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Repair Works on the Main Pavilion at Tohdaiji Temple

Restauration du temple de Tohdaiji, Japon

Reparaturarbeiten am Hauptgebäude des Tohdaiji-Tempels

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SUMMARY

The world's largest timber building, located at the Tohdaiji temple in Nara, Japan, underwent large scale repairs in the period 1905 to 1915 and again in the 1970s. The first major repair work might be especially interesting to structural and architectural engineers from the view-point of strengthening of building structures, because there have been a number of new ideas and practical applications used in the strengthening of decayed structural members and the joints of the building.

RESUME

Le pavillon central du temple de Tohdaiji, situé à Nara au Japon, est la plus grande construction en bois dans le monde. Il a été restauré dans son ensemble durant la période 1905-1915 et à nouveau entre 1970-1980. Cette première réalisation de la restauration en grande dimension pourrait être spécialement intéressante pour les ingénieurs du point de vue du renforcement des structures de bâtiments. De nombreuses idées nouvelles et des applications pratiques ont été réalisées pour le renforcement d'éléments structuraux en piteux état.

ZUSAMMENFASSUNG

Das grösste Holzgebäude der Welt ist das Hauptgebäude des Tohdaiji-Tempels in Nara, Japan. Es wurde während eines längeren Zeitabschnittes, von 1905 bis 1915, und erneut in den 70er Jahren repariert. Für Bauingenieure dürfte die erste grosse Reparatur-die Verstärkung der Gebäudestruktur - besonders interessant sein. Hier kam eine Anzahl neuer Ideen und praktischer Verfahren für die Instandstellung vermoderter Bauteile und Verbindungsstellen zur Anwendung

1. INTRODUCTORY REVIEW OF THE PAVILION

The Tohdaiji temple was constructed for the first time in 751 A.D., in the middle of the so-called "Nara" period (710-784 A.D.). Facilities for the temple such as the main pavilion, the lecture hall, the dinning hall, priests' residences, the grand gate, the inner gates, corridors, the bell towers, etc., were recorded to have been constructed during the decade following the year of 751.

The records have shown us that the original pavilion building has covered an area spanning 97.2 m in the east-west direction, and 61.8 m in the north-south direction. The height of the main building was said to be 47.5 m above the stone platform which alone was 2.1 m higher than the ground level. The diameters of the columns of the building were 1.1 m at the bottom and about 0.9 m at the top.

The original buildings of the Tohdaiji temple were burnt in 1180 A.D. due to a battle fire. Later on, the buildings were reconstructed, but they were again burnt out in 1567 due to the same reason. The secondly reconstructed main pavilion, in the period starting from the end of the 17th century to the early 18th century (1708 A.D.), is the one that we can see at the present time. In the event of this reconstruction, the scale of the building was considerably diminished. Nevertheless, the main pavilion is still the world's largest timber structure that we can ever see in the 20th century.

Japanese wooden buildings, particularly large-size buildings such as shrines and temples are considered to require roof replacement once in 50-70 years and overhauling for repairs once in 200-300 years, although there are some differences in the intervals depending on roofing materials and types of structure.

Buildings such as shrines and temples have long overhanging eaves, and the weight of the roofs with heavy tiles is transmitted to the pillars of the buildings, so that the heavy load is borne by various kinds of structural members. Timber, which is the main structural material of these buildings, gradually changes its shape and dimensions, is bent and twisted and becomes thinner in a long time, mainly due to the following two reasons.

One of the reasons is that, because of the large size of such buildings, working stress on structural members is large and therefore, in a long time, deformations grow gradually, leading to the so-called creep phenomenon.

The other is the deterioration of wood which proceeds both interiory and externally caused by the environment surrounding the buildings, such as the penetration of rain water and dew, the repeated shrinking and expansion of wood by the changes in temperature and humidity, the weathering of the surface of wood caused by the dirt blown to them by wind, damage done by insects and termites, propagation of bacteria and various types of polution by birds and animals.

Wear of and damage to rafters, extended beams, columns and beams, particularly at their cut ends, have been observed in almost all cases of overhauling for repairs of wooden buildings so far carried out in Japan. As it is required to restore these damaged parts to their original state, a number of specific methods of reinforcement have been suggested and executed.

