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VERIFICATION OF THE TOGGLE DAMPING SYSTEM FOR THE SRC BUILDING DURING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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Abstract. *A steel frame reinforced concrete building completed in 1965 was seismically retrofitted using seismic isolation braces with amplification mechanism. The building was subjected to shaking with a seismic intensity of upper 5 during the 2011 off the Pacific coast of Tohoku Earthquake. The seismic retrofit applied, however, minimized damage. The seismic retrofit performance was then examined based on the ground motions recorded in the building and the results of seismic response analysis using the records. As a result, it was revealed that the retrofit design goal was met and that the deformation of the building was controlled considerably as compared with the case with no retrofit.*

1 INTRODUCTION

The off the Pacific coast of Tohoku Earthquake that occurred on March 11, 2011 produced strong ground motions mainly in the areas along the Pacific coast in the Tohoku district near the source area. A maximum seismic intensity of 7 was observed in Kurihara City, Miyagi Prefecture. Seismic intensities of 5^{-} or greater were observed in areas in 17 prefectures.

Strong ground motions occurred also at around the site of the study building (hereinafter referred to as the Building). Buildings with low seismic performance suffered damage. The Building had been constructed in 1965 and designated as an existing non-conforming building. It had been retrofitted before the huge earthquake using damping system with amplification mechanism (hereinafter referred to as the toggle damping system). Then, the Building suffered only repairable minor damage to some of its nonstructural members.

Earthquake observation has been conducted in the Building since 2009. The seismic behavior of the Building during the main shock has been observed. This study examines the effectiveness of the toggle damping system for enhancing seismic isolation performance during the 2011 off the Pacific coast of Tohoku Earthquake based on the ground motions recorded in the Building and the results of seismic response analysis using the records..

2 OUTLINE OF STUDY BUILDING

The steel reinforced concrete Building was constructed in 1965 and has eight stories above the ground and two underground stories with a three-storied penthouse. It is supported directly on tuff bedrock. It is divided into the higher and lower sections. It can safely be assumed that the Building is structurally monolithic because shear forces can be transferred via slabs. Photo 1 presents a general view of the Building. Table 1 outlines the Building.

Photo 1 Over view of study building

Table 1 Outline of study building

Gross floor area	27,809m^2
Scale	8 stories above ground and 2 below
Structure	Steal Reinforced Concrete structure
Structural Type	Rigid-frame structures with shear wall
Foundation	Directed Independent foundation

3 OUTLINE OF SEISMIC RETROFIT METHOD

The Building was designed to the standards before the present seismic design method was developed. As a result of seismic diagnosis, the seismic retrofit index (Is) was determined to be not more than 0.6. Seismic retrofit was considered necessary. Seismic retrofit was therefore applied using the toggle seismic isolation method in order to enhance Is to 0.6 or higher as provided by present seismic design methods.

The toggle seismic isolation method amplifies the interstory displacement occurring in the building during an earthquake by two to three times and transfers it to the hydraulic damper and thereby efficiently absorbs seismic energy, using an amplification mechanism applying the principle of leverage. Figure 1 presents a schematic view of the toggle seismic isolation method.

In seismic retrofit, the design criterion was specified so as to set interstory displacement at 1/150 or less. The objective was to prevent the collapse threatening the lives of the people in the event of a strong ground motion that was likely to occur once during the service life of the Building (level-2 earthquake) as a minimum requirement. Accordingly, 94 and 88 seismic isolation braces were installed in the longitudinal (along the X axis) and transverse (along the Y axis) directions, respectively. Table 2 outlines seismic retrofit.

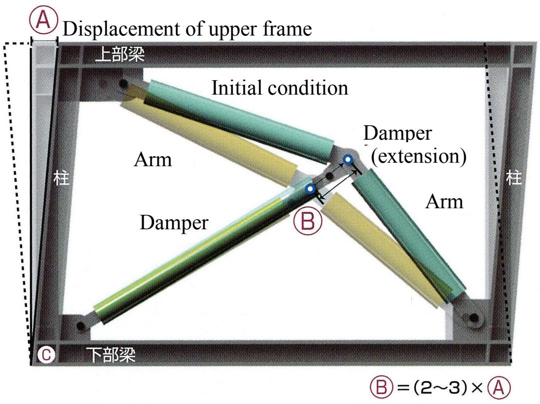


Figure 1 Toggle damping system (damping system with amplification mechanism)

Table 2 Outline of seismic retrofitted

Toggle damping brace	X direction : 94
	Y direction : 88
Shear wall (increased)	2
Structural slit	X direction : 12
Structural Type	Y direction : 8
retrofitting column	12

4 SEISMOLOGICAL OBSERVATION RECORDS

Figure 2 shows the locations of the Building and the assumed source region of the 2011 off the Pacific coast of Tohoku Earthquake. Figure 3 shows the acceleration waveform observed in the Building. Outstanding in the acceleration waveform on the first floor above the ground are two areas with large amplitudes. The source area of the off the Pacific coast of Tohoku Earthquake was assumed to be 450 km x 200 km. It was assumed that large failure occurred at least three locations. The two large amplitudes found in the acceleration waveform probably represent the effects.

