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Advancing Timber for the Future Built Environment

ADVANCED STRUCTURAL DESIGN OF TIMBER BUILDINGS IN JAPAN

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ABSTRACT: According to the Japanese Building Standards Law, load-bearing timber floor structures must have fireproof coatings/claddings. If the timber structure only resists lateral forces like seismic and wind, it can be left exposed. Accordingly, all three timber-steel hybrid frame systems designed for Haneda Airport Domestic Terminal have fireproof claddings. A newly developed system, called CROSS-WOOD, offers a more advanced solution for a timber-steel hybrid frame system that allows the exposure of wooden members while enhancing the aesthetic and sustainable appeal.

KEYWORDS: timber-steel hybrid structure, medium to Large Scale wooden buildings, fireproof construction

1 – INTRODUCTION

Azusa Sekkei, a Japanese architectural firm, is currently advancing several innovative methodologies in the structural design of medium to large-scale timber buildings. While hybrid structures, integrating timber and steel, are the predominant structural system for such projects, the firm is also undertaking initiatives involving pure timber construction.

An exemplary advanced hybrid timber-steel structure is set to be unveiled at the passenger terminal of Tokyo International Airport (Haneda), the busiest airport in Japan by passenger traffic. This will be the first timber-based structure at a major Japanese airport. Specifically, the design features a steel structure on the ground floor, with the upper floors constructed using three different types of timber structures, showcasing a highly innovative approach to structural design.

A notable example of an innovative pure timber project is the large roof ring, which serves as the main circulation space at the Osaka-Kansai Expo. This structure combines traditional Japanese "Nuki-column joint" with cutting-edge modern engineering, resulting in one of the world's largest timber buildings featuring a pure frame construction. In addition to the two previously mentioned examples, the development of the "CROSS-WOOD" hybrid timber-steel column-beam framework system will also be presented. This advanced system facilitates the use of exposed timber structural components while fully complying with the rigorous fire safety standards outlined in Japan's Building Standards Law.

2 – BACKGROUND

In 2021, Japan enacted the 'Act on the Promotion of the Use of Wood in Buildings, etc. to Contribute to the Realization of a Decarbonized Society,' driving the development of advanced medium- to large-scale timber building designs by various firms. Notably, hybrid timber-steel structures are recognized as highly effective solutions, meeting both Japan's stringent fire resistance standards and seismic performance requirements. In contrast, pure timber-based structural designs contribute significantly to sustainability and the advancement of structural engineering principles.

Tokyo International Airport (Haneda) is undertaking an expansion project to enhance airport functions, accommodate future demand growth, and improve passenger convenience, in line with the objectives set by the Ministry of Land, Infrastructure, Transport and Tourism. As part of its sustainability efforts, the airport operator has adopted a hybrid timber-steel structural design for the terminal building. The large roof of the Osaka-Kansai Expo is designed to embody a 'sustainable, circular society in harmony with nature', setting the stage

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for a new era of timber construction aligned with environmental sustainability. The design serves as a symbolic evolution of traditional Japanese timber architecture, enhanced by modern structural engineering, while conveying the message of 'diversity within unity' to a global audience.

"CROSSWOOD" is a hybrid structural system that integrates steel columns and beams, which bear long-term loads and seismic forces, with timber columns and beams designed to resist seismic forces. Since the timber components are solely responsible for seismic resistance, fireproofing is not required.

3 – PROJECT DESCRIPTION

3.1 TIMBER-STEEL HYBRID STRUCTURE FOR HANEDA AIRPORT

Tokyo International Airport (Haneda), the busiest airport in Japan by passenger traffic, is the first major Japanese airport to incorporate timber construction. The adoption of a visible timber design allows it to convey a powerful message to a broad audience, including inbound passengers.

Figure 1: Bird's-eye view

This facility requires a large-span structure to allow airport vehicles to pass through. Consequently, a hybrid steel-timber system with optimized material selection has been implemented. Specifically, the ground-level structure is steel, while the upper floors incorporate: 1) wall columns and roof structures made of CLT, 2) a cantilevered roof structure using large-section laminated timber, and 3) a mixed system with a steel frame on the ground floor and a timber frame on the second floor. The design features a three-layer structure, with distinct structural configurations for each layer.