2.LARGE-SCALE REPAIR ON THE MAIN PAVILION CARRIED OUT IN THE PERIOD OF 1905-15

About 80 years ago, it was observed that the roof of the pavilion hang, its eaves had become wavy, and the large beams inside sagged down more than 30 cm. The reinforcing posts set up in the four corners of the pavilion to support the upper and lower roofs, barely prevented the building from collapse, and structurally the entire pavilion was in a very dangerous state. (Fig.1)

The so-called great repair work of the Meiji era (overhauling for repairs) on the main pavilion was carried out from 1905 through 1915. For this purpose,

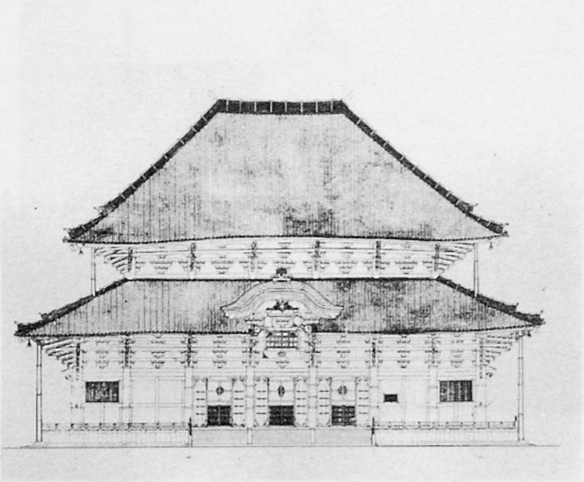

Fig.1 Front elevation in 1905

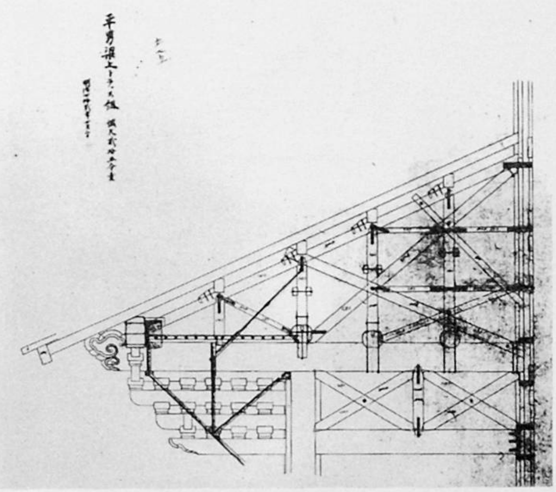

Fig.2 Reinforcement with steel

construction techniques and materials were actively introduced into Japan from European countries, marking an epoch in the overhauling and repairing of wooden buildings. This repair work was characterized by the following features.

1. Tiles on the ridges of the roofs were fixed with mortar using Portland cement which was imported into Japan for the first time in the 1900s.

2. Flat steel bars were used for the protection and preservation of the square framings of eaves and brackets. (Fig.2)

3. Rafters and extended beams, which are structural members to support the upper and lower roofs, were reinforced by using steel shapes and thick steel plates.

4. Steel frames made of rolled I-beams and channels, together with plates and angles, were embedded in the central parts of the cross-sections of wooden columns to enable them to withstand the bending moments on the columns. (Fig.3)

5. Hot-formed rivets were used to fasten the steel materials.

6. Double Warren steel trusses were provided under the existing huge timber beams in order to strengthen the frame for the large roofs and to enable them to

