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JOINT PERFORMANCE TESTING OF A CLAMPED JOINT FOR TIMBER STRUCTURES AND APPLICATION TO STRUCTURAL DESIGN

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ABSTRACT: The authors developed a clamped joint system, which they called *Tsunagi-clamp*, to assemble and reassemble timber structures easily without complex wood manufacturing. The purpose of this study is to make clear the performance of joints using *Tsunagi-clamp* and effective method of reinforcement, as well as to predict the horizontal resistance performance of a timber cubic frame structure that used this claimed joint system, in which the analysis was performed on the stiffness of the clamped joints during application. By testing the clamped joints under torsion loading and moment loading, it was confirmed that the stiffness of damaged joints reinforced with screw or wood putty were larger than that of undamaged joint. The assumed deformation by analyzing the cubic frame model, in which the stiffness of the joints deformed 1/100 radians, closely fitted the results of the horizontal resistance test. This result suggests that it is possible to verify the performance of other structures with *Tsunagi-clamp* by using the same analyzing method.

KEYWORDS: Clamped joint, Joint performance, Temporary structure, Structural design

1 INTRODUCTION

From a carbon emission point of view, the demand for medium to large-scale timber buildings is increasing. However, the specialization of the forest industry makes timber distribution complex, especially in Japan. This circumstance disturbs not only normal market principles but also the normal circulation of forests. The authors propose that providing consumers with the opportunity to directly construct human-scale timber buildings will help promote its widespread use. This goal is achieved by suggesting various structures that can be built, transformed, disassembled, and easily relocated. The authors call this structure *Tsunagi*, which means "connect" and "connecting wood" in Japanese.

The authors developed a simple clamped joint system, known as *Tsunagi-clamp*, so to assemble and reassemble the structures easily without complex wood manufacturing.

Figure 1: *Example of transforming "Tsunagi"*

The purpose of this study is to evaluate the performance of joints using *Tsunagi-clamp* and the horizontal resistance performance of a timber cubic frame structure using this clamped joint system and to apply the clamps to structural design.

2 DETAIL OF CLAMPED JOINT

Tsunagi-clamp has been developed based on scaffolding clamps [1], connecting orthogonal members as shown in Figure 2. This clamp is able to clasp a 45 mm squared cross-sectional timber by fastening the bolt at the tip of the clamp as shown in Figure 3.

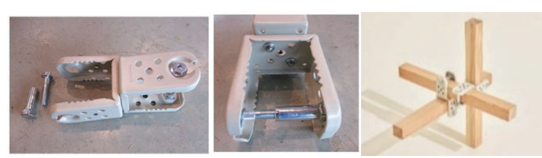

Figure 2: *Detail of Tsunagi-clamp*

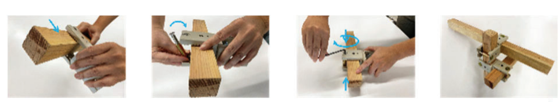

Figure 3: *How to use Tsunagi-clamp.*

One of the characteristic features of *Tsunagi-clamp* is the jagged teeth shape plate. Even if the timber shrinks upon

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drying, the clamp can grab the timber firmly using these jagged plates.

There are 5 holes in each plate to reinforce the joint by screws and to connect other components to the clamp. For example, braces can add to *Tsunagi* easily by connecting the eye bolts, or it becomes possible to fix the structure by grabbing poles by connecting to the scaffolding clamp as shown in Figure 4.

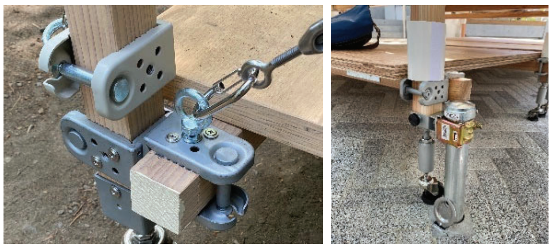

Figure 4: *Example of connecting Tsunagi-clamp and eye bolt or scaffolding clamp*

3 CLAMPED JOINT TESTING

To evaluate the performance of clamped joints, three types of tests were conducted. In all tests, the timber cross-sectional dimension was 45 mm squared, and the timber species was the Japanese Cedar (*Cryptomeria japonica*) with a Young's Modulus of 6000 N/mm^2.

