Amplitude Dependent Dynamic Characteristics of a Damaged 9-story Building During the 2011 off the Pacific Coast Tohoku Earthquake

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SUMMARY:
This paper describes the amplitude dependent dynamic characteristics of a 9 story building in Sendai before, during, and after the Tohoku earthquake including a fore-shock and some after-shocks. Dynamic hysteresis characteristic are investigated and the origin oriented type hysteresis and the inverse ‘S’ type hysteresis in time are recognized. Occurrence of partial uplifting in the transverse direction is suggested by the induced higher harmonics based on the non-stationary spectra using wavelet analysis. The system identification using the extended Kalman filter also performed to determine the amplitude dependency of natural frequency and damping factor. The identified parameters consistent with damage feature. Historical change of the dynamic characteristics is also discussed based on the long term monitoring data.

Keywords: 2011 Tohoku earthquake, building damage, long term monitoring, dynamic characteristics, partial uplifting

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 (Motosaka, 2012).

A 9-story SRC building on Aobayama campus, Tohoku University (hereafter, THU 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 (refer. to Figure 1).

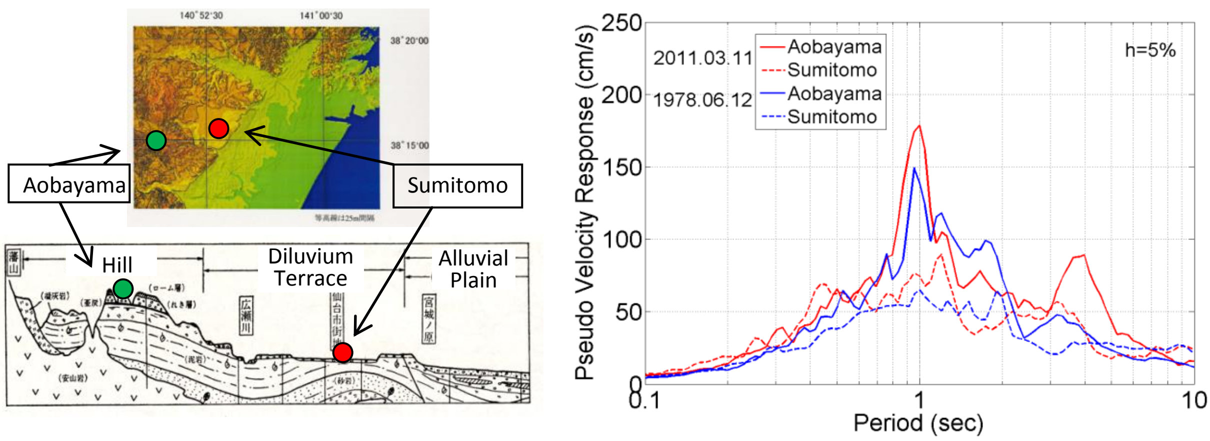


Figure1. Geological information and site specific spectral amplification in Aobayama hill, Sendai

Ground motions at around 1 period content are about 2 times compared to Sumitomo site. The amplification is also recognized for the 1978 Miyagi-ken Oki earthquake as shown in Figure 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 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. DESCRIPTION OF BUILDING DAMAGE AND OBSERVED STRONG MOTION

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

The THU building is a 9-story SRC (non-full web type) building (ref. to Photo 1 and Figure 2) constructed in 1969 and experienced 1978 Miyagi-ken Oki earthquake. The building was constructed on the slope site and has a foundation with RC cross piles (500φ). Pile length is 12m. Soil profiles at the site are referred to Figure 3.

Photo1. Overview of THU building

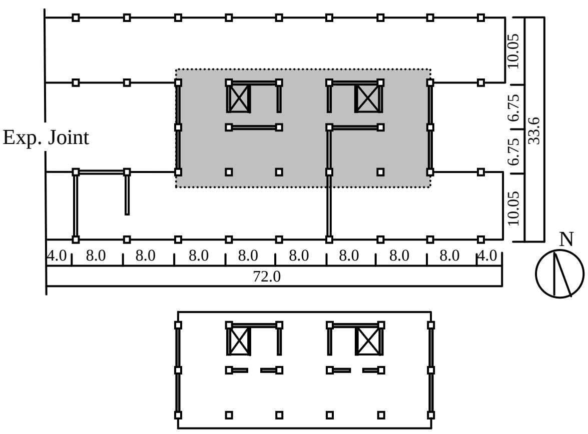


Figure 2. Plans at the 1st floor (top) and the 3rd floor (bottom)

