but also the flexible planning in the design, using high strength materials and long span structure systems as well.

The seismic data were recorded from the seismographs in Sendai MT building, when the Off -Miyagi earthquake occurred in May 26, 2003. These data showed that the base isolation system acted effectively on the high-rise building..

Keywords high-rise building, base isolation system, sliding bearing, rubber bearing, high strength materials

1. Introduction

The construction of base-isolated structures in Japan began about 20 years ago, during the 1980s. Currently approximately 100 such structures are constructed in Japan each year, and the total number of base-isolated structures exceeds one thousand. At the base-isolated structures, most of energy input from an earthquake is mainly absorbed by the base isolation devices. So the base isolation system can minimize the damage of superstructures and maintain the buildings' functions even after severe earthquakes. However, up to our proposal, this excellent system had been applied only to the low-rise buildings with natural period shorter than 1 second, and has been regarded as ineffective to the high-rise buildings. In the study of the high-rise buildings with the base isolation system, the authors faced the following design problems.

(1) The response reduction effect of the base isolation on the high-rise buildings was not clear.

(2) The base isolation system in the high-rise buildings might make the habitability worse in the case of strong winds.

(3) The adoption of the base isolation system might cause the construction cost to be significantly higher.

(4) The property and stability of the large size rubber bearings imposed tensile force on were unknown.

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2. EFFECT ON HIGH-RISE BUILDINGS

With regard to the problem (1) mentioned in the introduction, the parametric analyses [Ogura et al, 1997] were conducted to make the response reduction effect of the base isolation system clear for the low-rise to high-rise buildings consecutively.

Figure 1 shows the 2-mass model of the base isolated structure, representing the superstructure and the base isolation story as the two mass-points, respectively. The superstructure is assumed to be reinforced concrete frame and the base isolation system is to be the type of the hysteretic energy absorption. The force-displacement relation and the hysteretic rule of the springs are shown in Figure 2. With this model, the seismic response analyses were conducted under the seismic ground motion, El Centro (1940-NS, amplified with the max. velocity to be 1.00 m/sec) and the artificial seismic wave of BCJ-L2 (the max. velocity is 0.574 m/sec). The parameters are the natural period of the superstructure, varied to be from 0.2 to 5.0 by 0.2 second.

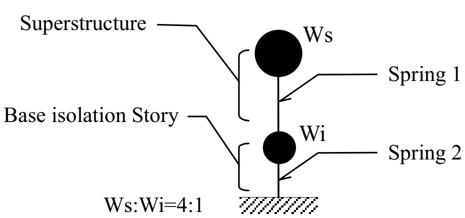

Figure 1 Analysis model

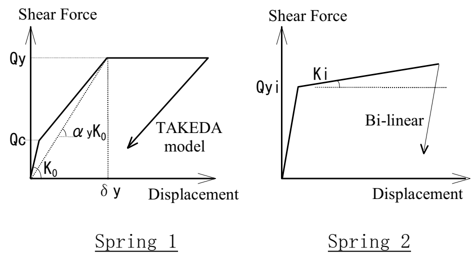

Figure 2 Properties of Springs

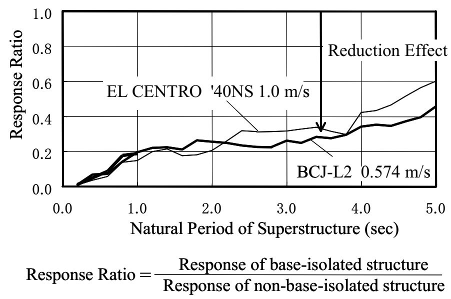

Figure 3 Response Displacement of Superstructure

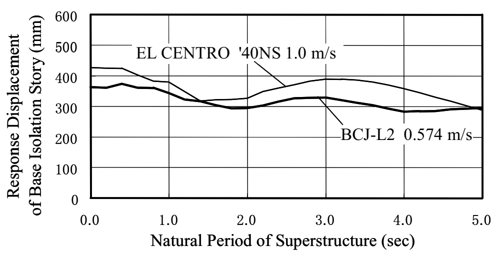

Figure 4 Response Displacement of Isolation Story

Figure 3 and Figure 4 show the response displacement of the superstructure and that of the base isolation story respectively, corresponding to the varied natural period of the superstructure. In Figure 3, the response showing with the vertical axis is defined to be the ratio of the response displacement to that of the case without the base isolation system.