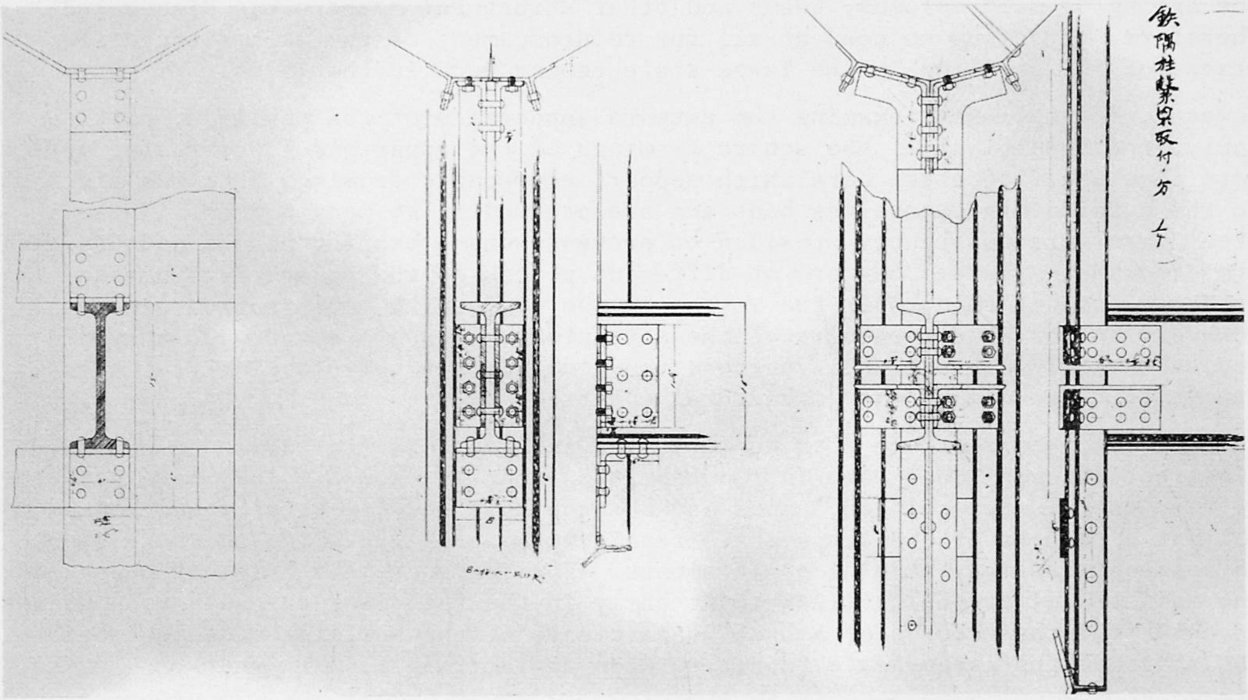

Fig.3 Details of the reinforcement of the wooden columns

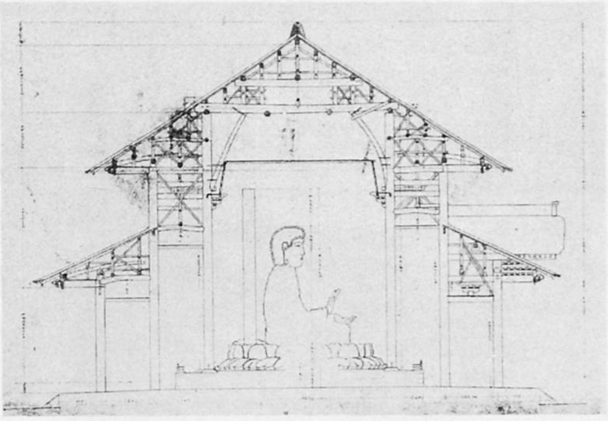

Fig.4 Deformed structural members

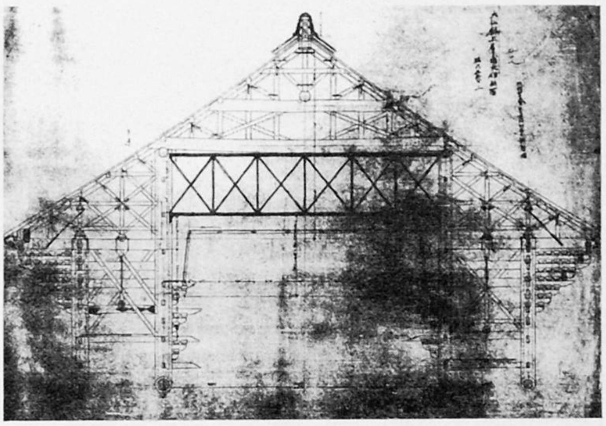

Fig.5 Double Warren truss inserted

bear the loads of the roofs, and further, the ceiling of the main pavilion was hung from these trusses. (Figs.4 and 5)

7. Wooden X-bracings were provided to the hidden parts of the building to reinforce the structural assembly, and the *"Kasugai"* clamps of the traditional Japanese style, bolts and nuts, and other steel materials were used in many places.

