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RESEARCH AND DEVELOPMENT OF SMALL-SCALE TIMBER CONSTRUCTION SYSTEM "BI-TREE STRUCTURE" WITH SMALL-DIAMETER TIMBER

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ABSTRACT: We propose a rational small-scale building structure system "Bi-tree structure" that incorporates the idea of biomimetics using red cedar (38 mm square, 900 mm), which is a short piece of wood. A bending loading test was carried out to determine the Young's modulus and the allowable stress, and a finite element analysis was performed using the obtained results to evaluate the allowable stress calculation and structural safety. The validity of the model was confirmed by comparing the analysis results with the tensile loading test results of the shed.

KEYWORDS: Small-Diameter Timber, Biomimetics, Tree structure, Allowable stress degree, Finite element analysis

1 INTRODUCTION

Considering the environment, many methods have been adopted for processing short and small lumber, which is leftover wood when sawing, into woody biomass fuel, wood chips, laminated lumber, and paper raw materials. However, it has been clarified that the above-mentioned method is generally expensive, and it is regarded as a problem. [1] If it can be applied directly to the building structural system without processing the offcuts, it will be an economical and rational way to utilize wood, but there are few such cases. The main reasons for this are that joining details using ready-made hardware cannot be used for short and small materials, and that using fitting details causes large cross-sectional defects and almost no yield strength can be obtained. In addition, although it is possible to propose a building structure with a lattice structure by applying pin joints to short and small materials, the number of members will inevitably increase, so it is rather uneconomical to build a building structure other than a large scale. It becomes a structure. Therefore, in this research, we propose a rational and small-scale building structural system using small-diameter timber.

Here, the dominant load of the structure changes depending on the scale. When constructing a large-scale wooden building, the vertical load (self-weight) becomes dominant compared to the horizontal load, and the vertical load is designed as the dominant load. There are many cases of adopting dendritic pillars and dendritic lattices. For example, "Yamaga City Yamaga Elementary School (Kumamoto Prefecture, Japan)" which designed by Kazumi Kudo + Hiroshi Horiba / Shirakansu K & H [2] shown in Figure 1 and "Roadside Station Aizu Yugawa / Aizu Bange (Fukushima Prefecture, Japan)" which designed by Arsed Building Research Institute shown in Figure 2 [3]. These are considered to be a structural system that regards the leaves of a tree as a load distributed to the entire canopy, supports it with twigs, and transmits it to the trunk by an optimal route. Regarding this tree structure (Figre 3), Gaudi and Frei Otto conducted an upside-down suspension test (Figure 4) to clarify the load propagation path [4] and to set the optimum member arrangement for low-stress members. Research [5] has been conducted to propose a method for removing the stress. However, these are verifications for vertical loads, and in the case of small buildings such as the shed in this study, horizontal loads are the dominant load rather than vertical loads, and the required

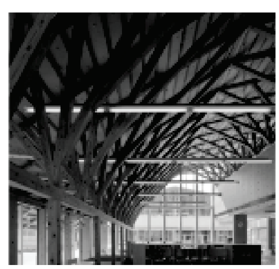

Figure 1: *Yamaga City Yamaga Elementary School, Kumamoto Prefecture, Japan [2]*

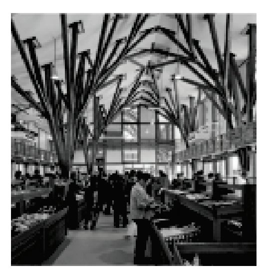

Figure 2: *Rest stop Aizu Yukawa and Aizu Bange, Fukushima Prefecture, Japan [3]*

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performance to the dominant load is different from the case of large-scale buildings.