From Figure 3, it is found that the response reduction tends to decrease in proportion to the increase of the natural period of the superstructure. But even when the natural period is 3-4 second, the response displacement can be reduced up to around 30-40% of the case without the base isolation. And the response displacement of the base isolation story is approximately 300-400 mm, so the response of the base isolated structure is considered to be very stable.

Judging from these results, if the design of the yield shear force and the stiffness after the yield of the base isolation story is appropriate, it is possible even for the high-rise building to obtain the high seismic performance.

3. BASE ISOLATION DEVICES

To obtain the effective force-displacement relation of the base isolation system, the combined use of the sliding bearings and the rubber bearings is developed, called Hybrid TASS system (Hybrid TAISEI shake suppression system). In this system, the yield shear force and the stiffness of the base isolation story can be easily designed by setting the ratio of these two type bearings and the stiffness of the rubber bearings. So this system can be widely applied to the low-rise to the high-rise buildings.

In the design of the high-rise buildings with the base isolation system, the stiffness of the system is designed to be as soft as possible to make the natural period long. However the initial soft stiffness of the ordinal base-isolation system might make the habitability worse in the case of strong winds (See Figure 5). Against this problem, which is mentioned in the introduction as the problem (2), Hybrid TASS system is effective. Figure 5 shows the typical force-displacement relation of Hybrid TASS system. To set the yield shear force of the base isolation story larger than the design wind force, the initial stiffness of the whole structure maintains almost the same as the building without the base isolation system. And to make the stiffness after the yield particularly soft, the high seismic performance can be expected in the case of hard earthquake attacks.

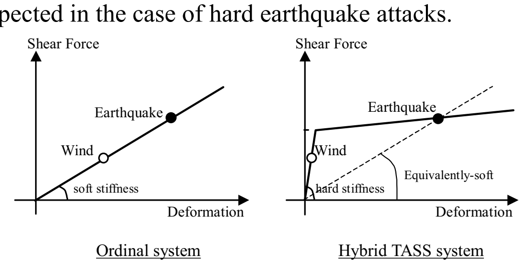

Figure 5 Force-Displacement Relation

Moreover, Hybrid TASS system is economically reasonable. Figure 6 shows the comparison between Hybrid TASS system and the ordinal base isolation system. In the ordinal system, the dampers such as the steel or lead energy absorption devices are necessary besides the isolators under the columns, while only the sliding and rubber bearings under the columns in Hybrid TASS system. So by the application of Hybrid TASS system, the high-rise building with the high seismic performance can be achieved without large increase of the construction cost.

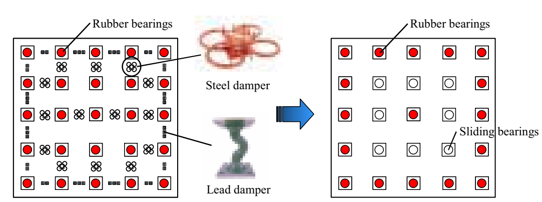

Figure 6 Comparison of Hybrid TASS System and Ordinal Base Isolation System

4. TESTS ON TENSILE PROPERTY OF RUBBER BEARING

In the design of the slender high-rise building, the uplift due to overturning and vertical forces during a large earthquake might act on the isolators especially at the corner. However, the property of large size rubber bearings subjected to the tensile force was unknown (problem (4)). In order to understand the tensile properties of the large rubber bearings, the tensile loading tests [Muramatsu et al, 2001] were carried out (Photo 1). Figure 7 shows the test specimen with the diameter of 1200mm. The relation between tensile and shear strain is shown in Figure 8, where the test results of these large size tests are plotted, together with those of the bearings with small diameter from other tests [Takayama et al, 1995]. There is a large difference of the safety limit between the small and the large size rubber bearings.

Considering this tendency, the hatched part in the figure is decided as the criteria in the design. There is an enough margin of the safety with respect to the limit of the tensile strain.

