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FEM Analysis Considering Stiffness of 3 Stepped Bracket Complex for ENGAKUJI SHARIDEN as a Historical Wooden Structure in Japan

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Abstract

Engaku Temple has been built at Kamakura City nearby Yokohama in 1285. The SHARIDEN is one of the facitilies there in order to store the Buddha’s bone and has been selected as Japanese national treasure. However, most of the original materials have been lost because of suffering from a fire in 1563. After that, the current SHARIDEN has been replaced by TAIHEI Temple which was also located in Kamakura.

In the former study[1], the FEM model for SHARIDEN has been established as a space frame and the linear elastic analyses have also been executed. In the present study, the following targets will be prepared to analyze the structural behaviours in detail.

(1) Reconfirm the coordinates of nodal points and member arrangement for the FEM model
(2) The structural behaviours of 3 stepped bracket complex has been simulated with 3D FEM solid model to obtain the equivalent frame to the real bracket
(3) Estimate more exact distribution of the vertical load on the top and lower roofs
(4) Investigate the effect of the deterioration at the joints on the whole structural behaviours by considering bending springs arranged at the both ends of members.

The numerical model has been assembled by CAD data originally created basing on the drawings edited by Kanagawa Prefecture. The number of unknowns reaches upto 13,000. The numerical model for 3 stepped bracket has also contains over 10,000 unknowns.
Through above investigations, the structural features and several suggestions for reinforcements would be discussed for such an important structure.

Keywords: historical structure, timber spatial structure, FEM, numerical modeling, static analysis

1. Introduction

The Engaku Temple, in Japanese being called as ENGAKUJI, is one of the most populer ZEN Buddhism temples at Kamakura City in Japan. The buildings have been established in 1285. Among them, SHARIDEN has been noticed as an important historical structure which has been selected as one of Japanese national treasures. However, the most of the original materials have been lost because of suffering from a fire in 1563. After that, the current SHARIDEN has been replaced by Taihei Temple which was also located in Kamakura.

Figure 1: SHARIDEN of Engaku Temple

The SHARIDEN is a typical Zen style structure. The Zen style is one of the architectural styles for temples and has been imported from China. As other famous Zen style building, JIZO-DO of Shofuku Temple can be found in Tokyo and it also has been selected as the national treasure. The noticeable features of Zen style are

(1) row of relatively slender columns in comparison with other styles
(2) 3-stepped bracket complex being called as Zen sect style bracket complex or Mitesaki-Tokyo, which is settled to support the extended edges of the roof.

The FEM model for SHARIDEN as a space frame has been provisionally established in the former study[1)]. In the same paper, linear elastic analyses have also been executed and there have been several conclusions to describe the structural behaviours. In the present study, the following targets will be prepared to analyze the structural behaviours in detail.

(1) Reconfirm the coordinates of nodal points and member arrangement for the former FEM model through both the drawings and photographs
(2) 3 stepped bracket complex has been simulated with 15 nodes isoparametric elements to establish the equivalent frame to the real bracket
(3) Estimate more exact distribution of the vertical load on the top and lower roofs

(4) Investigate the effect of the deterioration at the joints on the whole structural behaviours by considering bending springs arranged at the both ends of members.

Through the above analyses and investigations, the structural features and the several suggestions for reinforcements would be discussed and concluded for such an important structure.

2. Numerical modeling

2.1. SHARIDEN

The SHARIDEN has about 10m height and the plan is almost square whose edge length is about 8m. The coordinates of the nodal points and the section geometries of the members for 3 dimensional FEM model are settled by using detailed drawings [2] which have been edited by Kanagawa Prefecture. One example is introduced as Fig.2 showing section in Y3 plane of Fig.3. In order to digitize these data, a CAD application is utilized. In the working space of the CAD, the detailed drawings are traced by reading the measured lengths of the constitutive members. Almost members are taken into account to make a FEM model, but the small members that can be neglected to be not so effective on the structural behaviours, are out of considerations [1].

The present numerical model is illustrated in Fig.3. In the present study, the model is reviewed by reconfirming the drawings and the photographs taken in recent.

