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STRUCTURAL HEALTH MONITORING OF HISTORICAL TIMBER POST AND BEAM STRUCTURES IN NORWAY AND JAPAN

Vibration measurements of four Norwegian Stave Churches

Kaori Fujita[1], Hiroki Ishiyama[2], Bunji Izumi[3] and Per Berntsen[3]

ABSTRACT: This paper present the results of vibration measurement on four Stave Churches in Norway. The study was realized by the joint research team from Norway and Japan. The two countries share important characteristics from the perspective of architecture: the richness in timber resources, technological advancement in timber engineering and the existence of ancient architectural heritage of timber post and beam construction. Four Stave churches in Norway were investigated through multiple monitoring; vibration, temperature, humidity, moisture content measurements and 3D scanning. From these results the application to structural health monitoring on timber architectural heritage is discussed

KEYWORDS: Natural frequency, Structural health monitoring, Moisture content, Stavekirke, Architectural heritage

1 – INTRODUCTION

The application of vibrational measurements in structural health monitoring (SHM) is of prime interest in terms of maintaining architectural heritage as a non-destructive testing method for extremely long-lived architecture. Studies have been conducted in recent years based on this method on architectural heritage structures. However, the main target of these studies are masonry and application to timber structures are few. The authors have been conducting vibration monitoring on several historical timber structures in Japan over 10 years and the results show high potential for application to SHM, by considering the heat-humidity environment of the timber structures [1].

2 – BACKGROUND

Thus far, multiple methods for the evaluation of timber structures, based on calculations sometimes accompanied by joint or element tests, have been developed, tested, and applied. Non-destructive vibration measurements have also been used to elucidate the structural performance of existing structures. The most classical method is the ambient vibration test (microtremor measurement), which has been applied to timber structures in Japan since the 1920s (Omori 1921). The main objective of such studies was to determine the change in the natural frequency of the structure before, during, and after an earthquake, for evaluating the stiffness degradation of the structure.

Earthquake response monitoring has seen widespread applications since the end of 1990s. Due to the recent development of affordable sensors and devices, many structural health monitoring (SHM) studies have been conducted on various types of structures, based on earthquake monitoring.

2.1 Examples of vibration measurments of timber traditional structures in Japan

The application of vibrational measurements in structural health monitoring is of prime interest in terms of maintaining architectural heritage as a non-destructive testing (NDT) method. However, it is known that the results of ambient vibration tests have a wide variation. One reason is because the measurement is for extremely small displacement, and timber structures are known to

[1] Kaori Fujita, Professor, Department of Architecture, School of Engineering, the University of Tokyo. Tokyo, Japan. fujita@arch1.t.u-tokyo.ac.jp

[2] Hiroki Ishiyama, Assistant Professor, Department of Architecture, Osaka Metropolitan University, ishiyama@omu.ac.jp

[3] Bunji Izumi, Assistant Professor, Institute of Architecture and Technology, Faculty of Architecture and Design, Norwegian University of Science and Technology (NTNU), bunji.izumi@ntnu.no

[4] Per Berntsen, Assistant Professor, Institute of Architecture and Technology, Faculty of Architecture and Design, Norwegian University of Science and Technology (NTNU), per.berntsen@ntnu.no

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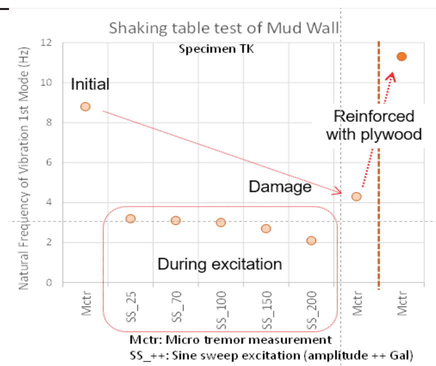
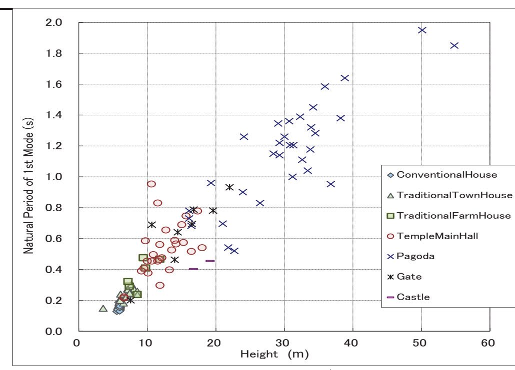
have strong non-linearity even in micro displacement range. Therefore the results of ambient vibration tests have been mostly used to compare the vibration modes determined by analysis.

