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DEVELOPMENT OF HIGH-STRENGTH WOODEN PALLETS UTILIZINGLOCAL TIMBER FROM EHIME PREFECTURE

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Key words: Wooden flat pallet, Bending stress, Flexural rigidity, Compressive displacement, Compression stiffness.

Abstract. *Wooden pallets account for a large percentage of pallets indispensable for logistics. From the viewpoint of strength and rigidity, pallets made of foreign timber (e.g., American pine) are the mainstream, and pallets made of domestic timber, especially cypress and cedar, which are inexpensive in terms of log price, are rarely distributed. The objective of this research is to develop a domestic wood pallet with high strength and rigidity comparable to that of American pine. Structural analysis using the finite element method was conducted to calculate stresses and strains under bending and compressive loads. The analytical results were also verified by JIS flat pallet bending and compression tests.*

1 INTRODUCTION

Pallets are used in transportation and logistics to facilitate cargo handling in factories, trucks, containers, and warehouses. When transporting, loads are placed on pallets and carried by inserting the jaws of a forklift or handlift into the perforated portions. Pallets are made of various materials such as plastic, steel, aluminum, and paper, but wooden pallets play a very important role during transportation because they are characterized by the fact that the loaded cargo does not slide. In addition, wooden pallets are widely used in transportation and logistics because they have sufficient strength and load capacity, are inexpensive to produce and dispose of, and are easy to repair even if partially damaged. The objective of this study is to develop a new pallet structure using inexpensive Ehime cypress and Japanese cedar with the same strength as that of foreign rice pine.

2 EXPERIMENTAL METHODS

2.1 Flat pallet fabrication

Two types of one-sided use type two-way insert (D2 type, JIS 0604) [1] wooden flat pallets commonly used in logistics sites were produced and are shown in Figure 1. Bay pine was used for the standard pallet, and Ehime cypress and Japanese cedar were used for the newly developed pallet. Both pallets have external dimensions of 1100 mm long, 1100 mm wide, and 144 mm high, and are composed of a top plate, a girder, and a bottom plate. The maximum loading capacity was 2 tons.

Fig.1 Wooden flat pallet.

2.2 Flat pallet strength test

Bending and compression tests were performed on flat pallets according to JIS Z0602.

2.2.1 Bending test

Place the bottom surface support material aligned with both ends of the bottom surface of the pallet and the top surface compression material as shown in Figure 2. Next, a load is applied through the top compression material and the bottom support material. The load is first applied at approximately 0.1 times the load equivalent to the maximum loading mass, and then up to 1.25 times the load equivalent to the maximum loading mass, and the amount of deflection is measured. In this case, the amount of deflection is the difference between the deflection (δ_1) when the pallet is loaded with approximately 0.1 times the load equivalent to the maximum loading mass and the deflection (δ_2) when the pallet is loaded with 1.25 times the load equivalent to the maximum loading mass. The deflection is measured with dial gauges arranged as shown in Figure 2 and expressed as the average value between A and B. The rate of deflection is based on Equation (1).

$$\text{Deflection rate (\%)} = \frac{\delta_2 - \delta_1}{L} \times 100 \quad (1)$$

L: Bending test length of pallet
δ_1: Deflection when 0.1 times the load corresponding to the maximum loading mass is applied
δ_2: Deflection when 1.25 times the load corresponding to the maximum loading mass is applied
δ_3: Deflection when the load is reduced to approximately 0.1 times the load equivalent to the maximum loading mass

Next, the load is reduced to approximately 0.1 times the load corresponding to the maximum loading mass, and the deflection of A and B is measured after the load is left until the deflection settles. In this case, the residual deflection is the difference between this measured value (δ_3) and the deflection (δ_1) when the load is initially applied at approximately 0.1 times the load corresponding to the maximum loading mass, and is expressed as the average value between A and B. The residual deflection ratio is based on Equation (2).

$$\text{Residual deflection rate (\%)} = \frac{\delta_3 - \delta_1}{L} \times 100 \quad (2)$$

