

DESIGN AND STRUCTURAL PERFORMANCE OF WOOD FRAMING WITH "FLEXIBLE WOOD"

Eito Atsuzawa¹, Tomoaki Soma², Satoshi Yasuda³, Koji Adachi⁴

ABSTRACT: Since wood construction using various wood materials has been realized in Japan, this study focused on "Flexible Wood", a composite material made by laminating and bonding wood veneers with a sheet-like adhesive. This wood material easily deforms when subjected to bending stress, allowing curved surfaces and curvilinear designs without advanced processing or techniques. However, its use has been limited to furniture and other applications. Therefore, we devised two ways to utilize the material as a structural element: as a component of a truss or arch structure to prevent bending stress, and as a face material to resist in-plane shear forces. The "Flexible Wood " was attached to a laminated wood frame as a structural element, and a prototype wooden pergola was designed and fabricated with high design quality by utilizing curved surfaces and curves. Additionally, force tests were conducted to confirm the performance of the wooden pergola, and the fracture characteristics were examined and compared with the calculated values of bearing capacity and stiffness.

KEYWORDS: flexible wood, flexibility, shear wall, wooden structure, glulam

1 – INTRODUCTION

In recent years, various wood materials have attracted attention in terms of effective use of domestic forest resources and reduction of carbon dioxide emissions, and the use of wood in the construction sector has been promoted. As shown in Fig.1, it is known that the overall strength of timber cut from mountains is statistically normally distributed[1], and the value of timber tends to be proportional to Young's modulus, making it difficult to handle timber with a low Young's modulus. Effective utilization of low Young's modulus timber is considered necessary to promote further timber utilization. Therefore, this study focused on "flexible wood [2],[3]" (Fig.2). Flexible wood is a composite material made by laminating and bonding wood veneers with a sheet adhesive, as shown in Fig. 3, and is a new type of wood material that can be bent and twisted at will. The easy bendability of this material makes it suitable for soft low-Young's modulus timber, and it was thought that it would enable the utilization of unused timber. However, as this wood material easily deforms under bending stress, it is difficult to use it as a component of a structure and has been limited to applications such as stools and bench seats [4]. In response to the above issues, the authors developed a construction method that enables the construction of wooden frames that utilizes the curves created by flexible wood, with the aim of extending new possibilities for the

use of wood and expanding the applications of flexible wood.



Figure 1. Relationship between Young's modulus classes and Value envisaged in the construction industry.



Figure 2. Material composition and deformation mechanisms

¹ Eito Atsuzawa, Taisei Advanced Center of Technology, TAISEI Corporation, Yokohama, Japan, atzeit00@pub.taisei.co.jp

² Tomoaki Souma, Taisei Advanced Center of Technology, TAISEI Corporation, Yokohama, Japan, sumtma00@pub.taisei.co.jp

³ Satoshi Yasuda, Taisei Advanced Center of Technology, TAISEI Corporation, Yokohama, Japan, satoshi.yasuda@sakura.taisei.co.jp

⁴ Koji Adachi, Institute of Wood Technology, Akita Prefectural Univ, Noshiro, Japan, kadachi@iwt.akita-pu.ac.jp

In this study, we designed and fabricated a wooden pergola (a shelf for twining vines in the eaves or in the garden) using this construction method, as shown in Fig.3, and conducted force tests, observed its deterioration by outdoor installation, and verified its development into various forms.



Figure 3. Wooden pergola

2 – New construction method

2.1 Flexible wood properties and structural devices

As shown in Fig.2, flexible wood is difficult to maintain its shape when subjected to bending stress, as the sheet adhesive between the laminated wood veneers deforms with significant shear displacement. Therefore, it was confirmed that the shape can be maintained by restraining this shear displacement with bolts or other means (Fig.4). To use the material as part of a structural frame while maintaining its shape, it must be constructed in such a way that bending stresses do not act on the material and the shape must be restrained by bolts or other means. Therefore, we investigated the use of the material as either (i) a component of a truss or arch structure, or (ii) as a face material that acts as a resistance element for in-plane shear forces, as is the case with face-mounted load-bearing walls used in conventional shaft construction methods. In the present study, the development of (ii) face-tensioned loadbearing walls with a relatively simple joint configuration were carried out.



Figure 4. "Flexible wood" variant restraints

2.2 Design of wooden pergolas

The wooden pergola (span $5,170 \times \text{height } 2,770 \times \text{depth}$ 3,060 mm) was designed and built using flexible wood for the bearing walls and roof structure (Fig.5). As a horizontal force resisting element, a wooden rigid-frame structure using laminated larch (different grade composition, E95-F270) for the columns and beams in one direction and a load-bearing wall structure using soft wood (cedar veneer + sheet glue) fastened to the columns and beams with screws as facing material in the orthogonal direction (Fig.5). As shown in Fig.5, the columns were made of two laminated timbers (240 × 60 × 2,760 mm) laminated together with LVL binders ($120 \times 60 \times 300$ mm). Five laminated columns were arranged at a pitch of 720 mm. The beams were also laminated in the same way as the columns, and the beam-column joints were designed to resist moments by means of a three-sided shear system with four drift pins. The soft wood was made in strips 300 mm wide \times 1,860 mm maximum length \times 9 mm thickness.



