VARIATION OF DYNAMIC CHARACTERISTICS OF MULTI-LAYER WOODEN BUILDING BASED ON CONTINUOUS OBSERVED RECORDS

K. Mitsuji[(1)], H. Adachi[(2)]

[(1)] *Professor, Yamagata University, mitu@e.yamagata-u.ac.jp*
[(2)] *Executive Director, Shelter, adachi@shelter.jp*

Abstract

Dynamic characteristics of multi-layer wooden building are estimated based on microtremor and earthquake records continuously observed. Variation of dynamic characteristics of the building due to snow and seismic load is investigated through observed records. The studied building is a three-story wooden office building constructed by large scale laminated wood with braces. Network type seismometers are installed at the first and top floor. Sensors can continuously observe and record from small amplitude as microtremor to large amplitude as strong motion earthquake, in 24 hours of 365 days. Daily and seasonal variation of dynamic characteristics found in a day and a year respectively is discussed by observed records analysis. Natural frequency of the first mode of the superstructure is estimated about 4.5Hz from microtremor data.

As the study of variation of dynamic characteristics of the building, variation of amplitude ratio of top and first floor in a day is firstly discussed for different time sections of a day from morning to midnight. Results indicate that the first mode natural frequency is almost the same in a day, however, amplitude of superstructure at the first mode natural frequency tends to be larger in daytime than early morning or midnight. Next, variation of amplitude ratio of top and first floor in a year is discussed through the comparison to seasonal variation of average temperature of a day. Correlation of the first mode natural frequency of the building and average temperature seems slight. However, comparison of the first mode natural frequency to accumulated snow depth shows that the first mode natural frequency tends to be lower in heavy snow days in winter due to snow load. Difference observed in the first mode natural frequency by snow load is estimated about 5-10% at maximum. Variation of damping factor at the first mode natural frequency, and natural frequency of torsional motion are also discussed through the comparison to average temperature and snow accumulation. Results show that those properties are not affected so much.

Several earthquakes are recorded by this observation system. Estimated natural frequencies of the first mode due to earthquake records are compared to those of microtremor records. Natural frequency of the first mode and damping factor are estimated about 4.0-4.5 Hz and 5-10%, respectively. Estimated natural frequencies under earthquakes are close to one from snow load.

Based on the results of observed records, seismic response model of this building is developed and seismic response analysis is carried out. Numerical model is refined by comparison of the observed response due to small earthquake, and numerical simulation results. Combining all the data observed at this building, seismic response for earthquake of this building is finally studied by numerical simulation.

Keywords: Wooden building; Dynamic characteristics; Microtremor measurement; Earthquake observation; Snow load

1. Introduction

In recent years, large-scale wooden buildings increase in school buildings, welfare facility buildings for the elderly, and shopping center complex buildings as fire resistant design techniques have being developed. It is expected that improvement of performance of fire resistant wood member and combination of wood with other materials as steel and concrete etc. will contribute development of large scale and high rise wooden buildings. Generally, wooden building relatively tends to be light and have less stiffness, compared to RC building in case of the same scale. Large or tall wooden buildings will be considered to be more developed and constructed in the near future. However, fundamental vibration characteristics of large or tall wooden buildings are not thoroughly understood and should be studied in more detail. Therefore, it is important to accurately estimate natural frequency of newly developed building for structural design [1].

In this paper, fundamental vibration characteristics of the existing wooden three-story office building are studied through continuous observed data of microtremor measurement and earthquake observation. Seismic response analysis is also conducted to confirm the vibration characteristics of the building estimated by observed data. Results are mainly discussed from those points of view described below.

1) Fundamental vibration characteristics of the building and the effect of surface ground
2) Daily and seasonal variations in the building vibration characteristics
3) Dynamic behavior of the building during earthquakes

Especially, continuous observation system keeps working on since 2014 and records microtremor data in 24 hours a day and strong motion data in case of earthquakes occur [2,3]. Based on the continuous observation system, daily and seasonal variation of vibration characteristics can be discussed by comparison of the difference of working people population in some periods of time and climate conditions like temperature, humidity and wind velocity etc. The effect of snow load to variation of natural frequency in winter will be studied through the seasonal change of vibration characteristics of the building. Finally, seismic response characteristics of the building is studied by the observed data and seismic response analysis is conducted to prepare the simulate model for dynamic behavior prediction of the building subjected to strong motion in the future.

Speaking the importance of the snow load effect to the seismic damage of buildings, in a day after the 2011 Tohoku Earthquake, old wooden houses covered with thickly accumulated snow on the roofs were severely damage by strong shaking in Nagano northern region that is famous as heavy snowfall area. Therefore, precise estimation of the effect of snow load is important for structural design of the building.

In this paper, the effects of seasonal temperature changes and snow loads on the vibration characteristics of the building are investigated by comparison of observed microtremor and earthquake records under different weather condition through a year. Discussion on the effect of snow load to variation of vibration characteristics are mainly focused. The analysis of the seismic observation records examines the effect of the difference in amplitude level to the vibration characteristics of the building compared to the microtremor observation.

