

## Design of Indoor Structures Using Small-Section timber Assembly Frame and Practice of Material Recycling

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**ABSTRACT:** There are two main types of wood use methods in architecture: construction of timber structure and wooden interior. In order to make the latter type of wooden interior, we developed a wood-based construction method "T-WOOD® SPACE Light (*TWSL*)" that enables the construction of indoor structures in a short time by utilizing a new jointing method of wood members. In this construction method, a frame unit consisting of four small-section sawn timbers is inserted from three directions to form a joint, making it easy to assemble and dismantle, and the hollow-section frame unit is lightweight and easy to transport and construct. Several interior spaces using this construction method were designed and constructed. They were exhibition booths, display panels, and on-board spaces of a trailer. In the design of the vehicle space, we designed a shear wall and clarified the in-plane shear performance by shearing tests. In addition, a part of the exhibition booth was used to reuse it for partition walls, tables, and storage baskets, and the problems that arise from practicing material recycling were identified.

**KEYWORDS:** small-section timber, indoor structure, joint method, lightweight frame, material recycling

### 1 – INTRODUCTION

To achieve carbon neutrality by 2050, the Act on the Promotion of the Use of Wood was revised in 2021. Previously, only public buildings were covered by the basic policy of this law, but with this revision, it has been expanded to include private buildings as well. As a result, construction companies now need to focus more on using wood.

Our company, under the "TAISEI VISION 2030/Mid-Term Management Plan," places Sustainability Transformation (SX) at its core, aiming to solve environmental and social issues through our business. Promoting the use of wood in the construction field to help form a sustainable society is one of our long-term goals.

There are two ways to use wood: wood construction and wood interior finishing. The former involves using wood and wood materials directly in the main structural parts of buildings. In urban buildings, which require high fire resistance, achieving wood construction is challenging in both design and construction. The latter involves using wood for furniture, fixtures, and interior finishes, which

has fewer legal restrictions, allowing for more design freedom and easier application. Even in RC (reinforced concrete) and steel buildings, which we specialize in, we can actively promote the use of wood through wood interior finishing, contributing both quantitatively and qualitatively. Therefore, we have chosen to focus on developing technology for wood interior finishing.

As a technology to promote the use of wood regardless of the building structure type, we have developed the wood frame "T-WOOD SPACE Light," which allows for quick indoor space construction using a new method of joining wood components (Photo 1). By joining lightweight wood components without using special metal fittings, it is easy to transport and construct by hand. This technology promotes the use of wood and reduces environmental impact by lowering CO<sub>2</sub> emissions during component manufacturing. The specific features of "T-WOOD SPACE Light" (*TWSL*) are as follows:

**Lightweight and Manually Transportable:** The axis material unit, which constructs the wooden frame for beams and columns, consists of four small cross-section

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Photo.1 Example of TWSL

lumber pieces joined together with binding material. This unit weighs 2.4 kg per meter, making it lightweight (about half the weight of solid cross-section lumber) and manually transportable even indoors where transport and lifting machinery cannot be used. The new joining method allows easy assembly and disassembly. As shown in Figure 1, simply inserting the axis material units from three directions enables strong fitting joints, constructing the columns and beams that support the structure.

**Easy Assembly with New Joining Method:** Simply inserting the axis material units from three directions enables strong fitting joints, constructing the columns and beams that support the structure. The joining of materials is simple, requiring no special processing or joining hardware, thus offering high workability. It can be manufactured with general processing machines.

**Structural Performance:** Increasing the number of components in the axis material unit can enhance the structural performance of columns and beams, allowing the construction of wooden spaces with a maximum span length of about 8 meters.

**Manufacturable Using General Lumber and Processing Machines:** The lumber that constitutes the axis material unit is commercially available and can be procured nationwide in Japan. Additionally, the new joining method eliminates the need for advanced pre-cutting technology, allowing manufacturing even in lumber mills without special processing machines.

