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EVALUATION OF VIBRATION CHARACTERISTICS OF EXISTING TIMBER ARCHITECTURE BY MICROTREMOR MEASUREMENT -EXAMINATION WHEN IT IS DIFFICULT TO INSTALL AN ACCELEROMETER IN THE ATTIC-

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ABSTRACT: In this paper, we investigate a method of understanding the natural frequency characteristics of existing two-story timber architecture by installing an accelerometer on the floor of the second floor and conducting microtremor measurement under the condition that an accelerometer cannot be installed in the attic. First, by surveying the trend of Registered Tangible Cultural Properties by the Agency for Cultural Affairs in Japan, we found that the architecture that needs seismic diagnosis in the future is two-story timber houses that are more than 50 years old. Next, we conducted a structural performance survey of existing timber architecture under the same conditions, using microtremor measurement and human excitation, and finite element analysis after the survey, and clarified the natural frequency characteristics of existing timber architecture by comprehensively judging the survey results.

KEYWORDS: Microtremor Measurement, Natural Frequency Characteristics, Seismic Diagnosis

1 INTRODUCTION

In Japan, the Law for the Protection of Cultural Properties was enacted in 1950 to protect and utilize architecture, paintings, sculptures, handicrafts, calligraphic works, classics, ancient documents, and other tangible cultural properties of high historical and artistic value, and to improve culture. In Japan, where earthquakes occur frequently, it is necessary to accurately understand the structural performance of old architecture and to reinforce it appropriately to utilize it. In 1996, the Agency for Cultural Affairs promulgated the "Guidelines for Ensuring Earthquake Safety of Cultural Property Buildings, etc." [1] to promote seismic retrofitting without compromising the cultural value of architectures. In this context, as a nondestructive seismic diagnosis method for architectures, microtremor measurement is utilized to grasp the structural characteristics of architecture on a global scale by installing highly sensitive accelerometers in the structure of the architecture to be investigated [2,3]. At present, earthquake-resistant diagnosis is steadily underway, and according to a survey on the current status of earthquake-resistant measures for national treasures and important cultural properties [4] conducted by the Agency for Cultural Affairs in 2019, 95% of national treasures and important cultural properties have been reinforced against earthquakes or measures have been taken to ensure the safety of users.

On the other hand, the Law for the Protection of Cultural Properties was revised in 1996 to introduce a system of registration of cultural properties to preserve more architectures with cultural value. Compared to national treasures and important cultural properties, the regulations of the cultural property protection system are less stringent, so registration is easier and the architectures are often small in scale. Nondestructive seismic diagnosis using microtremor measurement is desirable for such small architectures. However, most of the architectures, such as national treasures and important cultural properties, are relatively medium to large, and the accelerometers used for microtremor measurement were installed at any position by the investigator in the attic. However, in small architectures, it is difficult for the investigator to install the accelerometer at any position in the attic because the attic space is small and the cross-sectional dimensions of the components are small.

This study investigates a method to determine the natural frequency characteristics of an existing two-story timber architecture by installing an accelerometer on the floor of the second floor and conducting microtremor measurements under conditions where an accelerometer cannot be installed in the attic.

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2 Structural Performance Survey of Existing Architectures

Registered Tangible Cultural Properties provide a modest measure of protection against the loss of cultural heritage from the modern era due to rapid national and urban development in recent years. Compared to the recognition of National Treasures and Important Cultural Properties, the examination required for approval is less stringent, and the regulations for maintenance and management after recognition are also less stringent, making it easier to apply for protection.

2.1 Current Status of Registered Tangible Cultural Properties

Fig. 1 shows the changes in the number of registered tangible cultural properties during the period 1996 to 2021. In 1996, when the system of registered tangible cultural properties was established, 83 items were registered, and the number of registered items has been increasing every year since then, reaching 12,7740 items in 2021. From the change in the number of registered items shown in fig. 1, it can be seen that the trend of increase has been constant since the system was introduced, and is expected to continue to increase in the future.