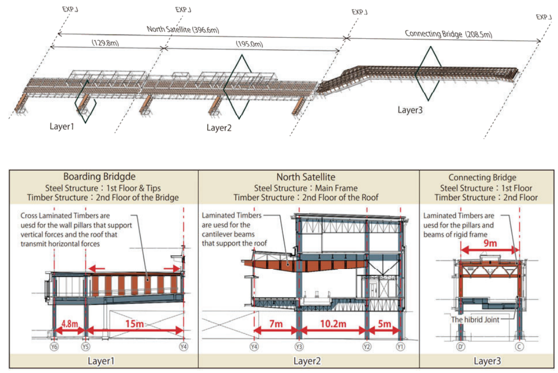

Figure 2: Three layers of the timber-steel hybrid structure

1) The CLT wall columns and roof structure are employed in the fixed bridge section connecting the concourse boarding gates to the aircraft. 2) The CLT wall columns, supported by the steel beams of the second-floor slab, bear the dead load of the roof. The CLT roof slab transfers seismic forces to the steel structures on both the concourse side and the far end of the fixed bridge.

Figure 3: CLT wall columns and roof structure (interior perspective)

2) The cantilever roof structure, utilizing large-section laminated timber, is implemented on the upper portion of the concourse's second floor. Timber beams with a maximum depth of 1.8 meters are spaced at 2-meter intervals and suspended from two points on the steel beams of the third floor, forming a 7-meter cantilever frame.

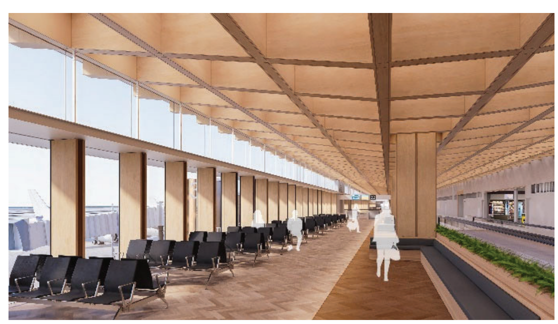

Figure 4: Cantilever roof structure utilizing large-section laminated timber (interior perspective)

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The cantilever beams are designed to resist both horizontal and vertical seismic loads. Horizontal bracing made of round steel incorporated at the beam ends to ensure in-plane stiffness. Additionally, 45mm square steel bars are positioned at the cantilever ends, above the intermediate eave, to mitigate creep deformation of the timber beams. The curtain wall at the cantilever ends is designed as a self-supporting structure based on the second floor, utilizing a steel frame. The timber beams on the third floor feature a mechanism that allows horizontal sliding, enabling the structure to accommodate deformations effectively.

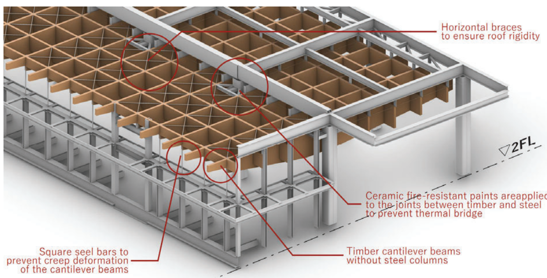

Figure 5: Structural system of the cantilever roof

3) The mixed structural system, consisting of a steel frame on the first floor and a timber frame on the second floor, is used in the connecting passage between the terminal and concourse. A timber frame structure with a 9-meter span, supported by a portal steel truss, is spaced at 4-meter intervals along the longitudinal direction above the steel frame on the first floor. To ensure high rotational stiffness at the connections between the timber columns and beams, glued-in-rod timber joints (GIR joints) are employed. This configuration meets the required overall stiffness ratio for the building, allowing the design to be submitted for approval under Structural Calculation Method, Route 2.

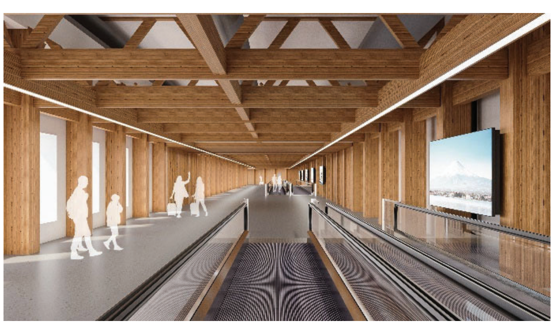

Figure 6: Mixed Structural System with Timber Frame (Interior Perspective)

The column base connections between the steel frames and timber columns utilize GIR joints, similar to those used in timber column-beam connections. While extensive research has been conducted on the joint strength of reinforced concrete and timber, there is limited data on the joint performance between timber and steel frames, leading to insufficient understanding of their strength and failure modes. To address this, full-scale column base prototypes were fabricated to assess their hysteresis behaviour.