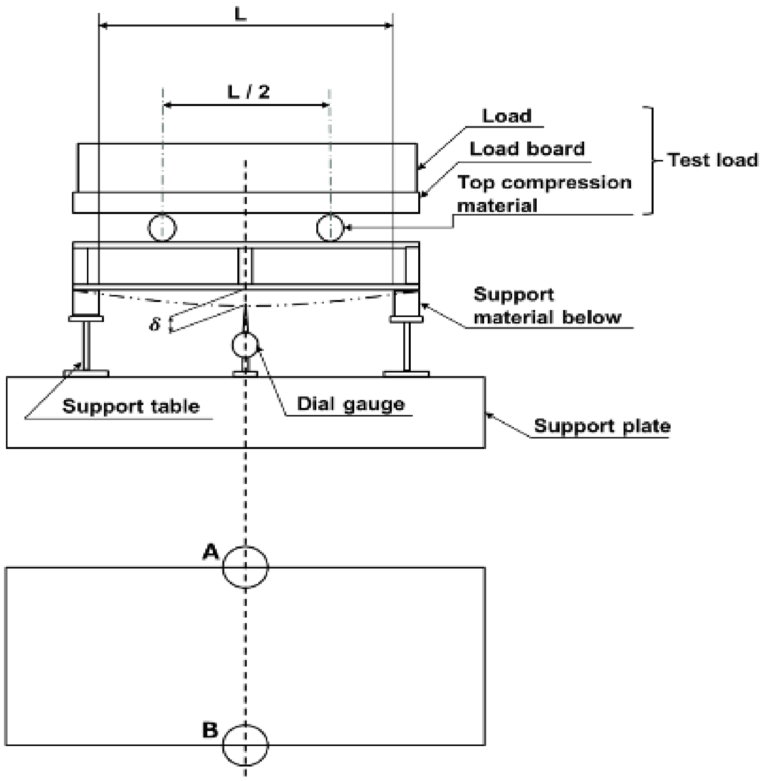

Fig.2 Pallet bending test [2].

2.2.2 Compression test

Place the pallet on a flat, solid, horizontal surface as shown in Figure 3, and place the top compression material on the top surface of the measuring section. Next, a compressive load is applied through the top compression material. The compression load is first applied approximately 0.25 times the load equivalent to the maximum loading mass, and then further applied up to approximately 1.1 times the load equivalent to the maximum loading mass, and the amount of compression strain is measured. In this case, the amount of compressive strain is the amount of displacement of point A on the underside of the load from the state where the pallet is loaded with approximately 0.25 times the load equivalent to the maximum loading mass to the point where the load is 1.1 times the load equivalent to the maximum loading mass. Then, after the load is removed, the legs are examined for abnormalities. The same test is performed at two locations on the diagonals A and B of the pallet, and the amount of compressive strain is obtained by averaging the respective measured values.

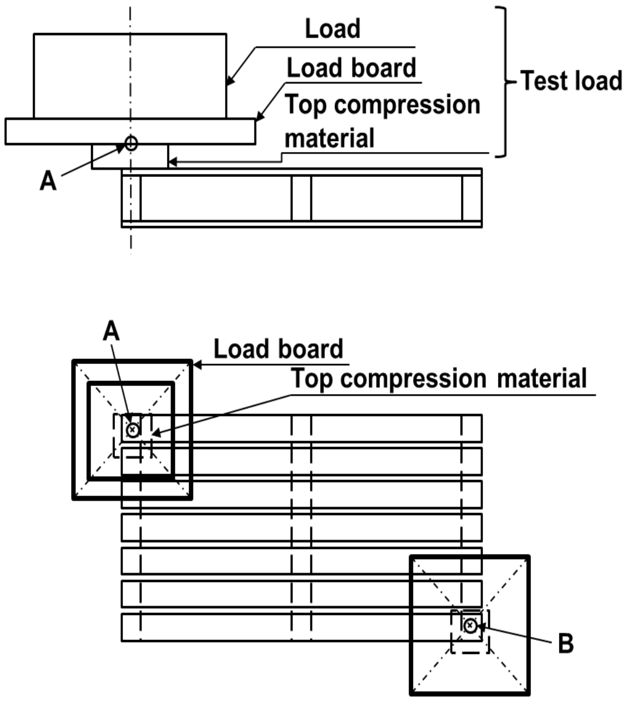

Fig.3 Pallet leg part compression test [3].