Timber trusses using a large number of bolts, nuts and other metal pieces that utilized the so-called new techniques in timber constructions developped in Germany and Britain in the beginning of the 20th century, were employed extensively for the wooden frames, for the main beams as well as the sloping beams (gathered beams) at the ridges of the pavilion.

It must be said that the large-scale repair work on the pavilion of Tohdaiji temple was successful in sufficiently strengthening this gigantic wooden building structurally. This repair work made it possible to remove the roof-supporting posts in the four corners of the building. Since then, the pavilion has withstood exposure to rain and snow for more than 70 years without its outward appearance being seriously damaged. When the author investigated the state of the structural frames of the pavilion 15 years ago, hardly any warping due to the ageing of main columns, beams and other structural members was discovered. Therefore, there was no need at all for reinforcement of the main structural frames of the pavilion in the large-scale repair work in the 1970s.

However, if we closely examine the outward appearance of the pavilion, particularly, the conditions of the square framings of the upper and lower roofs, we note that the flat steel bars which support the square framings from two sides on the outside are themselves bent and are protruding at many places. These steel bars were apparently provided to prevent square bearing blocks and bracket arms from being pushed outward at different places as the square framings and brackets are deformed under the weight of the roofs with long protruding eaves. However, so far as the results of these reinforcements are concerned, they did not necessarily achieve their purpose, and today these ugly-looking flat bars are still there without any structural contribution.

In the early years of the 20th century, new informations and knowledge on the construction techniques were introduced into Japan in excess. They were certainly very useful, but certain losses and unfavourable results were caused unexpectedly as a results of the large-scale repair work on the pavilion in those days, in spite of its many shining achievements. For instance, the original shape of the main frames of the pavilion built early in the 18th century can now be guessed only from the records of actual measurements of the building made just before the start of the large-scale repair work on it in 1905.

3. STRUCTURAL DESIGN OF THE DOUBLE WARREN TRUSSES

The double Warren trusses were designed, either in 1908 or in 1909, by a Japanese engineer who was in charge of the preparatory measurements and structural design so as to strengthen the main frames of the pavilion for overhauling. A sketch of the trusses, with the span of about 23.6 m and with the height of 4.83 m, is shown in Fig.6. Each chord member of the truss is consisted of two channels assembled side by side, with their legs protruding outward. At the inside web surface of the steel channels finished with the anti-corrosive paint, we can recognize a mark of SHELTON STEEL, CO. Also, we can find the mark of LANARKSHIRE STEEL CO., LTD, SCOTLAND at the web surface of other channels being used for the reinforcement of the roof structures of the building.

The top of the channels of the upper chords of the double Warren trusses are tightened together with a cover plate, a half inch (about 13 mm) thick and of 19 inches (48.3 cm) in the breadth. At the bottom of the upper chord members and at the top as well as the bottom of the lower chord members, there are tie plates of 12 by 19 inches (30 x 48.3 cm) and a half inch in the thickness, spaced at a pitch ranging between 90 cm and one meter. As the diagonal and vertical members of the trusses, there are used various structural steel shapes of T-5" x 3" x$^1/_2$", T-4" x 3" x $^1/_2$" and L-4" x 3" x $^1/_2$", together with flat steel bars of 4" x $^1/_2$", depending upon the working stresses on the members as calculated.

It may be interesting for structural engineers to see how the working stress on the members of the statically indeterminate trusses under the given vertical loads was obtained in that period of 75 years ago. As shown in Fig.6, there are the results obtained from graphical solutions of a Maxwell diagram for two trusses illustrated in the middle of the figure. It should be noticed that these two are the statically determinate trusses, and that each of them was looking like an elementary system of the double Warren trusses to be solved.

