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Timber species identification and selection principles of wooden components in the Sunjialou Cultural Relic Building, Nanyang City

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To support the scientific restoration of Sunjialou Cultural Relic Building (Nanyang City), optical microscopy was employed to identify the timber species of key wooden components. The results are as follows: (1) Timbers belong to four families and five genera including *Larix* sect. *Multiseriales*, *Pinus* sect. *Cembra*, *Cunninghamia lanceolata*, *Quercus* sect. *Cerris*, and *Ulmus* sect. *Madocarpus*. (2) Timber selection exhibits dual characteristics of functional adaptation and regional resource dependence: High-strength hardwoods were utilized for core load-bearing components; decay-resistant softwoods for secondary ones; and easily workable softwoods for non-load-bearing/decorative components. Most timber species are local or near-source, aligning with the principle of local or near-source material utilization. (3) The findings systematically reveal the timber selection characteristics of Sunjialou architecture, confirming the traditional construction wisdom of function-oriented material selection. Simultaneously, this study provides a scientific basis for its restoration and serves as a representative case for related research in southwestern Henan Province.

As material carriers of regional historical and cultural heritage, the timber selection for the wooden frames of ancient buildings not only embodies the traditional craftsmanship wisdom of material-property adaptation but also reflects the resource utilization patterns and socio-economic contexts of specific eras making it a pivotal focus in cultural heritage protection research. Located in the transitional zone between the Central Plains and Southern China, Nanyang developed a residential system integrating the regular layout of the Central Plains with adaptations to southern climatic conditions from the Ming and Qing dynasties to the modern period. The preserved wooden structures not only serve as critical tangible evidence for investigating the modern architectural history of the Central Plains but also act as repositories of diverse historical memories, including red culture and commercial heritage.

The Sunjialou Cultural Relic Building, situated east of the intersection of Jiefang Road and Minzhu Street in central Nanyang (33°01N, 112°3E), is a typical representative of such relics in the ancient city. First constructed during the Guangxu period of the Qing Dynasty (1875–1908), it was designated a Nanyang municipal-level cultural heritage site in 2002. Currently, the site comprises two courtyards (Fig. 1a): Courtyard No. 1, i.e., former residence of Yao Shiyi, president of the Nanyang Chamber of Commerce during the Republic of China, which witnesses the city's modern commercial development, and Courtyard No. 2, i.e., former site of the Central County Party Committee of the Communist Party of China in Nanyang and the ancestral home of revolutionary martyrs Cao Yunge and Cao Jianming, which embodies Nanyang's red history. Architecturally, Sunjialou features a "shop in the front, residence at the back" and "single-entry multi-courtyard" spatial layout, combined with a brick-wood composite structure, reflecting the construction logic of "li-long residences" (narrow alleyway residences) in southwestern Henan. Its wooden frame serves as the core load-bearing system, while blue bricks, gray tiles, and wall designs are adapted to Nanyang's subtropical monsoon climate of hot and rainy summers, dry and cold winters. Crafts such as door/window wood carvings and beam/column reliefs further enhance its historical and artistic value.

However, following a century of natural weathering and environmental deterioration, the Sunjialou Cultural Relic Building faces severe preservation challenges. Although the main structure remains relatively intact, the wooden components of the core load-bearing system have

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Fig. 1 | Layout diagram and current preservation status of the Sunjialou Cultural Relic Building in Nanyang City. a Layout diagram: ① north inverted seat, ② south inverted seat, ③ gateway, ④ north flanking hall of the first courtyard, ⑤ south flanking hall of the first courtyard, ⑥ through hall, ⑦ north flanking hall of the second courtyard, ⑧ south flanking hall of the second courtyard; **b** Decay of eave purlins and rafters; **c** Decay of eave purlins and rafters; **d** Insect infestation of eave purlins; **e** Insect infestation of eave rafters; **f** Decay of column bases; **g** Decay of column bases.

