STIFFNESS EVALUATION OF TRADITIONAL WOODEN FRAME FROM INFINITESIMAL TO LARGE DEFORMATION RANGE

Y. Kimoto(1), J. Nezaki(2), R. Hatada(3), M. Sugino(4), Y. Hayashi(5)

(1) *Undergraduate Student, Kyoto University, rp-kimoto@archi.kyoto-u.ac.jp*
(2) *Undergraduate Student, Kyoto University, rp-nezaki@archi.kyoto-u.ac.jp*
(3) *Graduate Student, Kyoto University, rp-hatada@archi.kyoto-u.ac.jp*
(4) *Associate Professor, Kyoto University, rp-sugino@archi.kyoto-u.ac.jp*
(5) *Professor, Kyoto University, hayashi.yasuhiro.3m@kyoto-u.ac.jp*

Abstract

The authors aim to utilize the natural frequency of Japanese traditional wooden buildings obtained from ambient vibration tests in three ways: simple seismic diagnosis, rapid damage assessment, and validation of the analytic model of buildings.

First, the simple seismic diagnosis uses maximum response deformation angle to assumed earthquake motions which is estimated form the amplitude dependency of equivalent natural frequency that is calculated from the natural frequency of buildings. However, the amplitude dependency of equivalent natural frequency was not quantified especially in the minute deformation angle in the past studies.

Second, in the rapid damage assessment, the maximum deformation angle that the building experienced during an earthquake is estimated based on the decreasing rate of natural frequency caused by the earthquake. To realize this damage assessment method, it is necessary to quantify the relationship between the decreasing rate of the natural frequency and the experienced maximum deformation angle.

Third, the validation of the analytic model of buildings uses the ratio of the natural frequency of the analytic model to the natural frequency of the building obtained from ambient vibration tests. The adequate ratio between them should be evaluated.

To realize the utilization of natural frequency in these three ways, we conducted experiments on four kinds of structural components to quantify the three relationships: the amplitude dependency of equivalent natural frequency, the relationship between the decreasing rate of natural frequency and the experienced maximum deformation angle, and the ratio between the natural frequency of specimens and that of analytic model prescribed by a Japanese agency, Agency for Cultural Affairs. Each specimen has two plane frame structures arranged in parallel which are connected with orthogonal beams so that the specimen can be self-supporting. For each specimen, three kinds of experiments were conducted: ambient vibration tests, vibration tests, and static loading tests. The change of natural frequency according to the experienced maximum deformation angle was grasped by the ambient vibration tests. The amplitude dependency of equivalent natural frequency is measured by vibration tests and static loading tests. The former is for minute deformation range and the latter is for large deformation range which finally reaches the collapse of the specimen. Besides, we calculated the ratio of the natural frequency of the analytic model and that of the specimen.

Through these experiments, we gained quantitative data of four kinds of structural components that is useful for the utilization of natural frequency that contributes to making traditional wooden houses more resistant to earthquakes. To develop methods for the utilization of natural frequency, further similar study and analysis are required.

Keywords: stiffness evaluation; traditional Japanese wooden houses; natural frequency; ambient vibration test

1. Introduction

There are many traditional wooden buildings in Japan, and they are appreciated for their historical and cultural significance. To protect them from earthquakes in the future, it is important to find buildings that have not enough seismic resistance and reinforce them appropriately. However, there is no simple method for evaluating buildings' seismic capacity; to find buildings which need reinforcement, a time-efficient and cost-effective diagnosis method is required.

Aiming at such the undemanding seismic diagnosis method, we have conducted researches that focus on utilizing ambient vibration tests [1, 2, 3, 4]. Through measuring ambient vibration with highly-sensitive accelerometers, the fundamental natural frequency of buildings can be obtained easily. It is possible to estimate the seismic resistance of buildings because there is a correlation between the seismic resistance and the natural frequency.

However, the method using ambient vibration tests has room for improvement in terms of accuracy because the natural frequency doesn't perfectly be proportional to the seismic resistance. Some building components, such as plasterboards, degrade the accuracy because they make the natural frequency higher, but scarcely contribute to seismic resistance of buildings. This is because these components resist external forces as long as their deformation is little but scarcely resist after their deformation became large to some extent. Therefore, to improve the accuracy, we should grasp the relationship between deformation and stiffness of building components (also called amplitude dependency of natural frequency), but there were not enough quantitative data that meets this need.

