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EVALUATION OF EQUIVALENT SHEAR STIFFNESS AT EACH RENOVATION STAGE IN THE TRADITIONAL WOODEN BUILDING

Hina TAKIZAWA[1], Yuya TAKAIWA[2]

ABSTRACT: In this study, we investigated the vibration characteristics of traditional wooden buildings in the renovation stage. We conducted constant microtremor measurements of the building three times: (1)before the roof frame was constructed, (2)after the roof frame was constructed, and (3)after the roof was tiled, and compared the natural frequencies and natural vibration modes. Furthermore, by calculating the equivalent shear stiffness of the target building and comparing the results of each measurement, we confirmed the influence of the building's equivalent stiffness on the vertical load of the roof weight. A parametric study was conducted using the rotational stiffness of the joints that make up the vertical structure as a parameter. As a result, the equivalent stiffness of the vertical structure after constructing the roof frame was 499~556 kN/rad/m, and after roofing with tiles it was 1090~1111 kN/rad/m. It was also revealed that the equivalent stiffness of the vertical structural surface changed by 2.08 times before and after tile roofing.

KEYWORDS: timber, microtremor measurement, equivalent stiffness, vertical load, vertical plane

1 – INTRODUCTION

Japan has four seasons and has large eaves and steeply pitched roofs to protect against strong sunlight and rain, so the roof area is large. They are often constructed of relatively heavy materials such as roof tiles. As a result, the weight of the roof tends to increase. It is thought that the vertical load due to roof weight is related to the structural performance of traditional wooden buildings. For example, traditional wooden buildings have a mechanism that resists them through frictional force, so it has been confirmed that the frictional force changes with vertical loads, which affects the structural performance of Dougong.[1][2][3] In addition, vertical loads may affect the structural performance of buildings by affecting the shear rigidity of load-bearing walls, which are the main load-bearing elements of buildings. [4][5] In verifying the stiffness of vertical structural surfaces, research has been conducted to clarify the influence of vertical loads on the in-plane shear stiffness by conducting in-plane shear tests on load-bearing walls under vertical loads. However, the effect of changes in vertical load on the rigidity of vertical structural surfaces when building a frame is not clear.

Therefore, in this study, we investigated the effect of roof weight on the equivalent shear stiffness of a building. We conducted a vibration property investigation during the roof renovation stage of traditional wooden buildings, which are said to have large eaves due to climatic and topographical reasons. Each renovation stage is shown below. (1)Condition before the roof frame is constructed, (2)The state before the roof is covered with roof tiles and covered with tiles and (3roof covered with tiles, A total of three measurements of the building's microtremors were carried out. From these results, we determined the natural frequency and natural vibration mode, compared them, and calculated the equivalent shear stiffness of the building. By comparing the results of each measurement, we confirmed the effect of changes in roof weight on the equivalent shear stiffness of the building. Using finite element analysis, we replaced the change in the equivalent stiffness of the vertical structure with the change in the rotational stiffness of the joint, and conducted a parametric study with the rotational stiffness of the joint as a parameter. As a result, the influence of roof weight on the equivalent shear stiffness of the building was evaluated as a change in the equivalent stiffness of the vertical structural surface.

[1] Hina Takizawa, Doctoral Student, Course of Architecture and Urban Design, Graduate School of Science and Engineering, Toyo University, Saitama, Japan, Takizawa.toyo@gmail.com

[2] Yuya Takaiwa, Associate Professor, Department of Architecture, Faculty of Science and Engineering, Toyo University, Dr. Eng., Saitama, Japan, takaiwa@toyo.jp

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2– TARGET BUILDING OVERVIEW

2.1 TARGET BUILDING OVERVIEW

The target buildings of this research are traditional wooden buildings that currently exist in Aichi Prefecture, Japan. This was completely destroyed by the Hoei earthquake that occurred in 1707, and was rebuilt in 1793. It was completely destroyed again by the Mikawa Earthquake that occurred in January 1945, and was rebuilt in 1948, with the roof repaired in 2022, and continues to this day. Figure 1 shows the floor plan, and Table 1 shows the architectural outline. The building size is 13.9m in the beam direction, 13.9m in the beam direction, and 4.5m in height. The walls are clay-lacquered and the roof is tiled.