2. Outline of the studied building

The building studied in this paper is the wooden three-story office building with mat foundation located on the alluvial plain of the western part of Yamagata city in Japan [1, 2, 3]. Fig. 1 shows a schematic diagram of the building plan, and Fig. 2 shows a schematic sectional view. The plan of the building forms a rectangle shape of 35m × 20m, the long side is the NS direction, and there is a large atrium of 6.6m × 13.2m in the center of the building. In this study, two kinds of observation are carried out for the estimation of the vibration characteristics of the building. One is the microtremor measurement using servo-type velocity sensors to estimate the overall vibration characteristics of the building. This microtremor measurement was carried out on 2014/3/14 [1]. Distribution of sensors is illustrated in Fig.1. The other one is continuous observation from microtremor to strong motion by network acceleration sensors. Observation started since

April 2014 and still keep ongoing at the present of 2020. Layout of network sensors is drawn in Fig.2. This continuous observation system records microtremor data during 24-hour in a day and strong motion data when earthquake occurs. Sampling frequency is 100Hz for both measurement and observation.

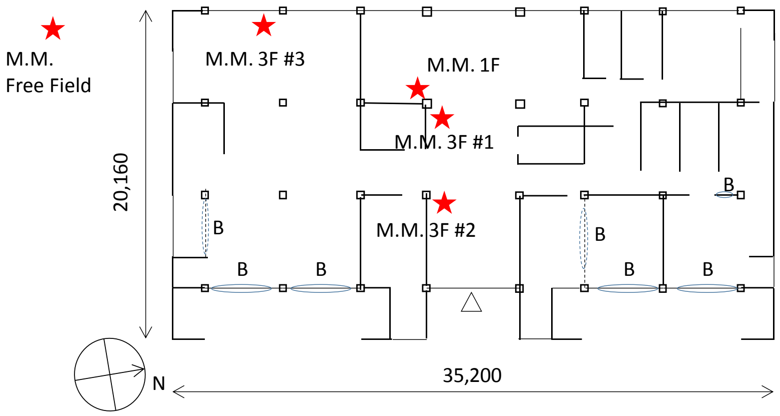


Fig. 1 – Schematic diagram of the first building plan

(“M.M.” means velocity sensor for microtrmor measurement, and “B” means brace)

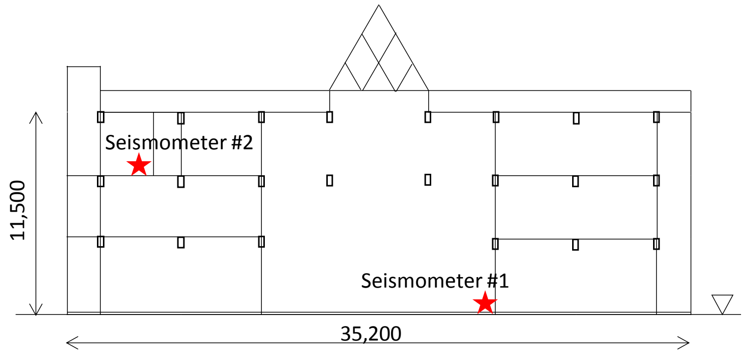


Fig. 2 – Schematic sectional view

3. First natural frequency of the building estimated from microtremor data [1]

Before installing seismometers for continuous observation, we conducted microtremor measurement to understand fundamental vibration characteristics of the building. Figures in Fig.3 show amplitude ratios of top floor to first floor (3F/1F). Results of left figure of Fig.3 are the case that the microtremor sensor of 3F is located close to the atrium (M.M. 3F #1). Results of right figure are the case that the microtremor sensor of 3F is located at the east side of the building (M.M. 3F #2). Spectral peaks of both results are indicating the first mode natural frequency of the building can be found around 4.5Hz in both horizontal directions of NS and EW. Difference found in Fig.3 can be considered to have observed the floor vibration of the top floor in case of the microtremor sensor close to the atrium (M.M. 3F #1). This may be considered because small peak in relatively low frequency range around 2Hz and some excitation in vertical motion (UD) are observed.

Ground vibration characteristics are estimated by H/V spectral ratio of observed data on surface ground close to the building in Fig.4. Distance between microtremor sensor on surface ground to the building is about 10m and then microtremor sensor of the top floor is placed at M.M. 3F #3 in Fig.1. Spectral peak of H/V spectral ratio can be found around 0.5Hz, however, predominant frequency of surface ground of this site should be estimated about 1.0Hz according to the results of our other observation [4, 5]. Amplitude ratios of

3F to surface ground (FF) indicating dynamic soil-structure interaction (SSI) effect are also shown in Fig.4. Spectral peak of the building shift to slightly lower due to the SSI effect (about 2%).

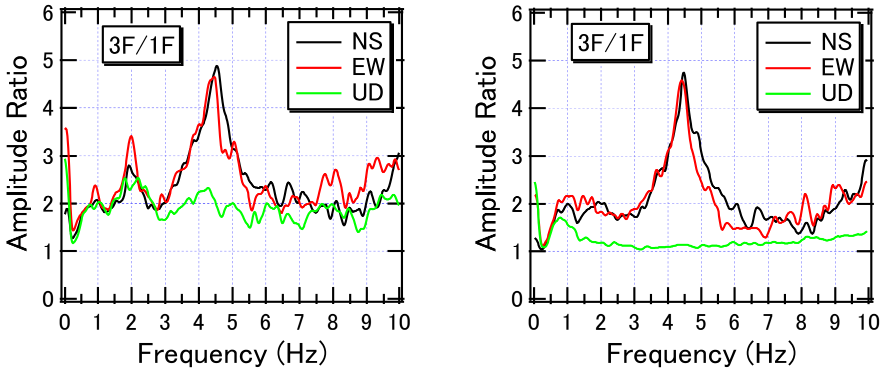


Fig. 3 – Amplitude ratios of top floor to first floor (3F/1F)

