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A 3D PRINTED JOINING SYSTEM FOR ASSEMBLING RECIPROCAL FRAME STRUCTURES WITH IRREGULAR NATURAL WOOD

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ABSTRACT: One of the problems associated with the current forest resource cycle and its financial sustainability is that wood that does not meet specifications, such as small-diameter wood and curved wood, has limited uses and is usually unused. By finding value in using irregular natural wood as building and furniture components, the 3D printed joining system will contribute to sustainability in a circular economy by expanding the cycle of forest resources and supporting their funding. The 3D printed joining system is designed to utilize irregular natural wood, such as small-diameter wood and curved wood, as components in buildings and furniture. Based on the data of wood captured by 3D scanning, the joints are manufactured by computer and 3D printing, making it possible to join irregularly shaped natural materials without damage. In addition, these joints are disassembled so that the wood can be reused. The system does not standardize the properties of each material; rather, it utilizes the properties of each material as they are. This paper adopts reciprocal frame structures to construct a space for people using irregular natural wood. By assembling reciprocal frame structures, it is possible to construct a large space even with shorter wood and to avoid the concentration of joints. The 3D printed joining system contributes to the sustainability of the circular economy by assembling reciprocal frame structures from irregular natural wood that is limited or not used.

KEYWORDS: Small-Diameter Wood, Additive Manufacturing, 3D Scanning, Disassembly, Unused Wood

1 – INTRODUCTION

Forest sustainability in a circular economy requires the appropriate maintenance and use of forest resources [1][2]. Furthermore, it is necessary to establish a circular system in which the use of forest resources generates sufficient funds to support the maintenance and management of forest ecosystems [1].

In this context, there are problems with the current forest resource cycle and its financing. One of tthem is that wood that does not meet specifications, such as small-diameter wood and curved wood, has limited applications and is usually not used [1][3][4][5]. Much of the off-market wood that does not meet specifications goes unused and is discarded or left in the forest [1][3][4][5]. In the world, these unused forest residues have been analyzed and studied from various perspectives and their problems have also been identified, such as in [4]-[8]. Even when used, most of them are used as fuel pellets or wood chips with little added value simply because of small-diameter or curvature, making it difficult to return them as funds [1]-[9]. In addition, as urban greening has been promoted in many countries in recent years, unused wood is being generated in urban areas, creating the problem that processing it takes time and money [1][9].

Japan is no exception to these problems. Japan, which ranks third among OECD member countries with 68.4% forest cover, is currently entering a period of planted forest utilization, and the use of wood is being promoted to realize a decarbonized society and a healthy forest resource cycle [9][10][11]. Even in Japan, unused forest residues are a problem in various kinds [9][10]. For instance, a large amount of unused forest residue is generated, some of which hampers the forestry industry and increases the risk of expanding damage in the event of natural disasters, which does not appear in statistical data [10][11][12]. Furthermore, even 60.3% of the collected wood is used as f fuel pellets or wood chips, a low-value use because of its small-diameter or curvature [10]. In addition, almost all of the unused wood generated by urban greening, such as pruned branches from street trees, is disposed of at great labor and expense [13].

Irregular natural wood that has limited use or no use is

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usually short in length. And considering the strength of such wood, it is necessary to avoid localized load concentrations. Assembling dome-shaped reciprocal frame structures allows the construction of large pillarless spaces even with short members, and avoids concentration of members at joints [14][15]. The concept of reciprocal frame structures is exemplified in Leonardo da Vinci's drawings, which have been employed in constructing wooden structures since the early 12th century [14]. On the other hand, it has been rarely used as a structural system until recently. The primary reasons are the challenge of accurately quantifying the angles at which members join in three dimensions and the difficulty of precise design and assembly [14][15]. In recent years, some of these problems have been largely eliminated with the development of computer technology, and its use in wood construction has gradually increased. However, joint angle adjustment and design complexity of construction are challenges when using reciprocal frame structures [14].

Studies utilizing small-diameter wood or natural wood have been reported in recent years [16]-[21]. However, there are no studies that focus on joints. There are also studies of reciprocal frame structures that deal with their geometric issues and use wood [14][15][22][23][24]. Although, there are slight examples of reciprocal frame structures using small-diameter irregular natural wood. In addition, even the few studies and examples of reciprocal frame structures with small-diameter wood that are available focus on flat reciprocal frame structures [17].

The presence of discarded or unused wood, as well as low-value materials such as fuel pellets and wood chips, represents one of the issues associated with the current forest resource cycle and its financial sustainability. Furthermore, the problem with using such wood for construction and furniture is that it is difficult to homogenize and handle due to its small-diameter, unevenness, and curvature. Another problem is that the small-diameter can significantly affect the mechanical performance of the wood due to defects caused by joining and processing.