3.1 Torsion tests

The torsion test used a T-shaped joint consisting of two 300 mm long members, connected by *Tsunagi-clamps*. There were five types of specimens as shown in Table 1.

To test the effect of the damage to the area of timber grabbed by the clamp, specimens T3 to T5 were cut down 2 mm in depth before the test. Specimen T2 and specimen T4 were reinforced by four screws, and specimen T5 was reinforced by filling the trimmed area with wood putty (main component was lacquer resin).

Figure 5 shows details of the experimental setup. Static monotonic loading was applied to the vertical member. Vertical force, vertical displacement, slip displacement, and angle of rotation of the vertical member were measured.

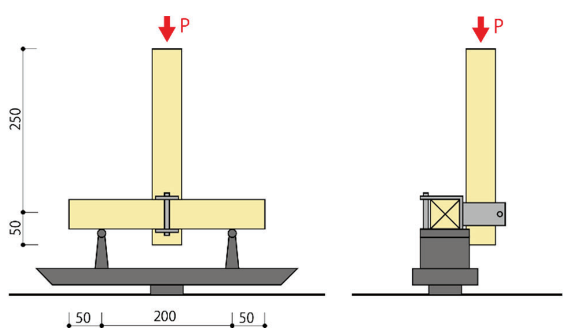

Figure 5: *Test setup of clamped joint torsion tests (units in mm)*

Table 1: *Specimens of the torsion tests*

Testing type	No.	Surface of timber	Reinforcement	Number of specimens
Torsion tests	T1	normal	—	3
	T2	normal	screw	3
	T3	damaged	—	3
	T4	damaged	screw	3
	T5	damaged	putty	3

By adding the vertical force, the nails of *Tsunagi-clump* caved into the horizontal members as shown in Figure 6. These fractures were less detected in Specimen T2 and T4.

Figure 7 shows the relationship between the vertical load and the vertical deformation of the specimens. In each graph, the line of average initial stiffness of T1 was drawn, which was calculated as the slope of the line from the point of $0.1 \times P_{max}$ to that of $0.4 \times P_{max}$, a method based on the structure design guide for framed wall construction houses [2]. This calculation method of initial stiffness was defined as Case 1 in this paper. The average initial stiffness of T4 was 2 times larger and and that of T5 was 4 times larger than that of specimen T1. These results suggest that both ways of reinforcement were effective even if the surface of the timber was damaged.

