Dynamic Characteristics of a Damaged Nine-story Building during the 2011 off the Pacific Coast Tohoku Earthquake

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Abstract: This paper describes the dynamic characteristics of a damaged nine story building in Sendai during the 2011 Tohoku Earthquake. Dynamic hysteresis characteristic is investigated. The system identification using the extended Kalman filter determined the amplitude dependency of natural frequency and damping factor, which are consistent with damage feature. Occurrence of partial uplifting in the transverse direction is suggested by the induced higher harmonics based on the wavelet analysis. Historical change of the amplitude dependent dynamic characteristics is also discussed based on the long-term monitoring data from microtremor level to strong motion level.

Key words: 2011 Tohoku Earthquake, dynamic characteristics, damaged building, long-term monitoring.

1. Introduction

On March 11, 2011, a huge earthquake (Mw9.0) occurred in the Pacific Ocean off the coast of Miyagi, Japan. This earthquake is officially named the 2011 Off the Pacific Coast Tohoku Earthquake, or simply the 2011 Tohoku earthquake. During this earthquake, strong ground motion with very long duration caused much structural damage. The authors have reported structural damage in relation to ground motion characteristics [1].

A nine-story SRC (steel reinforced concrete) building on Aobayama campus, THU (Tohoku University) building was heavily damaged during the Tohoku earthquake. The observed maximum acceleration at 9th floor was 908 cm/s/s for 333 cm/s/s at ground floor. One of the major reasons is the site specific ground motion amplification due to geological hill compared to the observed records at basement floor of Sumitomo building near the Sendai station, which is engineering bedrock in Sendai area. Ground motions at around 1 s period content are about two times compared to Sumitomo site. The amplification is also recognized for the 1978 Miyagi-ken Oki earthquake as shown in Fig. 1.

This paper describes the amplitude dependent dynamic characteristics before, during, and after the Tohoku earthquake including a fore-shock and some after-shocks. Historical change of the dynamic characteristics is also discussed based on the long-term monitoring.
monitoring data together with dynamic hysteresis characteristics. Furthermore, investigation of partial uplifting of the upper part from the set backed 3rd floor, which is suggested from damage feature, is described.

2. Dynamic Behavior of THU Damaged Building during the Tohoku Earthquake

2.1 Description of the THU Building and Structural Damage during the Tohoku Earthquake

The THU building is a nine story SRC (non-full web type) building and was constructed in 1969. After experience of the structural damage due to 1978 Miyagi-ken Oki earthquake (M7.4) [2], a retrofit work was done from autumn of 2000 to spring of 2001. It is noted that the seismic strength index, Is-value at the damaged 3rd floor in the transverse direction increased from 0.53 to 0.84. Before and after the retrofit, forced vibration tests were performed. Then, the building experienced many earthquakes including the 2005 Miyagi-ken Oki earthquake (M7.2), the 2008 Iwate-Miyagi Nairiku earthquake (M7.2), and so on. Amplitude dependent vibration characteristics have been investigated for more than 40 years not only strong motion observation but also micro-tremor observation [3]. The structural health monitoring system using the wide dynamic range sensors (NetDAS/MicroSMA) has been installed at 1st, 5th and 9th floor in 2007 and continuous observation has been done up to now [4]. The system enables to measure from microtremor to strong motion. In the building, SMAC-MD type seismometer is installed at 1st and 9th floor. The configuration of the building and sensor locations are shown in Fig. 2.

During the 2011 Tohoku Earthquake, THU Building was damaged [5]. Damage features are shown in Fig. 3. At the set backed 3rd floor, 4 corner columns were heavily damaged at the bottom. The severe crack of the side shear wall due to possibly partial uplifting was suggested at the level of third floor [6].
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The observed acceleration waveforms of the 2011 Tohoku Earthquake are shown in Fig. 4 which is obtained at 1st floor and 9th floor, respectively.

Fig. 5 shows acceleration waveforms in the NS direction (transverse direction) at 1st floor and top (9th) floor of THU building for the 2011 Tohoku Earthquake and the 1978 Miyagi-ken Oki earthquake.

Fig. 6 shows the spectral amplification in the THU Building for the two earthquakes. It is noted that the amplification characteristics of the 1st phase (phase A) and the 2nd phase (phase B) are different for the 2011 earthquake. In NS direction, the second phase is amplified by more than two times at around 1 sec period content at Aobayama campus compared to Sumitomo building near Sendai station. The amplification characteristics are almost the same as those of the 1978 Miyagi-ken Oki earthquake and the THU building was strongly amplified by resonance.

2.2 Dynamic Hysteretic Behavior

To investigate the dynamic hysteretic characteristics, the acceleration records at 9th floor and 1st floor are doubly integrated and the relative displacement is calculated. The maximum relative displacement is 31 cm in NS direction.

Fig. 7 shows the relative displacement waveform and the dynamic hysteretic behavior based on
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The force-displacement relation for the 16 time sections which are obtained from acceleration waveform at 9th floor and the relative displacement. Findings from this figure are as follows:

1. Starting from linear behavior at smaller amplitude level, hysteresis shows the inverse “S” shape slightly as recognized in section 5. Then shows linear behavior but the stiffness is reduced in section 6 compared to section 1;

2. Then, with increasing displacement, the hysteresis shows softening and hysteretic loop is recognized only for the larger displacement level. The hysteresis shows origin oriented behavior as recognized in section 7;

3. Then decreasing the displacement, the hysteresis shows the characteristic inverse “S” shape in section 9. Although the amplitude decreases from Section 9 to Section 10, the corresponding stiffness reduction is not seen, which consistent with almost the same dominant frequencies in these time sections;

4. Then decreasing displacement gradually returns to linear behavior with the reduced stiffness in sections from 13 to 16 compared to section 6. The stiffness change is consistent with micro-tremor observation before and after the earthquake.