(Left: M.M. 3F #3 / M.M. 1F, Right: M.M. 3F #2 / M.M. 1F)

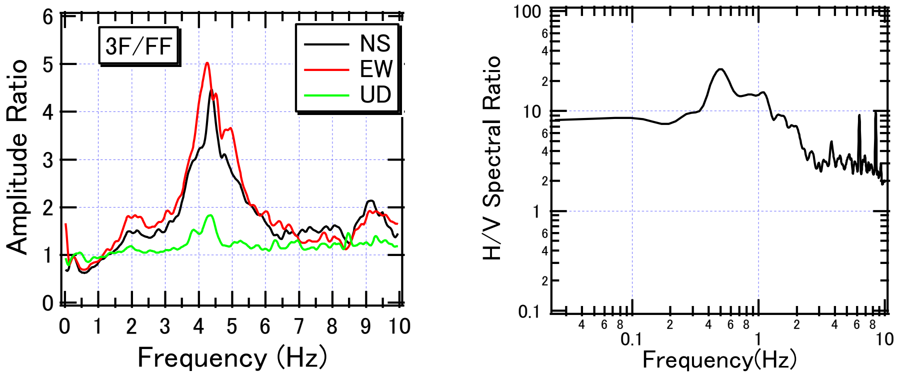


Fig. 4 –H/V spectral ratio of ground and amplitude ratio of 3F to ground

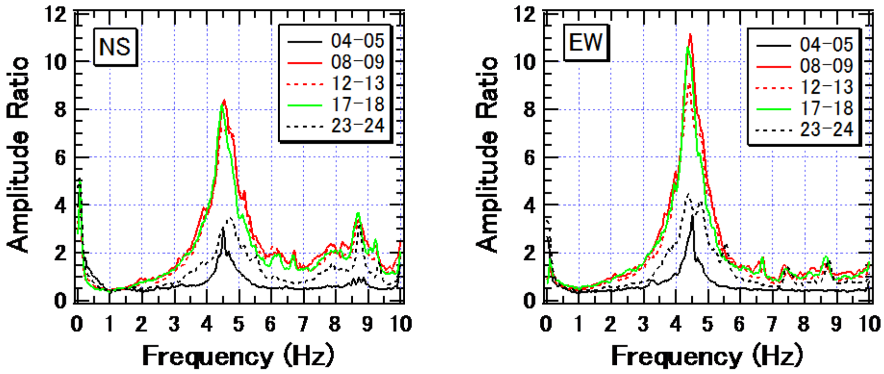
Based on the results of microtremor measurement, the first natural frequency of the building is estimated about f=4.5 (Hz) (T=0.22 (s) in period). In general, the first natural period for seismic design of standard Japanese wooden building is estimated by the equation of T=0.03H (s), where H (m) is the height of the building. Because the height of this building is H=11.5 (m), the first natural period of this building is estimated T=0.345 (s), therefore f=2.9 (Hz) in frequency by the equation. Comparison indicates that the first natural frequency of this building estimated from microtremor data is 1.57 times longer in period and the stiffness is about 2.5 times larger.

4. Daily variation of the first natural frequency of the building [2,3]

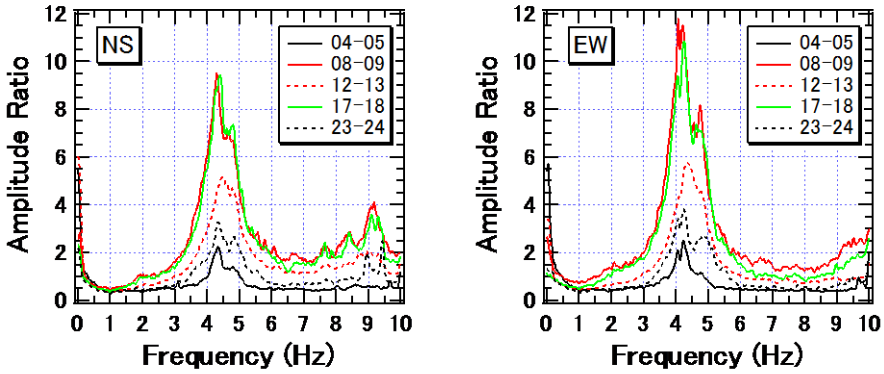
Continuous observation system measuring small amplitude of microtremor to large amplitude as strong motion earthquake has been installed and operated since April 2014. This system has two network sensors placed at the top and first floor respectively, and record microtrmor data during 24 hours in a day and strong motion data when occurring earthquake. Layout of those sensors are drawn in Fig.1.

Fig.5 shows daily variation of amplitude ratios of 3F and 1F in summer (August, 2014) and winter (January, 2015). Five sets of the period of time of 1-hour are selected to discuss the effect of working people population in the building, where five sets of the period of time are early morning (4:00-5:00), morning (8:00-9:00), afternoon (12:00-13:00), evening (17:00-18:00), and midnight (23:00-24:00). It can be considered that there were few people in the building in early morning and midnight because of the office building.

Results of Fig 5 show that amplitude ratios tend to be larger in the periods of time from morning to evening when more people are active at work than early morning and midnight when few people are in the building. Moreover, the first natural frequency is slightly shifted to lower frequency range in the period of time with more people. This can be considered because there are more vibration sources, and amplitude in those period of time due to that more people are active and machines are under operation in the building. In addition, some small spectral peaks can be found in relatively high frequency range. Seasonal variation will be discussed afterwards, but daily variations in summer and winter have the same tendency.