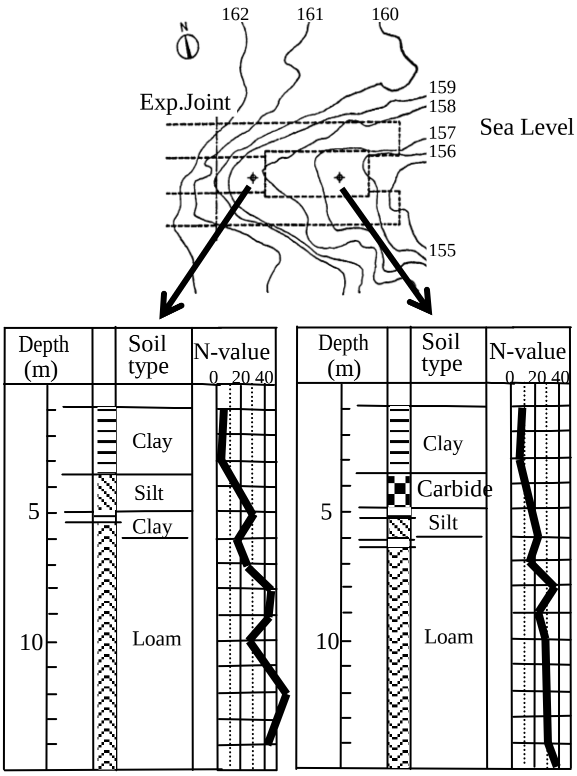
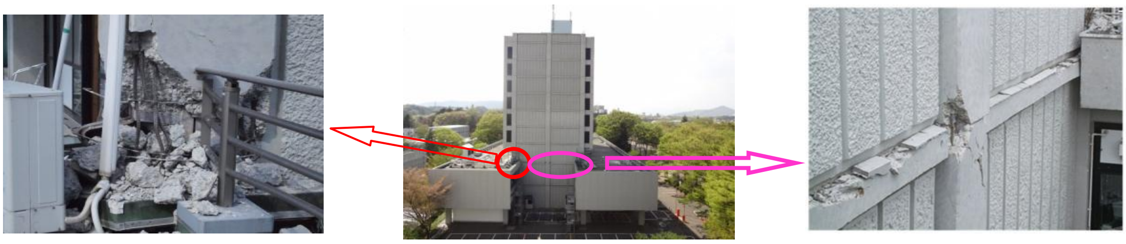


Figure 3. Original topography at the site and soil profiles

In the THU Building, long-term monitoring of dynamic characteristics has been performed by strong motion observation, forced vibration test, microtremor observation, and etc, for about 40 years since the completion of the building in 1969 (Motosaka, et al., 2004, Motosaka, et al., 2011). After experience of the structural damage due to the 1978 Miyagi-ken Oki earthquake (Shiga et al., 1981), seismic retrofit work was performed from autumn of 2000 to spring of 2001. Then, the building experienced the 2005 Miyagi-ken Oki earthquake, 2008 Iwate-Miyagi Nairiku earthquake, and 2008 Iwate Northern Coast earthquake, and so on.

Photo 2 shows the damaged THU Building. 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 (Tsamba and Motosaka, 2011). 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.



(a) Damage of corner column bottom (b) East view (c) Damage of shear wall at the 3rd floor level

Photo 2. Damage feature of bottom of one of the damaged four corner columns at 3rd floor of THU building

2.2 Observation Records

In the building, SMAC-MD type seismometer is installed at 1st and 9th floor. From December, 2007, a continuous monitoring system (NetDAS/ MicroSMA) with wide dynamic range sensors at 1st, 5th and 9th floor has been operated (Motosaka et al., 2008). The system enables to measure from microtremor to strong motion. The configuration of the building and sensor locations are shown in Figure 4. Figure 5 shows the observed acceleration waveforms of the 3 components at 1st floor and 9th floor.