3 SIMULATION ANALTSIS OF STREGTH TESTS

3.1 Wood Anisotropy

Wood has anisotropy derived from its microstructural structure and is generally treated as an orthotropic anisotropic material with axes in three directions: fiber (L), radial (R), and tangential (T) directions as shown in Figure 4 (1). Young's moduli E_{L}, E_{R}, and E_{T} in the three directions, shear moduli G_{RT}, G_{LT}, and G_{LR}, and Poisson's ratios ν_{LR}, ν_{RT}, and ν_{TL} used in the finite element analysis are listed in Table 1. Here, Young's modulus E_{L} in the fiber direction was set to 12 GPa for bay pine, 9 GPa for cypress, and 7.5 GPa for cedar [4]. The stress-strain curve in the L direction shown in Figure 5 was also used in the analysis [5]. Young's modulus in compression and tension are almost equal, the ratio of maximum stress in compression to tension is 1:2, and the stress at the elastic limit is about 2/3 of the maximum stress in compression and about 4/5 in tension. Here, the maximum stress is assumed to be the flexural strength. The transverse (T- and R-directions) strength was assumed to be 5% of the L-direction in the T-direction and 10% in the R-direction in both tension and compression [6].

Table 1 Average Young's modulus for coniferous tree.

E_R/E_L	E_T/E_L	G_{LR}/E_L	G_{LT}/E_L
0.075	0.040	0.060	0.050
G_{RT}/E_L	ν_{LR}	ν_{LT}	ν_{RT}
0.003	0.40	0.50	0.60

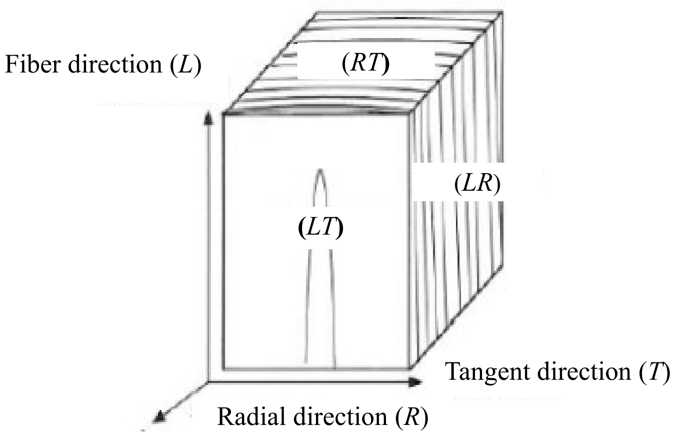

Fig.4 Anisotropy definition.

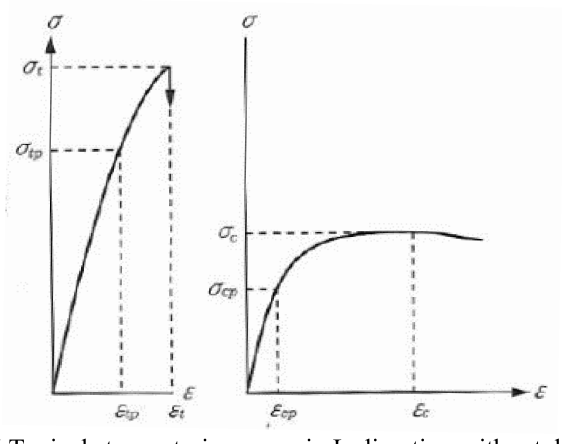

Fig.5 Typical stress-strain curves in L-direction without defects.

