

ORIGINAL ARTICLE

Comparative analysis of the material properties of four commonly used timber species in the restoration of historical buildings in Shanxi, China

Panpan Liu¹ , Sok Yee Yeo^{2*} , and Hiroatsu Fukuda¹ 

¹Department of Architecture, Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyushu, Fukuoka, Japan

²Department of Architecture, School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, China

Abstract

Historical timber buildings in Shanxi province, China, face significant restoration challenges due to natural degradation, extreme weather events, and restrictions on native timber harvesting, necessitating the use of alternative timber species for structural repairs. This study examines the material properties of four timber species – Chinese pine (*Pinus tabulaeformis* Carrière), larch (*Larix gmelinii* var. *principis-rupprechtii* [Mayr] Pilger), Douglas fir (*Pseudotsuga menziesii* [Mirbel] Franco), and Mongolian Scots pine (*Pinus sylvestris* var. *mongolica* Litv.) – commonly used in the restoration of historical timber buildings in Shanxi. Given the structural diversity of these buildings, six loading modes were applied to assess the suitability of each species for different structural components: compression parallel to the grain, compression perpendicular to the grain in the radial direction, shear parallel to grain along the longitudinal-radial plane, shear parallel to grain along the longitudinal-tangential plane, four-point static bending, and tension. Douglas fir exhibited the highest compressive strength parallel to the grain, making it well-suited for load-bearing components, while Chinese pine demonstrated strong compressive strength perpendicular to the grain in the radial direction. Larch and Douglas fir excelled in shear resistance, and all four species exhibited high bending strengths, supporting their use in primary structural components. In contrast, Mongolian Scots pine exhibiting lower shear and bending strengths is more appropriate for non-load-bearing applications where structural demands are minimal. Positive correlations between strength, density, and dynamic modulus of elasticity suggest that density and ultrasonic testing can serve as effective non-destructive evaluation methods. These findings provide valuable insights into material selection for heritage timber restoration, promoting species-specific applications that enhance structural resilience while preserving traditional carpentry techniques.

*Corresponding author:

Sok Yee Yeo
(yeosokyee@xjtu.edu.cn)

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1. Introduction

Traditional timber buildings represent a crucial aspect of East Asia's architectural heritage, with Chinese timber structures serving as one of the representative examples

of this traditional style. In China, 628 historical timber buildings, constructed between 750 and 1350 CE, have been documented, with 518 located in Shanxi province, China. Despite Shanxi's rich architectural history, many of these structures face significant restoration challenges due to inadequate funding. In addition, recent extreme weather events in Shanxi province, such as heavy and continuous rainfall and extended periods of high temperatures (Wang *et al.*, 2022), have exacerbated the deterioration of these timber structures. As a result, the urgent need to preserve the remaining historical timber structures has become increasingly apparent.

Larch (*Larix gmelinii* var. *principis-rupprechtii* [Mayr] Pilger) and Chinese pine (*Pinus tabulaeformis* Carrière) have historically been the most commonly used materials in historical timber construction. Both species are native to Shanxi province and belong to the Pinaceae family (Dong *et al.*, 2017). Ideally, repaired or restored components should be made from the same or compatible timber species as the original. However, due to limited forest resources, China has implemented a comprehensive logging protection system. According to the Ministry of Ecology and Environment of China, under Article 32 of the Forest Law of the People's Republic of China (2019), the felling of natural forests is subject to strict restrictions. Consequently, more readily available non-native timber species have become an option in restoration projects. Interviews with local restoration experts and traditional carpenters indicate that a significant portion of the wood used in Shanxi province's restoration projects is imported. Among the commonly used imported species include Douglas fir (*Pseudotsuga menziesii* [Mirbel] Franco) and Mongolian Scots pine (*Pinus sylvestris* var. *mongolica* Litv.), both from the Pinaceae family. These species are preferred due to their availability in larger lumber sizes, making them suitable replacements for structural timber components.

Wood is a naturally anisotropic composite material with three orthogonal directions: Longitudinal (L), radial (R), and tangential (T) (Barber & Meylan, 1964; Farhan *et al.*, 2020; Ramage *et al.*, 2017; Xie *et al.*, 2013; Zhang *et al.*, 2014) (Figure 1). The longitudinal direction is parallel to the grain, the radial direction is perpendicular to both the grain and the growth rings, and the tangential direction is perpendicular to the grain but parallel to the growth rings. Timber components in historical buildings are generally subjected to six mechanical loading types under vertical and horizontal loads: Compression parallel to grain (compression-L), compression perpendicular to grain in the radial direction (compression-R), shear parallel to grain along the longitudinal-radial (LR) plane

(shear-LR), shear parallel to grain along the longitudinal-tangential (LT) plane (shear-LT), bending perpendicular to grain and parallel to the growth rings (bend-L), and tension parallel to grain (tension-L). Different components experience different mechanical loading modes depending on their structural roles (Figure 2 and Table 1).

Due to the high variability of timber species and material properties, as well as the complex factors influencing test results, the standardization of testing methods for timber properties is essential (Arriaga *et al.*, 2023). At present, comparative testing of basic material properties primarily relies on tests conducted on small, clear wood specimens. Various organizations, such as the British Standards Institution, the American Society for Testing and Materials, the Chinese National Standardization Administration, and the International Organization for Standardization,

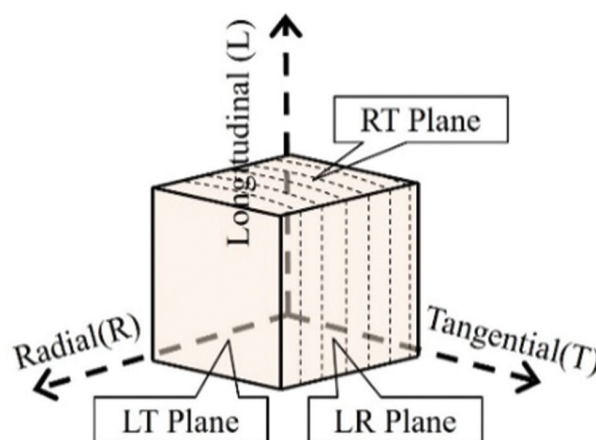


Figure 1. Three orthogonal directions of timber
Source: Drawing by the authors.

Table 1. Mechanical loading modes of main ancient building components

Mechanical loading modes	Name of components
Compression-L	Column (柱), Chashou (叉手), Tuoqiao (托脚)
Compression-R	Ludou (栌斗), Dadou (大斗), Tuofeng (驼峰), Hua Gong (华拱), Sandou (散斗), Qixindou (齐心斗), Jiaohudou (交互斗)
Shear-LR	Ludou (栌斗), Dadou (大斗), Jiaohudou (交互斗), Column (柱)
Shear-LT	Ludou (栌斗), Dadou (大斗), Sandou (散斗), Qixindou (齐心斗), Jiaohudou (交互斗)
Bend-L	Beam (梁), Column (柱), Ang (昂), Fang (枋), Nidao Gong (泥道拱), Ling Gong (令拱), Man Gong (慢拱), Guazi Gong (瓜子拱)
Tension-L	Beam (梁), Fang (枋)

Abbreviations: LR: Longitudinal–radial; LT: Longitudinal–tangential.

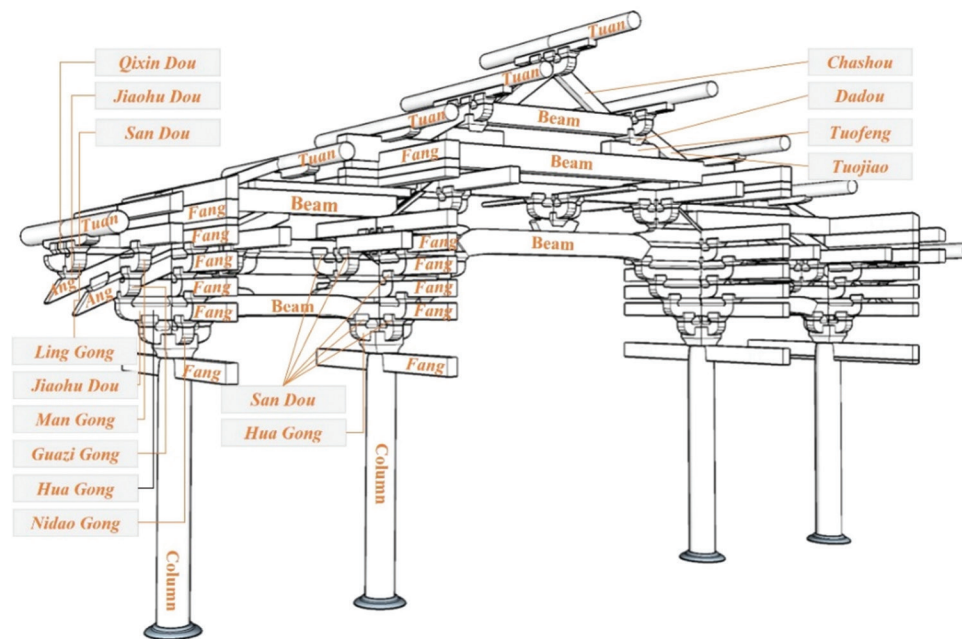


Figure 2. Timber component names in a typical ancient Chinese timber building
Source: Drawing by the authors.

have developed different testing standards. Based on these standards, extensive research has been conducted to assess timber properties.