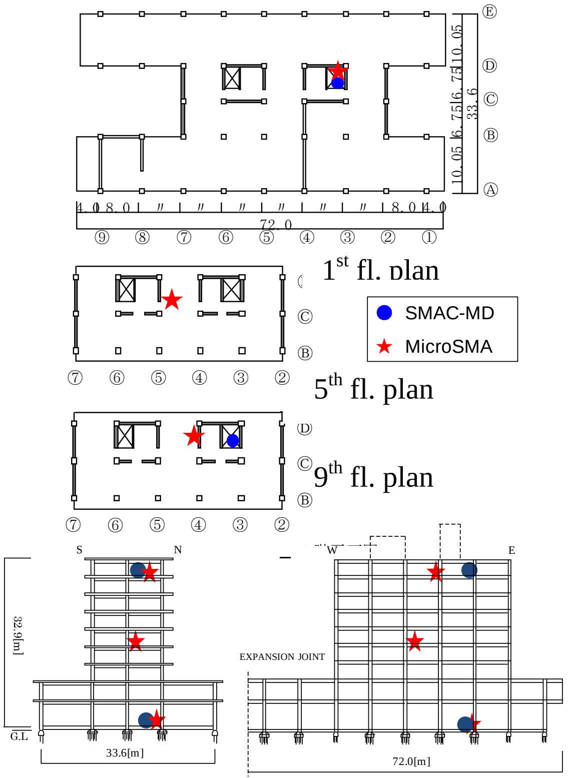
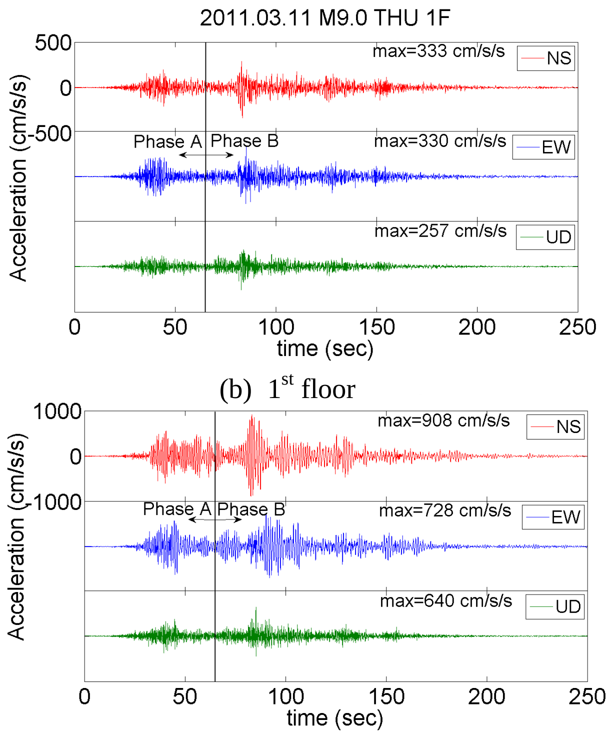


Figure 4. Configuration of THU Building and Sensor location



(b) 1st floor

(a) 9th floor

Figure 5. Observed records during the main shock

Figure 6 shows comparison of acceleration waveforms in the NS direction (Transverse direction) at 1st floor and top (9th) floor of THU building for the 2011 earthquake and the 1978 Miyagi-ken Oki earthquake.

Figure 7 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. In the NS direction, the second phase is amplified by more than two times at around 1s 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.

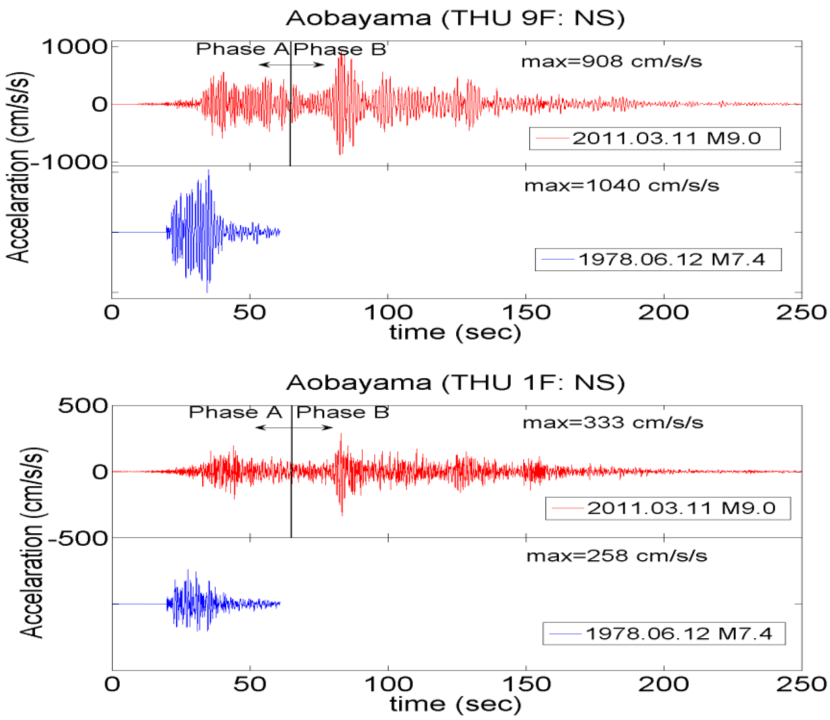


Figure 6. Comparison of observed records of 2011 Tohoku earthquake and 1978 Miyagi-ken Oki earthquake (NS direction)

