Experimental Analysis of Mechanical and Physical Properties of Ginkgo Scrimber

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Wood scrimber as a promising eco-friendly material in wood technology. This study evaluated the physical and mechanical properties of ginkgo scrimber, focusing on density, moisture content, water absorption, thickness swelling, flexural modulus of elasticity, bending strength, tensile modulus of elasticity, tensile strength, compressive modulus of elasticity, compressive strength, and shear strength. The results showed that the material had low variation in density and moisture content, indicating good homogeneity of the material. Mechanical properties tests showed that the material's mechanical properties met high-quality standards, although variability in bending strength suggested potential issues with adhesive application. Some specimens experienced fractures perpendicular to adhesive layers, affecting strength. Despite this, ginkgo scrimber exhibited mechanical properties comparable to or exceeding those of reconstituted bamboo and laminated veneer lumber. The findings highlight its potential for construction, with recommendations for improved adhesive application and manufacturing processes to enhance performance stability.

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INTRODUCTION

Wood scrimber, known for its eco-friendly properties and efficient utilization of small or low-quality timber, represents a promising material for constructing timber structures using fast-growing plantation forests. This innovative material is produced by milling and processing low-quality, fast-growing small-diameter and thinned timber into interlocking, longitudinally loose, and transversely unbroken bundles. These bundles undergo reassembly through processes including drying, gluing, laying, and hot pressing (Guo *et al.* 2017; Lin *et al.* 2020). Wood scrimber exhibits enhanced mechanical properties, which enhance material quality and increase the utilization efficiency of raw materials (Sharma *et al.* 2012; Reynolds *et al.* 2016). Currently, wood scrimber is predominantly utilized in wood structure construction, indoor furnishings, and outdoor flooring applications. Its introduction has significantly impacted the wood-based panel industry.

Traditional wood scrimber originated from a concept proposed in 1973 by John Douglas Coleman, an academic at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia. The Chinese Academy of Forestry (CAF) adapted the concept to bamboo-based materials, achieving industrial production of high-performance wood scrimber in 2014 after extensive research (Ji *et al.* 2022). Li *et al.* (2016) noted that while promising for structures, wood scrimber generally lags behind natural wood with respect to mechanical and physical properties (Wang *et al.* 2014, 2018). Early in China's wood scrimber industry, poplar (*Populus* L.) was the primary raw material (Zhang *et al.* 2018). Tests show that wood scrimber composite, from small-diameter trees like poplar, exhibits promising mechanical properties comparable to or better than traditional engineered wood. It shows ductile compression and brittle tension, shear, and bending behaviors, supporting its structural design reliability (He *et al.* 2016; Wang *et al.* 2016; Sun *et al.* 2021).

Due to the use of a single raw material, the work cited above is not conducive to the widespread production and promotion of the product. In recent years, there has been a gradual increase in research on using other raw materials to replace poplar to produce wood scrimber (Gao *et al.* 2023). Yu *et al.* (2015) studied density and resin content's impact on mulberry (*Morus alba* L.) branch-derived wood scrimber, finding that increased density and resin content significantly enhances its strength, hardness, and durability for structural applications. Mousa *et al.* (2024) evaluated palm tree leaf-derived wood scrimber's mechanical and dynamic properties (*Trachycarpus fortunei* (Hook.) H. Wendl.), demonstrating strong mechanical properties suitable for engineering applications. Sun *et al.* (2024) investigated resin content's effects on water resistance, mechanical, and thermal properties of radiata pine-derived wood scrimber (*Pinus radiata* D. Don), highlighting improved hydrolysis resistance and mechanical strength, with minor impact on thermal properties. Wood scrimber, which can be regarded as a new wood material in China's forestry sector, lacks standardized specifications. Current research also lacks comprehensive mechanical and physical property tests for specific types of wood scrimber, and comparisons with wood scrimber bamboo and veneer laminated timber are lacking. Mechanism analyses of its destructive morphology are also insufficient. This study investigated ginkgo-derived wood scrimber products using methods aligned with wood-based panel and veneer panel standards, alongside wood scrimber benchmarks. Tests cover density, moisture content, water absorption expansion, bending modulus, bending strength, tensile modulus, tensile strength, compression modulus, compression strength, and horizontal strength (GB/T 40247 2021; GB/T 50005 2017; GB/T 17657 2022; GB/T 35216 2017; ISO 18776 2008, respectively). Through analyzing these results and damage patterns, this study aims to compare the mechanical and physical properties of ginkgo wood scrimber with wood scrimber bamboo and veneer laminated timber. Based on the measured mechanical parameters, statistical and probabilistic methods can be applied to the study of product structures, using them as raw materials (Wang *et al.* 2021, 2022, 2023). This research is intended to promote design and production technology, establish standards, and improve wood utilization efficiency. At the same time, it can promote the widespread application of recycled wood and provide practical and extensive benefits.

