Title: **Seismic Retrofit of High-Rise Building with Deformation-Dependent Oil Dampers**

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Seismic retrofit of high-rise building with deformation-dependent oil dampers

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Biography

Hideshi Aono is a structural design engineer. He received his master in engineering from Tokyo University in 2001. After completing the master course, he joined Taisei Corporation in 2001. Taisei Corporation is a Japanese corporation which was established in 1873. Its main areas of business are building construction, civil engineering, and real estate development.

Abstract

Along the subduction-zone of the western Japanese islands, large earthquakes will occur around the middle of this century and long-period ground motions will reach major urban areas, and shake high-rise buildings violently. Since some of old high-rise buildings were designed without considering long-period ground motions, reinforcing such buildings is an important issue.
An effective method to reinforce existing high-rise buildings is installing additional dampers. However, a problem with ordinary damper is that they require reinforcement of surrounding columns and girders to support large reaction forces generated during earthquake ground motion. To solve this problem, a deformation-dependent oil damper was developed. The most attractive feature of this damper is to reduce the damping force at the moment when the frame deformation comes close to its maximum value. Allowing this feature, reinforcement of columns, girders, and foundations are no longer required.
The authors have applied seismic retrofitting with deformation-dependent oil damper to an existing 54-story office building (Shinjuku Center Building) located at Shinjuku ward, Tokyo Metropolitan in 2009, to suppress vibration under the long period earthquake ground motions. The seismic responses were observed in the 2011 off the Pacific coast of Tohoku Earthquake and it is clarified that the damping ratio was higher and the response lower by 20% as compared to the building without dampers.

Keywords:
seismic retrofit, high-rise building, oil damper, long-period ground motions, the 2011 off the Pacific coast of Tohoku Earthquake

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1. Transition of design ground motion and characteristics of long-period ground motions

Figure 1 shows the pseudo velocity response spectra of design ground motions. Most of high-rise buildings before 2000 were designed considering only “three standard design waves”: EL CENTRO NS, TAFT EW and HACHINOHE NS. In these days, it is recognized that the three standard design waves are small in the period domain longer than 3 seconds. The building law revised in 2000 gives a design spectrum whose value (80 cm/s up to 10 seconds) is larger than the three standard design waves. In addition, recent researches point out that the long-period ground motions are amplified by the thick sedimentary layers of the major plains and they surpass the building law spectrum in long-period domain.

The characteristic of long-period earthquake ground motions is that they travel long distance without being attenuated and have long duration. It is pointed out that existing high-rise buildings have a possibility to be stricken by two large earthquakes and more. Those conditions were not considered at the time when old buildings were constructed. The long duration and multiple strikes of large earthquakes make the cumulative damage exceed the capacity. Therefore, it is strongly required to reinforce the building to reduce the damage of structures and deformation of building.

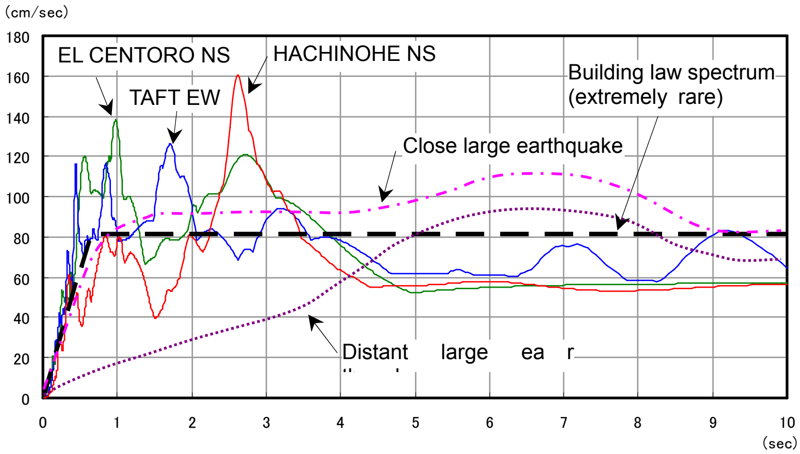

Figure 1. Velocity response spectra of design earthquake ground motions

2. Deformation-dependent oil dampers

Figure 2 illustrates the stress condition while the seismic force is acting a high-rise building. Oil dampers are installed with K-shape brace. One side is under tensile force and the other under compression force. Especially, the dampers near the foot of the building are under large tensile and compression forces.