This paper proposes a 3D printed joining system for assembling small-diameter, irregularly shaped natural wood with unique 3D printed objects and uniform scaffolding clamps. By 3D scanning the target wood, designing unique joints based on that data, and 3D printing the designed joints, it becomes possible to join such wood, which has traditionally been difficult to handle due to its non-uniform geometry. Then, the 3D printed joints are combined with swivel scaffolding clamps, significantly reducing the time required for joint printing. The scaffolding clamps possess sufficient strength to comply with international standards such as JIS A 8951, AS/NZS 1576.2, and ANSI/SSFI SC100-5/05. As a result, structurally reliable pin joints can be achieved. This jointing system enables 3D angle adjustable joints without processing, allowing for construction errors, even for small-diameter wood, which significantly affects the mechanical performance of the wood due to defects caused by joining and processing. In addition, since the system has disassembly performance, it is possible to replace or reuse the joints and basewood.

Furthermore, this paper demonstrates that small-diameter, irregularly shaped natural wood can be assembled into a module of complex dome-shaped reciprocal frame structures using the proposed 3D printed joining system. This paper adopts reciprocal frame structures to construct pillarless space using such wood. Assembly by using that joining system can solve such problems and realize reciprocal frame structures with simple construction.

This study contribute to the sustainability of a circular economy by utilizing discarded or unused wood, as well as low-value materials such as fuel pellets and wood chips, for construction or furniture. Using such wood in construction or furniture can reduce carbon dioxide emissions during construction, store the absorbed carbon dioxide for a long time, and eventually use it as a fuel.

2 – METHODOLOGY

2.1 TARGET WOOD

In this paper, the unused wood generated and left in the forest at Tokyo University of Science was used. It is shown in Fig. 1. The target wood has a diameter of 15-40 mm and a length of 500-1000 mm with bending. A 3D printed joining system assembles small-diameter, irregularly shaped natural wood (15-40 mm diameter and bent wood) into a module of reciprocal frame structures using unique 3D printed objects and uniform swivel scaffolding clamps. In this paper, One of the triangular modules composing the reciprocal frame structures is created with the three wood (wood A, B, and C) shown in Fig. 2. By following the joining procedure shown in Fig. 3, such wood can be joined at the intended angle.

Figure 1. The unused wood generated and left in the forest at Tokyo University of Science.

Name of Wood	Diameter [mm]	Length [mm]
Wood A	21	612
Wood B	27	841
Wood C	24	645

Figure 2. Three wood are used in a triangular module of reciprocal frame structures.

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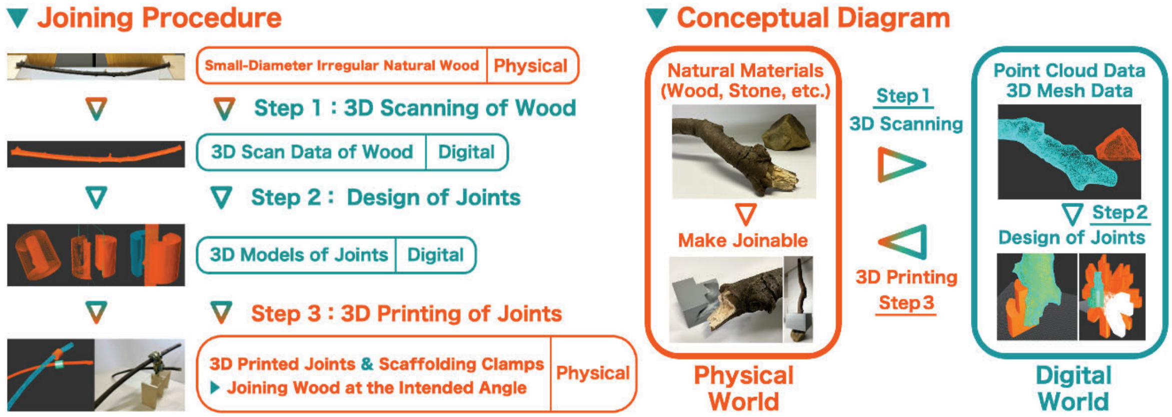

Figure 3. Joining procedure and conseptual diagram.

