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AN EXPERIMENTAL STUDY ON THE SAFETY PERFORMANCE OF A WOOD MASONRY STRUCTURE

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ABSTRACT: This paper presents the experimental results conducted to evaluate the mechanical properties and safety of a wood masonry structure called "Mirika no Ki" (Mirika) used in a complex cultural facility in Japan. Mirika is designed to prioritize the use of locally sourced wood and emphasizes its potential reusability during disasters or emergencies. The wood is stacked in 36 layers with a section size of 105 mm x 170 mm, and full-threaded screws are utilized for joints. The study evaluates the horizontal resistance of Mirika through an in-plane horizontal loading test on a wood masonry wall. Additionally, two further experiments were conducted to verify the structural integrity and functionality of the joints. The objective of this study is to provide fundamental data for designing wood masonry structures to promote the recycling of wood materials.

KEYWORDS: Wood masonry structure, Screw joint, Pull-out resistance of screws, In-plane shear test, Out-of-plane shear test

1 INTRODUCTION

Forests have multiple functions such as preserving national land and supplying forest products, so proper maintenance and preservation are necessary. In Japan, there is a movement to promote wood recycling through the establishment of laws related to the promotion of wood utilization. As part of the active use of wood, the renovation plan of a complex cultural facility in Nakagawa City, Fukuoka Prefecture, utilized a locally manufactured wood masonry structure "Mirika no Ki" (Mirika) with the concept of emphasizing space and gathering people under the tree (Figure 1).

Figure 1: Wood Masonry Structure" Mirika no Ki"

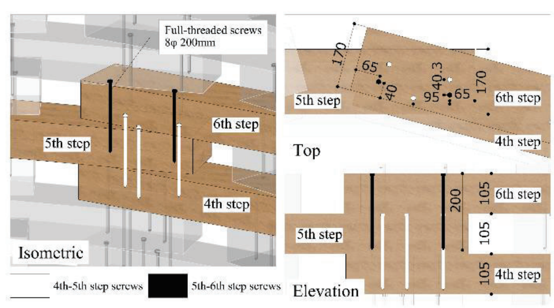

Figure 2: Detailed image of the joint

The design of Mirika prioritizes the use of raw wood harvested in Nakagawa City to emphasize its importance and provide the ability to reuse it in case of disaster or emergency. The lumber used to construct Mirika has a section size of 105 mm x 170 mm and is stacked in 36 layers by varying the length of the members. The joints between each piece of lumber are made from the top layer using full-threaded screws (Figure 2), which have high reproducibility, are easy to construct, and allow for freedom in shaping. Therefore, the development of Mirika is expected to greatly contribute to the promotion of wood material recycling. However, there are few similar structures, so data to design from is limited. Therefore, in this research, experiments are conducted to obtain basic data to design wood masonry structures. The forces acting on the joints are thought to arise in the screw in tension and shear directions and the wood in compression direction and are carried by the tension of the screw and the compression of the wood in the bending direction. This study aimed to evaluate the safety and mechanical properties of Mirika, a material used in wood masonry structures. In-plane wall experiments were conducted as well as joint pull-out and joint bending tests to validate the structural integrity and functionality of the joints. The