There are several methods for constructing indoor spaces with wooden frames, but the method of constructing axis material units, inspired by the chair designed by architect Rietveld, is unique. These units weigh about half as much as solid cross-section lumber and have an innovative joining method. Additionally, increasing the number of

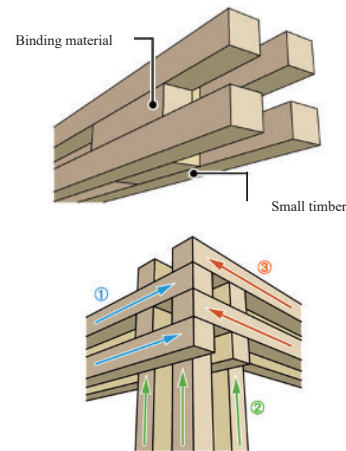


Fig.1 Axis material unit and joint detail

small cross-section lumber pieces in the axis material units allows for the construction of composite columns and layered beams, making it possible to accommodate large spans. This versatility makes the method unparalleled.

## 2 – STRUCTURAL ELEMENTS

### 2.1 Moment-Resistant Joints

The *TWSL* joints resist rotation both when opening and closing through (1) compressive strain inclined to the grain at the corners of the through-beam and (2) shear of linear fasteners (screws or wooden dowels) that secure the members together. Figure 2 shows an example of the resistance mechanism of the joint when the beam and column open. The stiffness, yield deformation angle, and yield strength of each element were determined, and the overall rotational stiffness  $K$  and yield strength  $M_y$  of the *TWSL* joint were calculated.

#### 2.1.1 Compressive strain inclined to the grain at the Corners of the Through-Beam

Figure 3 shows the model of moment resistance. Triangular compressive strain inclined to the grains occur at four corners of the beam. As compressive strain occur on both the beam and the column sides simultaneously, the rotational springs become series springs, doubling the deformation angle for the same force. Thus, as shown in Equation (1), the stiffness  $K_{0m}$  for a pair of triangular compressive strain inclined to the grains is halved.

$$K_{0m} = \frac{K_{0\text{Beam}} \cdot K_{0\text{Girder}}}{K_{0\text{Beam}} + K_{0\text{Girder}}} = \frac{K_0^2}{2K_0} = \frac{1}{2} K_0 \quad (1)$$

$$\sum N_R = \sum N_L = \frac{x_p^2 y_p c_y E_{90} \left(\frac{\theta}{2}\right)}{Z_0} \left(\frac{1}{2}\right) \quad (2)$$

$$\sum M_R = \sum M_L = \frac{x_p^3 y_p c_y E_{90} \left(\frac{\theta}{2}\right)}{Z_0} \left(\frac{1}{3}\right) \quad (3)$$

From the balance of moments, according to equation  $M = M_R + M_L + \mu N_R$ ,

$$\begin{aligned} M &= 2 \times \frac{1}{3} \cdot \frac{x_p^3 y_p c_y E_{90} \left(\frac{\theta}{2}\right)}{Z_0} + \mu \times \frac{1}{2} \cdot \frac{x_p^2 y_p c_y E_{90} \left(\frac{\theta}{2}\right)}{Z_0} \\ &= \left(\frac{1}{3} x_p + \frac{1}{4} \mu\right) \cdot \frac{x_p^2 y_p c_y E_{90}}{Z_0} \theta \end{aligned}$$

Thus, the rotational stiffness  $K_\theta$  is given by equation (4)

$$K_\theta = \frac{M}{\theta} = \left(\frac{1}{3} x_p + \frac{1}{4} \mu\right) \cdot \frac{x_p^2 y_p c_y E_{90}}{Z_0} \quad (4)$$

According to equations (1) and (4),

$$K_{\theta m} = \left(\frac{1}{3} x_p + \frac{1}{4} \mu\right) \cdot \frac{x_p^2 y_p c_y E_{90}}{2Z_0} \quad (5)$$

The yield deformation angle  $\theta_y$  can be expressed as shown in equation (6).

$$\theta_{ym} = \frac{Z_0 F_m}{x_p E_{90} \sqrt{c_x c_y c_{xm} c_{ym}}} \quad (6)$$

Here, since  $x_1 = 0$ ,  $y_1 = \infty$ ,  $c_x = 1$ ,  $c_y = c_{ym}$  and  $c_{xm} = 1 + \frac{4Z_0}{3x_p}$ ,  $c_{ym} = 1 + \frac{4Z_0}{3ny_p}$ .