2.2 3D SCANNING

Step 1 of the joining procedure (Fig. 3) is 3D Scanning. 3D scanning obtains the point cloud data of the collected small-diameter, irregularly shaped natural wood. The mobile device for 3D scanning is "iPad Pro" (Apple Inc.). The 3D scanning software is "Scaniverse" (Niantic, Inc.) [25]. “Scaniverse” is a mobile application for 3D scanning that is free and readily available to many. 3D Scanning uses a LiDAR scanner on a mobile device.

2.3 DESIGN OF JOINTS

Step 2 of the joining procedure (Fig. 3) is the designing of joints. The 3D scanned point cloud data is imported into the 3D CAD software to design unique joints that fit the individual irregularly shaped surfaces of the natural wood. Design the joint positions and the member angles so that the reciprocal frame structures can be assembled. The 3D CAD software is “Rhinoceros 3D and Grasshopper” (Robert McNeel & Associates) [26].

2.4 3D PRINTING

Step 3 of the joining procedure (Fig. 3) is the 3D printing of joints. A 3D printing (additive manufacturing / fused filament fabrication) is used as a method to manufacture the joints designed in step 2. The 3D printer is “Zortrax M300 Dual” (Zortrax), and the printing material is PETG (polyethylene terephthalate glycol) [27]. The 3D printer was a small desktop type product, relatively inexpensive and lightweight [27]. The slicing software to 3D printing is “Z-SUITE 2” [28].

2.5 ASSEMBLY

Then, using the 3D printed joints and scaffolding clamps to join the target wood A-C (Fig. 2), a triangular module of reciprocal frame structures is assembled (Fig. 3). The 3D printed joints are first joined along the wood surface to define the joint positions and the member angles and then wrapped around these with a swivel scaffolding clamps. The accuracy of the final jointed a triangular module is consistent with the unit that build part of the intended reciprocal frame structures is evaluated.

3 – RESULTS AND DISCUSSION

3.1 3D SCANNING

In principle, 3D scanning technology is not good at 3D scanning small-diameter slender wood. There are two main reasons why small-diameter, slender wood is a difficult material to 3D scan. The first reason is that the surface color and pattern do not vary greatly from place to place, resulting in a small amount of features. The second reason is that the small-diameter slender wood occupies only a small percentage of the camera's angle of view during 3D scanning. This section presents a tried and true method for obtaining the 3D scan data needed for structural studies and joint design.

The three woods A-C shown in Fig. 2 were 3D scanned. As a method of 3D scanning, the object was suspended by a thin string to enable a full 360-degree scan, as shown in Fig. 4-(a). However, the software failed to recognize the object. Therefore, the 3D scanning method was changed to scanning the 360 degrees by shining a light on and floating it near the ground, as shown in Fig. 4-(B).

The reason why the software did not recognize the object floating in the air when 3D scanning was because the application was created using the AR (Augmented Reality) platform of the mobile device. Therefore, by placing the object near the ground and having the software recognize the ground while 3D scanning the object on the application, as shown in Fig. 4-(B). By doing so, the software was able to scan even objects floating in the air. In addition, the scanning environment also affects the recognition of the object and the accuracy of the data. Therefore, the background of the object was made white with few features, and the scan was performed in a brightly lit environment, creating a suitable environment for 3D scanning, as shown in Fig. 4-(B).

Using the data obtained from the 3D scan of the entire object, which was scanned to design the reciprocal frame structures, an attempt was made to design microscopic joints. However, the data shown in Fig. 5-(A) was too coarse to design the joints, and a problem arose. Therefore, another 3D scan data was acquired, focusing only on the joint zone, as shown in Fig. 5-(b).

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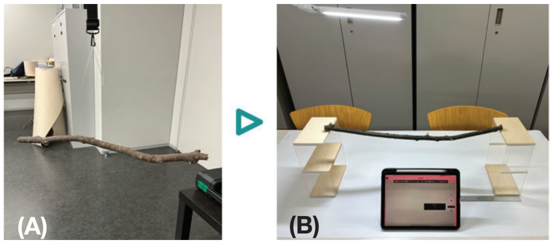
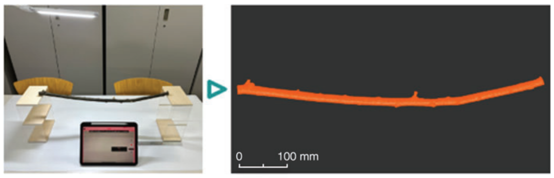
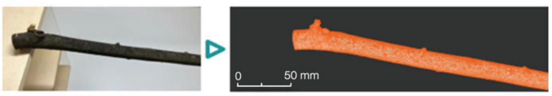


Figure 4. 3D scanning method: (A) Floating the object in the air, (B) Shining light on the object while floating near the grounds.