In the column base joint design, reinforcing bars are pre-assembled to create a plastic deformation zone, ensuring that the section yields before the timber columns experience splitting failure. This approach results in a column base with sufficient tensile capacity. Additionally, to ensure effective seismic force transfer from the timber columns to the substructure without displacement, the base plate and reinforcement are securely integrated using threaded connections. Full-scale testing confirmed that the design exhibits stable, spindle-shaped hysteresis behaviour and provides the necessary strength to meet performance targets.

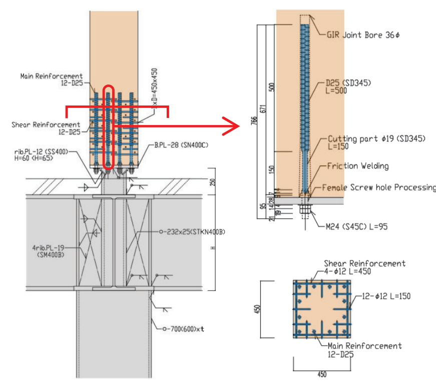

Figure 7: Detailed Drawings of Timber Column Base Joint

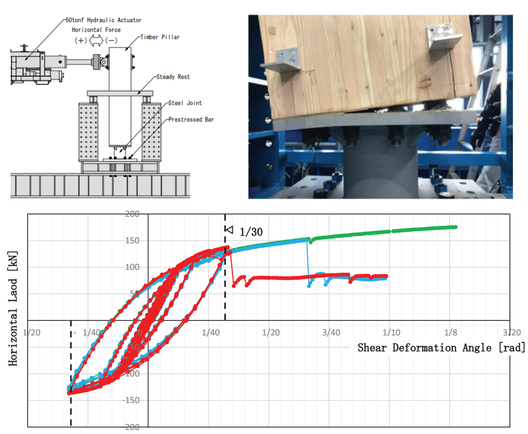

Figure 8: Full-Scale Experimental Results of Timber Column Base

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3.2 STRUCTURAL DESIGN OF THE GRAND RING FOR THE EXPO2025 OSAKA, KANSAI, JAPAN

The large ring-shaped roof of the Osaka-Kansai Expo serves as the main circulation pathway for the entire site and is one of the largest timber structures in the world, designed to embody the concept of 'diversity within unity.

Figure 9: Aerial Perspective (Courtesy of Japan Association for the 2025 World Exposition)

The large roof ring combines traditional Japanese timber construction techniques, such as the 'Nuki joint' used in shrines and temples, with modern structural engineering. This integration allows for the creation of a two-way frame structure without the need for diagonal bracing or shear walls. The structure covers approximately 60,000 square meters, with an inner diameter of 615 meters, an outer diameter of 675 meters, and a circumference of about 2 kilometres. It serves as the primary circulation route while also providing a comfortable space that shields visitors from rain, wind, and sunlight. The frame design is based on a 3.6-meter grid, with repeating columns measuring 420mm in cross-section and beams sized at 210mm by 420mm.

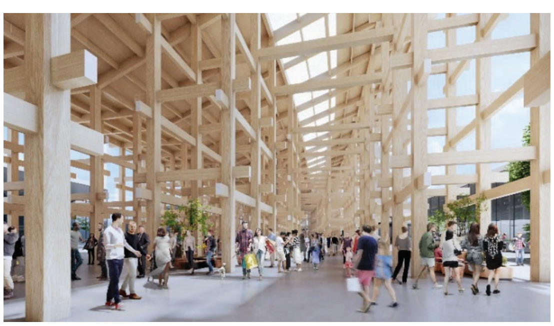

Figure 10: Interior perspective drawing (Courtesy of Japan Association for the 2025 World Exposition)

The large roof ring is composed of a series of radiating units: 4×8 units (4 spans in the circumferential direction and 8 spans in the radial direction) and 2×8 units (2 spans in the circumferential direction and 8 spans in the radial direction), arranged continuously in a radial pattern. The units are connected by beams with pin joints at the ends, forming a unified structure without the need for expansion joints (EXP.J).