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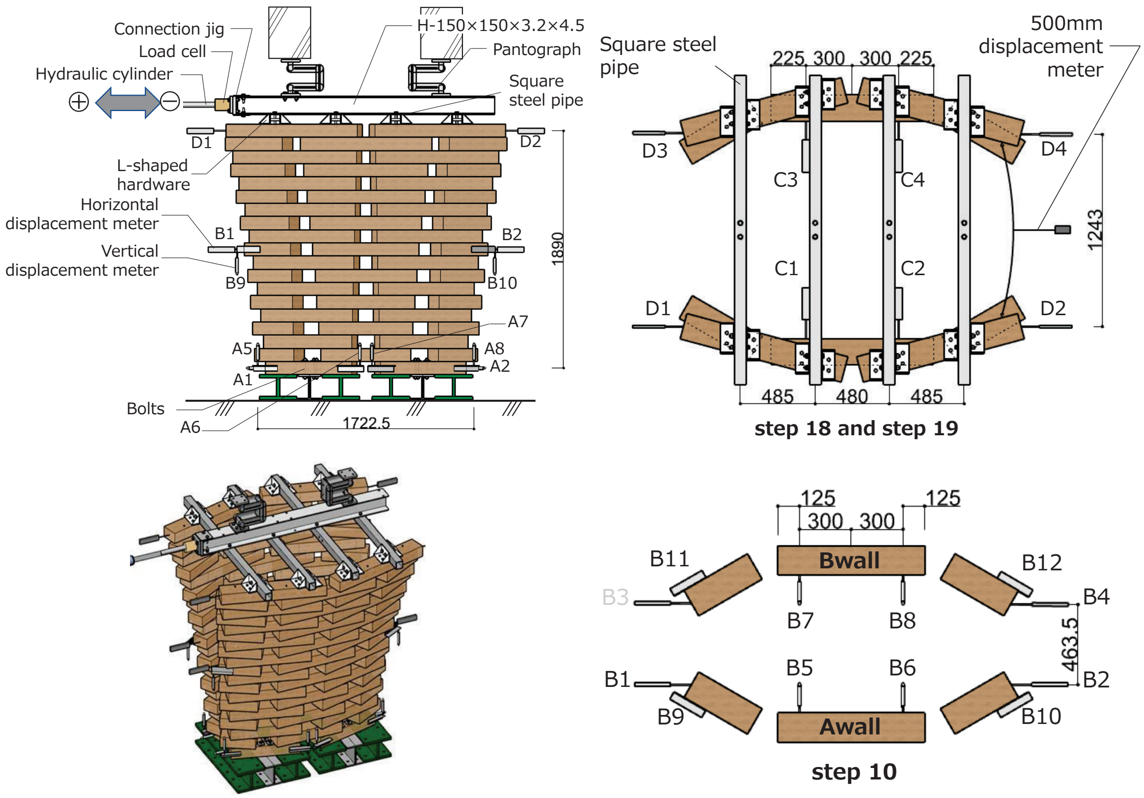

Figure 3: *Shear wall test specimen and setup*

results of these experiments provided fundamental data for the design of Mirika.

2 SHEAR WALL TEST

2.1 SPECIMENS AND SETUP

In Japan, elastic design is usually performed with a base shear coefficient of 0.2 to 0.3. However, since Mirika is thought to be unstable due to its high center of gravity, the base shear coefficient was set to 0.5. Therefore, Mirika's self-weight 0.5 times (15kN) was set as the target for horizontal resistance, and an in-plane horizontal loading test was conducted on a wood masonry wall. An experiment was conducted on the application of horizontal forces within the wall of the wooden assembly structure. The shape and dimensions of the test body in the wall test and the position of the displacement meter are shown in Figure 3.

The test body cuts out 1/6 of Mirika from the top and uses up to the 19th step, which is the height of the opening. Two test bodies were joined back-to-back, with the top of the two bodies were constrained by steel.

This is to consider the impact of stress on the surface and stabilize the test body shape and reproduce the resistance mechanism under the same condition where force is applied in the direction of the opening as Mirika. The sections of 105 mm x 170 mm cedar lumber were stacked vertically, and full-threaded screws 8Φ200 mm were used with 3 screws at each joint for the lower 5th step and 2 screws at each joint for the 6th step and above.

The loading schedule was implemented according to the literature and the apparent shear deformation angle was

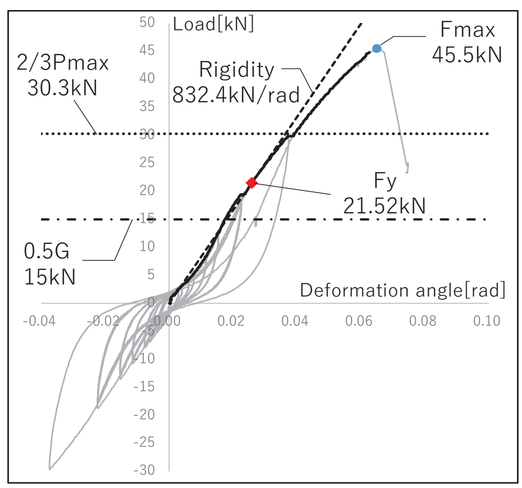

Figure 4(a): *Load deformation angle curve*

tested 3 times at various radian values (1/450, 1/300, 1/200, 1/150, 1/100, 1/75, and 1/50) in positive and negative alternation, with a single repetition at 1/30 rad. The loading was increased to reach the maximum load and then continued until it decreased to 80% of the maximum load.

