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Seismic retrofit of existing 256m high building by installing seismic dampers for long-period earthquake ground motions

T.Jinsenji[(1)], M.Yoshizawa[(2)], H.Tsukagoshi[(3)] , T.Asahi[(4)]

[(1)] *Structural Engineering Department, NIKKEN SEKKEI LTD, toshiko.jinsenji@nikken.jp*
[(2)] *General Manager, Structural Engineering Section, NIKKEN SEKKEI LTD, yoshizawa@nikken.jp*
[(3)] *General Manager, Structural Engineering Section, NIKKEN SEKKEI LTD, tsukagoshi@nikken.jp*
[(4)] *Structural Engineering Department, NIKKEN SEKKEI LTD, asahi.tomoki@nikken.jp*

Abstract

Long period earthquake motion was observed at 52-story steel-framed building located in the Osaka Bay area when Great East Japan Earthquake occurred in 2011 although the site of the high-rise building is 770 km away from epicenter. This paper deals with authors' elaborated seismic retrofitting design of the high-rise building to provide for future great quake such as Nankai megathrust earthquakes. To obtain strength and stiffness, steel dampers were installed in the long direction frames and to reduce the shaking of the building, oil dampers were installed in the short direction frames. After retrofitting, vibration test was conducted, of which results shows that damping ratio in the short direction has increased to more than double in virtue of the oil dampers added. Dynamic analysis results show that the maximum and the cumulative displacements on the 51st floor reduced remarkably. The test and analysis results of the first-stage seismic retrofitting verifies satisfactory effects of the damping system.

Keywords: retrofit ; long period earthquake ground motions ; high-rise building

1. Introduction

During the Great East Japan Earthquake, long-period earthquake ground motion was observed in a number of Tokyo skyscrapers. However, although it was recognized from before Great East Japan Earthquake that countermeasures against long-period earthquake ground motion were required for the many skyscrapers standing in Tokyo and Osaka, in actuality hardly no retrofitting construction has been performed. This paper will describe an outline of the first long-period earthquake ground motion retrofitting design on a skyscraper in Osaka and the effects of the retrofitting work.

2. Building outline and outline of originally designed structure design

The building is located on land reclaimed from Osaka Bay about 7km from the center of Osaka. It was designed as the World Trade Center Building with 3 underground floors and 52 above-ground floors, with a maximum height of 256m (Photo 1). Construction was begun in March 1991 and was completed in February 1995 immediately after the Great Hanshin Earthquake. In 2010, the building was purchased by Osaka Prefecture, and it currently serves as the Osaka Prefectural Government Sakishima Building.

Photo 1: Building appearance (at time of completion)

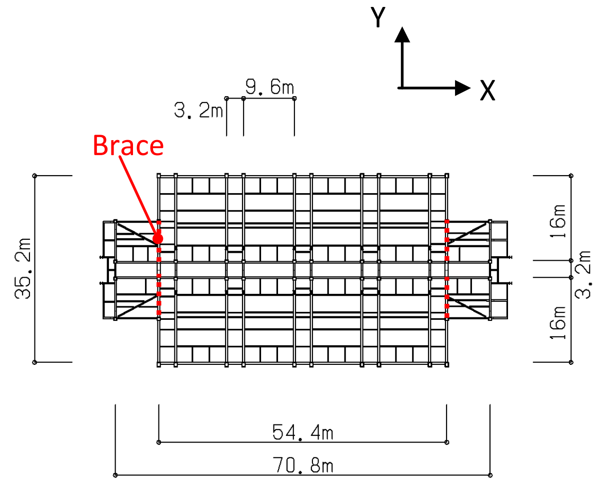


Fig. 1: Layout of framework for standard floor

The structure type is steel frame for the above-ground sections. The underground sections are steel-reinforced concrete frame having high rigidity and high strength with reinforced concrete shear walls and steel-reinforced concrete braces, and are designed to smoothly convey forces from the above-ground sections to the underground sections and the foundation.

Figure 1 shows the layout of framework for a standard floor, and Figure 2 shows the main framing elevations. In the long direction (X direction), it is designed as a moment resisting frame structure comprised of 2 planes of external frames and 2 planes of internal frames for a total of 4 planes. The column span alternates between 3.2m and 9.6m repeatedly and seismic columns are provided in the external frames every 11 to 13 floors to increase the horizontal rigidity of the entire building. The large atrium up to the 7th floor has columns at 3.2m intervals which are connected by beams approximately every 5m to increase rigidity as grouped columns as well as ensuring horizontal rigidity with seismic bracing installed from the 1st to 5th floors. The designed primary natural period in the long direction is 5.8 seconds.