The ground motion lasted a long time. The peak acceleration exceeded 50 cm/s^2 for a duration of approximately 130 seconds on the first floor above the ground and for 150 seconds on the penthouse. The peak acceleration was approximately 413 cm/s^2 on the floor above the ground and 853 cm/s^2 on the penthouse, both of which were observed in the second high-amplitude area starting at approximately 100 seconds.

Figure 4 shows the pseudo velocity response spectra (h = 0.05) on the first floor above the ground and on the penthouse. Shown with the response spectrum on the first floor above the ground is the spectrum of notification wave used as the seismic ground motion for design. It is clear that the ground motion observed on the first floor above the ground was nearly equivalent to level-2 ground motion considered in design. An explicit predominance is found in the pseudo velocity response spectrum on the penthouse near 0.9 second. It was therefore assumed that the Building behaved with the primary mode being predominant.

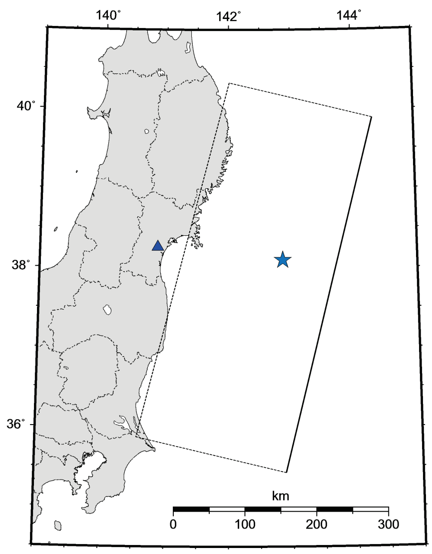


Figure 2 Location of the Building and source area of off the Pacific coast of Tohoku Earthquake

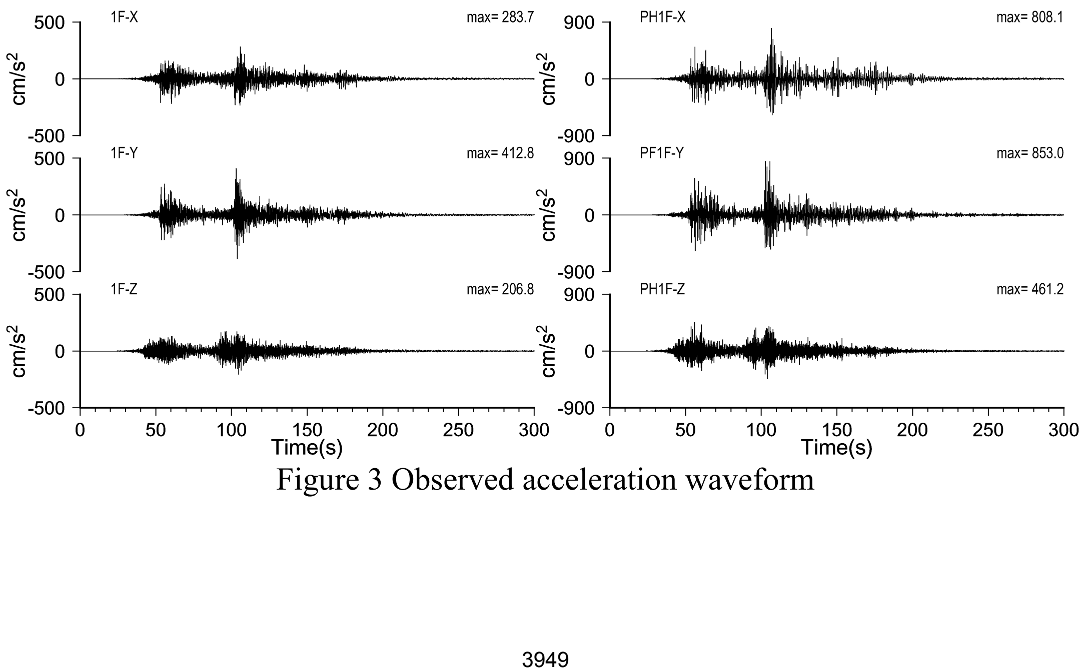
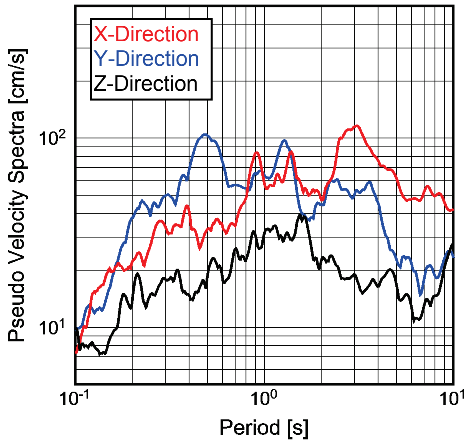
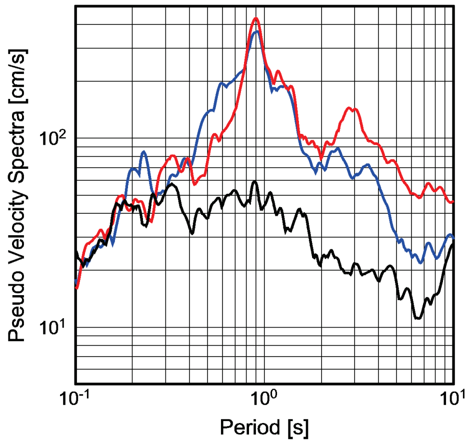