### 2.1.2 Two-Surface Shear of Connectors

When wood is used as the main and side material, the two-surface shear stiffness of bending yield-type connectors (screws or wooden dowels) is determined based on the timber structure design standards and the elastic foundation beam theory [1]. The yield strength is determined using the European Yield Theory (EYT). Considering the joint as a panel zone, the rotational stiffness is determined from the stiffness and strength per connector as follows.

$$K_{\theta s} = \sum K_s \cdot R^2 \quad (7)$$

In the case of a circular arrangement, the yield moment  $M_{ys}$  is determined as the sum of the moments when all screws simultaneously reach yield, as follows.

$$M_{ys} = \sum R \cdot P_{ys} \quad (8)$$

If the deformation angle at this time is  $\theta_{ys}$ , it can be expressed as shown in equation (9).

$$\theta_{ys} = \frac{M_{ys}}{K_{\theta s}} \quad (9)$$

### 2.1.3 Rotational Stiffness, Yield Deformation Angle, and Yield Strength of TWSL Joint

The overall stiffness  $K$  of the joint can be expressed as the simple sum of the embedment spring at the girder corner and the two-shear spring of the screw, as shown in equations (5) and (7).

$$K = K_{\theta m} + K_{\theta s}$$

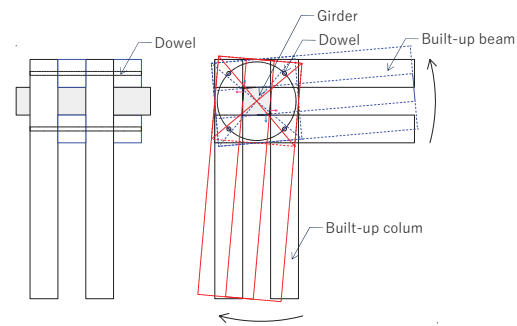


Fig.2 Moment resistance mechanism

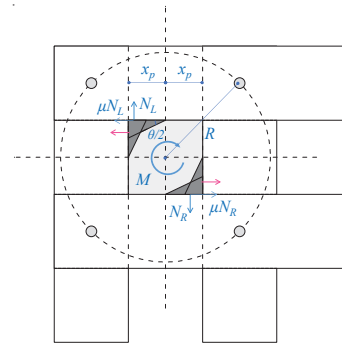


Fig.3 Moment resistance model

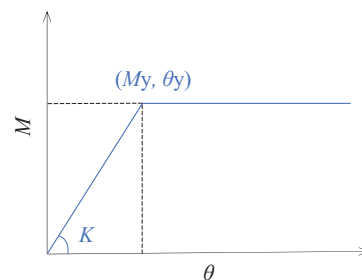


Fig.4 Relationship between  $M$  and  $\theta$

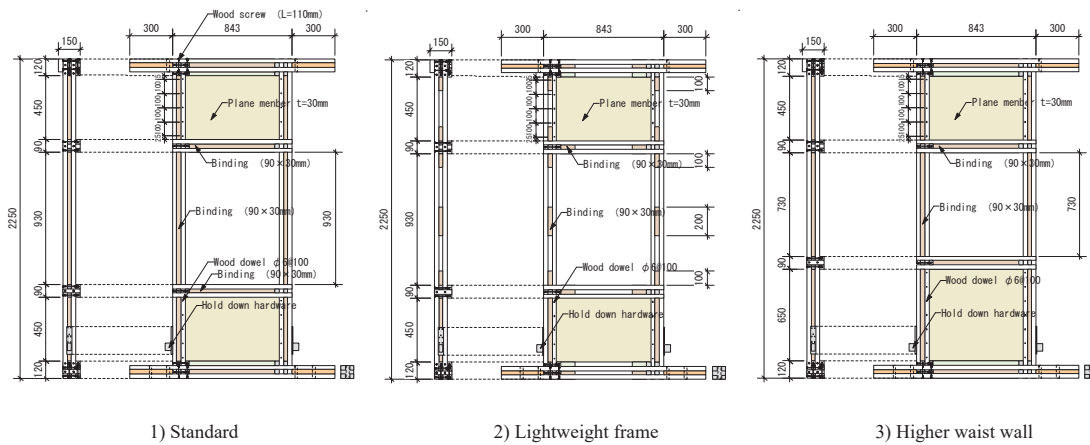


Fig.5 Shear wall specimens using TWSL

$$= \left( \frac{1}{3} x_p + \frac{1}{4} \mu \right) \cdot \frac{x_p^2 y_p c_y E_{90}}{2 Z_0} + \sum K_s \cdot R^2 \quad (10)$$

The yield deformation angle  $\theta$  can be expressed using equations (6) and (9) as the deformation angle when either the embedment at the girder corner or the two-shear deformation of the screw yields first.

$$\theta_y = \min(\theta_{ym}, \theta_{ys}) \quad (11)$$

Using equations (10) and (11), the yield moment  $M_y$  can be expressed as follows.

$$M_y = K \cdot \theta_y \quad (12)$$

The moment-rotation angle relationship in Figure 4 can be derived from the obtained characteristic values.

## 2.2 Shear Walls

The frame units that serve as columns and beams in TWSL are hollow. By effectively utilizing this space, shear walls in the form of drop walls and waist walls were constructed.

### 2.2.1 Design of Reinforced Walls

The standard shear wall design uses drop walls and waist walls as elements, with a window in the middle of the wall. The frame units are made from 30mm square lumber, forming columns, beams, and bases with an outer dimension of 90mm square. To serve as slip and buckling prevention at the joints, the same cross-section of binding material is placed, leaving a 30mm space between the 30mm square lumber. A 30mm thick planar member (constructed by attaching 3mm thick finishing plywood