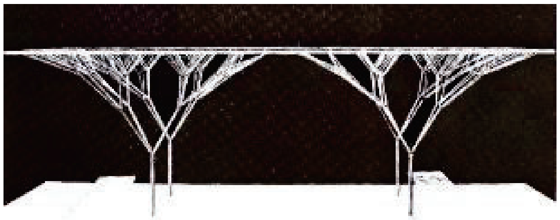

Figure 3: *A model of tree structure [4]*

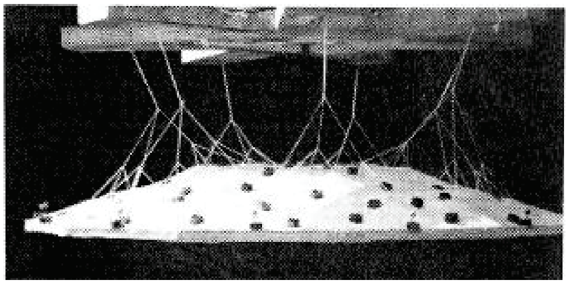

Figure 4: *Upside-down model [4]*

Therefore, in this research, we think that the structural system is different from that when constructing a large-scale building. And in order to construct a small-scale wooden building, we propose a structural system which has a rational dendritic shape not only for vertical load but also for horizontal load. Specifically, a tree system that transmits the load in the shortest path when a vertical load is applied, and a brace structure where the branch part is tensioned and compressed while bending resistance is generated in the trunk part and deformation is released when a horizontal load is applied. In this study, this structure is called "Bi-tree structure". In addition, there are only a few cases in the world where biomimetics are used in architecture, and we believe that this research will contribute to the development of biomimetics by becoming one of these cases.
Based on the above background, the allowable stress of the red cedar used in the proposed structural system was calculated by testing and calculation, and the stress transfer mechanism was clarified by finite element analysis. And a loading test was conducted after the shed construction to make a comparison with analysis model. By doing so, the validity of the analysis is verified.

2 THE OUTLINE OF ARCHITECTURE

2.1 THE OUTLINE OF THE SHED

2.1.1 Materials and dimensions

Figure 5 shows the appearance of the shed. A 38 mm square, 900 mm long red cedar was used as the structural material. Polycarbonate is used for the roofing material and exterior material. The dimensions are 4320 mm in width, 975 mm in depth, and 2000 mm in maximum height. The location is somewhere in Karuizawa Town, Kita-Saku District, Nagano Prefecture, Japan.

Figure 5: *Appearance of the shed*

2.1.2 MATERIALS

Figure 6: *Parts of the shed*

Figure 6 shows a reference to the members of the shed. The shed is made up of three types of members. Here, in this research, a 38 mm square lumber with a material length of 900 mm is a "Single Timber", two Single Timber laminated with an adhesive is a "Piled Beam", and a column which sandwiches three square lumbers between the two single materials is defined as " Intermitted column ". In the lower photograph of Figure 2, the Piled Beam is shown on the left side, the Intermitted Column is shown on the right side, and the other parts are all made of a Single Timber.

2.2 THE OUTLINE OF RED CEDAR

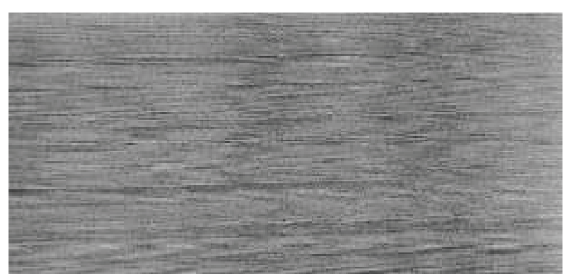

Figure 7: *Enlargement of a red cedar [6]*

An enlarged photograph of Red Cedar is shown in Figure 7 [6]. Red cedar is a softwood of the Cupressaceae family, and its absolute dry specific density is 0.37, which is close to that of Sugi. In addition to being used as solid wood for

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greenhouses and barns, it can also be used for building columns and fences by shaving it into a cylindrical shape.

2.3 ALLOWABLE STRESS OF RED CEDAR

In order to use building materials in buildings, the allowable stress must be defined. However, among the woods designated as building materials in Japan, the allowable stress level of red cedar is not defined as a structural member by the Building Standard Law. Therefore, a test was conducted (see Chapter 4), and the allowable stress level was set by itself based on the obtained results, making it possible to apply it to building structures.

3 STRUCTURAL PLAN

3.1 PROPOSAL OF STRUCTURAL SYSTEM

This time, we propose the following two structural systems. The first is the "Bi-tree structure," in which the axial force fluctuates when vertical or horizontal loads are applied, and also the type of structure changes.

Figure 8 shows the force flow when a vertical load is applied. When a vertical load is applied, a compressive force is transmitted from the upper surface to the tree part, which is decomposed to generate two thrusts, which are offset by acting in opposite directions. This is a structure that imitates the continuous arch in Figure 9.

Figure 8: *The shed when vertical load applies*

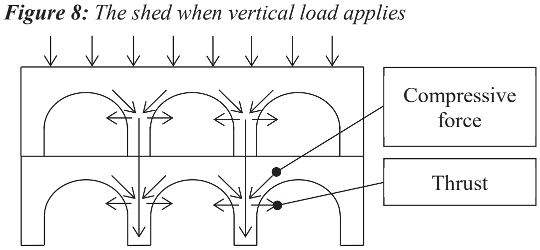

Figure 9: *The continuous arch when vertical load applies*

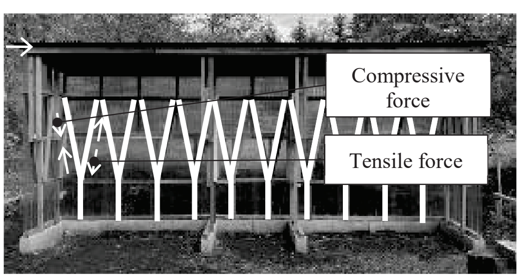

Figure 10: *The shed when a horizontal load applies*

Figure 10 shows the force flow when a horizontal load is applied. When a horizontal load is applied, one diagonal member bears the compressive force and the other diagonal member bears the tensile force in the tree part. This mimics the brace structure shown in Figure 11.