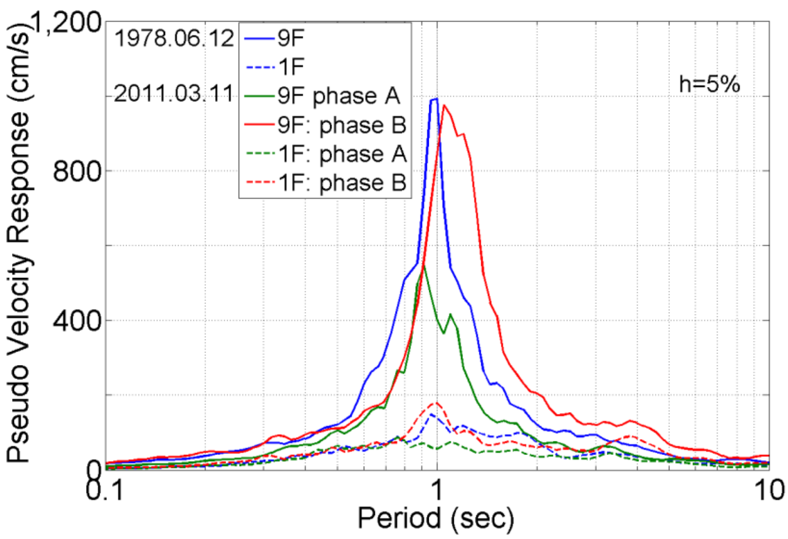


Figure 7. Comparison of response spectra of 2011 Tohoku earthquake and 1978 Miyagi-ken Oki earthquake

3. DYNAMIC BEHAVIOR AND SYSTEM IDENTIFICATION

3.1 Dynamic Hysteresis

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 31cm in NS direction.

Figure 8 shows the dynamic hysteretic behavior based on 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, this hysteresis leads to stiffness reduction, which consistent with the dominant frequency reduction.
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 microtremor observation before and after the earthquake.

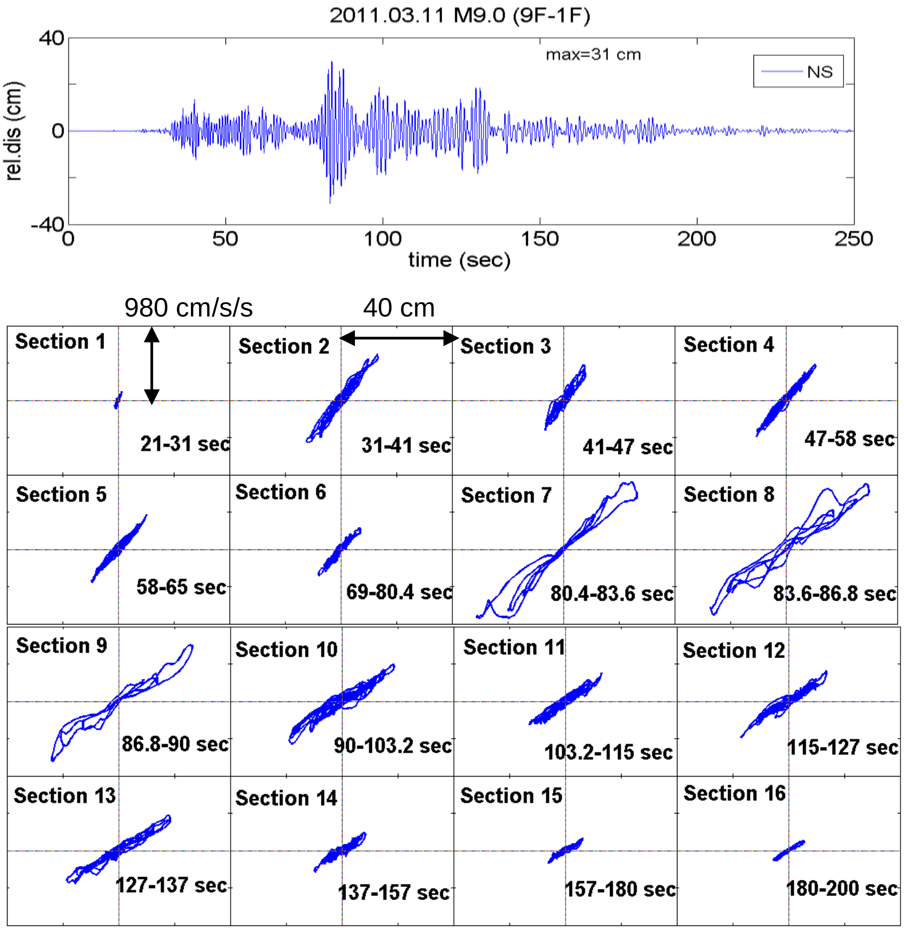
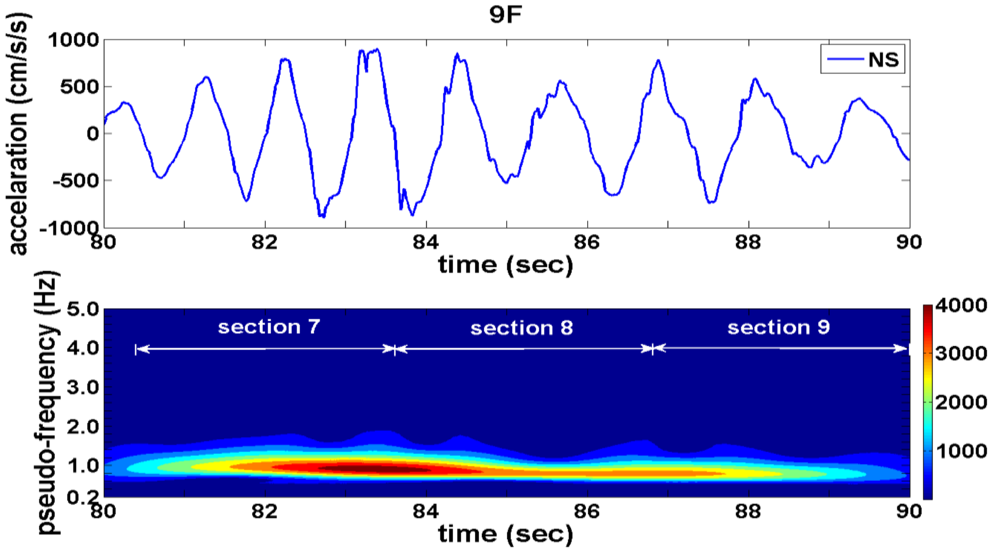