EXPERIMENTAL

Materials

The production of ginkgo (*Ginkgo biloba* L.) scrimber involves several key processes: log rotary cutting and trimming, log fibrillation treatment, phenolic resin impregnation, drying before and after gluing, and final paving and molding. A cold-pressed heat curing process is specifically utilized in this production, as shown in Fig. 1, where the term "demolding" means removal from the mold.

a. Secondary drying **b.** Cold pressing and shaping **c.** Cooling and demolding

Fig. 1. The main production process site of ginkgo scrimber

Equipment

For the experiments, a DHG-9030A electric heating convection drying oven (Ningbo Hinotek Instrument Co., Ltd., Ningbo, China), with a temperature range of +10 °C to 200 °C and precision of 1 °C was used.

An H-SWX-600BS type electric constant temperature water temperature box (Shanghai Shengke Instrument Equipment Co., Ltd., Shanghai, China) was also used. Its temperature range is +5 ℃ ~ 100 ℃, with a precision of 1 ℃, with temperature uniformity ± 1%.

Testing utilized a UTM4304SLXY electronic universal testing machine (Shenzhen SUNS Technology Stock Co., Ltd., Shenzhen, China), capable of applying a maximum force of 30 KN at a loading speed of 14 MPa/min. The machine's measurement accuracy is 1% of the load value.

One set of AG-IC Shimadzu universal mechanical testing machine (Shimadzu Corp, Kyoto, Japan) was used. It has a maximum test force of 100 kN, a test loading speed of 14 MPa/min, and a maximum test force of 10 kN.

Micrometer (Deli Group Co., Ltd., Ningbo, China), measuring range 0 mm to 200 mm, precision 0.01 mm was used throughout experiments, as well as Vernier calipers (Deli Group Co., Ltd., Ningbo, China), measuring range 0 mm to 200 mm, and a precision of 0.02 mm. An electronic balance with a precision of 0.01 g (Deli Group Co., Ltd., Ningbo, China) was used with a precision of 0.01 g.

Determination of Density and Moisture Content

Ginkgo wood scrimber specimens measured 100 mm × 100 mm × 20 mm, totaling 6 pieces. Testing methods followed the GB/T17657(2022) standard. The formula for density and moisture content is as follows,

$$\rho = \frac{m}{l \times b \times t} \times 1000 \tag{1}$$

where ρ is density (g/cm^3), m is mass of the specimen (g), l is the length of the specimen (mm), b is width of the specimen (mm), and t is the thickness of specimen (mm). The moisture content is given by Eq. 2,

$$H = \frac{m_0 - m_1}{m_1} \times 100\% \tag{2}$$

where H is specimen moisture content (%), m_0 is specimen mass before drying (g), and m_1 is specimen mass after drying (g).

Initially, six specimens were labeled as HM-1 to HM-6. Subsequently, the dimensions (length, width, thickness) and mass of each specimen were measured to determine its density, ρ. The specimens were then dried at 103 ± 2 °C until reaching a constant mass. After drying, they were promptly cooled in a desiccator and weighed at room temperature. Finally, the difference in mass before and after drying was recorded for each specimen to calculate its moisture content.

Physical Performance Testing of Water Absorption Thickness Expansion Rate

Wood scrimber specimens of ginkgo measured 50 mm × 500 mm × 20 mm, totaling 6 pieces. This testing method follows GB/T40247 (2021) for determining absorbent thickness expansion rate. The formula for density and moisture content is given as Eq. 3,

$$T_h = \frac{h_2 - h_1}{h_1} \times 100 \tag{3}$$

where T_h is absorbent thickness expansion rate (%), h_1 is thickness before immersion in water (mm), and h_2 is thickness after immersion in water (m).

Eight specimens, labeled P-1 to P-8, were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity until their mass stabilized. Initial thickness (h_1) measurements were taken. Each specimen was boiled in water at 100 ± 2 °C for 4 h, followed by drying in a forced-air oven at 63 ± 3 °C for 20 h. Boil the sample again in water at 100 ± 2 ° C for 4 hours. After drying, specimens were wiped dry and cooled for 10 min at room temperature before testing. Thickness (h_2) measurements were then taken at the original points of measurement after removing the specimens from water.