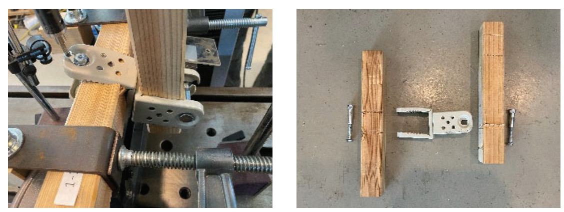

Figure 6: *Fracture of timber in the area grabbed by timber*

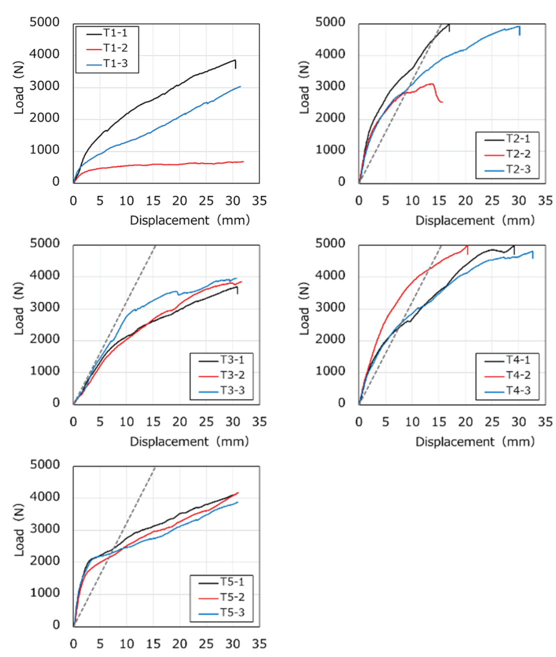

Figure 7: *Load (N) vs. vertical displacement (mm)*

It can be seen that by comparing T4 and T5, the stiffness of the reinforced specimen by screw became smaller gradually, but that by putty had a clear yield point. From this difference, it was assumed that the performance of wood putty method decreased above the initial deformation area.

Vertical displacement was divided into 2 types of displacements, rotate displacement ($= \delta_r$) and slip displacement ($= \delta_s$), both shown in Figure 8 and calculated by Equations (1) and (2). In the initial deformation area, the summation of δ_r and δ_s was closely equivalent to the measured vertical deformation ($= \delta_v$) shown in Figure 9

$$\delta_r = l_1 \times \theta_a \quad (1)$$

$$\delta_s = \delta_{ms} - l_2 \times (\theta_a - \theta_b) \quad (2)$$

Where δ_{ms}= measured slip displacement.

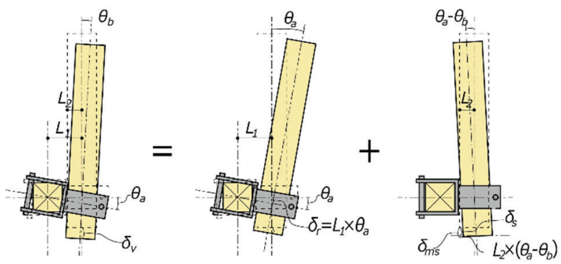

Figure 8: Model of the deformation in the torsion test

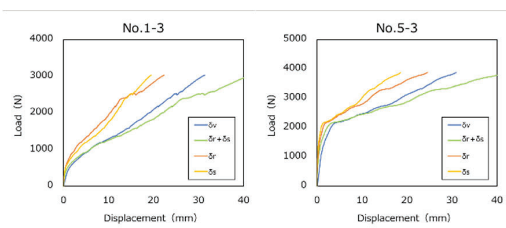

Figure 9: Load vs. displacement (mm)

The average stiffness K_r and K_s, calculated by δ_r and δ_s, are shown in Figure 10. In addition to Case 1, the slope of the line, from the starting point to point $\theta_a = \frac{1}{100}$ radians, was calculated as Case 2.

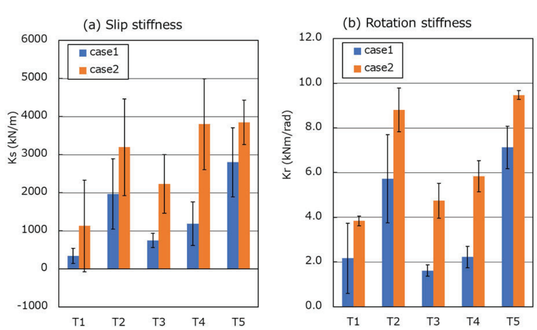

Figure 10: Average slip stiffness and rotation stiffness.

The stiffness in Case 1 were smaller than that of Case 2. In Case 1, the average stiffness while slip displacement occurred for T4 was about 1.6 times larger than T3 and T5 was 3.5 times larger than T3. When rotation displacement occurred in Case 1, the average stiffness of T4 was 1.4 times larger than T3 and T5 was 4.4 times larger than T3. From these results, it was assumed that putty was a more effective reinforcement than screws in both displacement cases.