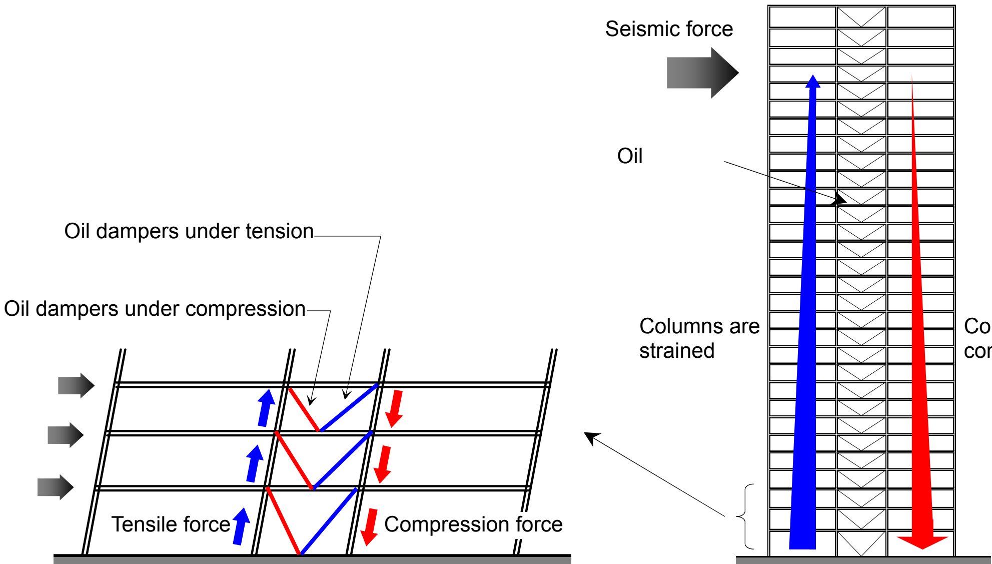

Figure 2. Stress condition while seismic force is acting

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Ordinary dampers change the damping force depending on velocity. When the velocity of piston reaches a threshold value, the relief valve opens and the damping force is kept constant. A problem with ordinary dampers is that they require reinforcement of surrounding frame such as columns, beams, and foundations because reaction force is large when the frame deformation comes close to its maximum value. It is difficult to reinforce surrounding frame of an existing building.

To solve this problem, a deformation-dependent oil-damper was developed as shown in Fig. 3. The damper has a one-way bypass route in addition to main valve (upper panel). When seismic force works on the damper and the deformation reaches the predetermined value, the one-way bypass opens and the damping force decreases (middle panel). When the piston goes back, the one-way bypass closes and the damper behaves as an ordinary damper (lower panel). Figure 4 shows the relationship of damping force and deformation for the ordinary damper and that of the deformation-dependent oil damper. The deformation-dependent oil damper reduces the damping force at the moment when the frame deformation comes close to its maximum value. Therefore, no reinforcement of columns, beams, foundations is required.

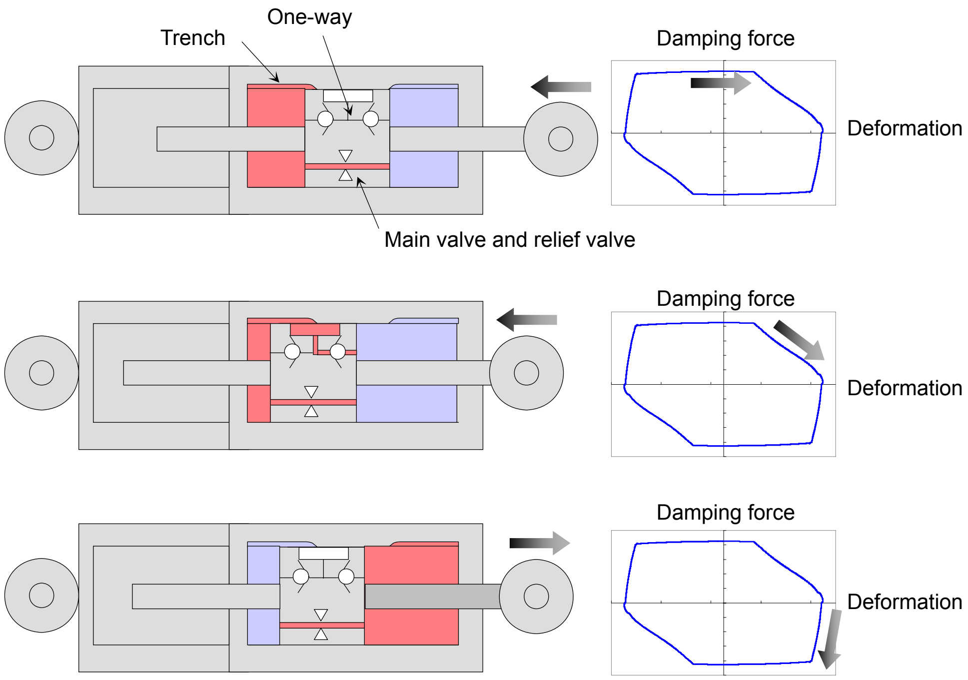

Figure 3. Mechanism of a deformation-dependent oil damper

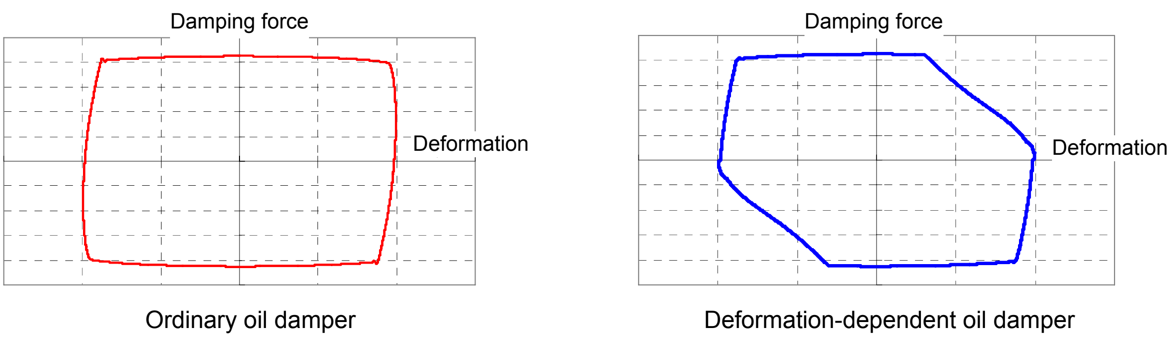

Figure 4. Relationship of damping force and deformation for an ordinary damper and a deformation-dependent oil damper

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3. Application to Shinjuku Center Building

3.1 Specification of the building

We applied the deformation-dependent oil dampers to an existing 54-story office building (Shinjuku Center Building) located at Shinjuku ward, Tokyo Metropolitan (fig. 5). This building was completed in 1979. Figure 6 shows the framing plan of a typical floor. It is 63.0m×42.0m rectangle. The longer edge consists of 3m units and the shorter edge consists of 15.4m, 11.2m and 15.4m spans.