Mechanical Properties Testing of Static Flexural Strength and Flexural Elastic Modulus

Ginkgo scrimber, measuring 450 mm × 50 mm × 20 mm for 12 pieces, had a moisture content of 9 to 12% and an air-dried density of 0.94 g/cm^3.

Testing methods followed GB/T17657(2022), specifically focusing on flexural strength and elastic modulus for wood scrimber. The three-point bending method was used for testing, and the calculation formula is shown in Eqs. 4 and 5,

$$\sigma_b = \frac{3 \times F_{max} \times l_1}{2 \times b \times t^2} \tag{4}$$

where σ_b is the flexural strength of the specimen (MPa), $F_{\max}$ is the maximum load of the specimen at the time of destruction (N), l_1 is the distance between the two supports (mm), b is width of the specimen (mm), and t is the thickness of specimen (mm). The bending elastic modulus in given by Eq. 5,

$$E_b = \frac{l_1^3}{4 \times b \times t^3} \times \frac{F_2 - F_1}{a_2 - a_1} \tag{5}$$

where E_b is the bending elastic modulus of the specimen (MPa), l_1 is the distance between the two supports (mm), b is width of the specimen (mm), t is the thickness of specimen (mm), $F_2 - F_1$ is the increase in load within the linear segment of the load-deflection curve, measured in Newtons (N), and $a_2 - a_1$ is the increase in deformation at the midpoint of the specimen, specifically the deformation within the force range of F2 to F1, measured in millimeters (mm).

For flexural strength testing, twelve specimens (labeled W-1 to W-12) were numbered and their width and thickness measured. Each specimen was then securely fixed on the testing machine with a 400 mm support span. Loading proceeded at 4 mm/min with a maximum displacement of 50 mm to ensure failure occurred within 30 to 60 s. After loading until failure, maximum tensile load (P_{max}) and flexural strength were calculated.

For elastic modulus testing, each specimen was placed flat on support rollers with its long axis perpendicular to the rollers and its center point under the loading roller. Throughout the test, the loading speed was adjusted to reach maximum load within 60 ± 30 s. Deformation at the midpoint of each specimen was measured to determine load-deflection curves and elastic modulus. The specimens and tests are shown in Fig. 2.

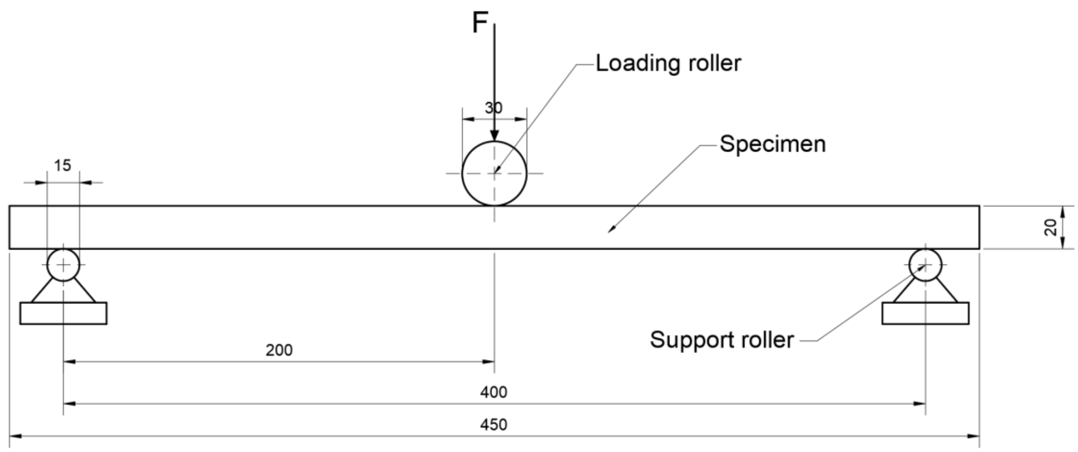


Fig. 2. Flexural test diagram

Mechanical Properties Testing of Tensile Strength and Tensile Elastic Modulus

Ginkgo scrimber, measuring 408 mm × 25 mm × 20 mm with 6 pieces, had a moisture content of 9 to 12% and an air-dried density of 0.94g/cm³. The testing method followed GB/T 40247 (2021) for determining tensile strength and tensile elastic modulus. The tensile strength was calculated following Eq. 6,