In order to utilize the results of onsite vibration measurements, such as ambient vibration and earthquake monitoring, to SHM it is essential to clarify the variation in the results of the test. Fig. 1 show several results of vibration measurements done by the authors. 1-1 show the change of natural frequency of vibration before and after shaking table test on traditional timber post and beam element. The result show that the natural frequencies of vibration in the first mode show distinct difference according to the damage and reinforcement of the specimen. 1-2 show the relation between height and natural period of vibration in the first mode of multiple trasitional timber post and beam structures in Japan. The empirical relation between height and natural period show linear relationship for traditional timber structures which have similar morphology, such as pagodas.

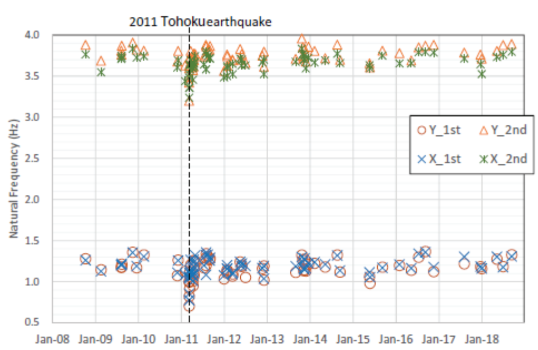
Fig. 1-3 to 1-6 show results of longterm earthquake monitoring of traditional timber Buddhist temple constructed in 1825 (Ref*). Between 2008 and 2019, 75 strong motion events were recorded. From the long-time monitoring, the influence of time due to deterioration and exterior force was expected, but the natural frequency of vibration/stiffness did not show any fluctuation in our 12 years of measurement. The experience of strong motion by 2011 Tohoku earthquake also did not result in a decrease in natural frequency/stiffness, as shown by comparing the pre- and postearthquake values (Fig.1-3). The natural frequency of vibration in the first mode showed a strong correlation with the natural logarithm of the maximum relative displacement (Fig. 1-4). However, the natural frequency of vibration varied between 10 and 20% for the same maximum relative displacement, and no significant effect of time was observed , but the results did vary depending on the climate (Fig. 1-4). The mechanical properties of wood were discussed. The natural frequency of vibration/ stiffness showed a constant value for the same displacement by modifying the value with its MC.



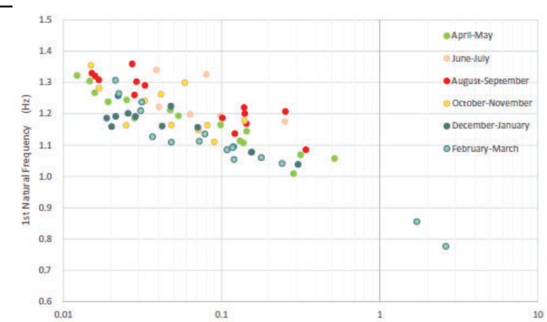
1-1 Change of natural frequency of vibration by shaking table test of traditional wall element. [1]



1-2 Relation of height and natural period (1st mode) of traditional timber structures in Japan [2]



1-3 Natural Frequency of vibration by date. Based on longterm vibration measurement of traditional timber ([3], Fig.5)



1-4 Maximum relative displacement by natural frequency of vibration in the first mode, by month. Based on longterm vibration measurement of traditional timber ([3] Fig.9)

