Design and Manufacture of Laminated Veneer Lumber Packaging Boxes and Pallets and Evaluation of Their Mechanical Properties

Rongzhuo Zhang,[a] Yuhang He,[a] Assima Dauletbek,[b] Zhaoyu Shen,[a] Yuhao Zhou,[a] and Zheng Wang [a,*]

Wooden packaging boxes and pallets are used in a wide range of applications. In this work, LVL from the same source and batch were used as the base material. After dynamic detection and grading, they were divided into two grades (A and B), according to their differences in elastic modulus. The packaging boxes and pallets of the same specifications were designed and manufactured as the research objects. Four mechanical properties studies and related analyses were performed. The three mechanical tests showed different deflection values of the two packaging boxes A and B, and the maximum error was 6.93%. In the rotational edge drop test, the edges of the nether end rails of the two grades of LVL boxes were damaged to varying degrees. Additionally, the nails at the connection between the middle longitudinal beam and the bottom plate also appeared to be pulled out, and the parts made of B-grade LVL were more obvious. The results show that the dynamic detection and quality grading for LVL can effectively distinguish the material grade. The grading results were consistent with the mechanical properties of the LVL packaging boxes and pallets of corresponding grades, which are suitable for use in production lines.

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Contact information: a: College of Materials Science and Technology, Nanjing Forestry University, Nanjing, Jiangsu, 210037, China; b: College of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China;
** Corresponding author: wangzheng63258@163.com*

INTRODUCTION

As a form of packaging for transportation, handling, and stacking, packaging boxes and pallets have been widely used around the world. In 2014 alone, the number of pallets in China reached 900 million, and the annual growth rate was 13%. Among them, wooden pallets account for about 86% of all kinds of pallets (Kang 2017). Wooden packaging boxes and pallets are used commonly to transport packaging containers. They can be made of wood as the base material and usually are assembled with steel nails, which have a certain resistance to shock and vibration and protect the contents from damage. Compared with other materials, wooden packaging boxes and pallets have the characteristics of high load-bearing strength, good compressive strength, anti-collision cracking, good cushioning, low price, and convenient production. They are widely used in the packaging and transportation of mechanical electronics, ceramic building materials, hardware appliances, precision instruments, and oversized items, especially large and medium-sized mechanical products

(Mills and Masso-Moreu 2005; Van Dijk *et al*. 2015; Kočí 2019; Ponzo *et al*. 2021). In recent years, due to the inadequate supply between global bamboo and wood resources, wooden packaging boxes and pallets have gradually abandoned solid wood manufacturing. They have been replaced by artificial boards such as oriented strand board (OSB) and laminated veneer lumber (LVL). This effectively alleviates the waste of high-quality wood and makes full use of the excellent mechanical properties of wood-based panels (Cui 2014; Dauletbek *et al*. 2021; Su *et al*. 2021; Yang *et al*. 2021).

As a type of modern wood-based panel, LVL has better dimensional stability, higher mechanical strength and stiffness, and better weather resistance than solid wood sawn timber. At present, it has been widely used in many fields such as a lintel, truss, truck bed, container floor, packing box, I-beam, herringbone beam, and so on (Strickler and Pellerin 1971; Çolak *et al*. 2007; Ardalany *et al*. 2012; Rahayu *et al*. 2015). The LVL is usually made of veneers cut from logs of similar material after drying, sizing, assembling blanks along the grain, cold or hot pressing, and curing (Llaufenberg 1982; Musselman *et al*. 2018). However, the differences in the quality of veneers, the structure of the board, and the sizing group lead to differences in appearance and mechanical properties even for the same batch of LVL products (Hing *et al*. 2005; Burdurlu *et al*. 2007). Clearly, the quality grading evaluation of the base material LVL will determine the quality assurance efficiency and market competitiveness of LVL packaging boxes and pallets. Over the years, researchers have devoted themselves to studying the mechanical properties of wooden packaging boxes and pallets under different working conditions and have achieved certain results. He and Lu (2008) studied the force analysis of wooden pallets under typical conditions such as storage and transportation. Kang (2017) conducted a series of compression tests on wooden pallets made of LVL and other materials to determine the deformation. Xu (2018) conducted the actual strength and stiffness tests of the bending test, forklift test, and stacking test on small-diameter wooden pallets and compared and summarized the mechanical test results and theoretical analysis. The above studies were all focused on the mechanical properties of wooden pallets, that is, products, and do not involve the evaluation of base material properties and quality grading.

In order to study the accuracy of dynamic detection and quality grading for Italian poplar (*Populus euramericana* cv.'I-214')LVL product performance evaluation, LVL of the same source and batch were used as the base material in this work. Firstly, the dynamic method was used to classify LVL into two grades (A and B), according to the difference of elastic modulus. Then, the two grades of materials were designed into identical packaging boxes and pallets as standard. Finally, four basic mechanical property testing studies were carried out on packaging boxes and pallets to analyze and evaluate the correlation between the quality grading results of LVL boards and the quality of actual packaging boxes and pallets. The results of this study are of practical significance for improving the quality assurance of Italian poplar LVL packaging boxes and pallets and the economic and social benefits.

EXPERIMENTAL

Dynamic Testing and Quality Grading of Elastic Modulus of LVL

The components of packaging boxes and pallets were dynamically measured by the transient excitation method, and their elastic modulus values were obtained by quality grading. The test measures the elastic constant values of each board in a batch of LVL.