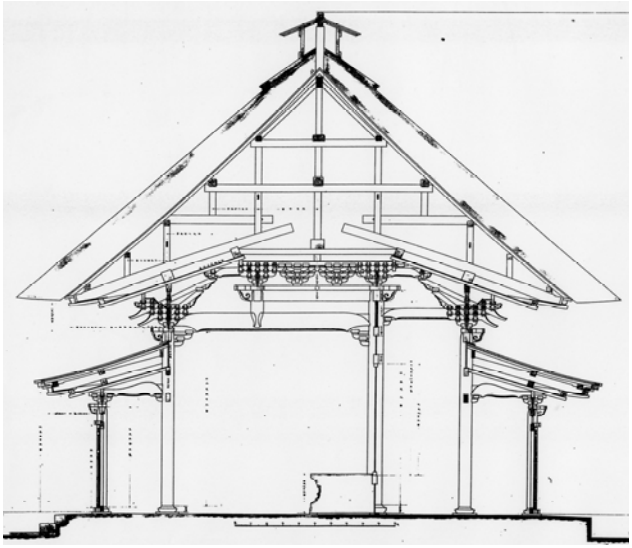

Figure 2: Drawing for Section of SHARIDEN from Ref.[2]

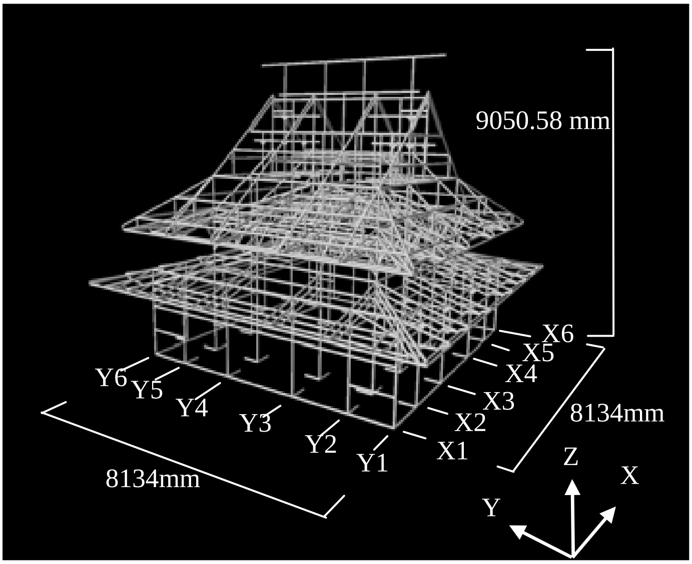

Figure 3: FEM model for SHARIDEN

2.1.1. Improvements for the former model

The present model has 1367 nodal points and 2374 members. The modified or improved parts in the present model compared with the former model [1] are notified as

(1) Sectional areas for the main and sub columns

(2) Sectional geometries of Tsumeki

(3) Stiffness of 3 stepped bracket complex.

The 1st and 2nd ones are reconfirmed through careful investigations for both the drawings and the recent photographs. The stiffness of the 3 stepped bracket complex is predicted by the FEM simulation with 15 nodes 3D elements. The descriptions for the modeling will be introduced in the next section and the analytical results will be shown in the next chapter.

2.1.2. Properties of constitutive members

The properties of the constitutive members are determined from the above-mentioned drawings and assumed ones can be found in Table.1. The table includes the Japanese expressions. Also in Figure 4, a part of the listed members are denoted by numbering. EBI-KORYO forming like a shrimp is a beam member which is divided into 2 elements, KORYO(1) and (2). KOHAI is the columns supporting the peripheral eaves like a cantilever. TAIRIN forms almost square and looks like a ring placing at the middle of the structural space.

All members are assumed to be made from a Japanese cypress and the Young's modulus and share elastic modulus are assumed to be 900kN/cm^2 and 56.25kN/cm^2, respectively.