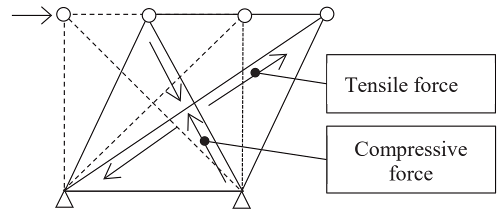

Figure 11: *A brace structure when a horizontal load applies*

The second is a structural system that applies the mechanism of independent columns with hanging walls, which is a traditional Japanese construction method. Independent columns with hanging walls are a construction method that is often used in traditional Japanese wooden houses, and are like the circled parts in Figures 12 and 13.

Figure 12: *An independent column with hanging walls*

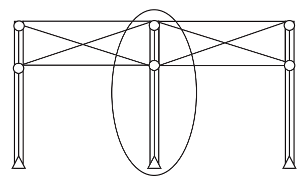

Figure 13: *A diagram of an independent column with hanging walls*

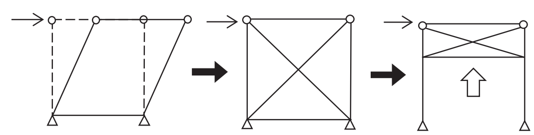

Figure14: *The origin of independent column with hanging walls*

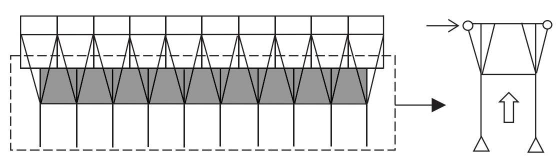

Figure 15: *The relation between trass part of the shed and an independent column with hanging walls*

Figure 14 shows the formation of an independent column with a hanging wall. With only a normal framework, the deformation becomes large when a horizontal load is applied, so a brace is incorporated to suppress the deformation of the entire wall. Furthermore, in order to secure a living space, the wall part is reduced. In this study, we applied this structure to the shed. As shown in Figure 15, the lower part of the truss part "Bi-tree structure" of the shed corresponds to the brace of the independent column with hanging walls. The position of the truss is raised to keep the truss away from the ground and protect it from moisture and water splashes. In this way, we make proposals to rationally incorporate traditional construction methods.

4 TEST

4.1 BENDING LOAD TEST 1

4.1.1 Purpose

The purpose of this test is to clarify the strength of red cedar and to obtain the value used for the allowable stress calculation.

4.1.2 The outline of specimens

The target materials in this test are the three bodies defined in Chapter 2, Section 2. The Single Timber is the specimen 1, the Piled Beam is the specimen 2, and the Intermitted Column is the specimen 3, as shown in Figures 15 to 17.

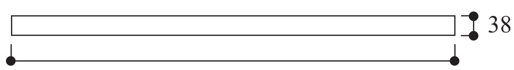

Figure 15: *Single timber; Specimen 1*

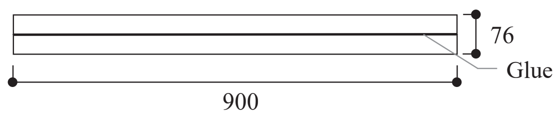

Figure 16: *Piled beam; Specimen 2*

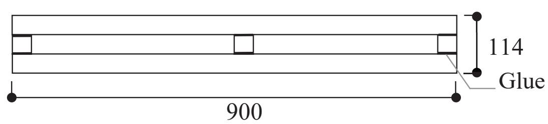

Figure 17: *Intermitted column; Specimen 3*

4.1.3 Test method

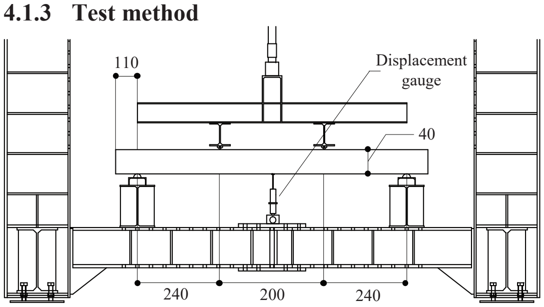

Figure 18: *Distance between fulcrums of a vertical hydraulic jack*

Figure 18 shows the distance between fulcrums and the equipment used. Using a vertical hydraulic jack, a load test was carried out by bending and loading at three equal parts of the push-off point at a load speed of 0.5 mm / sec. For the distance between fulcrums, we referred to the strength test manual [7] for structural timber established by the Japan Housing and Wood Technology Center.

