WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

Shaking table tests on the traditional timber structure of the stage on the cliff using the model of a 3D printer

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ABSTRACT: This study investigates the seismic performance of traditional timber structures, focusing on the stage of the main pavilion at Kiyomizu-Dera temple in Japan. Traditional timber connections in East Asia, including Japan, use notching and fitting techniques, resulting in superior seismic performance due to more prominent structural members than residential buildings. The research involved creating a 1/50 scale model of the pavilion and stage using a 3D printer based on static loading tests. The model's foundation was made from structural plywood, corresponding to the actual structure's column lengths. Seismic tests included white noise, simulated seismic waves from the Building Center of Japan, and 1995 Kobe earthquake data. Test observations revealed natural frequencies, damping, and load-deformation relationships. Results showed that the main pavilion's natural frequencies matched microtremor observations, while the stage's frequencies were lower. Additionally, reduced stiffness was found between the pavilion and the stage, suggesting a structural distinction between the two parts. The study concludes that the main pavilion and stage have different seismic characteristics, highlighting the complex dynamics of traditional Japanese timber structures.

KEYWORDS: traditional timber structure, shaking table test, natural frequency, model test

1 – INTRODUCTION

The traditional timber structures in Japan and East Asia are connected by notching members and fitting them together. Many temple buildings feature more prominent members than residential buildings, providing them with an advantage in seismic performance, including enhanced rigidity of connections and energy absorption capabilities. This study verifies the vibration characteristics of the stage on the cliff in the main pavilion of Kiyomizu-dera temple (Figure 1) using a model made with a 3D printer at a scale of 1/50. The system for the stage on the cliff, depicted in Figure 2, is known as kakezukuri, which comprises columns, pillars, and horizontal members such as nuke. The inner sanctuary of the main pavilion is constructed directly on the ground on the cliff. In contrast, the outer sanctuary is built on an artificial foundation supported by pillars and stakes, with the pavilion on top. As seen from the exterior, the roof is suspended over the inner and outer sanctuaries.

The kakezukuri consists of 78 pillars, each having a hexagonal cross-section with a diameter of approximately 700mm. They are constructed at a spacing of about 3m and feature up to six penetrations in both the beam-to-beam and girder-to-girder directions. The hall section includes round columns with diameters ranging from 400 to 600 mm. These pillars are interconnected through penetrations in the beam-to-beam and girder directions, with a maximum of six penetration levels, each exhibiting a cross-sectional dimension of 180mm wide and 360mm long.

Suzuki et al. have conducted ongoing microtremor measurements of the main pavilion of Kiyomizu-Dera Temple and assessed the constant microtremors of this structure. They found that the average first-order natural frequency is approximately 1.8 Hz. Analytical methods also evaluated the vibration characteristics of the temple. The results of the microtremor measurements support the findings from the constant microtremor assessments [1]. This study focuses on the entire hall, including the kakezukuri structure, though the specifics of the

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https://doi.org/10.52202/080513-0674

kakezukuri are not analysed. According to Chiba, an attempt was made to clarify the horizontal resistance mechanism of the hall, including the kakezukuri structure, based on a static loading experiment using a 1:20 scale model. This experiment indicated that the building's deformation characteristics also vary at the cliff's boundary, suggesting that multiple modes of vibration characteristics must also be taken into account [2].

Figure 1. The main pavilion of the Kiyomizu-Dera temple

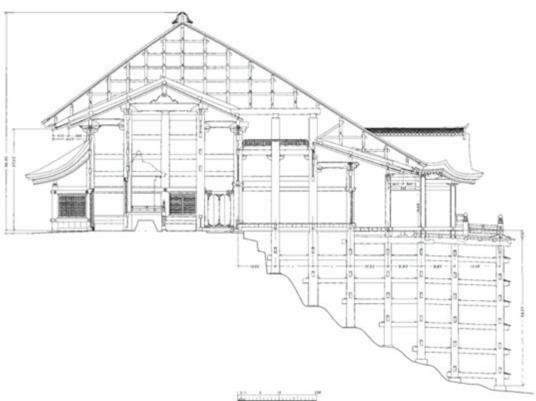

Figure 2. Cross section of the main pavilion [3]