Table 1 Members' properties

Parts Name	Diameter or Width (mm)	Height (mm)	Sectional Area (10^2mm^2)	Moment of Inertia I_y (10^4mm^4)	Moment of Inertia I_z (10^4mm^4)
1)Main Column	285	-	638	32394	32394
2)Sub Columns	236	-	437	15231	15231
3)KOHAI Columns	176	-	243	4711	4711
4)HAKOMUNE	254	254	646	34769	34769
5)Large Beam	117	371	436	50101	4996
6)KORYO(1)	98	156	153	3116	1218
7)KORYO(2)	98	274	268	16702	2131
8)TAIRIN	254	313	795	64813	42790
9)HAN Bean	98	215	210	8103	1674
10)TSUMEKI(1)	182	182	331	9103	9103
11)TSUMEKI(2)	212	212	450	16865	16865
12)MITESAKI Truss(1)	116	116	135	1522	1522
13)MITESAKI Truss(2)	105	105	110	998	998
14)Common Rafter	68	68	47	183	183
15)Others	156	156	245	4985	4985

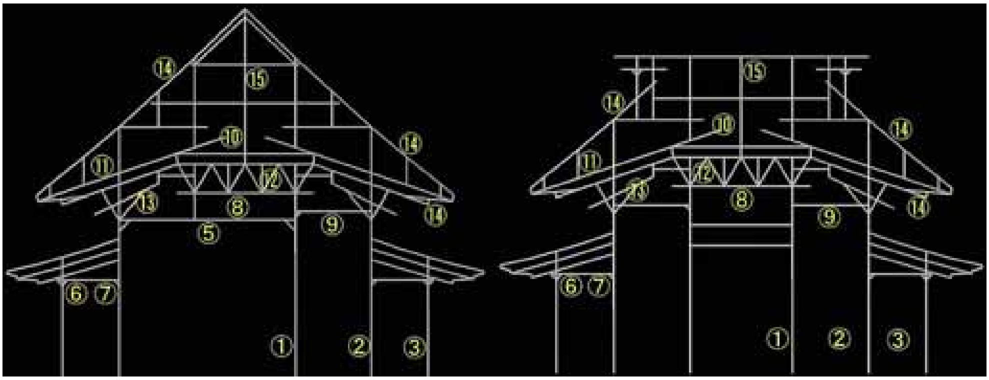

Figure 4: Member arrangements on Y3 and X4 planes

2.1.3. Loading & supporting conditions

The SHARIDEN is mainly composed of the trussed roof, lower frames and roofing materials. In the present study, the weight of the roofing materials being called as "Kokera Buki" is predicted by investigating the drawings [2]. The material is a rectangular peace of the wooden plate whose thickness is from 2 to 3mm. In Figure 5, the hatched parts explain the areas covered with roofing materials. The same figure also shows the nodal points where the concentrated loads are applied. The left figure illustrates the loads on the top roof, while the right one shows them on the lower eaves called as “Mokoshi”. The each load is equivalent to the uniformly distributed load considering the own weight of the members and the roofing materials.

Figure 6 shows the supporting condition at the foot ends of the main columns. The inner columns are restricted by the springs to express the frictions between the paving stones and the foot of the columns.