The result of the graphical solutions shows us that the Japanese engineer must have applied design vertical loads on both the elementary systems. After comparing the axial forces calculated for the members of the two statically determinate trusses with each other, he has adopted the larger value in either one of them as the stress for choosing cross-sections of the truss members.

It is well known nowadays that a high-speed electronic computer is useful to solve this type of statically indeterminate structures by basing upon the matrix methods. However, in the old days, the statically indeterminate structures consisted of the material which follows Hooke's law were treated in consideration of the strain energy, the principle of least work and the theorem of Castigliano, provided that the small displacements due to deformation can be neglected in discussing the action of the forces.

In a textbook of the strength of materials [1], there is a description that the principle of least work was stated first by F. Menabrea in his article, "Nouveau principe sur la distribution de tensions dans le systèmes élastiques", published in 1858, and that a complete proof of the principle was given by Castigliano, who

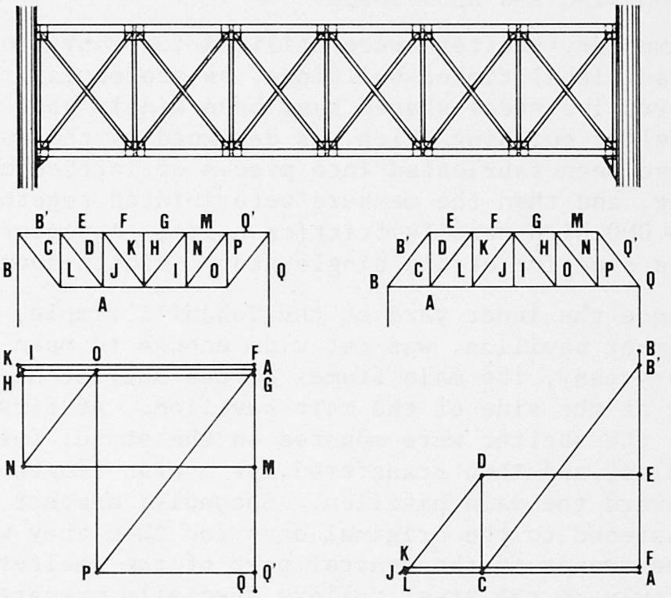

Fig.6 The truss and the results of solution

made this principle the fundamental methods of solution of statically indeterminate systems in the period of 1875-79. Also, the textbook tells us that "for an English translation of Castigliano's work see E.S. Andrews, *Elastic Stresses in Structures*, London, 1919."

If we think of the fact that in the early 1900s there was very little information in Japan on the Italian language papers in this specific field of building technology, we may conclude that the Japanese engineer who designed the double Warren trusses was not familiar with the Castigliano's work when he has engaged himself in the grand repair work of the pavilion of Tohdaiji temple. Of course, the introduction of the useful slope-deflection method [2] into Japan was a couple of years later than the grand repair work.

Thus, we can say now that the engineer has tried his own approach of obtaining the approximate values of the working stress on his statically indeterminate structure, without consulting the theories of structures being developped in the European countries at that time. Nevertheless, the author has proved a number of years ago that his results were not inadequate but his values were different from the exact values by only 10.7 % toward the safe side.

4. LARGE-SCALE REPAIR ON THE MAIN PAVILION CARRIED OUT IN THE 1970S

In 1969, the Tohdaiji temple and the Cultural Properties Protection Commission in the Nara Prefectural Office have established a joint committee, in which the author has been involved, for the survey and inspection of the roofs as well as the frame of the main pavilion. The investigation was carried out for the successive two years, and the scope and orientations of the renovation projects was decided. The following directions then have been drawn from the results of the preliminary survey:

1. Columns, beams and girders of the main pavilion are still in good condition, therefore, repair is not necessary but,

2. All the tiles shall be taken out completely for further inspection, and then the shingles and rafters shall be examined and repaired if corrosions will be observed, and

3. In order to make the renovation possible and easier, a new temporary shelter covering the pavilion will be indispensable. This shelter will render the renovation possible and safe even during rainy days and will protect the pavilion from wind and snow loads.

