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# TIMBER ROOF STRUCTURE WITH COMBINATION OF RIGIDITY INCREASE EFFECT OF FOLDED PLATE SHAPES AND RECIPROCAL SUPPORT EFFECT OF LATTICE FRAME

Yui Amano[1], Takahiro Yonezu[2], Takaharu Suzuki[3], Soichiro Kushima[4], Hiroomi Tanaka[5], Hidenori Tanaka[6], Mizuki Hayashi[7]

**ABSTRACT:** TOYOTA Mobility ShinOsaka Neyagawa Store is a single-story automobile dealership under construction in Osaka Prefecture, Japan. The structure type of the building is a hybrid construction that combines wooden and steel structures, and its steel-framed structure resists seismic forces. For the showroom space of the building, a long-span timber roof structure is achieved by using the rigidity increase effect of a folded plywood plate structure and the reciprocal support effect of a lattice frame. The directions of installing two-way beams were determined, considering both the structural optimal solution based on geometric shapes and the design concept, through the utilization of a computational design tool. We established a workflow focused on 3D modelling throughout the phases from design to construction, which enabled us to collaborate with the fabricators and constructors from an early stage. This collaborative approach facilitated high-precision 3D modelling that combined quality and constructability. As a result, the issues in production were smoothly resolved, which led us to achieve the digital fabrication of wooden members.

**KEYWORDS:** lattice frame, folded plate effect, digital fabrication, 3D modelling

## 1 – INTRODUCTION

The TOYOTA Mobility ShinOsaka Neyagawa Store is a reconstruction project of the 40-year-old automobile dealership building located in Neyagawa City, Osaka Prefecture, Japan. The building owner Toyota Mobility ShinOsaka Co., Ltd. has actively made efforts towards the reduction of environmental impact, such as use of environmentally friendly building materials and greening promotion. As this building is not an exception, the owner requested the use of wood for structural elements and interior and exterior finishing as part of the company's environmental efforts. Furthermore, we aimed to create a comfortable space where users can feel free to stop by from the perspective of contributing to the local community. This paper describes the process from design to construction of a special roof structure using exposed wood, and how to solve the issues.

## 2–BACKGROUND

The owner owns approximately 160 hectares of cedar forest in Wakasa Town, Tottori Prefecture, and requested the use of cedar trees in the company's forest which were ready for felling. Thus, we planned to use them mainly for the structural frame of the building. The owner purchased this forest around 1930 and has entrusted the local residents to manage it. The company's successive presidents have visited it to plant and maintain trees. A total of 455 cubic meters of approximately 60-year-old cedar trees were cut down by the middle of June 2024, sawn into lumber in Wakasa Town, and processed into glued laminated wood in Ishikawa Prefecture.

[1] Yui Amano, Design Dept., Takenaka Corporation, Osaka, Japan, amano.yui@takenaka.co.jp

[2] Takahiro Yonezu, Design Dept., Takenaka Corporation, Osaka, Japan, yonezu.takahiro@takenaka.co.jp

[3] Takaharu Suzuki, Design Dept., Takenaka Corporation, Osaka, Japan, suzuki.takaharu@takenaka.co.jp

[4] Soichiro Kushima, Design Dept., Takenaka Corporation, Osaka, Japan, kushima.souichirou@takenaka.co.jp

[5] Hiroomi Tanaka, Design Dept., Takenaka Corporation, Osaka, Japan, tanaka.hiroomi@takenaka.co.jp

[6] Hidenori Tanaka, Design Dept., Takenaka Corporation, Osaka, Japan, tanaka.hidenori@takenaka.co.jp

[7] Mizuki Hayashi, Construction Dept., Takenaka Corporation Nagoya Branch Office, Nagoya, Japan, hayashi.mizuki@takenaka.co.jp


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*Figure 1. Owner's company-owned forest*

*Figure 2. Ceder wood right after felling*

## 3–PROJECT DESCRIPTION

### 3.1 OVERVIEW OF ARCHITECTURAL PLAN

The building is a single-story structure with a building area of approximately 1,300 square meters. The floor plan has a polygonal shape that conforms to the site configuration. Fig. 3 shows the floor plan, the interior of which comprises a showroom zone, a maintenance workshop, and office areas. The showroom zone has a presentation room that functions as a car delivery room, in addition to a space for business discussions and meetings. The design concept is to provide visitors with a spatial experience that makes them feel like they are in a forest, aiming to create an inviting and comfortable store for customers.