For example, Senalik & Farber (2021) provided detailed data on the material properties of over 30 softwood and hardwood species. In China's timber design standards, different strength indicators are specified for various wood species based on their origin, species, and specifications. The Standard for Design of Timber Structures, published by the Ministry of Housing and Urban-Rural Development of the People's Republic of China (2017), provides detailed guidelines on these classifications. Data from these standards highlight significant variations in timber properties not only between softwood and hardwood but also within the same species from different regions.

Further studies reinforce this variability. Hrebenarova & Wald (2022) compared the radial compression and bending strengths of aged larch from historical buildings with those of new oak and spruce. Missanjo & Matsumura (2016) investigated the wood density and material properties of pine in Malawi. Lin *et al.* (2007) studied the effects of ring characteristics on the compressive strengths and dynamic modulus of elasticity of seven softwood species. Aydin *et al.* (2007) conducted research on the material properties of four timber species commonly used in Turkey, while Sun *et al.* (2022) examined the compressive material properties of larch wood across different grain orientations. In addition, Zhang (2024) compared the

material properties of aged and new larch, focusing on material aging and mechanical changes in larch timber components in historical buildings. These studies illustrate that timber material properties are influenced by multiple factors, such as origin, species, density, moisture content (MC), and growth ring characteristics, with species playing a major role. Different species exhibit varying performances, even within the same application context. Despite extensive research on timber material properties, there remains a gap in focused studies on the material properties of timbers commonly used in the restoration of historical buildings in Shanxi province. To address this gap, a comparative study on the material properties of Chinese pine, larch, Douglas fir, and Mongolian Scots pine – the four timber species most commonly used in Shanxi province's restoration projects – is essential.

This study aims to address this research gap by systematically comparing the material properties of Chinese pine, larch, Douglas fir, and Mongolian Scots pine, which are widely used in Shanxi's heritage restoration projects. Through standardized mechanical testing across six loading modes, we analyzed each species' strength characteristics and evaluated correlations with density and dynamic modulus of elasticity. The findings will contribute to more informed timber selection for restoration, balancing structural strength, historical authenticity, and practical availability, especially in the context of extreme weather resilience.

2. Materials and methods

2.1. Materials and specimen preparation

In this study, we selected Chinese pine and larch, commonly used in historical timber buildings in Shanxi province, China, along with Douglas fir and Mongolian Scots pine, which are more readily available for restoration projects. Given the frequent need for timber with large cross-sections in heritage restoration, we aimed to procure samples with greater diameter. One round wood sample was prepared for each of the four species. The final specimens included Chinese pine from Northeast China (aged 50 years), larch from North China (aged 55 years), Douglas fir from North America (aged 80 years), and Mongolian Scots pine from Russia (aged 70 years).

The specimens were divided into six groups, totaling 120 specimens, with each group containing four timber species and five specimens per species (Table 2). Sample tree collection, sampling methods, cutting scheme, general requirements, and growth ring width determination followed GB/T 1927.2 – 2021 and GB/T 1927.3 – 2021 standards. Dimensions and preparation standards of clear wood specimens adhered to GB/T 1927.9 – 2021, GB/T 1927.11 – 2022, GB/T 1927.12 – 2021, GB/T 1927.14 – 2022, and GB/T 1927.16 – 2022 standards (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, & Standardization Administration of China, 2021a; 2021b; 2021c; 2022a; 2022b; 2022c; 2022d) (Figure 3).

2.2. Loading scheme and strength formulas

According to GB/T 1927.2 – 2021, the test specimens were placed in a controlled environment using a constant temperature and humidity chamber (Model: Kingjo CK-80GN, Dongguan Qinzhuo Environmental Testing Equipment Co., Ltd., China) to adjust the MC until equilibrium was achieved. All specimens were conditioned at $20 \pm 2^\circ\text{C}$ and $65 \pm 2\%$ humidity for 7 days till the MC stabilized at $12 \pm 1\%$. Thereafter, each specimen's volume (V) and mass (m) were measured, and density (ρ) was calculated by dividing the mass by its volume. The ultrasonic wave velocity (v) in the direction parallel to the grain of each specimen was measured using an ultrasonic testing device (Model: Sylvatest Trio, Concept Bois Technologie-Concepts Bois Structure, Switzerland). The ultrasonic wave velocity test is a quick and non-destructive evaluation method commonly used to detect internal integrity, cracks, and defects in timber. A transmitting transducer and a receiving transducer were placed at opposite ends of each specimen, and a pulse was transmitted across the specimen parallel to the grain direction. The transmission time from one end to the other was recorded in microseconds. v of the

Table 2. Specimen numbers of six test types

Test types	La specimen no.	Ch specimen no.	Do specimen no.	Mo specimen no.
Compression-L	5	5	5	5
Compression-R	5	5	5	5
Shear-LR	5	5	5	5
Shear-LT	5	5	5	5
Bend-L	5	5	5	5
Tension-L	5	5	5	5

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.

Abbreviations: LR: Longitudinal-radial; LT: Longitudinal-tangential.

test specimen was then calculated by dividing the measured distance between the transducers by the transmission time. The dynamic modulus of elasticity (E_d) for each specimen was determined using Equation I:

$$E_d = v^2 \cdot \rho \quad (\text{I})$$

where ρ represents the density and v represents the ultrasonic wave velocity.

In recent years, non-destructive testing techniques have been increasingly utilized for field evaluations to determine the E_d value of wood as a physical property, aiding in the exploration of its relationship with other material properties (Arriaga *et al.*, 2022).

Subsequent mechanical tests were conducted using an electro-hydraulic servo testing machine (Model: MTS – 880/25T, MTS Systems Corporation, United States of America) at the State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University. The loading protocols were established following GB/T 1927.9 – 2021, GB/T 1927.11 – 2022, GB/T 1927.12 – 2021, GB/T 1927.14 – 2022, and GB/T 1927.16 – 2022 standards of China. After obtaining the force-displacement curves, strength values were calculated using the corresponding strength equations (Table 3).

3. Results and Discussion

3.1. Compression-L tests

3.1.1. Failure modes

In the compression-L tests, specimens subjected to compression parallel to the grain generally exhibited two primary stages: The linear elastic stage and the plastic stage (Figure 4A). During the linear elastic stage, all timber species demonstrated minimal deformation while effectively retaining their load-bearing capacity. As the load increased, the specimens entered the plastic stage, where fibers at the top or bottom were crushed, leading

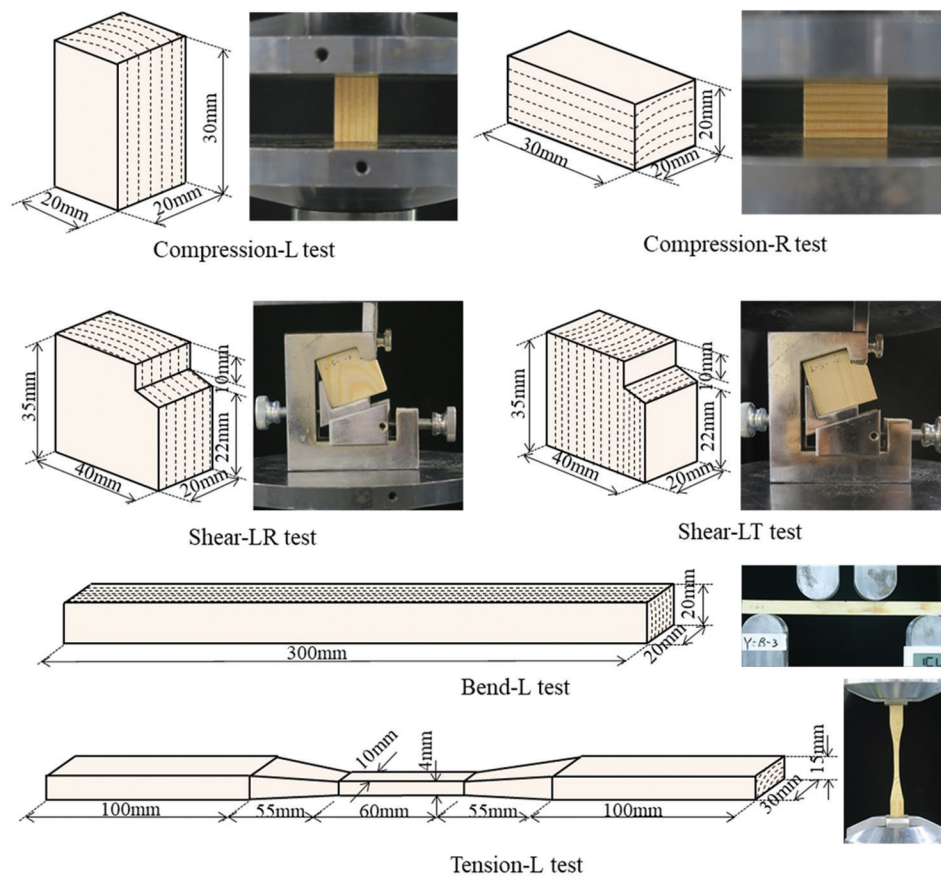


Figure 3. Specimen sizes and overview of the six test types
Source: Drawing by the authors.