4.1.4 Test result

Table 2: *Test result of Specimen 1*

Specimen	1-1	1-2	1-3	1-4	1-5
F_{max}	10.32	9.92	9.59	7.51	9.00
f_b	68.44	59.25	69.73	47.01	74.20
D	 Simple Tension	 Cross-grain Tension	 Splintering Tension	 Simple Tension	 Cross-grain Tension

F_{max}: Max load(N)
f_b: Bending Strength(N/mm^2)
D: Destruction Mode [8]

Table 2 shows the test results of Specimen 1. For the strength, the 95% lower allowable limit value at the 75% confidence level was obtained in consideration of the variation of each specimen, and this was treated as the lower limit value of 5%, and the allowable bending stress was evaluated as 39.9N/mm2 from that value. The Young's modulus was 9.268 kN/mm² from the average value of the five bodies.

Table 3: *Test result of Specimen2 and 3*

Specimen	2	3
F_{max}	9250	8500
f_b	25.76	10.23
D	 Simple Tension	 Cross-grain Tension

F_{max}: Max load(N)
f_b: Bending Strength(N/mm^2)
D: Destruction Mod [8]

Table 3 shows the test results of Specimen 2 and 3, and Specimen 2 showed the highest strength. In addition, the Specimen 3 had cracks not on the adhesive surface but on the base metal part.

4.1.5 CONSIDERATION

Regarding the Specimen 1, the reason why the Specimen 2 had the highest strength is considered to be that the adhesive surface was the widest compared to the other two bodies and it was able to resist bending. In addition, it was confirmed that the adhesive strength was higher than the base metal strength at the location where cracks occurred in the Specimen 3, and there was no problem with the strength of the members.

4.2 BENDING LOAD TEST 2

4.2.1 Purpose

The purpose of this test is to verify that there is no problem in the strength even if the joint part of the Piled Beam (Specimen 2 in Chapter 4.1) is shortened to 450 mm, which is half of 900 mm, and used as a long member. This is because it was necessary to construct a long member in order to provide an opening in a part of the shed.

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4.2.2 The outline of specimens

The target materials in this test is shown in Figere 19. This is a specimen whose the adhesive part of the Piled beam (Specimen 2 in Chapter 4.1) is shortened from 900 mm to half of 450 mm. And this is referred to as the Specimen 4.

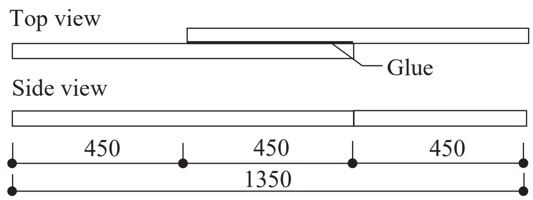


Figure 19: *Piled beams which were shortened their bonded zone in half; Specimen 4*

4.2.3 Test method

The test method is the same as that described in Chapter 4, Section 1, Section 3.

4.2.4 Test result

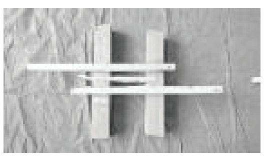


Figure 20: *The condition of specimen No.4 after broken*

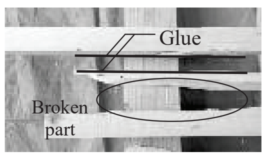


Figure 21: *Enlargement of Figure16*

Figure 20 shows the state after the destruction of the Specimen 4. In addition, as shown in Figure 21, in the loading test, the destruction of the material occurred not in the adhesive part but in the base material part.

4.2.5 CONSIDERATION

Since the destruction of the Specimen 4 occurred not in the adhesive part but in the base material part as in the Specimen 3, it can be confirmed that the adhesive strength is higher than the base material strength and there is no problem in the strength of the member.

5 STRUCTURAL ANALYSIS

5.1 THE OUTLINE OF ALALYSIS

The two types of analysis models created in this analysis are Model 1 and Model 2, respectively. The purpose of this analysis is to calculate the allowable stress using the results obtained from the analysis of Model 1 and to confirm whether the structure is as proposed. In addition, the results obtained from the analysis of Model 2 and the results of the tensile test of the shed in Chapter 6 are used to compare and consider the amount of deformation during load action.

5.2 ANALYSIS METHOD

We created and analyzed models using the finite element analysis software "midas iGen".