3.2 Moment tests

The specimens for the moment tests consisted of two units of L-shaped joints, arranged to avoid any torsion effects. The lengths of the timber were 300 mm for monotonic loading tests and 450 mm for cyclic loading tests. The 5 types of specimens are shown in Table 2. The condition of the timber surfaces and reinforcement were similar to that of torsion tests, M3 to M5 were damaged and M2 and M4 were reinforced by screws, and M5 was reinforced by wood putty. Monotonic loading was applied to specimens M2 and M5, and cyclic loading was applied to specimens M1, M3, and M4).

Figure 11 shows the details of the test setup. Static monotonic loading was applied to both units. Vertical force, vertical displacement, and rotation angle between each member were measured.

***Table 2:** Specimens of the moment tests*

Testing type	No.	Surface of timber	Reinforcement	Number of specimens
Moment tests	M1*	normal	–	6
	M2	normal	screw	3
	M3*	damaged	–	6
	M4*	damaged	screw	6
	M5	damaged	putty	3

*3 speciments were applied cyclic loading

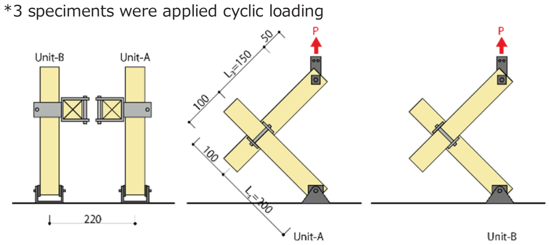

Figure 11: Test setup of the clamped joint moment tests (mm)

To analyze the relationship between the moment and angle of rotation, the moment of each unit was calculated by Equations (3) and (4).

$$M = PL \quad (3)$$

$$L = \frac{l_3 l_4 \sin\left(\frac{\pi}{2} + \theta\right)}{\sqrt{l_3^2 + l_4^2 - 2 l_3 l_4 \cos\left(\frac{\pi}{2} + \theta\right)}} \quad (4)$$

Figure 12 shows the relationship between the vertical load and the vertical deformation, and Figure 13 shows the comparison of the average rotational stiffness for the two cases. The initial stiffness of specimen M3 was 25% smaller than the average stiffness of specimen M1. The initial stiffness of specimen M4 was closely equal to that of specimen M3, and M5 was 35% larger than specimen

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M1. These results suggested that putty was a more effective reinforcement than screws, similar to the results for torsion loading.

On the other hand, it was assumed that both screw and putty cannot prevent fracture by moment strength effectively since the maximum moment was about 230 Nm for all specimen cases.