Photo 1 Test on Tensile Property

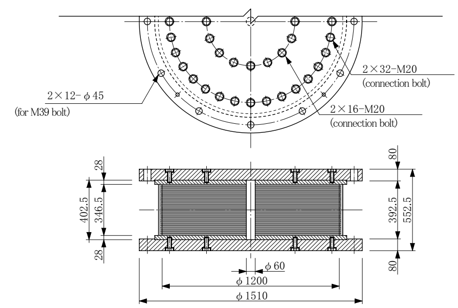

Figure 7 Test Specimen

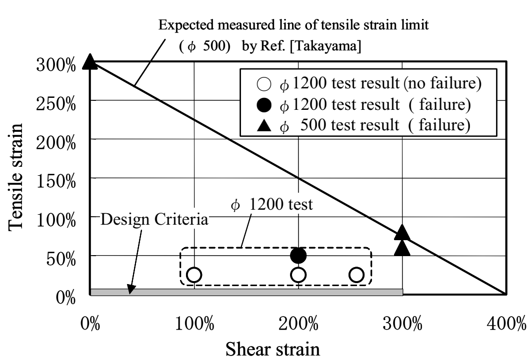

Figure 8 Relation of Tensile and Shear Strain

5. DESIGN OF HIGH-RISE BUILDINGS WITH HYBRID TASS SYSTEM

5.1 Sendai MT Building

Sendai MT Building is the 18-story office building with the height of 84.9m, located in Sendai City, Eastern Japan [Ogura et al, 1997]. This building is the first base-isolated building with over 60 m height in Japan (See Photo 2)

The structural features of this building are follows.

1) Use of the high strength materials such as concrete with compressive strength of 60N/mm^2 and SD 490 re-bars for the longitudinal reinforcement of the beams and the columns.
2) Application of the hybrid structure beams for the 15m-long spans. This beam consists of steel for the mid part and reinforced concrete for the both the ends of the beam.
3) The high-rise buildings with the base isolation system for the high seismic performance.

The client required the high seismic performance and the ability of the function maintenance after a large earthquake. To be satisfied this requirement, the application of the base isolation system, Hybrid TASS, was examined. Moreover, in order to obtain the large office space (See Photo 3), the long span beam system and the high strength materials were used . Figure 9 shows the frame elevation. The columns and the beams are the pre-cast members to ensure the quality of the structure and to make the construction term short possible.

Figure 10 shows the arrangement of the isolation devices at the isolation story below the first floor. The ratio of the sliding bearings among all the bearings under the columns was designed so that the yield force might be larger than the wind force. And to make the stiffness after the yield soft, the shape and rubber stiffness of the rubber bearings were designed. The sliding bearings are installed mainly under the inner columns, where the fluctuation of the axial force due to seismic forces is relatively small.

The seismic response analyses were conducted to confirm the target seismic performance, using several seismic ground motions. The input levels of the motions are categorized from the level 1 to the level 3, considering the occurrence probability during the use period of the building. Figure 11 shows the maximum response story drift angle. For the level 2 the drift angles are less than 1/330 and for the level 3 less than 1/230. From these results, the seismic design targets are satisfied and the high seismic performance is confirmed.

Photo 2 Sendai MT Building

Photo 3 Sendai MT Building (Office Space)