2014/08/19



2015/1/9

Fig. 5– Daily variation of amplitude ratio of 3F and 1F

5. Seasonal variation of the first natural frequency of the building

5.1 Variation between summer and winter [2,3]

Seasonal variation of fundamental vibration characteristics of the building will be discussed in this section by comparison of amplitude ratios of 3F and 1F in summer (August and September, 2014) and winter (December, 2014 and January, 2015). We have had most accumulation of snow in this winter season (Dec. 2014 – Jan. 2015) since the observation started. Fig.6 shows average temperature of a day in Yamagata city where the building is located. Average temperatures in early August are around 30 degree in Celsius, but temperature falls into about 20 degree in late August. In late September, temperature goes down under 20 degree. Average temperatures are below freezing in December and January, and the effect of snow can be observed [6].

Fig.7 shows the results of amplitude ratios of 3F and 1F in summer and winter in each period of time for discussion of seasonal variation of vibration characteristics. Difference of the first natural frequency in summer and winter can be clearly observed in all the cases. In both of NS and EW direction, the first natural frequency in winter tends to be lower than summer. The first natural frequencies in summer and winter are summarized in Table 1. Natural frequencies are likely lower in EW direction than NS because of the building plan. The lowest first natural frequency is 4.08 (Hz) in EW direction in 8:00-9:00 of 2015/01/09 among the estimated period. In the same period of time (8:00-9:00) and the same EW direction, the first natural frequency in summer (2014/08/19) is estimated 4.44 (Hz). This variation of the first natural frequency is estimated about 8%.

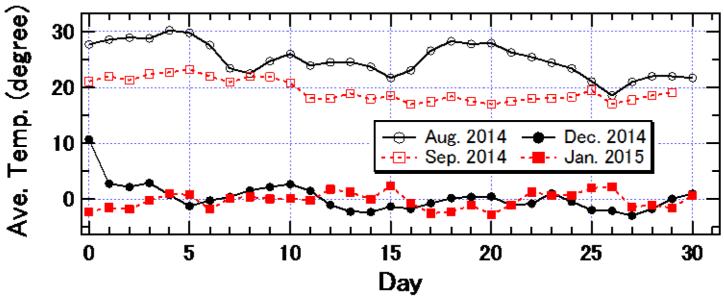
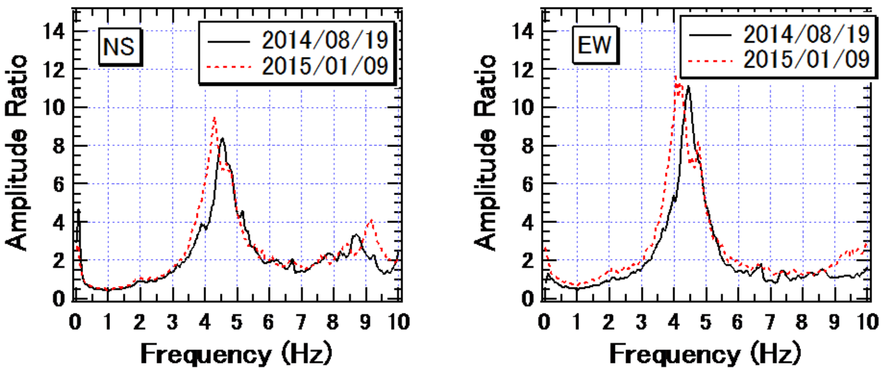
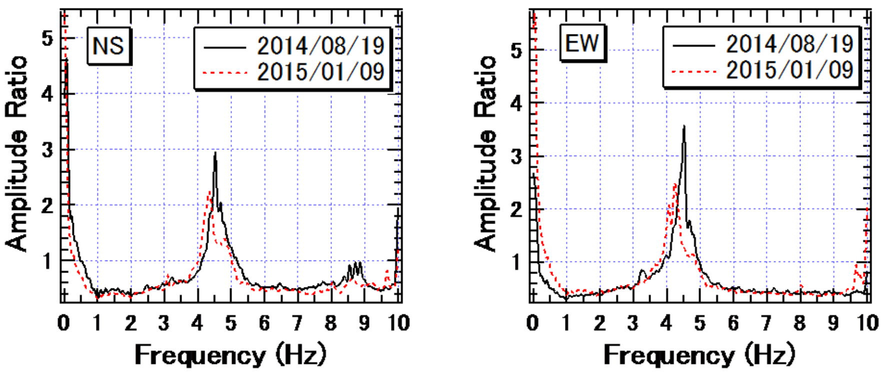


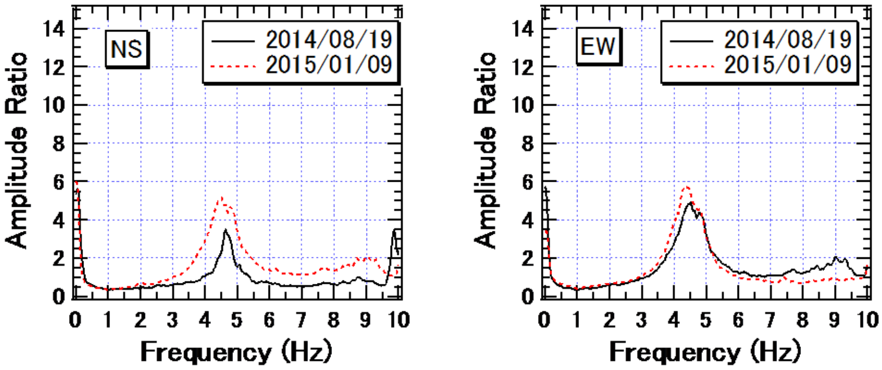
Fig. 6– Average temperature variation in summer and winter [6]