2.2 RESULTS

Load deformation angle curve and final failure condition in Figure 4. The graph uses a true shear deformation angle. The horizontal displacement of the beam material was measured using a 500 mm displacement transducer

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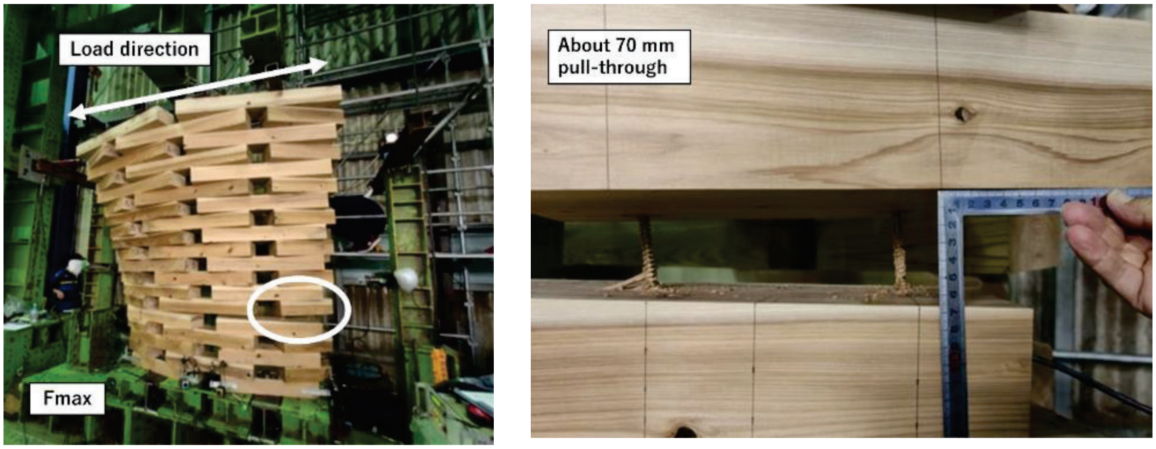

Figure 4(b): *Ultimate Fracture Properties (Left), pulling out of screws (Right)*