The part above the ground level is steel structure. As an earthquake-proof component, energy-absorbing walls using steel bar (hereafter cited as SBEAW) are installed around the central core in both direction. Moment Resisting Frame (MRF) frames connect the core and the external columns. Truss beams are constructed at the top story and middle stories in order to control flexural deformation (fig. 7). Table1 shows specification of the building. First natural period of this building is 6.2 second along transverse direction, 5.2 second along longitudinal direction.

Figure 8 shows the details of SBEAW. It consists of two pieces of reinforced concrete walls separated into upper and lower parts. Two parts are connected with comb-like steel bars which are deformed by shear force between the two pieces and absorb the energy with their bending ductility. By the experiment carried out before construction, it is confirmed that allowable cumulative plastic deformation ratio of connecting steel bars is around 135. This building has 12 SBEAW along the transverse direction, and 20 along the longitudinal direction in each story.

Figure 5. Shinjuku Center Building

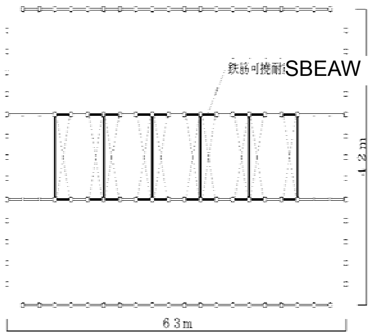

Figure 6. Framing plan

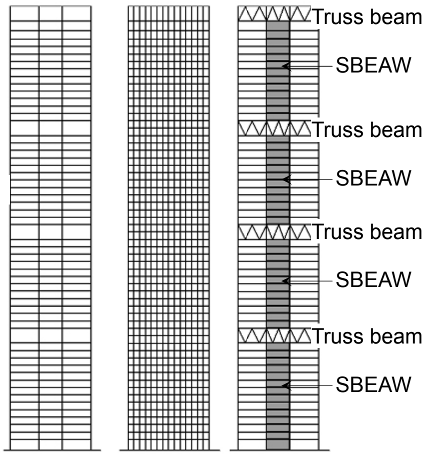

Figure 7. Elevation plan (transverse direction)

Table 1. Specification of the building

Location	Shinjuku-ward, Tokyo
Main uses	Offices
Building area	3,667m^2
Total area	183,064m^2
Number of stories	Five stories underground, 54 stories above ground, three-story penthouse
Height	216m
Structural type	Steel structure above ground part
Foundation	Spread foundation
Completion date	October 1979

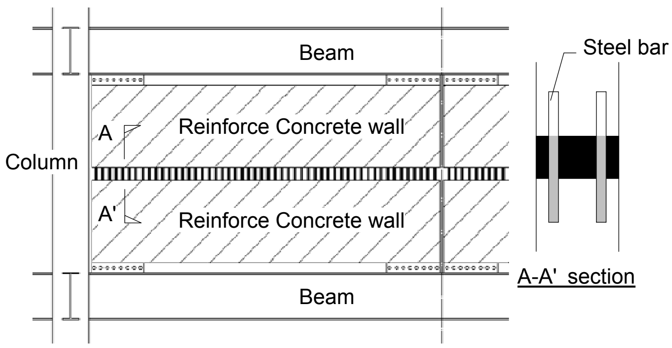

Figure 8. Details of SBEAW

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3.2 Criteria of structural design

The existing building was initially designed so that the deformation angle between two stories is less than 1/100 for the design ground motion based on building law spectrum and the three standard waves. The purpose of this project is to improve its earthquake-proof performance by installing the deformation-dependent oil dampers from the point of view of business continuity. The criteria of the structural design are as follows.

For both of the close large earthquake (Kanto earthquake) and the distant large earthquake (Tokai earthquake),

・the deformation angle between two stories is to be less than 1/100 and,

・the cumulative plastic deformation ratio of steel bars is to be less than η= 135.

3.3 Setting deformation-dependent oil damper

We set 12 deformation-dependent oil dampers in every 24 floors from 15th to 39th floor as shown in Fig. 9 and Fig. 10. The total number is 288. We choose these floors because the dynamic analysis shows that the deformation angle between stories and the cumulative plastic deformation ratio of steel bars are relatively large at these floors. Considering the relationship with the surrounding frame, we set the one-way bypass to open when the deformation reaches 5mm. In order to reduce the vibration excited by the long-period earthquake ground motions, we use high-damping type whose release velocity Vr is 1.7cm/sec. Table 2 and Fig. 11 show the specification of the oil damper.

Oil damper is installed between bottom of brace and base plate settled on the slab as shown in Fig. 12. The joint of brace and girder, and the joint of base and base plate is performed by press-bond with PC bar. No weld is required. We set the tension of each PC steel bar to be 250kN so that the brace and the girder do not slide.