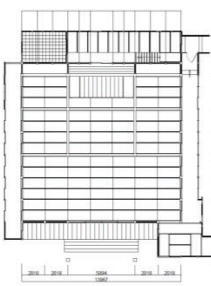

Figure 1: Plan view

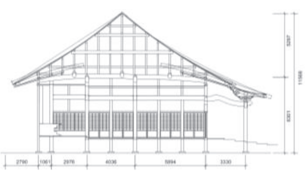

Figure 2: Cross section

Table 1: Architectural overview

Building	Ridge height	13.9m
	Eave height	4.5m
Specification	Roof	Tiled roof
	Ceiling	None during renovation
	Wall	Earthen wall
	Floor	Wooden board

2.2 CONDITION OF THE TARGET BUILDING AT THE TIME OF EACH MEASUREMENT

In this study, we constantly measured microtremors at each construction stage during renovation. The situation of the building at the time of each measurement is shown below. At the time of the first measurement, the parts below the girders (columns, walls, etc.) remained in their existing state, and the newly built dome, beams, and girders were constructed on top of them (hereinafter referred to as ``Phase 1"). At the time of the second measurement, the roof structure was in place from the first survey and the roof boards were up (hereinafter referred to as "Phase 2").During the third measurement, the roof was covered with tiles (hereinafter referred to as "Phase 3"). Photos 1 to 3 show the status of each renovation stage. Photo 4 shows what it looks like after the renovation.

In Phase 1, the roof frame was removed for roof renovation. As the phase progresses, the roof will be constructed.

Photo 1: Phase1

Photo 2: Phase2

Photo 3: Phase3

Photo 4: After renovation

At the time of renovation, the walls had their fittings removed and plywood was pasted to the front of the building. At the time of renovation, the walls had their fittings removed and plywood was pasted to the front of the building. At the rear of the building, the existing clay wall remained. The floor was made of wood, and the ceiling had only a lattice. Photos 5 to 6 show the walls after renovation, Photo 7 shows the ceiling after renovation, and Photo 8shows the ceiling and floor after renovation.

Photo 5: Phase1

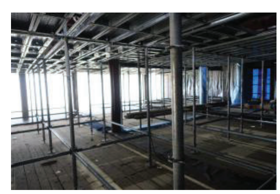

Photo 6: Phase2

Photo 7: Phase3

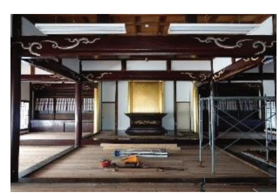

Photo 8: After renovation

3– MICROTREMOR MEASUREMENT

3.1 OVERVIEW OF MICROTREMOR MEASUREMENT

We conducted constant microtremor measurements to understand the building's natural frequency and vibration mode. Continuous microtremor measurement is a method to measure the behavior of buildings in response to minute vibrations using highly sensitive acceleration sensors, and to clarify the vibration characteristics (natural frequencies and vibration modes) of buildings.

Photo 9: Measuring equipment

Photo 10: Accelerometer

3.2 MEASUREMENT METHOD AND MEASUREMENT LOCATION

In this study, measurements were performed using a total of five 3-axis wireless acceleration sensors. One sensor was installed on the ground to measure the input data of the transfer function, and the remaining four sensors were installed on the building. By performing FFT analysis on the acceleration waveform obtained through measurement, it is possible to obtain the dominant natural frequency of the building using the transfer function. Since the natural frequency of traditional wooden buildings is approximately 1 to 2.5 Hz, the sampling frequency for measurement was set to 100 Hz so that the analysis frequency was 50 Hz. The measurement time was set to 32,768 points to maximize the frame size for FFT analysis. In order to clarify the dominant natural frequency, smoothing was performed using a Parzen window with a bandwidth of 0.1 Hz, and the dominant natural frequency was obtained. Make a vibration measurement plan as shown in Figure 3. In order to perform measurements to understand the vibration properties of the entire building, we installed four sensors at the four corners of the building and one sensor on the ground.