Temporary shelters were utilized for many projects of repairing the large-scale traditional timber buildings, as stated later. This time, high-tensile, anti-corrosive steel shapes have been widely used as the principal material of the shelter building which was designed by the author. The wide flange steel shapes have been fabricated into pieces of lattice members of the frames by shop welding, and then the members were jointed together at site by using a total of about 33,000 high-tensile friction bolts, A number of track cranes were employed for the erection of the single-story, single-spanned steel frames. (Fig.7)

Since the inner yard at the Tohdaiji temple, surrounding the world's largest timber pavilion, was not wide enough to make the erection of the steel shelter very easy, the main frames of the shelter had to be assembled on a stage prepared at the side of the main pavilion. At first, three frames of the central part of the shelter were mounted on the stage, fastened each other with the friction bolts, and then transfered for a span length of 5.4 m in the east-west direction toward the main pavilion. Secondly, another frame was erected on the stage and fastened to the original ones and then they were moved again for 5.4 m. Thus, the frames of the central part of the shelter building have been moved very slowly on the steel rollers specially prepared. After the frames were settled down at the designated position, they were anchored to the foundation, and then the frames at both sides of the shelter were erected.

Thus, the main pavilion was covered by the steel shelter of about 86 m in the east-west direction, and of about 79 m in the north-south direction measuring from the center lines of its corner columns. The exterior columns were spaced at 5.4 m around the perimeter of the building. The height of the shelter was about 55 m. The shelter had 16 spans in the longer direction whereas 15 spans along the shorter direction.

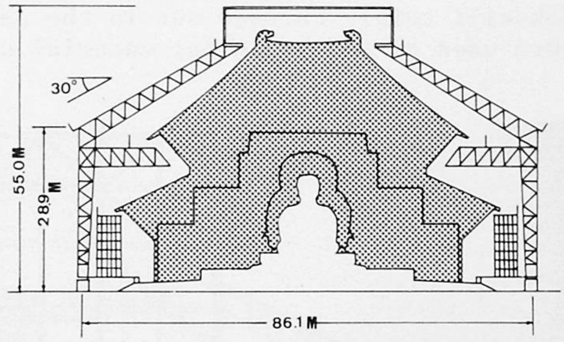

Fig.7 The steel shelter used in 1974-78

The roof construction of the shelter consisted of a layer of very thin steel plates, corrugated and painted on both surfaces. The corrugated plates were further constrained by flat steel bars so as to prevent them from being blown off. Two inch (5 cm) deep steel purlins of cold-rolled light-gauge shapes were placed at a pitch of approximately 60 cm. The purlins were spanning about 1.8 m between the supporting beams.

The side walls of the shelter were covered with cotton sheets and metal meshes. The wind resisting system consisted of rigidly connected frames interacting with diagonal braces. Virtually, every available column was thus mobilized to contribute to the lateral-force-resisting system.

An extremely comprehensive wind investigation, involving meteorological studies and wind tunnel testing, was carried out. The latter was conducted at the Disaster Prevention Research Institute, Kyoto University. A pressure model was used to define the pressures acting on the faces of the shelter. The wind climate of the building location was determined in terms of wind frequencies by direction and speed as well as velocity variations with height together with the turbulence structure.

In addition to the dead and live loads, as well as snow and wind loads, the shelter has carried moving loads of travelling cranes. Their capacity of two tons each carried the roof tiles and rafters of the main pavilion. One must be surprised to hear that the size of a wooden rafter is of about 30 x 30 cm in the cross-section and it is approximately 10 m long, weighing roughly 450 kilograms. The travelling cranes were supported by the cantilever trusses in the shelter, the tip of which were surrounding the eaves of the upper roof of the main pavilion.

5. CONCLUSIONS

In doing repair work on traditional wooden buildings, it is necessary to preserve their original appearance as much as possible, and it is extremely effective for this purpose to utilize steel members as auxiliary ones, wherever necessary, in order to remove structural defects due to ageing. However, there is a danger that the timber in contact with corroded steel members is deteriorated by rust so that it is indispensable to pay sufficient attention to prevent this. It happens very often that modern rolled steel nails swell as they get rusty and that cracks are caused in wooden members into which such nails were driven. In view of this, the use of forged nails made from iron sand by the traditional Japanese manufacturing method appears to be more suitable for the permanent preservation of wooden members.