on both sides of a 30×24mm frame material around the perimeter) is inserted into this space and secured with φ6mm wooden dowels, creating a true wall-style shear element. The wooden dowels penetrate through the lumber and planar member, providing resistance through two-shear mechanisms. Based on this configuration, a reinforced wall equivalent to a wall magnification of 1.0 was designed.

### 2.2.2 In-Plane Shear Test

An in-plane shear test was conducted on the reinforced wall. The test frame diagram is shown in Figure 5. Three types of test specimens were used: a) standard, b) lightweight frame, and c) waist wall height. The standard specimen had drop wall and waist wall heights of 520mm each, measured from the beam center to the tie beam center, with uniform binding material in all positions except the ends, resulting in a solid cross-section. The binding material was joined with wooden dowels and adhesive. The lightweight frame specimen had intermittently placed binding material, with hollow sections except for the column base where hold down hardware was attached, reducing weight. The waist wall height specimen had a waist wall height of 740mm, reducing the opening height of the standard specimen by 200mm.

The test method was a fixed column base, unloaded type. The base and loading beam were extended 300mm from the outer surface of the column, with the base secured to the test frame with M16 anchor bolts, and the column base fixed with hold down screws. The connection between the loading beam and column was made with 12 screws ( $L=110\text{mm}$ ) from three directions at overlapping

positions. The loading method involved three cycles of alternating positive and negative loads, with repetitions at apparent shear deformation angles of 1/450, 1/300, 1/200, 1/150, 1/100, 1/75, and 1/50 radians.

### 2.2.3 Test Results

The standard failure behavior is shown in Photo 2. When horizontal force was applied, the bending deformation of the column at the opening position became predominant. At the ultimate stage, tensile failure occurred at the upper position of the waist wall on the tensile side column, leading to a decrease in strength. Additionally, the finishing surface material buckled out-of-plane due to the bracing effect in the drop wall.

The load-displacement relationships (envelopes) of each test specimen are shown in Figure 6. The lightweight frame had lower initial stiffness  $K$  and maximum strength  $P_{max}$  compared to the standard. Conversely, the waist wall height improved overall  $K$  due to the smaller opening and shorter bending length of the column, but  $P_{max}$  remained almost the same due to the same failure location.