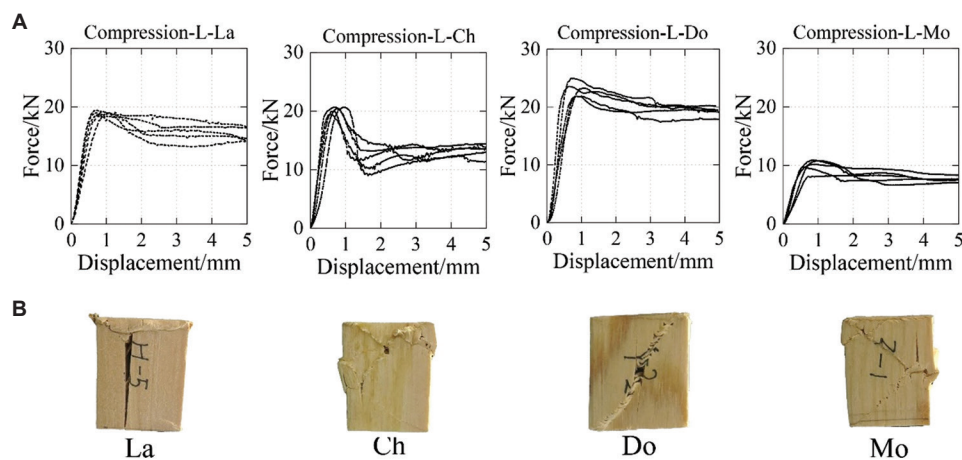


Figure 4. Monotonic test results and failure modes of compression-L tests. (A) Force-displacement curves of the four wood species. (B) Typical failure modes of specimens. Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.
Source: (A) Graphs by the authors. (B) Photos by the authors (2024).

to the formation of a wrinkle band. This band, located at the Center of the specimen, could be vertical, horizontal, or inclined (Figure 4B). Further deformation resulted in

vertical splitting and shear slippage between fibers near the wrinkle band, leading to separation and crack formation. These cracks propagated along the grain, progressively

Table 3. Loading protocols and strength formulas for the six material tests

Type of test	Loading protocol	Strength equation (s)
Compression-L test	The specimen was placed between two horizontal planes and subjected to a vertical monotonic load at a constant speed of 0.5 mm/min for 10 min or until failure. The machine's sampling frequency was set to 100 Hz.	$\sigma_L = \frac{P_{max}}{bt} \quad (II)$ σ_L: Compressive strength parallel to grain at MC 12%; SI unit: MPa. P_{max}: Failure load, SI unit: Newtons (N). b: Specimen width, $b=20$ mm. t: Specimen height, $t=20$ mm.
Compression-R test	The specimen was placed between two horizontal planes and subjected to vertical monotonic load at a constant speed of 0.5 mm/min for 20 min or until failure mode was reached. The machine's sampling frequency was set to 100 Hz.	$\sigma_R = \frac{F_p}{A} \quad (III)$ σ_R: Compressive proportional limit strength perpendicular to the grain in a radial direction at MC 12%, measured in MPa. F_p: Proportional limit load, SI unit: Newtons (N). A: Bearing area, $A=b \times l=600$ mm², where b and l are the specimen's width and length, respectively, SI unit: Millimeters (mm).
Shear-LR test	The specimen was placed onto a shear test device and subjected to vertical monotonic load at a constant speed of 1 mm/min until failure mode was reached. The machine's sampling frequency was set to 100 Hz.	$\tau_{LR} = \frac{0.96P_{max}}{bl} \quad (IV)$ τ_{LR}: Shear strength parallel to grain along the LR plane at MC 12%, SI unit: MPa. P_{max}: Failure load, SI unit: Newtons (N). b: Shear plane width, $b=20$ mm. l: Shear plane length, $l=25$ mm.
Shear-LT test	The specimen was placed onto a shear test device and subjected to vertical monotonic load at a constant speed of 1 mm/min until failure mode was reached. The machine's sampling frequency was set to 100 Hz.	$\tau_{LT} = \frac{0.96P_{max}}{bl} \quad (V)$ τ_{LT}: Shear strength parallel to grain along the LT plane at MC 12%, SI unit: MPa. P_{max}: Failure load, SI unit: Newtons (N). b: Shear plane width, $b=20$ mm. l: Shear plane length, $l=25$ mm.
Bend-L test	The specimen was placed on a four-point bending test device and subjected to vertical monotonic load at a constant speed of 5 mm/min until failure mode was reached. The machine's sampling frequency was set to 100 Hz.	$\sigma_B = \frac{P_{max}l}{2bh^2} \quad (VI)$ σ_B: Bending strength at MC 12%, SI unit: MPa. P_{max}: Failure load, SI unit: Newtons (N). l: Span between the two supports, $l=240$ mm. b: Specimen width, $b=20$ mm. h: Specimen height, $h=20$ mm.
Tension-L test	The specimen was clamped at both ends in the grips of the testing machine and subjected to vertical monotonic load at a constant speed of 0.5 mm/min until failure mode was reached. The machine's sampling frequency was set to 100 Hz.	$\sigma_T = \frac{P_{max}}{bh} \quad (VII)$ σ_T: Tensile strength parallel to grain at MC 12%, SI unit: MPa. P_{max}: Failure load, SI unit: Newtons (N). b: Specimen width, $b=10$ mm. h: Specimen height, $h=4$ mm.

Abbreviations: MC: Moisture content; SI: International System of Units; LR: Longitudinal-radial; LT: Longitudinal-tangential; MPa: Megapascals.

reducing the specimen's load-bearing capacity. The average failure loads (P_{max}) for larch, Chinese pine, Douglas fir, and Mongolian Scots pine were recorded as 19.3 kN, 20.5 kN, 24.0 kN, and 9.9 kN, respectively. Among these, Douglas fir exhibited the highest bearing strength, while Mongolian Scots pine showed the lowest.

3.1.2. Data and analysis

Table 4 presents the mean compressive strength ($\overline{\sigma_L}$), density ($\overline{\rho}$), and dynamic modulus of elasticity ($\overline{E_d}$) for the four timber species at 12% MC.

Table 4. Results of compression-L tests

Specimen no.	σ_L (MPa)	$\overline{\sigma_L}$ (MPa)	ρ (kg/m ³)	$\overline{\rho}$ (kg/m ³)	E_d (MPa)	$\overline{E_d}$ (MPa)
La-1	48.0	47.6 (SD=0.8)	562	545 (SD=31)	37,601	56,321 (SD=22,628)
La-2	47.7		571		94,360	
La-3	47.5		513		51,333	
La-4	46.4		570		57,000	
La-5	48.6		510		41,310	
Ch-1	51.7	51.2 (SD=2.1)	698	703 (SD=23)	69,750	65,920 (SD=36,143)
Ch-2	51.7		696		46,582	
Ch-3	50.1		718		118,742	
Ch-4	54.1		733		73,250	
Ch-5	48.5		673		21,278	
Do-1	63.8	59.9 (SD=3.5)	605	580 (SD=18)	37,601	55,701 (SD=3,932)
Do-2	62.9		591		94,360	
Do-3	59.5		579		51,333	
Do-4	55.1		564		57,000	
Do-5	58.4		561		41,310	
Mo-1	27.4	24.8 (SD=2.4)	449	399 (SD=44)	69,750	36,917 (SD=6,106)
Mo-2	20.9		429		46,582	
Mo-3	25.7		409		118,742	
Mo-4	24.5		360		73,250	
Mo-5	25.7		348		21,278	

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine; SD: Standard deviation.

The test results in Figure 4A indicate that Douglas fir exhibited the highest mean compressive strength at 59.9 MPa (standard deviation [SD] = 3.5 MPa). Chinese pine recorded an average compressive strength of 51.2 MPa, with slightly lower variability (SD = 2.1 MPa). Larch exhibited a moderate average strength of 47.6 MPa with low variability (SD = 0.8MPa), indicating stability across samples. Mongolian Scots pine showed the lowest mean compressive strength at 24.8 MPa, with relatively higher variability (SD = 2.4MPa).

Comparing these results with existing literature highlights differences potentially attributable to timber origin, age, and sample size. As noted in the *Wood Handbook* (Senalik & Farber, 2021), the compressive strengths of North American Douglas fir generally range from 43 to 51.2 MPa. Our higher test result of 59.9 MPa may be due to the age and origin of the test samples, which were 80 years old. Similarly, a study by Zeidler *et al.* (2022) on 70-year-old Douglas fir reported a compressive strength of 48.4 MPa, reinforcing the notion that age influences strength variability.

For Chinese pine, our test results (51.2 Mpa) closely align with those reported by Jin *et al.* (2024) (49.5 – 52.5 MPa) for 41 – 60-year-old samples.