Figure 8. Relative displacement waveform and hysteresis loops for each time section (NS-Direction)

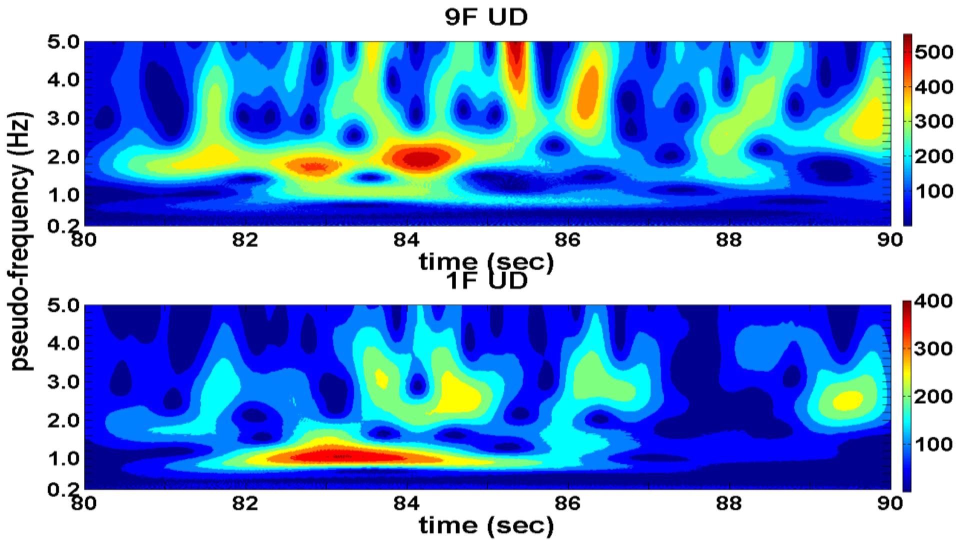
3.2 Investigation of Partial Uplifting

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 (Motosaka and Nagano 1993).

Figure 9 (a) shows non-stationary characteristics expressed by wavelet coefficients of the 9th floor's acceleration waveform in the transverse direction for 10 sec time sections including the three time sections, from section 7 to section 9 in Figure 8. Figure 9 (b) shows the wavelet coefficients of 9th floor and 1st floor for the vertical direction.



(a) Acceleration waveform at 9F and wavelet transform



(b) Wavelet transforms of acceleration in the vertical direction at 9F and 1F.

Figure 9. Acceleration waveform at 9F and its wavelet transform and Wavelet transforms of acceleration in the vertical direction at 9F and 1F.