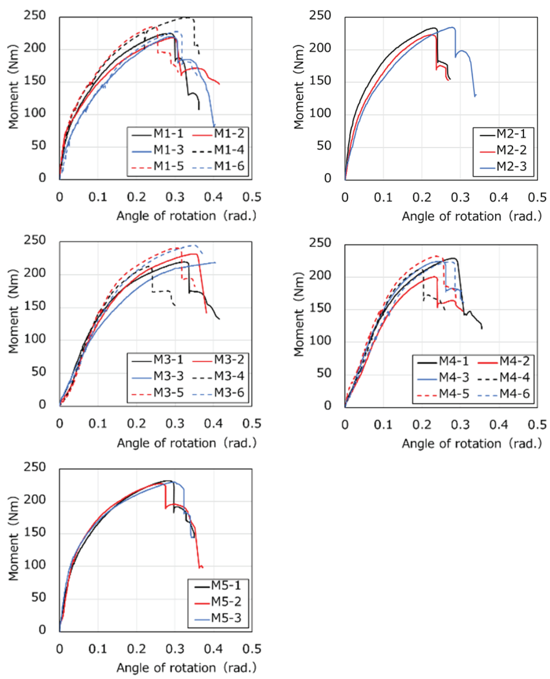


Figure 12: *Moment (Nm) vs. angle of rotation (rad)*

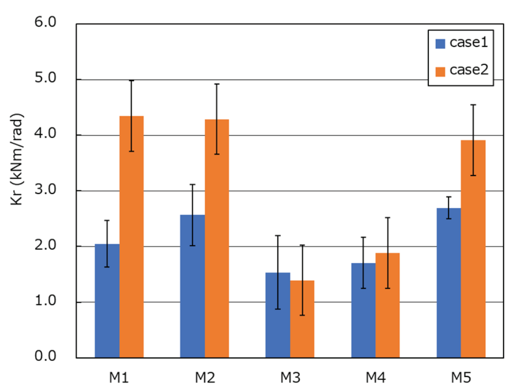


Figure 13: *Average rotational stiffness (kNm/rad)*

3.3 Long-term loading tests

To analyze the behavior of clamped joints under described two types of loading conditions, Long-term loading tests had been conducted for 300 days long. There were 3 types of specimens in each type of loading as shown in Table 3. Specimen LT2 and LT3 were conducted in outdoor conditions. The surface of LT3 was reinforced by filling the trimmed area with wood putty. Specimen LM2 was tested under the same condition as LT2, and LM3 was the same as LT3.

Figure 14 and Figure 15 show the details of the test setup. Static loading was applied to each specimen by hanging mass blocks. Vertical displacement and rotation angle between each member were measured.

Table 3: *Specimens of long-term tests*

Testing type	No.	Surface of timber	Reinforcement	Location	Number of specimen	Loading (N)
Tosion test	LT-1	normal	-	indoor	1	1,000
	LT-2	normal	-	outdoor	1	1,000
	LT-3	damaged	putty	outdoor	1	1,000
Moment test	LM-1	normal	-	indoor	1	100
	LM-2	normal	-	outdoor	1	100
	LM-3	damaged	putty	outdoor	1	100

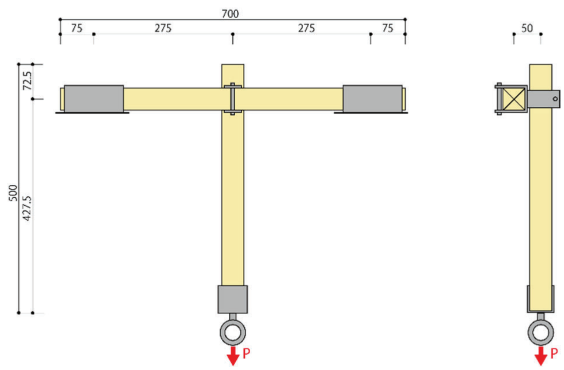


Figure 14: *Test setup of long-term torsion tests (mm)*

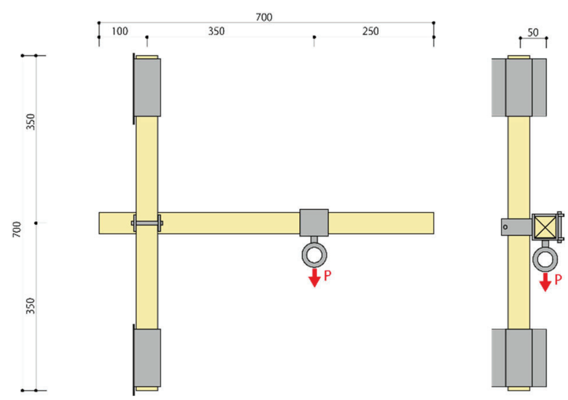


Figure 15: *Test setup of long-term moment tests (mm)*

Figure 16 shows the relationship between the time and angle of rotation. In both tests, the angle of rotation of LT1 increased slower than LT2 and LT3. In the torsion test, the angle of rotation of LT2 was 2 times larger than LT1, and LT3 was 5 times larger than LT1. In the moment test, the angle of rotation of LT2 and LT3 were 2.5 times larger than LT1. The results suggest that under outdoor conditions, filled putty tend to lose the performance of reinforcement, especially for the torsion loading condition.