This research aims to capture amplitude dependency of natural frequency from infinitesimal to large deformation range through experiments. Note that amplitude dependency of natural frequency is the relationship between deformation and equivalent natural frequency, not fundamental natural frequency. Equivalent natural frequency is proportional to secant stiffness but fundamental natural frequency is the natural frequency of buildings as a single mass system in a stable state.

There is another intention in this study. It is important to provide the owners of earthquake-experienced buildings with information that is useful to judge whether the building is possible to use or not rapidly. We have pointed out that ambient vibration tests can be also useful in this case [5]. It is known that the fundamental natural frequency decreases according to experienced deformation, so the experienced damages can be inferred through ambient vibration tests. The other end of this study is to collect data that is useful for it.

In addition, we examined a skeleton curve model prescribed by a Japanese agency, Agency for Cultural Affairs [6], through comparing the experimental results with it. We compared the initial stiffness of the skeleton curve model with the initial stiffness of the specimen based on the natural frequency. It is necessary to do this because we intend to develop a method for validation of the analytic model of buildings.

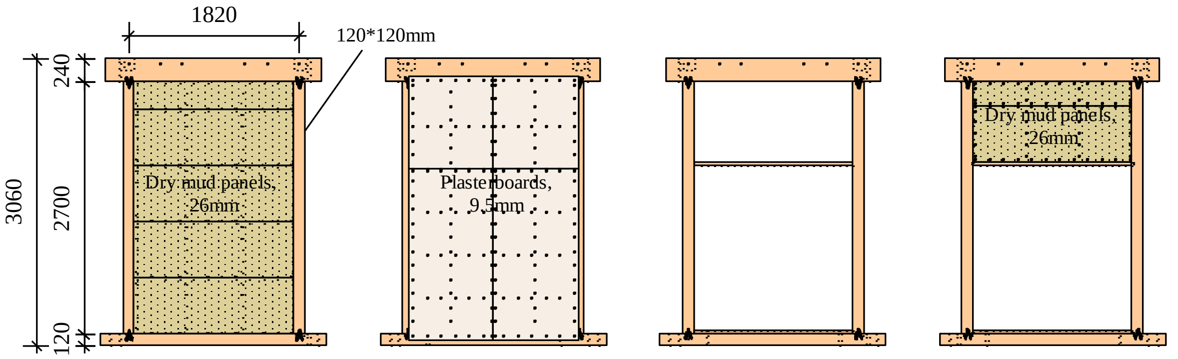
2. Methods

This chapter contains a description of specimens and the way of three kinds of experiments. The first experiment is ambient vibration tests, which enable us to capture how the natural frequency of the specimen changes according to its experienced maximum deformation. On the other hand, the second and third experiment is to investigate the relationship between the deformation of the specimen and its equivalent natural frequency. The second experiment is vibration tests, whose aim is to scrutinize the change of equivalent natural frequency within a minute deformation range. The third experiment is static loading tests, whose end is to explore the change of equivalent natural frequency within a large deformation range.

2.1 Specimens

There are four kinds of specimens, WDN, WPN, FNK and HDK, as shown in Fig. 1. Each specimen has its own two wooden plane frame structures. They are arranged in parallel and connected by two orthogonal beams and stainless steel braces. The span of the wooden plane frame is 1820 mm and the height of each column is 2700 mm. WDN has walls made of dry mud panels, whose thickness is 26 mm. WPN has walls made of plasterboard, whose thickness is 9.5 mm. FNK doesn't have walls but has lintel called *kamoi*. HDK has not only *kamoi* but also hanging walls made of the dry mud panels, and the height of the wall is 900 mm.

Columns of all specimens are made of Japanese cedar and are E90 in Japanese Agricultural Standard. The cross-section of each column is 120 x 120 mm. Every joint of the column and the beam or the foundation is a mortise joint (30 x 84 x 52.5 mm). Every joint is reinforced with metallic plates on both sides. A weight is loaded on the top of the specimen and the mass is determined so that the column will not be lifted when the static loading test is conducted.



(a) WDN (b) WPN (c) FNK (d) HDK

Fig. 1 – Specimens

In the subsequent analysis, each specimen is regarded as a single mass system. The mass of this system is the mass of the upper part of the specimen from the center of the column. Besides, the natural frequency of the specimen is obtained from ambient vibration tests. Table 1 shows the mass m and the initial natural frequency f_0 of each specimen.