undergone significant deterioration, posing substantial threats to the building's structural integrity. On-site investigations (Fig. 1b–g) revealed varying degrees of deterioration in key wooden components consisting of column bases, eave rafters, and eave purlins, primarily concentrated in moisture-prone zones. Decayed wood displays color transitions from light yellow to brown or black, with a brittle and crumbly texture; some components even crumble upon contact, directly compromising the structural load-bearing capacity. Insect-infested components feature dense circular holes (1–3 mm in diameter) on the surface of some wooden colums and crisscrossing internal tunnels (Fig. 1g). Based on the morphological characteristics of the damage and regional insect species distribution in Nanyang's subtropical monsoon climate, the infesting insects are identified as powder-post beetles. On-site inspections were conducted, no fresh frass was observed around the holes, indicating that the infestation is currently inactive. These deteriorations not only alters the anatomical structure of wood[1,2], degrades its chemical composition[1–4], and impairs its physical and mechanical properties[2,5], but also impairs the structural integrity of component[5], ultimately endangers the overall structural safety of buildings[6]. Without targeted protection, irreversible loss of historical information will occur.

In traditional Chinese architecture, timber selection for wooden components follows commonly recognized principles to balance functional needs and regional conditions[7]. Functional adaptation is a core principle. Timber properties are matched to component functions. High-strength, decay-resistant timbers are used for core load-bearing components to ensure structural stability. Lightweight, decay-resistant timbers are employed for secondary load-bearing components to reduce structural burden. Easily workable, fine-textured timbers are chosen for non-load-bearing or decorative components to facilitate processing and meet esthetic demands. Regional resource dependence is another key principle. Craftsmen prioritize local or near - source timbers to lower transportation costs, reduce transit material loss, and make the selection align with the era's resource endowments and transportation capabilities. Climate adaptation is also considered. Timbers with low moisture absorption, thermal stability, or insect resistance are selected according to local climatic features to extend component service life. These principles together reflect traditional craftsmen's practical wisdom in material selection.

The restoration of ancient wooden components must strictly comply with the principles of "authenticity" and "minimum intervention", and accurate timber species identification constitutes a fundamental prerequisite. Timber species exhibit significant variations in density, mechanical strength, decay resistance, and workability, e.g., *Quercus* sect. *Cerris* exhibits high strength but is susceptible to insect infestation, while *Cunninghamia lanceolata* offers good decay resistance but has low impact toughness. The use of inappropriate species can result in poor compatibility between the restored components and the original structure, accelerating aging. Additionally, tracing timber sources via species identification enables the reconstruction of Nanyang's modern construction supply chain and resource utilization patterns, filling the research gaps in traditional construction techniques in southwestern Henan.

Limited studies have systematically examined the timber species and their selection mechanisms for Ming and Qing Dynasties ancient buildings in this region, characterized by distinct north-south cultural and climatic transitions. This research gap restricts in-depth understanding of regional traditional construction techniques and the scientific implementation of heritage restoration. To address this limitation, the present study focuses on the wooden components of the Sunjialou Cultural Relic Building as the research object, focusing on key load-bearing components including columns, beams, purlins, rafters. Optical microscopy is employed to observe the anatomical characteristics of the wood samples, and timber species are identified in line with international and domestic wood taxonomic standards. The objectives of this study are to clarify the composition of original timber species of the building's wooden components, uncover the inherent principles of timber selection that integrate functional adaptation and regional resource dependence, provide scientific basis for subsequent restoration and protection work including targeted insect-proof and moisture-proof treatments and rational selection of replacement timbers, and offer a reference for similar studies on wooden components of heritage buildings in regions with similar north-south transition characteristics.

Methods

Sampling objects and location

Considering that the renovation of Courtyard No. 2 was sequentially completed between 2022 and 2024, sampling for this study was primarily conducted on wooden components from Courtyard No. 1, including core load-bearing components (columns for vertical load transmission and beams for horizontal load distribution), secondary load-bearing components (purlins connecting beams and rafters, and rafters supporting the roof structure), and non-load-bearing components (doors and windows). In the present study, the wood species of columns, beams, purlins, and rafters were first classified and identified using the macroscopic visual observation method, followed by sampling of selected wooden components.