In Fig. 2, we show a breakdown of the registered tangible cultural properties by year of completion as of 2022. From Fig. 2, it can be confirmed that the number of registered buildings is dominated by young architecture. The largest proportion of the registered architectures is from 1900 to 1950. The reason why the number of registered architectures between 1950 and 2000, which are the youngest in fig. 2, is small is that the number of architectures that meet the condition of "more than 50 years old" is generally small. More time is needed before the value of architectures from this period will be recognized as having cultural value worthy of preservation, and as time passes, the number of registrations will increase, as it has for architectures from other periods, and they will become the element that accounts for the largest percentage in the future.

Fig. 3 shows the registered uses of architecture for each age group, with the lowest percentage of "House" registered for architecture built before 1600 to 1750, and similar percentages for other uses. For architecture built between 1750 and 1800, "House" accounted for the largest percentage of registrations, followed by "Industries". For architecture built between 1950 and 2000, the percentage of "House" is smaller again. In the case of buildings built between 1950 and 2000, the share of "House" is again small. This is thought to be because the number of houses with cultural value is small in younger architecture. In other words, the ratio of the use of architecture in this age group is expected to change in the future.

Fig. 4 shows the number of floors of houses certified as registered tangible cultural properties. Fig. 4 shows that most of the houses of any age are "One story" or "Two-story". The ratio of "One story" houses is higher in older houses and the ratio of "Two-story" houses is higher as the age of the houses decreases. This trend is consistent with the history of multi-story houses in Japan due to modernization. However, we cannot discuss the trend of houses built between 1950 and 2000 because the number of registered houses is small at this stage.

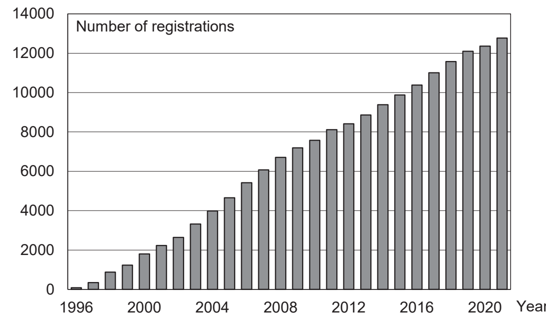


Fig. 1 *Number of registered tangible cultural properties*

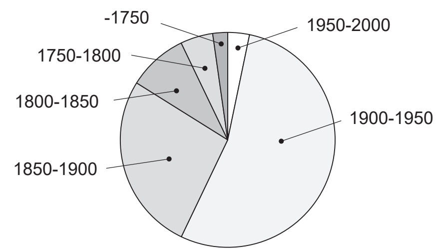


Fig. 2 *Breakdown of registered tangible cultural properties by year of completion*

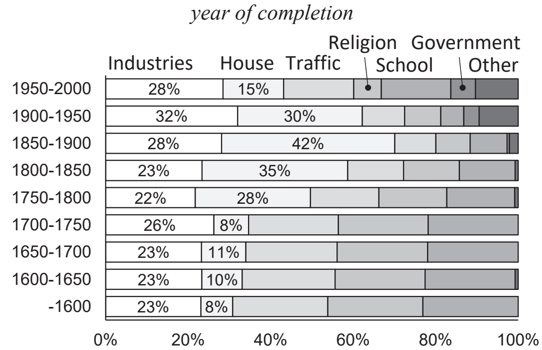


Fig. 3 *Architecture use*

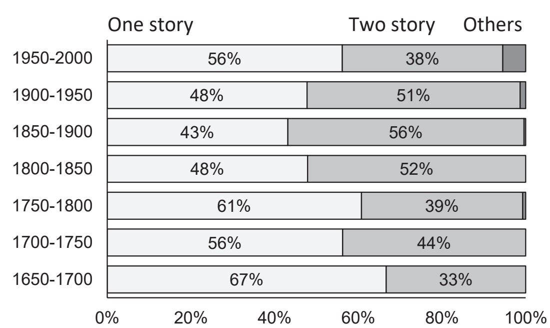


Fig. 4 *Number of Floors in Residential Architectures*

A survey of the trends in architectures recognized as registered tangible cultural properties revealed the following:

1. The number of registered architectures is increasing year by year.
2. The number of registered architectures that are young is high.
3. The number of registered architectures for housing use is high.
4. More two-story houses are registered.