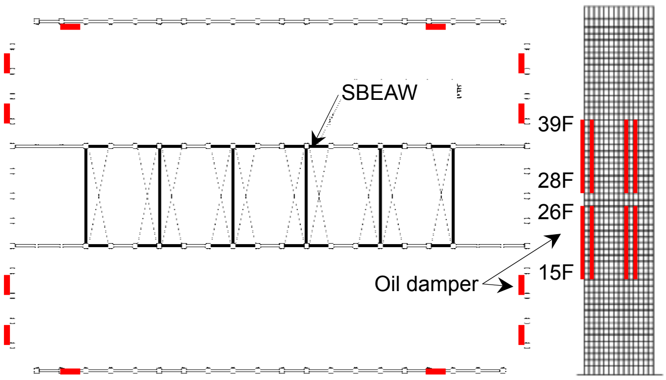

Figure 9. Layout of oil dampers

Figure 10. picture of the oil damper

Table 2. Specification of the oil dampers

C1	235kN・sec/cm
C2	3.5kN・sec/cm
Vr	1.7cm/sec
Vmax	15 cm/sec
Fr	400kN
Fmax	446kN

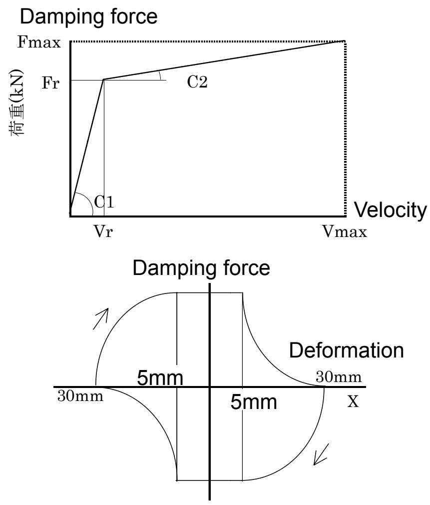

Figure 11. Specification of the oil dampers

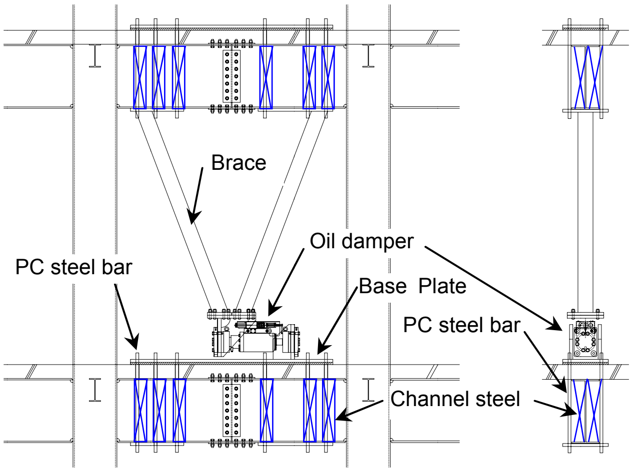

Figure 12. Detail of attachment

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3.4 Long-period earthquake ground motions
3.4.1 Assumed South Kanto earthquake

Assumed earthquake ground motions are synthesized by the empirical Green's function method [Irikura, 1986] at the period domain below 4 seconds and by the three dimensional finite difference method [Graves, 1996] above 4 seconds. Adding those two results, a broadband synthetic ground motions are generated. Figure 13 shows the three components of the synthetic acceleration waveform of assumed South Kanto earthquake. Figure 14 shows the pseudo velocity response spectra (h=5%).

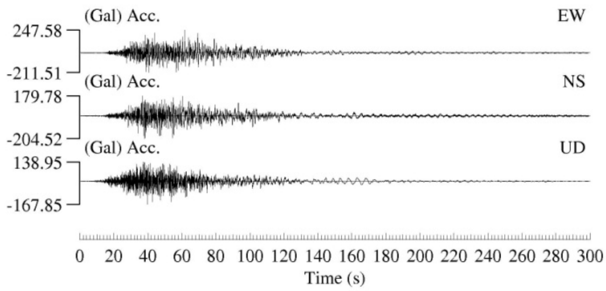

Figure 13. Acceleration waveforms of assumed South Kanto earthquake

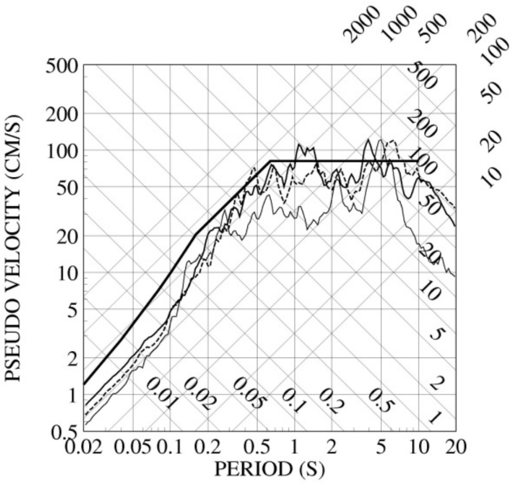

Figure 14. Response spectra of assumed South Kanto earthquake (h=5%)

3.4.2 Assumed Tokai earthquake

Assumed earthquake ground motions are synthesized by the empirical Green's function method in the period domain below 4 seconds and by the domain reduction method [Bielak et al, 2003] [Yoshimura et al, 2003] above 4 seconds. Adding those two results, a broadband synthetic ground motions are generated. Figure 15 shows the three components of the synthetic acceleration waveform of assumed Tokai earthquake. Figure 16 shows the pseudo velocity response spectra (h=5%).

