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INFLUENCE OF MATERIAL PROPERTIES OF COMPONENTS ON ROOF CURVE IN TEMPLE ARCHITECTURE

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ABSTRACT: The curvature of the roof of Japanese traditional architecture called "*Nokizori*" influences the facades of the architecture and is one of the most important aspects of Japanese temple design. The traditional Japanese wooden roof construction method developed from ancient times to the early modern period and has reached perfection. The roof is divided into two layers, and the eaves are supported by an element called "*Hanegi*", which is placed between the two layers. As the eaves sag under the weight of the roof, changes in the material properties of the components are thought to cause changes in *Nokizori*. We investigated *Nokizori* at a renovation site and performed static deadweight analysis to understand the effect of Young's modules of the components on *Nokizori*. The results of the analysis indicated that the component that affects *Nokizori the most* was *Hanegi*.

KEYWORDS: Curveture of the roof，Temple architecture，Cantilever，Young's modulus，Static response analysis

1 – INTRODUCTION

Temples' roofs are one of the symbols Japanese architecture, and the curvature of the eaves is an important element in determining the facades of the temple. The curvature of the roof is called "*Nokizori*" in Japan. It was introduced from Asian continent as one of the techniques for building temples, and has since changed in Japan due to the need to adapt to the climate and cultural influences. *Nokizori* is determined by a drafting technique by a carpenter called *KIKU-JUTSU*, which allows for roof design. On the other hand, *Nokizori* can be affected by the weight of the roof [1], and the roof curve can also be affected by Young's modulus of the planks [2]. On the other hand, Most of the research on *Nokizori* has been conducted on *KIKU-JUTSU*, but there has been no research on the influence of *Nokizori* on architectural components. In this study, we conduct a parametric study of static self-weight analysis based on a measured survey of a temple building that was renovated in the modern era to clarify the influence of the material properties of the components on *Nokizori*.

2 – VARIATION IN FRAME DESIGN AND *NOKIZORI* OF JAPANESE TEMPLES

2.1 CHANGE IN FRAME DESIGN

Japanese temples have undergone many developments since *Horyu-ji* Temple, the oldest surviving wooden structure in Japan. In particular, the invention of the "*Hanegi*" technique around the 8th century extended the size of temples and created the deep eaves that are characteristic of traditional Japanese architecture. "*Hanegi*" are large cross sectional timbers placed in the gap that was created by the separation of the roof and the frame structure. They support the eaves using the weight of the roof based on the principle of leverage. The separation of the hipped roof and frame structure took shape in the medieval and early modern periods, and the structure of temples reached its completion in the early modern period. The *Taishi-do* Hall of *Kakurin-ji* Temple was renovated in the 13th century, with a double-layered roof made of protective layer and a decorative roof, a coffered ceiling, and *Hanegi* arrangement. Photo 1 shows the external view and Figure 1 shows the cross-sectional view. The main hall of *Saimyo-ji* Temple in Shiga Prefecture, Japan, was built in the Middle Ages and extensively renovated in the Modern Period. Photo 2 shows the external appearance and Figure 2 shows a cross-sectional view. *Senjo-ji* Temple Mieido Hall, which was built in the early modern period (17th century),

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was a large temple that people stopped by on their way to Ise Shrine. Photo 3 shows the exterior view and Figure 3 shows the cross section. Despite the increase in size, temples of all sizes are built in the same way, with the same post-and-beam framework, double roofs, hipped roofs, and bell towers. The form was inherited, and the same structural form has been carried over to the present day.