Figure 5. Shear wall by "Flexible wood"

The material consisted of 1 mm thick cedar veneers glued together for eight layers with double-sided adhesive tape (approximately 0.14 mm thick) conforming to JIS Z1541. As shown in Fig.6, two layers of wood veneer with orthogonal fibre directions were inserted at 150 mm from the edge to prevent punching fracture at the screw heads when screwed in place.



Figure 6. Material composition

The construction method involved bending strips of soft wood along notches in the mating columns and beams and weaving them into the front and back (Fig.7). In another experiment, it was confirmed that soft wood with this cross-sectional configuration can be stably deformed up to a curvature of about 3.5 rad/m in actual measurements. For cedar plywood with resorcinol glue of the same thickness, the curvature is 0.35~0.45 rad/m, which is about 8~10 times greater than that of cedar plywood with resorcinol glue. In the present wooden pergola, the curvature was set to be about 2 rad/m, based on the results of the test construction using a preliminary mock-up. The pillar pitch and notch depth were determined according to this curvature. As shown in the Fig.7, the high deformation performance of the pergola made it possible to easily construct the curvature manually, which would normally require advanced techniques such as bending with heat or cutting from a large piece of material. A joint was made at the location of the mating columns so that the length of the flexible wood was less than 2m, which is the manufacturing limit length. At that joint position, the soft wood is braided into the bend. At the joints, the flexible wood is not bent, but is flat and fastened along the columns with 6 screws on each of the two sides, for a total of 12 screws, and this part functions as a face load-bearing wall (Fig.8). For positioning purposes, two screws were used to fix the joints at the location of the mating columns (or beams) outside of the joints.





Figure 8. Part of the shear wall

2.3 Resistance organisations

Fig.9 shows the resistance mechanism against horizontal force Q. Flexible wood is woven into the front and back of the laminated columns, so that the facing sections are scattered across the front and back of the wall. The total resistance moment Mi of these facing sections, ΣMi , is assumed to be the resistance moment of the entire wall, which resists the horizontal force Q.



Figure 9. Resistance Mechanism

The equation for the equilibrium between the sum of the resisting moments ΣMi and the horizontal force Q is shown in Equation (1), where the height of the wall is H.

$$\sum M_i = Q \cdot H \tag{1}$$

The resisting moment Mi per facing due to flexible wood was calculated based on [5]. The neutral axis of the facing is determined from the arrangement of the screws, and Mi is calculated based on the distance from the neutral axis and the one-sided shear resistance of the screws. As shown in Fig.10, calculations were carried out using the area enclosed by the 12 screws as the face material section. The screw pitch was set to 50 mm and the minimum clearance distance was 15 mm due to the thickness of the column. The number of scattered facing pieces was 18 per wall surface. The bearing capacity and stiffness per screw was calculated using European yield theory. The material thickness used was assumed to be 7 mm (1 mm \times 7 layers) of cedar veneer, which constitutes flexible wood. As surface cracking was observed due to outdoor use, as described below, it was assumed that one surface layer and the adhesive layer would not bear structural performance. Screws were $\varphi 4.1 \times 51$ mm (stainless steel). The yield capacity was assumed to be determined by the flexible wood, the side members, and the material strength of the laminated wood of the frame and the cedar veneer of the flexible wood was referred to the values in [6].



3 – Full-scale experiments

3.1 Experimental design

Full-scale force tests were conducted on the designed wooden pergola. Fig.11 shows the force apparatus. On each of the east and west walls, the independent foundation blocks at the column footings were fixed with steel frames, and the steel beams for loading, which were screwed to the sides of the column heads, were loaded by a center-hole jack (capacity 200 kN). The force was applied in one direction only, with repeated unloading and loading at deformation angles of 1/450, 1/300, 1/200 and 1/100. As the independent foundations of the footings could not be fixed to the ground, the load-bearing test method for the column leg fixing method was referred to based on [7], and the shear deformation angle was calculated as the difference between the overall deformation angle, the rotation angle due to wall uplift and the rotation angle due to foundation uplift.



3.2 Experimental results

The main failure behaviour at maximum load is shown in Fig.12. Out-of-plane buckling of the members due to oblique compressive forces was observed in scattered loadbearing wall sections as a result of shear deformation. In addition to the edge failure of the screws in the face members, which were assumed to be the resisting element, the penetration of the flexible wood edges in the notches of the laminated timber columns and the mutual friction and penetration of the members at the upper and lower flexible wood intersections were also observed. The friction and penetration resistance caused the flexible wood members to behave like through-joints and the load continued to increase.