2 – METHOD

As shown in Figure 3, a foundation with steps was constructed using 12 mm thick structural plywood to accommodate the ground slope. The model above was assembled and installed on this foundation, with a 10 mm diameter and 5 mm deep indentation made at the column position to insert the column. During the vibration test, this arrangement prevented the column legs from moving horizontally and caused them to act like pins. Weights equivalent to the roof load were affixed to the column heads of the model. The roof's weight was estimated to be about 30,000 kg, while the weight of the cypress bark roofing was approximated at 30 kg/m2. A load of 2 persons/m2 was also factored in for the stage. Assuming that the load is proportional to the square of the specimen's scale, 12 kilograms of the roof load and 6 kg for the stage load were evenly distributed across each column. Markers were attached to the column heads and legs of the Y1 structure to measure displacement using motion capture (Optiteck). Excitation was conducted using white noise, the north-south component of seismic waves recorded at the Kobe Marine Observatory during the 1995 Hyogo-ken Nanbu earthquake (JMA-Kobe NS), and simulated seismic waves from the Building Center of Japan (BCJ-L1).

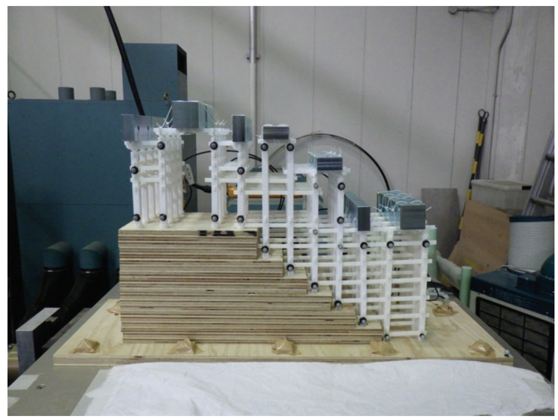

Figure 3. Installation for optical motion capture and weight equivalent

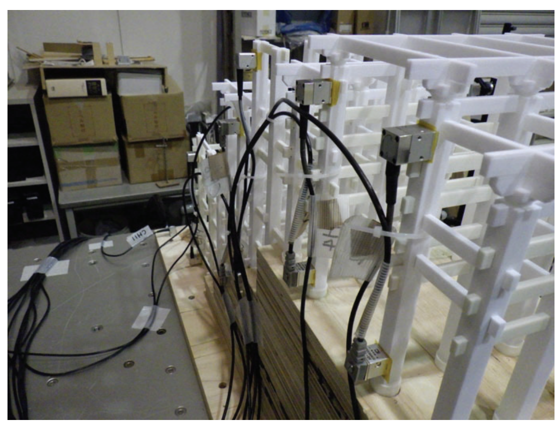

Figure 4. Installation of acceleration sensors

The roof structure covering the inner and outer sanctuary was omitted, leaving only the pillar heads connected by head nippers and other means. These headstones are also found in the actual building and were not added for supplemental rigidity. The rigidity of the building as a whole is generally maintained. The model's structural surfaces X1 to X5 are referred to as the main pavilion (inner sanctuary), X6 and X7 as the main pavilion (outer sanctuary), and X8 to X12 as the stage. This is because the results of static loading tests in previous studies have shown that the structural characteristics may differ, and

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it is expected that differences in planar spatial functions may appear as differences in structural functions.

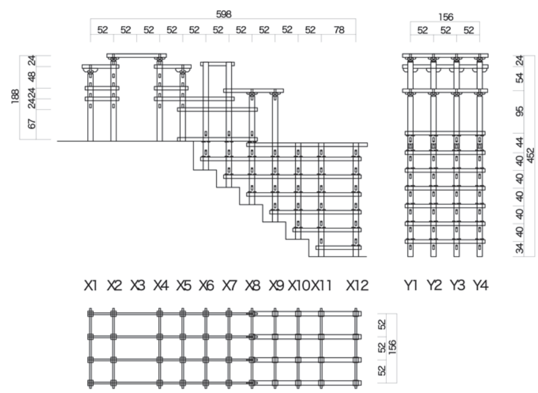

Figure 5. Outline of specimen (unit: mm)

Table 1. Difference between Full Scale (Kiyomizu-Dera temple) and a model of the specimen

	Full scale (Kiyomizu-Dera)	Model
Column cross-section	Circular	Rectangular
Wedge	Present	Absent
Joint at Nuki Penetration Connection	Present	Absent

3 – RESULTS AND DISCUSSION

3.1 Load-Deformation angle relationship

The load-displacement relationships are depicted in Fig.6 to Fig.10 for each column row of X2, X4, X7, X8, and X12 where accelerometers were installed. Here, the deformation angles contain errors due to being derived from the second-order numerical integration of the accelerometer measurements. The load is calculated from the product of the measured acceleration and the applied load. The maximum deformation angle is approximately 1/50 rad (the comparison graph for the maximum deformation angle is inconsistent, so confirmation is necessary), but the behaviour remains elastic. The deformation angle gradually decreases from the main hall to the stage side.