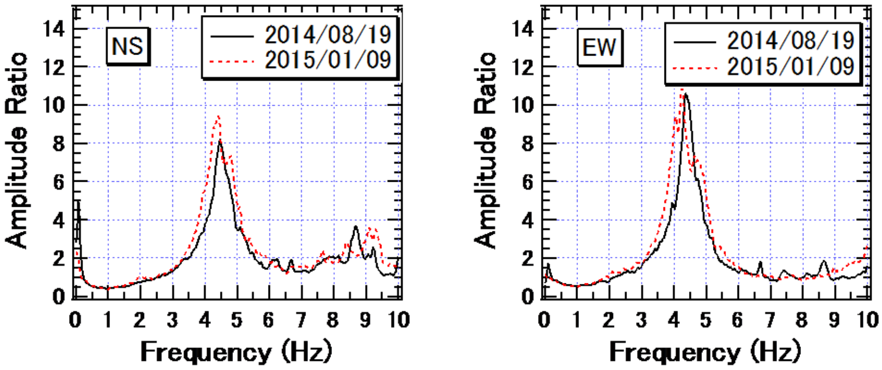
Early morning (4:00-5:00)



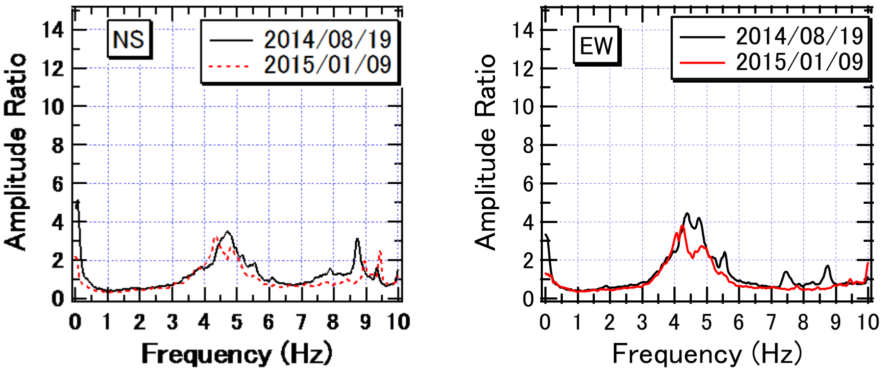
Morning (8:00-9:00)



Afternoon (12:00-13:00)



Evening (17:00-18:00)



Midnight (23:00-24:00)

Fig. 7– Seasonal variation of amplitude ratio of 3F and 1F

Table 1 – Estimated First natural frequency

NS	8/19	9/6	12/29	1/9
04:00–05:00	4.52	4.49	4.37	4.35
08:00–09:00	4.54	4.54	4.44	4.30
12:00–13:00	4.64	4.64	4.39	4.52
17:00–18:00	4.47	4.54	4.32	4.39
23:00–24:00	4.71	4.59	4.37	4.35

EW	8/19	9/6	12/29	1/9
04:00–05:00	4.52	4.49	4.32	4.25
08:00–09:00	4.44	4.44	4.27	4.08
12:00–13:00	4.42	4.49	4.27	4.37
17:00–18:00	4.37	4.42	4.47	4.25
23:00–24:00	4.39	4.47	4.30	4.25

Thermal expansion coefficient of wooden material is relatively small compared to other typical construction materials like steel and concrete. Physical property of wood can be considered not so sensitive to temperature variation. Therefore, snow accumulation is focused as the reason that the first natural frequency becomes lower in winter. Figures in Fig. 8 show snow fall in Yamagata city and snow accumulation in Dec. 2014 and Jan. 2015 officially published by JMA (Japan Meteorological Agency). Accumulation of snow is about 30cm in the day of 2015/01/09 indicating the lowest natural frequency. The statistics indicate that there should have been considerable amount of snow accumulated on the roof of the building. Considering those results and statistics, the first natural frequency shifting to lower frequency range in winter can be concluded because of the increase of roof weight due to snow accumulation.

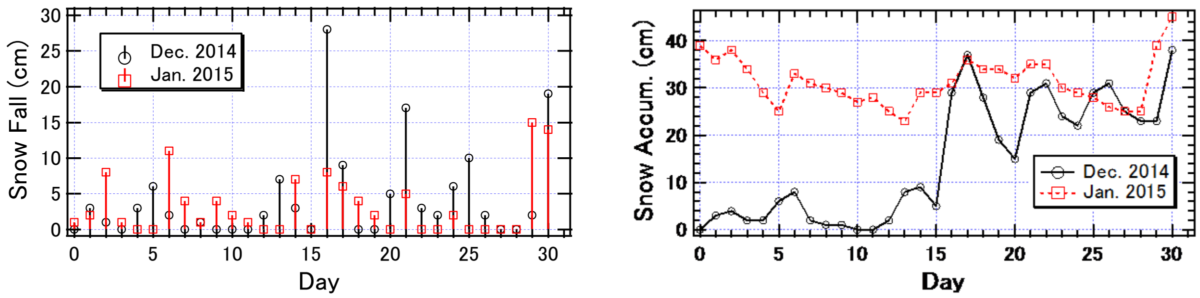


Fig. 8– Snow fall and snow accumulation from Dec. 2014 to Jan. 2015 [6]

5.2 Variation in one year of 2018 [7]

Seasonal variation of the vibration characteristics of the building in one year of 2018 is discussed using the continuous observation data. Left figure of Fig.9 shows the variation of daily average temperature of Yamagata city from 2017/12/20 to 2018/12/31. Right figure of Fig.9 shows the variation of snow-fall and accumulation of snow in Yamagata city from 2017/12/20 to 2018/3/31. The highest average temperature in summer is about 30 degree in Celsius and the lowest is about -3 degree in winter. It has been cold with much snow accumulated during days of January 2018. Snow accumulation data in days during January 2018 suggest that there were much snow accumulated on the roof of the building.