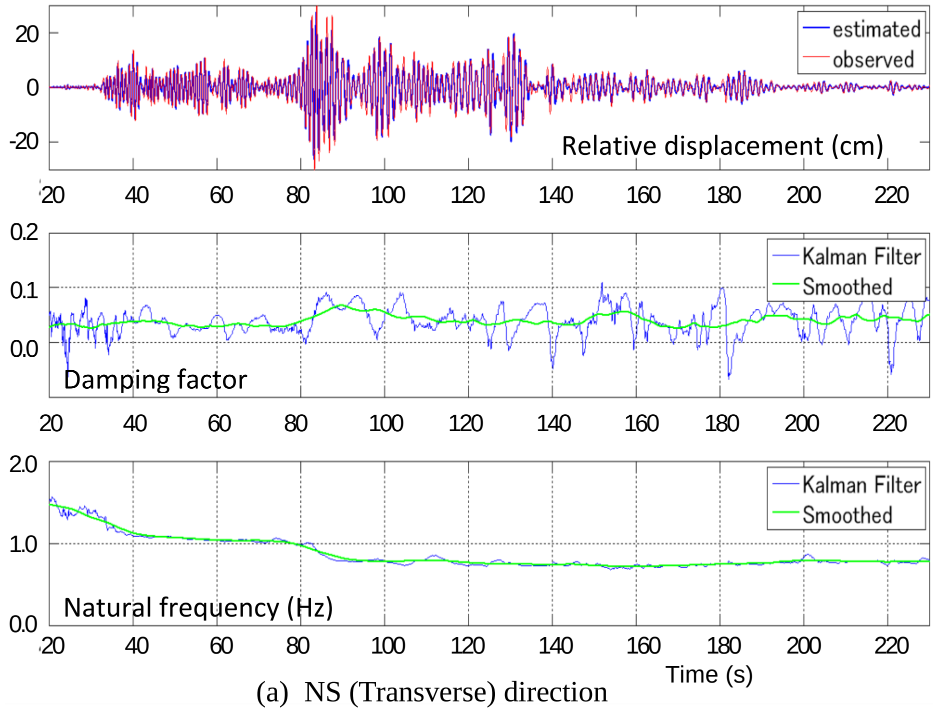
Findings from these figures are as follows.

1) The dominant frequency corresponding to the two times frequency (about 2Hz) of the vertical direction is clearly seen at large amplitude range corresponding to the time sections from 7 to 9 in Figure 6. 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.

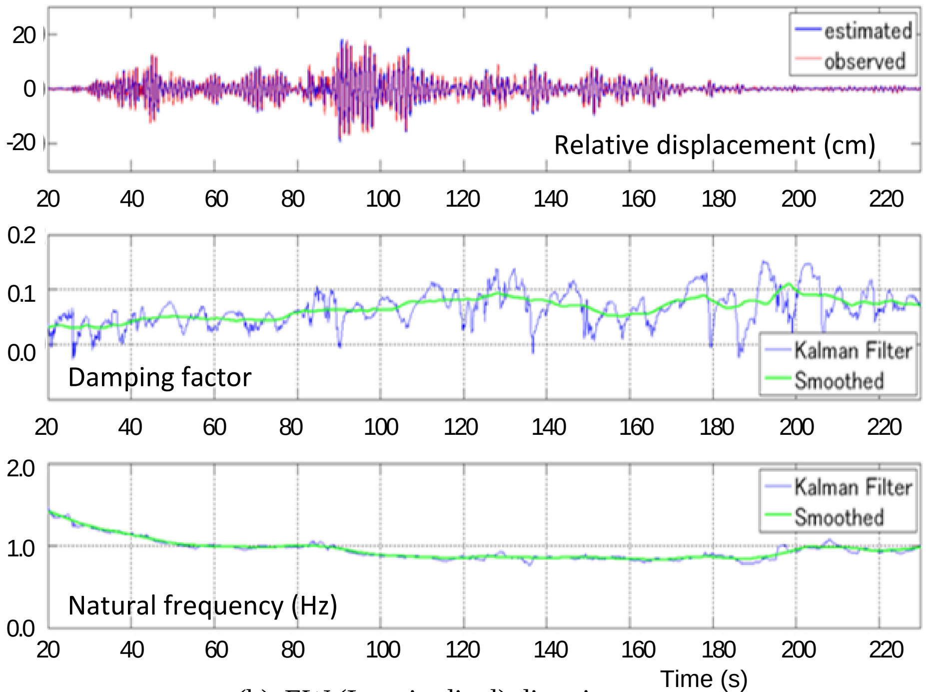
3.3 System Identification

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 system (Takahashi et al., 2010).

Figure 10 show 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 these figures.



(a) NS (Transverse) direction



(b) EW (Longitudinal) direction

Figure 10. Identified damping and natural frequency in the horizontal two directions

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 Figure 8 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 lager compared to the transverse direction. This may be due to difference of hysteretic energy consumption.

4. LONG TERM MONITORING OF DYNAMIC CHARACTRISTCS 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 (Motosaka et al., 2004).

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 micotremor 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 (1.61Hz) before and after the 3/9 foreshock and also the same (1.26Hz) in the two directions during the foreshock. But during the main shock, reduction of the natural frequency is remarkable in the NS direction compared to the 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 37% 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 the NS direction and 72% in the EW direction.