Photo 1. Appearance of Kakurin-ji Temple Taishido

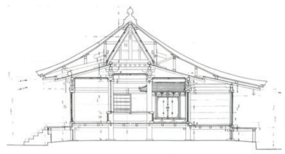

Figure 1. Cross section of Kakurin-ji Temple Taishido [3]

Photo 2. Appearance of Saimyo-ji Temple Hall

Figure 2. Cross section of Saimyo-ji Temple Hall[4]

Photo 3. Appearance of Senjo-ji Temple Hall

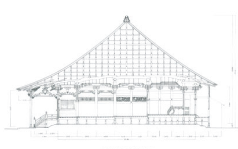

Figure 3. Cross section of Senjo-ji Temple Hall[5]

2.2 CHANGES IN *NOKIZORI* OF JAPANESE TEMPLES

According to a past study [6], *Nokizori* changes as shown in Figure 4. Eaves warps are created by *KIKU-JUTSU*. According to the reference [7], the source of curve in the early modern era was often a corner pillar, and the source of *Nokizori* in the modern era is also a corner pillar.

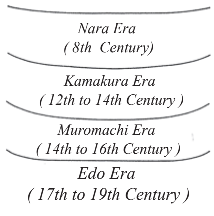

Figure 4. Changes in temple's Nokizori[4]

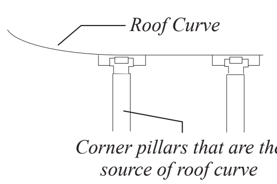

Figure 5.Roof curve of early modern temples

3 – SURVEY OF ACTUAL MESUREMENT AT RENOVATION SITE

3.1 OUTLINE OF SUBJECT ARCHITECTURE

The architecture under study is the main hall of *Seiman-ji* Temple in Aichi Prefecture, Japan. Photo 4 shows the exterior of the main hall, Photo 5 shows the interior of the roof, Figure 6 shows the floor plan, Figure 7 shows the cross section and Table 1 shows the outline of the Architecture. The building size is 13.9m in the beam direction, and 4.5m in height. The walls are clay-lacquered and the roof is tiled. The temple was completely destroyed by an earthquake in 1707, rebuilt in 1793, completely destroyed again by an earthquake in January 1945, rebuilt in 1948, and renovated in 2023.

Photo 4. Exterior view of the main hall of Seiman-ji Temple

Photo 5. Inside the roof

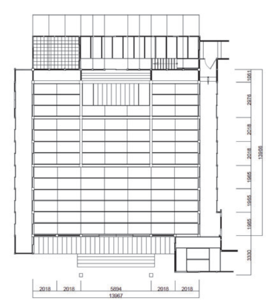

Figure 6. Floor Plan

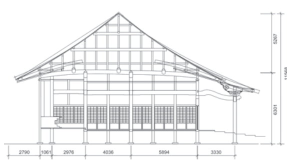

Figure 7. Cross section

Table 1. Architectural Outline

Architecture	Maximum Height	13.9 m
	Eave Height	4.5 m
Specification	Roof	Tiled roof
	Celling	None at time of renovation
	Wall	Mud wall
	Floor	Boarding

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3.2 MEASURING METHODS AND LOCATIONS

Nokizori measurement points are shown in Figures 8 and Figure 9. To mesure, fix a piece of wood to a corner tree and stretch a leveling string horizontally using a laser marker. *Nokizori* is determined by measuring the distance from the leveling string to the negative contact point between the rafter and thatch, using the string as a reference point. The target temples were surveyed not only in 2023, but also will be surveyed several years and decades in the future to determine changes over time, and thus standards were set and measurements were taken.

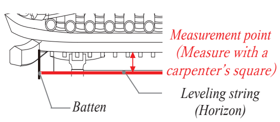


Figure 8. Elevation of measurement point

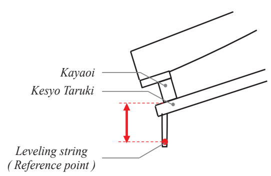


Figure 9. Cross-section of measurement point

3.3 MEASUREMENT RESULTS

The curve on the left side of the front face is the subject of the analysis for the investigation of the total eave length. The measurement results are shown in Figure 10. The subject temple eaves are all curved. *Nokizori* was observed to begin warping from the center, with a large warp starting near the corner pillars at the eave ends. This is thought to have been the choice of the temple carpenter in charge of the renovation. *Nokizori* were suppressed at the locations where *Hanegi* were placed, indicating that *Hanegi* had an effect on *Nokizori* from the beginning of the construction. *Nokizori* of the subject temple is larger than that of the thatched roof, although it is written in the reference [8] that the warp is equivalent to the thickness of one thatch. This is thought to be because it was necessary to change the warp height of *Nokizori* according to the size of the roof in order to make the temple look beautiful.