Figure 3 Observed acceleration waveform



(a) 1F



(b) PH1F

Figure 4 Pseudo velocity spectra (h=0.05)

5 VERIFICATION OF THE EFFECT OF RETROFIT

The story deformation angle used as a seismic retrofit performance index was adopted as an index for verification. The variance between the behavior during the main shock and that in the case where no retrofit was applied (case with no retrofit) was regarded as the seismic retrofit effect.

Computing story deformation angle required displacement waveforms on respective floors. Seismographs were, however, installed only on the first floor above the ground and on the penthouse, so obtaining story deformation angle based on the seismological observation records was impossible. Then, the building was represented by a mass system model on a fixed foundation. The ground motion observed on the first aboveground floor was input and displacement waveforms on respective floors were computed based on the results of seismic response analysis.

The analysis model was independent in the directions of X and Y axes. It was designed that the predominant period during a strong ground motion matched the predominant period during a strong ground motion obtained based on the seismological observation records.

The accuracy of seismic response analysis was verified based on the reproducibility of observed displacement waveform on the penthouse. Figure 5 shows the observed and analysis displacement waveforms in layers. The observed displacement waveform was computed by applying a band-pass filter of 0.1 to 10 Hz to the observed acceleration waveform and using Fourier integral.

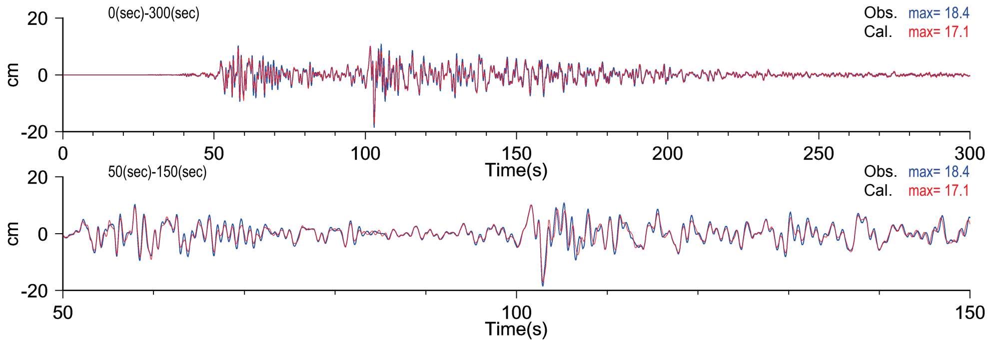
The observed and analysis displacement waveforms were in agreement with each other highly accurately in terms of amplitude and phase. Thus, the observed displacement waveform was accurately reproduced based on the results of seismic response analysis. It was therefore assumed that the displacement waveforms on other floors than the penthouse could be estimated similarly based on the results of seismic response analysis.

Figure 6 shows story deformation angles computed based on the results of seismic response analysis. Story deformation angle is not more than 1/150, the design criterion, in both directions. The retrofit design goal was thus achieved.