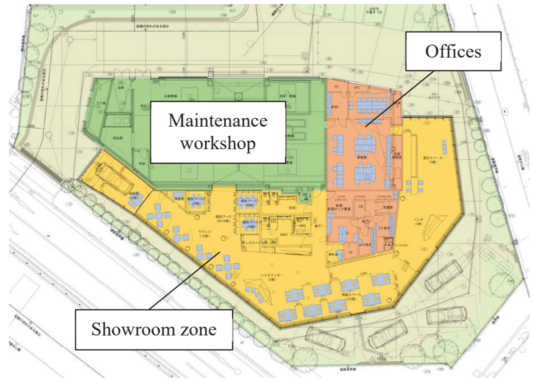


*Figure 3. Floor plan*

### 3.2 EXTERIOR AND INTERIOR DESIGNS

Figs. 4 and 5 respectively show the renderings of the exterior and interior of the building. The exterior design mainly features the roof shape consisting of hill-like volumes that evoke the majestic mountain range of the company-owned forest. The interior design is intended to induce a spatial experience that makes visitors feel like they are under a canopy of trees by supporting the roof structure with a lattice frame using exposed cedar wood from the company's forest.

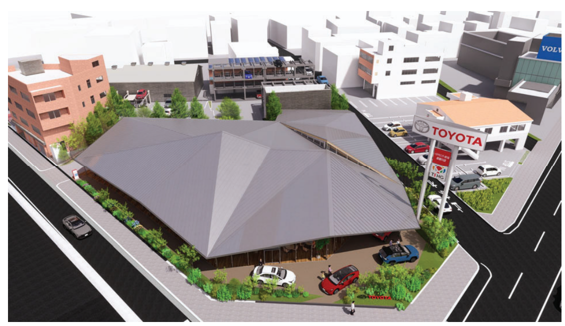


*Figure 4. Rendering of exterior*

*Figure 5. Rendering of interior*

The two-way beams as the components of the frame are designed to differ in installing direction for each face of the folded roof composed of triangles, achieving a structure that meets the required structural performance and architectural design quality, which is described later.

## 4–DESIGN PROCESS

### 4.1 STRUCTURAL PLAN

The structure type of the building is a hybrid construction that combines steel and wooden structures. The office and maintenance workshop areas are constructed in steel, while the showroom zone is constructed in wood. They are clearly zoned but integrated as one building. For the structural style, we applied a rigid-frame (Rahmen) structure with vertical braces arranged in the steel structure to bear seismic forces, which enabled us to minimize the wooden member cross-sections by keeping the wooden structure of the showroom zone free from seismic forces and using it only for a long-term design. Besides, the front of the showroom zone consists of a point-fixed glazing system, the outer perimeter of which has equally spaced steel columns with diameters as small as 80 mm, creating a space open to the outside. The overall framed structure is designed in accordance with the Japanese Building Standards Act, Order for Enforcement of the Act, and related notifications [1][2][3]. The Structural Calculation Route 2 is applied, considering the scale of the building. The aim of designing based on the Route 2 is to ensure the safety during a large earthquake by reducing the rigidity change and eccentricity in the height direction and thus keeping the strength, rigidity, and toughness above given levels. Since mainly the vertical braces in the steel structure are used to bear seismic forces in this building, the allowable stress has been calculated by increasing the seismic force according to the horizontal force sharing ratio of the braces.