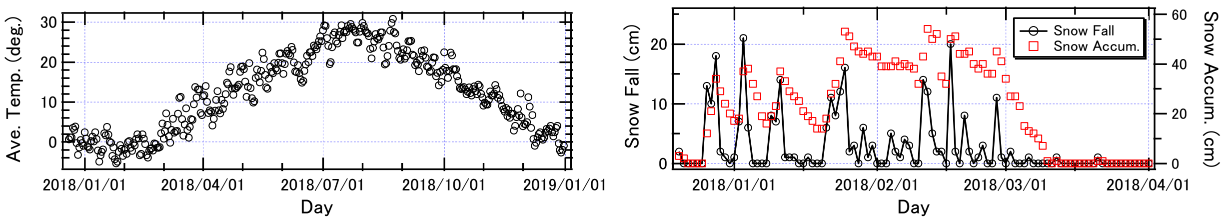


Fig. 9– Correlation of first natural frequency to average temperature (Left) and average humid (Right)

Seasonal variations of the first natural frequency due to average daily temperature, humidity, and wind velocity are shown in Fig.10 to 12. The first natural frequency is obtained by finding the largest peak frequency in spectral ratio of 3F and 1F. The first natural frequency tends to be lower in EW direction than NS, because of the rectangular shape of building plan and braces installed into walls. The first natural frequency decreases in Jan. and Feb. and recovers to the original after March. Although some cyclic fluctuation in the frequency can be observed after April, the first natural frequency keeps higher than the period with snow accumulation in winter. The effect of temperature can be found in variation of the frequency because temperature is related to snow-fall and accumulation. However, it seems difficult to find out the correlation of humidity and wind velocity to frequency variation. Damping ratios are also obtained from the results of spectral amplitude ratio using the resonance curve technique [8]. Average damping ratio in a year is estimated 7% in NS and 6% in EW direction. Damping ratio in winter is relatively small as about

5%, on the other hand, damping ratio tends to be larger and varies, and damping ratio over 10% can be found in summer.

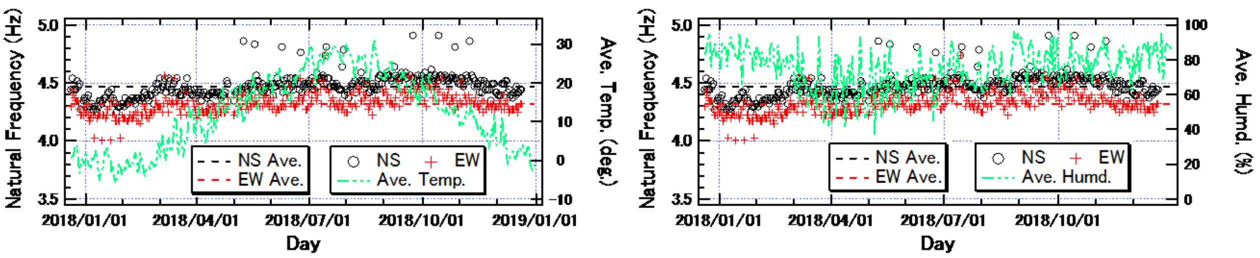


Fig. 10– Correlation of first natural frequency to average temperature (Left) and average humid (Right)

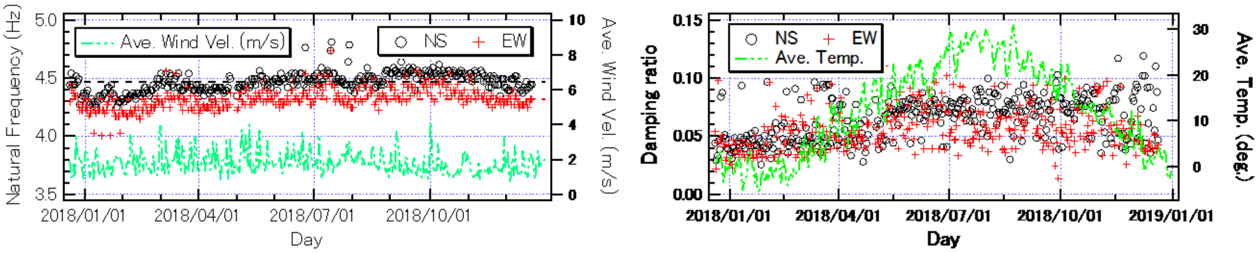


Fig. 11– Correlation of first natural frequency to average wind velocity (Left) and damping ratio to average temperature (Right)