In the short direction (Y direction), it is comprised of 2 planes of external frames with seismic braces and 8 planes of internal unbraced frames. The internal frame is comprised of 16m, 3.2m, and 16m spans, and seismic columns are provided at the corners of the elevator core for the long spans below the 20th floor. The external frames have seismic columns provided every 11 to 13 floors in the same way as for the X direction. For the large atrium up to the 7th floor, in order to spread the axial forces of upper floors to the outside as much as possible and in order to reduce the aspect ratio, both the outer columns and inner columns are large truss frames that spread outward. The designed primary natural period in the short direction is 5.3 seconds.

256m

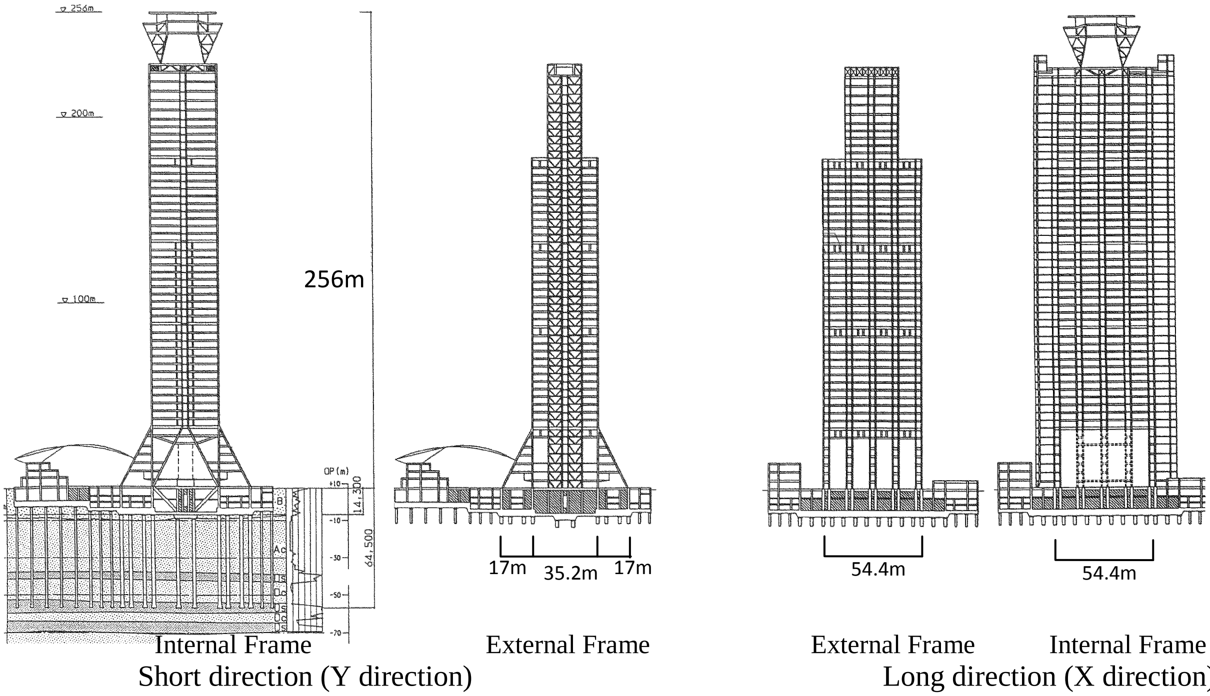


Fig. 2: Framework elevations at time of original design

For the seismic design at the time of original design, when seismic response analysis was performed using 6 observable waves with the input maximum speed of earthquake ground motion normalized to 50cm/s, it was confirmed that the stress generated in the members was less than the elastic limit strength and the maximum inter-story drift angle was 0.01 rad or less. On the other hand, for wind resistant design, wind tunnel testing was carried out, and for a reproduced 500-year-period wind load, it was confirmed that the stress generated in the members was less than the elastic limit strength. It should be noted that 2 sets of tuned active dampers have been installed at the top of the building in order to increase living comfort in daily winds.

3. Swaying in the Great East Japan Earthquake

The Osaka Prefectural Government Sakishima Building, in preparation for the ocean-type earthquake which has a high probability of occurring in the Nankai Trough, began a general study from 2008 prior to the building purchase and proceeded with retrofitting design against long-period earthquake ground motion, and prior to the seismic retrofitting construction, the shelves, desks, etc. on the floors into which the Osaka Prefectural Government would move (18th floor and above) were secured in place. However, when the Great East Japan Earthquake occurred on March 11, 2011, major swaying occurred in the building which was thought to be due to long-period earthquake ground motion. Table 1 shows the maximum sway values observed by accelerometers installed in the building by the Building Research Institute.