2.3 System Identification

To investigate non-stationary dynamic characteristics due to structural non-linearity, the system identification technique using the extended Kalman filter is used to determine natural frequency and damping factor as equivalent SDOF (single-degree-of-freedom) system [7].

Fig. 8 shows the result of the identified system parameters, natural frequency and damping factor for NS direction and EW direction, respectively. In these figures, the calculated relative displacement waveform is compared to that obtained from observed records.
As for the identified system parameters, natural frequency and damping factor, the smoothed curves are shown in figures. Findings from the system identification results are as follows:

1. In the transverse (NS) direction, dominant frequency decrease down to about 0.8 Hz with increasing amplitude and the dominant frequency is not changed even if amplitude is decreased;

2. The damping factor in the transverse direction increases with increasing the amplitude at time section 7 in Fig. 7. At the time sections with the inverse “S” type hysteresis, damping factor is decreasing with increasing the amplitude;

3. In the longitudinal (EW) direction, dominant frequency decrease down to about 0.9 Hz but return to about 1 Hz when amplitude level becomes small;

4. The smoothed damping factor in the longitudinal direction seems to be larger compared to the transverse direction. This may be due to difference of hysteretic energy consumption.

2.4 Investigation of Uplifting Vibration

In case of structural vibration with partial uplift, odd number higher harmonics are induced in the horizontal directions and even number higher harmonics are induced in the vertical direction [8]. Fig. 9 shows non-stationary characteristics expressed by wavelet coefficients of the 9th floor’s acceleration waveform in the transverse direction for 10 s time sections including the peak value.

Fig. 10a shows the wavelet coefficients of 9th floor for the vertical direction. Fig. 10b is the wavelet coefficients of 1st floor for the vertical direction.

Findings from these figures are as follows:

1. The dominant frequency corresponding to the two times frequency (about 2 Hz) of the vertical direction is clearly seen at large amplitude range corresponding to the time sections from seven to nine. But the dominant frequency is not seen at the 1st floor;

2. This suggests the occurrence of partial uplift of the damaged building at the 3rd floor.

3. Long Term Monitoring of Dynamic Characteristics of THU Building

In the building, earthquake observation has been performed since completion in 1969 and microtremor observations also have been performed. The forced vibration test was performed before and after the retrofit work in 2000. The amplitude dependent dynamic characteristics have been investigated [4].

Table 1 shows change of 1st natural frequency of the building based on not only the earthquake records of main shock and foreshock and together with microtremor records before and after the earthquake events. It is noted that the natural frequency of the two directions due to microtremor observations were the same (1.61 Hz) before and after the 3/9 foreshock and also the same (1.26 Hz) in the two directions during the foreshock. But during the main shock, reduction of the
natural frequency is remarkable in NS direction compared to EW direction, which is consistent with the damage feature of the building. The frequency reduction is large in the second phase (phase B). The stiffness reduced up to 23% in NS direction and 30% in EW direction compared to the stiffness due to microtremor before the main shock. The stiffness in the microtremor level was reduced to 53% in NS direction and 72% in EW direction.

It is noted that the THU building was temporary repaired at the damaged 3rd floor in May, which lead to the natural frequency increase from 1.17 Hz to 1.37 Hz in NS direction and 1.37 Hz to 1.48 Hz in EW direction. But the microtremor observation at May 3 (before the repair work) shows no natural frequency change from March 19, even if the building was shaken by the large aftershock on April 7 and April 11.

Table 2 shows the maximum acceleration list of major earthquake observation records at THU building.

Table 2 Maximum acceleration list of major earthquake observation records at THU building.

<table>
<thead>
<tr>
<th>Date</th>
<th>Magnitude</th>
<th>1 Floor (max.acc(cm/s/s))</th>
<th>9 Floor (max.acc(cm/s/s))</th>
<th>Area name</th>
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<td></td>
<td></td>
<td>NS</td>
<td>EW</td>
<td>NS</td>
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<td>170</td>
<td>114</td>
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<td>203</td>
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Tohoku Earthquake, Term4: after Tohoku earthquake. Furthermore, Term 3 and Term4 are divided into two terms.

Findings from this figure are as follows:

(1) The amplitude level of the first phase (phase A) is smaller than that of the 1978 earthquake in NS direction but the amplitude level of the second phase (phase B) became larger compared to 1978 earthquake in both directions;

(2) The change of the natural period due to the 2011 Tohoku Earthquake is larger in NS direction compared to EW direction, which is consistent with the damage feature;

(3) It is confirmed through the continuous observation that the dominant period at microtremor level is not changed if the deflection level is smaller than the experienced maximum deflection.

4. Conclusions

In this paper, the dynamic behavior of the damaged nine-story SRC building during the 2011 Tohoku earthquake is investigated. The amplitude dependent dynamic characteristics are also investigated based on the long-term monitoring data for more than 40 years from microtremor level to strong motion level. Findings in this study are as follows: (1) Structural damage of THU building was caused by the resonance vibration to input motion amplified by geological condition, (2) Dynamic hysteresis shows origin oriented type in the time section of the largest deflection in the severely damaged NS direction. The hysteresis of inverse S type was also recognized from actual observation data, (3) Amplitude dependency of natural frequency and damping factor is also investigated based on system identification for the severely damaged building, (4) Occurrence of the partial uplifting at the 3rd floor of the THU building was suggested by the induced harmonics, which is consistent with damage feature and (5) Long term monitoring of amplitude dependent dynamic characteristics is summarized. The obtained information based on the observation data would be very informative in the seismic design of building structures.

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References


