Structural Design for Improving the Strength of Flat Wooden Pallets

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Abstract. The purpose of this study is to develop a new pallet structure using the inexpensive hinoki wood, which is produced in the Ehime Prefecture, having the same strength as the conventional Oregon pine wood. A new pallet structure was proposed for achieving high strength by improving the flexural stiffness and compressive stiffness and achieving high-cost performance by using the inexpensive hinoki wood. The results obtained in this study are summarized as follows: deflection of the new type is reduced compared to the standard type, due to the increased bending rigidity of the edge board and deck board; compressive displacement of the new model decreases, as the compressive stiffness of the pallet legs increases; new mold pattern 6 made is higher in strength and rigidity than the standard mold; cost of the new type #6 is 72% of that of the standard type pallet, and cost can be reduced by 28%.

1. Introduction

Pallets are used in transportation and logistics to facilitate load handling in factories, trucks, containers, and warehouses. During transportation, goods are placed on pallets, and forklift or pallet jacks are inserted into the openings in the pallets for carrying the goods. Pallets are made from various materials, including plastic, steel, aluminum, and paper. However, wooden pallets are characterized by the fact that loads do not slip. Thus, they play a very important role in transportation. Wooden pallets are widely used in transportation and logistics because they have sufficient strength and load carrying capacity. Furthermore, they offer a good overall balance of low-cost production and disposal while being easy to repair when partly damaged.

The purpose of this study is to develop a new pallet structure using the inexpensive hinoki wood, which is produced in the Ehime Prefecture, having the same strength as the conventional Oregon pine wood. A pallet structure was proposed for achieving high strength by improving the flexural stiffness and compressive stiffness.

2. Pallet Fabrication and Strength Experiments

2.1. Production of Flat Pallets

Two types of single-sided square difference (D2 type, JIS Z 0604) flat pallets [1] were manufactured, which are commonly used in distribution sites, as shown in Figure 1. Oregon pine wood was used to manufacture the standard pallet, whereas hinoki wood was used to manufacture the proposed pallet. The external dimensions of both the pallets were 1100 × 1100 mm with a height of 144 mm and...
(a) Standard type

(b) New type

**Figure 1.** Flat wooden pallets.

**Figure 2.** Anisotropy definition.

**Figure 3.** Typical stress-strain curves in L-direction without defects.
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        |
| $G_{RT}/E_L$ | $\nu_{LR}$ | $\nu_{LT}$ | $\nu_{RT}$ |
| 0.003    | 0.40     | 0.50         | 0.60         |

maximum loading mass of 2 t.

2.2. Flat Pallet Strength Tests

Flat pallet bending tests and compression tests were performed based on JIS Z 0602 [2]. In the bending tests, the deflection ratio was calculated by measuring the deflection in the central portion of the lower edge board. In the leg compression tests, the compressive displacement was measured in the central portion of the top surface of the two legs of the pallet and calculated the average compressive strain using the compressive area.

3. Simulation analysis of strength tests

3.1. Wood Anisotropy

The anisotropy of wood is derived from the tissue structure. Wood is generally considered as an orthogonal anisotropic material with axes along three directions: the fiber ($L$) direction, radial ($R$) direction, and tangential ($T$) direction, as shown in Figure 2 [3]. Table 1 shows the Young's modulus $E_L$, $E_R$, and $E_T$, shear modulus $G_{RT}$, $G_{LT}$, and $G_{LR}$, and Poisson's ratio $\nu_{LR}$, $\nu_{RT}$, and $\nu_{TL}$, along the three axes used in the finite element method analysis. In this study, $E_L = 12$ GPa was used for Oregon pine wood and $E_L = 9$ GPa was used for hinoki wood [4]. Furthermore, a stress–strain curve along the L direction was used as shown in Figure 3 for analysis [5]. The Young's modulus for compression and tension are almost equal. The ratio of maximum stress of compression to tension is 1:2, whereas the elastic limit stress is approximately 2/3 and 4/5 of the maximum stress during compression and tension, respectively. In this study, the maximum stress was achieved by the bending strength. The strength in the lateral direction ($T$ direction and $R$ direction) for tension and compression was 5% of that in the $L$ direction in the $T$ direction and 10% in the $R$ direction [6].