As stated earlier, at the time of original design, the designed primary natural periods were 5.8 seconds in the long direction and 5.3 seconds in the short direction, and the interaction between the ground and building was not considered. In addition, the damping factors for the building long direction and short direction were both set at 2%.

Table 1: Building sway during Great East Japan Earthquake

		Level 51	Level 18
Maximum Displacement	Long Direction	86 cm	32 cm
	Short Direction	137 cm	30 cm
Maximum Acceleration	Long Direction	88 cm/s^2	39 cm/s^2
	Short Direction	131 cm/s^2	41 cm/s^2

But when the building sway that occurred during the Great East Japan Earthquake and its aftershocks were analyzed, it was found that the primary natural periods were approx. 6.6 to 6.9 seconds in the long direction and approx. 6.4 to 6.6 seconds in the short direction, which are different from the values at the time of original design. In light of these differences, it was decided to modify the analysis model and damping factors to match the actual phenomena, and then review the retrofitting design details.

Specifically, the building weight in the analysis model was revised to match the current weight, and in addition a vertical spring that takes into account the supporting soil and piles was provided. As a result, the primary natural periods of the building before retrofitting became 7.0 seconds in the long direction and 6.6 seconds in the short direction, and by setting the damping factors to 2% in the long direction and 1% in the short direction, it was confirmed that the building behavior during the earthquake could be roughly reproduced.

Table 2 shows the primary natural periods and damping factors at the time of original design and after revising the model. In addition, Figure 3 shows graphs comparing the observation results and the analysis results for the 51st floor when analysis is performed by inputting the recorded 1st floor acceleration at the time of the Great East Japan Earthquake (main shock at 14:46 JST) into the analysis model as the first floor constant. The analysis results are generally consistent with the observation results, and it was judged that the analysis model was valid.

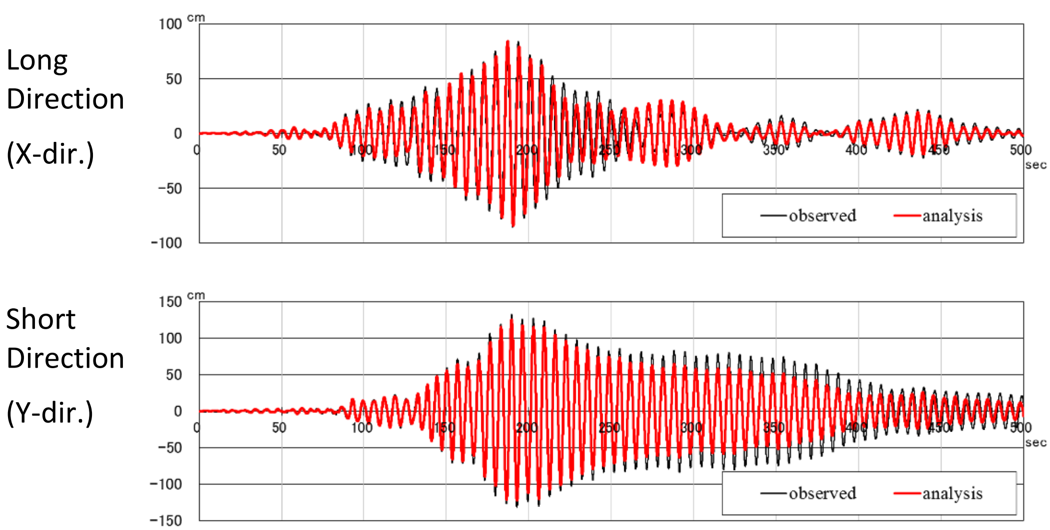


Fig. 3: Comparison of observed results and analysis results

(51st Floor displacement)

Table 2: Comparison of primary natural periods and damping factors

	Original Model		Revised Model	
	Long Direction	Short Direction	Long Direction	Short Direction
Primary Natural Period	5.8 sec	5.3 sec	7.0 sec	6.6 sec
Damping Factor	2 %	2 %	2 %	1 %

4. Retrofit design overview

If ocean-type earthquake ground motion occurs with the epicenter in the Nankai Trough, earthquake ground motion with a larger long-period component than that of the earthquake ground motion assumed at the time of original design will be applied to this high-rise building standing next to Osaka Bay. Furthermore, since the primary natural period is 6 to 7 seconds, it can be said that the impact of the long-period earthquake ground motion will be exceedingly large.