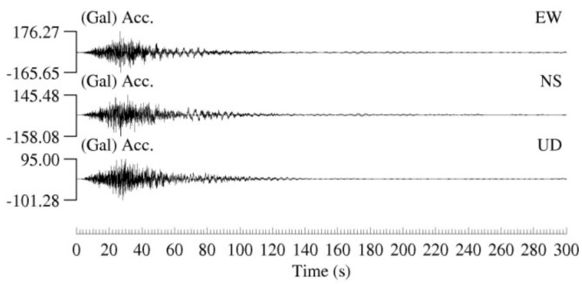

Figure 15. Acceleration waveforms of assumed Tokai earthquake

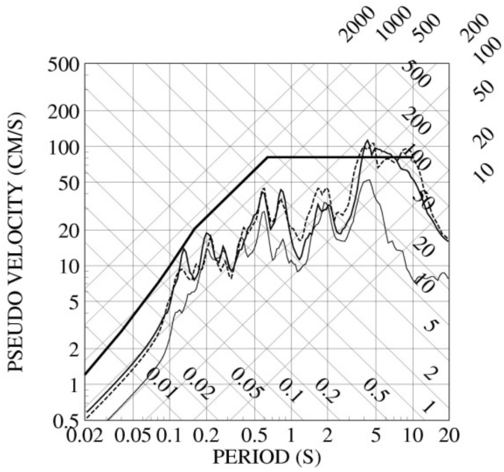

Figure 16. Response spectra of assumed Tokai earthquake (h=5%)

3.5 Result of Dynamic Analysis

Dynamic analysis is carried out under the condition such that 1st story column is fixed. Figure 17 shows the result of maximum deformation angle at each story and cumulative plastic deformation ratio of SBEAW steel bars of transverse direction before setting oil damper. For Tokai earthquake, the maximum deformation angle is less than 1/100 and cumulative plastic deformation ratio of SBEAW steel bars is also less than 135. However, for the south Kanto earthquake, the maximum deformation angle reaches 1/93 and cumulative plastic deformation ratio of SBEAW steel bars reaches 145, that violates the criteria shown in 3.2.

Figure 18 shows comparison of responses with and without oil damper. We can see that after setting oil damper all the design criteria are satisfied, that is to say, the maximum deformation angle is 1/100 and the cumulative plastic deformation ratio of SBEAW steel bars is 110.

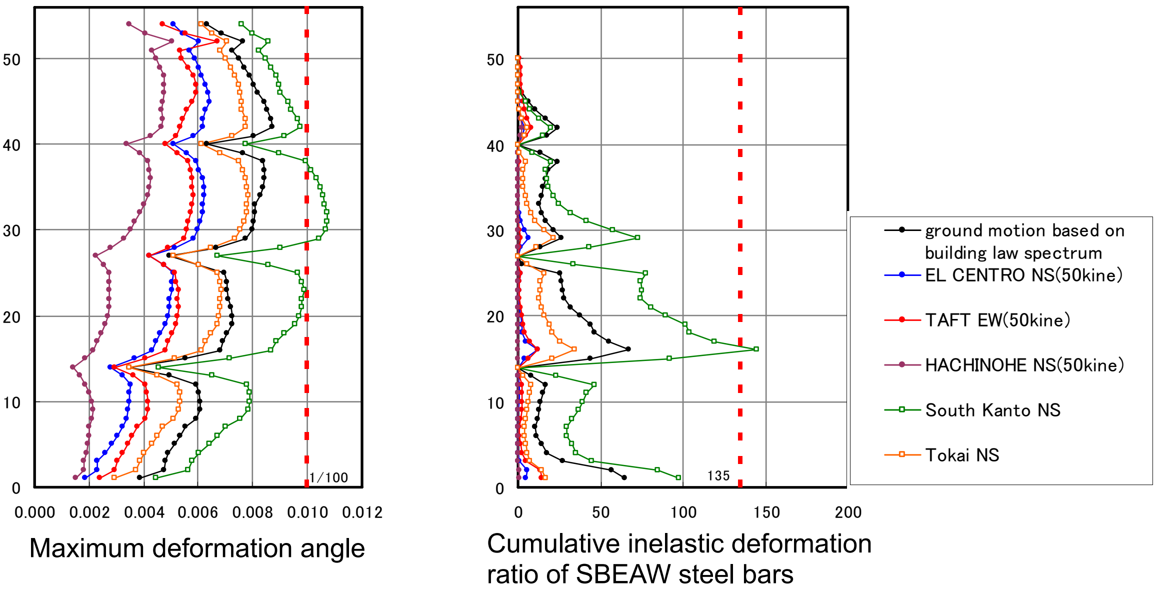

Figure 17. Maximum deformation angle at each story and cumulative plastic deformation ratio of SBEAW steel bars of transverse direction before setting oil damper