4 – PARAMETRIC STUDY TO UNDERSTAND THE EFFECT OF MATERIAL PROPERTIES ON *NOKIZORI*

4.1 FINITE ELEMENT ANALYSIS OVERVIEW

In this study, an analytical model of the subject building is created using finite element analysis, and the effect of the material properties of the constituent members on *Nokizori* is determined by static dead-weight analysis. Figure 11 show the specifications of the analytical model, respectively. The frame structure is modeled as a beam element and the mud wall is modeled as a plate element. The wood species and Young's modulus of each member were *Hinoki* (E = 9000 N/mm^2) [9] for columns, and *Pine* (E = 10000 N/mm^2) [9] for beams, girders, foundations, and shed-roof components. The thickness of the mud wall was 100 mm to 150 mm, and the sheer stiffness was calculated from a past study [10]. The joints were pin connections. The tilting restoring force was taken into account for the facing pillars and for the 200mm diameter round pillars inside the building [11]. Loads were applied to the entire roof surface with the weight of the pier tile roofing 483 N/m^2 [12] and the weight of the role tiles, respectively. The results of the eigenvalue analysis and the constant microtremor measurements showed that the order of the vibration modes was consistent with translation in the girder direction, translation in the beam-to-beam direction, and torsion, and thus the analytical model was judged to be valid.

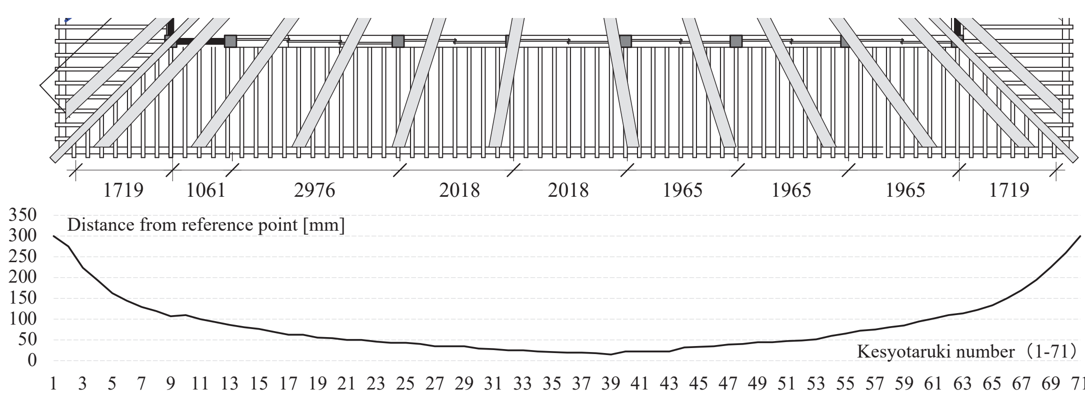


Figure 10. Roof framing Plan and Nokizori

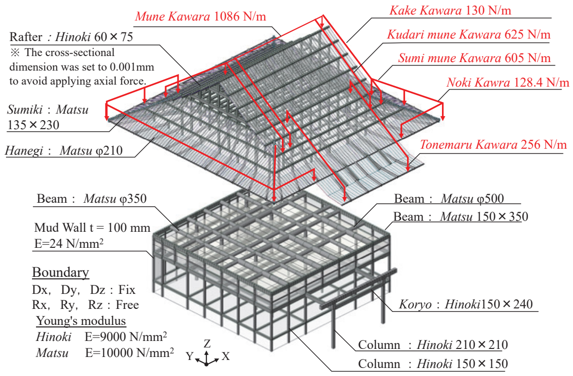
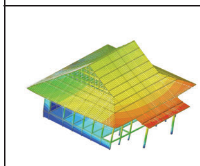
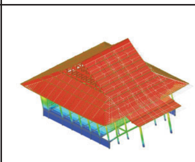
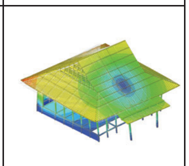
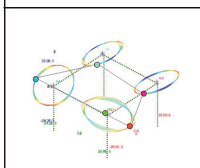
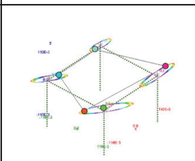
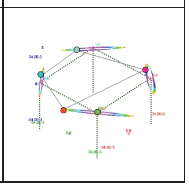