▲ (A) 3D scan of the entire object



▲ (B) 3D scan forcusing on the joint zone

Figure 5. Two 3D scan data: (A)the entire object, (B) the joint zone.

The accuracy of the 3D scan data with mobile applications can be improved by scanning with movements, distances, and speeds according to the characteristics of the software. On the other hand, movements, distances, and speeds during 3D scanning can cause variations in the 3D scan data. Therefore, the same object was scanned at least five times, and the point cloud data from each scan was compared with each other. In addition, each 3D scan data was compared to the actual object using the AR function. The most accurate data was then selected. This method enables 3D scanning that meets the required accuracy.

The number of points in each point cloud is shown in Table 1. For each object, there are a total of three scan data: one that scans the entire object and two that scans only the joint zone. The joint zones are the joint positions for assembling the triangular modules of the reciprocal frame structures; there are two joint zones on each piece of wood, with a length of 48 mm. For wood A, the entire data consisted of 76,197 points, one of the joint zone data consisted of 15,224 points and the other data consisted of 16,743 points. For wood B, the entire data consisted of 127,222 points, one of the joint zone data consisted of 15,891 points and the other data consisted of 20,069 points. For wood C, the entire data consisted of 84,942 points, one of the joint zone data consisted of 18,673 points and the other data consisted of 19,040 points.

Table 1. The number of points in each point cloud data.

	The Entire Data	The Joint Zone Data 1	The Joint Zone Data 2
Wood A	76,197 points	15,224 points	16,743 points
Wood B	127,222 points	15,891 points	20,069 points
Wood C	84,942 points	18,673 points	19,040 points

3.2 DESIGN OF JOINTS

In the design of the joints, by using two different types of 3D scan data (the entire data, the joint zone data) obtained in step 1 of Fig. 3, the member angles, the joint positions, and the joint shapes could all be designed. The entire data was used to determine the member angles and the joint positions. The joint zone data was used to design the joint shapes.

The member angles and the joint positions were designed as shown in Fig. 6, based on the positional relationships and angles when the reciprocal frame structures are assembled with straight wood, and the straight wood is replaced with the wood A-C（Fig. 2）, an irregularly shaped wood. Specifically, the 3D scanned wood point cloud data is considered as the linear component of a straight line connecting the center points of the cross-section of the entire shape derived from the data and is replaced by the 3D scanned wood shape from the straight wood, , as shown in Fig. 7. A more ideal design method would be to assume the shape of the wood itself and determine joint positions and member angles so that the reciprocal frame structure takes advantage of the shape characteristics of the wood itself.

As shown in Fig. 7, it was necessary to confirm that the member angles could be joined within the restrictions, since there were restrictions on the member angles due to a scaffolding clamp. The scaffolding clamps are products with an applicable diameter of 42.7-48.6 mm.

The shape of the joint was determined by using the point cloud data of the joint zones, converting it to mesh data, and performing a Boolean operation in the form of 0.3 mm clearance so that the joint would fit along the surface of the wood. In addition, the joint was designed to be assembled in two parts, using an algorithm to judge the contact with the wood during the joining process. The joint contact detection algorithm was created using Grasshopper and is a brute force approach to determine if there is an jointing path that allows the split joints to be joined without coming into contact with wood.

As shown in Fig. 6, a cylindrical model created based on the inside data of a scaffolding clamp was placed at the joint position according to the member angles to be joined while checking the constraint conditions (Fig. 7). Then, as shown in Fig. 8, a boolean operation was performed while setting a clearance of 0.3 mm to design a fitting joint shape that fits the surface shape of the wood, and then the joint was divided so that it could be attached to the wood while using a contact judgment algorithm.

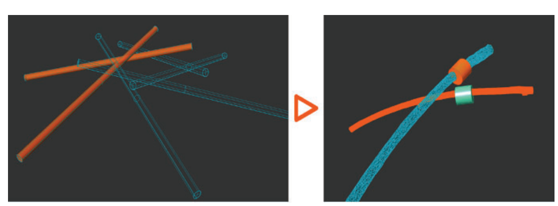


Figure 6. Design of he member angles and the joint positions.