Table 1. Change of fundamental frequency

Date	Event name	Natural frequency (HZ)	
		NS	EW
2011/3/9	Microtremor	1.61	1.61
2011/3/9	Foreshock (Sanriku Oki)	1.26	1.26
2011/3/11	Microtremor	1.61	1.61
2011/3/11	Main shock (Phase A)	1.05	1.05
	Main shock (Phase B)	0.78	0.88
2011/3/19	Microtremor	1.17	1.37
2011/3/19	Aftershock (Ibaraki-Ken)	0.93	1.16
2011/5/3	Microtremor	1.17	1.37
2011/5/31	Microtremor	1.37	1.48

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 1.17Hz to 1.37Hz in NS direction and 1.37Hz to 1.48Hz 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. Figure 11 shows the relation between the deflection angle and the natural period for both two directions. In the figure, the different symbols are used for the 4 terms, namely, Term 1: From completion to 1978 earthquake, Term 2; After 1978 earthquake to retrofit work in 2000, Term 3: After retrofit work to 2011 Tohoku Earthquake, Term4: After Tohoku earthquake. Furthermore Term 3 and

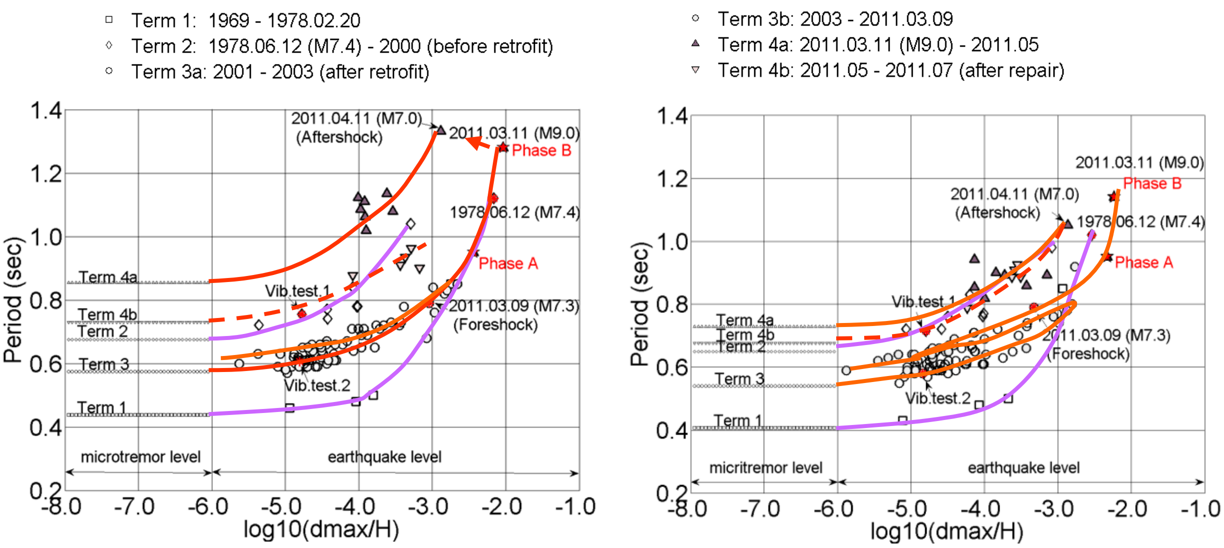
Term4 are divided into two terms.

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 the both directions.
2) The change of the natural period due to the 2011 Tohoku Earthquake is lager 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 mictotremor level is not changed if the deflection level is smaller than the experienced maximum deflection.

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

Date	Magnitude	1 Floor (max.acc (cm/s/s)		9 Floor (max.acc (cm/s/s)		Area name
		NS	EW	NS	EW	
1978/2/20	6.7	170	114	421	298	Miyagi-Ken Oki
1978/6/12	7.4	258	203	1040	523	Miyagi-Ken Oki
1998/9/15	5.2	138	451	190	379	Miyagi-Ken Southern
2003/5/26	7.1			231	264	Miyagi-Ken Oki
2003/7/26	6.2	33	27	98	102	Miyagi-Ken Northern
2003/9/26	8.0			29	22	Tokachi Oki
2005/8/16	7.2	87	81	329	287	Miyagi-Ken Oki
2008/5/8	7.0	19	22	261	226	Ibaraki-ken Oki
2008/6/14	7.2	88	70	392	293	Iwate-Miyagi inland
2008/7/24	6.8	59	77	275	367	Iwate-Ken North Coast
2011/3/9	7.2	37	34	171	89	Sanriku Oki
2011/3/11	9.0	207	216	594	617	Off Pacific Coast Tohoku (Phase A)
		333	330	908	728	(Phase B)
2011/3/19	6.1	15	18	34	56	Ibaraki-ken Northern
2011/4/11	7.0	72	70	141	172	Fukushima-Ken Southern
2011/4/12	6.4	24	28	43	84	Fukushima-Ken Oki
2011/4/23	5.4	17	27	23	57	Fukushima-ken Oki
2011/7/10	7.1	21	18	95	58	Sanriku Oki
2011/7/23	6.5	10	11	60	42	Miyagi-Ken Oki
2011/7/25	6.2	48	62	106	99	Ibaraki-ken Northern
2011/7/31	6.4	36	31	70	45	Fukushima-ken Oki