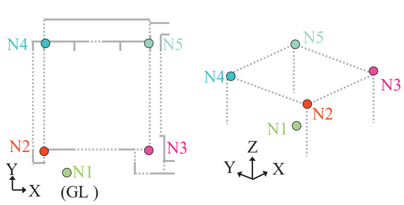

Figure3: Measurement points

3.3 MEASUREMENT RESULT

Table 2 shows the transfer functions and natural vibration modes from Phase 1 to Phase 3. When checking the transfer function of Phase 1, remarkable dominant natural frequencies were confirmed at 1.50~1.53Hz, 2.64~2.67Hz, and 3.61Hz. When checking the natural vibration modes, it was confirmed that 1.50~1.53Hz and 3.61Hz are shear deformation modes, and 2.64~2.67Hz shows behavior with the same sign in the X direction at all measurement points N2~N5. It was confirmed that the mode was vibrating in the X direction.

When checking the transfer function of Phase 2, remarkable dominant natural frequencies were confirmed at 1.80Hz, 2.75Hz, 3.72Hz, and 4.31Hz. When the natural vibration mode was confirmed, at 1.80Hz, all measurement points N2 to N5 showed behavior with the same sign in the X direction, so it was confirmed that the mode was vibrating in the X direction. At 2.75Hz, all measurement points N2 to N5 exhibit behavior with the same sign in the Y direction, which confirms that the mode is vibrating in the Y direction. Furthermore, when the natural vibration mode was confirmed at 3.72Hz, a torsional mode was confirmed, and when the natural vibration mode was confirmed at 4.31Hz, a shear mode was confirmed.

When checking the transfer function of Phase 3, remarkable dominant natural frequencies were confirmed at 1.73Hz, 2.24Hz, 3.36Hz, and 4.80Hz. When checking the natural vibration mode, at 1.73Hz and 2.24Hz, it shows behavior in the X direction at all measurement points N2 to N5. On the other hand, it was confirmed that the behavior was different between measurement points N2, N5 and N3, N4, and behavior similar to torsion and shear mode was confirmed at 3.36Hz and 4.80Hz. However, it was confirmed that the behavior was different between measurement points N2, N5 and N3, N4.

3.4 COMPARISON OF EACH MEASUREMENT RESULT

Table 3 shows a comparison of vibration properties at each construction stage. We will compare the vibration properties at each construction stage of the target building. Comparing Pase1 and Pase2 states, the change in natural frequency was 1.19 times. In Phase 1, the measurement points did not show similar behavior, but in Phase 2, all measurement points began to show similar behavior. It is presumed that this is because the building was integrated with the roof frame and roof.

Comparing Phase 2 and Phase 3, the change in natural frequency was 0.83 to 0.95 times in translational mode. The natural frequency has decreased because the weight of the building has increased due to the roof being covered with tiles. The building weight was estimated to be approximately 579kN in Phase 2 and 854kN in Phase 3 using the finite element analysis model described below. The results revealed that the equivalent stiffness increased by 1.36 times.

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Here, it became clear that the equivalent stiffness of the building increased as the building weight increased. This is thought to be because the weight of the building increases the vertical load, which in turn increases the frictional force acting on the joints, the stiffness of the vertical structural surfaces, and the tilt restoring force of the column, thereby increasing the equivalent shear stiffness of the building.