5.3 ANALYSIS MODEL SPECIFICATIONS

5.3.1 Model 1

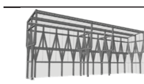
Table 4: *List of elements in analysis Model 1*

	Widen (mm)	Height (mm)	Bending Strength (N/mm^2)	Young's Modulus (kN/mm^2)
Single timber	38	38	39.90	
Piled beams	38	76	25.76	9.268
Intermittent column	38	38	10.23	

Model 1 is model 2 (leftmost column of Figure 18) with the exterior material removed. The specifications are shown in Table 4. For the Young's modulus, the average value of 9.268 kN/mm^2 of the five bodies obtained in Chapter 4, Section 1 is used.

5.3.2 Model 2

Table 5: *List of elements in analysis Model 2*

	W	D	T	E	S
Roof	4300	862	5	2.15	58.8×10^{-9}
Wall	38	76			

References
W: Widen (mm) D: Depth (mm) T: Thickness (mm)
E: Young's Modulus (kN/mm^2) S: Specific Weight (kN/mm^3)

The specifications of Model 2 are shown in Table 5. It is used to compare the amount of displacement with the loading test of the shed.

5.3.3 Joining/supporting

As shown in Figure 19, all the joints are pin joints, and the 15Φ screw is used. The support is also pin-joined.

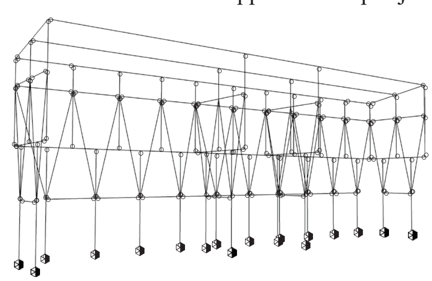


Figure 22*: Structure of joint and support*

5.4 SAFETY EVALUATION USING ANALYSIS RESULTS

To evaluate the structural safety, we carried out the allowable stress calculation. Also, we made sure that the structure of the building was not hindered by deformation or vibration.

5.4.1 The outline of allowable stress calculation

Calculate and confirm whether the design stress is less than the allowable stress.

Table 6: *Testal Result of Specimen from No.1 to No.3*

Specimen	1-1	1-2	1-3	1-4	1-5	2	3
F_{max}	6200	5350	6300	4250	6700	9250	8500
f_b	68.44	59.25	69.73	47.01	74.20	25.76	10.23
f_m			39.90			25.76	10.23

References
F_{max}: Max load(N) f_b: Bending Strength(N/mm^2)
f_m: Adopted Bending Strength(N/mm^2)

Table 7: *Long and short allowable stress degree of Specimen from No.1 to No.3*

Specimen	1	2	3
Long Allowable stress degree(N/mm^2)	14.63	9.45	3.75
Short Allowable stress degree(N/mm^2)	26.60	17.17	6.82

Table 6 shows the outline of the test results in Chapter 4. From this, the long-term and short-term allowable stress of each member is obtained. It is necessary to evaluate long-term allowable stress such as fixed load and snow load using long-term allowable stress, and rarely generated force such as seismic load and wind load using short-term allowable stress. The long-term allowable stress and the short-term allowable stress are calculated by multiplying the reference strength by 1.1 / 3 and 2/3, respectively. Table 7 is the value obtained by the above calculation. We evaluate safety by comparing these with the design stress degree of each member.
The following equation (1) is the equation to obtain the design stress degree of each member.

$$\sigma = \frac{M}{bh^2/6} \quad (1)$$

Here, σ = design stress degree (N / mm²), M = bending moment (N ・ mm), b = wood width (mm), h = wood fault (mm).

5.4.2 Allowable stress degree calculation for Single Timber

We calculate the allowable stress of a single timber. The parts shown in a and b in Figure 23 are composed of a single material, and the maximum bending moments in the vertical and horizontal directions show the same value of 10550 N ・ mm. Therefore, the calculation is as follows from Eq. (1).

$$\sigma = \frac{10550(N \cdot mm)}{38(mm) \times 38(mm) \times 38(mm)/6}$$

From this, the following results can be obtained.

$$\sigma = 1.153594\, N/mm2$$

Comparing this result with the long-term allowable stress of 14.63N / mm2 and the short-term allowable stress of 26.60N / mm2 for a single material in Table 7, the following results are obtained.

$$\sigma = 1.153594\, N/mm2 < 14.63\, N/mm2$$
$$\sigma = 1.153594\, N/mm2 < 26.60\, N/mm2$$

From this, it was confirmed that the values were smaller than the long-term and short-term allowable stress degrees. Here, the long-term allowable stress and the short-term allowable stress divided by the obtained allowable stress are defined as the safety factors in the vertical and horizontal directions, respectively. The calculation is as follows.