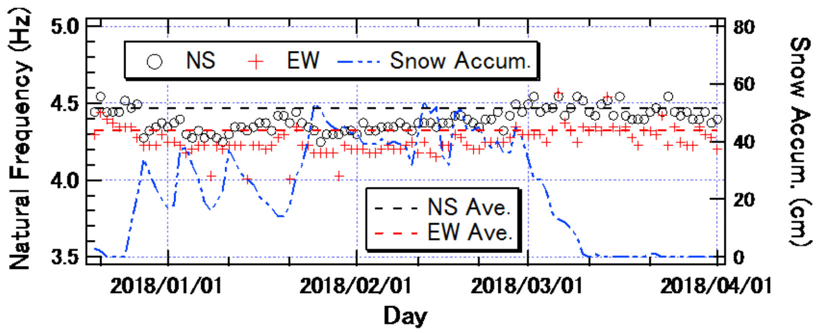


Fig. 12– Correlation of first natural frequency to snow accumulation

6. Seismic response of the building [7]

In this continuous observation system, strong motion of earthquake can be also recorded. Since observation started, some small earthquakes have been recorded. Time histories of the largest earthquake observed at 6:00 in the morning of 2016/11/22 are shown in Fig. 13 that are the largest records since the observation started. Spectral amplitude ratios of 3F and 1F of the building for five observed earthquakes are show in Fig. 14. Red solid lines mean the average spectral amplitude in each direction. The average first natural frequencies are estimated about 4.26 (Hz) and 4.15 (Hz) in NS and EW direction, respectively. Compared to the results of microtremor, the first natural frequencies tend to lower in earthquake than microtremor, and as high as in winter with snow accumulation. Damping ratios are also estimated 9% and 8% in NS and EW direction, respectively.

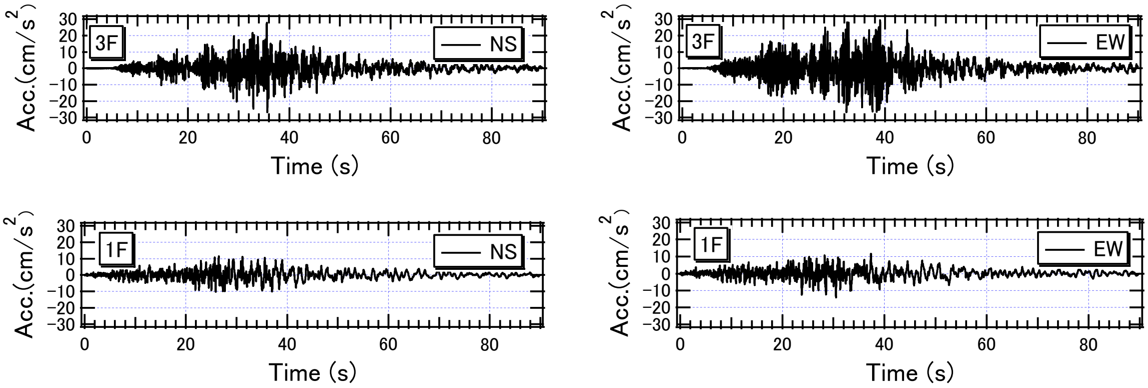


Fig. 13– Time history of observed earthquake of 2016/11/22

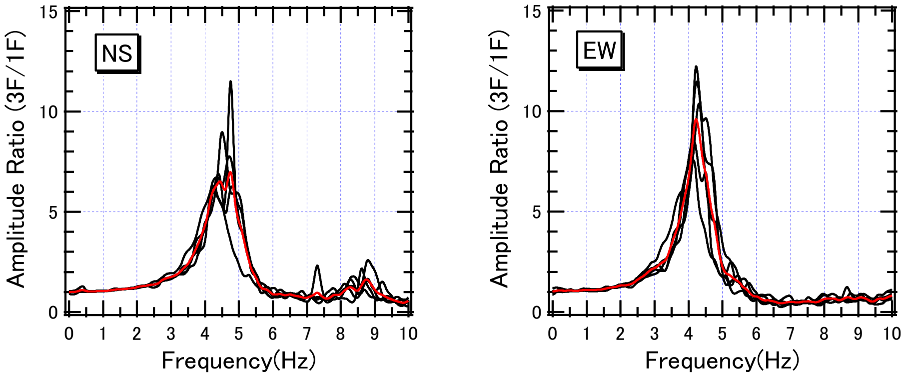


Fig. 14– Amplitude ratios of 3F and 1F from five observed earthquake data

(Red solid line is the average of five earthquakes)

Based on the observed earthquake data, seismic response analysis model of the building is developed. Properties of the seismic response analysis model are described in Table 2. Seismic response analysis model is assumed multi-degree of freedom system (MDOF) with masses and shear springs. Weight of each floor is assumed 3kN/m^2. This is estimated by optimizing the first natural frequency of the building due to the increase of weight by snow accumulation. Shear modulus of each layer is estimated so that the first natural frequency derived from eigen value analysis meets good agreement with the estimated one from earthquake observed data. Damping ratios are assumed so that simulated peak amplitude ratio can fit the observed one at the first natural frequency. As a result, damping ratios are estimated relatively high compared to typical case of seismic response analysis of building.