Table 1 – The mass and the natural frequency of each specimen

Specimen	m (t)	f_0 (Hz)
WDN	2.52	5.66
WPN	2.48	7.05
FNK	2.43	1.25
HDK	2.50	2.08

2.2 Vibration tests

We conducted three kinds of vibration tests. The first one uses a shaker, the second one uses a large beetle, and the third is pushing by manpower. All of them aim to excite free vibration without causing damages. In addition, we vibrate the specimen many times so that the experienced deformation angle $R_{\max}$ will be large little by little.

In the shaker using tests, the specimen is vibrated with a shaker which is on the top of it. The shaker has 43 kg mass that vibrates a single horizontal direction. The total amplitude is 50 mm and the maximum acceleration is 8.1 m/s^2. The input acceleration wave is Ricker wavelet which is determined by two parameters, a dominant frequency f_p and maximum acceleration A_p. Each specimen was excited by two kinds of waves which have a different dominant frequency. The dominant frequency of the first one is slightly higher than the natural frequency f_0 of the specimen. The dominant frequency of the second one is 2/3 times as high as that of the first one. We input each wave many times and increased the amplitude every time. Table 2 shows the input acceleration parameter of each specimen.

Table 2 – The input acceleration parameter of each specimen

Kinds of specimens	Input wave No.1		Input wave No.2	
	f_p (Hz)	Specified max. acceleration.	f_p (Hz)	Specified max. acceleration.
WDN	6	100,200,300,400,500,600,700,800	4	100,200,300,400,500
WPN	7.5	100,200,300,400,500,600,700,800	5	100,200,300,400,500,600,700,800
FNK	1.5	50,100,150,200,250	1	50,100,150
HDK	2.25	50,100,200	1.5	50,100

In the large beetle using tests, the top of the specimen is hit by a beetle, whose mass is about 8 kg.

In the manpower pushing tests, one person or two people pushed the top of the specimen and excited free vibration.

The displacement of the top of the vibrating specimen was measured with accelerometers and displacement meters. In the subsequent analysis, we used the mean displacement of both frames. The wave obtained by accelerometers was transformed into displacement wave, through second-order integration on the frequency domain.

The amplitude and equivalent natural frequency f were calculated as follows. First, the extrema were extracted. Second, the nth extreme value x_n, the (n+1)th extreme value x_{n+1}, and the interval time of them T_n were gained. The amplitude and equivalent natural frequency were calculated from $(x_n + x_{n+1})/2$ and $1/(2\ T_n)$ respectively.

In this paper, the relationship between the displacement and the equivalent natural frequency f is called amplitude dependency of natural frequency. In the vibration test, many amplitude dependencies of natural frequency were obtained because the specimen vibrated many times. In the following analysis, only one of them was used. The adapted one satisfies the following conditions. First, at the least deformation angle, the equivalent natural frequency f is almost the same with the natural frequency f_0. Second, adapted one describes the relationship until the largest deformation among those which satisfies the first condition.

2.3 Static loading test

After the vibration tests, the static loading tests were conducted. In the static loading tests, the top of the specimen was pushed statically using a force application machine that is composed of oil jack and iron frames. First, the specimen was pushed in the positive and negative direction until the aimed deformation angle alternately 2 times. The aimed deformation angle was specified to be gradually large, namely: 1/300, 1/150, 1/120, 1/100, 1/75, 1/50, 1/30, 1/20, 1/15, 1/10, 1/8, 1/6, and 1/5 rad. After that, the specimen was pushed in a positive direction until the specimen loses its resistance force or the deformation reaches a feasible deformation limit.

Measurements in the static loading tests were conducted as follows. The displacement of both frames was measured with displacement meters. The resistance force of both frames was measured using load cells which were set between the specimen and the force application machine. In the subsequent analysis, the means of the frames were used.

The equivalent natural frequency f was calculated from the load and deformation relationship. First, the skeleton curve was acquired from the relationship. Second, the secant stiffness of each point on the skeleton curve was calculated and then transformed into equivalent natural frequency f.

2.4 Ambient vibration tests

In order to research how the fundamental natural frequency of the specimen changes according to its experienced deformation angle, the ambient vibration tests were conducted. We measured both at the foundation and at the top of the specimen with the accelerometers. The measured waves transformed into Fourier spectra and the ratio of Fourier spectrum of the top to that of the foundation was calculated. At the natural frequency, the Fourier spectrum ratio takes its maximum value.