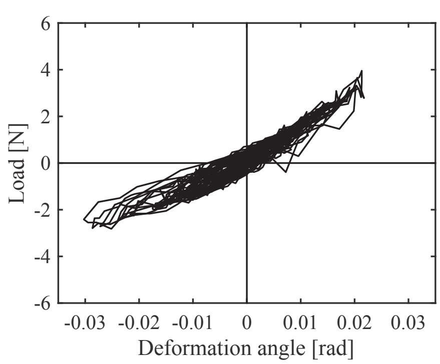

Figure 6. Load-Deformation Angle relationship(X2)

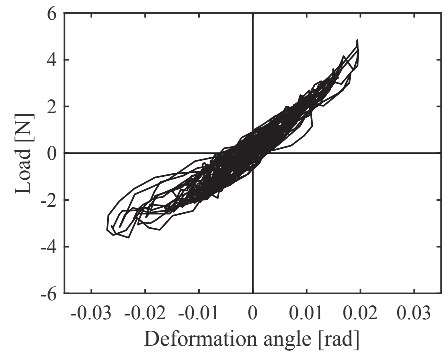

Figure 7. Load-Deformation Angle relationship(X4)

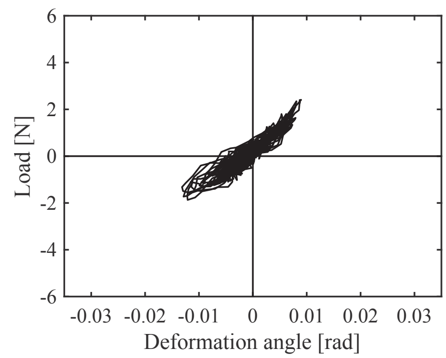

Figure 8. Load-Deformation Angle relationship(X7)

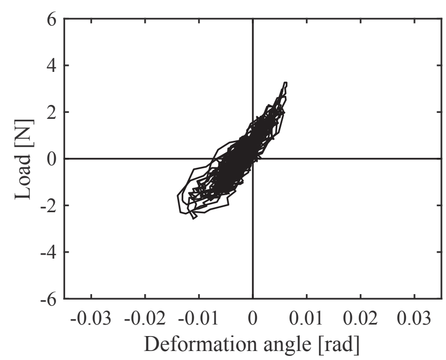

Figure 9. Load-Deformation Angle relationship(X8)

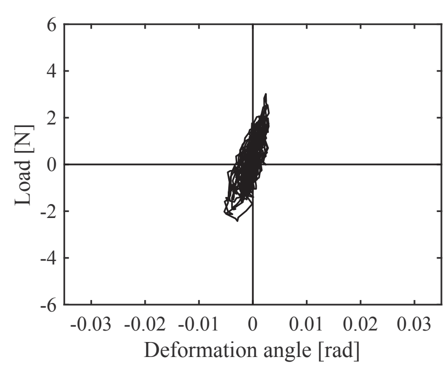

Figure 10. Load-Deformation Angle relationship(X12)

3.2 Displacement of each column line

Figure 11 illustrates the maximum deformation angle of each column as the BCJ wave input strength gradually increases. With the rise in input intensity, all columns exhibit significant deformation angles. Furthermore, the deformation angle on the main building side tends to be more pronounced at the X7 column. The load-displacement graph shows that the main hall and the stage do not function as a single entity. This suggests that they are shaking as if they were two separate buildings.

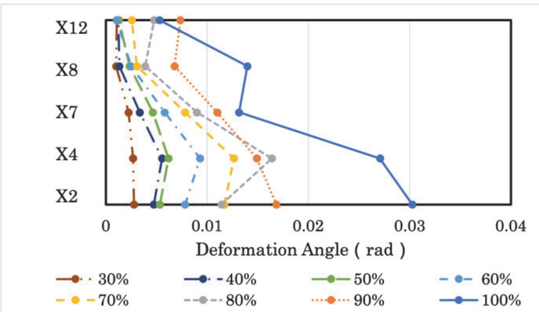

Figure 11. Maximum deformation angle at each input wave power

3.3 Natural Frequency

The natural frequencies of each column head are shown in the table. Whitenoise was used as the input wave, and the response waveform was measured while the amplitude of the vibration table was gradually increased. The measured waveforms were FFT-processed with a frame size 4096, and segments shifted by 2048 steps under the following conditions. The average was taken.