Both the columns and beams are made from uniform-grade laminated timber. The columns use either Scots Pine with a strength grade of E95-F270 or Japanese Hinoki Cypress E95-F270, while the beams use Sugi (Japanese Cedar) E65-F225 or Scots Pine E105-F300. The flooring is made of CLT.

To achieve a purely timber two-way frame structure, a height difference of 840mm (twice the beam depth) is incorporated between the circumferential and radial beams. The column-beam joints are designed as moment-resisting joints with rotational stiffness, utilizing the traditional Nuki joint.

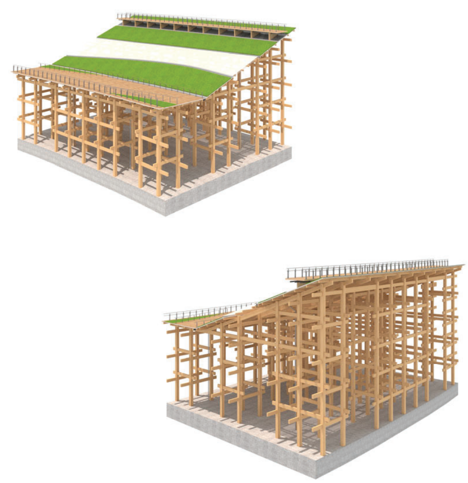

Figure 11: Model of the Two-Way Frame Timber Structure

This building is classified as a "Laminated Timber Structure" under Article 46, Paragraph 2, Item 1 of the Building Standards Act Enforcement Ordinance and is exempt from the wall area regulations specified in Paragraph 4 of the same article. With a height between 13 and 31 meters, the building follows the "Structural Calculation Method Route 2" for timber structures.

The interlayer displacement angle has been verified to be within 1/120, in accordance with Article 82-2 of the Building Standards Act Enforcement Ordinance. This ensures that major structural components will not suffer significant damage under seismic forces.

To meet these design criteria, the basic design specifies the required rotational stiffness for the column-beam joints to be approximately 15,000 kNm/rad, and for the column base joints, approximately 30,000 kNm/rad.

A typical Nuki joint forms a connection by passing the beam through a hole in the column, resulting in a joint secured by the interlocking of the components. The rotational stiffness and bending strength of the joint are primarily governed by the embedment behaviour of the wooden members resisting the bending moment. Therefore, the rotational stiffness of the Nuki joint is typically calculated based on the embedment of the beam's top and bottom surfaces in the perpendicular direction to the grain (triangular displacement embedment), as this is the dominant failure mode when the beam rotates through the column hole.

For this building, a higher rotational stiffness is required. Therefore, Glue-in-Rods (GIR) are inserted in the perpendicular direction of the beam's fibers, and steel plates are attached to prevent fiber embedment in the beam's upper and lower surfaces. This improves both rotational stiffness and bending strength. The construction process involves inserting the GIRs and attaching the steel plates at the factory, then passing the beam through the column's hole on-site, driving wedges, and applying axial force to secure the assembly.

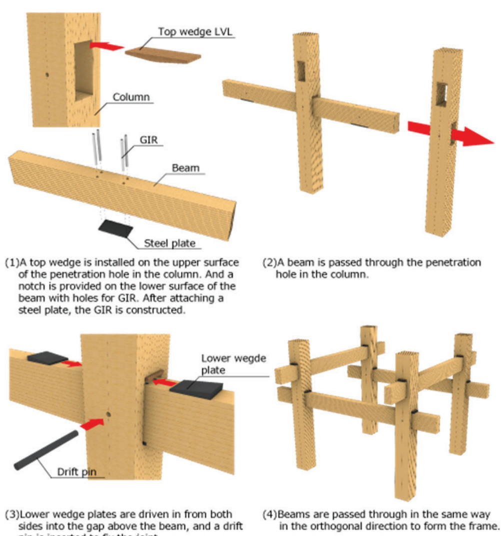

Figure 12: Configuration of the 'Nuki Joint' for Enhanced Rotational Stiffness

The rotational stiffness of the Nuki joint is determined by combining the rotational stiffness derived from the axial stiffness of the Glue-In Rods (GIR) inserted into the beam, and the rotational stiffness calculated from the compressive stiffness of the fiber embedment in the top and bottom surfaces of the straight-through-hole in the column. These are treated as springs in series. The axial stiffness of the GIR is based on experimental data from the 'Mid-Scale Timber Building Research Group Design Support Database (Ki).' The calculated rotational stiffness of the Nuki joint (approximately 13,000 kNm/rad) closely matches the target value. Consequently, full-scale testing will be conducted to assess the actual rotational stiffness and load-bearing capacity.