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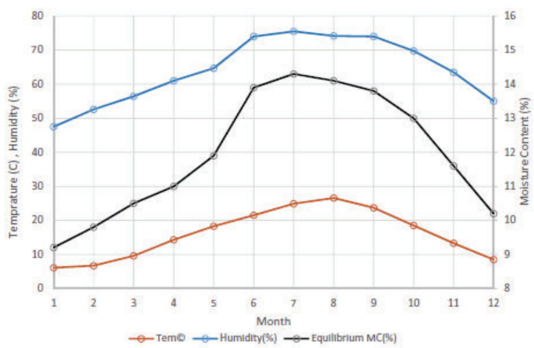
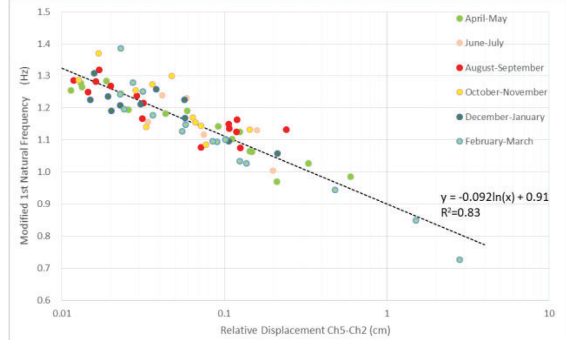


1-5 Average temperature, humidity, and equilibrium MC of wood (Japan Meterorological Agency), [3] Fig. 11



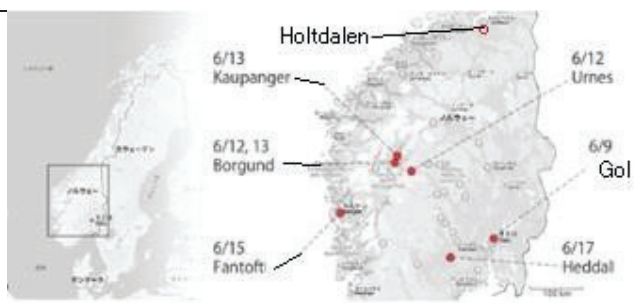
1-6 First-mode natural frequency of vibration by relative displacement (Ch4/1) for 12% MC. Based on longterm vibration measurement of traditional timber ([3] Fig.12)

Figure 1. Vibration measurements in Japan by the authors

3 – PROJECT DESCRIPTION

In Japan the construction system of historic and traditional architecture is of timber post and beam construction. Whereas in most parts of Europe and North America, the major traditional construction system of timber architecture is of log construction. Norway is exceptional from this point, that there exist 29 Stave Churches of post and beam construction some remaining from the 12th century. The climatic conditions are totally different for the two countries; Norway being boreal to hemi boreal whereas Japan being temperate humid. Thus these two countries provide ideal fields to study the influence of climatic conditions on the vibration characteristic of historical timber post and beam construction.

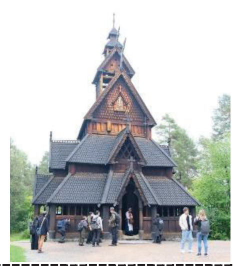
Onsite investigation of seven Norwegian Stave Churches was conducted. The method of experiment were, documentation by 3D scaniing, onsite investigation of structural elements, temperature/humidity monitoring and ambient vibration measuremet. Vibration measurements were conducted on four churches (Fig.2).



2-1 Location of investigated Stave Churches 2022 to 2024 [5]

2-2 Example of 3D scanning of Holtdalen [4]

2-3 Ambient vibration measurement of Stave Churches



Name (Year of Construction) Location, Date of Measurement	Urnes Church (11th c), Ornes Aug. 2022, Mar. 2023, June. 2024	Holdalen (1150), Trondheim September 2023	Gol (1170), Oslo September 2023	Borgund (1180), Ornes June 2024

Figure2. Onsite investigation of Norwegian Stave Churches 2022 to 2024

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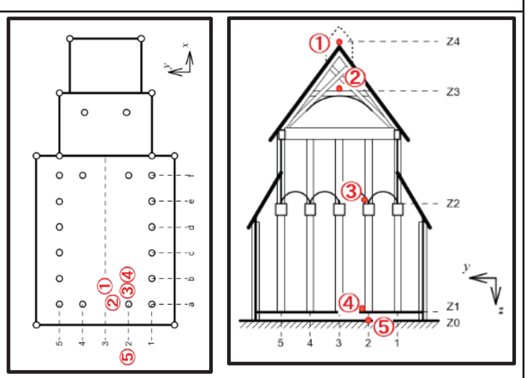
4 – EXPERIMENTAL SETUP