Through probability distribution, the larger elastic constant was selected as grade A, and the smaller one was marked as grade B. The free support state when testing the first-order bending frequency of the LVL specimen is shown in Fig. 1 (Xie 2020). The average moisture content of LVL was 13%, and the average air-dry density was 549 kg/m^3. The average elastic modulus values of LVL specimen A and B were 13.16 GPa and 11.09 GPa, and the shear modulus was 838 MPa and 770 MPa, respectively. The raw material for production was Italian poplar (*Populus euramericana* cv. 'I-214'), a fast-growing material produced in Jiangsu, China. The elastic modulus was calculated according to Eq. 1,

$$E = 0.946\,2\rho \frac{L^4 f_1^2}{h^2} \tag{1}$$

where E is the elastic modulus of the specimen (Pa); ρ is the air-dry density of the specimen (kg/m^{-3}); f_1 is the first-order bending frequency of the specimen (Hz); L is the specimen length (m); and h is the specimen thickness (m) (Wang *et al*. 2014, 2015, 2018; Zhou *et al*. 2021). The shear modulus was calculated according to Eq. 2,

$$G = \frac{\pi^2 \rho (L/2)^2 b^2 (f_2)^2}{7.5\beta h^2} \tag{2}$$

where β = 1/16{16/3 - 3.36h / b[1 - 1/12(h / b)4]}; ρ is air-dry density of the specimen (kg/m^{-3}); f_2 is first-order torsional frequency of the specimen (Hz); L is the specimen length (m); and h is the specimen thickness (m) (Wang *et al*. 2016, 2019).

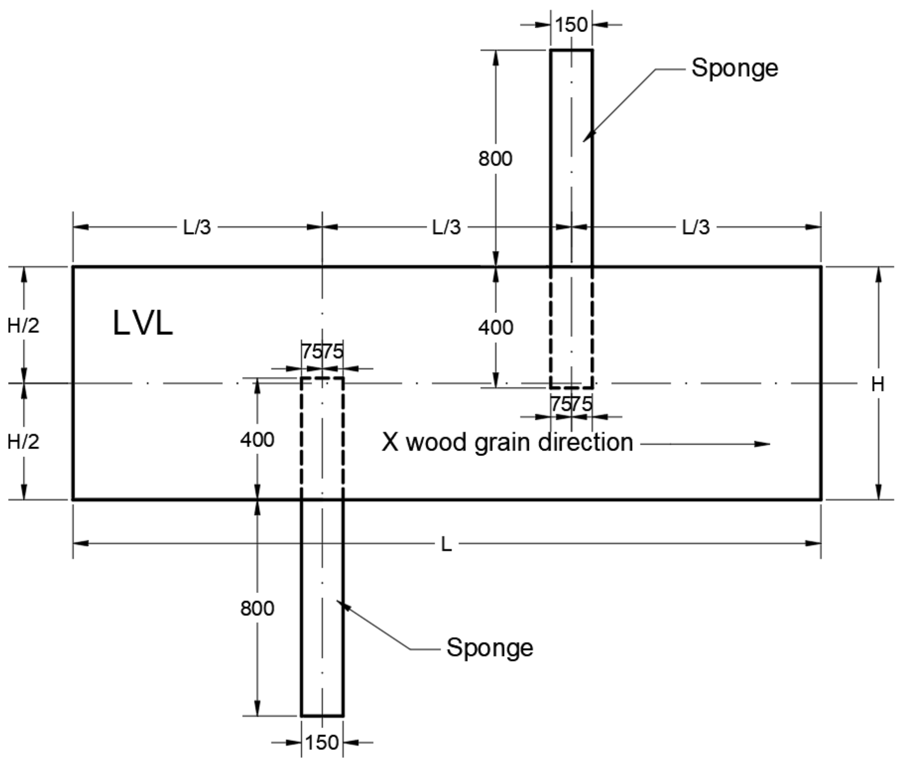


Fig. 1. Schematic diagram of placing condition of a free plate LVL on a sponge

Design of LVL Packaging Boxes and Pallets

In this paper, according to the requirements of GB/T 34364 (2017), LVL packaging boxes and pallets with reasonable sizes were designed. Among them, the LVL structure, technical conditions of appearance, moisture content, and dipping peel strength, all met the relevant regulations in GB/T 20241 (2006). The dimensional deviations of the width and thickness of the LVL component are shown in Table 1.

Table 1. The Dimensional Deviations of the Width and Thickness of the LVL Components

Classification	Deviation (mm)	Evaluate
Width	2.0	Qualified
Thickness	0.8	Qualified

The packaging boxes and pallets designed and manufactured in this study were made of LVL materials with different mechanical grades. The specific structural design of the LVL packaging box is shown in Fig. 2, and the specifications and dimensions of the packaging box components are shown in Table 2.