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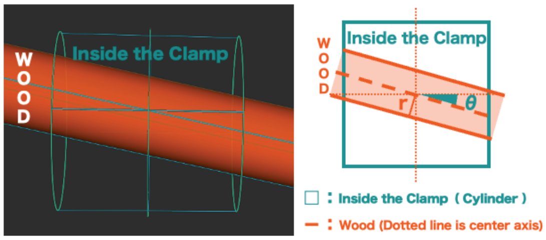

Radius of Wood : r [mm] Inner Diameter of Clamp : 48.6[mm], Clamp length : 48[mm]	
Maximum Angle between Clamp and Wood	$\theta_{Max.} \approx \tan^{-1}\left(\frac{48.6 - 2r}{48}\right)$ [rad] ※ $\theta_{Max.} = \cos^{-1}(0.02083r-0.7027\sqrt{(1-0.086r^2)})$ [rad]
Maximum Angle between Wood	$2\theta_{Max.}$ [rad]
In the case of a swivel scaffolding clamp, there are no restrictions on the angle of rotation of the clamp.	

Figure 7. Constraints on Member Angles in Joining.

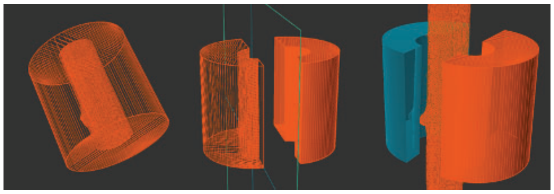

Figure 8. Design of joints that can fit into wood.

3.3 3D PRINTING

The joint designed in step 2 of Fig. 3 was 3D printed. The nozzle diameter was 0.4 mm, the layer height was 0.15 mm per layer, and the joint was able to follow the shape of the wood surface as shown in Fig. 9 by processing to set a clearance of 0.3 mm, which was found to be necessary from the prior fitting 3D printed joint test. In terms of accuracy, the joints were 3D printed with an accuracy of about 0.3 mm in the X and Y directions, and with an error of 0.1 mm or less in the Z direction.

The clearance setting is an important parameter for successfully assembling joints. Understanding the accuracy and properties of the 3D printer in advance and setting the appropriate clearance help ensure proper mating joints without looseness. It is also necessary to ensure that the contact surface with the wood surface, where accuracy is required, does not become the bottom surface during 3D printing. The 3D printed joints, with appropriate clearance, can be attached to wood simply by mating without processing, and also serve to indicate the joint positions.

The combination of 3D printed joints and a scaffolding clamp can reduce the time required to model the joints, and can also ensure strength while providing ease of installation through pin joints. In addition, the 3D printed objects inserted between the wood and metal act as a buffer layer compared to the direct joint method, preventing damage to the wood itself. This prevents damage to the wood itself. Since this is a disassemblable joint method, the joints and components can be repaired, replaced, and reused.

Figure 9. A 3D printed joint that can fit into wood.

3.4 ASSEMBLY

As shown in Fig. 10, the 3D printed joints and scaffolding clamps were used to join the target wood A-C at the defined joint positions to assemble a triangular module with a reciprocal frame structure as shown in Fig. 11.

Since the 3D printed joints follow the surface shape of the wood at the time of joining, the joint position can be uniquely determined by checking the fit as the joints are applied. Therefore, as long as the approximate joint position is known, the joint position can be easily and accurately found at the time of installation. Moreover, because a scaffolding clamp is installed with the joint positions and member angles determined by the 3D printed joints, it is now possible to install a reciprocal frame structure with high accuracy and simplicity, which was previously difficult due to the complexity of the joints and components can be repaired, replaced, and reused.

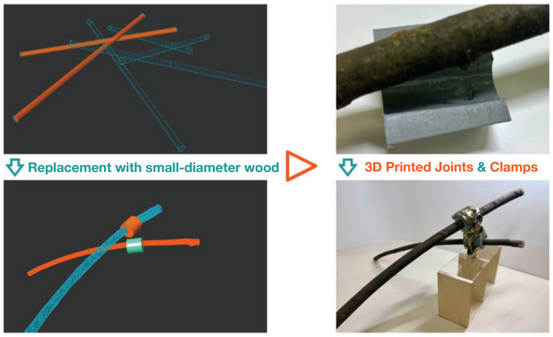

Figure 10. Assumed joint (left) and actual joint (right).

Figure 11. A triangular module with a reciprocal frame structure using the wood A-C.

4 – CONCLUSIONS

In this paper, we presented a 3D printed joining system for assembling modules of reciprocal frame structures using small-diameter, irregularly shaped natural wood. This study contribute to the sustainability of a circular economy by utilizing discarded or abandoned unused wood, as well as wood with low unit prices such as fuel pellets and wood chips, for construction or furniture. Using such wood in construction or furniture can reduce carbon dioxide emissions during construction, store the absorbed carbon dioxide for a long time, and eventually use it as a fuel.

5 – ACKNOWLEDGEMENT

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