At the time of retrofitting design in 2011, it was known that the probability of a massive earthquake occurring in the Nankai Trough was high, but there was no announcement regarding the progress of studies in the Cabinet Office of Japan on what scale of long-period earthquake ground motion would occur taking into consideration what had happened in the Great East Japan Earthquake. However, because it was necessary to promote countermeasures against long-period earthquake ground motions urgently, for the first stage of retrofitting, the long-period earthquake ground motion used for retrofitting design was created using the engineering bedrock surface waves of the Osaka Bay area included in the "Draft proposal on countermeasures for skyscrapers, etc. against long-period earthquake ground motions" issued by the Ministry of Land, Infrastructure and Transport in December 2010 before the Great East Japan Earthquake and taking site surface soil characteristics into consideration. This is referred to hereinafter as the "Trial Wave". The pseudo-velocity response spectrum (pSv) of the design earthquake ground motion is shown in Figure 4. Near the building's primary natural period (6 to 7 seconds), pSv is slightly less than 150 cm/s, but around the period of 2 seconds, the impact of site surface soil amplification is large and pSv becomes around 180 cm/s.

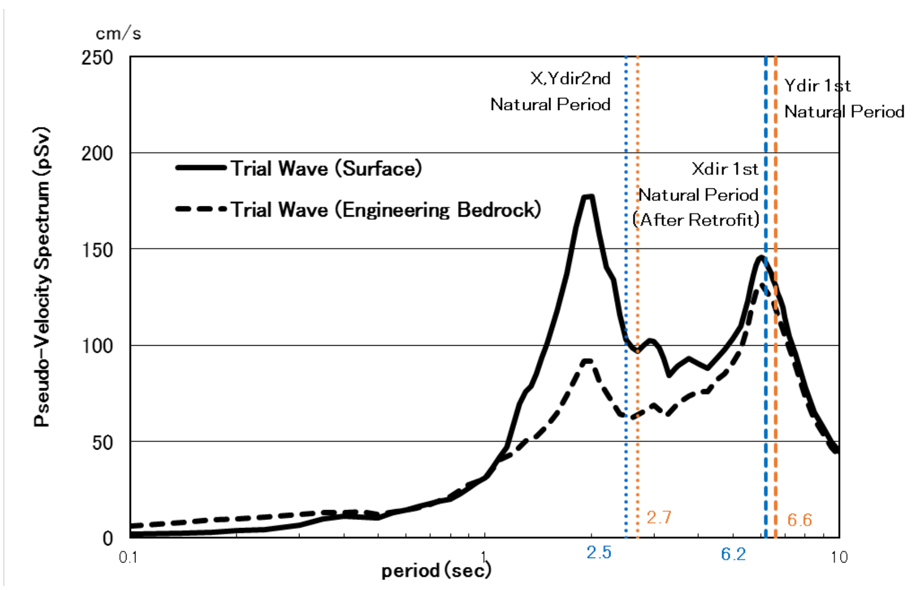


Fig. 4: Pseudo-velocity response spectrum (h=5%) for design simulated ground motions

Using the previously described revised analysis model, the results of examining the response characteristics using the above simulated earthquake ground motion showed that the structural safety could not be ensured in the long direction, and it was decided to perform retrofitting to add rigidity and strength. On the other hand, in the short direction, it was decided to perform retrofitting to reduce the sway width and sway duration, to increase safety in rooms and to reduce the psychological burden of building users. Figure 5 shows the retrofitting concept drawings. In order to add strength and rigidity in the long direction, a total of 88 steel dampers with a yield axial force of 2000 kN each will be added to the building's exterior framework on the 7th to 17th floors, and a total of 64 steel dampers with a yield axial force of 3000 kN each will be added to the interior framework on the 8th to 17th floors and the 21st to 26th floors. The steel dampers are buckling restrained braces that use a steel with a low yield point (yield stress = 225 N/mm^2) as the core material. In order to add a damping force in the short direction, a total of 140 oil dampers with a maximum damping force of 2000 kN each will be added to the building's exterior framework on the 8th to 17th floors and the 21st to 28th floors. Photos 2 and 3 show the installed steel dampers and oil dampers.