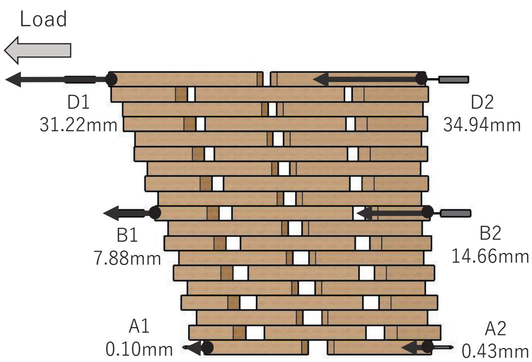

Figure 5: *Awall horizontal displacement*

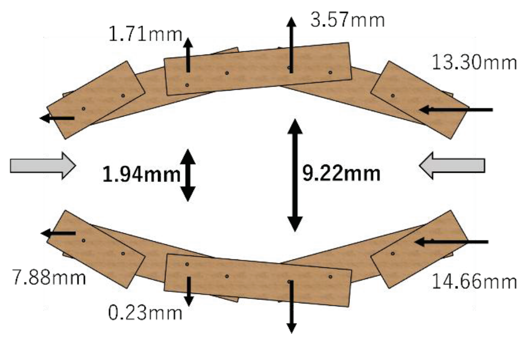

Figure 6: *10th step horizontal displacement*

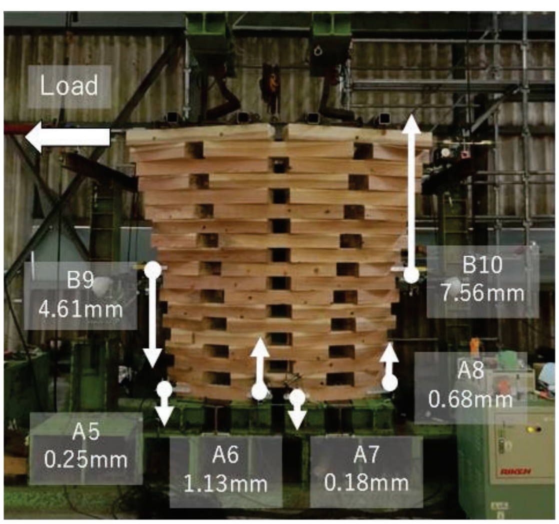

Figure 7: *Awall Vertical displacement*

attached to the shaft of the 19th step. For the horizontal displacement of the foundation, the average value of the horizontal displacement meters A1 to A4 of the 1st step is used.

For the vertical displacement of the column foot, the average value of the vertical displacement meters A5 and A9 of the first section and the average value of A8 and A12 are used to calculate. The characteristic value was calculated based on reference 4). The final fracture behavior was the pullout of screws at the 5th and 6th steps when the horizontal displacement of the 19th step was 140 mm and the maximum bearing capacity was 45.45kN, and the maximum pullout of about 70 mm was observed after the fracture. Figure 5 shows the horizontal deformation of Awall at 0.5G, and Figure 6 shows the horizontal displacement at the 10th step, which is the middle of the w all. The deformation on the right side is larger than that on the left side at the 10th step. Also, at the 10th step, both the deformation in the direction outside the surface and the deformation in the direction inside the surface are larger on the right side compared to the left side. Therefore, while the 10th step undergoes shear deformation in the direction of the applied force, it collapses in the direction inside the surface and deforms in the direction outside the surface. Figure 7 shows the vertical displacement at 0.5G (15kN). On the tenth floor, the deformation on the left side of Awall is 4.61mm vertically downwards and on the right side it is 7.56mm vertically upwards, which means it is rocking in the left direction. The safety of the wall as Mirika has been confirmed from the results exceeding the target of this structure's 0.5G in terms of buckling strength and 2/3Pmax.

3 PULL-OUT TESTS

3.1 SPECIMENS AND SETUP

A pull-out test was conducted to confirm the characteristics of the joint part when subjected to tension force in this structure. The test body consisted of cedar wood (density: 411.7kg/m3 (avg.), moisture content: 14.7% (avg.)) with dimensions of 105 mm x 170 mm × 250 mm and was fastened using 8φ200 mm full-threaded screws (Figure 8). The number of full-threaded screws was varied in two ways, 1 screws (S1) and 2screws (S2), with each variation resulting in 6 test bodies for a total of 12 test bodies. The load was applied at a uniform speed of 1mm/min using a universal testing machine (2000kN). The measurement item was the average value obtained from two displacement gauges, which were placed on the wood in the vertical direction and measured the bolt pull-out amount δ. The load was increased until the maximum strength was exceeded by 0.8Pmax or the wood was cracked, ending the experiment.