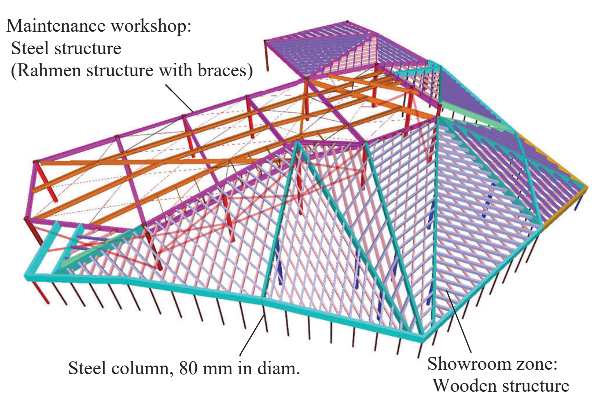


*Figure 6. Basic structural plan*

### 4.2 FIRE RESISTANCE DESIGN

The wooden members of this building needed to be designed so that it might not collapse during the 45-minute fire period because it is a semi-fireproof building. Specifically, they are designed so as to keep their cross-sections, except for the 35-mm thick burning layer around the wooden members, from exceeding the allowable stress level for temporary loading when sustained load is applied. Moreover, we performed a fire resistance experiment to determine the thickness of the fireproof paint for the steel mullions so that the steel temperature which would rise during a fire might not reach the ignition temperature of the wooden members at the joints between the steel columns along the outer perimeter and the laminated wood girders. Fig. 7 shows the profile and section of the test specimen. We have confirmed that when the coating thickness of the fireproof paint is 5 mm, the steel temperature does not reach 260 degrees Celsius, the ignition temperature of the wood, and this result was used to determine the paint specifications (Fig. 8).

| | |
|---|---|
| Steel | FB-100×50<br>(L=1,200mm) |
| Fireproof paint coating thickness | 5mm |

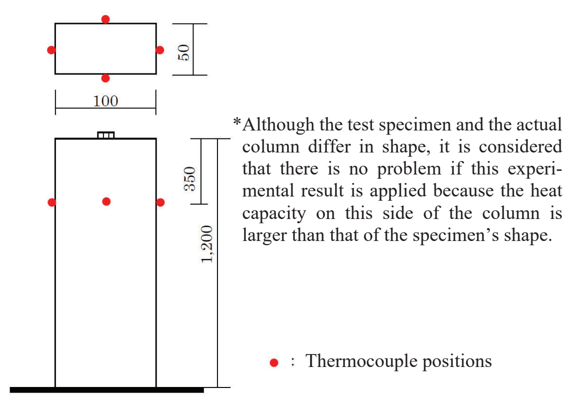


*Figure 7. Profile and section of test specimen*


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Image of specimens before test

Face with thermocouple (3) (Long side)
Expansion ratio: 6
Condition of carbonized layer: Good

Face with thermocouple (2) (Short side)
Expansion ratio: 4
Condition of carbonized layer: Good