Considering the above, a structural performance survey will be conducted for existing timber structures that are more than 50 years old and have a traditional building composition. In the survey, microtremor measurement will be carried out to understand the natural frequency characteristics of the housing scale structure.

2.2 Overview of the surveyed architectures

The architecture to be surveyed is an existing timber architecture in Taito-Ku, Tokyo. Built-in 1954, the architecture consists of four dwelling units surrounding a courtyard on the east side and another large dwelling unit on the west side. The architecture is located on the north side of the site, with a garden on the south side. Most of the architecture is one-story, and only the central part of the building is two-story. In the structural survey of the architecture, the area including the two-story part was chosen as the survey area.

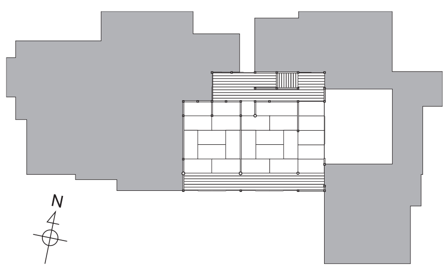


Fig. 5 *Scope of investigation*

Fig. 5 shows the survey area of the architecture. The horizontal force-resisting elements of the architecture are the full-wall and hanging walls, which consist of earthen walls, and the plank walls, which consist of three layers of small wide boards. The earthen walls have been in place since the construction of the architecture was completed, and the plank walls were replaced by earthen walls to improve the resistance of the architecture to seismic forces. The walls on the east and south sides of the survey area do not have any walls on all sides so that the view of the courtyard and garden can be seen from inside, and most of the bearing elements are hanging walls. On the other hand, the west and north sides of the architecture have many full-face walls as corridors and room boundaries.

In past earthquakes, one of the reasons for the collapse of timber architectures was the uneven distribution of load-bearing elements such as this architecture [5,6]. The uneven distribution of bearing elements has been observed in many existing architectures built before the establishment of seismic performance evaluation [7]. If the load-bearing elements are unevenly distributed, the architecture will exhibit twisting behavior during an earthquake, and the entire building will collapse in a twisting manner due to large deformation and destruction of the surface with few load-bearing elements (the surface facing the courtyard and garden in the present building).

2.2.1 Outline of the microtremor measurement

In the survey, multi-point simultaneous measurement using a total of six 3-axis wireless accelerometers is performed. Photo 1 shows the measurement system. Fig. 6, 7, and 8 show the installation locations of the accelerometers. The coordinate axes shown in the figures are the three-axis coordinates of the accelerometers, and the direction shown in the figures was chosen based on the installation conditions of the accelerometers. The measured acceleration waveforms were subjected to fast Fourier transform (FFT) to obtain the natural frequency from the transfer function. The input data of the transfer function is measured from one accelerometer installed in the garden, and the output data is measured from five accelerometers installed on the floor of the second floor.

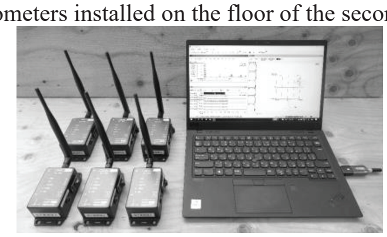
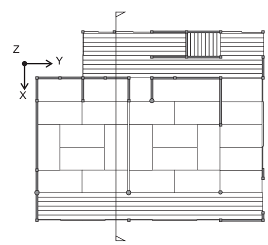