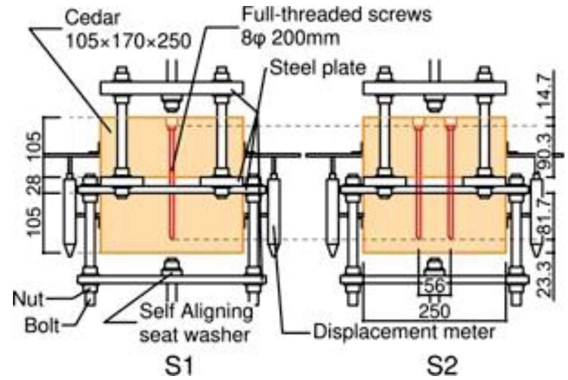

Figure 8(a): Specimen configuration and set-up

3.2 RESULTS

The load-deformation curve of the pull-out test is shown in Figure 9. The calculation of characteristic values was based on the manual for designing wooden joints 1). The final failure mode of the S1 test specimen was screw head embedment for 1 of the 6 specimens, and destruction by pulling out the tip of the screw for 5 specimens (Figure 10). The average ultimate strength of S1 was 6.16kN, which was 37% higher than the calculated value assuming a wooden screw in the "Standard for structural design of timber structures" (AIJ standard[1]). The final endurance was over the calculated value for 5 out of 6 bodies and had a higher distribution than the calculated value overall. Defects may have affected it, as there were knots and cracks of around 4d size in the vicinity of the screw within 7d from the screw location of the used lumber. The large variation in test results may be due to the high-density variability (CV) of 12% in the lumber and instability in the shape of the test body. The final destructive properties of the S2 test bodies were that 1 out of 6 bodies had the tip of the screw pulled out and 5 bodies were broken by cracking along the fibers of the wood (Figure 11). The test bodies that were broken by cracking had almost linear stiffness increases until the yielding and cracking of the wood occurred around 0.8mm and the load dropped once. The average final resistance per screw in S2 was 6.38kN, which was 42% higher than the calculated value assuming