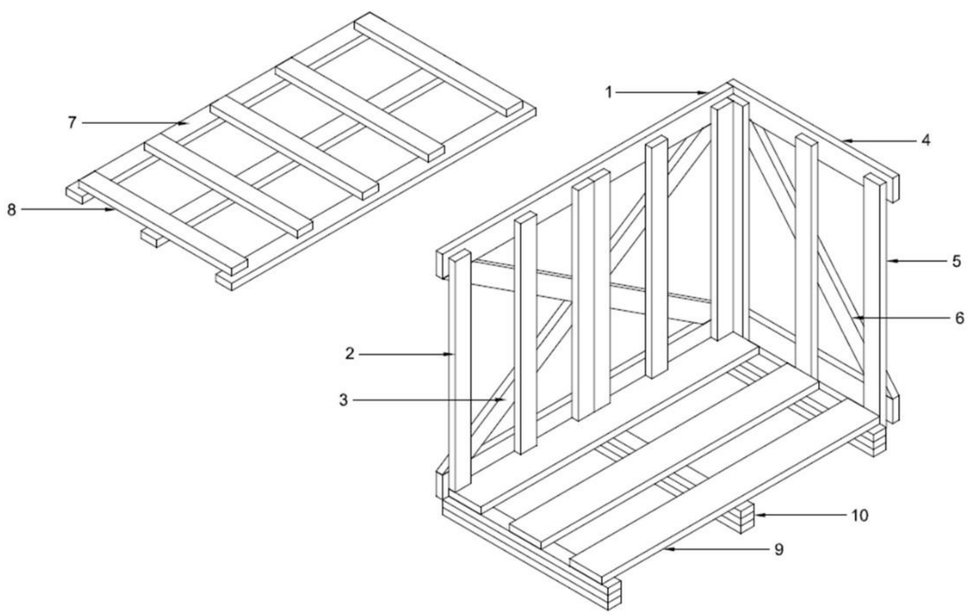


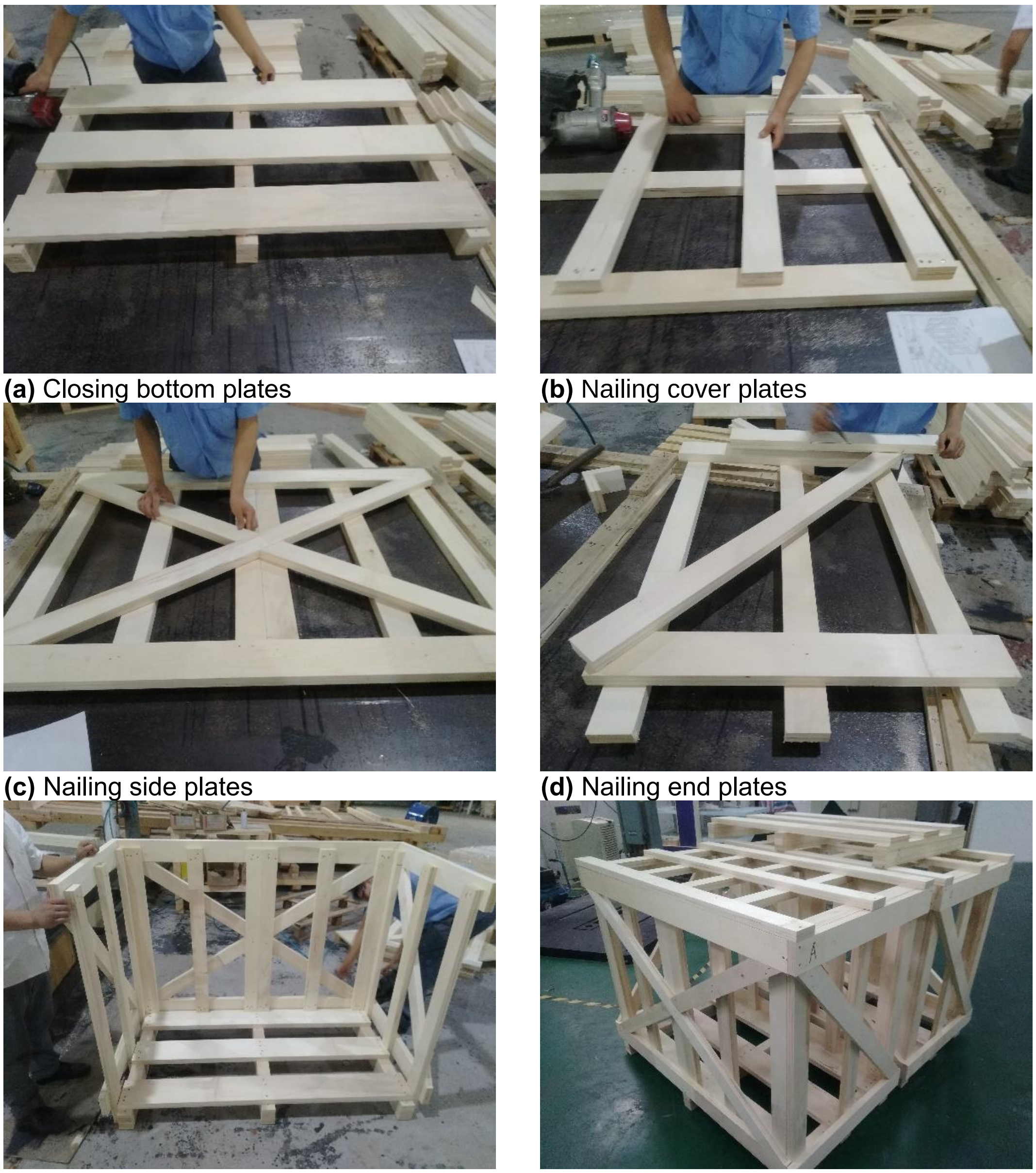
Fig. 2. Structural design of the LVL packaging box

Table 2. Specifications and Dimensions of the Packaging Box Components

Number	Components	Length (cm)	Width (cm)	Thickness (cm)	Quantity
1	Side Rail	137	10	3	4
2	Side Plate	94	7.5	3	12
3	Side Brace	168	7.5	3	4
4	End Rail	78	10	3	4
5	End Plate	106	7.5	3	6
6	End Brace	121	7.5	3	2
7	Cover Rail	143	7.5	3	3
8	Cover Plate	72	7.5	3	6
9	Bottom Plate	131	15	3	3
10	Longitudinal Beam	78	6	9	3

Manufacturing Process of LVL Packaging Boxes and Pallets

The Italian poplar LVL packaging box was produced only with A or B grade LVL boards as the base materials, respectively. The production process of the packaging box is divided into 6 parts, namely cutting out plates, closing bottom plates, nailing cover plates, nailing side plates, nailing end plates, and closing the box body. According to the design requirements, a woodworking table saw was used to cut the Italian poplar LVL to the specified size.



(a) Closing bottom plates **(b)** Nailing cover plates
(c) Nailing side plates **(d)** Nailing end plates
(e) Closing box body **(f)** Finished product

Fig. 3. On-site manufacturing steps of the Italian poplar LVL packaging box

To meet the transportation requirements, such as forklifting and hoisting, and the main mechanical load-bearing requirements, the longitudinal beams nailed to the bottom plate were processed with a section size of 60 mm × 90 mm. Steel nails of 50 mm were used to assemble LVL packaging boxes, and at least two steel nails were used to fix each connection part to ensure the necessary connection performance. The on-site manufacturing steps of the Italian poplar LVL packaging box are shown in Fig. 3. Moreover, LVL pallets were manufactured in the same way as the bottom plate of the packaging box.