Among the collected specimens, timber column samples were mainly obtained from the south inverted seat, north inverted seat, and through hall; beam specimens were primarily collected from the through hall; purlin specimens were mainly sourced from the south inverted seat and through hall, as well as the south flanking hall of the second courtyard; rafter specimens were mainly sampled from the south inverted seat wing, north inverted seat wing, and through hall, along with the south flanking hall and north flanking hall of the second courtyard; and door and window specimens were mainly collected from the south flanking hall of the first courtyard (Fig. 1a).

Sampling strictly adhered to the "minimum intervention" principle for cultural heritage protection to minimize additional damage to the building. An increment borer with an inner diameter of 10 mm (Model: 10–100–1027; Manufacturer: Haglöf AB, Sweden) was utilized for non-destructive or micro-destructive sampling. Sampling locations were prioritized in areas with evident deterioration but no adverse impact on the core load-bearing capacity, including column bases (moisture-prone decayed zones), beam ends (joint connection zones), eave purlin ends (exposed weathering zones), and eave rafter tips (moisture-prone decayed zones). A total of 18 valid samples were collected, with specific sampling information detailed in Table 1.

Embedding pretreatment of samples

To address severe decay, e.g., crumbly texture, fragmented structure, or insect infestation, e.g., dense internal tunnels, compromised integrity in some samples, a polyethylene glycol (PEG) chemical consolidation method for decayed wooden components of ancient buildings[8,9] was employed. A three-step process including vacuum degassing, gradient PEG impregnation, and shaping and embedding, was adopted to consolidate the samples, providing structural support for subsequent section preparation.

Vacuum degassing: Samples were placed in a vacuum desiccator, and a vacuum was applied to remove air from the wood pores and promote the penetration of the impregnation solution. After turning off the vacuum pump, the samples were allowed to stand for 30 min.

Gradient PEG impregnation: Samples were sequentially immersed in aqueous PEG solutions (molecular weight: 2000) with mass concentrations of 20%, 40%, 60%, 80%, and 100%. Each concentration was incubated in a constant-temperature oven at 60 °C for no less than 48 h; the 100% PEG solution was applied twice to ensure complete filling of the wood cell wall pores.

Embedding: The cutting surface of each sample was fixed facing downward at the bottom of a stainless steel embedding mold. Molten 100% PEG at 60 °C was poured into the mold, and a plastic embedding box was immediately covered to prevent air bubble formation. After natural cooling and solidification, a solid block tightly bonded to the sample was formed to prevent sample fragmentation during sectioning.

Table 1 | The sampling information of wooden components

Sample No.	Sampling Location	Sample No.	Sampling Location
No.1	Wooden column in south inverted seat	No.10	Wooden column in through hall
No.2	Eave rafter in south inverted seat	No.11	Eave rafter in through hall
No.3	Door/window in south flanking hall of the first courtyard	No.12	Eave rafter in through hall
No.4	Eave rafter in south inverted seat	No.13	Eave rafter in north flanking hall of the second courtyard
No.5	Eave purlin in south inverted seat	No.14	Wooden column in through hall
No.6	Eave rafter in north inverted seat	No.15	Door/window in south flanking hall of the first courtyard
No.7	Eave purlin in through hall	No.16	Wooden column in north inverted seat
No.8	Eave rafter in north inverted seat	No.17	Wooden beam in through hall
No.9	Eave purlin in south flanking hall of the second courtyard	No.18	Wooden beam in through hall

Table 2 | Identification results of timber species

Wood Category	Sample No.	Family	Genus	Section	Species
Group I	No.2, No.4, No.5, No.6, No.7, No.9, No.11, No.13	Pinaceae	*Larix*	sect. *Multiseriales*	*L. chinensis*, *L. mastersiana*, *L. potaninii*, *L. potaninii* var. *macrocarpa*, *L. speciosa*.
Group II	No.3, No.15		*Pinus*	sect. *Cembra*	*P. armandii*
Group III	No.8, No.12	Taxodiaceae	*Cunninghamia*	*Cunninghamia* spp.	*Cunninghamia lanceolata*
Group IV	No.1, No.16, No.17	Fagaceae	*Quercus*	sect. *Cerris*	*Q. chenii*
Group V	No.10, No.14, No.18	Ulmaceae	*Ulmus*	sect. *Madocarpus*	U. *macrocarpa*, *U. pumila*

Preparation of sample sections

Wood sections were prepared in accordance with the the wood sectioning techniques reported by Yang et al.[10,11]:

Sectioning: Embedded samples were mounted on the stage of a Leica HistoCore AUTOCUT microtome (Leica Microsystems, Germany). Transverse, radial, and tangential sections (10–15 μm in thickness) were prepared.