The characteristic values obtained from the evaluation method are shown in Table 1. In all specifications, the wall magnification was determined by the strength at 1/120 rad, resulting in 1.56, 0.93, and 2.05 times for the standard, lightweight frame, and waist wall height,

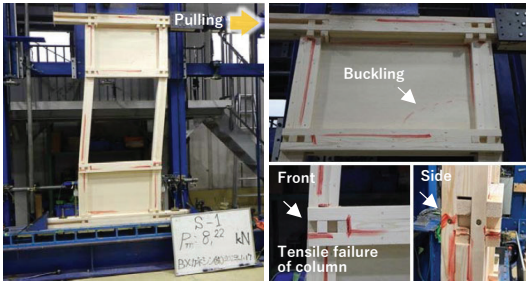


Photo.2 Destruction characteristics

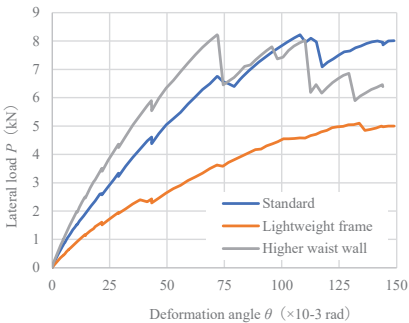


Fig.6 Relationship between  $P$  and  $\delta$

Table.1 Characteristic values

Specimens	Stiffness	Yield strength		Ultimate strength		Max. load		Wall magnification
	$K$	$P_y$	$\delta_y$	$P_u$	$\delta_u$	$P_{max}$	$\delta_{max}$	
	kN/mm	kN	mm	kN	mm	kN	mm	
a) Standard	0.102	5.02	49.4	7.65	149	8.22	108	1.56
b) Lightweight frame	0.053	2.67	50.3	4.83	149	5.10	134	0.93
c) Higher waist wall	0.152	4.15	27.2	7.09	129	8.22	71.8	2.05

respectively. The reason for determining the strength at 1/120 rad is considered to be the predominant bending deformation of the column at the opening position, leading to lower overall wall stiffness. The target wall magnification of 1.0 was satisfied for both the standard and waist wall height specifications.

### 3 – CONSTRUCTION EXAMPLES

The following are construction examples using the "T-WOOD® SPACE Light" method. The basic cross-sectional dimensions of the small-section lumber and binding material that make up the frame units are 30mm square. Depending on each example, the connection between the lumber and binding material was made using screws or dowels combined with adhesive.

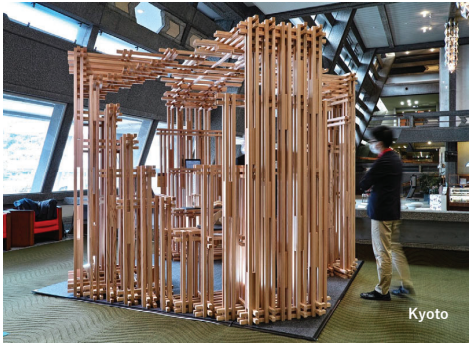


Photo.3 Booth A

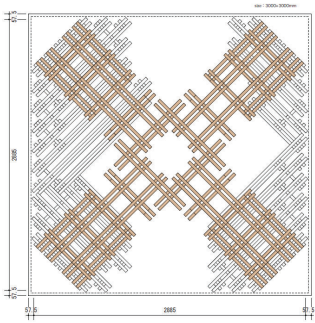


Fig.7 Roof plan of Booth A

### 3.1 Exhibition Booth A

Exhibition Booth A was set up at WOODRISE2021 KYOTO held in Kyoto in 2021. The setup is shown in Photo 3. Based on the concept of "connecting tradition and modernity," traditional Japanese wooden construction techniques such as *kumiko*, lattice, and dougong were used as design motifs. The condition was to fit within a 3m square, with four wall-like members placed at the corners. An arched roof was connected to each vertex along the diagonal. The roof plan is shown in Figure 7. The inside of each wall member is stepped, allowing visitors to efficiently observe the exhibits placed on each step.