Photo 1 *Measurement system*



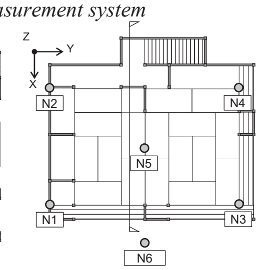


Fig. 6 *First floor plan* ***Fig. 7*** *Second floor plan*

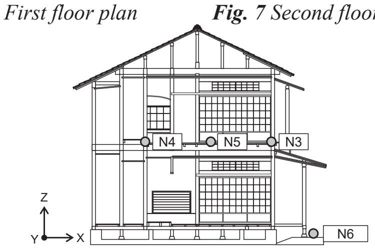


Fig. 8 *Cross-sectional view*

The sampling frequency of the measurement was set to 100 Hz so that the analysis frequency range would be 50 Hz, taking into consideration the fact that the main natural frequency of timber architectures is around 15 Hz at maximum and that the effect of aliasing caused by FFT should be eliminated. The measurement time is 360 seconds to accommodate a maximum FFT frame size of 32,768 points. When the FFT is performed on data with a sampling frequency of 100 Hz and a frame size of 32,768 points, the frequency resolution is approximately 0.00305 Hz, which enables analysis with fine precision. The FFT converts the sampled discontinuous microtremor waveform into a continuous waveform by using a window

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function. The window function used is the Hanning window, considering that the microtremor is a continuous oscillation and that it can be analyzed with high-frequency resolution.

2.2.2 Human-powered excitation

An accelerometer was installed in the area to be investigated, and free vibration was induced by human force excitation. The natural frequencies are determined by the FFT of the acceleration data. Since the acceleration measurement is limited to the time when the vibration generated by human force excitation continues, the frame size for FFT is 1,024 points, which can be measured in about 10 seconds. As a result, the frequency resolution is inferior to that of FFT using a frame size of 32,768 points for constant microtremor measurement. Fig. 9 shows the direction of human-powered excitation, and Fig. 10 shows the locations of the accelerometers.

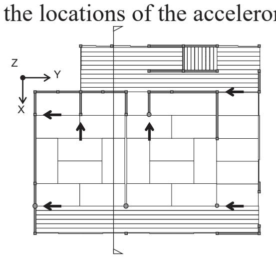

***Fig. 9** Direction of vibration*

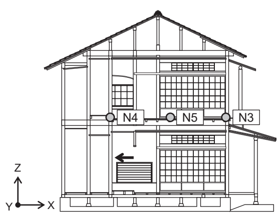

***Fig. 10** Installation location*

The locations of the accelerometers are the same as those used in the microtremor measurement, but accelerometer N6, which was installed in the garden in the microtremor measurement, is not used because the input vibration from the ground to the building does not need to be considered in the human force excitation measurement.

We decided to push the columns on the first floor so that the second mode, in which the horizontal movement of the second-floor floor dominates, would appear in the human power excitation. Some of the columns where the accelerometers were installed had walls attached to them, and such columns could not be physically pushed. Therefore, two pillars were pushed in the X-axis direction, and the pillars around N2 and the pillars directly below N1, N3 and N4 were pushed in the Y-axis direction. The pillars were chosen symmetrically in the direction of vibration to prevent artificial twisting due to excitation.

3 Results of various measurements

3.1 Results of normal microtremor measurement

The Fourier spectrum was obtained by FFT using the Hanning window as the window function for the acceleration data observed from the microtremor measurement. Next, the transfer function is obtained using the input waveform of accelerometer N6 installed in the garden and the output waveform of the other five accelerometers N1 to N5. The natural frequency of the architecture is determined to be the frequency at which the transfer function is dominant.

Fig. 11 and 12 show the frequency-transfer function relationship in the x-axis and y-axis directions. From the waveform, multiple excitations can be confirmed. This is probably because there are several architectures attached to the surveyed area, and the natural frequencies of these architectures were observed simultaneously. It is difficult to grasp the natural frequency of the surveyed area from this waveform alone.

From the graph in the X-axis direction, it can be confirmed that the waveforms of the combinations of N1 and N2 and N3 and N4 are identical. These combinations are located on a common beam in the X-axis direction. Next, from the graph in the Y-axis direction, it can be confirmed that the waveforms are identical for the combinations of N1 and N3, and N2 and N4. This combination is installed on a common beam in the Y-axis direction. The waveforms of the combinations of measuring points in each axis direction are identical, and the waveforms of the combinations of measuring points parallel to each axis are different, indicating that the shear deformation is caused by the low in-plane shear stiffness of the horizontal structure.