Table3: Comparison of vibration properties

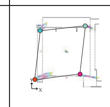
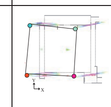
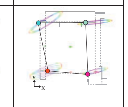
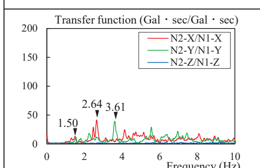
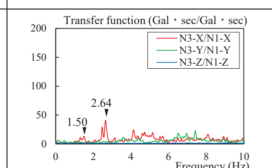
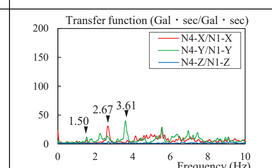
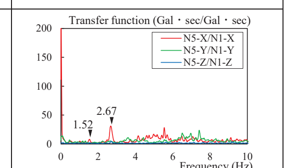
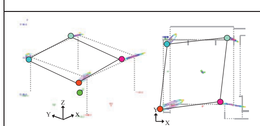
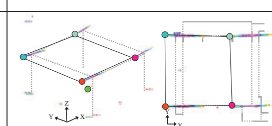
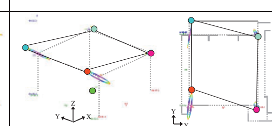
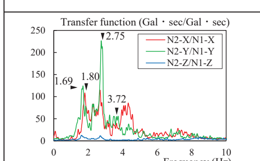
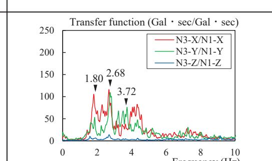
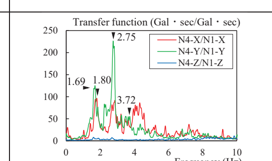
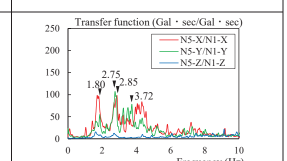
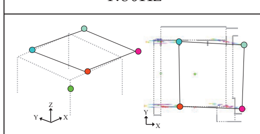
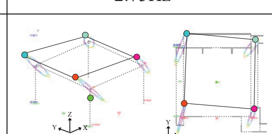
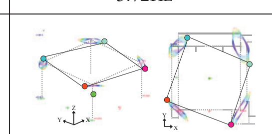
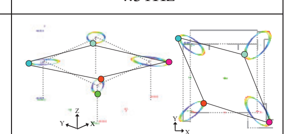
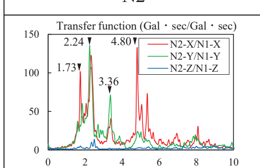
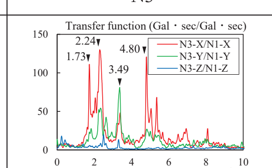
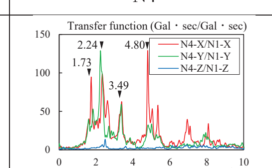
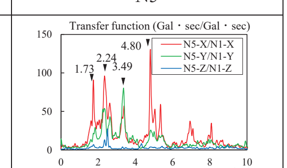
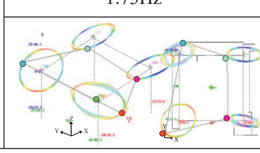
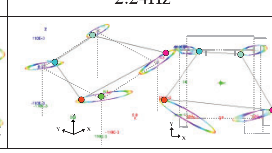
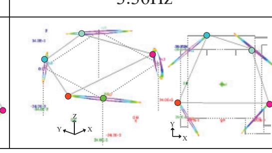
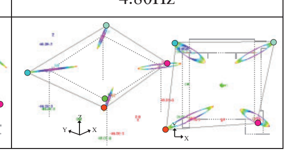
natural frequency (Hz)	1.51	1.80	1.73
natural vibration mode			
equivalent stiffness (kN/m)	3564	7557	10296
Rate of change (kN/m/kN/m)	2.12		1.36