3.2 Simulation Analysis Model

For the bending test model, a quarter model was created due to symmetry of the boundary conditions. For the compression test model, a full model was created due to asymmetric loading. Elasto-plastic analysis was performed using 3-D isoparametric elements, taking into account the anisotropy of the wood and the different flow stress behavior on the tensile and compression sides. Eleven models were created from the material mechanics point of view to increase the strength of the structure by increasing stiffness and from the material point of view to reduce cost. Based on structural and cost limitations, Model 1 was designed using cypress with higher flexural strength than the reference model made of bay pine. Next, Model 2 was designed with the same strength as the reference model made of bay pine by reducing the bending stiffness for cost considerations.

Next, Models 3 through 5 were designed to increase leg compressive strength. Next, model 6 was designed to exceed the standard model made of Japanese spruce in all evaluation items of bending strength, compressive strength of the legs, and cost. Next, models 7 and 8 were designed with the same structure as model 6, but using a combination of Japanese cypress and Japanese cedar for cost considerations. Next, we designed Model 9, which is the same structure as Model 6, using Japanese cedar to reduce cost while maintaining strength. Next, a model 10 was designed by cutting a part of the girder to reduce the volume and further reduce the cost. Finally, we proposed Model 11, which has the same structure as Model 10, but with the girder divided into upper and lower sections and combined in consideration of anisotropy.

4 RESULTS AND DISCUSSION

4.1 Distribution of Bending Stress and Deflection in Center Section under Bending Load

The bending stress distribution at a bending load of 1.25 times the maximum loading mass (25 kN) is shown in Figure 6 for Model 11 as an example. In both structural patterns, the greatest bending stress and deflection were found to occur in the center cross-section of the bottom surface of the pallet, except in the area of stress concentration near the contact with the rigid support.

4.2 Distribution of leg compressive stress and compressive displacement under compressive load

The compressive stress distribution at a compressive load of 1.1 times the maximum loading mass (22 kN) is shown in Figure 7 for Model 11 as an example. In both construction patterns,

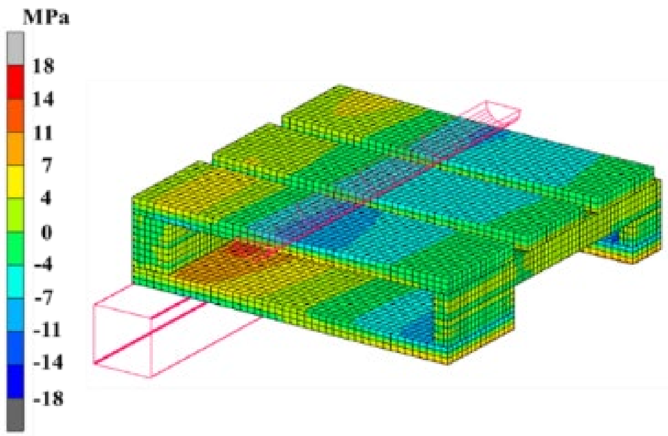

Fig.6 Bendig stress distribution (Model 11)

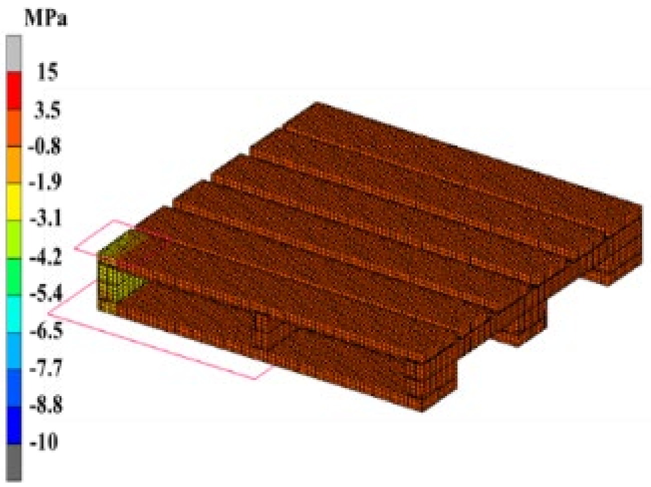

Fig.7 Compressive stress distribution (Model 11)

the stress distribution was almost equal in the cross section of the legs.