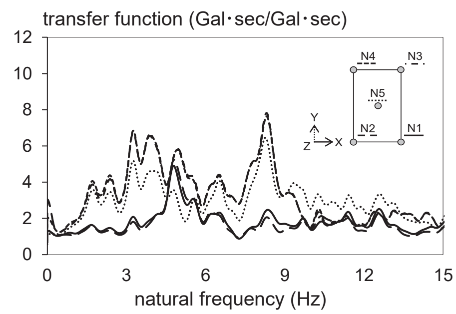

***Fig. 11** X-axis frequency-transfer function relationship*

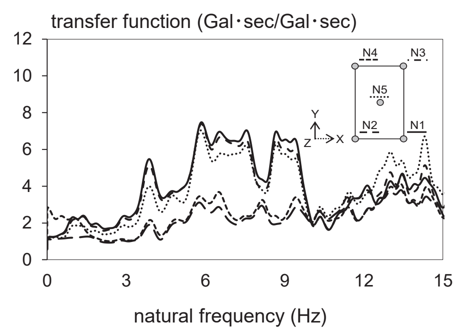

***Fig. 12** Y-axis frequency-transfer function relationship*

3.2 Results of Normal Microtremor Measurement and Manpower Excitation

In this survey, the natural frequency of the surveyed area could not be determined because multiple excitations were observed only by microtremor measurement. Therefore, the natural frequency was determined by combining the results of microtremor measurement with the results of free vibration by human power excitation. Fig. 13 and 14 show the results of constant microtremor measurement and free vibration in the X- and Y-axis directions. From the measurement results, it can be confirmed that there is a frequency that is dominant in the constant microtremor measurement but not in the free vibration. This frequency is considered to be the natural frequency of the architecture in the range where no vibration is applied (outside the survey area) or the natural frequency of the first mode in the survey area. Therefore, the natural frequency of the second mode of the surveyed area is judged to be the frequency that shows excellence in both microtremor measurement and free vibration. From the measurement results, the natural frequency of the second mode in the investigated range is 3.26 Hz in the X-axis direction and 3.88 Hz in the Y-axis direction.