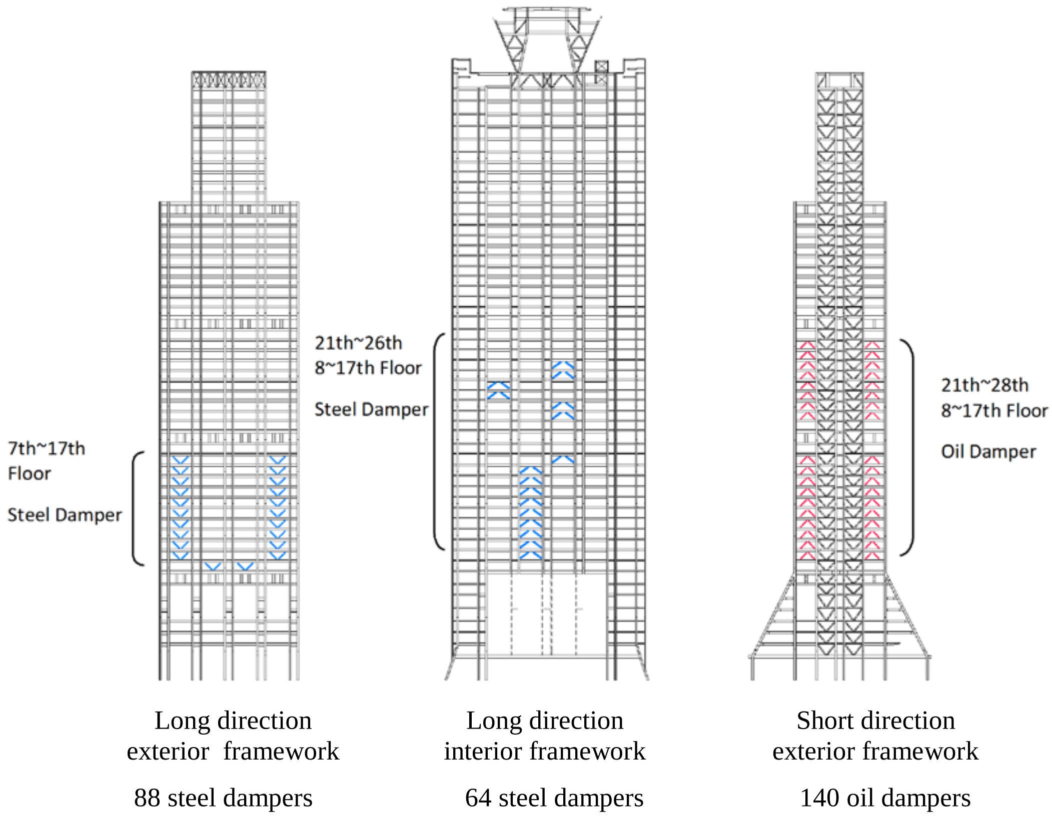


Fig. 5: Structural retrofitting concept images

Photo 2 – Steel Damper in Long Direction

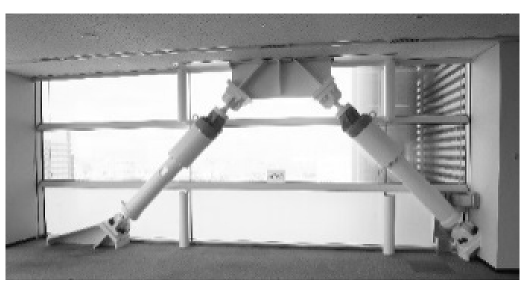


Photo 3 – Oil Damper in Short Direction

It should be noted that in the long direction, the structure was equipped with seismic braces on the 1st to 5th floors to ensure the rigidity and strength of the atrium's lower-floors section, but it was forecast that if the assumed long-period earthquake ground motions were applied, the axial strength limit of the 1st and 2nd floor brace-side columns would be reached due to the additional axial force of the braces, and so retrofitting was performed by adding steel frames with T-shaped cross sections. Also, in addition to structural retrofitting, countermeasures against long-period earthquake ground motions for elevators, reinforcement of drop-prevention members of system ceilings, countermeasures against stairwell wall materials falling off, changes to the shape of the releases of fire doors so that they do not easily open in the event of the building swaying, making water tanks earthquake-resistant, etc. have also been performed[1].

For long-period earthquake ground motions, since the effects of building primary mode vibrations are considered significant, the analysis model used for vibration response analysis is based on an equivalent shear type model of 53 point masses for the above-ground floors. First, incremental analysis of the static loads created by the horizontal external forces of the maximum story shear force distribution shape due to the Trial Wave of preliminary analysis was performed using the all-member three-dimensional element model shown at the left in Figure 6. From those results, the relationships between the story shear force and inter-story displacement taking into consideration the P-delta effect were created respectively for the long direction and short direction, and these were replaced by equivalent tri-linear springs. For damping characteristics, from the verification results in the Great East Japan Earthquake, rigidity-proportional internal viscous damping was used with the primary dampers set to 2% in the long direction and 1% in the short direction, and in the short direction the damping force of the oil dampers was taken into consideration. It should be noted that since there is also influence from the vibrations of higher-order modes, vibration response analysis using an all-member model was also performed, and the validity of the analysis results was confirmed.