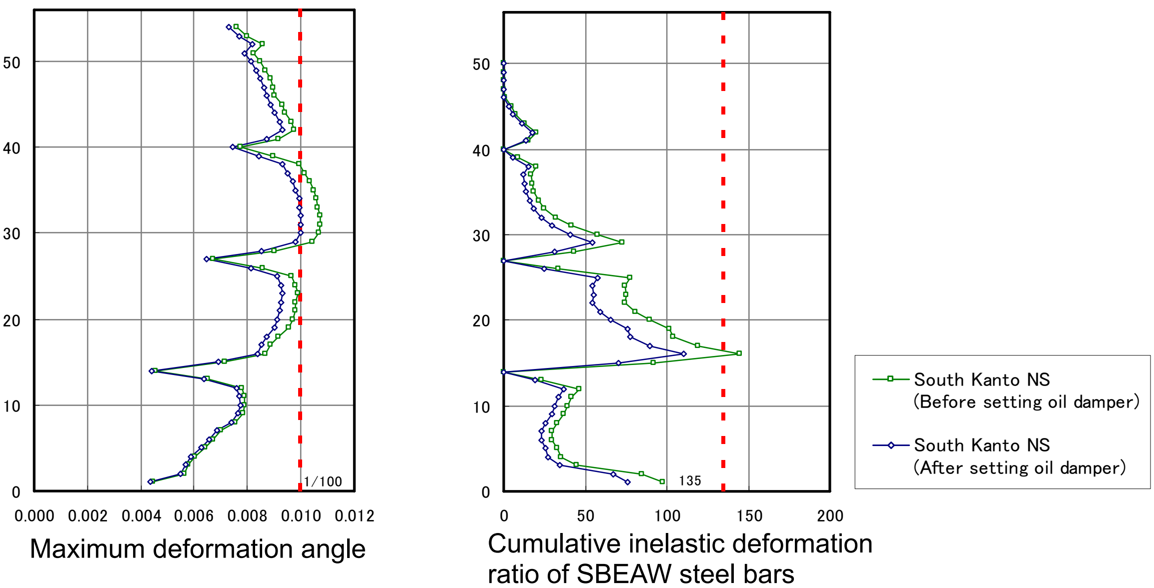

Figure 18. Comparison of responses with and without oil damper

4 OBSERVATION RESULTS

4.1 Outline of the 2011 off the Pacific Coast of Tohoku Earthquake

The 2011 off the Pacific coast of Tohoku Earthquake occurred at 14:46 on March 11th 2011, epicenter located in Sanriku Sea with moment magnitude of 9.0. Figure 19 shows the velocity response spectra with h=5% and Figure 20 shows the energy spectra with h=10%, recorded at first floor of Shinjuku Center Building. The three standard design waves: EL CENTRO NS, TAFT EW and HACHINOHE NS, and the uniform design spectra regulated by building standard law (rare and extremely rare earthquake motion) are also plotted for comparison of the level of earthquake motion. The level of the earthquake motion in Shinjuku is in the middle between rare and extremely rare earthquake motion of the uniform design spectra regulated by building standard law. Proportion of the component with period less than 1 second is small and the component with long period (especially 2-3 seconds) is relatively large.

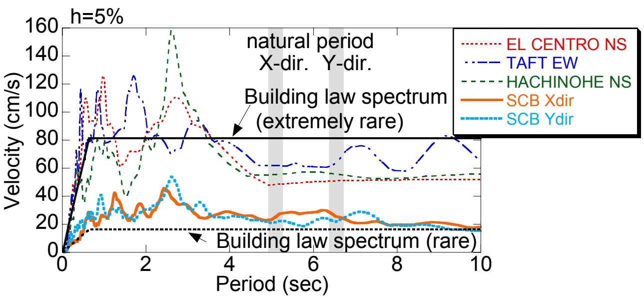

Figure 19. Velocity response spectra of earthquake ground motions

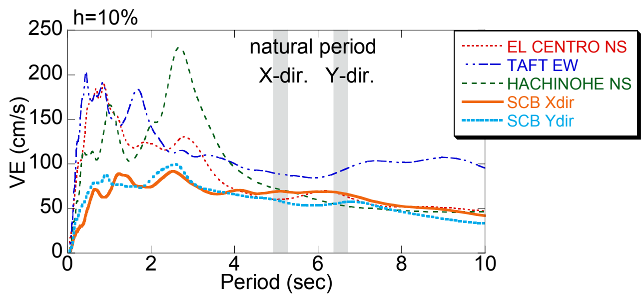

Figure 20. Energy spectra of earthquake ground motions

4.2 Response of the Shinjuku Center Building

Shinjuku Center Building has been recording earthquake motions since the completion of the building [Nii et al, 2011]. There are many earthquake records obtained since then, including recent the 2011 off the Pacific coast of Tohoku Earthquake. The maximum values recorded from the 2011 off the Pacific coast of Tohoku Earthquake are summarized in Table 3. Figure 21,22 and 23 respectively illustrates acclerogram and relative displacement motion between RF and 1F. As shown in the figures, the earthquake motion continued for long time and the building was shaking for longer than 10 minutes.

The maximum acceleration of the top floor was 236.0Gal in the longitudinal direction (X) and the maximum displacement of the top floor was 54.2cm in the transverse direction (Y), the average story drift angle which is figured out by dividing the maximum displacement of the top floor by the height of the building was 1/399. Therefore it is evaluated that there are no damages on the main structure such as columns and girders. In the inspection of the dampers after the earthquake, no abnormality was reported such as scratch, corrosion, peeled of paint or oil leakages.

Table 3. Maximum observed responses

	Maximum acceleration (Gal)		Maximum deformation (cm)	
	Longitudinal (X)	Transverse (Y)	Longitudinal (X)	Transverse (Y)
RF	236.0	161.3	49.4	54.2
28F	112.7	171.3	26.3	33.3
1F	94.3	142.1	-	-

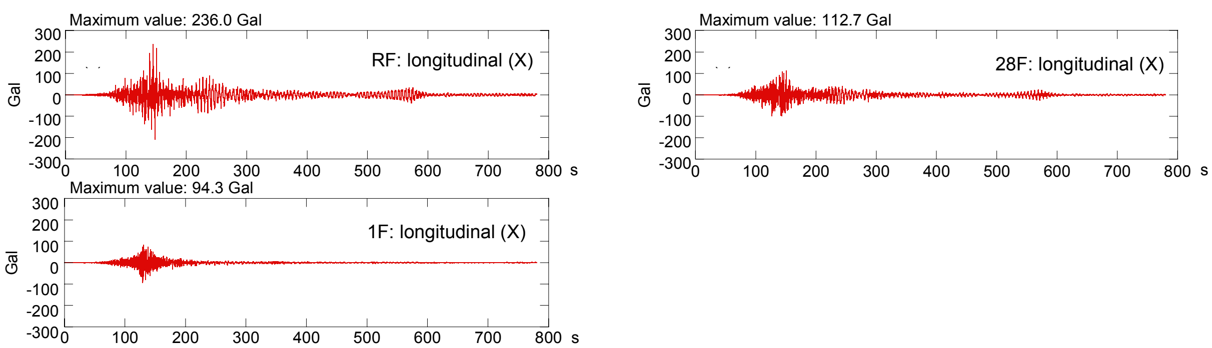

Figure 21. Observed acceleration waveform (longitudinal direction)