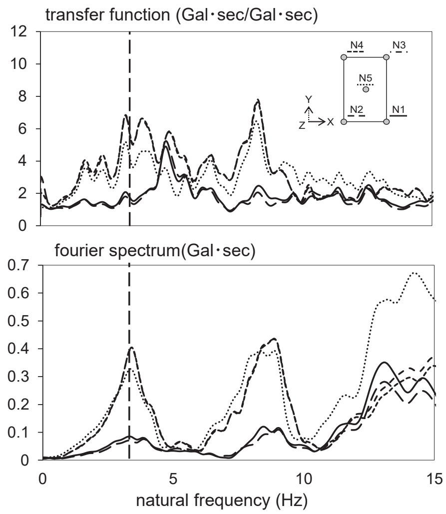

Fig. 13 *X-axis vibration*

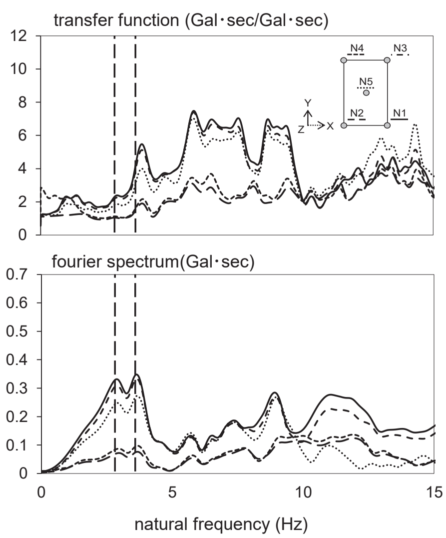

Fig. 14 *Y-axis vibration*

Fig. 15 shows the vibration modes at the dominant natural frequency. The vibration modes at 3.26 Hz and 3.88 Hz are the same, although the frequencies are different. From the vibration modes in the X-axis direction, it can be confirmed that the amplitudes of N1 and N2 are small, and those of N3 and N4 are large because the amplitudes of N1 and N2 are small due to the wall dividing the room. On the other hand, the amplitude of N3 and N4 is larger because they are adjacent to the courtyard and there is nothing to disturb the vibration. The amplitudes of N2 and N4 are small, and those of N1 and N3 are large because the walls of the corridor are placed on the N2 and N4 sides, which restricts the vibration. On the other hand, the amplitude of N1 and N3 is larger because they face the garden and there is no wall to disturb the vibration.

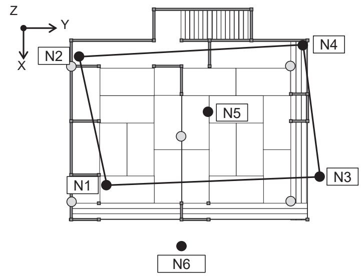

Fig. 15 *Vibration modes (3.26 Hz and 3.88 Hz)*

4 Finite element analysis

Fig. 16 shows an overview of the model. The columns and beams are "beam elements", and the walls are "braced elements". All joints are pin joints because rotational rigidity is not expected. The cross-sectional dimensions of each member were measured in the structural survey, and the column cross-sectional dimensions were approximately 105 mm square. The columns are made of cedar with a bending Young's modulus of 7 kN/mm2 and a density of 380 kg/m3, and the beams are made of cypress with a bending Young's modulus of 9 kN/mm2 and a density of 380 kg/m3 [8,9]. The stiffness of the earthen wall is based on the specific deformation angle of 1/250 rad by the Agency for Cultural Affairs [10]. The in-plane shear stiffness of the wall in the micro-deformation region observed by microtremor measurement is approximately three times the specified deformation angle [6], which is determined by the in-plane shear test. Since the purpose of the present finite element analysis is to determine the natural frequency in the small deformation region, the in-plane shear stiffness of the wall is set to be three times the stiffness at the specified deformation angle of 1/250 rad. The weight of the roof is 1250 N/m2 for a pier-tile roof and 100 N/m2 for a pole-vaulted ceiling [8].

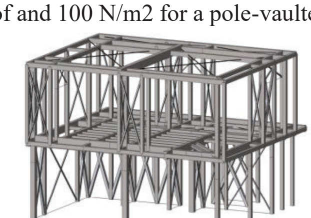

Fig. 16 *Model overview*

4.1 Analysis results

Figs. 17, 19, and 23 show the natural frequencies and vibration modes of the finite element analysis model, and Figs. 18, 20, and 24 show the natural frequencies and vibration modes of the microtremor measurement results corresponding to the analysis model. Figs. 18, 20, and 24 show the natural frequencies of the finite element analysis

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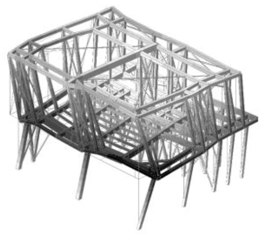
results and the microtremor measurement results in parentheses.



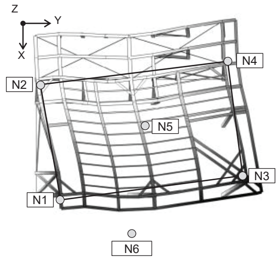


Fig. 17 *Eigen vibration mode (3.64 Hz)*

Fig. 18 *Natural modes of vibration (3.64Hz/3.26Hz)*

From the vibration mode of 3.64 Hz in the finite element analysis shown in Fig. 17, it can be confirmed that this is the second mode of architecture because only the floor of the second floor deforms horizontally. From the natural vibration mode shown in Fig. 18, it can be seen that the 3.64 Hz vibration mode of the finite element analysis and the 3.26 Hz vibration mode of the microtremor measurement coincide. This indicates that the dominant natural frequency of 3.26 Hz observed by human power excitation and microtremor measurement is the natural frequency of the second mode of the architecture, and confirms that the analytical model is correctly modeled.