Test Object and Device

In this study, according to GB/T 4996 (2014) and GJB 2711 (1996), four kinds of tests were conducted for LVL packaging boxes and pallets of two quality grades A and B, namely, bending test, top stacking test, simulated forklifting test, and rotational edge drop test. Each test was performed three times to ensure the accuracy of the test.

The test equipment includes a compression testing machine and a forklift. The whole box compression testing machine "CT-5000C" made in Hangzhou, China was adopted for the experiment. The testing machine was equipped with a mechanical transmission and controlled by the upper computer. The compression space was 1500 × 1500 × 1500 mm^3, the measurement range was 0 to 50 kN, the force value accuracy was 0.25 N, and the displacement accuracy was 0.1 mm. The machine was mainly used for strength tests and stacking tests of various packaging boxes and pallets to simulate the ability of wooden packaging boxes to resist external deformation during actual transportation, loading, and unloading.

Test Principle and Method

Pallet bending test

The principle of this test is to simulate the bending stiffness under the actual conditions by measuring the deflection value of the pallets after being compressed by the mechanical testing machine, as shown in Fig. 4.

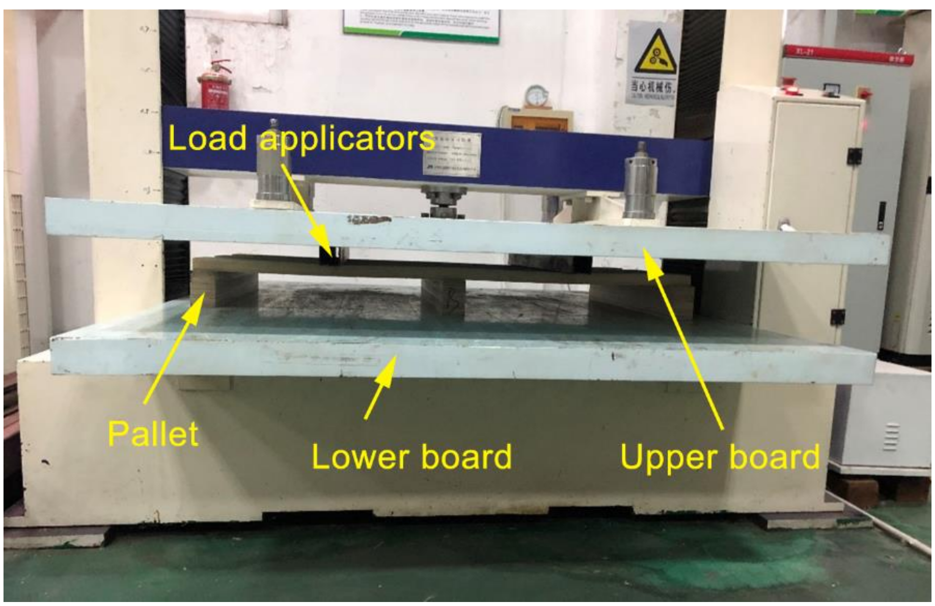


Fig. 4. Structure diagram of pallet bending test

The specific operation steps are as follows: first, use the compression testing machine to test two LVL pallets of the same grade in the length and width directions. The deflection value in the length direction was selected because the results show that it is greater than 15% of the width direction. Next, a new pallet identical to the test above was selected and placed on the lower board. Next, ensure that the load applicator and the loading board protrude beyond the outer edge of the pallet. To evaluate the part with the lowest rigidity, the load applicator was located at the respective quarter points. Then, according to 1.5% of the measured limit load value, 40 kN was selected as the reference load of the test. Then, the test load was applied to the upper board at a speed of 12 mm/min, and the maximum deflection value at the base load recorded. Because the designed pallet is a single-sided form, the LVL pallet is directly placed on the lower board to simulate the support state.

Top stacking test

This test is suitable for evaluating the pressure bearing capacity of the bottom transport package and the ability of the package to protect the contents when stacked in the same transport package or with the top liner.

The specific steps were as follows: first, the LVL packaging box was placed in the center of the lower board according to the predetermined state. Then, three load applicators were placed evenly on the top of the box so that the load applicators protruded beyond the outer edge of the box. Next, the testing machine was controlled to move the upper board. The load was applied until a predetermined value was reached. The predetermined load was calculated according to the provisions in 5.1.2 of GJB 2711 (1996), and the two calculation results were approximately 10 kN. In this test, the displacement values were used to measure the difference between the stacking capacity with the top between the two grades of LVL boxes (A and B), and the preset value may be set to 30 kN. After the test, the appearance of the LVL packaging boxes and the damage of each structural component were checked.