Our larch results are consistent with findings from Sun *et al.* (2022) (44.9 Mpa) and Cheng *et al.* (2023) (45.8 MPa).

In the case of Mongolian Scots pine, density appears to have played a critical role in compressive strength. Zhang (2022) reported a strength of 32.8 Mpa for samples with a density of 480 kg/m³. Our lower test result of 24.8 MPa is likely due to the lower density of our specimens.

In addition to the compression-L tests, we observed that in the compression-R tests, shear-LR tests, and shear-LT tests, the measured ultrasonic wave propagation velocities predominantly fell within the range of 10,000 m/s – 11,000 m/s. These results differ significantly from those obtained in the bend-L tests and tension-L tests. Based on comparisons with previous studies (Arriaga *et al.*, 2022; Carrillo *et al.*, 2019; Cunha *et al.*, 2021; Ettelaei *et al.*, 2019; Krause *et al.*, 2015; El Najjar & Mustapha, 2021), we believe that the results from the bend-L tests and tension-L tests are more reliable. We attribute this discrepancy to the precision limitations of the measuring instruments. Specifically, when the timber specimen lengths fall below a certain threshold, the measurements exceed the instrument's effective range (Beall, 2002; Olisa *et al.*, 2021). To address this issue, future research should focus on specialized

experiment designs that explore the relationship between ultrasonic wave measurement instruments and specimen dimensions. Such research is crucial for improving the precision of non-destructive testing methodologies. Due to the unreliability of ultrasonic velocity measurements, we report only the dynamic modulus of elasticity results for the compression-L tests, compression-R tests, shear-LR tests, and shear-LT tests, without correlating them to the strength of the specimens.

Different wood species inherently exhibit distinct density ranges, which influence their mechanical properties. In this study, the measured densities of the four timber species show notable differences. The results from the compression-L tests suggest a positive correlation between compressive strength and material density (Figure 5). As a physical property, density is closely tied to the wood's microstructure, underscoring its significant influence on material behavior. Consequently, when selecting timber species, it is essential not only to choose the appropriate species but also to ensure that the material's density falls within the typical range for that species. If a wood sample exhibits abnormal density values, further testing is required to evaluate its material properties.

In summary, Douglas fir, with its high compressive strength, is ideal for historical building components that require compression parallel to the grain, such as columns and *Chashou* (叉手). Chinese pine, which has a similar load-bearing capacity, serves as an excellent alternative when cost or material availability is a concern. Larch is suitable for moderate load applications, while Mongolian Scots pine, with its lower compressive strength, is better suited for less load-bearing components, such as *Tuojiao* (托脚). Moreover, continued research on ultrasonic testing methods is needed to establish more reliable correlations

for non-destructive testing of timber, particularly for historical structure preservation.

3.2. Compression-R tests

3.2.1. Failure modes

In the compression-R tests, specimens were subjected to compression perpendicular to the grain, generally experiencing three stages: Linear elastic stage, plastic stage, and strengthening stage (Figure 6A). In the linear elastic stage, all four timber species exhibited minimal deformation. In the plastic stage, the early wood within each growth ring was compacted first due to the applied compression perpendicular to the growth ring orientation. In addition, localized areas of the specimens deformed significantly due to the non-uniformity of the wood. Resin extrusion and overflow were also observed in this stage, especially in Chinese pine. In the strengthening stage, the specimens exhibited increased rigidity or, in some cases, experienced shear failure under continued compression loading (Figure 6B). The average failure load (F_p) values measured for larch, Chinese pine, Douglas fir, and Mongolian Scots pine were 7.4 kN, 10.2 kN, 7.4 kN, and 5.4 kN, respectively.

3.2.2. Data and analysis

Table 5 presents the mean compressive strength perpendicular to the grain in the radial direction (σ_R), density (ρ), and dynamic modulus of elasticity (E_d) results for the four timber species at 12% MC. Chinese pine exhibited the highest mean radial compressive strength, measuring 17.1 MPa with a SD of 3.5, indicating noticeable variability among specimens. Douglas fir recorded an average strength of 12.4 MPa with a SD of 1.2 MPa, suggesting relatively consistent values across samples.

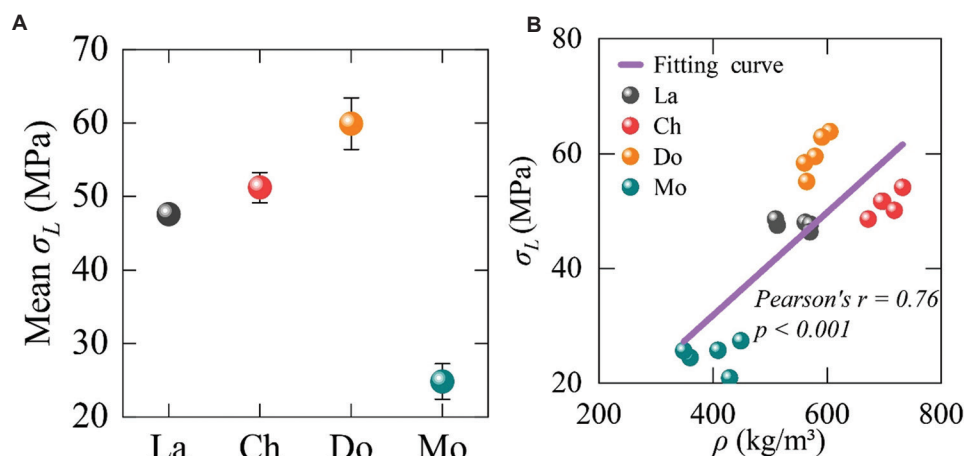


Figure 5. Comparison of σ_L and ρ values in compression-L tests. (A) σ_L of four species. (B) Relationship between σ_L and ρ . Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine. Source: Graphs by the authors.

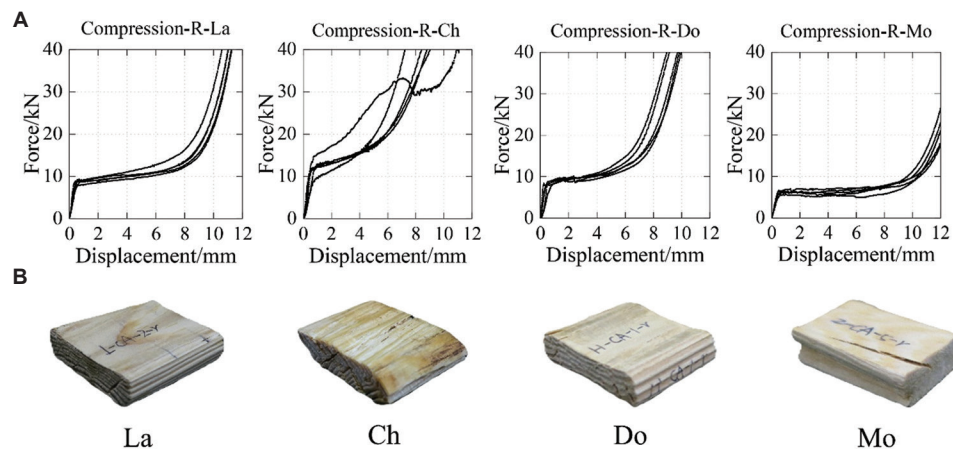


Figure 6. Monotonic test results and failure modes of compression-R tests. (A) Force-displacement curves of the four wood species. (B) Typical failure modes of specimens.

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.

Source: (A) Graphs by the authors. (B) Photos by the authors (2024).

Table 5. Results of compression-R tests

Specimen no.	σ_R (MPa)	$\bar{\sigma}_R$ (MPa)	ρ (kg/m ³)	$\bar{n}$ (kg/m ³)	E_d (MPa)	$\bar{E}_d$ (MPa)
La-1	12.7	12.3 (SD=0.8)	528	537 (SD=10)	52,833	69768 (SD=28,050)
La-2	12.7		553		55,333	
La-3	12.7		538		53,750	
La-4	12.6		539		68,237	
La-5	10.9		528		118,688	
Ch-1	20.3	17.1 (SD=3.5)	700	679 (SD=35)	70,000	68756 (SD=10,004)
Ch-2	20.9		656		53,122	
Ch-3	15.6		724		72,416	
Ch-4	12.3		637		80,577	
Ch-5	16.3		677		67,666	
Do-1	11.2	12.4 (SD=1.2)	573	558 (SD=26)	72,562	111094 (SD=47,178)
Do-2	12.8		548		54,750	
Do-3	14.0		594		133,686	
Do-4	12.7		549		123,561	
Do-5	11.0		528		170,910	
Mo-1	8.4	9.0 (SD=1.1)	395	395 (SD=21)	18,932	31182 (SD=12,476)
Mo-2	8.9		393		31,793	
Mo-3	10.1		394		49,887	
Mo-4	7.6		428		34,628	
Mo-5	10.1		368		20,672	

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine; SD: Standard deviation.

Larch exhibited a mean strength of 12.3 MPa with minimal variation (SD = 0.8 MPa), indicating stability across measurements. Mongolian Scots pine, with a mean radial compressive strength of 9.0 MPa and a SD of 1.1 MPa, had the lowest strength value among the tested species.