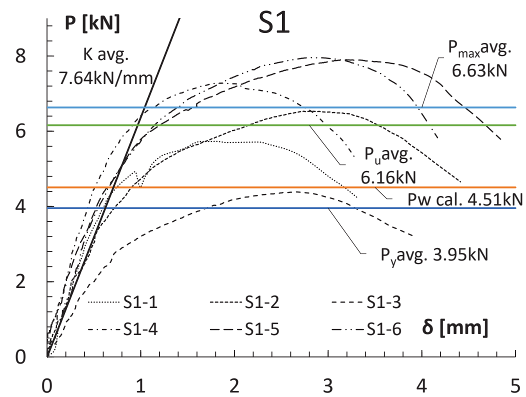

Figure 9(a): S1 load-deformation curve

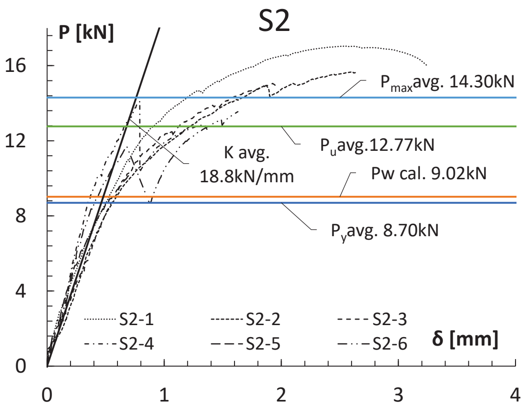

Figure 9(b): S2 load-deformation curve

Figure 8(b): *Picture of pull-out test*

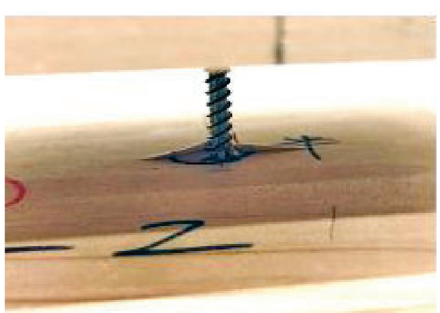

Figure 10: *S1 pulling out the tip of the screws*

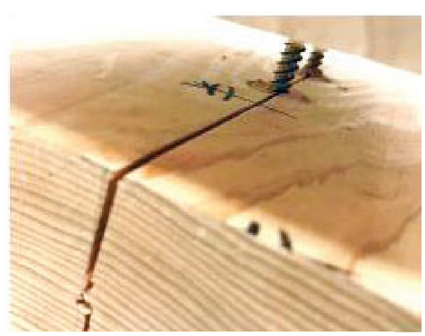

Figure 11: *S2 cracking along the fibers*

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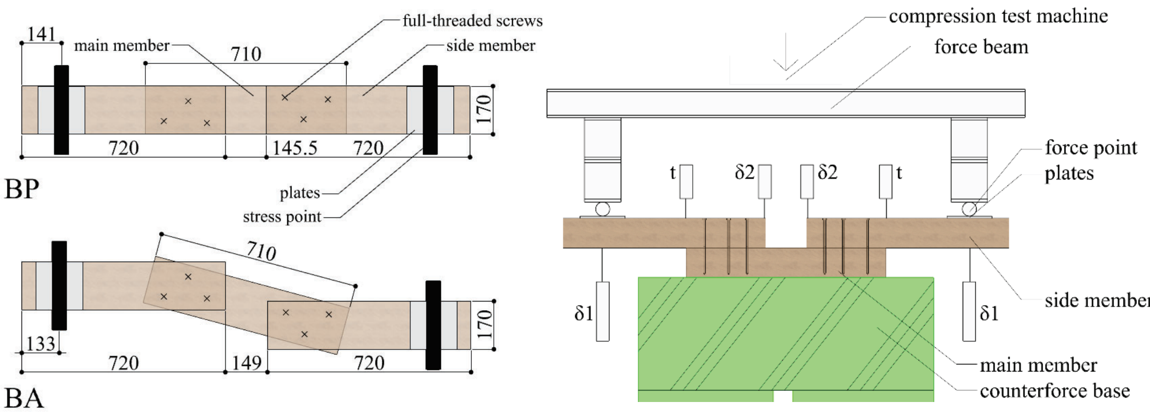

***Figure 12**: Joint test specimen shapes and installation*

wood screws using AIJ standards. When compared with the yielding resistance of S1, S2 demonstrated more than 2 times the yielding resistance. From this, it can be said that there is no reduction in withdrawal resistance due to multiple screws in the joint.

4 JOINT TEST

4.1 SPECIMENS AND SETUP

The experiment outline and test body dimensions are shown in Figure 12. The purpose of the bending experiment of the joint is to understand the mechanical characteristics when the locking deformation by the horizontal force causes the overturning moment in Mirika. The test body was shaped to reproduce the shape of the joint's 1st-2nd steps, which was considered to generate the most bending stress in Mirika.

The test body was made by layering two Sugi timber materials with main timber dimensions of 105 mm x 170 mm × 710 mm and side timber with the same cross-sectional length of 720 mm in the fiber direction parallel (BP) or rotated 15 degrees in the plane (BA), and with a water content of 16.3% (avg.), the density of 412kg/m3 (avg.), and Young's modulus of 6892.2N/mm2 (avg.). Three full-threaded screws 8Φ 200 mm were driven vertically.

The shape of the test body was layered symmetrically left and right to consider stability during loading. The rotation angle of BA is the same as that of Mirika. The screw insertion position was determined by the edge distance and spacing based on the AIJ standard for lag screw joints. Both BP and BA were arranged similarly to the first and second sections of Mirika. The number of test bodies was 6 for BP and 7 for BA. The measurement items were vertical displacement δ1 [mm] at the applied force point, compression amount t [mm] at the main member mouth position, and vertical displacement δ2 [mm] at the side member end.

The test body was placed on a counterforce base, plates for preventing compressive strain, and cylindrical fixtures were installed at both applied force points, and a uniaxial compression test machine with 2000kN was used to apply vertical force through an applied force beam. The applied force schedule was to reach the maximum strength in about 10 minutes, and the force was applied

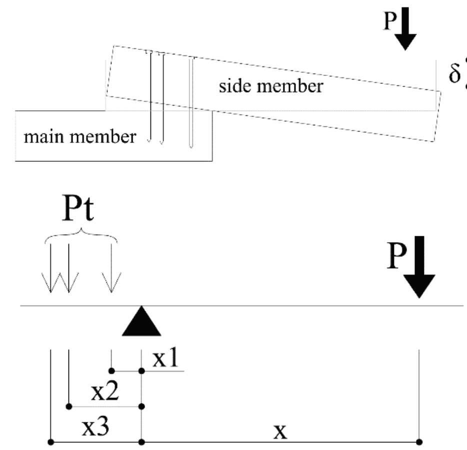

***Figure 13**: Joint dynamics model*

$$P = P_t \cdot \frac{x_1 + x_2 + x_3}{x} \qquad (1)$$

P: Estimated Bending Strength P_t: Screw Pull-out Strength
x: Distance from the bottom of the timber to the point of application
x_1, x_2, x_3: Distance from timber edge to screw core

until it reached 0.8Pmax after reaching the maximum strength. The estimated maximum strength was calculated by assuming the wood to be a rigid body and using the balance Equation of the pulling strength of the screw and the moment depending on the insertion position based on Equation (1) (Figure 13)