Table 2: Transfer function and natural vibration mode

Phase1		N2	N3	N4	N5
	Transfer function				
		1.50~1.53Hz	2.64~2.67Hz	3.61Hz	
	natural vibration mode				
Phase2		N2	N3	N4	N5
	Transfer function				
		1.80Hz	2.75Hz	3.72Hz	4.31Hz
	natural vibration mode				
Phase3		N2	N3	N4	N5
	Transfer function				
		1.73Hz	2.24Hz	3.36Hz	4.80Hz
	natural vibration mode				

4– FINITE ELEMENT ANALYSIS

4.1 FINITE ELEMENT ANALYSIS OVERVIEW

In this study, we performed eigenvalue analysis using finite element analysis. Figure 3 show the specifications of the analytical model, respectively. The framework members were modeled as beam elements, and the clay walls were modeled as plate elements. The wood species and Young's modulus of each member are Hinoki (E=9000N/mm^2)[7], for columns, and Matsu (E=10000N/mm^2)[7] for beams, girders, foundations, and roof frame components. The wall thickness of the clay-coated wall was 100 mm to 150 mm, and the shear stiffness was calculated from the literature[8] . During renovation, the temporary wall had a shear stiffness of 0.2 times the wall magnification. The joints were pin connections, and the tilting restoring force was taken into account for the facing pillars and the 200mm diameter round pillars inside the building [9]. The load was applied to the entire roof surface by the weight of the roof tiles, 483N/m^2 [10], and the weight of the roof tiles.

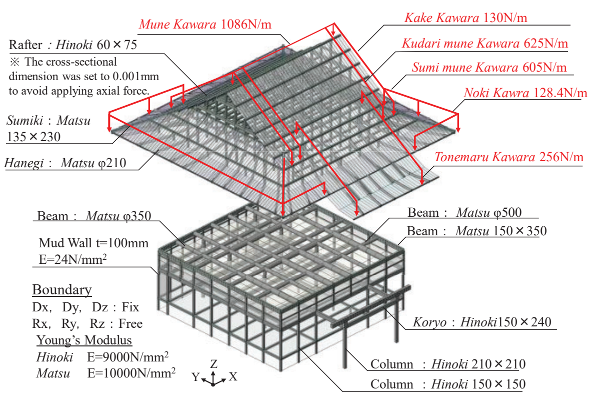
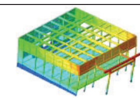
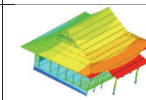
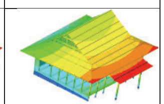


Figure 3: Analysis model specifications

Table 4 shows a comparison of the eigenvalue analysis results and the results of continuous microtremor measurements. From the eigenvalue analysis results, the building weight in Phase 1 was 388kN, the natural frequency was 0.77Hz, and the equivalent stiffness was 929kN/m. In Phase 2, the building weight was 576kN, the natural frequency was 0.61Hz, and the equivalent stiffness was 868kN/m. In Phase 3, the building weight was 854kN, the natural frequency was 0.49Hz, and the equivalent stiffness was 826kN/m. Comparing with the actual measured values, the analytical value at the natural frequency in Phase 1 was approximately 51% of the actual measured value, confirming the validity of the analytical model. In Phase 2 and Phase 3, the analytical value was approximately 28 to 34% of the actual measured value for the natural frequency, and it was confirmed that the difference between the analytical value and the actual measured value became larger as the renovation stage progressed. This is thought to be because in an actual building, the rigidity of the building changes as the weight of the building increases.

Table 4: Comparison of eigenvalue analysis results and continuous microtremor measurement results

	Phase1	Phase2	Phase3
			
M (kN)	388	579	854
Fa(Hz)	0.77	0.61	0.49
Fm(Hz)	1.51	1.80	1.73
Ka(kN/m)	929	868	826
Km(kN/m)	3564	7557	10296
Ta(Hz/Hz)	0.94		0.95
Tm(Hz/Hz)	2.12		1.36

M: Building weight (kN)