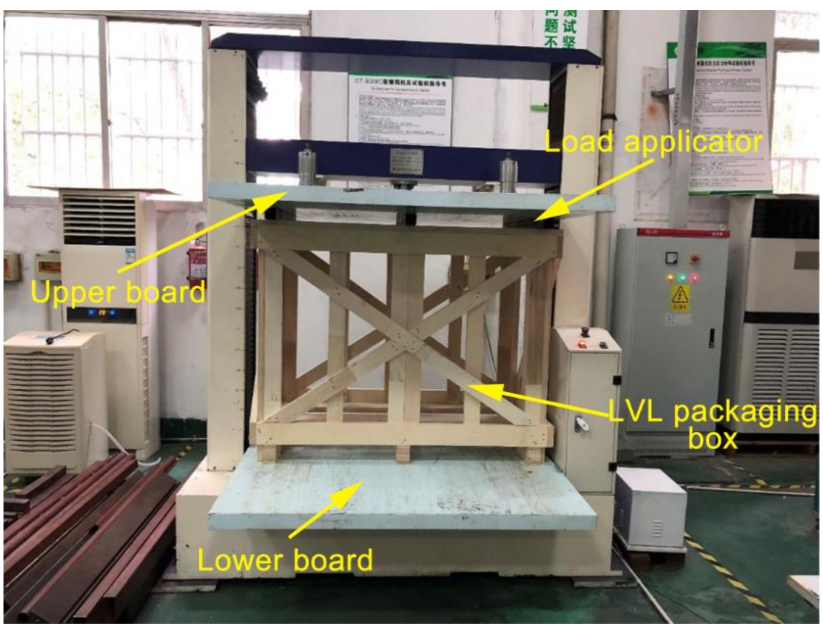


Fig. 5. Structure diagram of top stacking test

Simulated forklifting test

The principle of this test is to determine the limit working state of the pallet through the deflection value when the single or double-deck pallet is supported by the fork arm, as shown in Fig. 6. In this paper, the simulated forklifting test was used to test the overall stiffness of the LVL packaging box. The performance differences of the two LVL packaging boxes were evaluated by simulating extreme working conditions.

The specific test steps are as follows: first, according to the actual length of the LVL packaging box, two supports were arranged on the lower board, and the distance between the supports was 570 mm. Next, the box was placed on the stand along its length and three load applicators were placed evenly on top. The load applicators were checked to be in alignment with the longitudinal beams such that the length of the supports and load applicators extended beyond the outer edge of the box. Finally, the upper board was loaded at a constant speed until the load reached 40 kN.

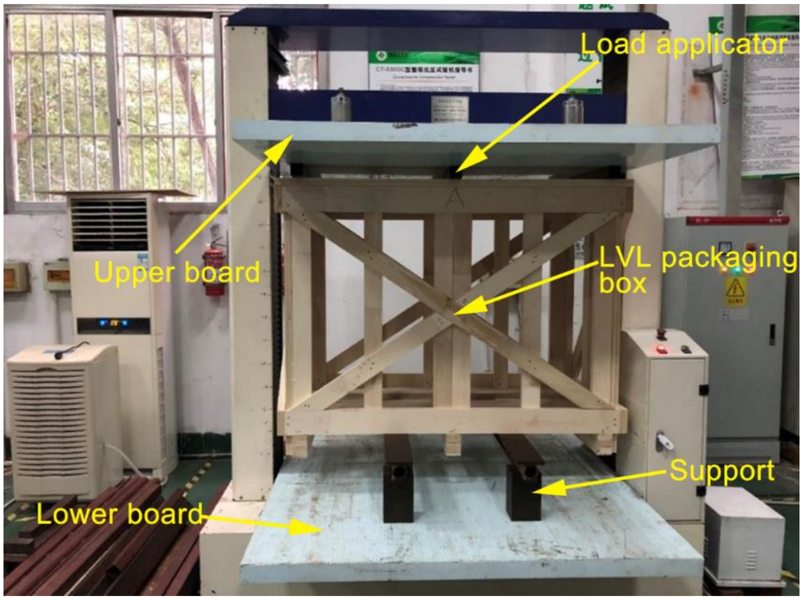


Fig. 6. Structure diagram of simulated forklifting test

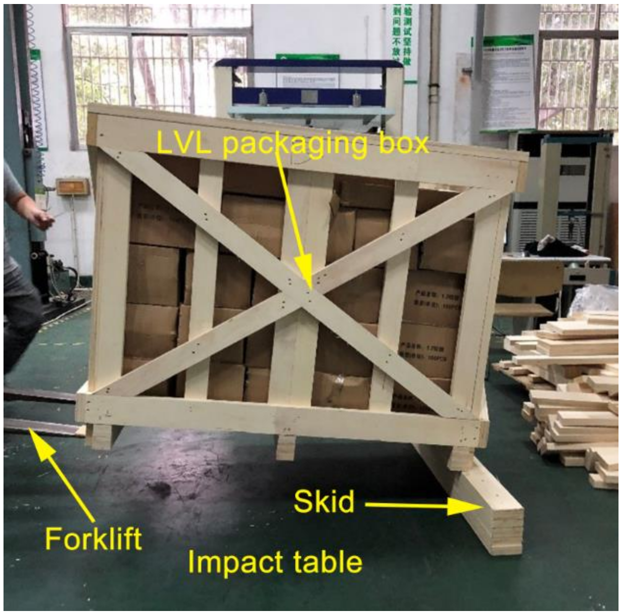


Fig. 7. Structure diagram of rotational edge drop test

Rotational edge drop test

The principle of this test is to determine the impact resistance of the packaging box and the protection ability of the packaging by dropping the packaging box in the rotational edge and angle directions, as shown in Fig. 7.

The specific test steps were as follows: first, fill the LVL packaging box with goods and pack them. Then, use a forklift to lift one end of the box to a quadrangular prismatic skid with 150 mm height. Raise the other end 500 mm above the ground and let it fall freely, to create an impact.

It should be noted that the test table is the impact table specified by the standard. During the test, there was no relative sliding among the packaging box, the forklift, and the skid. To ensure no obstruction and support at both ends when the box falls, the longitudinal beam was placed on 1/3 of the skid.

RESULTS AND DISCUSSION

Table 3 shows the maximum deflection values of the packaging boxes and pallets.