The first modes of the eigenvalue analysis of the same model are shown below.

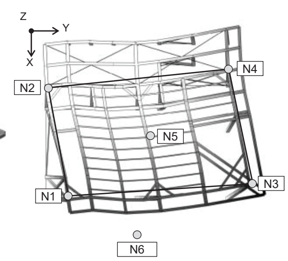


Fig. 19 *Eigenmode (0.91Hz)*

Fig. 20 Eigenmode (0.91Hz/1.05Hz)

From the vibration mode of 0.91 Hz in the finite element analysis shown in Fig. 19, it can be confirmed that 0.91 Hz is the natural frequency indicating the first mode of the architecture because the horizontal deformation of the entire second floor is large. Since the second floor has more walls than the first floor, the deformation of the first floor is dominant in the overall behavior, while the second floor behaves like a rigid body with little deformation. From the natural vibration modes shown in Fig. 20, it can be confirmed that the amplitude of N2 and N4 is small, while that of N1 and N3 is large. This is because the walls of the corridor restrain the vibration of N2 and N4, but there are no walls to restrain the vibration of N1 and N3 facing the edge.

Fig. 21 and 22 show the frequency-transfer function relationship in the X- and Y-axis directions. The natural frequency of the first mode of 0.91 Hz revealed by the eigenvalue analysis corresponds to the measured value of 0.98 Hz in the Y-axis direction, and there is no dominant value close to 0.91 Hz in the X-axis direction. In the finite element analysis, the horizontal displacement in the Y-axis direction is dominant, which confirms the validity of the observed waveforms in the X- and Y-axis directions.

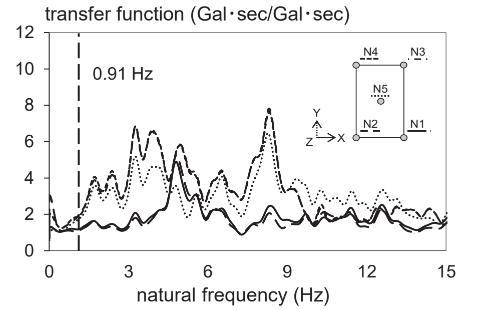


Fig. 21 *Relationship between frequency and transfer function in X-axis direction*

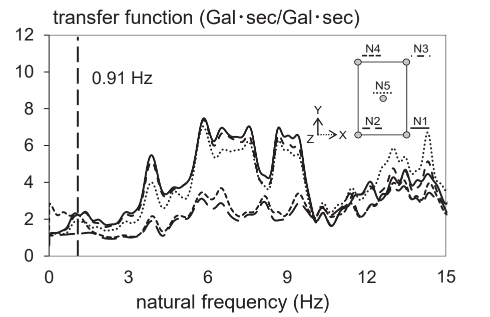


Fig. 22 *Y-axis frequency-transfer function relationship*

Among the results of the microtremor measurement where multiple excitations were observed, the excitation of the natural frequency of the first mode in the Y-axis direction was about 36% larger than that of the other frequencies, which would normally be ignored. In addition, despite the first mode, only N1 and N3 are dominant in the graph due to the difference in the amount of deformation of N1 and N3 and N2 and N4 caused by the uneven distribution of the wall, while N2 and N4 are not dominant. It is difficult to conclude that 0.98Hz is the natural frequency of the first mode under normal circumstances.