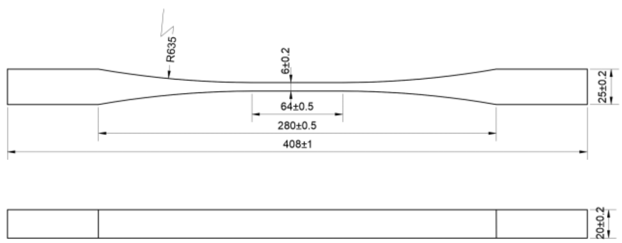
$$\sigma_t = \frac{P_{max}}{bt} \tag{6}$$

where σ_t is the tensile strength of the specimen (MPa), $P_{\max}$ is maximum load at the time of destruction of the specimen (N), b is width of the specimen (mm), and t is the thickness of specimen (mm). The tensile elastic modulus was calculated following Eq. 7,

$$E_t = \frac{L_0 \times \Delta P}{b \times \mathrm{t} \times \Delta L} \tag{7}$$

where E_t is the tensile elastic modulus of the specimen (MPa), l_0 is the measurement distance (mm), b is width of the specimen (mm), t is the thickness of specimen (mm), ΔP is the increase in load within the linear segment of the load-deflection curve, and ΔL is increment within the gauge length l_0 corresponding to the load increment ΔP (mm).

Six specimens, labeled L-2-1 to L-2-6, were measured for thickness and width. They were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity until stable. Positioned vertically with a 408 mm spacing between grips on a tensile testing machine, each had a deformation measurement device. Tension was applied at 5 mm/min to ensure complete failure within 60 ± 30 s, yielding ΔP for elastic deformation, ΔL for deformation, and $P_{\max}$ at failure. Finally, σ_t and $P_{\max}$ were determined for tensile strength and elastic modulus, respectively. The specimens and tests are shown in Fig. 3.



a. Tensile specimens

b. Specimen L-2-3 is used for tensile test

Fig. 3. Tensile test diagram

Mechanical Properties Testing of Compressive Strength and Compressive Elastic Modulus

Ginkgo scrimber, measuring 140 mm × 25 mm × 20 mm with 6 pieces, has a moisture content of 9 to 12% and an air-dried density of 0.94 g/cm³. This testing method followed GB/T 40247 (2021) for determining compression strength and compression elastic modulus, as shown in Eq. 8,

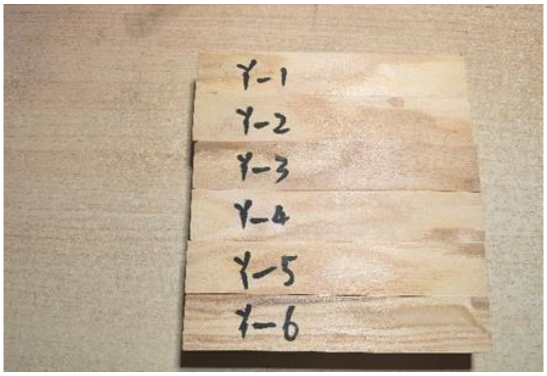
$$\sigma_c = \frac{P_{max}}{bt} \tag{8}$$

where σ_c is the compression strength of the specimen (MPa), $P_{\max}$ is maximum load at the time of destruction of the specimen (N), b is width of the specimen (mm), and t is the thickness of specimen (mm). The compression elastic modulus was calculated as follows,

$$E_c = \frac{L_0 \times}{b \times t \times \Delta L} \tag{9}$$

where E_c is the compression elastic modulus of the specimen (MPa), l_0 is the measurement distance (mm), b is width of the specimen (mm), t is the thickness of specimen (mm), ΔP is the increase in load within the linear segment of the load-deflection curve, and ΔL is increment within the gauge length l_0 corresponding to the load increment ΔP (mm).

Initially, six specimens were labeled Y-1 to Y-6, and their width and thickness were measured. Subsequently, the specimens were positioned between the two compression heads of the testing machine, spaced approximately 140 mm apart. They were then subjected to pressure at a rate of 5 mm/min until complete failure occurred within (60 ± 30) s. Finally, the experiment yielded values for the loading loads at different stages, corresponding deformation values, the ΔP increment within elastic deformation, ΔL deformation increment, and the maximum load P_{max} at specimen failure. The compressive strength σ_c and compressive elastic modulus E_c were subsequently calculated. The specimens and tests are shown in Fig. 4.



a. Compression of specimen

b. Y-6 specimen compression

Fig. 4. Compression test diagram

Mechanical Properties Testing for Horizontal Shear Strength

Specimens and Equipment

Ginkgo scrimber specimens were used for surface pressure testing. The surface pressure specimens measured 120 mm × 40 mm × 20 mm (6 pieces), and the side pressure specimens measured 120 mm × 20 mm × 20 mm (6 pieces).