3.2. Simulation Analysis Model

A bending test model was made, that was a 1/4th of the actual model and accounted for the symmetry of the boundary condition. Additionally, a full-sized model for compression tests was created because of load asymmetry. Elasto-plastic analysis were performed though using three-dimensional isoparametric elements accounting for the anisotropy of wood and different flow stress behaviour between the tension and compression sides. From the perspective of material mechanics, to achieve high structural strength by improving stiffness, we created six types of new pallet models. Table 2 shows the dimensional differences of each constituent component compared to the standard type. In terms of structural and cost limitations, we modelled a new type of pallet (type #1) having higher bending strength than the standard pallet built using Oregon pine wood. Next, accounting for cost, we designed the type #2 pallet by lowering the bending stiffness while maintaining the same strength as the standard type. Next, to increase the leg compressive strength, we modelled types #3 to #5. Finally, in type #6, all evaluation items exceeded the standard type in terms of bending strength, leg compressive strength, and cost.
Table 2. Dimensional difference between new type and standard type (mm)

| Component parts | New type | # 1 | # 2 | # 3 | # 4 | # 5 | # 6 |
|-----------------|----------|-----|-----|-----|-----|-----|-----|
| Top surface     |          | Width | Height | Width | Height | Width | Height | Width | Height | Width | Height |
| Deck board      |          | -8   | 4    | -8   | 4    | -8   | 4    | -8   | 4    | -8   | 4    |
| Edge board      |          | -8   | 4    | 25   | 4    | 25   | 4    | 25   | 4    | 25   | 4    |
| Digit           |          | -16  | -8   | -16  | -8   | -16  | -8   | -16  | -8   | -16  | -8   |
| Center digit    |          | 10   | -8   | 12   | -8   | 13   | -8   | 12   | -8   | 13   | -8   |
| Edge digit      |          | 10   | -8   | 13   | -8   | 10   | -8   | 12   | -8   | 13   | -8   |
| Bottom surface  |          | -8   | 4    | 25   | 4    | 25   | 4    | 25   | 4    | 25   | 4    |

Figure 4. Bending stress contour (# 6).

Figure 5. Deflection contour (# 6).

4. Results and Discussion

4.1. Central Plane Bending Stress and Deflection Distribution in Bending Load

Figure 4 and Figure 5 show an example of bending stress and deflection distribution when the bending load is 1.25 times the maximum payload (25 kN), respectively. It was found that in both structural types, the largest bending stress and deflection were produced in the lower central plane of the pallet, excluding an area of concentrated stress near the contact portion with the rigid body support. Incidentally, the bending stress was maximized in the central portion, but the deflection was maximized outward. Figure 6 shows the relationship between flexural stiffness and deflection. It was found that the deflection of all pallets built using hinoki wood was lower than that of the standard type made using Oregon pine wood (excluding the hinoki wood-made standard type #0).

4.2. Distribution of Leg Compressive Stress and Compressive Displacement under Compressive Loading

Figure 7 and Figure 8 show examples of the compressive stress and strain distributions when the compressive load is 1.1 times the maximum payload (22 kN), respectively. The stress distribution was almost even in the cross section of the legs in either structural type. Figure 9 shows the relationship between the compressive stiffness and compressive displacement of the legs. Only the hinoki-made
Figure 6. Relation between deflection and flexural rigidity.

Figure 7. Compression stress contour (#6).

Figure 8. Compressive displacement (#6).

Figure 9. Relation between compressive displacement and compression stiffness.
**Table 3. Comparison of new and standard type.**

| Type                  | Items to be evaluated | Deflection (mm) | Compressive displacement (mm) | Cost (Japanese yen) |
|-----------------------|-----------------------|-----------------|-------------------------------|---------------------|
| Standard Type         |                       | 12.85           | 2.96                          | 1264                |
|                       |                       | (6.040)         | (0.3952)                      |                     |
| New Type (#6)         |                       | 8.83            | 2.06                          | 906                 |
|                       |                       | (3.994)         | (0.3803)                      |                     |

( ) : Analysis value

Type #6 showed compressive displacement lower than the standard type created using Oregon pine wood, not use any macros for the figures and tables.

4.3. Comparison between New and Standard Types

Table 3 shows a comparison of the strength test results and cost of the Oregon pine-made standard type and the hinoki-made type #6 pallets. The hinoki-made type #6 pallet was found to be superior to the Oregon pine-made standard type pallet.

5. Conclusion

The purpose of this study is to develop a new pallet structure using the inexpensive hinoki wood, which is produced in the Ehime Prefecture, having the same strength as the conventional Oregon pine wood. A new pallet structure was proposed for achieving high-strength by improving the flexural stiffness and compressive stiffness and achieving high-cost performance by using the inexpensive hinoki wood. The results obtained in this study are summarized as follows.

1. Deflection of the new type #6 is reduced compared to the standard type, due to the increased bending rigidity of the edge board and deck board.
2. Compressive displacement of the new type #6 decreases, as the compressive stiffness of the pallet legs increases.
3. Cost of the new type #6 is 72% of that of the standard type of pallet, and the cost can be reduced by 28%.

6. References

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