Table 2 – Properties of the building for seismic response analysis

NS	Weight W	Shear modulus K	Damping ratio hi		EW	Weight W	Shear modulus K	Damping ratio hi	
	kN	kN/m	h1	h2		kN	kN/m	h1	h2
3F	1060	4.50E+05	0.085	0.085	3F	1060	3.20E+05	0.11	0.11
2F	2100	5.60E+05	0.085	0.085	2F	2100	4.00E+05	0.11	0.11
1F	2120	6.80E+05	0.085	0.085	1F	2120	5.50E+05	0.11	0.11

Observed records at the first floor of the earthquake of 2016/11/22 is adopted as input motion for seismic response analysis. In those figures, “sim.” means the result of seismic response analysis, and “obs.” means observed record. It can be said that results of seismic response analysis meet good agreement with observed records in time domain in Fig 15. After the results of frequency characteristics in Fig 16, the Fourier amplitude spectra of 3F obtained from seismic response analysis indicate good accordance with the observed records in lower frequency range than the first natural frequency for both horizontal directions. On the other hand, Fourier amplitude spectrum of seismic response analysis excesses the observed record in higher frequency range than the first natural frequency in NS direction.

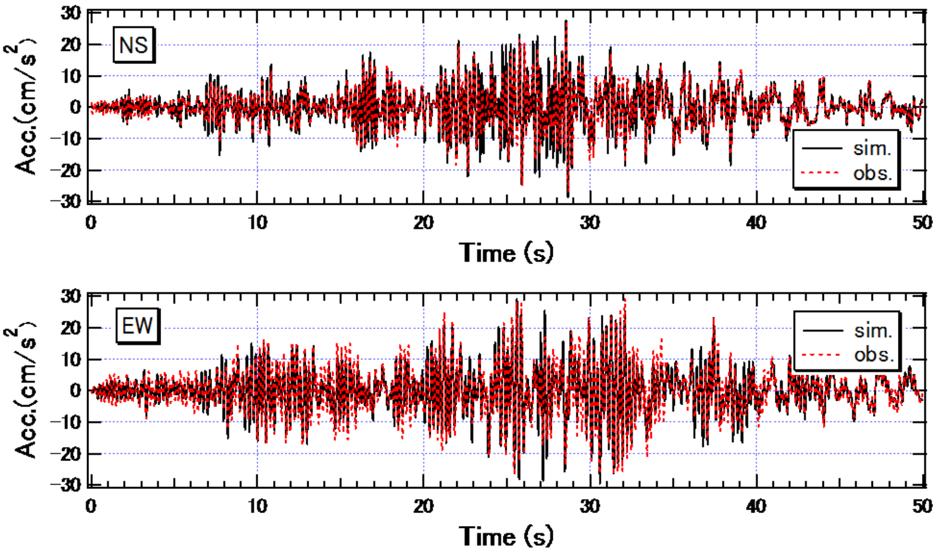


Fig. 15– Time history of response acceleration of 3F (observed and simulated)

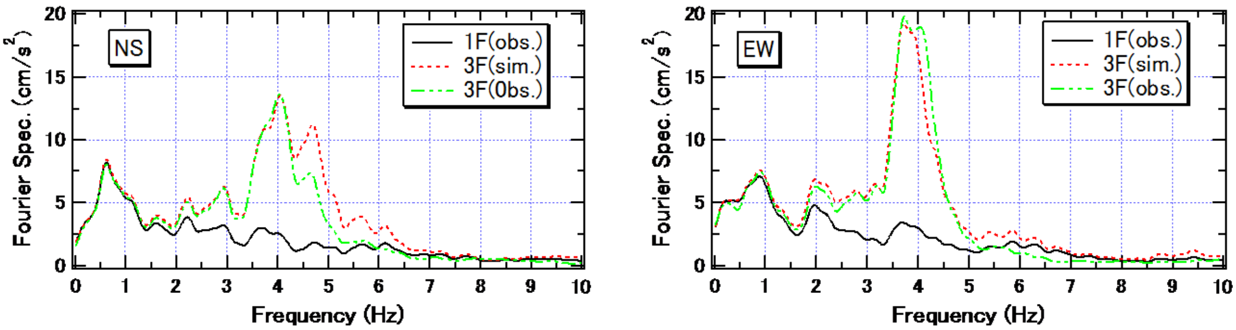


Fig. 16– Fourer sepctra

7. Conclusions

Vibration characteristics of multi-layered wooden building with large atrium are estimated using continuous observed data of microtremor and earthquake. Especially daily and seasonal variation of vibration characteristics are studied. The building exists in the snowfall area, and the effect of snow load to vibration characteristics of the building is also discussed. Results are summarized below.

1) The first natural frequency of the building is estimated 4.5 (Hz) that is relatively high compared to the same-scale typical wooden building. Estimated first natural period is 1.57 times shorter and shear modulus is 2.5 times stiffer than the estimation by the equation of T=0.03H.

2) Daily variation of the vibration characteristics of the building indicates that amplitude at the first natural frequency tends to be larger in the daytime than early morning and midnight because of more working people population in the building.

3) Seasonal variation of the vibration characteristics of the building shows that the first natural frequency tends to lower in winter than summer, due to accumulated snow on the roof of the building.

4) Seasonal variation through a year of 2018 describes that the first natural frequency tends to be lower in winter due to snow accumulation, however, it is difficult to find significant correlation between the first natural frequency and average temperature, humidity, and wind velocity. Additionally, it is pointed out that estimated damping ratios are widely variated.

5) The first natural frequencies estimated from earthquakes are about 4.0 (Hz) that are close to one estimated under the snow accumulated condition.

6) Seismic response analysis model is developed based on the observed data analysis for preparation of simulation in case that subjected to heavily strong motion earthquakes.

8. Acknowledgments

The authors are grateful to all the involved parties; Ms. O.Tsuchida, Mr. T.Konno, Mr. N. Satoh. A part of the earthquake records were observed by K-NET (NIED).

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