To analyze the experimental findings, the compressive strength results were compared with prior studies, highlighting key factors attributed to specimen density and growth ring characteristics. For instance, the study by Jin *et al.* (2024) reported a radial compressive strength of

6.6 MPa for Chinese pine samples, which is lower than the values obtained in the present study. This difference is likely attributable to the lower density of the specimens used in their research. Similarly, the *Wood Handbook* (Senalik & Farber, 2021) documents the radial compressive strength of North American Douglas fir as ranging between 5.1 and 5.5 MPa at 12% MC, values that are significantly lower than the 12.4 MPa recorded in the present study. Notably, no cases were identified in the literature where specimens with densities higher than those in this study were used. It is hypothesized that the greater differences observed in the results of the compression-R tests, compared to the compression-L tests, are due to the higher sensitivity of the compression-R tests to specimen density and growth ring characteristics. However, despite the observed variations, the comparative results among the four species align with findings from other research. For instance, Meng (2016) examined larch and Mongolian Scots pine and reported strength trends consistent with the patterns observed in the present study, where larch consistently demonstrated higher compressive strength than Mongolian Scots pine.

Based on these findings, Chinese pine's high compressive strength perpendicular to the grain in a radial direction makes it well-suited for load-bearing structural components, such as *Ludou* (栌斗), *Tuofeng* (驼峰), *Dadou* (散斗), and *Huagong* (华拱). Douglas fir provides a viable alternative, especially where consistency and moderate strength are required. Larch is appropriate for moderate-load applications, while Mongolian Scots pine, due to its lower compressive strength, is better suited for less pressurized components such as *Sandou* (散斗), *Qixindou* (齐心斗), and *Jiaohudou* (交互斗). The results also highlight a strong correlation between compressive

strength and density, reinforcing the importance of considering density when selecting materials for structural applications (Figure 7).

3.3. Shear-LR tests

3.3.1. Failure modes

In the shear-LR tests, specimens were subjected to shear parallel to the grain along the LR planes. During the initial loading phase, all specimens exhibited elastic deformation with negligible displacement, maintaining their structural integrity across all four timber species. As the applied shear force increased, localized fiber distortion initiated microcracks along the shear plane. These microcracks gradually propagated along the shear plane, reducing the specimen's shear capacity. Final failure was characterized by fiber separation and layer sliding along the LR plane, ultimately resulting in a loss of load-bearing capacity. The average failure load (P_{max}) values measured for larch, Chinese pine, Douglas fir, and Mongolian Scots pine were 4.5 kN, 3.5 kN, 4.5 kN, and 3.5 kN (Figure 8).

3.3.2. Data and analysis

Table 6 presents the mean shear strength ($\overline{\tau_{LR}}$), density (ρ), and dynamic modulus of elasticity ($\overline{E_d}$) results for timber specimens in the shear-LR tests. Larch exhibited the highest mean shear strength of 8.94 MPa, demonstrating strong performance along the LR plane. Douglas fir displayed a similar mean shear strength of 8.94 MPa, with low variability across samples, indicating consistent shear resistance. Chinese pine recorded a lower mean shear strength of 7.05 MPa, with noticeable variation among specimens, suggesting some inconsistency in its shear response. Mongolian Scots pine, with an average shear

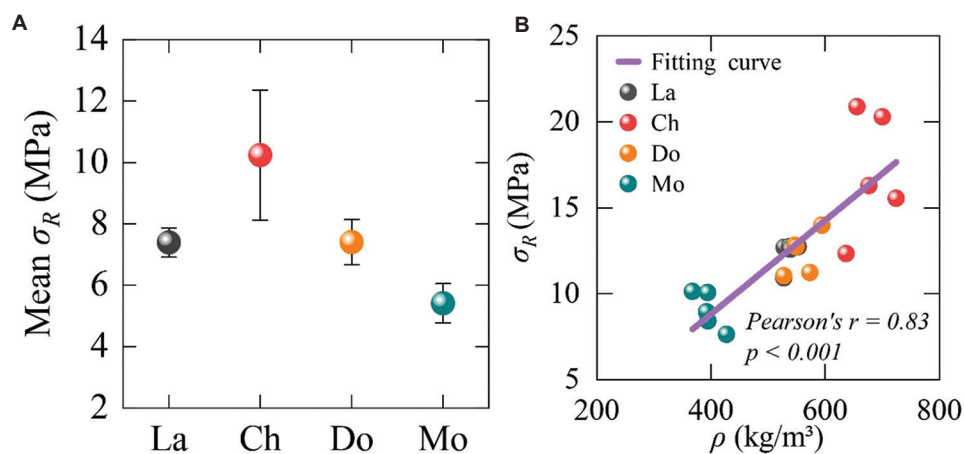


Figure 7. Comparison of $\overline{\sigma_R}$ and $\overline{\rho}$ values in compression-R tests. (A) $\overline{\sigma_R}$ of four species. (B) Relationship between $\overline{\sigma_R}$ and $\overline{\rho}$. Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine. Source: Graphs by the authors.

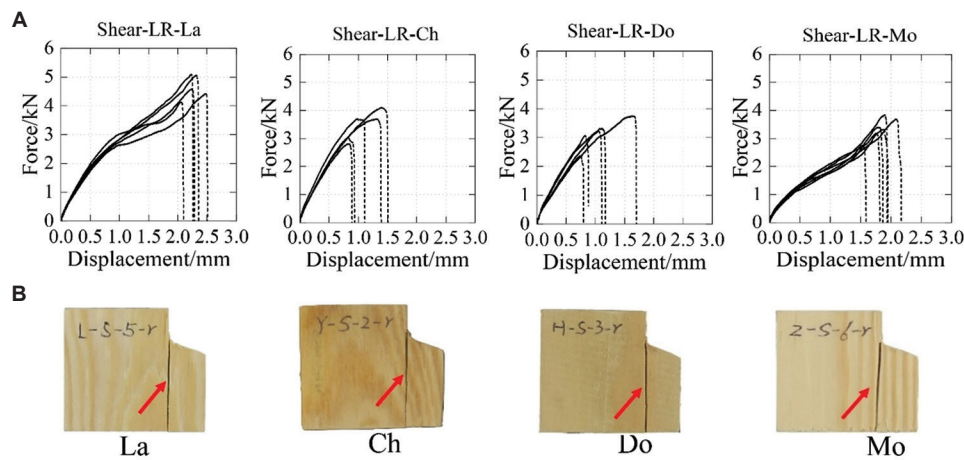


Figure 8. Failure modes of shear-LR tests. (A) Force-displacement curves of the four wood species. (B) Typical failure modes of specimens.
Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.

Source: (A) Graphs by the authors. Red arrows indicate cracks. (B) Photos by the authors (2024).

Table 6. Results of shear-LR tests

Specimen no.	τ_{LR} (MPa)	$\bar{\tau}_{LR}$ (MPa)	ρ (kg/m ³)	$\bar{\rho}$ (kg/m ³)	E_d (MPa)	$\bar{E}_d$ (MPa)
La-1	9.8	8.9 (SD=0.8)	565	561 (SD=7)	30,360	49,124 (SD=18,679)
La-2	7.9		556		29,899	
La-3	8.5		562		68,032	
La-4	9.7		569		50,565	
La-5	8.8		553		66,855	
Ch-1	7.9	7.1 (SD=1.3)	752	725 (SD=17)	16,714	30,238 (SD=9,454)
Ch-2	8.7		707		25,438	
Ch-3	7.1		726		39,022	
Ch-4	5.8		716		31,204	
Ch-5	5.7		722		38,812	
Do-1	9.8	8.9 (SD=0.80)	520	524 (SD=5)	27,974	67,514 (SD=26,150)
Do-2	7.9		520		62,948	
Do-3	8.5		528		63,936	
Do-4	9.7		520		90,577	
Do-5	8.8		529		92,136	
Mo-1	7.9	7.1 (SD=1.28)	421	438 (SD=10)	73,289	49,974 (SD=23,339)
Mo-2	8.7		442		77,086	
Mo-3	7.1		444		30,217	
Mo-4	5.8		440		39,090	
Mo-5	5.7		444		30,190	

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine; SD: Standard deviation.

strength of 7.05 MPa, exhibited the weakest shear performance along the LR plane.

Larch's high shear strength and consistency make it well-suited for applications requiring reliable shear

resistance along the LR plane, such as *Ludou* (栌斗), *Dadou* (大斗), and column (柱). Douglas fir, with comparable shear strength, serves as a strong alternative, especially when availability or cost is a consideration. Chinese

pine, with moderate shear strength and some variability, is appropriate for applications with moderate load requirements. Mongolian Scots pine, which exhibited the lowest shear strength, is more suitable for less pressurized components. Interestingly, Chinese pine presented an anomaly in the relationship between density and strength. Despite having the highest density among the tested species, its shear strength was relatively low (Figure 9).