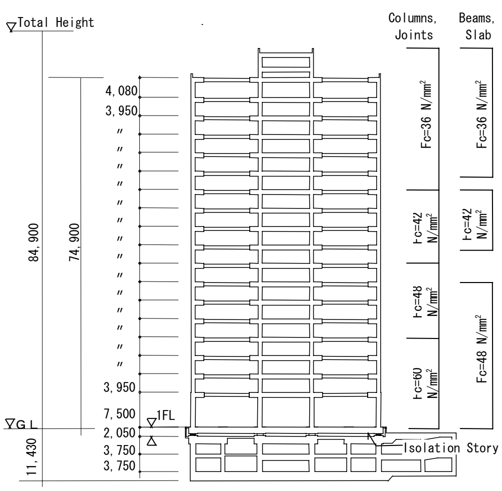

Figure 9 Frame Elevation

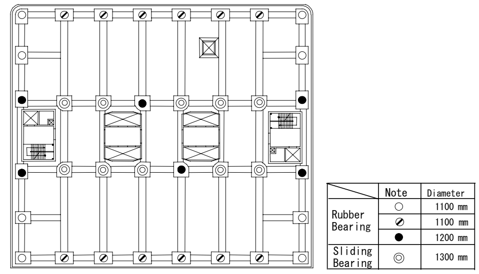

Figure 10 Arrangement of Isolation

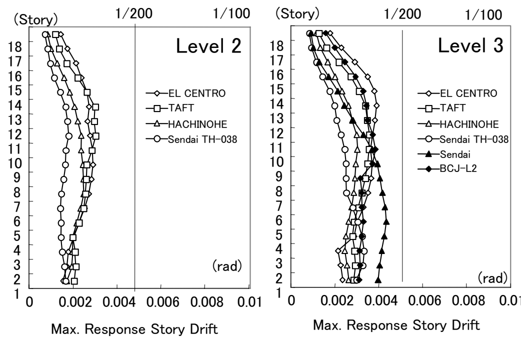

Figure 11 Maximum Response Story Drift

5.2 Thousand Tower

Thousand Tower is the residential Tower situated in Kawasaki City, Kanagawa Prefecture, and is the reinforced concrete structure with 41 stories above ground [Kawabata et al, 2001] (Photo 4). The base isolators place at the isolation story below the first floor. Figure 12 and 13 shows the frame elevation and the structural plan, respectively. The total height is 135.0 m and the aspect ratio is 3.83 in Y directions, so this building is the relatively slender structure.

The pre-cast and pre-stressed concrete beams as shown in Figure 14 are used for the 12m-span. The pre-stressing steel tendon is arranged at the clear mid-span of the beam and the longitudinal reinforcement of the steel bars is through the beam and developed at the beam-column joints. By adopting this long span system, no column exists in the residential area.

The high-strength concrete with strengths up to 100 N/mm^2 is used for the columns and the high strength re-bars (SD 490, USD 685) used for the longitudinal reinforcement of the beams and the columns. By using these high strength materials, the number and the cross-section of the structural members can be reduced, so that the effective architectural space can be used for the planning.

The seismic response analyses were conducted using several artificial ground motions, (see Table 1). The artificial ground motion H is based on the seismic activity and the soil properties at the building location.

The level 2 maximum response of the isolation story in Y direction is shown in Fig. 15. The level 2 maximum response story drift angle in Y direction is shown in Fig.

16. Compared with the response of the non-isolated model, the responses are effectively reduced by the base isolation system.

Photo 4 Thousand Tower

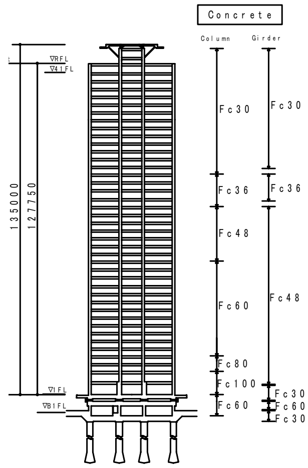

Figure 12 Frame Elevation

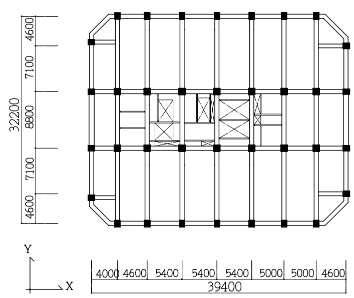

Figure 13 Structural Plan

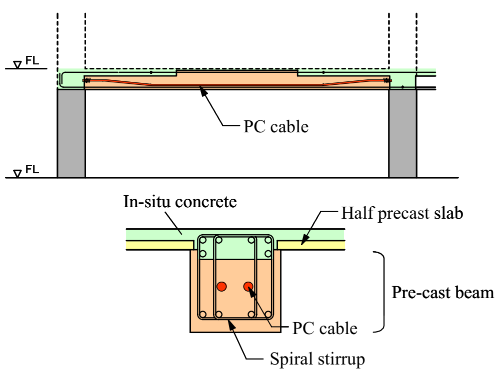

Figure 14 Pre-cast and Pre-stressed Beam

Table 1 Seismic waves

	Level 1 (m/s^2)	Level 2 (m/s^2)	Level3 (m/s^2)
BCJ-L2	−	0.574	−
Artificial wave H	0.237	0.474	0.595

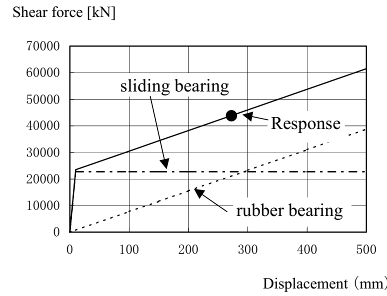

Figure 15 Maximum Response of Isolation Story

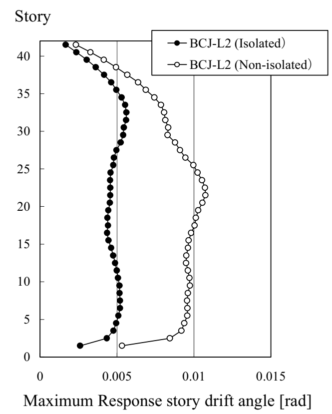

Figure 16 Maximum Response Story

6.SEISMIC RECORD AT OFF-MIYAGI QUAKE, MAY 26, 2003

The seismic data were obtained from the seismographs set at the floors of the isolation story, the 1st, 10th and 18th stories, in Sendai MT building, when the Off -Miyagi earthquake occurred in May 26, 2003 The maximum accelerations at these floors are shown in Table 2 and the acceleration waves of the E-W direction shown in Figure 17.