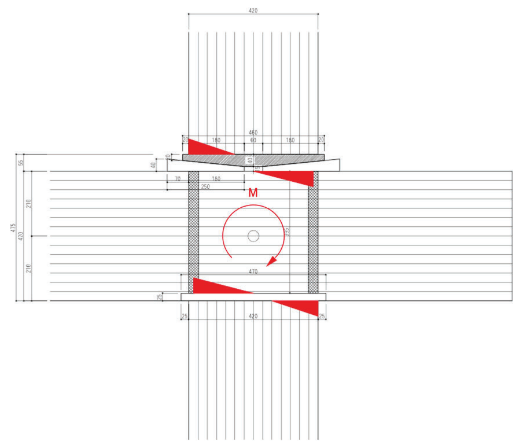

Figure 13: Conceptual Illustration of Rotational Stiffness of the Nuki Joint

Table 1: Rotational Stiffness Based on the Axial Stiffness of the GIR

Axial stiffness of GIR	$K_{\_GIR}$	246	[kN/mm]
Center distance of GIR	j	388	[mm]
Number of GIR (one side) 2 [pieces]	n	2	[本]
Axial force corresponding to 1mm	$N = K_{\_GIR} \times 1$	246	[kN]
Bending moment corresponding to 1mm	$M = n \cdot N \times j$	190.9	[kNm/mm]
Rotational deformation angle corresponding to 1mm	$\theta = 1/(j/2)$	1/194	[rad/mm]
Rotational stiffness of GIR	K_{θ_GIR} (=M/θ)	37034	[kNm/rad]

Table 2: Rotational Stiffness Based on Compressive Stiffness of Fiber Embedment Along the Column's Fiber Orientation

Young's Modulus of Column Member	E_0	9500	[N/mm²]
Column member size	D	420	[mm]
Triangular displacement embedment length	xp	120	[mm]
riangular displacement embedment width	yp	210	[mm]
Stress center distance	$j = D-(2/3 \cdot xp)$	340	[mm]
Surface pressure stiffness of force perpendicular to the fibre direction	$k_{\_90} = E_0(0.008+1/xp)/(70-0.3xp)$	4.6	[N/mm³]
Surface pressure stiffness of force along the fibre direction	$k_{\_0} = 5 \cdot k_{\_90}$	22.8	[N/mm³]
Axial force corresponding to 1mm	$N = (xp \cdot yp/2) \times k_{\_0}$	287.5	[kN/mm]
Bending moment corresponding to 1mm	$M = N \times j$	97.8	[kNm/mm]
Rotational deformation angle corresponding to 1mm	$\theta = 1/(D/2)$	1/210	[rad/mm]
Rotational stiffness of embedment along the fiber direct	K_{θ_C} (=M/θ)	20529	[kNm/rad]

Table 3: Rotational Stiffness of the Nuki Joint Combined as Springs in series

Rotational stiffness of GIR	K_{θ_GIR}	37034	[kNm/rad]
Rotational stiffness of embedment along the fiber direct	K_{θ_C}	20529	[kNm/rad]
Rotational Stiffness of the Joint of "*Nuki* joint"	K_θ $(=1/(1/K_{\theta\_GIR}+1/K_{\theta\_C}))$	13207	[kNm/rad]

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3.3 ABOUT CROSS-WOOD

CROSS-WOOD is assembled as the Step 1-6 shown below.

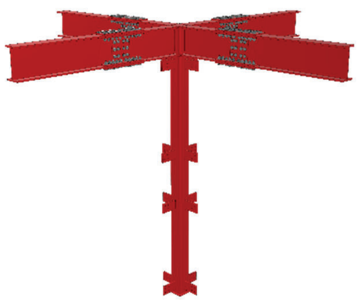
Step 1: Steel frames of CROSS-WOOD are moment rigid frames. The gusset plates on the steel column faces connecting wood columns are attached in 2 orthogonal directions at 4 different heights per column.