This testing method follows GB/T40247 (2021) for determining horizontal shear strength,

$$\tau = \frac{3F}{4bt} \tag{10}$$

where τ is the horizontal shear strength of the specimen (MPa), F is maximum load at the time of destruction of the specimen (N), b is width of the specimen (mm), and t is the thickness of specimen (mm).

Twelve specimens were numbered: six for vertical loading (labeled ⊥1 to ⊥6) and six for horizontal loading (labeled ∥7 to ∥12). The width and thickness of each specimen were measured. The span between the supports was adjusted to 80 mm to match the specimen thickness. The specimens were placed on the supports with the loading roller axis perpendicular to their centerlines, ensuring uniform load distribution. Loading proceeded at 2 mm/min. Each specimen was tested until failure within (60 ± 30) s of loading initiation to determine its maximum load capacity (F) and horizontal shear strength (τ). Examples of the tests are shown in Fig. 5.

a. The specimen(⊥5) is tested for horizontal shear strength

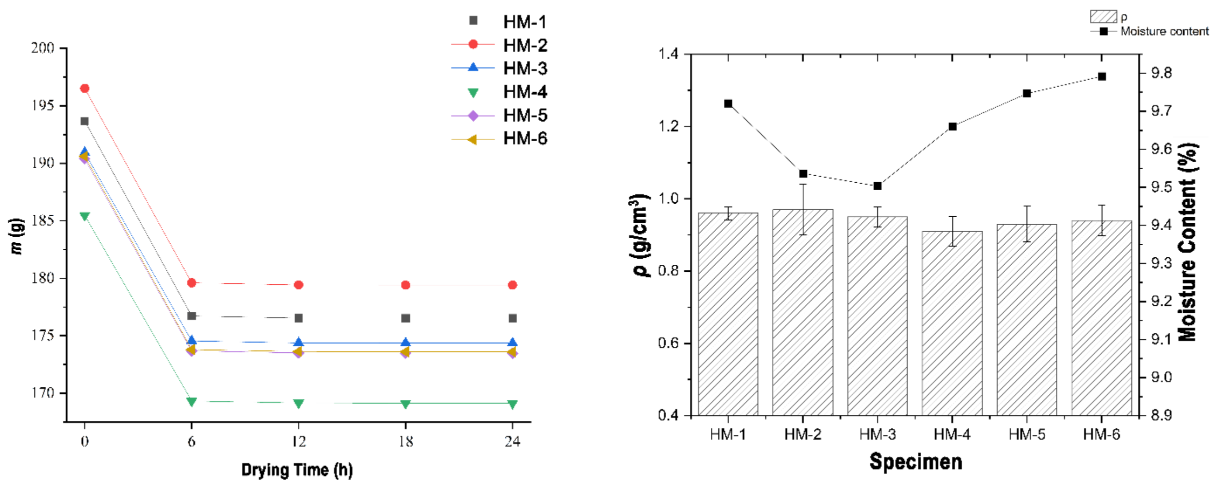
b. Specimen(∥8) is tested for horizontal shear strength

Fig. 5. Horizontal shear strength test diagram

RESULTS AND DISCUSSION

Density and Moisture Content Test Results and Analysis

The experimental results are shown in Fig. 5. The average density of Ginkgo scrimber is 0.94 g/cm^3, and the average moisture content is 9.7%.



a. Determination of moisture content of ginkgo scrimber

b. Density and moisture content of ginkgo scrimber

Fig. 6. Average density and moisture content of ginkgo scrimber

Figure 6 shows that the coefficient of variation for density and moisture content measurements of six specimens is 2.3% and 1.2%, respectively. These values meet the standards outlined in GB/T 40247 (2021).

Absorption Thickness Expansion Rate Test Results and Analysis

The experimental results are shown in Fig. 6. The average absorption thickness expansion rate of Ginkgo scrimber is 1.6%.

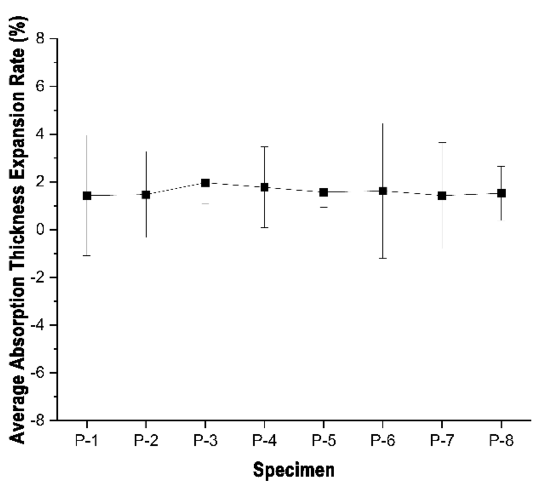


Fig. 7. Average absorption thickness expansion rate of ginkgo scrimber

Figure 7 shows that the coefficient of variation for absorbent thickness expansion value of 8 specimens was 11.8%. The values met the standards outlined of W2.0 level regulations in GB/T 40247 (2021).