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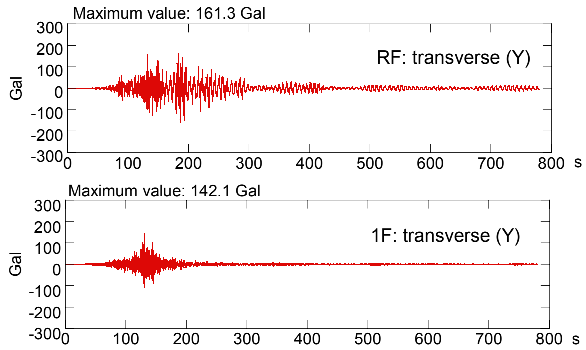

Figure 22. Observed acceleration waveform (transverse direction)

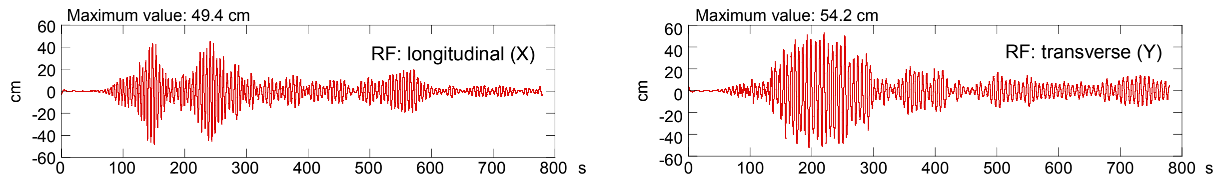

Figure 23. Relative displacement waveform between RF and 1F

5 PERFORMANCE VERIFICATIONS

5.1 Estimation of additional damping ratio with oil dampers

To estimate the additional damping ratio with the dampers, the modal damping ratio of the building is identified using multi-input-multi-output ARX model method [Saito, 1998] from the seismic records obtained before / after installation of the dampers. Damping ratio from 1st to 3rd mode in each direction was evaluated by composing the single input (acceleration of the first floor) and second output (acceleration of the top floor and the 28th floor) ARX models.

Figure 24 shows the damping ratio of 1st mode obtained from several earthquakes before / after installation of dampers and it is plotted against the amplitude of 1st modal accelerations. Table 4 shows the estimations of damping ratio of the 2004 Mid Niigata Prefecture Earthquake M=6.8 (before installation of damper) and the 2011 off the Pacific coast of Tohoku Earthquake (after installation of damper). From these figure and table, it is observed that there is an increase in the damping ratio after installation of the dampers. The damping ratios of the 1st mode for the longitudinal (x) direction and transverse (y) direction of the building were increased by these oil dampers about 0.3 and 1.4 percent, respectively.

Table 4. Estimated modal damping ratios before / after installation of the dampers

Dir.	Mode	Period	Damping ratio h (%)	
		T (sec)	without damper *1	with damper *2
Longitudinal (X)	1	5.4	1.55	1.89
	2	1.8	0.77	2.67
	3	1.0	1.92	2.29
Transverse (Y)	1	6.5	1.26	2.72
	2	2.0	1.57	2.88
	3	1.0	1.99	2.51

*1: estimated from the 2004 Mid Niigata Prefecture Earthquake
*2: estimated from the 2011 off the Pacific coast of Tohoku Earthquake

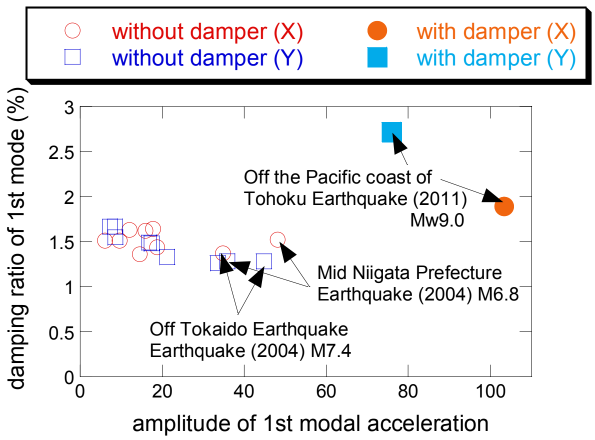

Figure24. Relationship between amplitude of 1st modal acceleration and damping ratio of 1st mode

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5.2 Observed and simulated response with / without oil damper

The vibration control effect of this damper under the 2011 off the Pacific coast of Tohoku Earthquake was verified by simulation analysis. In this verification, transverse (y) direction was considered as more dampers installed and larger deformation was recorded in this direction. Lumped mass model with 52 stories (linear) was used for the analysis. Dynamic analysis is conducted by the mode superposition method to the 10th mode. For under the 3rd mode, the damping ratio which is identified from the seismic records obtained before / after installation of dampers (Table 4) is used. For over the 3rd mode, the damping ratios are constant. As an input earthquake ground motion, acceleration waveform recorded at first floor was used.
Figure 25 shows the analysis results of maximum displacement and acceleration of each story with or without dampers. Figure 26 shows the simulated relative displacement in transverse (y) direction between RF and 1F and the simulated acceleration at the top floor with or without dampers. Figure 27 shows simulated and observed response waveform with damper in transverse (y) direction at the top floor. The maximum displacement at top floor was 76.4cm without the dampers and 60.8cm with the dampers (the actual observed result was 54.2cm). This indicates that the dampers reduced displacement by 20%. The maximum acceleration was 220.3 Gal without the dampers and 184.1 Gal with the dampers (the actual observed value was 161.3 Gal) and there is about 20% reduction. Consequently, the performance of the seismic retrofitting of the super high-rise building was confirmed and the analytical results were in good agreement with the observed record.