Step 2: Steel plates are fixed to wood columns with many screws. The wood columns are not directly attached to the steel columns but are attached as the high strength bolted friction joint through these steel plates. The steel plates and the screws disperse the forces flowing from the high-strength bolts.

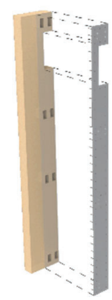
Step 3: The gusset plates on the steel column faces and steel plates on the wood columns are connected as the high strength bolted friction joint.

Step 4-5: The adhesive is applied to the surfaces of the wood columns in multiple circles where the wood beams will be attached, and the wood beams are inserted into the pre-drilled holes in the wood columns and fixed with the screws.

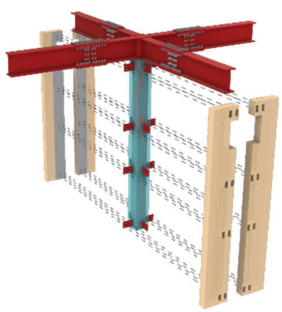
Step 6: The orthogonal wood beams intersect at the different levels. The assembly of the unit will be completed in this way. The wood beam-beam joints are supposed to be located near the center of the beam span, and the units are combined to complete the whole frame structure.



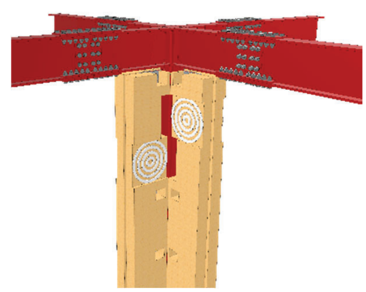
Step 1: Steel frame



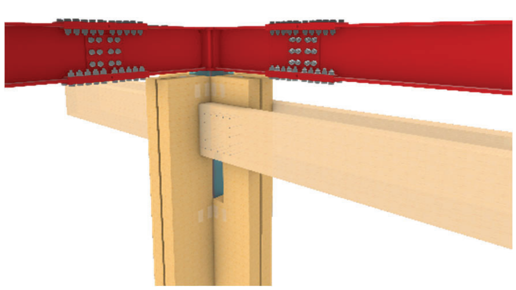
Step 2: Wood Column



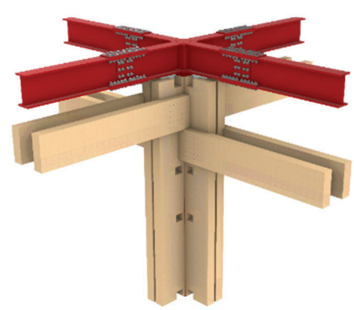
Step 3: Connection of wood columns



Step 4: Adhesive on the wood column



Step 5: Connection of wood beams



Step 6: assembled frame

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4 – EXPERIMENTAL SETUP (MAIN TEXT)

The experiment was conducted in the way shown in Fig. 14, with a steel column and a wood column-beam frame assembled in only one direction, upside down. Each end of the beam was supported and the distance between the supports is 3.6 m. The Top of the specimen, which was originally the bottom of the steel column, was set as the force point and the applied forces were positive-negative alternating incremental cyclic forces based on Japanese performance evaluation methods, and the cyclic history was conducted at positive-negative deformation angles of 1/450, 1/300, 1/200, 1/150, 1/100, 1/75, and 1/50 rad of shear deformation of the structure. High-sensitivity displacement sensors were used to measure the rotation angle of the joint, and the relative displacement of the column to the beam was determined from the values of DG5-8 in Fig. 14, using a displacement sensor interval (l0) of 1,370 mm on either side.

As an experiment of joint, an analysis of the result was also conducted using the M-θ curve, which evaluates the bending moment and the rotation angle applied to the joint. However, the P-δ curve, which is the relationship between applied force P and inter story displacement δ, is more useful for design purposes, so the results are described based on the P-δ relationship. The inter story displacement (δ) was obtained from the following equation.

$$\delta = (DG2 - (DG3+DG4) / 2) \text{ [m]} \quad (1)$$

The performance required for CROSS-WOOD is to be able to bear a shear force of 100kN at the displacement of 1/200rad. In this experiment, a large bending moment to the joints was required with a small amount of force, so the test was executed as cantilevered column, but when CROSS-WOOD is applied to the real building, beams are attached with both the top and bottom of columns. Therefore, the inflection point of the bending moment of the column is expected to be near the center of the story, and a shear force of 50 kN at the displacement of 1/200 rad is sufficient for this experiment.