The ambient vibration tests were conducted when specimen had experienced maximum deformation in the vibration tests and when specimen experienced aimed deformation angle in the static loading tests. In this way, we researched the relationship between fundamental natural frequency f_m and experienced maximum deformation angle $R_{\max}$.

3. Results of experiments

3.1 States of damages

The specimen had no remarkable damage in the vibration tests. On the other hand, they were heavily damaged in the static loading tests. Fig. 2 shows each specimen under the largest deformation.

(a) WDN (b) WPN (c) FNK (d) HDK

Fig. 2 – Specimen at the largest deformation

As for WDN, shear cracks ran through the dry mud panels in the loading test to 1/50 rad. And the panel started to collapse under the loading test to 1/15 rad.

In the case of WPN, nails which supported the edge of plasterboards became null under the loading test to 1/30 rad. The boards began to fall in the loading test to 1/5 rad.

For FNK, damages were discovered at the joints of the columns and foundations under the loading test to 1/10 rad.

As for HDK, the dry mud panel cracked in the loading test to 1/30 rad. Then, the panels deformed to the out-of-plane direction under the loading test to 1/10 rad. Some panels began to collapse in the loading test to 1/8 rad. In the loading test to 1/6rad, most of the dry mud panel of the one side of the frames fall.

3.2 Comparison between specimens

In this section, a comparison of the experimental outcomes between specimens is illustrated. The objects of comparison are skeleton curves, amplitude dependency of natural frequency, the relationship between natural frequency and experienced maximum deformation angle.

Fig. 3 shows the comparison of skeleton curves. WDN has the largest maximum strength, and the FNK is the smallest of them. WDN and WPN rapidly lose their resistance force after they reach their peak.

Fig. 4 shows the comparison of amplitude dependency of natural frequency. The character f/f_0 means the quotient that is acquired from dividing equivalent natural frequency f by the initial natural frequency f_0. Where the small deformation range is obtained from the outcome of vibration tests, and where the large deformation range is obtained from the outcome of static loading tests.

This figure indicates that the specimens might be classified into those which resist lateral force by mainly its walls, and those which resist lateral force by mainly its frames. WDN and WPN are the former, FNK and HDK are the later. The natural frequency of the former doesn't decrease so much in the minute deformation domain, but when the deformation angle becomes larger than a certain point, it decreases rapidly. The form of the figure can be represented with two lines. On the other hand, the natural frequency of the later decreases from a relatively small deformation angle. However, it doesn't decrease so rapidly as the former. The form of the figure is S-curve.

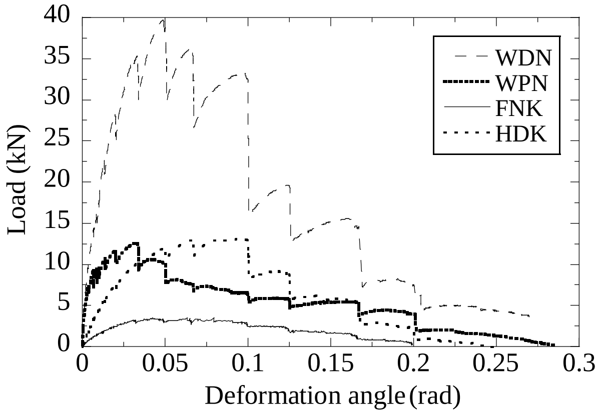


Fig. 3 – Comparison of skeleton curves

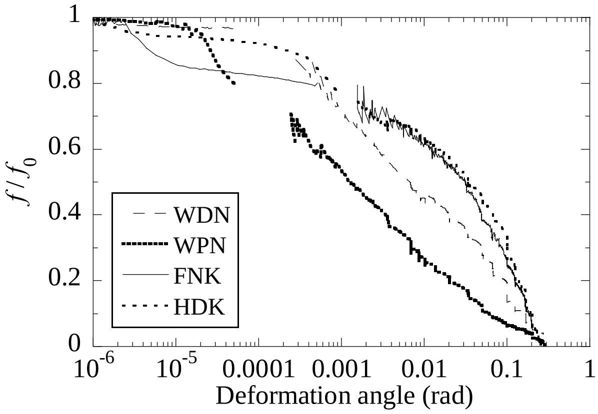


Fig.4 – Comparison of amplitude dependency of natural frequency

Fig. 5 shows the relationship between experienced deformation angle $R_{\max}$ and natural frequency. As the figure shows, in terms of decreasing rate of the natural frequency, WPN is the highest, after HDK and WDN. On the other hand, the natural frequency of FNK hardly decreases. The difference between FNK and the others is having walls or not. Therefore, the breakage of walls might be the cause of the decrease in the natural frequency.