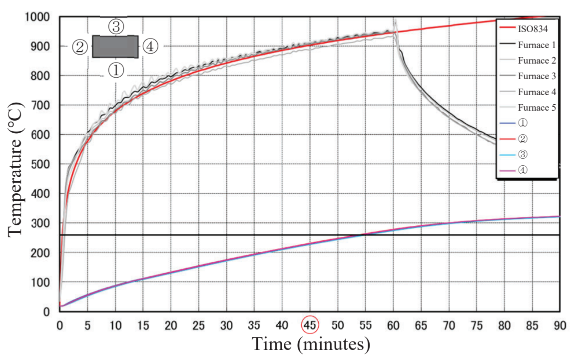


*Figure 8. Fire resistance test results*

## 4.3 DESIGNING OF TIMBER ROOF STRUCTURE

The timber roof structure was originally planned to support the roof by arranging binding beams in one direction within each triangle enclosed with girders. However, the architect requested that the cross-sectional shapes of binding beams should be minimized as much as possible in terms of architectural design despite the roof span as long as up to approximately 18 meters. Furthermore, the structural conditions were extremely strict because the cross sections were studied on the assumption that the 35-mm thick burning layer around the members would be lost during a fire, based on the concept of burning layer design. As a result, when binding beams were arranged only in one direction, extremely large sections were required with the beam height exceeding one meter. Therefore, we thought of minimizing the cross-sectional shape per binding beam by arranging binding beams in two directions, producing a reciprocal effect (Fig. 9). The binding beams arranged in upper and lower stages reduced the load shared by one beam, which enabled us to design the beams with a height of approximately 300 mm and use the cedar wood from the company-owned forest. Meanwhile, strong Douglas fir wood is used for the ridgeline girders to support binding beams, adding contrast to the structure plan. Fig. 10 shows the cross-sectional structure of the roof. Rafters are installed on the binding beams, and plywood supports are equally spaced between the rafters. Structural plywood, 24 mm thick, is applied on them. The horizontal forces on the roof surfaces are transferred through the structural plywood. Since the roof shape consists of combined triangular folded plates, the rigidity was increased as a whole because of the folded plate shapes, which was found to result in the reduction of stress and deflection by approximately 10-20%. By combining this rigidity increase effect with the reciprocal effect of a lattice frame, we successfully established a long-span timber roof frame in terms of structural design. The following materials and cross-sectional dimensions are used for the members: laminated Douglas fir board - 210 mm by 600-750 mm for the ridgeline girders, laminated cedar board - 120 mm by 300 mm and laminated Douglas fir board - 150 mm by 360 mm for the upper binding beams of the lattice frame, and laminated cedar board - 120 mm by 300 mm for the lower binding beams (Fig. 11).


*Figure 9. Comparison in interior view between different methods of arranging binding beams*

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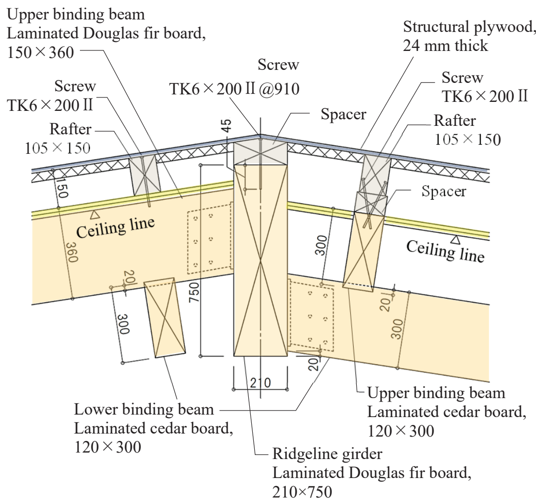