Table 4 shows the creep coefficient in one week and one month, analyzed with power-law creep [3]. For the moment test, the coefficient ranged from 2.5 to 3.5 regardless of condition. On the other hand, for the torsion test, the factor ranged from 2.3 to 4.4 during normal surface conditions and ranged from 4.7 to 9.3 during wood putty reinforcement. These results suggested that reinforcement by wood putty were not suitable for outdoor usage.

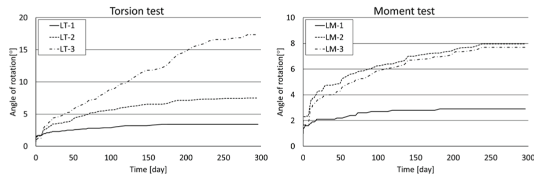


Figure 16: *Angle of rotation (°) vs. Time (day)*

Figure 17: *The nail of the clamp caved into specimens LT-3 and LM-3*

Table 4: *Increasing coefficent of deformation*

	LT-1	LM-1	LT-2	LM-2	LT-3	LM-3
a week	2.32	2.50	3.06	2.32	4.66	2.62
a month	2.72	2.86	4.41	2.91	9.32	3.51

4 ANALYSIS OF CUBIC FRAME STRUCTURE

To confirm the horizontal resistance performance of *Tsunagi* with *Tsunagi-clamp*, an analysis of the cubic frame structure was performed. The model of the cubic frame structure is shown in Figure 19. The model had dimensions of 2.8 m × 2.8 m × 2.1 m and was designed to be used as a medical booth, as shown in Figure 18.

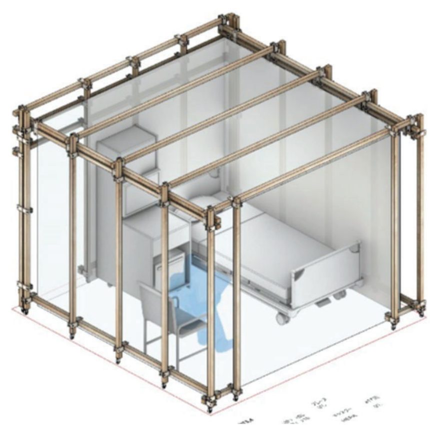


Figure 18: *Modeling of Tsunagi used as a medical booth*

Each lumber was replaced with beam elements (drawn as red lines in Figure 19), each joint was replaced with elastic springs (drawn as black short lines in Figure 19), and the stiffness of clamp joints are listed on Table 5. These stiffnesses of y and z direction were the slip stiffness of T1 shown in Figure 10, these of rotation x direction was the rotational stiffness of T1 shown in Figure 10 and these of rotation y and z direction were the rotational stiffness of M1 shown in Figure 13. These stiffnesses of x direction were set by other joint tests.

The boundary conditions were the 8 pin supports at the base of the columns on both the left and right sides of the booth and the 5 roller supports at the base of columns on both the front and back sides of the booth as shown in Figure 19. Monotonic loadings were applied horizontally at Points A and B.

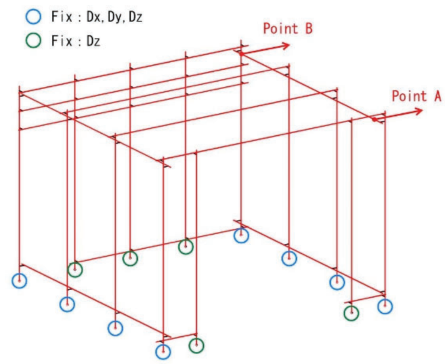
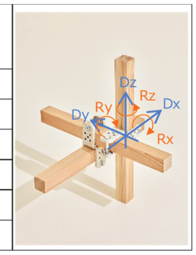