Fa: Natural frequency obtained from eigenvalue analysis

Fm:Natural frequency obtained from continuous microtremor measurement

Ka: Equivalent stiffness obtained from eigenvalue analysis

Km:Equivalent stiffness obtained from continuous microtremor measurements

Ta:Rate of change in equivalent stiffness obtained from eigenvalue analysis during the renovation stage

Tm:Rate of change in equivalent stiffness obtained from continuous microtremor measurements during the renovation stage

4.2 RATIO OF BENDING DEFORMATION AND SHEAR DEFORMATION OF THE TARGET BUILDING

Since the target building has load-bearing walls only attached to the rear of the building, it is assumed that shear and bending deformations occur simultaneously in response to horizontal loads. Therefore, we calculate the ratio of horizontal displacement due to bending deformation and horizontal displacement due to shear deformation to the horizontal displacement of the target building. The calculation method is shown below. Replace the deformation of the column with bending deformation and shear

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deformation. Calculate the bending deformation component of the total interstory displacement. From the axial strain (Δv_{ij}) of the column and the axial force (N_{ij}) of the column, find the equivalent overall bending rotation angle (θ_{ei}) that makes the strain energy equal, and calculate the horizontal displacement due to bending deformation.柱 Figure 4 shows a conceptual diagram of the calculation, and Eq. (1) to Eq. (3) show the calculation formulas.As a result, the horizontal displacement due to bending deformation is 0.3~6.9% of the horizontal displacement of the target building, and the horizontal displacement due to shear deformation is 93.1~99.7%.It was confirmed that the target building had a high rate of shear deformation.

$$\Sigma_i(N_{ij} \cdot \Delta v_{ij}) = \Sigma_i(N_{ij} \cdot \Delta \theta_{ei} \cdot l_{ij}) \quad (1)$$

$$\delta_m = \Delta \theta_{ei} \cdot h_{ij} \quad (2)$$

$$\delta_s = \delta_t - \delta_m \quad (3)$$

N_{ij}: Column axial force

Δv_{ij}: Column axial strain

θ_{ei}: Equivalent overall bending rotation angle such that strain energy is equal

l_{ij}: Distance from center of rotation

h_{ij}: Column length

δ_m: Horizontal displacement due to bending deformation

δ_s: Horizontal displacement due to shear deformation

δ_t: Horizontal displacement

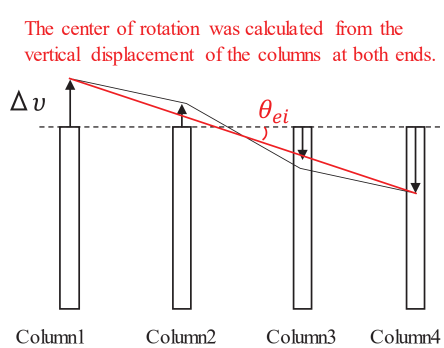

Figure 4 How to calculate horizontal displacement

4.3 EVALUATION OF THE EFFECT OF EQUIVALENT STIFFNESS DUE TO TILED ROOFING

In the previous chapter, as the renovation stage progressed, the building weight increased, which caused the natural frequency to increaseIt was revealed that the increase was 2.12 times from Phase 1 to Phase 2, and 1.36 times from Phase 2 to Phase 3. This is thought to be because the rigidity of the vertical structure increased due to the weight of the building. However, since the target building has an earth-coated wall only on the rear side, increasing the shear stiffness of the load-bearing wall will hardly contribute to the equivalent shear stiffness of the building. Therefore, in this study, we replaced the equivalent stiffness of the vertical structural surface with the rotational stiffness of the joint. A parametric study was conducted using the rotational stiffness of each joint of the members (columns, girders, beams, foundations, and throughs) that make up the vertical structure as a parameter. Specifically, from Phase 1 to Phase 2 and from Phase 2 to Phase 3, the rotational stiffness of the joint is determined when the rate of change of the natural frequency becomes the same value as the actual measurement value. Here, the parameters are numerical values rather than relative values of rotational stiffness. The reason for this is explained below. When setting the relative value of the rotational stiffness of a beam element, it is not possible to set the same value of rotational stiffness at each joint because the rotational stiffness changes depending on the length, Young's modulus, and cross-sectional area of the beam element. Therefore, we decided to set a numerical value.Figure 5 shows the results of a parametric study of the rotational stiffness of the joints that make up the vertical structural surface. In Phase 2, it was confirmed that when the rotational stiffness of the joints of the members constituting the vertical structural surface is 500 to 600 kNm/rad, the rate of change of the natural frequency from Phase 1 to Phase 2 matches the analytical value and the experimental value. In Phase 3, it was confirmed that when the rotational stiffness of the joints of the members constituting the vertical structural surface is 4000 to 4500 kNm/rad, the analytical value and experimental value for the rate of change of the natural frequency from Phase 2 to Phase 3 match.