4.2 RESULTS

The load-deformation curve is shown in Figure 14, the experimental conditions are shown in Figure 15, and the characteristic values are shown in Table 1. The vertical axis of Figure 14 is the load on the side that broke among the left and right of 1 test body, and the horizontal axis is the vertical displacement of the point where the load was applied on the side that broke. The calculation of the characteristic values is the same as for the pull-out test.

The final fracture behaviour is dominated by the pull-out of the screws in both BP and BA, and the fracture is accompanied by wood compressive displacement. Brittle fractures were not observed in all test specimens, and the load gradually decreased after the maximum strength. In BA, rotational deformation in the direction of twisting of

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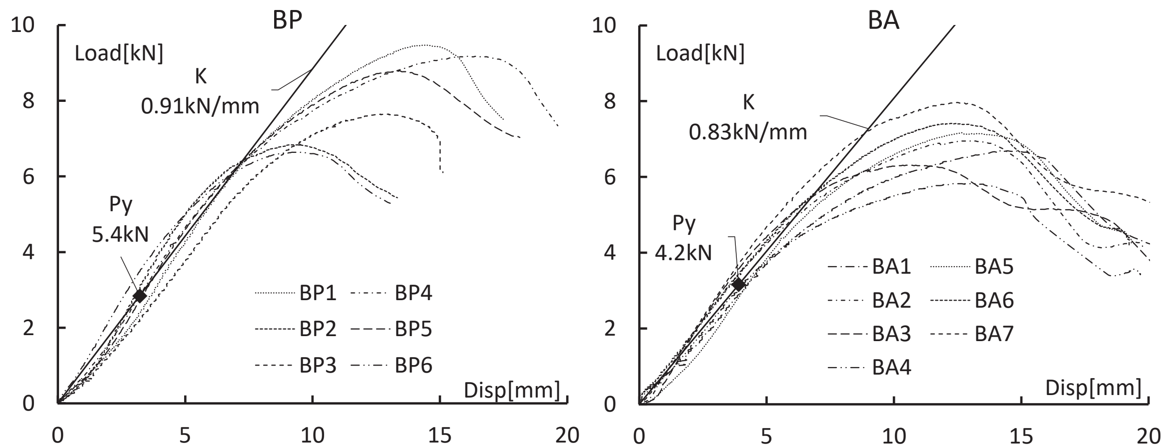

Figure 14: *Joint test load-deformation curve*

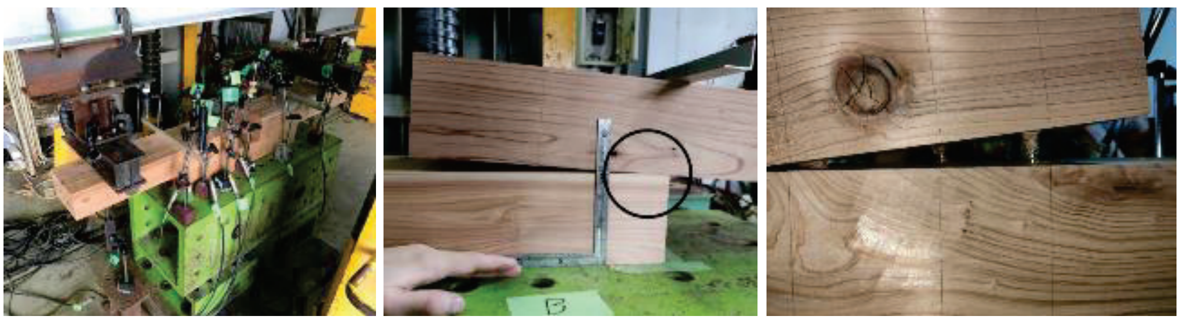

Figure 15: *Joint test process (Left), wood compressive displacement (Middle), pulling out of screws (Right)*