Figure 19: *Model of the cubic frame structure*

Table 5: *Stiffness of the clamp joints*

	Direction (kN/m)		Rotation (kNm/rad)		
Case1	x	420	x	2.2	
	y	340	y	2.0	
	z	340	z	2.0	
Case2	x	420	x	3.8	
	y	1100	y	4.3	
	z	1100	z	4.3	

5 CUBIC FRAME STRUCTURE TESTING

To confirm the horizontal resistance performance of the cubic frame structure, the authors conducted a full-scale horizontal load experiment as shown in Figure 20. The composition of the frame structure was the same as the analysis model. In order to replicate the boundary conditions used in the analysis, the bottom of each vertical member was fixed by setting the weights.

Monotonic loading of 100 N each was applied step by step to the top of the structure in the horizontal direction. Horizontal force and horizontal displacement at the top of the structure were measured.

The displacements of the frame structure by experiment and by analysis in former section are shown in Figure 21. Due to the difference in the number of joints, displacement at point A was bigger than that at point B. The displacement by case 1 analysis was smaller than the displacement by the experiment in the initial displacement area. But the results of case 2 analysis were closely matched the experimental results in the initial displacement area. Since *Tsunagi* was generally used only when the interlaminar deformation angle was under 1/100 radians, it was assumed more appropriate to use the

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stiffness of case 2 in the analysis of *Tsunagi*. In addition, these results support this analysis method can adopt to other types of *Tsunagi* consisted with timber and clamped joint.

Figure 20: *Exsample of specimen of the horizontal loading tests*

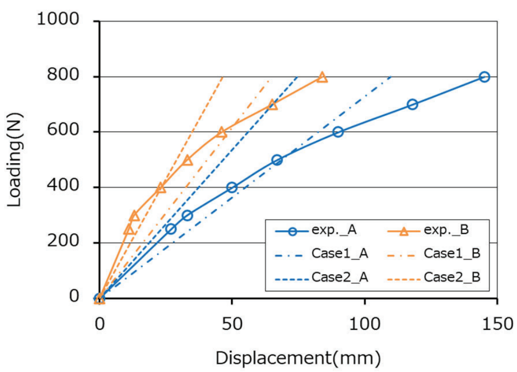

Figure 21: *Displacement of frame structure by analysis and by experiment*

6 EXAMPLE OF STRUCTURE WITH CLAMPED JOINT

The authors used *Tsunagi-clamp* to build cubic frame structures at KITAYA PARK, Shibuya. The overall structure consisted of three cubic structures and the dimensions each structure was 0.9 m × 1.8 m× 1.95 m. Each structure consisted of 13 timbers members and 22 *Tsunagi-clamps* and was built by 2 people in about an hour. To move them easily, these structures had wheels at the bottom of each vertical member. By changing the combination of each structure, the overall structure can be adapted for various usage as shown in Figure 22.

In this park, there is a building that used removable timber for exterior materials. It is envisioned that these *Tsunagi* could be built as temporary tents for emergency support by using this exterior timber in case of disaster.

7 SUMMARY AND CONCLUSION

By testing the clamped joints with *Tsunagi-clamp* in two types of loading conditions, the performance of this joint was analysed. It was confirmed that the reinforcements with screws or putty were effective for the improvement of the stiffness of joints even the surface of timber was damaged. On the other hand, considering long-term use, reinforcement with putty is not effective enough to prevent an increase in joint deformation.

The deformation by analysis of the cubic frame model with the stiffness of clamped joint tests in Case 2 was almost equivalent to that of the horizontal loading test. By analyzing with that stiffness, this clamped joint system can be applied to structural design and the prediction of other types of structure with this joint system are possible.

The authors have designed and constructed a structure as *Tsunagi* and plan to continue this activity to promote wood utilization.

Figure 22: *Tsunagi in KITAYA PARK*

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