【Vertical direction】

$$14.63\, N/mm^2 / 1.153594\, N/mm^2 = 8.196 \ldots ≒ 8.2$$

【Horizonal direction】

$$26.60\, N/mm^2 / 1.153594\, N/mm^2 = 23.05 \ldots ≒ 23.1$$

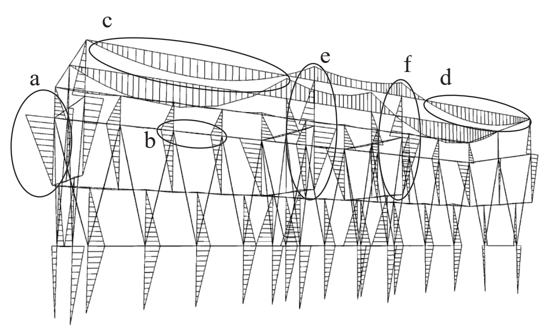


Figure 23: *Bending moment diagram of the shed when dead load and seismic load work*

From this, it can be said that the single timber can withstand up to about 8 times the vertical force and about 23 times the horizontal force.

5.4.3 Allowable stress degree calculation for Piled Beam

Similarly, we calculate the allowable stress of the Piled Beam. C and d in Figure 23 are composed of Piled Beams, which receive bending moments only in the vertical direction. Therefore, the calculation is as follows from Eq. (1).

$$\sigma = \frac{10550(N \cdot mm)}{38(mm) \times 76(mm) \times 76(mm)/6}$$

$$\sigma = 0.288398\, N/mm^2$$

Comparing this with the long-term allowable stress of 9.45 N / mm² for the lap beam in Table 7, the following results are obtained.

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$$\sigma = 0.288398\,N/mm2 < 9.45\,N/mm2$$

From this, it was confirmed that the obtained allowable stress is smaller than the long-term allowable stress. If the safety factor is calculated in the same way as for a Single Timber, it will be as follows.

$$9.45\,N/mm2 / 0.288398 N/mm2 = 32.76 \ldots ≒ 32.8$$

From this, it can be said that the Piled Beam can withstand up to about 33 times the force in the vertical direction.

5.4.4 Allowable stress degree calculation for Intermitted Column

Similarly, we calculate the allowable stress of the Intermitted Column. e and f in Figure 23 composed of Intermitted Column, which receives the bending moment only in the horizontal direction. Therefore, the calculation is as follows from Eq. (1).

$$\sigma = \frac{10550(N \cdot mm)}{38(mm) \times 38(mm) \times 38(mm)/6}$$

$$\sigma = 1.153594\,N/mm2$$

Comparing this with the short-term allowable stress of 6.82 N / mm² for the lap beam in Table 7, the following results are obtained.

$$\sigma = 1.153594\,N/mm2 < 6.82\,N/mm2$$

From this, it was confirmed that the obtained allowable stress is smaller than the short-term allowable stress. When the safety factor is calculated in the same way as for single materials and lap beams, it is as follows.

$$6.82 N/mm2 / 1.153594 N/mm2 = 5.91 \ldots ≒ 5.9$$

From this, it can be said that the Intermitted Column can withstand up to about 6 times the horizontal force.
From the all above calculations, it can be evaluated that the safety of this shed is maintained in small and medium-sized earthquakes and does not collapse in large earthquakes.

5.4.5 Impact on buildings due to deformation and vibration

We check if the building is hindered by vertical and horizontal deformation and vibration.
First, we evaluate the vertical weight and snow load. According to the "Deflection Limit" of the Building Standard Law in Japan, it is necessary to satisfy the condition of the following formula (2) when a fixed load and a live load are applied.

$$\frac{\delta}{\ell} \leq \frac{1}{250} \tag{2}$$

Here, let δ = deflection amount (mm) and ℓ = member length (mm). From Figure 24, the amount of deflection in the vertical direction σ = 0.21 (mm) and the member length ℓ = 1700 (mm), so the ratio of the amount of deflection to the member length in this shed is as follows.

$$\frac{\delta}{\ell} = \frac{0.21}{1700}$$

Therefore, it can be compared with Eq. (2) as follows.