The target of the experiment were on four stave churches in Norway; Urnes, Gol, Haltdalen and Borgund. Example of the plan, section, experimental setup and vibration mode of Urnes Stavekirke (constructed in 1130) is shown in Fig. 3. To perform the measurements, 5 three-axial accelerometers (M-A352AD10, EPSON) with quartz resonator sensor were used. Ambient (micro tremor) and free vibration tests were performed on the structure. The measurement was conducted in August 2022, March 2023, and June 2024.

Acceleration was measured with sampling of 200 Hz, five minutes for each measurement. Together with vibration measurement 3D scanning and measurement of the structural members were conducted. Also temperature and humidity at the location of the church were monitored and recorded between August 2022 to March 2023, and November 2023 to June 2024.

3-1 Interior of Urnes Church and setting of device



3-2 Example of setting of accelerograms

Figure 3 Example of experimental setup of Urnes Church

5 – RESULTS

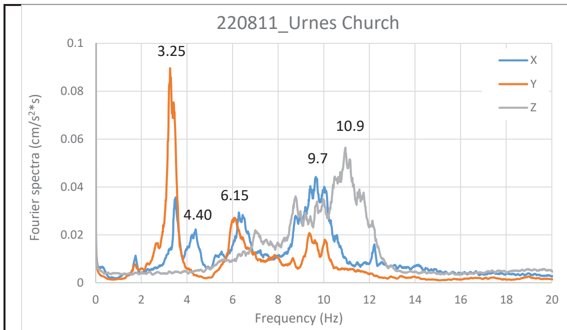
Vibration measurements on Urnes Church were conducted on 11th August 2022, 1st March 2023 and 12th June 2024. Examples of the results of the vibration measurements of Urnes Church are shown in Fig. 4. Fourier analysis was done for 8192 data, and Hanning window was used. The analysis was further done for the same experiment from 8,192 to 63,000 data (54,808 Data in total). From the Fourier spectra, the Y (short) direction show clear response in 3.5 Hz and 6.2 Hz. The results for the X (longitudinal) direction is less clear. There are responses at 3.53, 4.5, 6.3 and 10 Hz. The magnitude at 10 Hz is large for Channel 3, which was set on top of the column entablature. Response are also observed at Channels 1, 2 and Z direction at around 10 Hz, which can be the local response of the column. For the Z (vertical) direction response can be seen at 7 Hz and 9-11 Hz.

The vibration modes were determined from the transfer function for the assumed natural frequencies in both directions (August 2022). For the Y direction, 3.5 Hz and 6.2 Hz seem to be the first and second modes. For the X direction the response is observed at 3.52, 4.33 and 6.37 Hz but the vibration modes are complex and difficult to explain. As we see large amplitude in the Y direction at 3.5, and 6.2 Hz the vibration could have been induced in the X direction. Therefore 4.42 Hz is assumed to be the first mode in the X direction. The large amplitude at 9 to 10 Hz show that top of the first floor column show response and it can be assumed to be the natural frequency of the column.

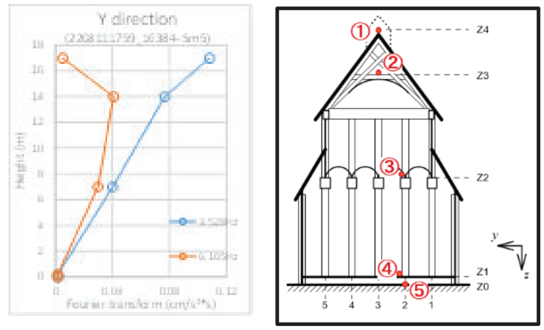
The same measurement was conducted in March 2023, and the results show that for the Y direction 3.51Hz, 6.56Hz and 8.7Hz. For X direction: 4.02, 4.73, 7.03 8.71, and 10.91 Hz. The results are close for the 1st mode Y direction and for the other values slightly higher for the measurement in March.