•Hanning window

•0.1Hz low cut and 100Hz high cut

The peak frequencies obtained for each measurement are shown in Fig. While the peak frequency is above 10 Hz at low input strength, it increases as the input strength rises. However, as the input strength increased, the peak frequency for all columns decreased to about 1.3 Hz. The natural frequency of the first-order vibration mode of a full-scale building is 12-13 Hz when converted to a 1/50 scale. This corresponds to the case of weak input intensity. Considering the amplitude dependence, this result seems reasonable, but further verification is needed.

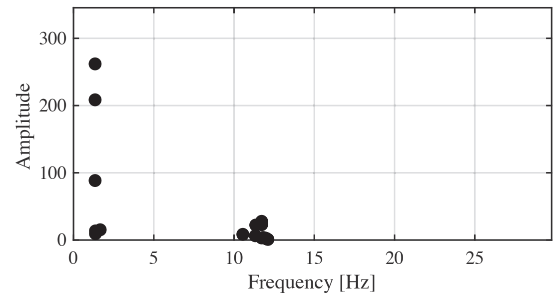

Figure 12. Distribution of Natural Frequency(X2)

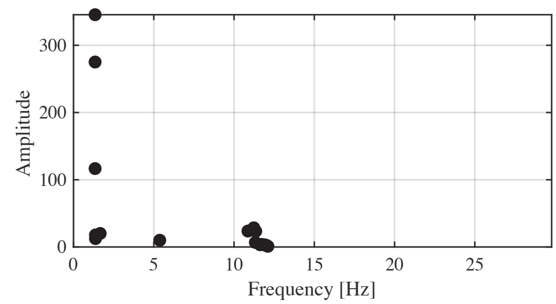

Figure 13. Distribution of Natural Frequency(X4)

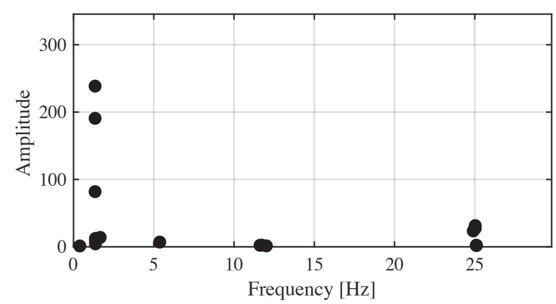

Figure 14. Distribution of Natural Frequency(X7)

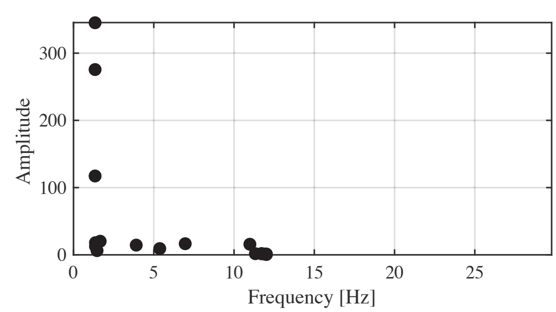

Figure 15. Distribution of Natural Frequency(X8)

https://doi.org/10.52202/080513-0674

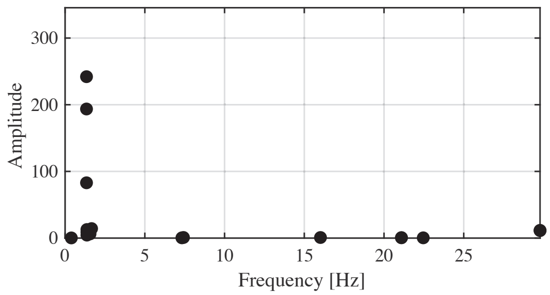

Figure 16. Distribution of Natural Frequency(X12)

4 – CONCLUSION

Shaking table tests conducted on a 1/50 scale model of the Kiyomizu-Dera temple yielded the following results.

・The deformation angle of X2 was greater than that of X12, which was the end of the stage.

・The natural frequencies of the main pavilion generally aligned with the results from the microtremor observation, whereas those of the stage appeared to be lower than the microtremor findings.

It has been suggested that the stiffness differs between the main pavilion and the stage.

5 – ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number JP 23H01557.

6 – REFERENCES

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