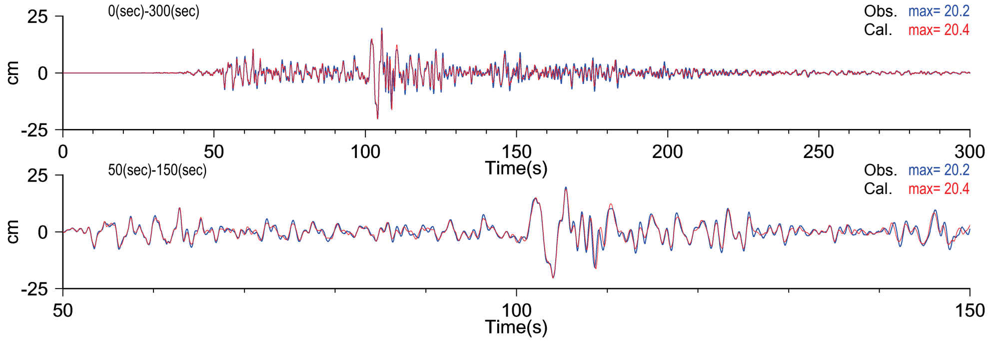
Story deformation angles in the case with no retrofit were estimated also based on the results of seismic response analysis. The analysis model was developed by removing the toggle seismic isolation members from the analysis model used during the main shock. Figure 6 shows the distribution of story deformation angles in the case with no retrofit. Story deformation angle exceeded the design criterion of 1/150 on multiple floors. It increased to 1/61 in the direction of X axis and to 1/58 in the Y axis direction. It is therefore highly likely that the building suffered great damage in the case with no retrofit.

If the variance from the story deformation angle during the main shock was regarded as the effect of seismic retrofit, it was assumed that seismic retrofit reduced story deformation angle in the building to 1/4 at the maximum and helped avoid great damage.

Figure 7 shows the distribution of relative displacements on the first floor above the ground. Seismic retrofit reduced relative displacement to 1/3 at the maximum. It is clear that displacements were controlled considerably throughout the building.

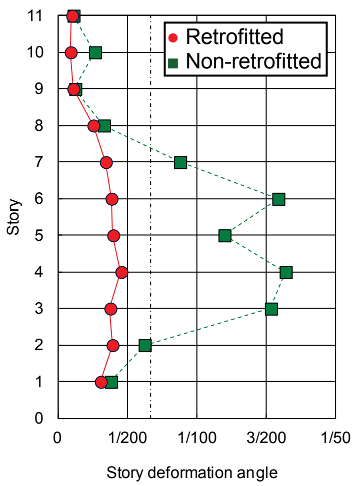


(a) X direction

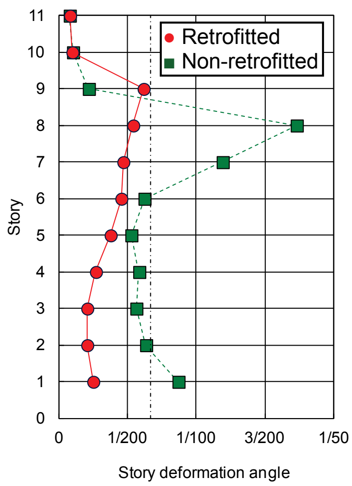


(b) Y Direction

Figure 5 Comparison between calculated displacement waveform of PH1F and observed one

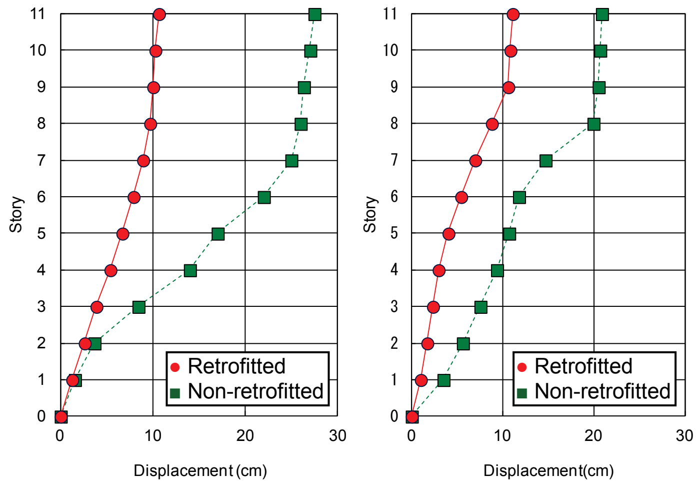


(a) X direction



(b) Y Direction

Figure 6 Comparison of story deformation angle distribution (Retrofitted/Non-retrofitted)



(a) X direction (b) Y Direction

Figure 7 Comparison of relative displacement distribution (Retrofitted/Non-retrofitted)

6 CONCLUSIONS

The effectiveness of seismic retrofit of a steel frame reinforced concrete building using a damping system with amplification mechanism was examined based on the seismological observation records during the 2011 off the Pacific coast of Tohoku Earthquake and on the results of seismic response analysis. As a result, the following conclusions were obtained.

- Story deformation angle of the building was not more than 1/150 during the main shock. The seismic retrofit performance goal was therefore achieved.
- Seismic retrofit reduced story deformation angle of the building to 1/4 and relative displacement to 1/3.
- In the case where no seismic retrofit was applied, the building may have suffered great damage.