3.4. Shear-LT tests

3.4.1. Failure modes

In the shear-LT tests, specimens were subjected to shear parallel to the grain along the LT plane. Initially, all specimens underwent elastic deformation with minimal deformation, maintaining their structural integrity across the four timber species. As shear force increased, localized fiber distortion initiated microcracks along the shear plane. Unlike in the shear-LR tests, where microcracks propagated along the shear plane, shear-LT tests exhibited crack extension along the grain direction, progressively degrading shear capacity due to fiber disengagement. Final failure was characterized by fiber separation and layer sliding along the LT plane, resulting in a loss of load-bearing capacity in all timber species. The average failure load (P_{max}) values measured for larch, Chinese pine, Douglas fir, and Mongolian Scots pine were 3.0 kN, 4.0 kN, 5.9 kN, and 2.0 kN, respectively (Figure 10).

3.4.2. Data and analysis

Table 7 presents the mean shear strength ($\bar{\tau}_{LT}$), density (ρ), and dynamic modulus of elasticity (E_d) results for the timber specimens subjected to shear-LT testing. Douglas fir exhibited the highest mean shear strength

along the LT plane, measuring 11.8 MPa with moderate variability (SD = 1.6 MPa), reflecting robust resistance to shear forces in this direction. Chinese pine followed, with a mean shear strength of 8.1 MPa and low variability (SD = 0.7 MPa), indicating stable shear performance along the LT plane. Larch displayed a lower mean shear strength of 6.0 MPa with higher variability (SD = 1.9 MPa), indicating inconsistencies in shear performance under LT loading. Mongolian Scots pine exhibited the lowest mean shear strength at 4.1 MPa, with minimal variability (SD = 0.4 MPa), suggesting limited load-bearing potential under LT shear forces.

Studies on shear strength in timber along both the LR and LT planes remain limited. The study by Jin *et al.* (2024) on 40 – 60-year-old timber specimens recorded average shear strengths ranging from 6.87 to 8.03 MPa across these planes. In this study, Chinese pine specimens (aged 60 years) displayed an average shear strength of 8.1 MPa across these planes, closely aligning with Jin *et al.*'s (2024) findings. The *Wood Handbook* (Senalik & Farber, 2021) reported North American Douglas fir with an average shear strength of 7.8 to 10.4 MPa at 12% MC, values similar to the 11.8 MPa measured in the present study. Both compressive and shear strength comparisons indicate that the Douglas fir specimens in this study demonstrate higher overall strength than those reported by Senalik & Farber (2024), further underscoring the natural variability in timber properties.

Considering results from both shear-LR and shear-LT tests, Douglas fir emerged as the strongest timber, demonstrating high shear strength across both orientations. While larch performed well in the shear-LR test, its shear

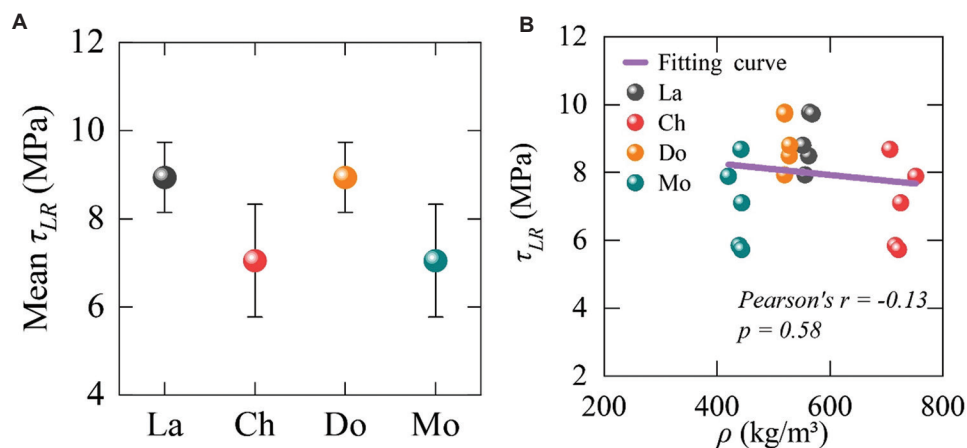


Figure 9. Comparison of $\bar{\tau}_{LR}$ and ρ values in shear-LR tests. (A) $\bar{\tau}_{LR}$ of four species. (B) Relationship between $\bar{\tau}_{LR}$ and ρ . Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine. Source: Graphs by the authors.

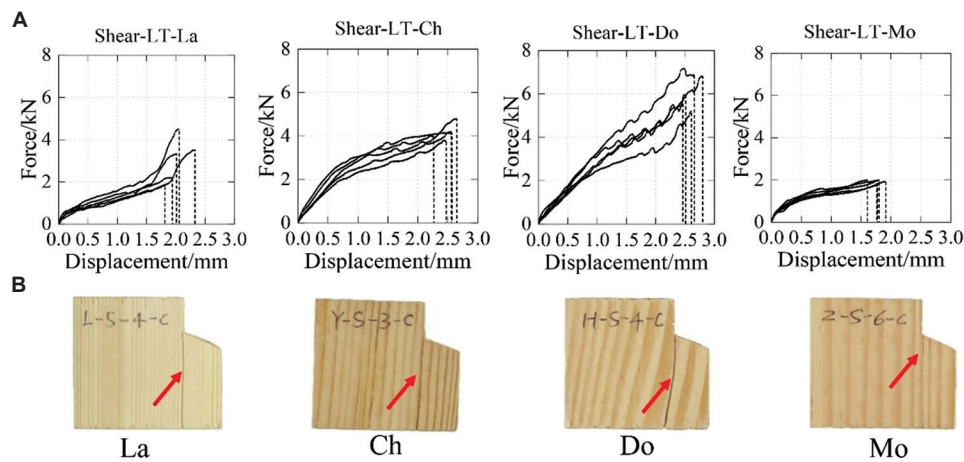


Figure 10. Failure modes of shear-LT tests. (a) Force-displacement curves of the four wood species (b) Typical failure modes of specimens. Red arrows indicate cracks.

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.

Source: (A) Graphs by the authors. (B) Photos by the authors (2024).

Table 7. Results of shear-LT tests

Specimen no.	τ_{LT} (MPa)	$\overline{\tau_{LT}}$ (MPa)	ρ (kg/m ³)	$\bar{\rho}$ (kg/m ³)	E_d (MPa)	$\overline{E_d}$ (MPa)
La-1	8.7	6.0 (SD=1.9)	591	590 (SD=8)	71,470	72,766 (SD=50,056)
La-2	4.2		580		39,460	
La-3	6.8		585		159,323	
La-4	4.1		601		40,890	
La-5	6.4		593		52,686	
Ch-1	8.0	8.1 (SD=0.7)	733	706 (SD=39)	18,896	14,846 (SD=5,251)
Ch-2	9.2		726		14,049	
Ch-3	7.7		736		12,527	
Ch-4	8.1		694		20,991	
Ch-5	7.3		644		7,767	
Do-1	13.8	11.8 (SD=1.6)	602	580 (SD=15)	26,237	19,530 (SD=10,694)
Do-2	11.5		574		9,759	
Do-3	13.1		588		6,403	
Do-4	10.8		574		25,017	
Do-5	10.0		562		30,234	
Mo-1	3.8	4.1 (SD=0.4)	483	474 (SD=6)	58,427	43,294 (SD=9,389)
Mo-2	3.8		470		41,754	
Mo-3	4.8		468		41,616	
Mo-4	3.8		475		42,204	
Mo-5	4.0		477		8,250	

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine; SD: Standard deviation.

strength in the LT direction was lower than that of Douglas fir and Chinese pine, indicating directional variability in shear performance. Chinese pine exhibited balanced and stable shear strength across both orientations, making it a reliable choice for structural applications. Douglas

fir and Chinese pine are recommended for components experiencing shear forces in multiple directions, such as *Ludou* (栌斗) and *Dadou* (大斗). The results also confirm a positive correlation between density and shear strength (Figure 11).

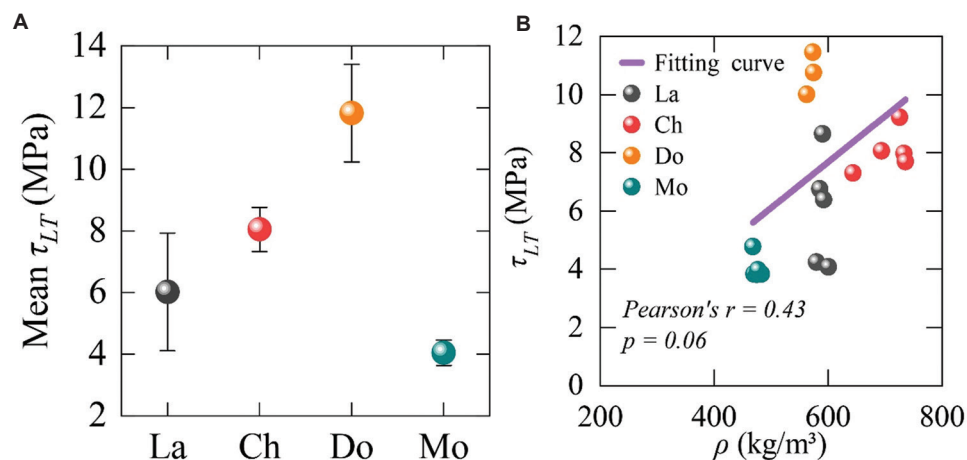


Figure 11. Comparison of τ_{LT} and ρ values in shear-LR tests. (A) τ_{LT} of four species. (B) Relationship between τ_{LT} and ρ .
Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.
Source: Graphs by the authors.