$$\frac{\delta}{\ell} = \frac{1}{3695.65} ≒ \frac{1}{3696} < \frac{1}{250}$$

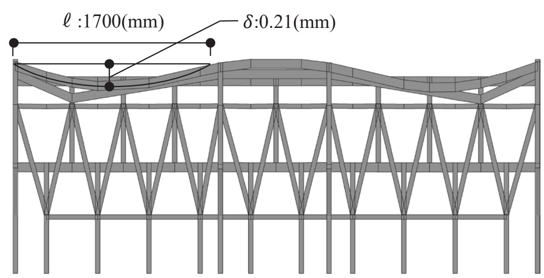

Figure 24: *Displacement diagram of the shed when vertical load works*

From the above, it can be evaluated that the building is not hindered by deformation and vibration caused by its own weight and snow load because it satisfies the deflection limit of the Building Standard Law.
Next, we evaluate the horizontal seismic load and wind load with reference to the guideline of deformation angle and damage rank in wooden buildings. There are four damage ranks: "Minor damage", "Small damage", "Medium damage", and "Great damage". When a horizontal load is applied to the shed, it is desirable that it be suppressed with minor damage, in which case the deformation angle must be less than 1/120, as in Eq. (3).

$$\frac{\delta}{\ell} \leq \frac{1}{120} \tag{3}$$

Here, δ = deformation amount (mm) and ℓ = member length (mm). From Figure 25, the horizontal deformation amount σ = 15.08 (mm) and the member length ℓ = 1900 (mm), so the ratio of the deformation amount to the member length in this shed is as follows.

$$\frac{\delta}{\ell} = \frac{15.08}{1900}$$

Therefore, it can be compared with Eq. (3) as follows.

$$\frac{\delta}{\ell} = \frac{1}{125.99} ≒ \frac{1}{126} < \frac{1}{120}$$

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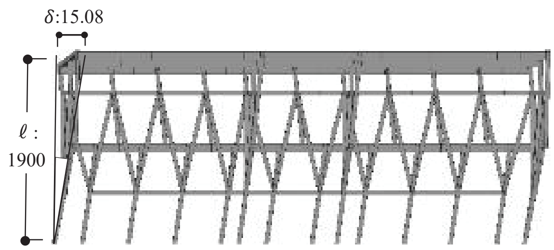

Figure 25: *Displacement diagram of the shed when horizontal load works*

From the above, it can be evaluated that the deformation and vibration caused by the seismic load and the wind load do not cause any trouble to the building because the deformation angle and the damage rank of the wooden building are satisfied.

Here, there was a difference between the comparison result with the deflection limit in the vertical direction and the comparison result with the deformation angle in the horizontal direction and the guideline of the damage rank. We give a reason for this.

Table 8: *Total amount of snowfall (as of May 11,2021)*

Munici-palities	Site	Total amount of snowfall (cm)	The ratio this year: Common year(%)	Common value (cm)
Nagano City	Nagano	107	43	250
Karuizawa town, Kita-Saku District	**Karuizawa**	**35**	**30**	**117**

First, we paid attention to the snow load in the vertical direction. When snow accumulates on the upper surface of the shed, the snow load is a load that acts for a long period of time, so the vertical direction was set safely to prevent creep. In addition, as shown in lower column of Table 8, it is hard to say that Karuizawa Town, where the shed is located, is a heavy snowfall area when considering only the amount of snowfall. However, considering the frequency of natural disasters caused by abnormal weather in recent years and the damage situation, it was designed so that it can withstand sufficient strength even in the unlikely event of heavy snowfall.

Next, in the horizontal direction, we focus on earthquakes for evaluation. J-SHIS data show that the probability of earthquake occurrence within 30 and 50 years in the major active fault zone near Karuizawa Town is 0%, and that the ground amplification factor at the same site is low[9]. Therefore, it was judged that the probability of damage to the building due to the earthquake is not high.

The above are reasons for differences between the comparison result with the deflection limit in the vertical direction and the comparison result with the deformation angle in the horizontal direction and the guideline of the damage rank.

5.5 COLLATION OF SUGGESTIONS AND ANALYSIS

Using the axial force diagram obtained from the analysis, we confirm whether the structure of this shed proposed in Chapter 3 is realized. First, we proposed a "Bi-tree structure" in which a force like a continuous arch structure acts on the tree part when a vertical load is applied.

Figure 26 is an axial force diagram when a vertical load is applied to the shed. It can be seen that in the tree structure, the two thrusts generated by the decomposition of the compressive force work in opposite directions and cancel each other out.

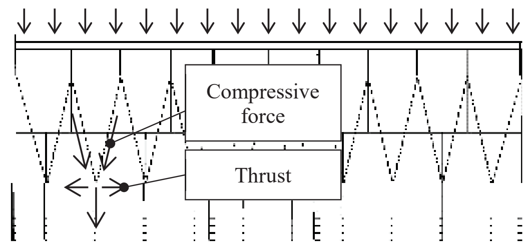

Figure 26: *Axial force diagram of the shed when vertical load works*

We also proposed a frame in which the dendritic part becomes a force flow like a brace structure when a horizontal load is applied.