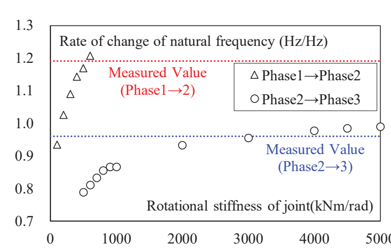

Figure 5: Relationship between rotational stiffness of joint and rate of change of natural frequency

The shear rigidity of the vertical structural surface is determined from the rotational rigidity of the joints of the members that make up the vertical structural surface, where the rate of change of the natural frequency matches the analytical value and the experimental value. Therefore, we created models of the vertical structural surfaces of the columns, beams, and foundations. The shear stiffness of the vertical structural surface was confirmed using the rotational stiffness of the joints obtained from the parametric study for the column-beam and column-foundation joints. Figure 6 shows the specifications of the analytical model. As a result, the shear stiffness was confirmed to be 499 to 556 kN/rad/m in Phase 2 and 1090 to 1111 kN/rad/m in Phase 3. The wall magnification was 2.2 times for Phase 2 and 4.7 times for Phase 3When the change in the equivalent stiffness of the building when changing from Phase 2 to Phase 3 was replaced with the change in shear stiffness of the vertical structural surface, it was revealed that the change was 2.08 times.

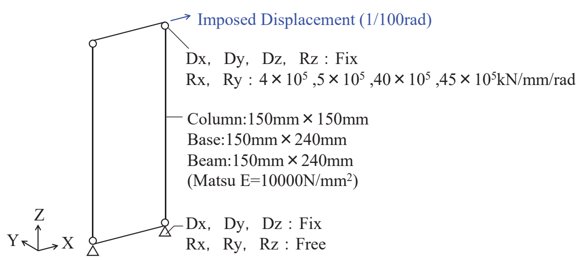

Figure6: Vertical structural surface analysis model specifications

5– CONCLUSION

We clarified the influence of equivalent shear stiffness of traditional wooden buildings through constant microtremor measurements and finite element analysis during the renovation stage.

(1) Due to the construction of the building's roof frame, the natural frequency changed by 1.19 times and the equivalent shear stiffness changed by 2.12 times.

(2) The weight of the roof increased due to roof tiles, and the natural frequency changed by 0.96 times and the equivalent shear stiffness changed by 1.36 times.

(3) It was found that building a roof frame or roofing with tiles increases the weight of the building, which causes the natural frequency to decrease, but the equivalent stiffness to increase.

(4) It was confirmed that of the horizontal displacement of the target building due to the horizontal load, the horizontal displacement due to bending deformation was 0.3~6.9%, and the horizontal displacement due to shear deformation was 93.1~99.7%.

(5) A parametric study was conducted using the rotational stiffness of the joints that make up the vertical structure as a parameter. As a result, the equivalent stiffness of the vertical structure after constructing the roof frame was 499~556 kN/rad/m, and after roofing with tiles it was 1090~1111 kN/rad/m. It was also revealed that the equivalent stiffness of the vertical structural surface changed by 2.08 times before and after tile roofing.

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