(a) NS (TR) direction (b) EW (LN) direction

Figure 11. Relation between deflection angle and 1st dominant period

5. CONCLUDING REMARKS

In this paper, the amplitude dependent dynamic characteristics of a the damaged 9 story SRC building during the 2011 Tohoku earthquake are investigated based on the long-term monitoring data for more than 40 years from microtremor level to strong motion level. The dynamic behaviour of the building during the 2011 Tohoku Earthquake is also discussed based on the obtained strong motion data.

The dynamic hysteresis characteristics showing origin oriented hysteresis loop and the inverse ‘S’ type hysteresis loop obtained from the strong motion data of the damaged building will become very important information in the field of structural engineering. The partial uplifting of the upper part from 3rd floor of the damaged building is suggested based on the induced vertical motion with even number higher harmonics. The phenomenon is consistent with the damage feature. It is also confirmed through the continuous observation that the dominant period at mictotremor level is not changed if the deflection level is smaller than the experienced maximum deflection.

Long term structural monitoring based on continuous observation system will provide important information to discuss structural damage and contribute to accurate structural modelling.

REFERENCES

Motosaka, Masato, (2012), LESSONS OF THE 2011 GREAT EAST JAPAN EARTHQUAKE FOCUSED ON CHARACTERISTICS OF GROUND MOTIONS AND BUILDING DAMAGE, JAEE International Symposium on the 2011 Great East Japan Earthquake March 3-4. (in print).

Motosaka, Masato and Tsamba Tsoggerel. (2011). “Investigation of High Acceleration Records at K-NET Tsukidate Station During the 2011 off the Pacific Coast Tohoku Earthquake”, 2011-JAEE Annual Meeting, 24-25.

Motosaka, Masato and Masayuki Nagano. (1993). “Dynamic partial uplift analysis of a structure on a 3-D layered half space based on recursive evaluation of Interaction forces using dynamic stiffness of the unbounded soil in frequency domain”, Journal of Structural and Construction Engineering, AIJ, No.45, 79-88. (in Japanese with English abstract)

Motosaka, Masato , Makoto Homma, Serdar H. Kuyuk, and Francisco Arrecis. (2008). “DEVELOPMENT OF AN INTEGRATED EARLY WARNING AND STRUCTURAL MONITORING SYSTEM TO REAL TIME EARTHQUAKE INFORMATION”, AIJ. Technol . Des. Vol. 14; No. 28: 669-674. (in Japanese with English abstract)

Motosaka, Masato, Takeshi Sato, and Yu Yamamoto. (2004). “Amplitude Dependent Dynamic Characteristics of an Existing Building”, 13WCEE, CD-ROM No.1023, 2004

Motosaka, Masato, Kazuya Mitsuji, Shoko Tanaka, Toshihide Kashima, and Susumu Ohno. (2011).”Change of Dynamic Characteristics of a Damaged Building Before, During , and After the 2011 Off Pacific Coast Tohoku Earthquake”, Summaries of Technical Papers of 2011 AIJ Annual Meeting, Structure II, 45-46. (in Japanese)

Shiga, Toshio, Akenori Shibata, Jun’ichi Shibuya, and Jun’ichi Takahashi. (1981). “Observations of strong earthquake motions and nonlinear response analyses of the building of architectural and civil engineering departments, Tohoku University”, Transactions of Architectural Institute of Japan, No.301, 119-130. (in Japanese with English abstract).

Tanaka, Shoko and Masato Motosaka, (2008), JAEE Annual Meeting.

Takatashi, Yoshiyuki, Kazuya Mitsuji, and Masato Motosaka. (2010). “Estimation of vibration characteristics of the existing building by using Kalman Filter”, Tohoku Journal of Natural Disaster Science, No.45, 107-111. (in Japanese)

Tsamba, Tsoggerel and Masato Motosaka. (2011). “Investigation of Dynamic Behavior of a Damaged 9-story Building during the 2011 off the Pacific Coast Tohoku Earthquake”, 2011-JAEE Annual Meeting, 44-45.