### 3.2 Exhibition Booth B

Exhibition Booth B was a space design using *TWSL* exhibited at the Green Factory EXPO held in Nagoya and Tokyo in 2023. The setup is shown in Photo 4. This exhibition space was named "Flexible Factory" to

express its adaptability to various situations. The roof plan is shown in Figure 8. A gate-shaped frame was constructed with *TWSL*, and by shifting the column positions while extending in the depth direction, a space with a gentle curve in the plan view was created.

### 3.3 Exhibition Booth C

Exhibition Booth C was a space design using *TWSL* exhibited at the Kyushu Semiconductor Industry Exhibition held in Fukuoka in September 2024. The most common material used in semiconductors is silicon, which has a cubic crystal structure. To represent this crystal structure with *TWSL*, frames with uniform edge lengths were tilted at a 45-degree angle to form a mesh-like arch. The setup is shown in Photo 5.

Exhibition Booth C was later modified and its components reused at the "JAPAN BUILD Decarbonization EXPO" held in Tokyo in December 2024. The setup is shown in Photo 6. The event focused



Photo.4 Booth B

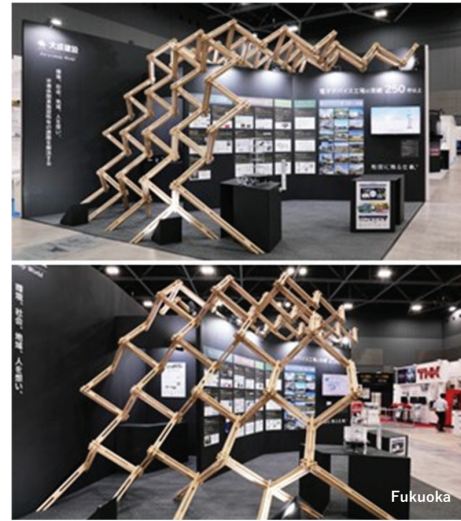


Photo.5 Booth C

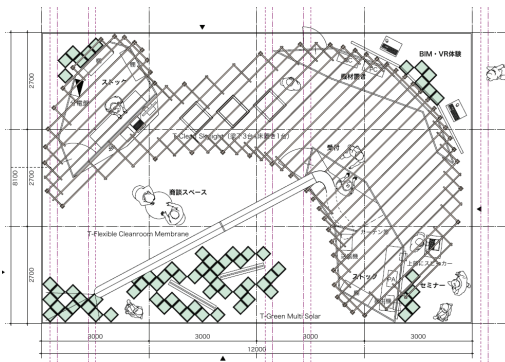


Fig.8 Roof plan of Booth B



Photo.6 Transformed Booth C

on renewal, with a major theme being the change in shape and reuse of materials.

At the Decarbonization EXPO, cubic *TWSL* frames were arranged vertically and horizontally, stacked while shifting them by half a unit to create the space.

### 3.4 Mobile Infill®

"*Mobile Infill*®" (*MI*) is a portable building unit mounted on a trailer. The frame of this unit was constructed using *TWSL*. Photo 7 shows *MI* being towed, and Photo 8 shows it deployed as a building infill. Here, a portable building unit is defined as a movable building infill that can be separated from the building skeleton while maintaining the function and purpose of the building space.

Assuming a maximum acceleration of 2.0 G due to sudden starts and stops by the towing vehicle, shear walls with wooden panels embedded in the *TWSL* frame, as shown in section 2.2, were applied to withstand the horizontal forces.

## 4 – MATERIAL RECYCLING

To organize the issues in material recycling of wooden components, an attempt was made to recycle the materials from Exhibition Booth A shown in section 3.1.

### 4.1 Product Design with Change of Use

Based on Exhibition Booth A, three items were designed: partitions, tables, and seat storage baskets. The image diagrams of each product are shown in Figure 9. The design conditions were: 1) no new materials added, 2) maintaining a high recycling rate, and 3) considering repair methods for materials as needed. The design aimed to minimize cutting processes and accommodate variations in material lengths, as shown in the partition design in Figure 9. The total volume of materials for each product was 0.56m<sup>3</sup>, with a recycling rate of approximately 56% per volume.