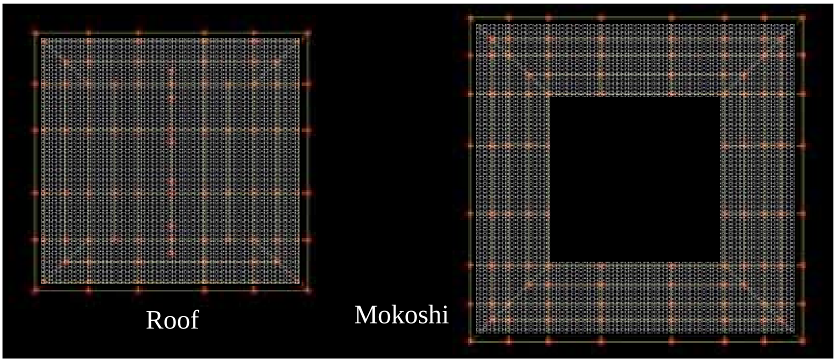

Figure 5: Loading points on the roof plan

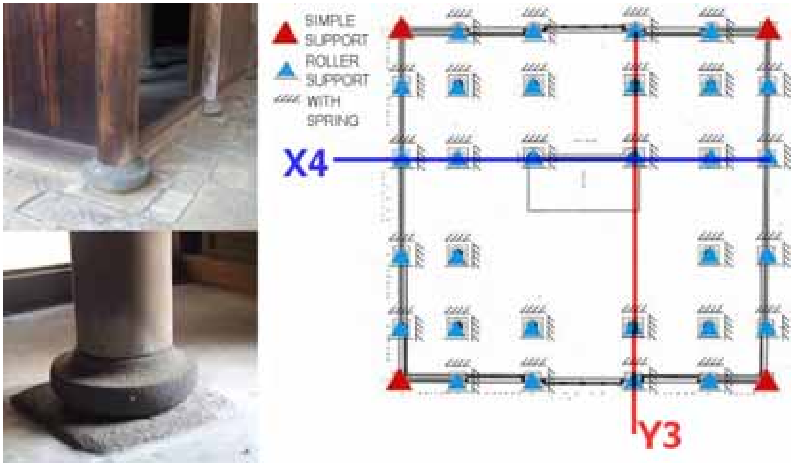

Figure 6: Supporting conditions

2.1.4. Consideration for connection deteriorations

Basically, all the members are connected rigidly to each other. But, the old wooden structure has some looseness at the connection with passing away. The effects of such a deterioration is considered by introducing the bending springs into the connections. Figure 7 explains the arrangement of the bending spring at the end of the beam member. In the present analyses, the springs are settled at the both ends of the largest beam called as "Dai-Koryo". The beam is placed between inner colums and numbered as 5 in the left of Figure 4.

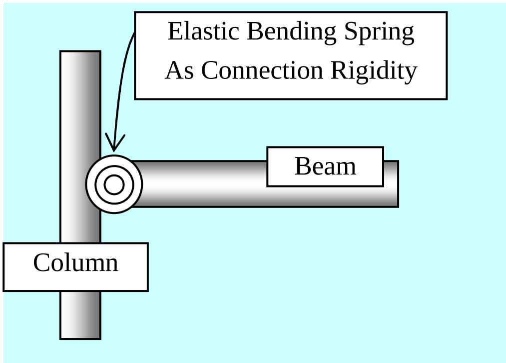

Figure 7: How to Consider Joint Deteriorations

2.2. 3 stepped bracket complex (Mitesaki-Tokyo)

The photos in Figure 8 describe the brackets supporting the overhanging eaves that constitute the roof plane. The brackets are called as "Mitesaki-Tokyo". The Mitesaki-Tokyo is so complex, obviously from those photos. To confirm the structural behaviours, 3 dimensional solid FEM model is prepared as shown in Figure.9. The model contains 6570 nodal points and 1394 elements.

Figure 8: 3 stepped bracket complex to support overhanging eaves

Figure 9: FEM solid model for 3 stepped bracket complex

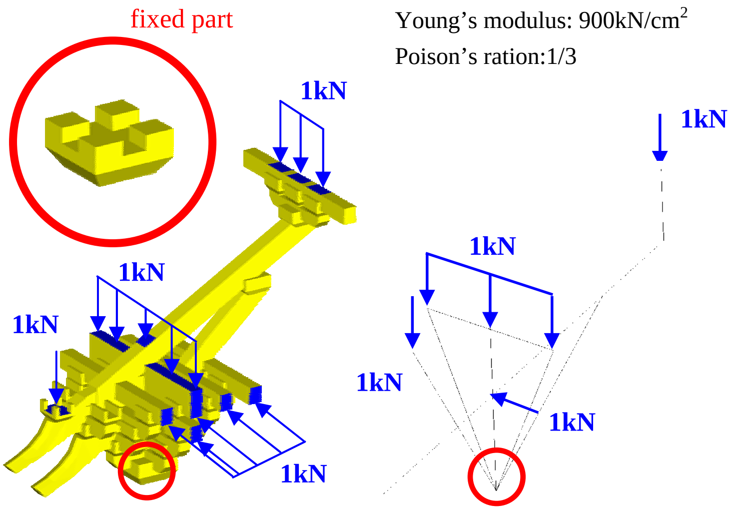

Figure 10: Simplified model and loading condtions

In Figure 10, the loading and boundary conditions are described. Unit load 1kN is distributed on horizontal and vertical planes where are colored in blue and may be connected the peripheral members. The nodal points on lower plane of the red circled part are only restricted simply. The right frame in the same figure, is a simplified model which would be bulit in the whole structural model for the SHARIDEN. From the simulated results for the realistic model, the member mechanical properties for the simplified model are determined after several attempts. The material is assumed as Japanese cypress and the Young's modulus and Poisn's ration are given by 900kN/cm^2 and 1/3, respectively.