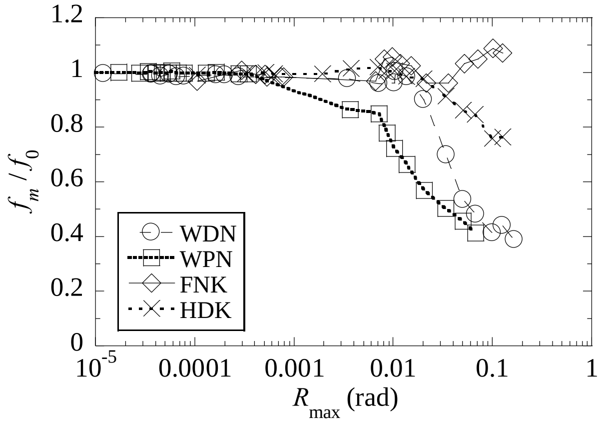


Fig. 5 – Comparison of the relationship between R_{max} and natural frequency

4. Examination of existing skeleton curve model

In this chapter, we compare the outcome of the experiment with the skeleton curve model which is prescribed by a Japanese agency, Agency for Cultural Affairs, in a document titled “Implementation Guidance for Basic Seismic Assessment of Important Cultural Properties (Buildings) [6].” The document designates two kinds of skeleton curves. The first one is for full-length earthen walls and the second one is for pillars with (earthen) hanging walls. We compared the former with WDN and the later with HDK.

The Agency for Cultural Affairs formulates the skeleton curve model of full-length earthen walls as shown in Fig.6. It is a line graph that consists of four segments and determined by three parameters—story height, wall thickness, and wall length. The comparison with WDN is shown in Fig.7. We determined parameters so that the maximum resistance force will be the same; specifically, the story height is 2.7 m, the wall length is 1.8 m, and the wall thickness is 0.276 m, which is much thicker than actual thickness, 0.026 m.

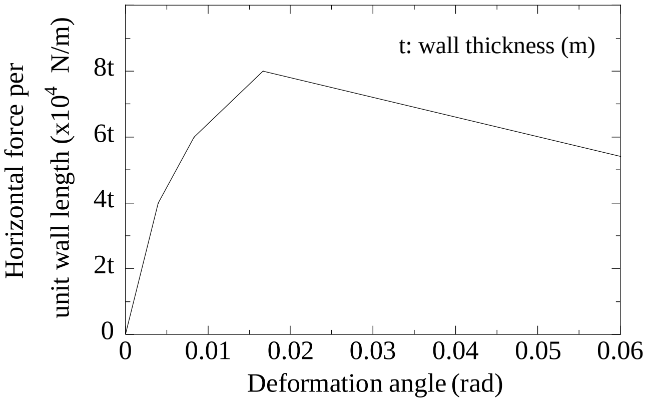
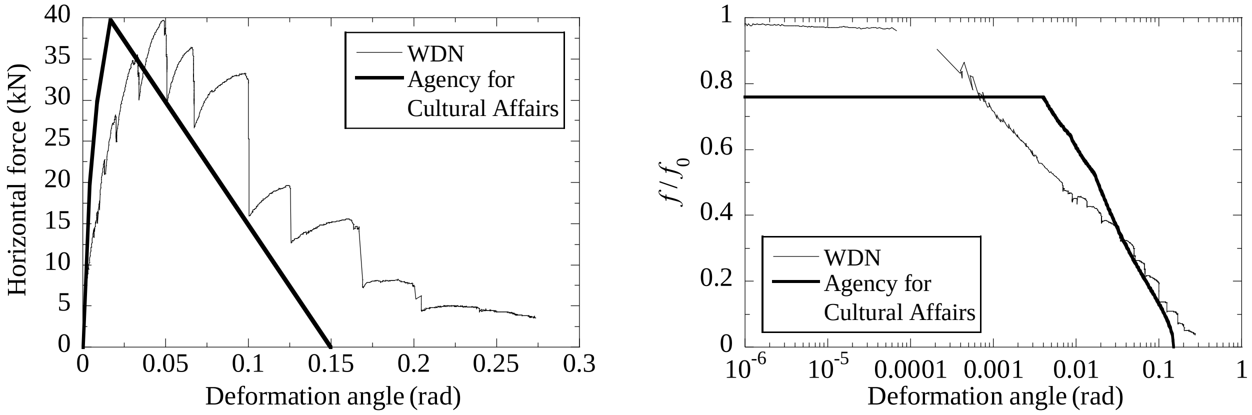