### 4.2 Recycling Practice

#### 4.2.1 Disassembly and Transportation

The exhibition booth was divided into four large sections at the existing location, cut into smaller pieces with a saw to sizes that could be loaded onto a truck for transport to the reprocessing factory. The disassembly, cutting, and loading were completed in a few hours, all done manually



Photo.7 Towed Mobile Infill®



Photo.8 Expanded Mobile Infill®

(4 workers per hour) without using large lifting machinery.

#### 4.2.2 Reprocessing

The disassembled parts were brought to the reprocessing factory, where the binding material shown in Figure 1 was removed, and almost all assembly components were separated into small-section lumber. Since the existing location was semi-outdoor, some materials had swelled, shrunk, or become dirty. The surface was shaved by about 0.5mm to remove dirt and repair dimensions. Repainting was done at the stage of individual components before assembly.

#### 4.2.3 Assembly and Installation

Reassembly was carried out at the factory. The assembly procedure was planned considering the reduced width dimensions due to planing. The components had pre-drilled holes for  $\phi 6$ mm wooden dowels, which partially exposed the surface. Care was taken to avoid placing these holes on the upper surface to prevent rainwater ingress during semi-outdoor installation.

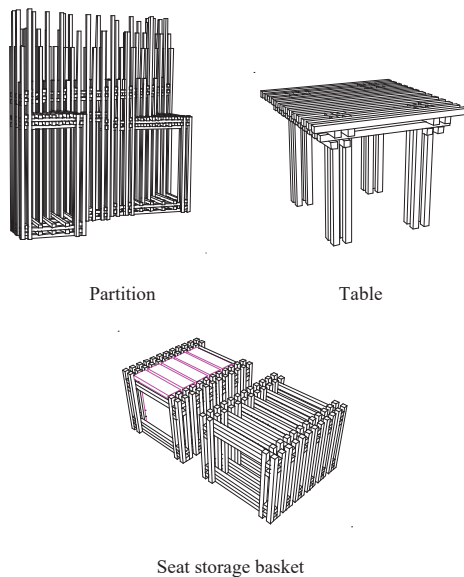


Fig.9 Three types of recycled products

The tables and seat storage baskets were assembled and completed at the factory, while the partitions were checked for assembly, then divided into two parts for transport by truck. Installation at the site was done manually without using heavy machinery.

#### 4.2.4 Organizing Issues

It was found that dirt on the wood could be removed by planing about 0.5mm, but reuse planning and construction needed to consider the reduced width dimensions. To improve the recycling rate, redesigning to accommodate variations in material lengths was effective.

## 5 – CONCLUSION

Utilizing a new method of joining wooden members, we developed the "T-WOOD® SPACE Light" wooden construction method, enabling rapid indoor space construction, and carried out several designs and constructions.

Based on the exhibition booths, we redesigned and remanufactured partition walls, tables, and storage baskets. The conditions were to avoid adding new materials, maintain a high recycling rate, and consider repair methods for the materials as needed. As a result, it was confirmed that: 1) wood contamination can be removed by planing, and 2) redesigning with



Photo.9 Disassembly of the exhibition booth A



Photo.10 Removing stains by shaving

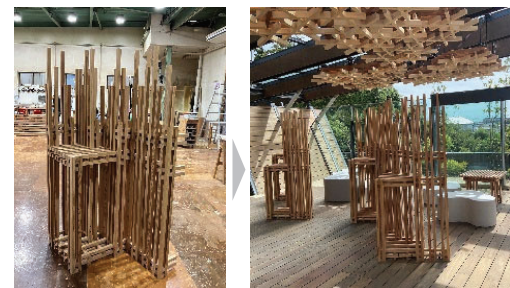


Photo.11 Factory assembly and on-site installation

consideration for variations in material length is effective for improving the recycling rate.

As one of the wooden technologies to achieve carbon neutrality and a circular economy, we plan to continue expanding the use of TWSL widely in the future.

## 6 – REFERENCES

- [1] Architectural Institute of Japan, "Standard for Structural Design of Timber Structures-Allowable Stress Design and Allowable Strength Design Method-(4th edition)", 2013