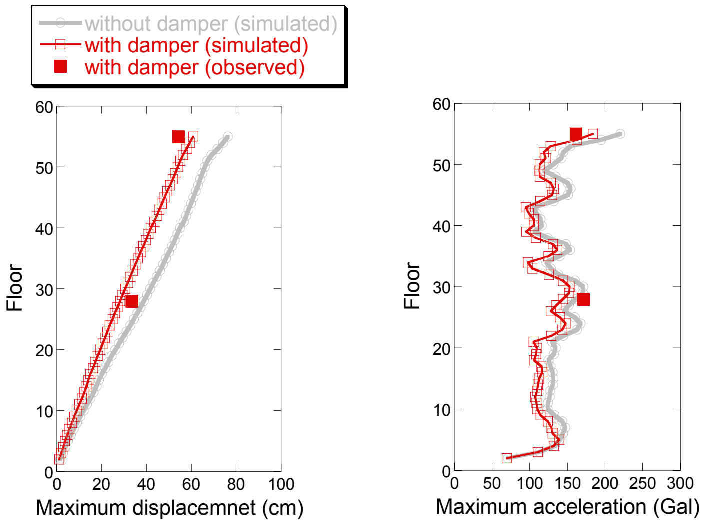

Figure 25. Comparison of observed and simulated maximum response of each story with / without dampers

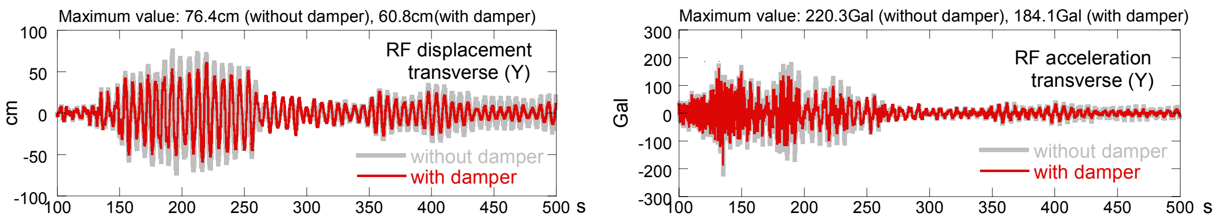

Figure 26. Comparison of simulated response waveform with/without dampers

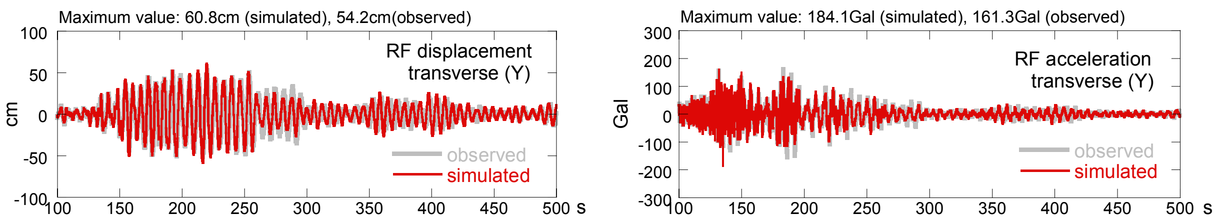

Figure 27. Comparison of simulated and observed response with dampers

Conclusions

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The authors have developed a deformation-dependent oil damper and applied to 54-storey super high-rise building to reduce the vibration induced long-period earthquake ground motion. The seismic responses were observed in the 2011 off the Pacific coast of Tohoku Earthquake and system identification using ARX model and simulation analyses were conducted to estimate the control performance of damper.
It is clarified that the damping ratio was higher and the response lower by 20% as compared to the building without dampers, and the observed responses of the buildings are mostly well simulated, thereby confirming the performance of the seismic retrofitting of super high-rise building with damper.

References

Irikura, K. (1986) Prediction of strong acceleration motions using empirical Green's function, Proc. 7th Japan Earthq. Eng. Symp., p. 151-156

Graves, R. W. (1986) Simulating seismic wave propagation in 3D elastic media using staggered-grid finite differences, Bull. Seism. Soc. Am., 86, p. 1091-11106

Bielak J., K. Loukakis Y. Hisada, and C. Yoshimura, (2003) Domain reduction method for three-dimensional earthquake modeling in localized regions. Part I: Theory, Bull. Seism. Soc. Am., Vol.93, No.2, p. 817-824

Yoshimura, C., J. Bielak, Y. Hisada, and A. Fernandez. (2003) Domain reduction method for three-dimensional earthquake modeling in localized regions. Part II: Verification and applications, Bull. Seism. Soc. Am., Vol.93, No.2, p. 825-840

Nii, I., Maseki, R., Nagashima, I., et al. (2011) Development of seismic and wind observation monitoring system and its application to the high-rised building", Transactions of AIJ annual meeting, B2, pp.365-366

Saito, T. (1998) System identification of a highrise building applying multi-input-multi-output ARX model of modal analysis", Transactions of AIJ, No.508, pp.47-54