Fig. 6 – Skeleton curve of earthen wall proposed by Agency for Cultural Affairs ([6])



(a) Skeleton curve (b) Amplitude dependency of natural frequency

Fig. 7 – Comparison of the skeleton curve model and the outcome of the experiment

Although the skeleton curve model takes its maximum resistance force at 1/60 rad, WDN takes that at approximately 1/20 rad. In addition, the initial stiffness of the model is 0.58 times as high as that of WDN. As for amplitude dependency of natural frequency, the both are nearly the same in the large deformation range, but don't correspond well where the deformation angle is smaller than 1/100 rad.

Next, we compared HDK with the skeleton curve model of pillars with the hanging wall shown in Fig.8. There are three main suppositions in this model. First, horizontal displacement at the top of the pillar δ is the sum of the shear deformation of the hanging wall δ_w and the bending deformation of the column δ_c. Second, the column doesn't bend where the column and the hanging wall are jointed. Third, the relationship between the horizontal force P and the shear deformation of the hanging wall δ_w is the same with the model of full-length earthen walls. This model actually takes into consideration the bending failure of the pillars, but we supposed that the pillars don't break in this examination.

The skeleton curve model consists of four sections and is determined by the specifications of the hanging walls and the pillars. We specified the bending Young's modulus of pillars (N/m^2) as the means of that of 4 pillars, which is obtained from bending tests. In addition, we adjusted the thickness of the wall so that the maximum resistance force will be the same with HDK. Specifically, the bending Young's modulus is 9.93 N/m^2, and the wall thickness is 0.137 m, which is much thicker than actual thickness, 0.026 m.

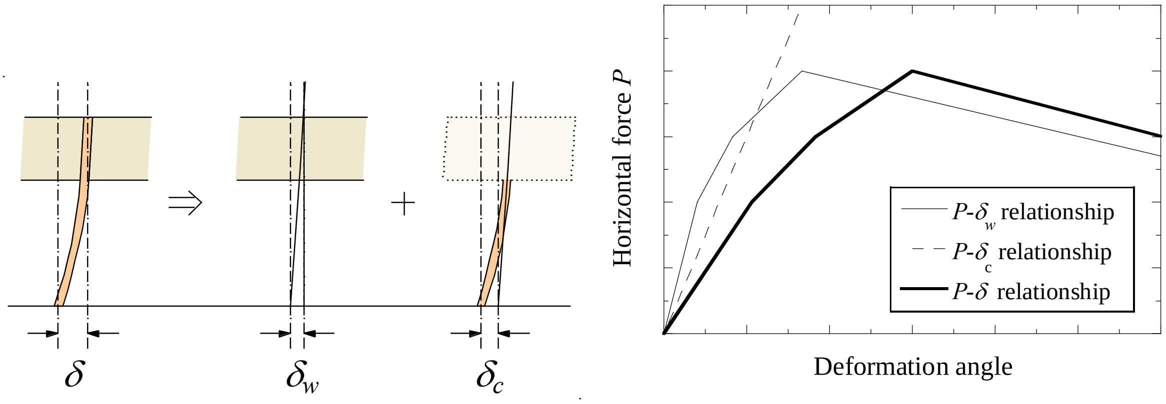


Fig.8 – The pillars with hanging walls and its skeleton curve model ([6])

In the static loading test, the hanging walls of HDK broke off the pillars in the large deformation range. Therefore, we conducted comparisons in two cases as shown in Fig.9. Case A: The whole specimen was regarded as a collection of four pillars, each of which has half of the hanging wall; Case B: The whole specimen was regarded as a collection of two pillars, each of which has the whole of the hanging wall.