*Figure 10. Cross-sectional structure of roof*

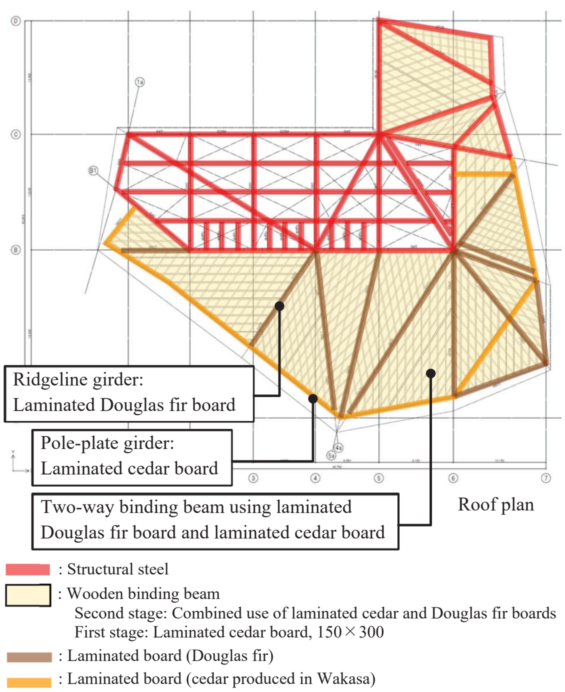


*Figure 11. Cross-sectional configuration of members*

## 4.4 DESIGN PROCESS OF LATTICE FRAME

There is co-relationship between the geometric shapes of triangles and the angles and structural rationality of binding beams [4]. The most structurally advantageous method of installing two-way binding beams is installing them continuously in the directions parallel to the straight lines connecting the tangent points of inscribed circles in triangles, where it is assumed that the straight lines connecting the tangent points of inscribed circles are called the first principal axis and the second principal axis in order from the longer-distance line. By arranging binding beams in parallel to those principal axes in two directions, the reciprocal effect is maximized, achieving the minimization of the stresses and maximum deflection of each binding beam. On the other hand, this method of installing binding beams causes the individual pieces to be shortened as a whole, and consequently is undesirable in terms of architectural design. The architect requested that binding beams should be installed in parallel to at least one of the two long sides of each triangle, considering the sequence from the entrance to the presentation room. Thus, we decided to determine the installing direction according to the architectural design for the lower binding beams close to people's eyes and make adjustments between the angles of the first and second principal axes for the relatively invisible upper beams (Fig. 12).

We incorporated this rule into the verification using computational design, extracted a combination that possesses both architectural design quality and structural rationality while keeping both stress and deflection within the acceptable limits, confirmed it with the architect, and determined the angles of the binding beams. Specifically, a model was created with the specified angles through Grasshopper, a type of visual programming language, using the angles of the two-way beams for each triangle as parameters, and then analysis was conducted using the structural analysis software Midas iGen, the results of which were output into a txt file. The stress and displacement information of the model was extracted using the programming language Python. Then, we built a program that plots the analysis results for each angle to visually check whether they met the criteria. The optimization tool "mode FRONTIER" automatically executed their entire flow (Fig. 13), which has led us to develop a design tool that enables smooth consensus building with the architect.

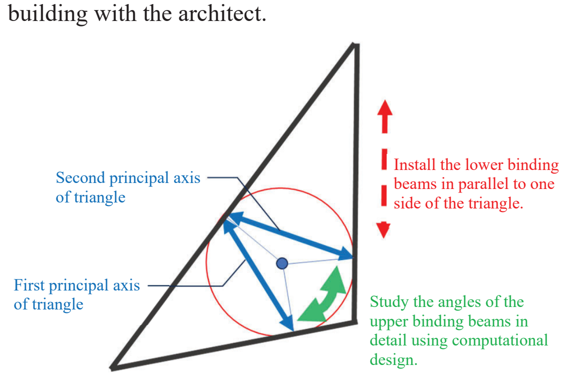


*Figure 12. Principal axes of triangle and directions of installing binding beams*


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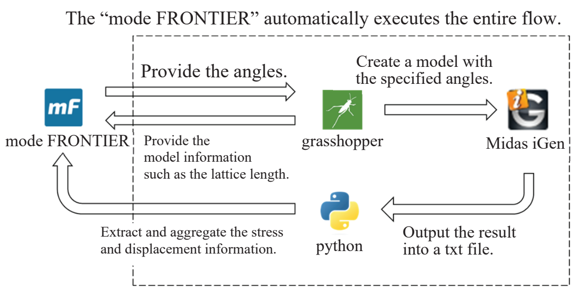


*Figure 13. Entire flow of program*

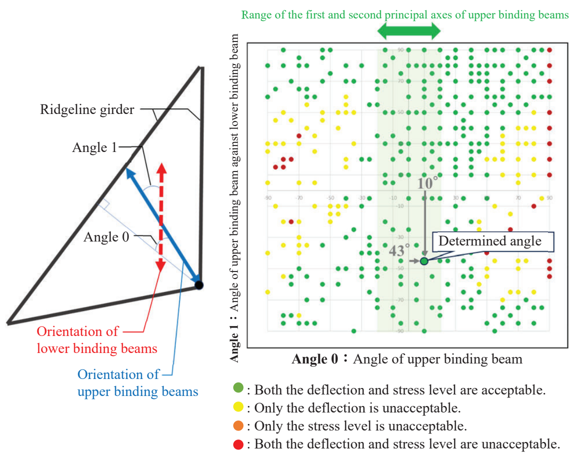


*Figure 14. Plot diagram of analysis results according to beam angles*

For the stress analysis model, the ridgeline girders and two-way beams were modelled using the line elements provided with material information and cross-sectional shapes. Spring elements were input into the joints between two-way beams so that the vertical and horizontal displacements might be in agreement in order to consider reciprocal effect appropriately. The increase in deformation caused by creep needs to be considered for wooden members. For this building, the absolute deformation of 50 mm, relative deformation of 30 mm, and deflection angle of 1/250 have been set as the criteria, considering the creep coefficient of 2. This process has contributed to the achievement of the roof structure incorporating the architect's design concept as well as the most structurally advantageous method of installing binding beams that depends on the geometric shapes of triangles.