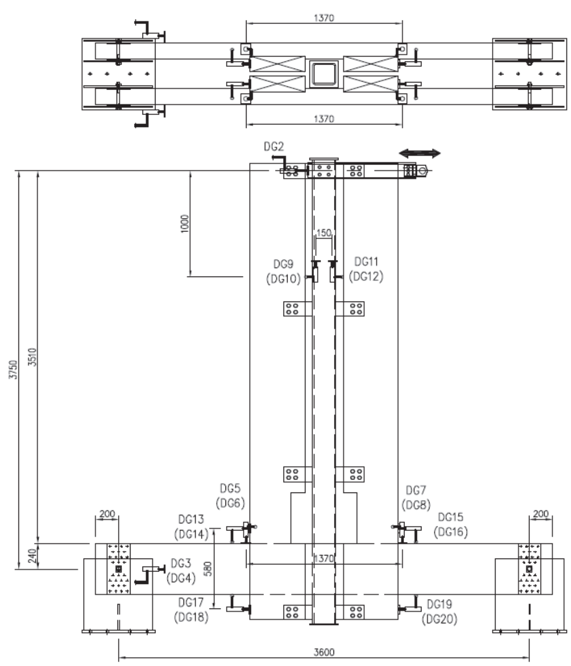

Figure 14: specimen

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5 – RESULTS

Three test specimens were prepared, and the average of the results from each shall be used. Initial stiffness was calculated by the following equation based on the result of the experiment.

$$K = Py / \delta y \text{ [kN / cm]} \tag{2}$$

where Py: yield force [kN]

δy: yield displacement [cm]

And the short-term reference strength, which is used as the frame strength for the short-term load combinations was calculated by the following equation.

$$F = min(Pa,Pb,Pc,Pd) \text{ [kN]} \tag{3}$$

where Pa: yield force Py [kN]

Pb: ultimate strength $Pu \times 0.2 \sqrt{(2\mu\text{-}1)}$ [kN]

Pc: maximum strength $Pmax \times 2 / 3$ [kN]

Pd: force at the displacement of 1/120 rad [kN]

Table 4 and 5 show the stiffness and the strength of CROSS-WOOD from the result of the experiment. The displacement of 1/200 rad means the δ = 18.75 mm because the height of the story is 3,750 mm in this experiment. Since the average initial stiffness from the experimental result is 2.67 [kN/mm], this means that the cantilevered column in the experiment bears a shear force of 50.06 [kN] during the 1/200 rad deformation. Short-term reference strength was determined by the force at the displacement of 1/120 rad (Pd). And as is shown in the P-δ curve of Fig. 8, although the adhesive broke off and the strength was gradually reduced after the maximum strength had been reached, the frame showed the high ductility until the stop of forcing. Picture 1-6 shows the specimen No.2 after the experiment.

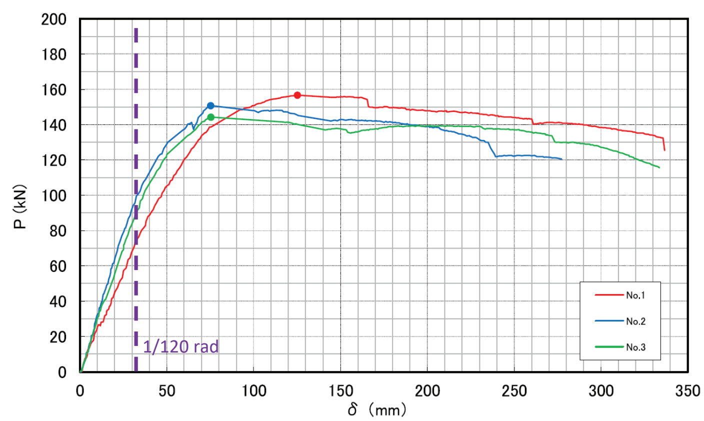

Figure 15: P-δ curve of each specimen

Table 4: stiffness

specimens	Pmax	δmax	Py	δy	ultimate strength Pu	ultimate displacement δu	ductility factort μ	initial stiffness K
	kN	mm	kN	mm	kN	mm	-	kN/cm
No.1	156.68	125.23	91.01	41.40	145.35	336.69	5.09	21.98
No.2	150.71	75.32	89.35	29.12	137.77	277.28	6.18	30.68
No.3	144.27	75.36	97.69	35.61	135.39	333.77	6.76	27.43
average	150.55	91.97	92.68	35.38	139.50	315.91	6.01	26.70