3. Simulation results

3.1. 3 stepped bracket complex

The numerical simulation has been carried out under the conditions mentioned in Section 2.2. The deformations are described in the Figures 11 and 12.

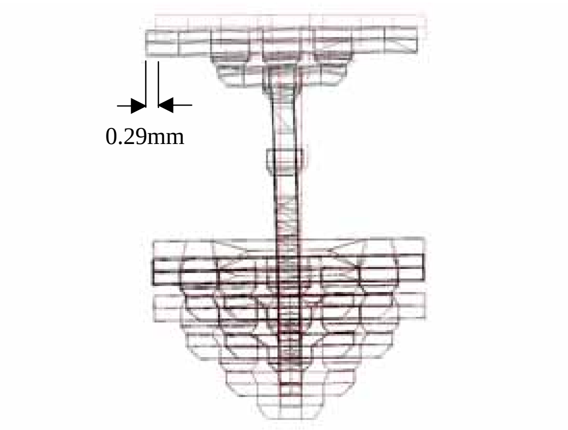

Figure 11: Deformation of 3 stepped bracket complex in front view

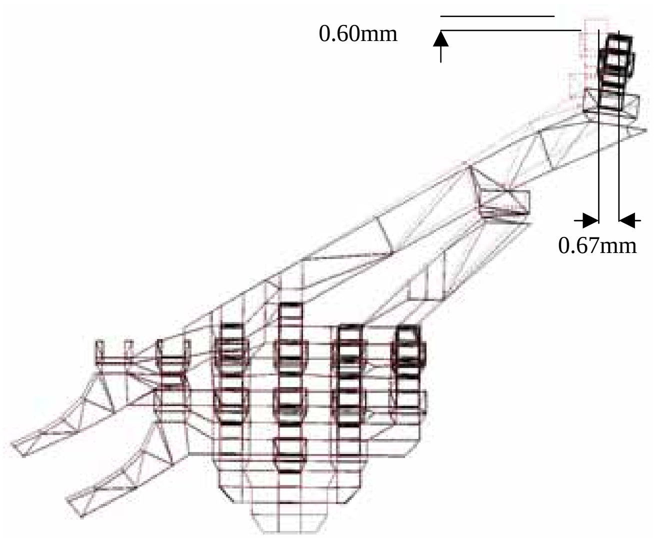

Figure 12: Deformation of 3 stepped bracket complex in side view

The remarkable displacements are found at the top where is connected to the upper columns which can bring the axial stress down to the lower bracket parts. From the results, the bending stiffness for the simplifed frame in the right one of Figure 10 is needed as abount twice for the former assumed frame in the Ref.[1]. However, the estimation is relatively irresponsible and the further analyses for the simplified frame are required to represent the real 3 stepped bracket complex.

3.2. SHARIDEN

From the results for the 3 stepped bracket complex, the members constituting the bracket are refined as shown with Table 1. The static linear elastic analyses are executed under the conditions denoted in Section 2.1. The obtained maximum stress is assumed as

$$\sigma_{\max} = \left|\frac{N}{A}\right| + \left|\frac{M}{Z}\right| \quad (1).$$

The obtained stress is compared with the allowable stress of Japanese cypress. The allowable stress is assumed as 2.07kN/cm^2 for the long term loading and 1.4kN/cm^2 for the short term. The safety factor can be predicted with dividing the maximum stress by the allowable stress.

3.2.1. Under own weight

Under the own weight only, the normal stress distribution for the SHARIDEN is shown in Figure 13. Meanwhile the displacements are so small to illustrate and the maximum value is found as 0.02cm at the edges of the Mokoshi. In the vertical direction, the Shariden would have so great stiffness against the own weight.