4.3 Comparison of new type and standard type

Based on actual tests, comparisons were made for deflection ratio, residual deflection ratio, and compressive strain. Figures 8 and 9 show the relationship between the ratio of bending stress (maximum bending stress at 2.5 kN load) to allowable bending stress (α), deflection ratio, and residual deflection ratio for the test specimens. Figure 10 shows the relationship between the ratio β of the compressive stress (the maximum compressive stress when a load of 2.2 kN is applied) to the allowable compressive stress of the specimen and the compressive displacement of the leg. α and β are expressed by equations (3) and (4).

$$\alpha = \frac{\text{(Maximam bending stress at 2.5 kN load)}}{\text{(Allowable bending strength of materials used)}} \times 100\ [\%] \quad (3)$$

$$\beta = \frac{\text{(Maximam compressive stress at 2.2 kN load)}}{\text{(Allowable compressive strength of materials used)}} \times 100\ [\%] \quad (4)$$

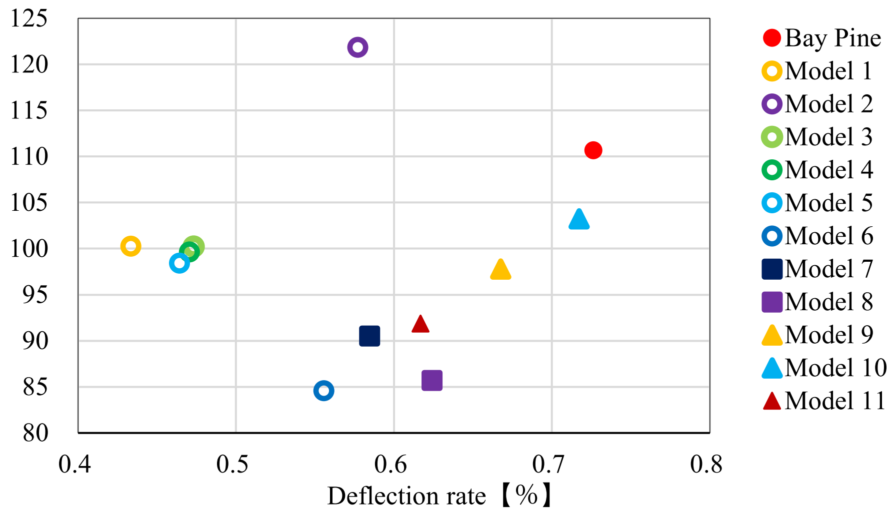

Fig.8 Relationship between α and Deflection rate

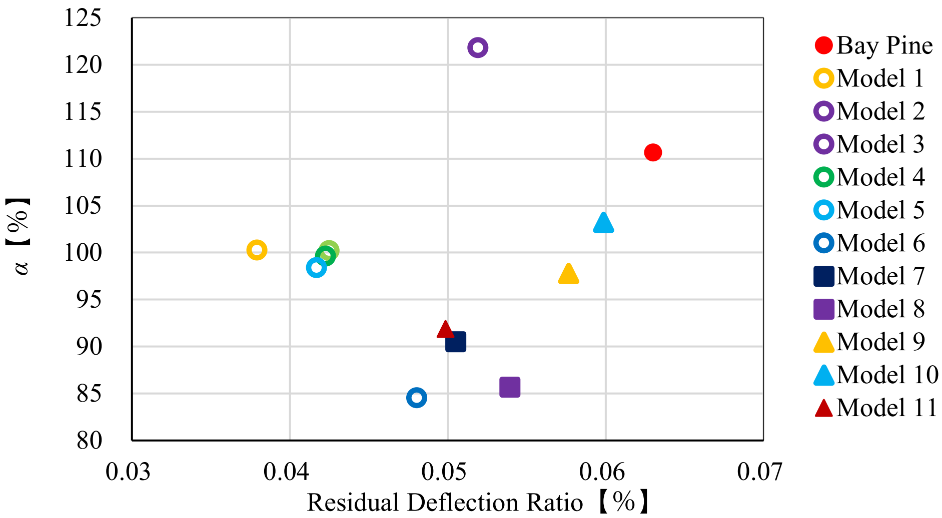

Fig.9 Relationship between α and Residual Deflection Ratio

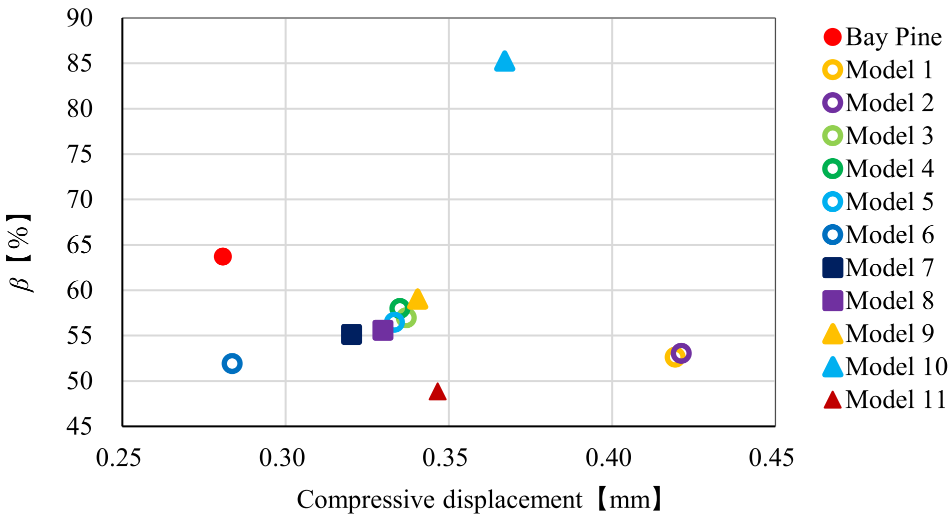

Fig.10 Relationship between β and Compressive displacement

4.4 Test results and costs