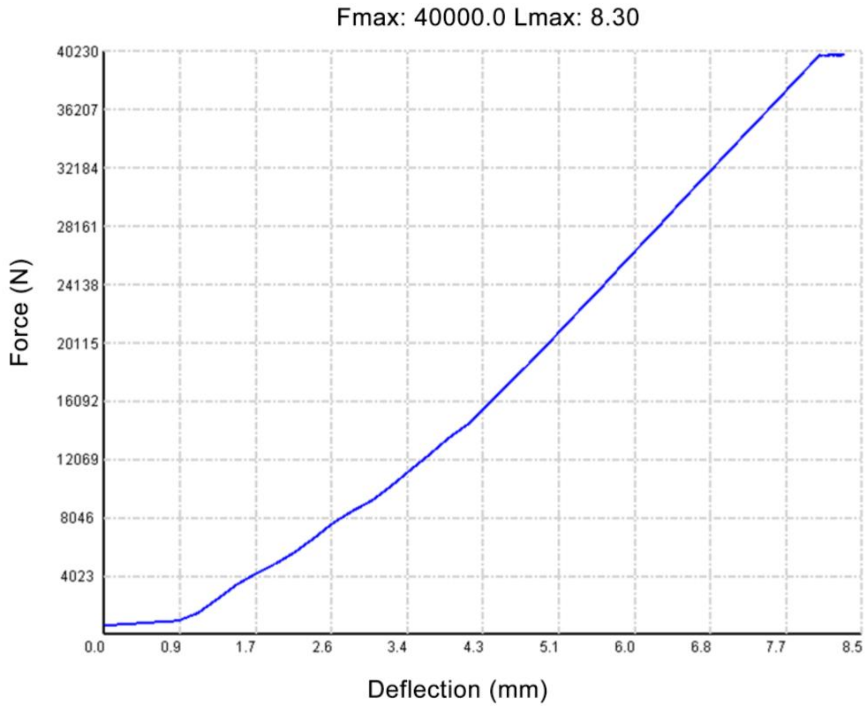
Table 3. Maximum Deflection Values of the Packaging Boxes and Pallets

Objects	Deflection Value (mm)		
	Pallet Bending Test	Stacking Test with Top	Simulated Forklifting Test
Packaging box A	\	5.30	9.40
Packaging box B	\	5.40	10.10
Pallet A	8.30	\	\
Pallet B	8.60	\	\
Standard deviation	0.15	0.05	0.35

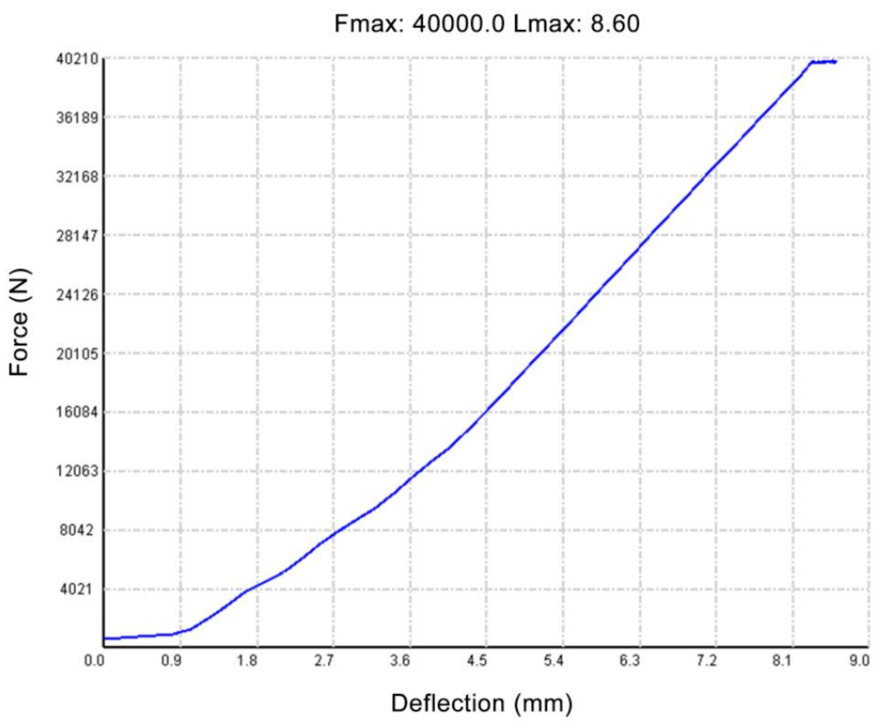
Results and Analysis of Pallet Bending Test

It can be seen from the load-displacement diagram in Fig. 8 that when the preset load reached 40 kN, the maximum deflection of Italian poplar LVL pallet A was 8.30 mm. The maximum deflection of the pallet B under the corresponding load was 8.60 mm. In the pallet bending test, the deflection value of the packaging box using A-grade LVL decreased 3.49% compared with the packaging box using B-grade LVL. The test results were close to the mean load disturbance of 9.24mm in the study (Xu 2018).

Before the displacement by 4.3 mm, there was no direct linear relationship between the load and displacement. This was because the base material of the pallet was an engineered wood product, and the joints were nailed. This led to the inconsistency of the initial strength of the joints among the components. A certain load was necessary to remove the void part in the early stage before it could move to the linear elastic stage. After the bending test, the pallet A was only slightly bent and deformed. There was no obvious damage, and the components were not functionally damaged. There was also no obvious damage to pallet B, for which only the bottom plate was slightly deformed, showing a concave trend. The components were not functionally damaged.