## 4.5 WORKFLOW FOCUSED ON 3D MODELLING

It was difficult to two-dimensionally grasp the conditions of the members on the faces of a polyhedral roof structure having a lattice frame. Particularly the two-way beams are angled both in the member axis direction and in the cross-sectional direction, which required us to check the members as to how the beams were connected to the ridgeline girders for the purpose of joint fabrication. Therefore, we have created a workflow focused on 3D modelling throughout all the phases from design to fabrication by starting the utilization of a 3D model in the preliminary design phase and brushing up the model during the period between the detailed design and implementation phases.

First, in the preliminary design phase, individual 3D models were created using specialized applications for each of the design, MEP, and structure functions. They were superimposed on each other to check for any interference and clarify design issues. Although the precision of the 3D models is not high in this phase, it is possible to extract issues such as fatal interference conditions at an early time and consider countermeasures because editing is relatively easy. Since the plan can often change in the phase, it is easier to review it if it is not elaborated too much in detail.

Meanwhile, in the detailed design phase, the models created using different applications for architectural and structural designs were unified into one using Rhinoceros. Thus, we created a 3D model into which information was integrated. Since the structural steel model incorporated a model produced by the steel fabricator, it also incorporated the representation of the parts at joints, such as bolts and diaphragms. The wood fabricator also produced a wood model, which incorporated even small members such as wood furring for ceilings and level adjustment materials. Therefore, it was possible to study the details of the parts and members with higher precision. Furthermore, participation of fabricators at an early stage made it possible to incorporate their comments in the design phase, which successfully led to the enhancement of constructability as well as the quality.

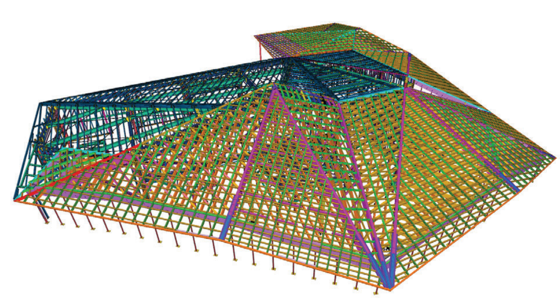

*Figure 15. 3D model in detailed design phase*

We were also able to check for interference between the steel model and wood model and the connections of steel members with wood members. Moreover, since those models were produced by the fabricators, members could be produced from this integrated model through digital fabrication. If the processes from design to construction are focused on 3D modelling, inconsistency between design drawings and shop drawings can be prevented in advance, and errors in the members are unlikely to occur.

### 4.6 STUDY OF JOINT DETAILS

Because this building is a hybrid structure of wood and steel, the connections at joints are likely to be complicated. Therefore, we studied the details of the metal fittings for the joints, making use of the 3D model. Particularly at a point where multiple members are concentrated, it is necessary to avoid interference of fittings while securing spacings of through bolts and drift pins. Fig. 16 shows the detail of the joints of pole-plate girders to steel mullions and to binding beams. At those joints, the drift pins are subjected to the shear forces at the binding beam ends and transfer them to the steel mullions through the steel plates inserted into the wood. Even in the case of complicated details that are difficult to check two-dimensionally, visualizing them three-dimensionally makes it easy to understand the whole picture. Fig. 17 shows the detail of the intersection between two-way beams. Shear forces and tensile forces occur at those intersections. The shear forces are transferred by cogging the binding beam cross-sections at the intersections and engaging them, while the tensile forces are transferred through hold-down pipes.