The diagrams at the center and right in Figure 6 are diagrams of the deformation in the long direction and short direction in the static load incremental analysis. When the ratio between the shear deformation and bending deformation (frame bending deformation and foundation rocking deformation) in the deformation was analyzed, it was found that shear deformation was predominant in the long direction, at around 80% for lower floors and around 60% for upper floors. On the other hand, in the short direction deformation was almost entirely rocking deformation for the large truss framework up to the 7th floor. For floors above that, bending deformation increased as the floor number increased ,around 40% for lower floors and 80% for upper floors.

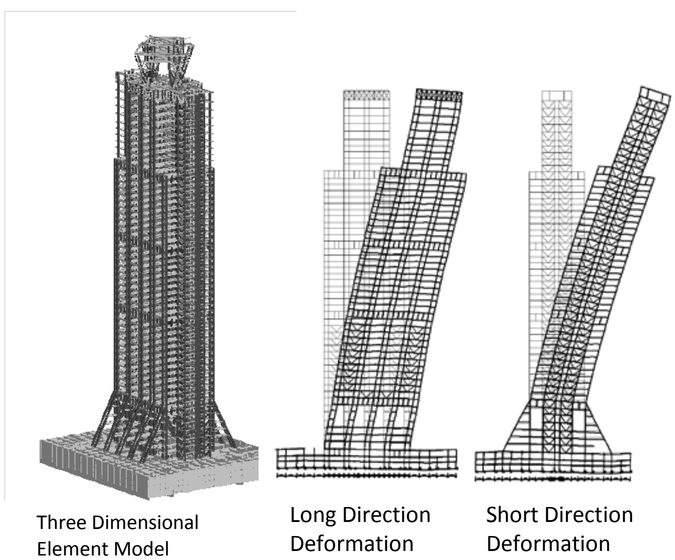


Fig. 6: Horizontal deformation characteristics in all-member three-dimensional framework models

The seismic design criteria for the superstructure against the trial wave were set as being below confirmed horizontal holding strength, maximum inter-story shear drift angle of 0.01 rad or less, and story ductility ratio of 2.0 or less. Table 3 shows the response analysis results. It was confirmed that the set seismic design criteria were satisfied.

Table 3: Trial Wave vibration response analysis results

	Long Direction	Short Direction
Maximum Story Drift Angle	9.43×10^{-3} rad	6.90×10^{-3} rad
Maximum Ductility Ratio	1.50	1.35
Horizontal Displacement at Level 51	199 cm	224 cm

5. Verification of effects of retrofitting

Figure 7 shows graphs comparing the observation results and the analysis results for the 51st floor when analysis is performed by inputting the recorded 1st floor acceleration at the time of the Great East Japan Earthquake (main shock at 14:46 JST) into the post-retrofit analysis model as the first floor constant. Figure 8 shows response analysis results for the Trial Wave before and after retrofitting. Table 4 shows the maximum displacement value and cumulative displacement amount at the 51st floor. In the analysis using the Great East Japan Earthquake, the maximum displacement values of the 51st floor in both the long direction and short direction were reduced to approximately half. In the analysis using the Trial Wave, although the maximum displacement did not change much between before and after retrofitting, it was possible to reduce the cumulative displacement amounts in both the long direction and short direction to approximately half, and it was confirmed that the response converges more quickly so that later swaying is reduced.