Pallet A

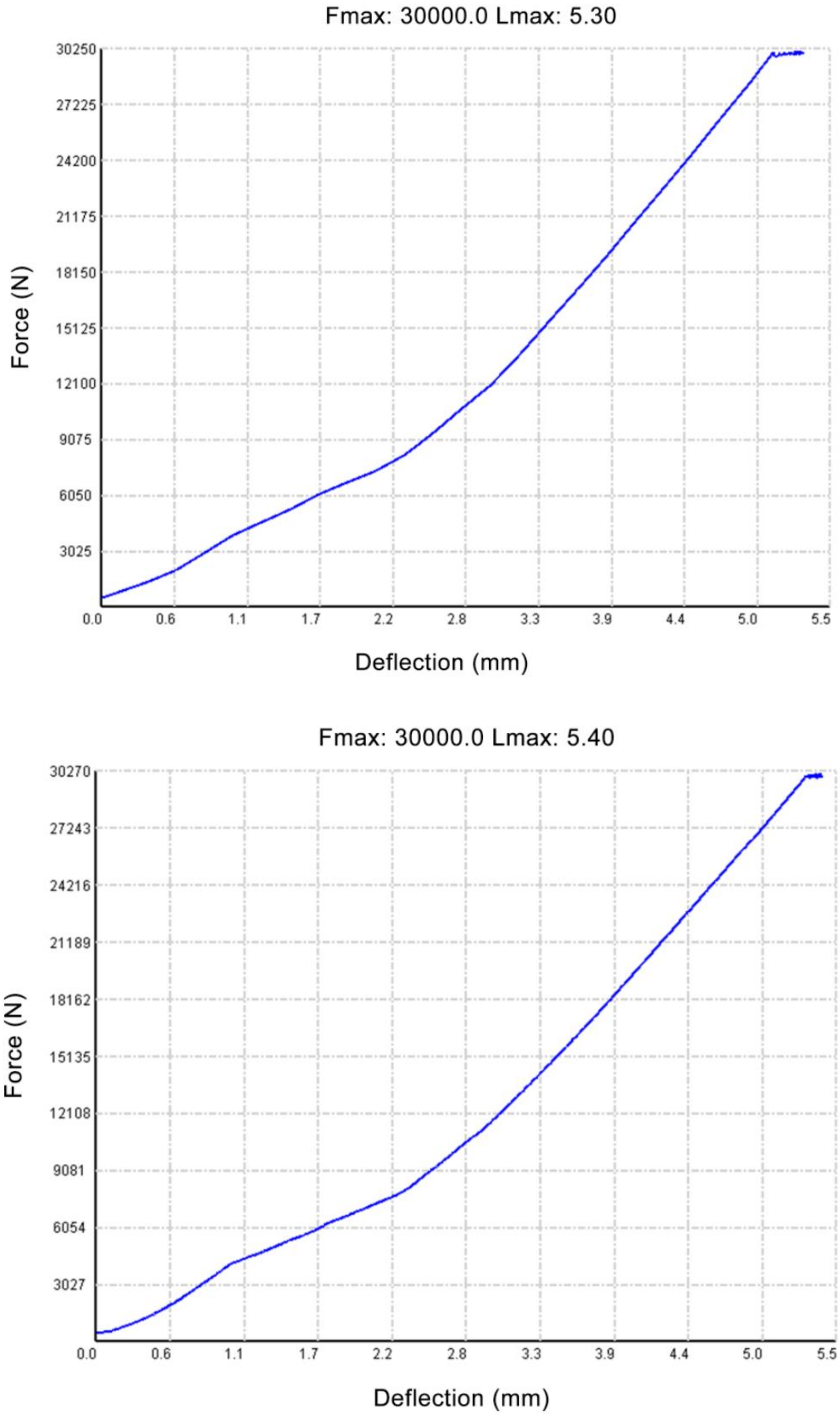


Pallet B

Fig. 8. Load-displacement diagram of pallet bending test

Results and Analysis of Top Stacking Test

From the load-displacement diagram in Fig. 9, the maximum deflection of packaging box A under the preset load was 5.30 mm, while that of packaging box B was 5.40 mm, with a difference of 1.85%. This indicated that LVL of grade A had better deformation resistance than grade B. After the stacking test, there was no obvious damage to packaging box A and no functional damage to its components. However, the side plates of the packaging box B were slightly deformed, and the components were not functionally damaged.