Figure 11. Analytical Model Parameters

Table 2. Comparison of natural frequencies in microtremor measurement and natural vibration modes in natural vibration analysis

Longitudinal DirectionTranslation al Mode: 0.49Hz （1.73） *	***Span Direction Translational Mode : 0.59Hz （2.24）*** *	***Torsional Vibration Mode : 0.99Hz （3.36）*** *
		
		

*In □ HZ (○), □ denotes the analytical value and ○ denotes the result of constant microtremor measurement.

4.2 SELF-WEIGHTING ANALYSIS OF STATIC

The analytical model created in 4.1 is subjected to static dead-load analysis to determine the effect of the material properties of the constituent members on *Nokizori*. Figure 12 shows the components that support the eaves. A parametric study was conducted using the material properties of the planks, columns, and tohoku as parameters. Three parameters are established from material tests in previous studies: a maximum value, a minimum value, and a reference value to be applied in design.

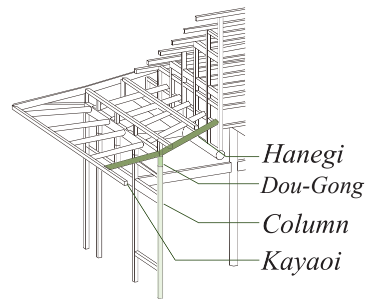


Figure 12. Components supporting the eaves

4.2.1 EFFECT OF YOUNG'S MODULUS OF *HANEGI* ON *NOKIZORI*

Figure 13 shows the deflection of the eaves as a function of the Young's modulus of *Hanagi*. From the literature [13] [14], the parameters of the pine that constitutes *Hanegi* are 7000 N/mm^2, 10000 N/mm^2, and 18000 N/mm^2. It was confirmed that a decrease in Young's modulus causes deflection in the eaves. The center of the eaves shows greater deflection than the eave ends, but this is thought to be due to the fact that the eaves are supported by more members at the eave ends. The deflection of *Nokizori* curve decreased as the Young's modulus of *Hanegi* increased, indicating that Hanegi plays an important role in maintaining *Nokizor*i.

4.2.2 EFFECT OF YOUNG'S MODULUS OF PILLAR ON *NOKIZORI*

Figure 14 shows the deflection of *Nokizori* as a function of the Young's modulus of the columns. From a past study [14] [15], the parameters for Young's modulus of the hinoki cypress that constitutes the columns are 6700 N/mm^2, 9000 N/mm^2, and 13100 N/mm^2. The analytical results suggest that the effect of changes in the Young's modulus of the columns is minimal.

4.2.3 EFFECT OF YOUNG'S MODULUS OF DOUGONG ON *NOKIZORI*

Figure 15 shows the amount of deflection of *Nokizori* as a function of the Young's modulus of the hinoki cypress that makes up the tokyo. From a past study [14] [16], the parameters for Young's modulus of Japanese cypress are 100 N/mm^2, 180 N/mm^2, and 500 N/mm^2. As with the columns, the effect on *Nokizori* is small. However, because the toomina is located near the roof and is easily affected by wind and rain, it will be necessary to study the effect of aging on this structure.