Static Flexural Strength and Flexural Elastic Modulus Results and Analysis

Table 1 indicates that the recombinant wood used in this experiment met the superior grade requirements of the GB/T 40247(2021) standard for bending elastic modulus and flexural strength. The COV is coefficient of variation.

Table 1. Determination Results of Static Flexural Strength and Flexural Elastic Modulus (Parallel Loading) of Recombinant Ginkgo Scrimber

Number	Direction of Pressure	*b* (mm)	*t* (mm)	*l* (mm)	F_{max} (N)	σ_b (MPa)	E_b (MPa)
W-1	Parallel to the direction of the wood grain	50.5	20.36	400	3681	105.5	11220
W-2		50.6	20.43	400	3576	101.6	12160
W-3		50.6	20.47	400	4184	118.4	11020
W-4		50.7	20.36	400	3660	104.5	10980
W-5		50.5	20.34	400	4102	117.8	11540
W-6		50.8	20.32	400	3319	94.9	10000
Average						107.1	11150
COV (%)						8.7	6.4
W-7	Perpendicular to the Direction of the Wood Grain	50.6	20.52	400	3325	93.6	11220
W-8		50.9	20.38	400	3796	107.7	12160
W-9		50.6	20.38	400	4012	114.5	11020
W-10		50.4	20.50	400	3965	112.3	10980
W-11		50.4	20.44	400	3666	104.5	11540
W-12		50.9	20.48	400	4460	125.3	10000
Average						109.7	11260
COV (%)						9.7	6.2

Specimen W-5 fractured perpendicularly to the adhesive layer on its tensile surface, causing an overestimation of its breaking load and experimental errors. This led to inflated values for the specimen's flexural strength and elastic modulus. Figure 8 shows that part of specimen W-3 appeared darker due to uneven glue immersion and excessive adhesive application during the glue immersion and hot pressing process.

Fig. 8. Damage pattern of some specimens

This resulted in increased strength, maximum destructive load, static bending strength, and elastic modulus of the specimen. Consequently, the coefficients of variation for the specimen's bending strength and elasticity modulus were higher in the parallel three-point bending test, but they remained within the acceptable 0% to 10% range for reliable experimental results.

Figure 9 illustrates specimen W-12 with extensive adhesive layer cracking, resulting in the specimen fracturing into three sections during testing. This led to an overestimated maximum load, causing experimental errors and inflating both the specimen's flexural strength and elastic modulus. Consequently, the coefficients of variation for these properties were higher in the vertically loaded three-point flexural test but remained within the acceptable 0% to 10% range for reliable results.

Fig. 9. Damage morphology of specimen 12

The flexural strength and elastic modulus values for Ginkgo scrimber were comparable under both parallel and perpendicular loading conditions in the three-point bending test, averaging 108.4 MPa and 11210 MPa, respectively.

Tensile Property Test Results and Analysis

Figure 10 displays the fracture surfaces of specimens L-2-2, L-2-4, L-2-5, and L-2-6, situated centrally with appropriate widths and relatively smooth fractures, ensuring reliable tensile strength and elastic modulus values. These specimens exhibited average tensile strength and elastic modulus values of 89.3 MPa and 9290 MPa, respectively.

Fig. 10. Failure morphology of tensile specimens

Table 2. The Results for Tensile Strength and Elastic Modulus of Ginkgo Scrimber

Number	b (mm)	t (mm)	l (mm)	P_{max} (N)	σ_t (MPa)	E_t (MPa)
L-2-2	6.34	8.21	408	4541.26	87.3	9617
L-2-4	5.38	6.23	408	2811.04	83.9	8598
L-2-5	5.23	6.00	408	2985.85	95.2	9754
L-2-6	7.45	8.32	408	5632.76	90.9	9373
Average					89.3	9285
COV (%)					5.40	5.27

Compression Performance Test Results and Analysis

Figure 11 indicates an average compressive strength of 79.61 MPa (COV: 4.%) and an average compressive elastic modulus of 8910 MPa (COV: 5.1%) for the specimens. These values for compressive strength and elastic modulus of the wood scrimber used in this study met the requirements of GB/T 40247 (2021) for superior quality.