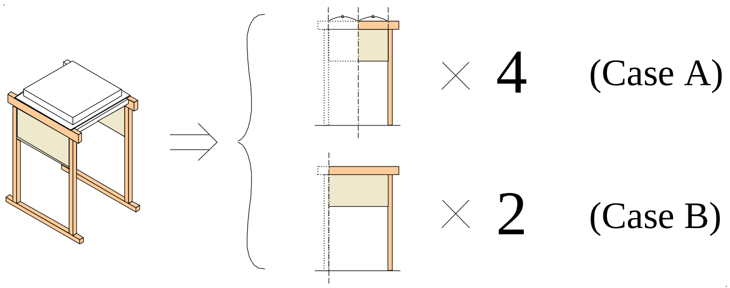
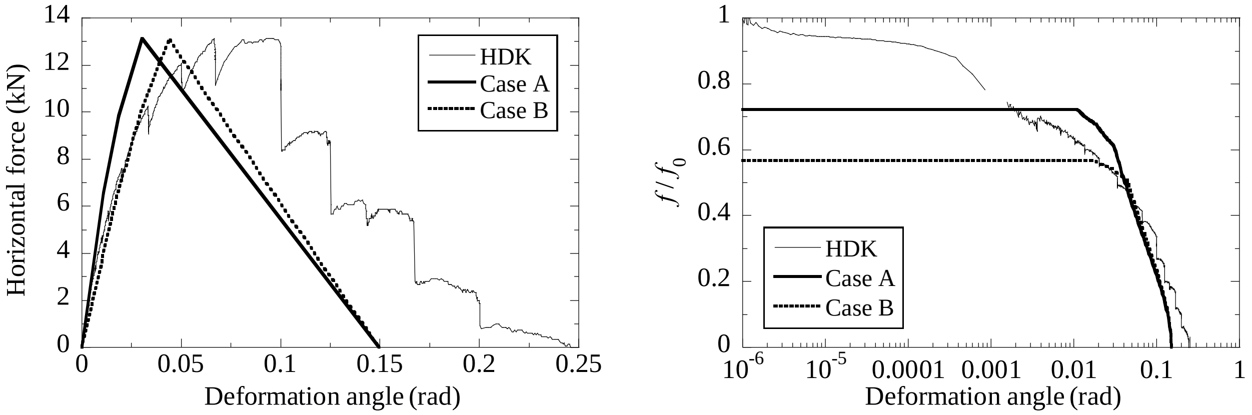


Fig.9 – Two ways of modelling

Figure 10 shows the comparison of the skeleton curve and the amplitude dependency of natural frequency. As for skeleton curve, case B is closer to HDK than case A. However, Amplitude dependency of natural frequency shows that where the deformation angle is smaller than 0.01 rad, case A is closer to HDK than case B, but there are un-ignorable discrepancies between the model and HDK. The initial stiffness of case A is 0.54 times as high as that of HDK, and that of case B is 0.34 times as high as that of HDK. To conclude, the skeleton curve model doesn't properly represent stiffness in the minute deformation range.



(a) Skeleton curve

(b) Amplitude dependency of natural frequency

Fig. 10: Comparison of the skeleton curve model and the outcome of the experiment

5. Conclusions

We have conducted an experimental study on traditional wooden buildings to construct a method to estimate the maximum response deformation angle using ambient vibration tests. We have conducted vibration tests and static loading tests on four kinds of structural components to specify the mechanical characteristics of them from the infinitesimal deformation range, which corresponds to ambient vibration tests, to a large deformation range, which finally reaches the collapse.

We have gained the following results for the four kinds of building components.

1. We have gained the relationship of the ratio of equivalent natural frequency during an earthquake and natural frequency that is obtained from ambient vibration tests before the earthquake (f/f_0) (i.e. amplitude dependency of natural frequency).
2. The decreasing ratios of natural frequencies after an earthquake to the natural frequency before the earthquake (f_m/f_0) have been gained. It can be possible to utilize those results for estimating the maximum response deformation angle, which buildings experienced during an earthquake.
3. We have gained the ratio of natural frequency calculated from the skeleton curve model prescribed by Agency for Cultural Affairs to that of the specimen. This result is useful to examine the validity of the analytic model of buildings by comparing the natural frequency of the model with the natural frequency obtained from ambient vibration tests.

5. Acknowledgements

This research was supported by Grants-in-Aid for Scientific Research (A) (No. 19H00793).

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