Based on the analysis results, tests were conducted on models 6, 7, and 9, and the results are shown in Table 2. All models tested were found to meet the JIS test standard values (deflection rate of 2.5% or less, residual deflection rate of 0.5% or less, and compressive strain of 4 mm or less). Model 11 can also be predicted to meet the test standard values based on the analytical values.

Table 2 Test results.

	Deflection rate [%]	Residual deflection rate [%]	Compressive displacement [mm]	Cost [Japanese yen]
Standard type (Beimatsu)	1.26	0.10	2.16	2020
Model 6 (Hinoki)	0.85	0.07	1.25	1090
Model 7 (Hinoki & Sugi)	0.88	0.10	1.08	990
Model 9 (Sugi)	1.14	0.10	2.20	910
Model 11 (Sugi)	-	-	-	790

CONCLUSION

In this study, we developed a pallet that can combine high-strength functionality with low-cost economy through structural design and found the following from experimental and analytical results.

The increased bending stiffness of the edge boards and deck boards results in lower deflection than Bay Pine pallets.

The increased compressive stiffness of the pallet legs resulted in lower compressive displacement than that of the Bay pine pallet.

Model 6, made of Japanese cypress from Ehime Prefecture, has higher strength than pallets made of bay pine, and cost about 46% less.

Model 7, made of Ehime cypress and Japanese cedar, has higher strength than pallets made of bay pine, and cost about 49% less.

Model 9, which uses cedar from Ehime Prefecture, has the same strength as pallets made of bay pine, at a cost reduction of about 55%.

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