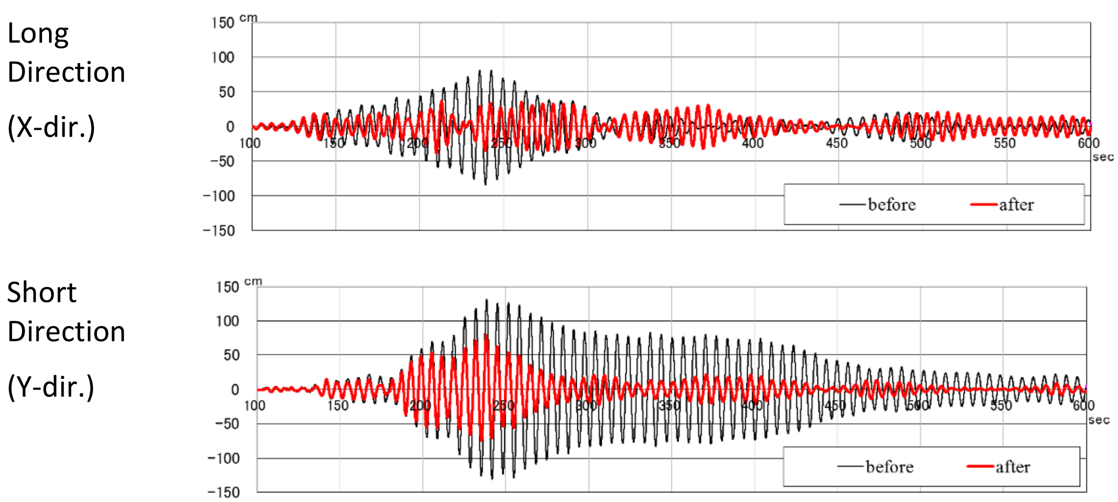
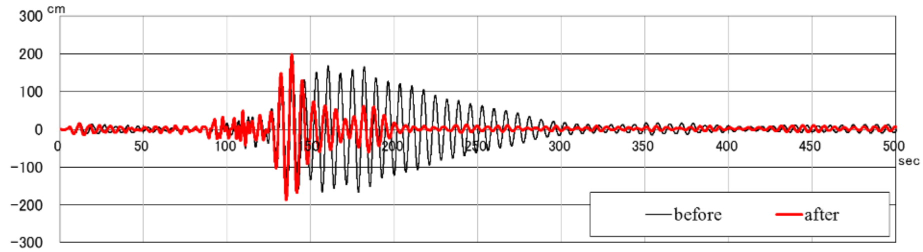


Fig. 7: 51st floor displacement vibration response simulation results before and after retrofitting

(using March 11, 2011 earthquake)

Long Direction

(X-dir.)



Short Direction

(Y-dir.)

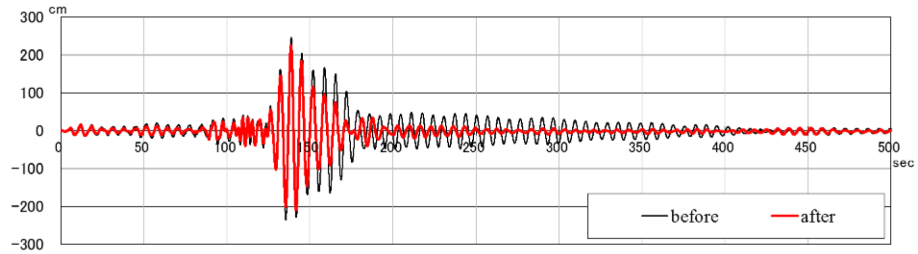


Fig. 8: 51st floor displacement vibration response simulation results before and after retrofitting

(using Trial Wave)

Table 4: Retrofitting Effect

		Maximum displacement at Level 51			Cumulative displacement at Level 51		
		Before Retrofitting	After Retrofitting		Before Retrofitting	After Retrofitting	
March.11,2011 Wave	X-dir.	86cm	38cm	-56%	7548cm	6673cm	-12%
	Y-dir.	137cm	79cm	-42%	17986cm	6193cm	-66%
Trial Wave	X-dir.	192cm	199cm	+4%	13384cm	6742cm	-50%
	Y-dir.	246cm	224cm	-9%	12234cm	6867cm	-44%

The Trial Wave energy balance over time for the post-retrofit model is shown in Figure 9. In the long direction, the energy absorbed by the steel dampers is 32% of the total, the damping over time of the main frame is 15% of the total, and internal viscous damping is 53% of the total. In the short direction, the energy absorbed by the oil dampers is approximately 57% of the total, the damping over time of the main frame is 8% of the total, and internal viscous damping is 33% of the total.

Long Direction

(X-dir.)

Short Direction

(Y-dir.)