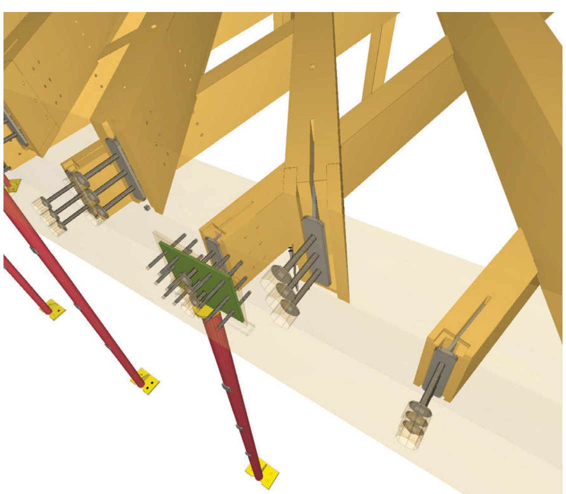

*Figure 16. Joints of pole-plate girders to steel mullions and to binding beams*

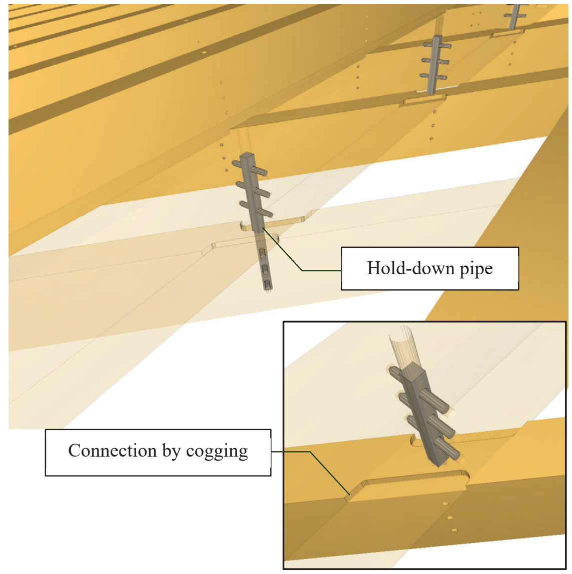


*Figure 17. Joint between upper and lower binding beams (cogging)*

At points where wood members are connected to steel girders, the bolt holes need to be provided with adjustment allowances to absorb the erection errors. We made loose holes for adjustments in the supporting plate for the steel plate inserted into the wood (Fig. 18). All those joint adjustments were made using the 3D model.

The method called “glued-in-rod (GIR)” joint system is employed for the girder-beam joints and column-girder joints. This is a joining method by drilling holes in the wood, inserting rod-shaped joint elements in the holes, and injecting/filling adhesive into the gaps, where the curing of the adhesive works to transmit tensile stress through its adhesive force and the joint elements and generate joint strength. This method enables bending stress transmission by securing the distance between joint elements (Fig. 19).

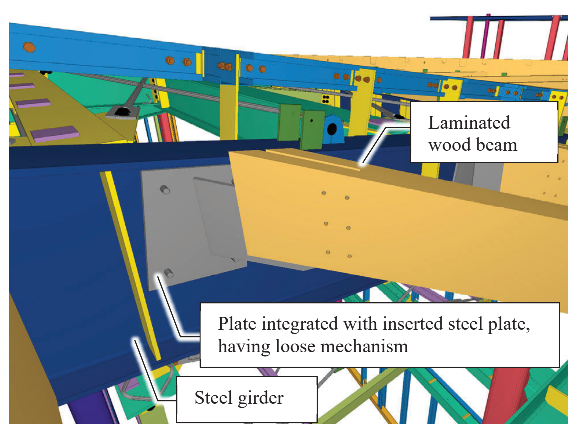


*Figure 18. Joint between steel girder and laminated wood beam*


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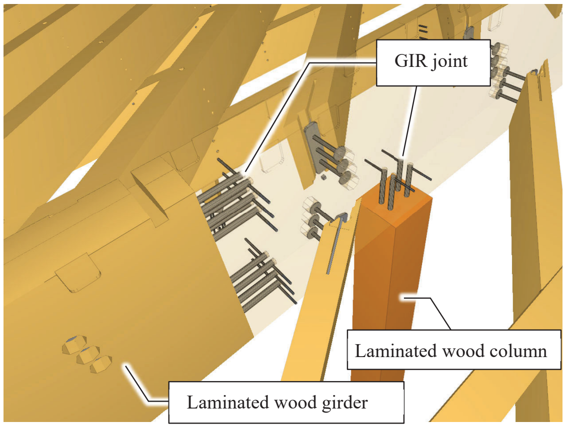