3.5. Bend-L tests

3.5.1. Failure modes

In the bend-L tests, specimens were subjected to bending perpendicular to the grain. The loading process generally consisted of an initial linear elastic phase, followed by plastic deformation, and culminating in fracture. During the linear elastic phase, all four timber species exhibited minimal deformation, maintaining their structural integrity. As the load increased, the convex side of the specimen experienced localized compression, while the concave side underwent tension, resulting in bending. As the test progressed, a crack formed along the growth ring in the middle of the specimen. Once this crack was extended, the load-carrying capacity of all wood species ceased to increase. Final failure was marked by fracture, leading to a sudden loss of load-carrying capacity (Figure 12).

3.5.2. Data and analysis

Table 8 summarizes the mean bending strength (σ_B), density (ρ), and dynamic modulus of elasticity (E_d) for each timber species in the bend-L tests. Larch exhibited the highest average bending strength, followed closely by Chinese pine and Douglas fir, while Mongolian Scots pine displayed the lowest values. Chinese pine had the highest density, while larch and Douglas fir had moderate densities, and Mongolian Scots pine had the lowest density. The dynamic modulus of elasticity values was relatively stable in larch and Douglas fir, whereas greater variability was observed in Chinese pine and Mongolian Scots pine. The average failure load (P_{max}) values recorded for larch, Chinese pine, Douglas fir, and Mongolian Scots pine were 2.9 kN, 2.8 kN, 2.8 kN, and 1.7 kN, respectively.

This study employed a four-point bending setup, differing from the three-point bending method commonly used in other studies. As a result, a direct comparison of bending strength values is not feasible. However, the bending modulus of elasticity (E_b) measured in this experiment can be compared with previous studies to assess the reliability of the results. The recorded E_b values were as follows: larch (12,561 MPa), Chinese pine (10,721 MPa), Douglas fir (11,765 MPa), and Mongolian Scots pine (7,385 MPa). Comparing these values with those from prior studies, larch's E_b aligns closely with values reported by Cheng *et al.* (2023) (12,900 MPa), Jin *et al.* (2024) (12,000 MPa), and Wang *et al.* (2022) (12,199 MPa). The E_b for Chinese pine (10,721 MPa) is similar to Cheng *et al.*'s (2023) 11,270 MPa, but higher than Jin *et al.*'s (2024) 7,800 MPa, likely due to differences in sample density. For Douglas fir, the E_b in this study (11,765 MPa) falls within the range of 10,300 – 13,400 MPa reported by Senalik & Farber (2021). Mongolian Scots pine, with an E_b value of 7,385 MPa, was lower than the 9,320 MPa reported by Cheng *et al.* (2023), which may be attributed to the lower density of the samples used in this study. The strong correlation of the E_b values with previous findings supports the reliability of this study's measurements.

Overall, the bend-L tests demonstrated a positive correlation between density, dynamic modulus of elasticity, and bending strength (Figure 13). Larch, Chinese pine, and Douglas fir exhibited high and comparable bending strengths, making them suitable for structural components requiring substantial bending capacity, such as beams, columns, Tuan (榑), Fang (枋), and Ang (昂). In contrast, Mongolian Scots Pine may be an option for smaller

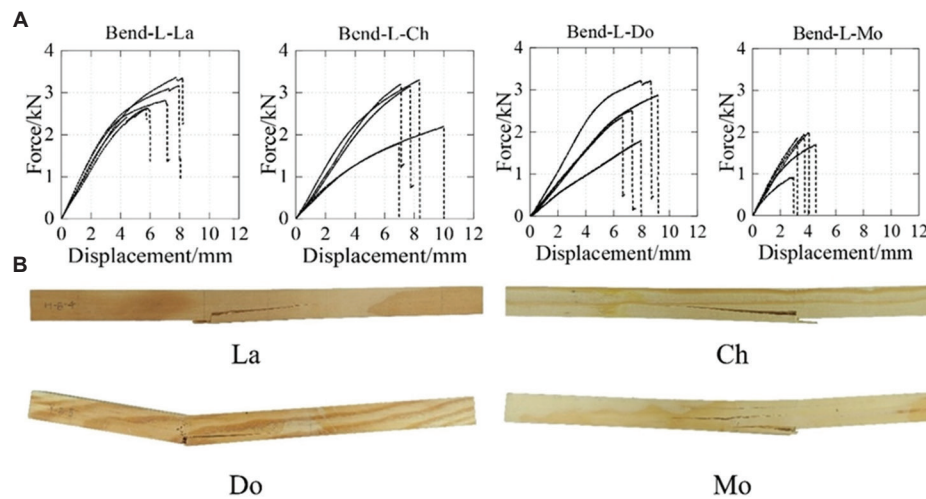


Figure 12. Failure modes of bend-L tests. (A) Force-displacement curves of the four wood species. (B) Typical failure modes of specimens.

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.

Source: (A) Graphs by the authors. (B) Photos by the authors (2024).

Table 8. Results of bend-L tests

Specimen no.	σ_B (MPa)	$\overline{\sigma_B}$ (MPa)	ρ (kg/m ³)	$\bar{n}$ (kg/m ³)	E_d (MPa)	$\overline{E_d}$ (MPa)
La-1	50.7	44.1 (SD=4.9)	590	586 (SD=20)	19,396	19,254 (SD=1,451)
La-2	39.7		574		17,073	
La-3	47.7		614		20,712	
La-4	39.8		563		18,723	
La-5	42.6		589		20,366	
Ch-1	47.6	41.2 (SD=0.3)	769	729 (SD=64)	15,887	15,475 (SD=474)
Ch-2	48.2		722		15,866	
Ch-3	49.8		727		14,725	
Ch-4	33.2		798		15,520	
Ch-5	27.2		629		15,369	
Do-1	45.7	42.2 (SD=5.4)	572	560 (SD=10)	17,018	17,031 (SD=1,624)
Do-2	38.0		551		19,842	
Do-3	35.5		550		15,977	
Do-4	43.4		560		16,251	
Do-5	48.6		567		16,066	
Mo-1	30.4	25.7 (SD=6.7)	424	424 (SD=46)	7,231	10,227 (SD=2,605)
Mo-2	28.4		366		7,559	
Mo-3	29.5		423		12,592	
Mo-4	26.0		412		11,814	
Mo-5	14.1		494		11,938	

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine; SD: Standard deviation.

components where bending strength is less critical, such as *Nidao Gong* (泥道拱), *Ling Gong* (令拱), *Man Gong* (慢拱), or *Guazi Gong* (瓜子拱) in smaller timber

buildings. However, its density, dynamic modulus of elasticity, and bending performance should be further assessed to confirm its reliability.

3.6. Tension-L tests

3.6.1. Failure modes

In the tension-L tests, specimens were subjected to tension parallel to the grain, initially undergoing elastic stretching with minimal deformation across all timber species under low loads. As the tensile force increased, microcracks formed along the grain due to fiber separation, particularly in weaker regions or at the interface between earlywood and latewood. With continued loading, these cracks propagated along the grain, eventually leading to complete tensile failure. This failure was characterized by fiber rupture and separation, resulting in a significant decline in load-bearing capacity across all four timber species (Figure 14). The average failure load (P_{max}) values measured for larch, Chinese pine, Douglas fir, and Mongolian Scots pine were 2.9 kN, 2.8 kN, 2.82 kN, and 1.7 kN, respectively.

3.6.2. Data and analysis

Table 9 summarizes the tensile strength ($\overline{\sigma}_T$), density ($\overline{\rho}$), and dynamic modulus of elasticity ($\overline{E}_d$) for each timber species. Larch exhibited the highest average tensile strength at 195.0 MPa, though with considerable variation (SD = 47.9). Chinese pine followed, with an average tensile strength of 140.1 MPa, while Douglas fir recorded 146.4 MPa, both showing similar variability. Mongolian Scots pine had the lowest tensile strength, averaging 93.0 MPa, with the greatest variation (SD = 33.3). In terms of density, Chinese pine and larch had relatively high densities, Douglas fir was moderate, and Mongolian Scots pine had the lowest density. Ultrasonic wave velocities were relatively stable across larch, Chinese pine, and Douglas fir, while Mongolian Scots pine exhibited greater variability.