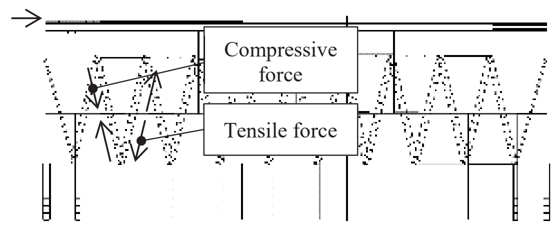

Figure 27: *Axial force diagram of the shed when horizontal load works*

Figure 27 is an axial force diagram when a horizontal load is applied to the shed. The tree part of the shed, which has a brace structure and is a diagonal lumber, bears the compressive and tensile forces, respectively.

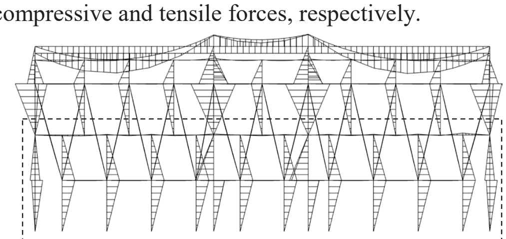

Figure 28: *Bending moment diagram of the shed when dead load and horizontal load work*

Furthermore, we proposed a frame with reference to the structure of an independent column with hanging walls, which is a traditional construction method. Figure 28 is a bending moment diagram of this shed. It can be seen that the bending moment diagram of the lower part (broken line part) of the shed that adopted the structure of the

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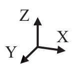
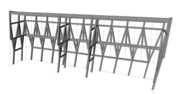
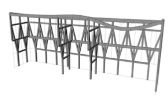
independent column with hanging walls matches the bending moment diagram of the independent column with hanging walls.
Based on the collations with the above three analysis results, the structural system of this shed is as proposed in Chapter 3.

5.6 COMPARISON OF THE AMOUNT OF DEFORMATION BETWEEN ACTUAL MEASUREMENT AND ANALYSIS

We performed a manual tensile test to show the reproducibility of the analytical model and the validity of the proposal.

Table 9: *Tensile testing and deformation of analysis model*

	Photo of tensile testing	Deformation (Analysis model No.2)
X-direction		
Y-direction		
Z-direction		

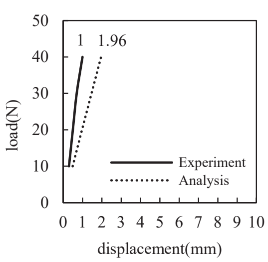


Figure 28: *Load-displacement graph of X-direction*

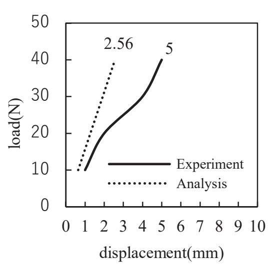


Figure 29: *Load-displacement graph of Y-direction*

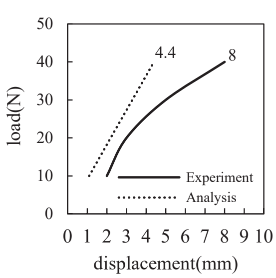


Figure 30: *Load-displacement graph of Z-direction*

As shown in Table 9, we defined three directions in the shed, and compared the amount of deformation when an arbitrary point was manually pulled in each direction with the amount of deformation when a load was applied in the analysis. The model used for the analysis is Model 2 with the exterior material. The displacement charts when a load is applied in each direction are shown in the rightmost column of Table 9, and the graphs comparing the amount of deformation in each direction are shown in Figures 28, 29, and 30.
The maximum value of the displacement error in each direction was 3.6 mm in the Z direction.
From this, it can be said that the analysis model can almost reproduce the real thing, and the proposal is valid.

6 CONCLUSIONS

In this research, we proposed a rational small-scale building structure system "Bio-tree structure" using small-diameter timber. This is a tree system that transmits the load in the shortest path when a vertical load is applied, and a structure in which the branch part becomes a tension / compression brace structure while causing bending resistance in the trunk part and allowing deformation to escape when a horizontal load is applied. In addition, we conducted a bending load test of red cedar, determined the allowable stress level indispensable for building design, calculated the allowable stress degree, evaluated the safety, and it became possible to design a small-scale building. Furthermore, we shown the validity of the proposal by performing numerical analysis and actual loading test on the proposed structural system. These are the results that suggest the possibility that small-diameter timber will be used for building structural systems in the future, and it can be expected to contribute to the development goals of SDGs "11. Creating a town where people can continue to live" and "15. Protecting the abundance of greenery", and the development of biomimetics in architecture.

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