*Figure 19. Laminated wood girder joint and laminated wood column-girder joint*

## 4.7 FABRICATION OF MOCK-UP

Prior to the actual construction, we fabricated a partial mock-up of two-way beams and checked the construction sequence and joint details. Cogging applied to the joint between the two-way beams is one of the traditional joint details used in the Japanese wooden architecture.

*Figure 20. Confirmation of mock-up two-way beams*

This method not only prevents the wooden binding beams from sliding sideways against each other by digging grooves in both two wood beams and engaging them with each other but is also expected to transmit shear forces during an earthquake. Combination of the Japanese traditional construction method with a strong hold-down pipe ensures stable transmission of loads. We used a mock-up to confirm with the constructor that those joints could be made without any problem.

## 4.8 CEDAR FELLING AND PLANTING IN OWNER'S COMPANY-OWNED FOREST

We were present with the owner of the building at the cedar felling in the company-owned forest in May 2024 prior to the construction commencement. The forest has been carefully maintained by the local residents for over 60 years, and the cedar trees were in very good condition. The owner has a strong attachment to the trees. He told us that he felt deeply moved, thinking that the trees planted by his predecessors would remain as a building for future generations. The Mayor of Wakasa Town in Tottori Prefecture which owns the whole forest land also hopes greatly that using the cedar of Wakasa for a store in the urban area will revitalize the local forestry industry. The felled cedar wood is milled into lumber at a sawmill in the Town. Utilization of forest resources not only preserves the environment but also contributes to the local community. After felling a total of 300 trees, we planted trees together with the building owner in the company-owned forest in September of the same year. Promoting the cyclic use of forest resources will enable use of wood into the future while ensuring appropriate forest maintenance.

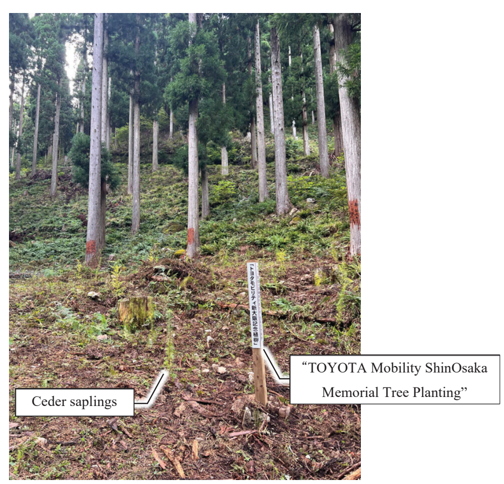


*Figure 21. Cedar planting in owner's company-owned forest*

### 4.9 CONSTRUCTION PROCESS

The building construction was commenced in July 2024. The steel structure erection was complete at the end of 2024, and then the wooden structure erection was commenced in January 2025. Fig. 22 shows how the wooden structure is being erected. The members precut for joints and connections with high precision through digital fabrication are being quickly installed on site. The wooden structure erection is scheduled to be completed in approximately three months. The building is currently under construction, due for completion in September 2025.

*Figure 22. Erection of wooden structure*

## 5 – RESULTS

Application of a hybrid structure of steel and wood and new combination of the rigidity effect of a folded plate structure with the reciprocal support effect of a lattice frame have led to achievement of a long-span wooden framed structure with relatively small member cross-sections. In addition, utilization of high-precision 3D modelling, such as studying the steel-wood joints in detail, has enabled smooth resolution of the issues in production.

## 6 – CONCLUSION

This research has revealed that the reciprocal support effect of a lattice frame in the case of a triangular framework depends on the orientations of the principal axes. By taking advantage of this property, it is possible to construct large space structures using beams with relatively medium-sized cross sections. We will continuously deploy this technology horizontally to share it across project teams as a useful technology to reduce the quantities of members and improve the quality in terms of architectural design.

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