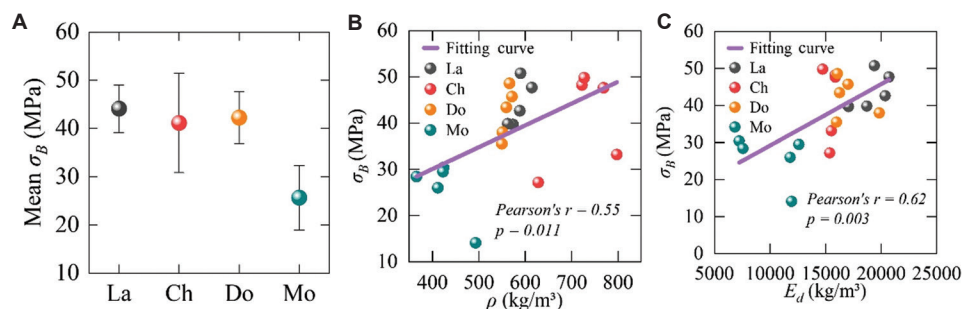


Figure 13. Comparison of $\overline{\sigma}_b$, $\overline{\rho}$, and $\overline{E}_d$ values in bend-L tests. (A) $\overline{\sigma}_b$ of four species. (B) Relationship between $\overline{\sigma}_b$ and $\overline{\rho}$. (C) Relationship between $\overline{\sigma}_b$ and $\overline{E}_d$.

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.

Source: Graphs by the authors.

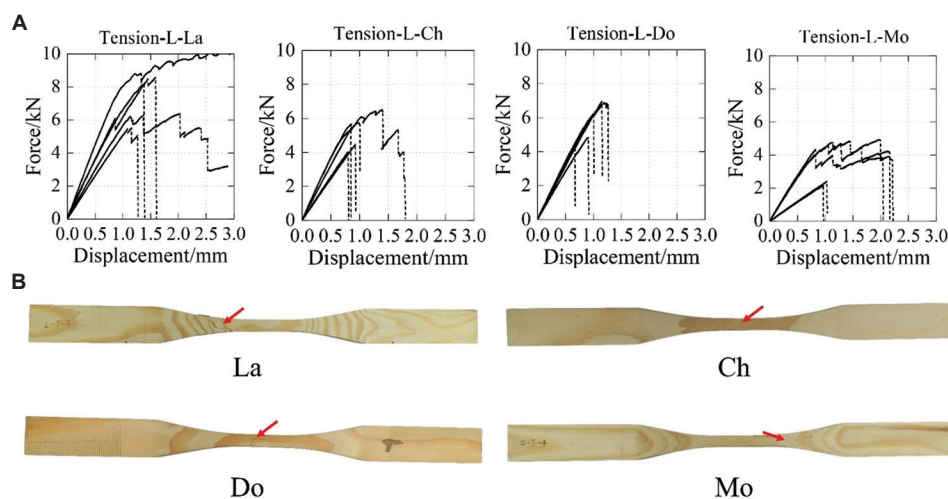


Figure 14. Failure modes of tension-L tests. (A) Force-displacement curves of the four wood species. (B) Typical failure modes of specimens. Red arrows indicate cracks.

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.

Source: (A) Graphs by the authors. (B) Photos by the authors (May 2024).

Since timber is rarely used for tensile components, there is limited comparable tensile strength data in existing studies. Xin *et al.* (2017) reported tensile strengths of 107.96 MPa, 131.4 MPa, and 81.4 MPa for Changbai larch, Xing'an larch, and Mongolian Scots pine, respectively. However, the study did not provide density or ultrasonic velocity data, making direct comparisons difficult. The differences observed may result from inherent material variability. From a material selection standpoint, larch, Chinese pine, and Douglas fir exhibit higher tensile strengths than Mongolian Scots pine.

However, tensile timber components are uncommon in historical wooden structures, and timber under tensile stress often fails due to other reasons before reaching tensile failure. Therefore, compared to other loading modes, tensile strength should be considered a secondary reference when selecting materials. In summary, the tension-L tests demonstrated a positive correlation between density, dynamic modulus of elasticity, and tensile strength, suggesting that these properties can serve as supplementary reference indicators for assessing wood's tensile strength (Figure 15).

Table 9. Results of tension-L tests

Specimen no.	σ_T (MPa)	$\bar{\sigma}_T$ (MPa)	ρ (kg/m ³)	$\bar{\rho}$ (kg/m ³)	E_d (MPa)	$\bar{E}_d$ (MPa)
La-1	203.8	195.0 (SD=47.9)	638	619 (SD=29)	21109	20571 (SD=1421)
La-2	137.5		579		18558	
La-3	214.5		638		20902	
La-4	159.5		596		19924	
La-5	259.5		642		22362	
Ch-1	134.8	140.1 (SD=36.2)	647	694 (SD=44)	19154	21031 (SD=4241)
Ch-2	111.8		651		17678	
Ch-3	163.2		741		25037	
Ch-4	101.5		698		17148	
Ch-5	188.9		734		26136	
Do-1	121.0	146.4 (SD=30.0)	549	561 (SD=30)	17796	19457 (SD=1529)
Do-2	174.3		515		18144	
Do-3	108.6		580		20219	
Do-4	155.9		566		21523	
Do-5	172.1		593		19603	
Mo-1	123.5	93.0 (SD=33.3)	554	470 (SD=89)	20178	14936 (SD=6430)
Mo-2	60.1		394		8502	
Mo-3	118.9		506		18832	
Mo-4	108.4		539		19816	
Mo-5	54.1		358		7353	

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine; SD: Standard deviation.

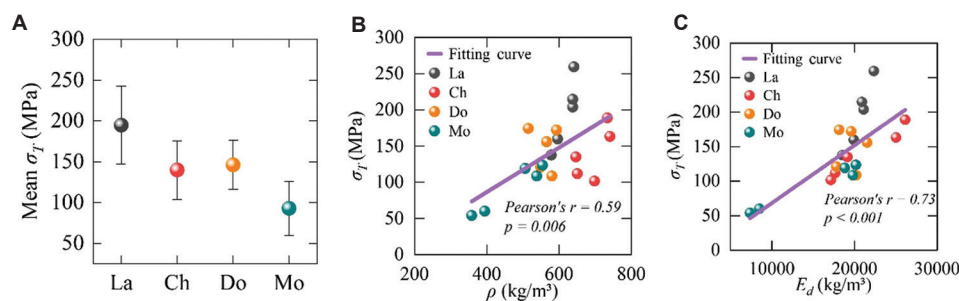


Figure 15. Comparison of $\bar{\sigma}_T$, $\bar{\rho}$, and $\bar{E}_d$ values in bend-L tests. (A) $\bar{\sigma}_T$ of four species. (B) Relationship between $\bar{\sigma}_T$ and $\bar{\rho}$. (C) Relationship between $\bar{\sigma}_T$ and $\bar{E}_d$.

Notes: Ch: Chinese pine; Do: Douglas fir; La: Larch; Mo: Mongolian Scots pine.

Source: Graphs by the authors.

4. Conclusion

This study provides a comparative analysis of the material properties of four timber species – Chinese pine, larch, Douglas fir, and Mongolian Scots pine – commonly used in the restoration of historical timber buildings in Shanxi province, China. Each species was tested under six loading modes, including compression parallel to the grain, compression perpendicular to the grain in the radial direction, shear parallel to the grain along the LR and LT planes, four-point static bending, and tension. These findings provide important insights into the structural suitability of these timbers for heritage conservation.

- (i) Compression tests: Douglas fir displayed the highest compressive strength (59.9 MPa) in the compression-L tests, making it ideal for load-bearing components, such as columns and *Chashou* (叉手). Chinese pine (17.1 MPa) excelled in the compression-R tests, making it suitable for structural components such as *Ludou* (栌斗) and *Dadou* (大斗). A positive correlation was observed between compressive strength and density across all tested species.
- (ii) Shear tests: Douglas fir and larch exhibited greater shear resistances along both LR and LT planes compared to Chinese pine and Mongolian Scots pine, making them reliable choices for shear-stressed components, such as *Ludou* (栌斗), *Dadou* (大斗), and columns. Mongolian Scots pine, with lower shear strength, may be more appropriate for non-critical components. Shear strength correlated positively with density across all four species.
- (iii) Bending tests: Larch, Chinese pine, and Douglas fir demonstrated higher bending strengths compared to Mongolian Scots pine, making them suitable for main structural components, such as beams, columns, *Tuan* (榑), *Fang* (枋), and *Ang* (昂). Mongolian Scots pine, with its lower bending strength, is more suitable for non-load-bearing components, such as *Nidao Gong* (泥道棋), *Ling Gong* (令棋), *Man Gong* (慢棋), or *Guazi Gong* (瓜子棋), in smaller timber buildings. A positive correlation was observed between bending strength, density, and dynamic modulus of elasticity.
- (iv) Tensile tests: Larch exhibited the highest tensile strength (195.0 MPa), with Douglas fir and Chinese pine also performing well. Density and dynamic modulus of elasticity correlated with tensile strength, providing reference points for evaluating tensile performance.

These results support a strategic approach to timber selection in heritage restoration, balancing structural strength, historical authenticity, and material availability. Future research on the long-term durability of these

species under varying climatic conditions will further refine material guidelines, contributing to the sustainable preservation of historical timber architecture.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Panpan Liu, Sok Yee Yeo, Hiroatsu Fukuda

Investigation: Panpan Liu

Methodology: Panpan Liu, Sok Yee Yeo, Hiroatsu Fukuda

Writing – original draft: Panpan Liu

Writing – review & editing: Panpan Liu, Sok Yee Yeo

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The data used in this work can be made available on reasonable request to the corresponding author.

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