Figure 12. Fracture mode (west side)

The load-deformation angle relationships for the east and west bearing walls are shown in Fig.13. No clear reduction in load was observed even after the deformation angle exceeded 1/15, and the jacking stroke limit was reached, so the application was terminated. In comparison between the east and west faces, the load-bearing wall on the east face had lower values for both stiffness and load-bearing capacity. As shown in Fig.14, the lifting of the foundation increased on the east side as the force increased, and although the force was applied by load control, the load could not be made completely uniform, and differences in load and deformation were observed between the east and west sides. The experimental values of the yield capacity (average of east and west) and the calculated values using black solid lines and black dotted lines, respectively. The experimental values were approximately three times higher than the calculated values. The reason for this is that the shear-resisting elements of the faceplate were subjected to interlocking of the flexible wood members and edge penetration, in addition to the one-sided shear of the screws. The distance from the neutral axis of the facing was greater at the location of these embedded points than at the location of the screws, resulting in a larger area of the facing than expected, and thus the experimental values of the yield capacity exceeded the calculated values. The shear buckling increased the deformation at the corner on the tensile side, and the position of the neutral axis moved to the compressive side, which is thought to have caused the different properties from the referenced resistance mechanism.



Figure 13. Load-deformation angle relationship



Figure 14. Uplift of leg foundations

4 - outdoor use demonstrations

Although flexible wood is basically intended for indoor use, a wooden pergola was installed outdoors on a trial basis so that the weather resistance of the members could be checked as an accelerated deterioration test. The installation period was approximately 4 months. The flexible wood used in this study was composed of materials with the same fiber direction and species, except at the ends. As a result, as shown in the Fig.14,15 only the first surface layer was repeatedly deformed by temperature and humidity changes and direct sunlight in about two weeks, and the second and subsequent layers did not follow the deformation, and peeling, rippling, and swelling of the members were observed. These changes occurred on the entire wall surface, and there was no significant difference between the east and west walls. There was no unevenness in the deterioration of the entire wall surface, and the rippling and cracking were concentrated in the joints with screws. The cause of this is thought to be that the flexible wood in the joints rippled due to the tightening pressure of the screws, and that the swelling and contraction caused by temperature and humidity changes and sunlight increased the deformation of the wood, resulting in the development of cracking. Solutions to the deterioration identified include measures that protect the flexible wood as a whole, such as using stronger materials with less deformation in the surface layer and covering it with water- and weatherresistant materials. In addition, in joints where deterioration is severe, it may be effective to carve out the heads of screws to relieve the tightening pressure, to use a joint method in which the tightening force is generated in a plane, and to prevent rainwater from entering the joints.



0 week 2 weeks later Figure 15. Deterioration of the entire wall surface





Rippling and cracking of surface

Swelling of the component

Figure 16. Issues identified through outdoor use.

5 – other forms and development of unit construction

The construction method developed in this study can be applied to various forms, as long as the frame is made of flexible wood woven into the structure. The Fig.17 shows an actual example of the application of this construction method to an arch shape. The dimensions of the arch frame are $3.2 \text{ m high} \times 6 \text{ m long} \times 3 \text{ m deep}$, which are almost the same as those in Chapter 2.



Figure 17. Arch-type pergola.

In this type of pergola, the arch frame is made up of six parts, each of which is assembled at the factory until the flexible wood is attached, and only the joining of the units is done on site(Fig.18). This reduces the overall weight of the frame and makes it possible to reduce the size of the heavy equipment required for installation. Furthermore, by attaching the flexible wood at the factory, the on-site work was labor-saving, and the construction period was completed in one day for the arch frame pergola, compared to two days for the ramen frame pergola.



Figure 18. Unit construction.

The larger the area of flexible wood, the greater the twisting and deformation of the material itself. Therefore, for the arch-type pergola, the width of the timber was reduced to the extent that structural performance could be secured, and the width was set at 150 mm. Furthermore, as shown in the Fig.19, the joints with screws, where deterioration was concentrated, were covered with wood to protect them from rainwater intrusion and ultraviolet rays. The proposed construction method can be applied to various forms.





Installation of cover

After cover installation

Figure 19. How to protect joints.

6 – CONCLUSION

A wooden frame utilizing flexible wood was proposed to expand new possibilities for wood utilization, and force tests were conducted to confirm its structural performance. results are shown below.

(1) We developed a technology that enables the use of "flexible wood" as a part of the wooden frame by using it as a face material of the bearing wall.

(2) Using the developed technology, a wooden pergola was constructed utilizing curves and curved surfaces, which are difficult to achieve with ordinary wood.

(3) Force tests were conducted to confirm the average maximum bearing capacity of 10.1 kN, the average initial stiffness of 376 kN/rad, and the fracture characteristics of the structure.

(4) Changes such as rippling and cracking of the surface layer and swelling of the members were confirmed by observation of the exterior appearance during outdoor use.

(5) The applicability of the developed construction method to arch structures was verified, and the use of unit construction realized a reduction in on-site work.

In the future, we intend to utilize the free-form characteristics of the construction method in forms other than wooden pergolas (as part of trusses and arches) and as interior materials that are gentle to the human body.

7 – REFERENCES

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