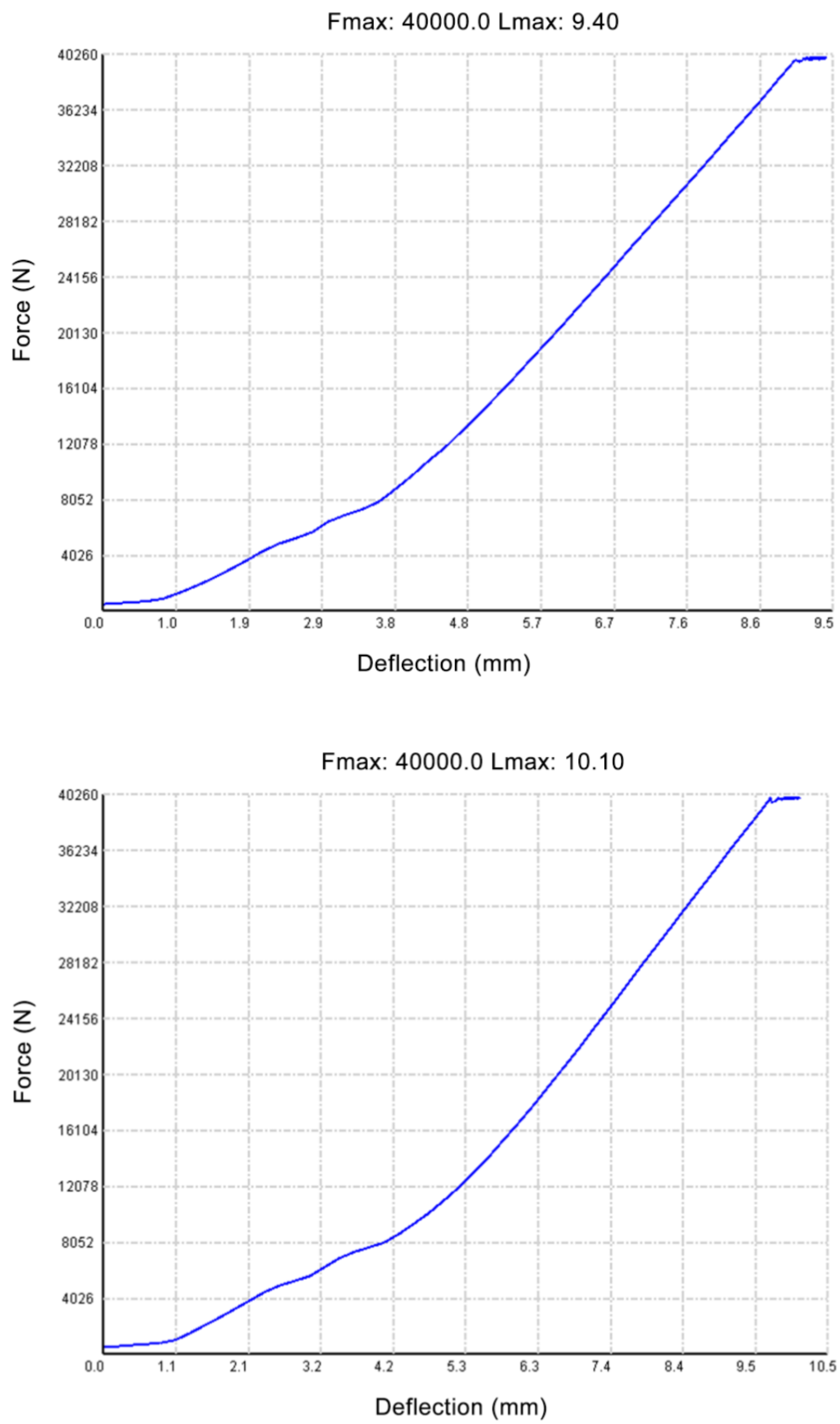
Packaging box A

Packaging box B

Fig. 9. Load-displacement diagram of top stacking test

Results and Analysis of Simulated Forklifting Test

From the load-displacement diagram of the simulated forklifting test in Fig. 10, the maximum deflection of box A was 9.40 mm, while the maximum deflection of box B was 10.10 mm, with a difference of 6.93%. Compared with the above two tests, the difference between the two graded LVL pallets in the extreme working state was more obvious, indicating the dynamic detection and classification accuracy and reliability.



Packaging box A

Packaging box B

Fig. 10. Load-displacement diagram of simulated forklifting test

For the packaging box A at the displacement of 3.8 to 9.0 mm and B at the displacement of 5.3 to 9.6 mm, the load-displacement relationship can be approximated to the linear elastic stage of the test sample. Compared to packaging box A, box B had a larger fluctuation before the displacement of 4.2 mm. This was because in the process of load application, the asymmetry caused the local component nodes of the packaging box B to preferentially transmit the load, resulting in a certain yield phenomenon of the connection, which was more obvious for the B-grade LVL with lower material properties. After the nails' ends of some specific nodes were partially pulled out, the change ranges of the load and displacement began to show a slowly increasing trend again. In addition, due to the difference in the base material of the packaging boxes, the load-displacement diagram of the packaging box A reached an approximate linear stage earlier.

After the simulated forklifting test, there was no obvious functional damage to the packaging box A and its components. However, there was a phenomenon of nail pulling out between the longitudinal beams and the bottom plates at both ends of the packaging box B in the length direction.

Results and Analysis of Rotational Edge Drop Test

It can be seen from the damage diagram of the rotational edge drop test (Fig. 11) that under the same height of the skid, the lifting height of the forklift and the loading weight, the edge of the lower end rail of the packaging box A was slightly damaged. This was the first contact surface when the packaging box hit the table. The nails at the connection between the middle longitudinal beam and the bottom plates also appeared to be pulled out, which was caused by the impact of the goods in the packing box. Other components were not functionally damaged.

Packaging box A

Packaging box B

Fig. 11. Load-displacement diagram of rotational edge drop test

For the packaging box B, the edge of the lower end rail had a large area of damage. The middle longitudinal beam also showed the phenomenon of pulling out at the connection with the bottom plates, and the length of the nail pulling was longer. Other components of box B were not functionally damaged. This showed that the packaging box made of A-grade LVL had better impact resistance and protection of the loaded items than B-grade LVL, which also verified the accuracy of dynamic grading.

From the results analysis, it can be seen that the packaging box and pallet using A-grade LVL performed better in the overall test than the packaging box and pallet using B-grade LVL, which verified the results detected on the production line.

CONCLUSIONS

1. In this paper, Italian poplar laminated veneer lumber (LVL) boards of the same batch of A and B grades, dynamically detected and graded by the transient excitation method, were used as the base material. The LVL packaging boxes and pallets of A and B grades were designed and manufactured, and four tests with analysis were conducted, including top stacking test. The research showed that the deflection values of pallets made of two grades of LVL were 8.30 mm and 8.60 mm under the preset reference load in the bending test, respectively. Thus, they differed by 3.49%. In the top stacking test, the deflection values of the specimens when they reached the preset reference load were 5.30 mm and 5.40 mm, respectively. In this case they differed by 1.85%. In the forklifting test, the difference between the two deflection values which were 9.40 mm and 10.10 mm, corresponding to a 6.93% difference.
2. In the rotational edge drop test, the edges of the lower end rails of the two grades of packaging boxes were damaged to different degrees. In addition, the nails at the connection between the middle longitudinal beam and the bottom plates also appeared to be pulled out, and this phenomenon was more obvious for the parts made of B-grade LVL. The mechanical properties of LVL packaging boxes and pallets of grades A and B meet the standard requirements.
3. The obtained results showed that the dynamic test elastic modulus and its quality grading for LVL effectively distinguished the material grades, and the mechanical properties of the LVL packaging boxes and pallets of the corresponding grades were consistent with the results, which were suitable for use in production lines. Clearly, as long as the quality grading of LVL components is well controlled, the quality of LVL packaging boxes and pallets made from these components can be predicted. This can effectively improve the quality assurance efficiency of packaging products and improve the engineering application value of LVL structural materials. Moreover, more emphasis should be placed on the simplified processing of LVL product quality inspection to improve efficiency and profitability in the future.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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