The temperature and humidity of Urnes church was measured by TR-72wb of T&D cooperation, Japan. The temperature and humidity were, -11.9 to 24.5 degrees Celsius, and 28 to 92% respectively. Monthly average of the temperature and humidity is shown in Fig. 4-3 (Note 1).

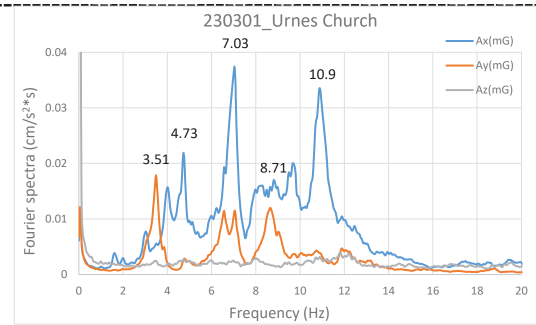
The deteremined natural frequency of vibration and the temperature/humidity of the measured date are shown in Table 4-1. The first mode in the Y direction is the most clear value in morphology as well as the measured value. The result show that the values were both 3.51Hz (0.285 sec) when the temperature were 20 degrees different and humidity were both about 70%.



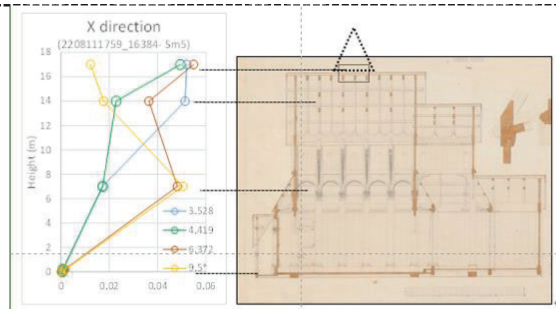
Fourier Spectra of Urnes Stave Church (August 2022)



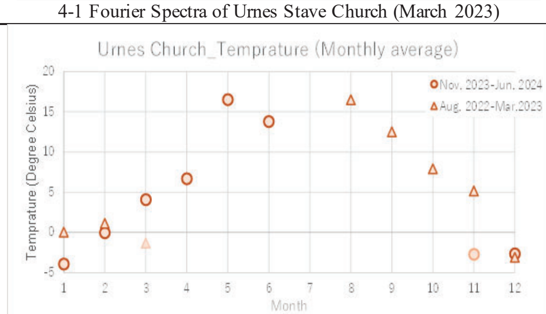
Vibration Mode in Short (Y) direction

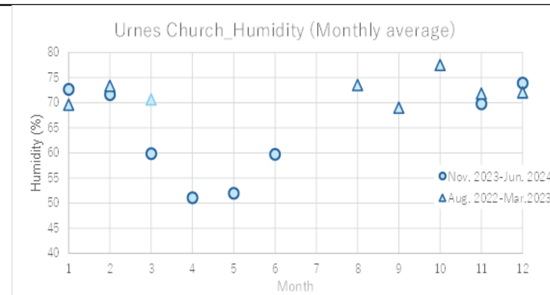


4-1 Fourier Spectra of Urnes Stave Church (March 2023)



4-2 Vibration Mode in Longitudinal (X) direction

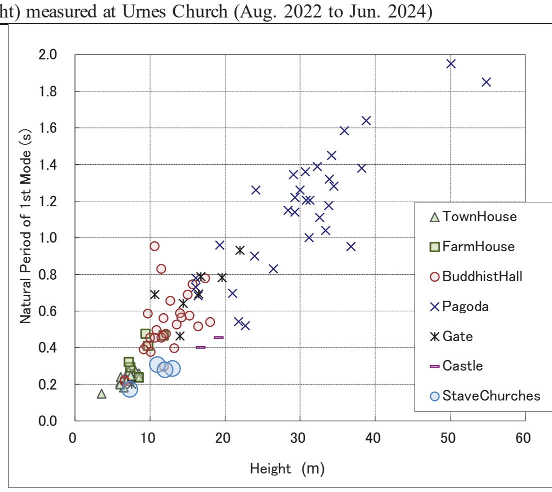




4-3 Monthly average temperature (left) and humidity (right) measured at Urnes Church (Aug. 2022 to Jun. 2024)