Photo 5 shows the observed track of the relative displacement between the 1st floor and the floor below, which means the displacement of the isolation story. From this result, the maximum displacement of the isolation story is found to be about 20mm and there is no remain displacement. Considering with the relation between the force and the displacement in the design, the sliding occurred and the isolation system is thought to have acted well.

With the recorded ground motion, the response analyses using the design model were carried out. Figure 18 shows the comparison of the analyzed and recorded maximum acceleration. Figure 19 shows the displacement track of the isolation story from the analyses. The good correspondences between the analyses and the records are found in these charts.

From these data and the analyses, it can be said that the base isolation system acted effectively on the high-rise building and the design analysis model is adequate.

Table 2 Maximum Accelerations

	NS Dir. (mm/s^2)	EW Dir. (mm/s^2)	UD Dir. (mm/s^2)
18th Floor	572	820	1040
10th Floor	507	796	683
1st Floor	357	550	486
Isolation Story	542	699	473

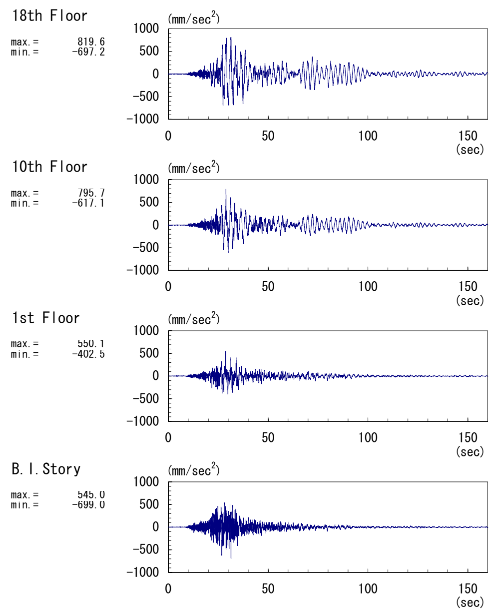

Figure 17 Acceleration waves of E-W Direction

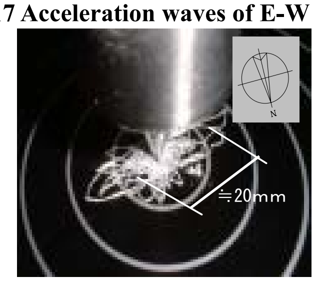

Photo 5 Observed Track of Relative Displacement

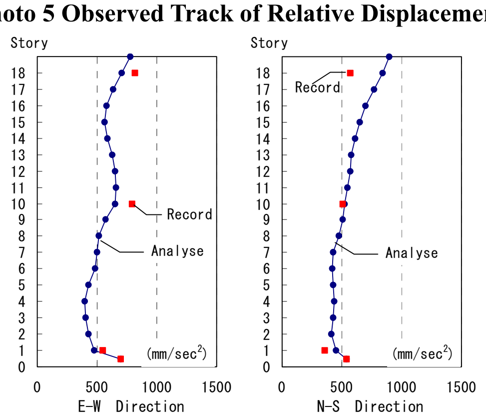

Figure 18 Comparison of analyses and record

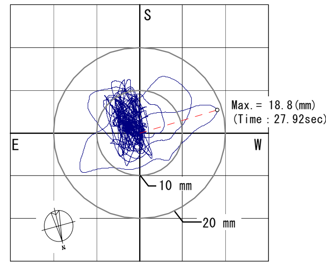

Figure 19 Analysed Displacement Track

7. CONCLUSIONS

1. The authors applied the base isolation systems to the high-rise buildings as a pioneer, getting out of the conventional ideas.
2. The several actual design problems have been resolved for the applicability of the base isolation system to the high-rise buildings.
3. Using the high strength materials and the long span structure systems, Sendai MT building and Thousand Tower possess not only high seismic performance, also the flexible planning in design.
4. The recorded data of the seismographs and the analyses show that the base isolation system acted effectively in Sendai MT building, when the Off -Miyagi earthquake occurred in May 26, 2003.

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