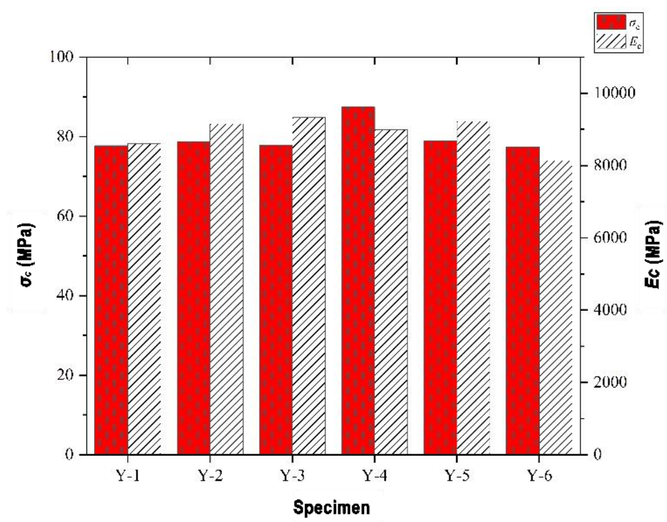


Fig. 11. The results for compressive strength and elastic modulus of ginkgo scrimber

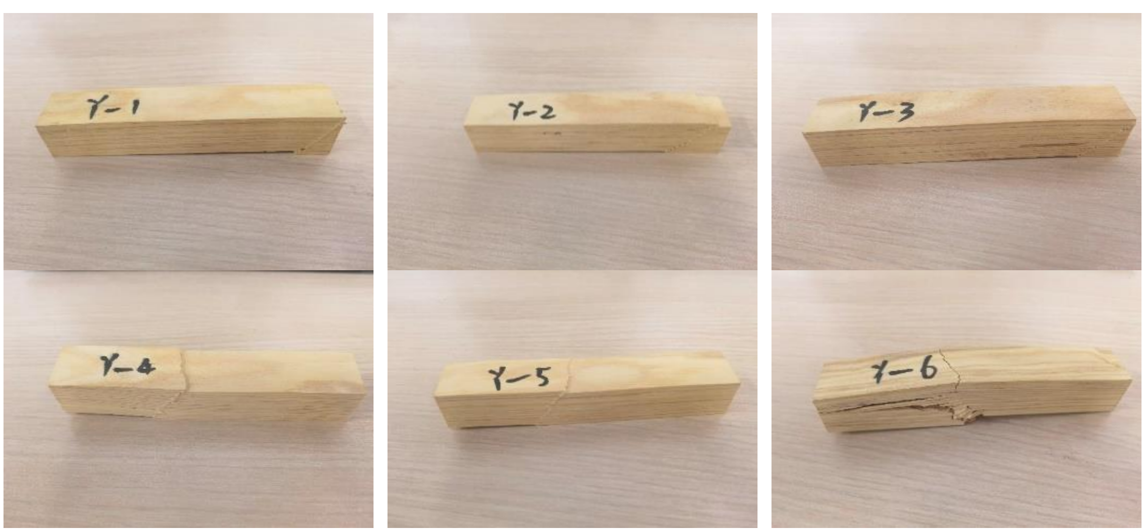
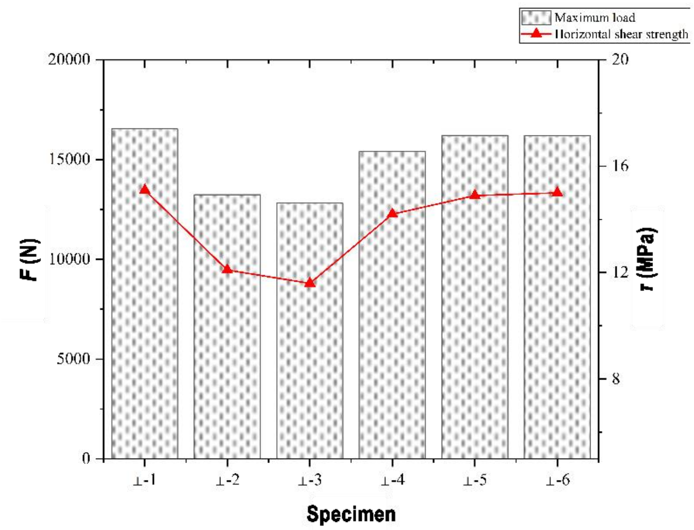