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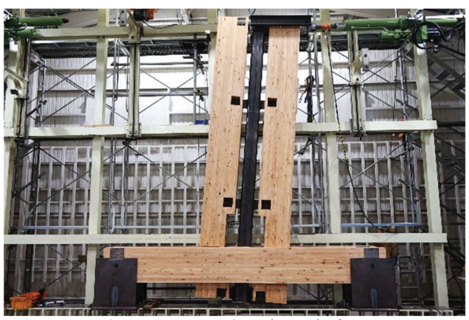
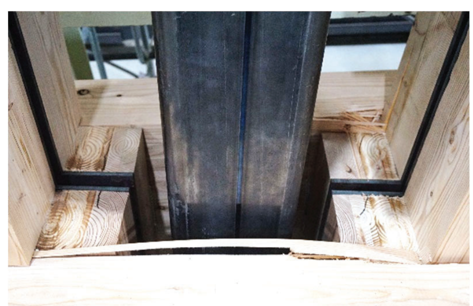
Table 5: strength

specimens	force	(a) Py [kN]	(b) $Pu \times 0.2\sqrt{(2\mu-1)}$ [kN]	(c) 2/3 Pmax [kN]	(d) 1/120rad P [kN]
No.1	positive-negative alternating incremental cyclic forces	91.01	88.08	104.45	70.95
No.2		89.35	92.87	100.47	95.05
No.3		97.69	95.81	96.18	86.95
average		92.68	92.25	100.37	84.32
standard deviation		4.41	3.90	4.14	12.26
variation coefficient		0.048	0.042	0.041	0.145
dispersion coefficient		0.977	0.980	0.981	0.932
short-term reference strength		90.55	90.41	98.46	78.59


Picture 1: specimen No.2 at the end of experiment


Picture 2: rotation of column-beam joint


Picture 3: compression to the beam


Picture 4: cleavage of the beam


Picture 5: face of the beam at the joint


Picture 6: deformation of the wood-wood screws

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6 – CONCLUSION

The structural design for medium- and large-scale timber buildings by Azusa Design, a leading Japanese architectural firm, presents cutting-edge approaches in timber construction. A notable example is the hybrid timber-steel structure employed in the Passenger Terminal at Tokyo International Airport (Haneda), which serves as a pioneering model of sustainable construction. The integration of timber and steel in the terminal's design led to a reduction of 2,630 tons of CO2 during construction, while the completed building has the capacity to sequester 1,435 tons of CO2 over its operational lifetime.

Another groundbreaking example of a fully timber structure is the large roof ring at the Osaka-Kansai Expo, which functions as the main circulation pathway. By combining traditional Japanese timber joinery techniques, such as the "Nuki joint," with advanced modern structural engineering, a novel joint system was developed that significantly enhances strength and stiffness compared to conventional Nuki joints. This innovation enabled the realization of a pure frame structure, devoid of braces or shear walls, making it one of the world's largest timber buildings.

Additionally, the development of the hybrid timber-steel column-beam frame system "CROSS-WOOD" was discussed. Full-scale testing confirmed that the system meets the targeted strength and stiffness requirements. This innovative structural solution was granted a patent (No. 7061739) in Japan in April 2022. Moving forward, efforts will focus on obtaining a technical evaluation to establish the system's potential for widespread application in medium- and large-scale timber buildings, enhancing its flexibility and applicability in future projects.

7 – REFERENCES

Citations: References are given in square brackets like this [1]. Examples:

[1] Masahiro Inayama (2019), "[Structural Design Guide for Medium and Large-Scale Wooden Buildings] Chudaikibo mokuzo kenchikubutsu no kozo sekkei no tebiki (in Japanese)".