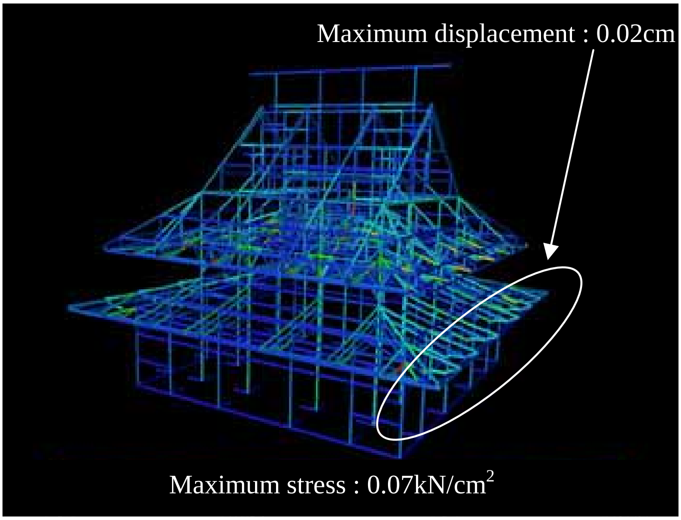

Figure 13: Distrinbution of normal stresses under only vertical loading

The predominant bending moment can be found at the center and both ends of the largest beam called as “Dai-Koryo”. At the short veritical part which is connected to the Dai-Koryo, the maximum stress is found. The safety factor can be predicted there as about 28 for the own weight.

3.2.2. Under vertical and horizontal loadings

Figure 14 shows the deformation under the own weight and the half of it as the horizontal loading. The maximum displacement is found at the top of the structure and the supporting columns incline remarkably. The maximum member stress reaches to 0.66kN/cm^2 on the four columns at the inside corners of the SHARIDEN. The safety factor would be predicted as around 3.

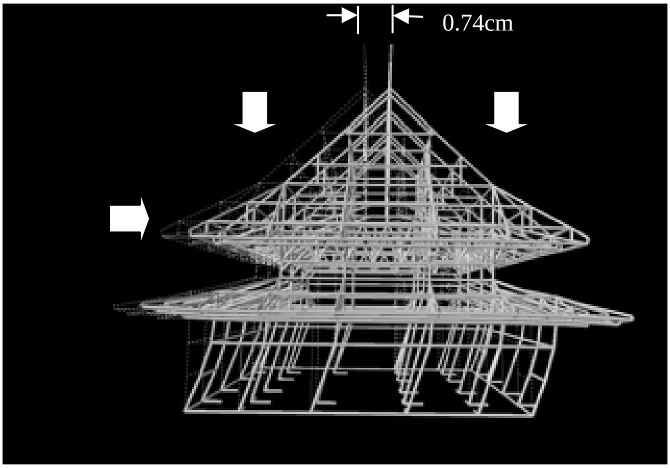

Figure 14: Deformation under vertical and horizontal loadings

3.2.3. Considering deterioration of particular connections

In the same model, the joint rigidity at the both ends of Dai-Koryo which has been illustrated as no.5 member in Figure 4 is assumed as 0.8 times to rigid one. The columns are still without decrement of the joint rigidities because of that the ends of the Dai-Koryo are connected to the side of the seamless columns. The safety factor for the long term loading is decreased to 8.8 when the main columns are focused. For the short term, the safety factor is almost unchanged to the one described in the previous sub section. The effect of the bending rigidity of the beam on the horizontal loading is estimated as not so severe.

4. Discussions and conclusions

From the results obtained from the several simulations, the structural behaviours and safety degree against the external loadings for the SHARIDEN are estimated simply. The tendencies of the structural behaviours are

1) the stiffness of the 3 stepped bracket complex is predicted as about twice to the one of the former model [1], but the influence upon the whole behaviours of the SHARIDEN is not so severe

2) the columns being inner from corridor play important roles especially for the short term loading included the horizontal one

3) under the loading of the own weight, the deformation and stresses are not severe for the structural safety

Meanwhile, the structural safety is observed from the investigations for the yielded maximum member stresses when the joints were still rigid enough. In the case of that there is fatal looseness at the joints, the most effective reinforcement would be considered as inserting the brace members between the inner columns. However, the treatment is not in realistic because of immersing the space where has to be opened. There are still necessities to carry out the precise analyses and to make a reinforcement plan for such a structure. Therefore, the practical investigations are also needed to observe the real stiffness of the SHARIDEN.

Acknowledgement

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