Fig. 12. Compression failure morphology of the specimen

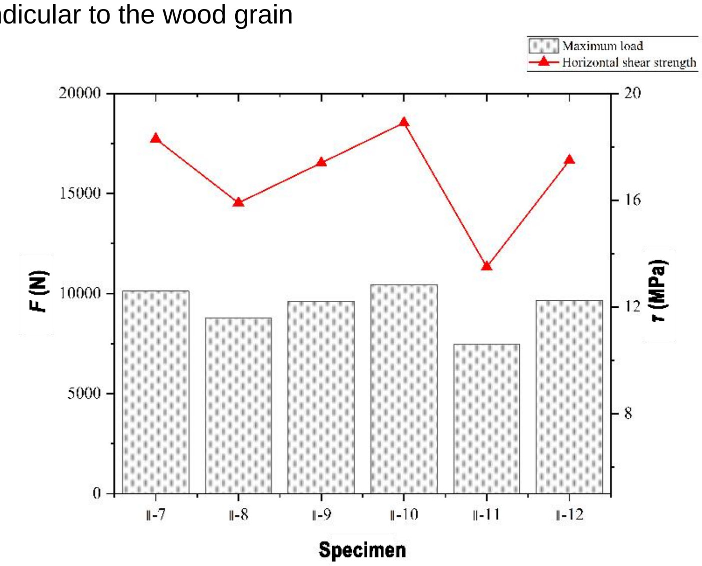
In Fig. 12, specimens Y-1, Y-2, and Y-3 are shown in the region of the specimen damage site near their ends in this test.

Horizontal Shear Strength Performance Test Results and Analysis

According to GB/T 40247(2021), the interlayer gluing strength of ginkgo wood scrimber is judged.



a. Loading perpendicular to the wood grain



b. Loading parallel to the wood grain

Fig. 13. The results for horizontal shear strength of ginkgo scrimber

Figure 13 shows that the maximum destructive force under vertical loading exceeded that under parallel loading, reaching up to 16,500 N. In contrast, the horizontal shear strength under parallel loading was higher, with a maximum of 18.9 MPa. This horizontal shear strength value met the requirement specified in GB/T 40247 (2021)'s 12V-15P level.

Comprehensive Analysis and Evaluation of Ginkgo Scrimber Test Results

The outstanding mechanical properties of Ginkgo scrimber allow direct comparison with bamboo scrimber, structural laminated veneer lumber (LVL), and structural plywood, which share similar manufacturing processes, as detailed in Tables 3 and 4. Ginkgo scrimber clearly surpassed these materials in flexural strength, elastic modulus, and horizontal shear strength values.

Table 3. Comparison of Static Flexural Strength and Elastic Modulus Indicators

Materials	σ_b (MPa)	E_b (MPa)
Structural LVL (ISO 18776 2008)	45 (SLVL Type-I)	10.5×10^3 ~12×10^3 (120E)
Structural plywood (GB/T 35216 2017)	20	4×10^3
Bamboo scrimber (GB/T 40247 2021)	90 (pass)-120 (excellent)	9×10^3
Ginkgo scrimber	108.4 (COV: 8.9%)	11.2×10^3 (COV: 6.1%)

Table 4. Comparison of Horizontal Shear Strength Indicators

Materials	τ (MPa)	
	Loading parallel to the wood grain n	Loading perpendicular to the wood grain
Structural LVL (ISO 18776 2008)	6.5 (65V-55H)	5.5 (65V-55H)
Structural plywood (GB/T 35216 2017)	3.2	
Bamboo scrimber (GB/T 40247 2021)	15	12
Ginkgo scrimber	16.9 (COV:11.5%)	13.8 (COV:11.3%)

CONCLUSIONS

1. The bending elastic modulus, flexural strength, compression strength, and compression elastic modulus of ginkgo scrimber met GB/T 40247 (2021) ‘Bamboo scrimber’ superior grade requirements. The water absorption thickness expansion rate and horizontal shear strength values aligned with GB/T 40247 (2021) W2.0 and 12V-15P levels.
2. Ginkgo scrimber achieved a horizontal shear strength level of 65V-55H according to ISO 18776 (2008) with static bending strength and elastic modulus reaching 120E level.
3. Ginkgo scrimber exhibited superior flexural strength, elastic modulus, and horizontal shear strength compared to bamboo scrimber, structural veneer laminates, and structural plywood.
4. The amount of applied glue significantly affects mechanical properties, necessitating further study of its influence.

5. Comparative analysis of mechanical properties showed that ginkgo scrimber outperformed structural LVL, structural plywood, and recombinant bamboo, which can be attributed to ginkgo wood's fine texture, abundance of conduits in broadleaf wood, and effective glue penetration.

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