Table 1: *Joint test characteristic value*

		Initial stiffness K [kN/mm]	Yield strength Py [kN]	Maximum capacity Pmax [kN]	Ultimate strength Pu [kN]
BP	Average	0.92	5.40	8.09	7.45
	Lower limit	0.88	2.84	5.49	5.16
	Equation (1)	—	6.37	—	—
	Equation (2)	—	2.84	—	—
BA	Average	0.83	4.23	6.90	6.35
	Lower linit	0.81	3.16	5.37	4.75
	Equation (1)	—	6.02	—	—
	Equation (2)	—	3.02	—	—

the side member also occurred due to the angle of the material. The average yield strength obtained from the experiment was lower than the predicted strength calculated by equation (1), with 85% for BP and 70% for BA. This is the effect of the moisture content of the wood used and the compression between the woods. The average moisture content of the wood used in both series was about 22%, exceeding the recommended value of the AIJ standard, so there is a possibility of a decrease in screw withdrawal resistance and an increase in compression amount. And the compression between the wood pieces resulted in a triangular compression that maximizes the end of the main member. This causes the rotation center of the main member during the bending deformation of the joint to move from the end of the main member to the center of gravity of the triangular compression, resulting in experimental values lower than

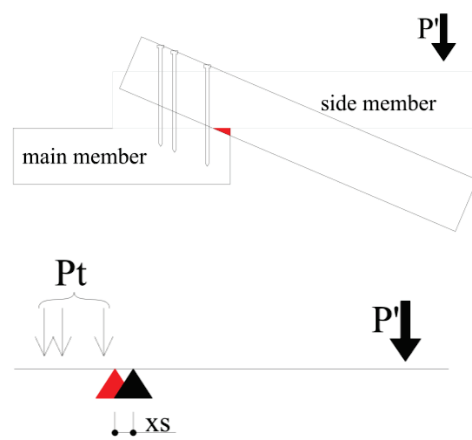

Figure 16: *Joint dynamics model considered compression*

$$P' = P_t \cdot \frac{x_1 + x_2 + x_3 - 3x_s}{x + x_s} \qquad (2)$$

P': Estimated Bending Strength x_s : $x_p/3$
x_p : Main material compression length

the bending resistance assumed in Equation (1) when the wood is assumed to be a rigid body.

Therefore, there is a possibility that the estimated value will be closer to the experimental value by modelling the support point that considers the compression of the wood. Considering the above factors, the lower limit of the bending-yield capacity of this joint was calculated using Equation (2) (Figure16), which was developed from

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Equation (1) using the wood-screw pullout capacity equation in the AIJ Standard and the penetration equation in the Design Manual for Wood Structural Joints. Here, it is assumed that the dominant area of wood compression is near the edge of the main member, based on the extra-length condition and the experimental results. The bending capacity was estimated by applying the fulcrum reaction force of Figure 16 to ΣN in the denting equation to obtain x_p and using the moment balancing equation if the center of rotation moves to one-third of that value. Comparing the estimated values calculated above with the experimental values, the BP series and BA series are -0.3% and -4.3%, respectively, and the bending-yield capacity of the joints in this test specimen shape can be estimated on the safe side using Equation (2).

5 CONCLUSION

The mechanical properties of wooden composite structures were verified through experiments. The following are the results obtained from this study.

1. The mechanical properties of the joints in Mirika were experimentally understood.
2. In the pull-out experiment, the average ultimate strength of the S2 series was 2.07 times that of the S1 series, and it is considered that there was no reduction in initial rigidity in the wooden joint shape in the scope of this experiment.
3. When considering the rotation of the joint, there is compression between the wooden materials, and it is necessary to consider the movement of the rotation center in estimating the strength.
4. In the wall inside the surface experiment, the yielding strength was 21.5kN and 2/3Pmax was 30.3kN, and the safety as a structural body of the wall was confirmed as the result exceeded the target weight of the bookshelf (15kN).

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