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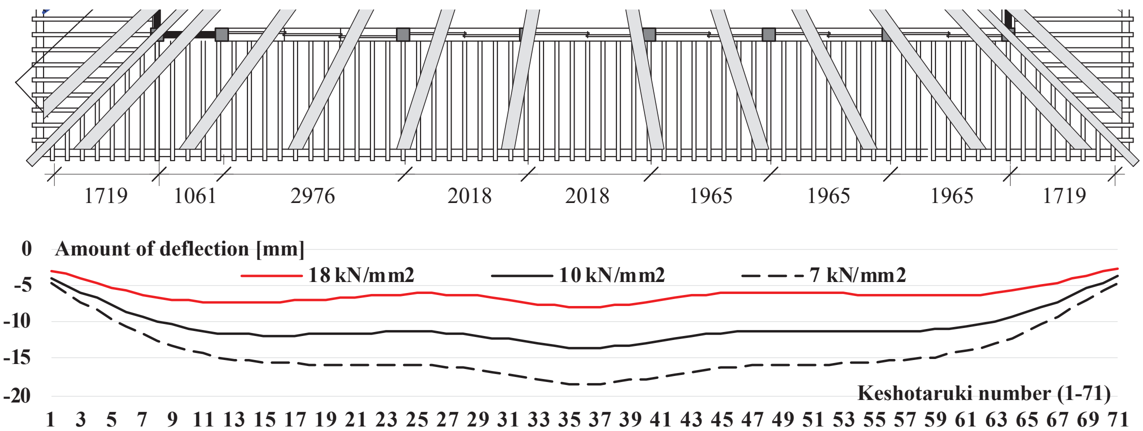

Figure 13. Deflection of Nokizori Due to Change in Young's Modulus of Hanegi (Analytical Value)

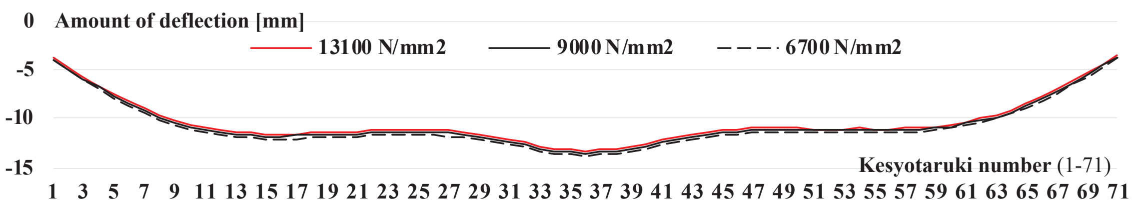

Figure 14. Deflection of Nokizori Due to Change in Young's Modulus of the pillar (Analytical value)

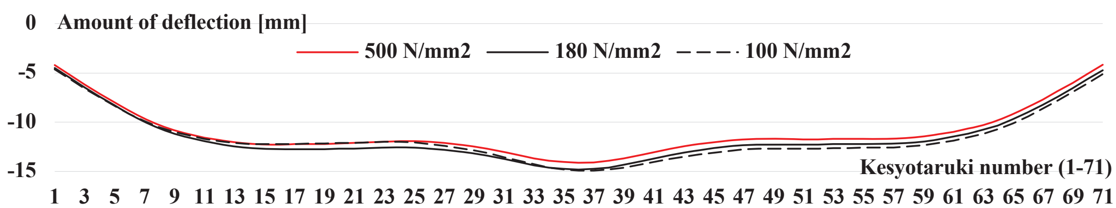

Figure 15. Deflection of Nokizori Due to Change in Young's Modulus of Dougong (Analytical value)

5 – CONCLUSION

The total length of eaves warp was obtained from a survey of temple buildings, and static analysis was conducted to understand the effect of the material properties of the components on *Nokizori*. The subject temple was renovated in the modern period, and the source of *Nokizori* is usually defined as the warp starting near the corner pillars, but the surveyed temple eaves are all curved. Static analysis based on the survey revealed that the material properties of the components had an effect on *Nokizori*, with *Hanegi* having the greatest influence among the components. *Hanegi*, which has been introduced since ancient times, plays an important role in maintaining eaves warp. Although eaves warp is mostly evaluated by *KIKU-JUTSU,* the results suggest that it is necessary to measure the total length of the eaves and consider the effects of the material properties of the constituent members in order to understand cuveture of the roof.

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