Table4-1 Natural frequency (period) of vibration, temperature humidity at Urnes Stave Church

		Date	11.Aug2022	1.Mar.2023	12.Jun.2024
		Temperature	19.8°C	-0.8°C	14°C
		Humidity	71%	73%	54%
Y (short)	1st		3.25 Hz	3.51 Hz	3.11 Hz
			0.307 sec	0.285 sec.	0.321 sec
	2nd		6.15 Hz	7.03 Hz	5.69 Hz
	3rd		9.70 Hz	8.71 Hz	9.00 Hz
X (longitudinal)	1st		4.40 Hz	4.73 Hz	3.99 Hz
			0.227 sec	0.211 sec	0.250 sec
	2nd		6.27 Hz	7.03 Hz	5.89 Hz
	3rd		9.70 Hz	10.9 Hz	9.12 Hz



4-4 Relation between height and natural period of vibration in the first mode of traditional timber post and beam construction

Figure4. Results of vibration measurement of Urnes Stave Church 2022 to 2024

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The same measurement and analysis were conducted for the other three stave churches. The results show that the first mode of vibration were fairly clear for the short direction, but in the longitudinal direction the Fourier spectra and the vibration modes were complex in the longitudinal direction, as in the case of Urnes Church. This is due to the influence of the bell tower and alters located behind the main frame structure. Therefore the first mode of vibration in the short span direction is compared in relation with the height of the structure. The relation is illustrated in Fig. 4-4 together with the measured results of traditional timber structures in Japan and Nepal. The measured results in Norway are still few in number but it shows fairly linear relationship, and the natural periods are comparatively lower than the Japanese timber post and beam construction.

6 – CONCLUSION

Fundamental vibration characterisitcs were determined through vibration measurement for four stave churches in Norway. Though the results of the stave churches are still scarce in numbers, it show consistency with the relation of the height of the structure as these structures have similar structural system and morphology.The dependacy of large difference in temperature can not be observed, when the humidity was constant. Together with preceding research this suggest the infulencial factor of vibration is not temperature but humidity.

7 – REFERENCES

[1] Kaori Fujita, Isao Sakamoto et. al., Shaking Table Tests and Analyses of Walls used in Traditional Timber Structures in Japan, Proceeding of International Association of Bridge and Structural Engineering, T903, 2001

[2] K. Chiba, K. Fujita, H. Sato, S. Takahashi and A. Baba, Seismic Diagnosis and Structural Performance Evaluation of Existing Timber Houses in Tokyo, Part5 Application of Micro Tremor Measurement, Proceedings of Building Stock Activation 2007, pp. 41-48, 2007.11

[3] K. Fujita and K. Chiba, "Long-Term Earthquake Response Monitoring of Nineteenth-Century Timber Temple Kencho-ji, Japan", In. Journal of Architectural Heritage, 2023, VOL. 17, NO. 8, 1240–1255.

[4] Karin Kobayashi, Master Thesis, Kyoto Institute of Technology, 2024. Supervised by Prof. Martinez Alejandro

[5] Yusuke Kawakami, Graduation Project, School of Engineering, The University of Tokyo, Jan. 2024

[6] Kaori Fujita , D. Ponce , T. Toyoda, M. Morii , Y. Niitsu , T. Hanazato , J. Subedi & M. Shakya (2020): Microtremor Measurement and Damage Investigation of Historical Timber–masonry Composite Tiered Temples in Nepal, International Journal of Architectural Heritage, DOI: 10.1080/15583058.2020.1808909

(Note 1) The device was set from The device was set from 12th August 2022 to 1st March 2023 and 23rd November 2023 to 12th June 2024. One measurement in one hour.The data of March 2023 and November 2023 were too few, so the illustration is shown in lighter color.

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