Furthermore, there are many cases in which wooden buildings dismantled for repair are covered with temporary shelters. Fig.8 is the drawing of the temporary shelter built up for the large-scale repair work on the main pavilion of the Tohdaiji temple carried out in the period of 1905-15, showing us that the logs were used as the principal material and that how the shelter was assembled.

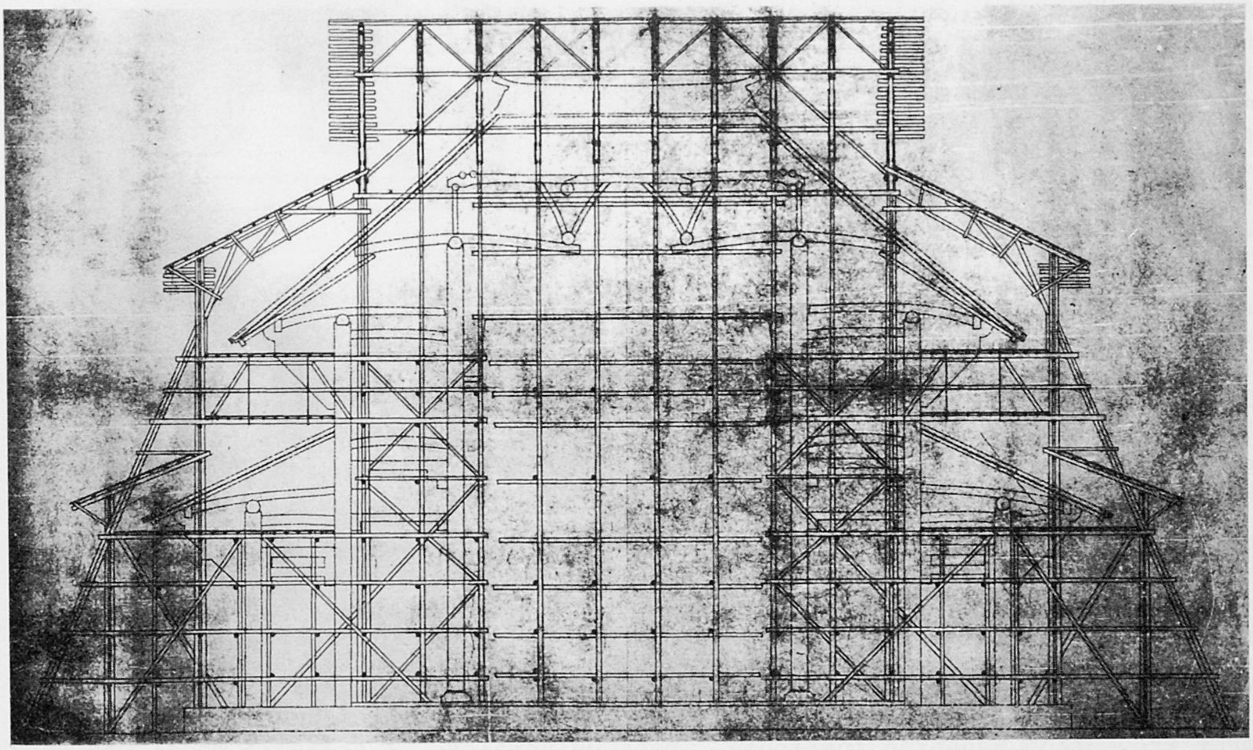

Fig.8 Section of the temporary shelter used for the project in 1905-15

In recent years, temporary shelters consisting of steel frames have been used extensively because of the shortage of timber resources for construction work and also of the regulations concerning the safety and hygiene of workers involved. In the latter case, it is easy to install overhead travelling cranes and other lifting mechanisms in the temporary shelter, which can serve not only to increase the safety of workers at the site but also to secure higher efficiency in handling the materials. We are very proud to say that the grand repair work on the main pavilion of the Tohdaiji temple has been completed satisfactorily in October 1980 without any accidents.

6. ACKNOWLEDGEMENT

The author wishes to express his gratitude to the engineers at the Cultural Properties Protection Commission in the Nara Prefectural Office for their support and cooperation.

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