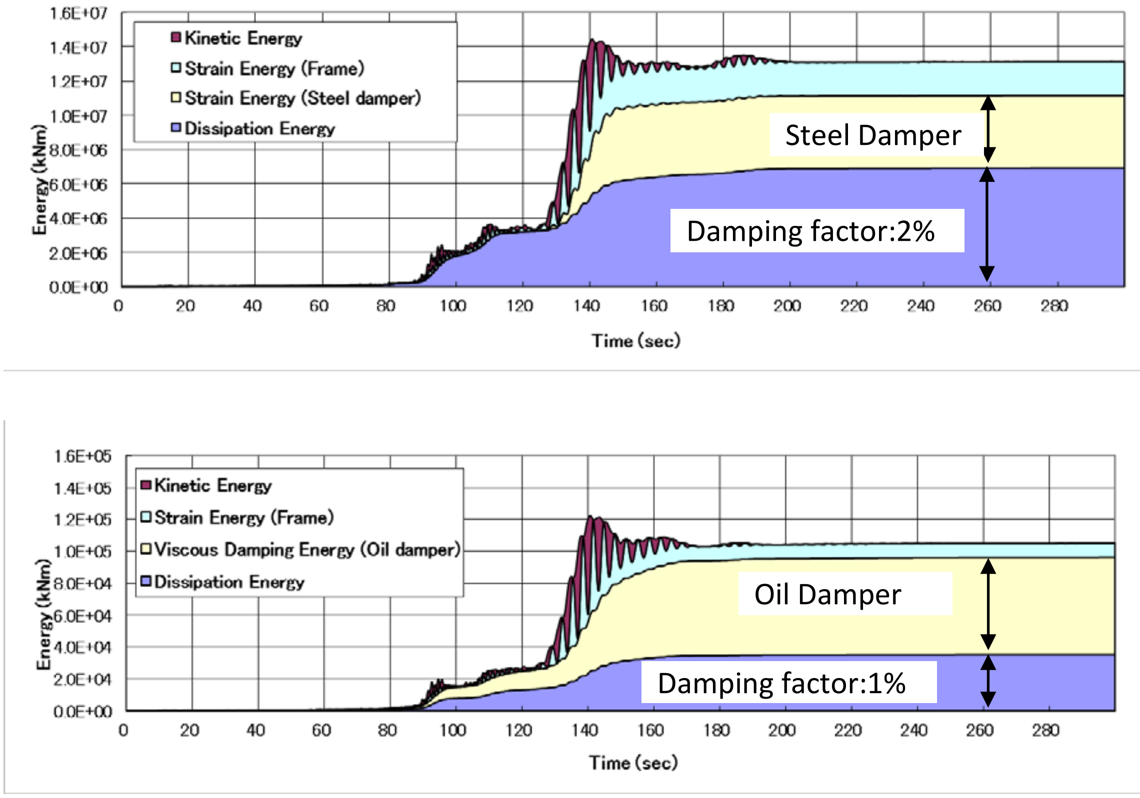


Fig. 9: Energy balance in post-retrofit simulation (using Trial Wave)

Furthermore, the results of confirming the period and damping factor by performing vibration testing using the tuned active dampers installed at the top of the building as countermeasures to wind sway are shown in Table 5. Since the natural period is amplitude-dependent, when small vibrations are applied, for the long direction where exterior materials and interior materials have a great impact on building rigidity, the primary natural period in pre-retrofit vibration testing is shorter than the observed results at the time of the Great East Japan Earthquake. The damping factor in the short direction increased from 0.7% prior to retrofitting to 1.9%, showing the effect of the oil dampers.

Table 5: Results of vibration testing

	Direction	Before installing dampers		After installing dampers	
		Period	Damping factor	Period	Damping factor
Vibration testing results	Long direction	6.44sec (7.04sec)	2.9% (2.0%)	5.78sec (6.21sec)	2.1% (2.0%)
	Short direction	6.42sec (6.56sec)	0.7% (1.0%)	6.33sec (6.56sec)	1.9% :Including oil dampers (1.0% :Excluding oil dampers)

Values in parenthesis ( ) in the table are analysis model values

6. Conclusion

Thus, by installing dampers as the first stage of retrofitting, it was possible to reduce building sway during an earthquake as well as greatly improve the structural safety of the building.

The "Report on long-period earthquake ground motions due to a major earthquake along the Nankai Trough" issued by the Cabinet Office of Japan on December 17, 2015 and the "Proposal on countermeasures for skyscrapers, etc. against long-period earthquake ground motions due to a major earthquake along the Nankai Trough" issued by the Ministry of Land, Infrastructure, Transport and Tourism on December 18, 2015 both propose earthquake ground motions that are more powerful than the Trial Wave. Countermeasures against such ground motions will be planned together with building owners in the future.

7. Acknowledgements

The strong vibration data for this building used herein are data from the seismographs installed by the Building Research Institute.

8. References

[1] Osaka Prefecture Government: Status of implementation of countermeasures against long-period earthquake ground motions in the Osaka Prefectural Government Sakishima Building

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