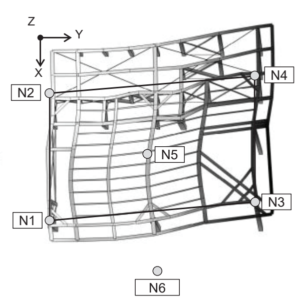


Fig. 23 *Eigenmode (1.68Hz)*

Fig. 24 *Eigenmode (1.68Hz/1.72Hz)*

Fig. 23 shows that the entire second floor deforms horizontally in the X-axis direction in the vibration mode of 1.68 Hz based on finite element analysis, indicating that 1.68 Hz is the natural frequency of the first mode of the architecture. The amplitudes of N1 and N2 are small, and those of N3 and N4 are large, according to the vibration modes in Fig. 24. This is because the vibration of N1 and

N2 is constrained by the wall dividing the room, but there is no wall to constrain the vibration of N3 and N4 facing the courtyard. Figs. 25 and 26 show the frequency-transfer function relationship in the x- and y-axis directions. The natural frequency of the first mode, 1.68 Hz, which was revealed by the eigenvalue analysis, corresponds to 1.72 Hz in the X-axis direction, and there is no dominant value close to 1.68 Hz in the Y-axis direction.

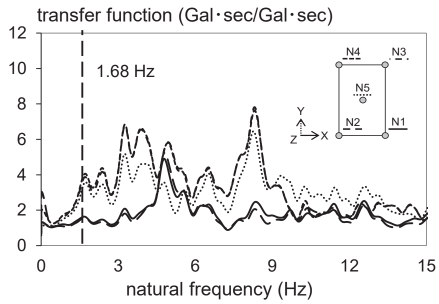
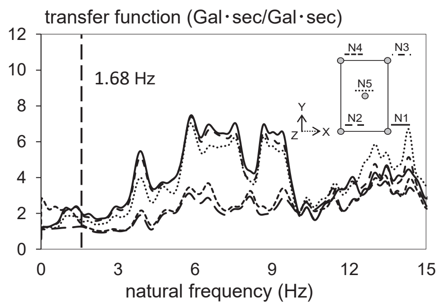


Fig. 25 *X-axis frequency-transfer function relationship*



Since the horizontal displacement in the X-axis direction is dominant from the vibration modes of the finite element analysis, the validity of the observed waveforms in the X- and Y-axis directions can be confirmed. Among the results of the microtremor measurement where multiple excitations were observed, multiple excitations were observed near the natural frequency of the first mode in the X-axis direction, and it is difficult to determine the natural frequency only from the results of the microtremor measurement. In addition, only N3 and N4 show the predominance in the graph due to the difference in the amount of deformation of N1 and N2 and N3 and N4 caused by the uneven distribution of the wall, while N1 and N2 do not show any predominance. It is difficult to determine that 1.68 Hz is the natural frequency of the first mode under normal circumstances.

5 CONCLUSIONS

In Japan, the Law for the Protection of Cultural Properties was enacted to preserve the cultural value of historical architecture, and seismic diagnosis for national treasures and important cultural properties has been developed. However, there is no progress in the development of seismic diagnosis methods for registered tangible cultural properties, which are newly subject to preservation under the revised Law for the Protection of Cultural Properties. In this study, the following findings were obtained by conducting a structural survey of historical timber architecture with specifications similar to those of registered tangible cultural properties:

1. By analyzing the data on registered tangible cultural properties published by the Agency for Cultural Affairs, we found that the number of architectures of registered tangible cultural properties is large, and that two-story architecture accounts for half of the total.
2. By conducting microtremor measurement on the existing architecture, we observed multiple excitations of the architectures.
3. The dominant natural frequencies of the second modes were determined by analyzing the resonant frequencies of human power excitation on the first floor of the building.
4. The model was modeled by finite element analysis, and the correctness of the model was confirmed by using the natural frequencies of the second modes observed by microtremor measurement.
5. The natural frequencies of the first modes were determined using the analytical model whose correctness was confirmed, and by comparing them with the measurement results of the microtremor measurement, a slight predominance was confirmed, and the vibration mode was confirmed to be the first mode.

To understand the natural frequency characteristics of existing architecture, it was necessary to consider the results of three methods: microtremor measurement, human power excitation, and finite element analysis.
In this study, we have dealt with only one case of a structural survey, but there are various measurement environments for microtremor measurement, and it is necessary to develop seismic diagnosis methods that can cope with various measurement environments in the future.

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