Gradient dehydration: Sections were sequentially immersed in 50%, 75%, 95%, and 100% ethanol aqueous solutions for 10 min per step to gradually remove moisture, thereby preventing tissue wrinkling during subsequent degreasing and mounting.

Degreasing and clearing: Dehydrated sections were immersed in xylene for 3–5 min to remove grease and improve transparency, enhancing the clarity of microscopic observation.

Mounting and preservation: Neutral resin was applied to clean glass slides, and the degreased sections were uniformly spread on the resin surface. A coverslip was carefully placed to prevent air bubble entrapment, and slides were air-dried in a well-ventilated environment. Permanent sections were obtained following complete resin curing.

Observation and identification of timber species

Microscopic observation: Permanent sections were examined under a Nikon ECLIPSE Ni-U biological microscope (Nikon Corporation, Japan) at magnifications of 4×, 10×, 20×, and 40×. The anatomical characteristics of the transverse, radial, and tangential sections were documented, and microscopic images were captured.

Basis of timber species identification: The identification was based on authoritative international and domestic wood anatomical standards and literature, including: *IAWA List of Microscopic Features for Softwood Identification*[12] and *IAWA List of Microscopic Features for Hardwood Identification*[13] issued by the International Association of Wood Anatomists (IAWA); *Atlas of Chinese Woods*[14], which systematically compiles anatomical characteristics, distribution, and uses of native Chinese tree species; *Names of Chinese Main Woods*[15], which standardizes the naming and classification of major domestic timber species.

Process of timber species identification: For softwoods, key characteristics included growth ring distinctness, tracheid properties (gradual or abrupt transition from earlywood to latewood, presence or absence of spiral thickenings, type of bordered pittings on radial walls), type of resin canals (presence or absence, axial or radial), and ray cell morphology (presence or absence of ray tracheids, serrations on the inner walls of ray tracheids, type of cross-field pittings). For hardwoods, key characteristics included growth ring distinctness, vessel properties (distribution, arrangement, grouping pattern, type of perforation plates, type of intervessel pitting, presence or absence of spiral thickenings), type of axial parenchyma (apotracheal or paratracheal), type of wood fibers, type of wood rays (homocellular or heterocellular), and presence or absence of gum canals. The observed characteristics were compared with those documented in the aforementioned standards, literature, and type specimens to determine the timber species.

Results

Microscopic anatomical observation and comparative analysis of 18 wooden component samples covering columns, beams, purlins, rafters, and doors/windows revealed that the timber species used in the Sunjialou Cultural Relic Building belong to 5 taxonomic groups, 5 genera, and 4 families (Pinaceae, Taxodiaceae, Fagaceae, Ulmaceae) (Table 2). The anatomical characteristics, identification results, and adaptability to building construction are discussed below:

Group I Wood: *Larix* sect. *Multiseriales*

Key anatomical characteristics of this wood Group (Samples No. 2, No. 4, No. 5, No. 6, No. 7, No. 9, No. 11, No. 13) are presented in Fig. 2:

Growth rings: Boundaries slightly distinct (Fig. 2a); gradual transition from earlywood to latewood (Fig. 2a).

Tracheids: Earlywood tracheids with thin walls (square, rectangular, or polygonal); latewood tracheids with thick walls (rectangular or square) (Fig. 2a, b); tracheid pitting in radial walls (in earlywood only) predominately uniseriate; helical thickenings in longitudinal tracheids absent (Fig. 2c).

Axial parenchyma: Absent (Fig. 2a, b).

Ray type and composition: Two types including uniseriate (5–15 cells in height) and fusiform (2–3 cells in width, 3–12 cells in height) (Fig. 2e, f); ray cells are isodiametric or slightly isodiametric, comprising ray tracheids

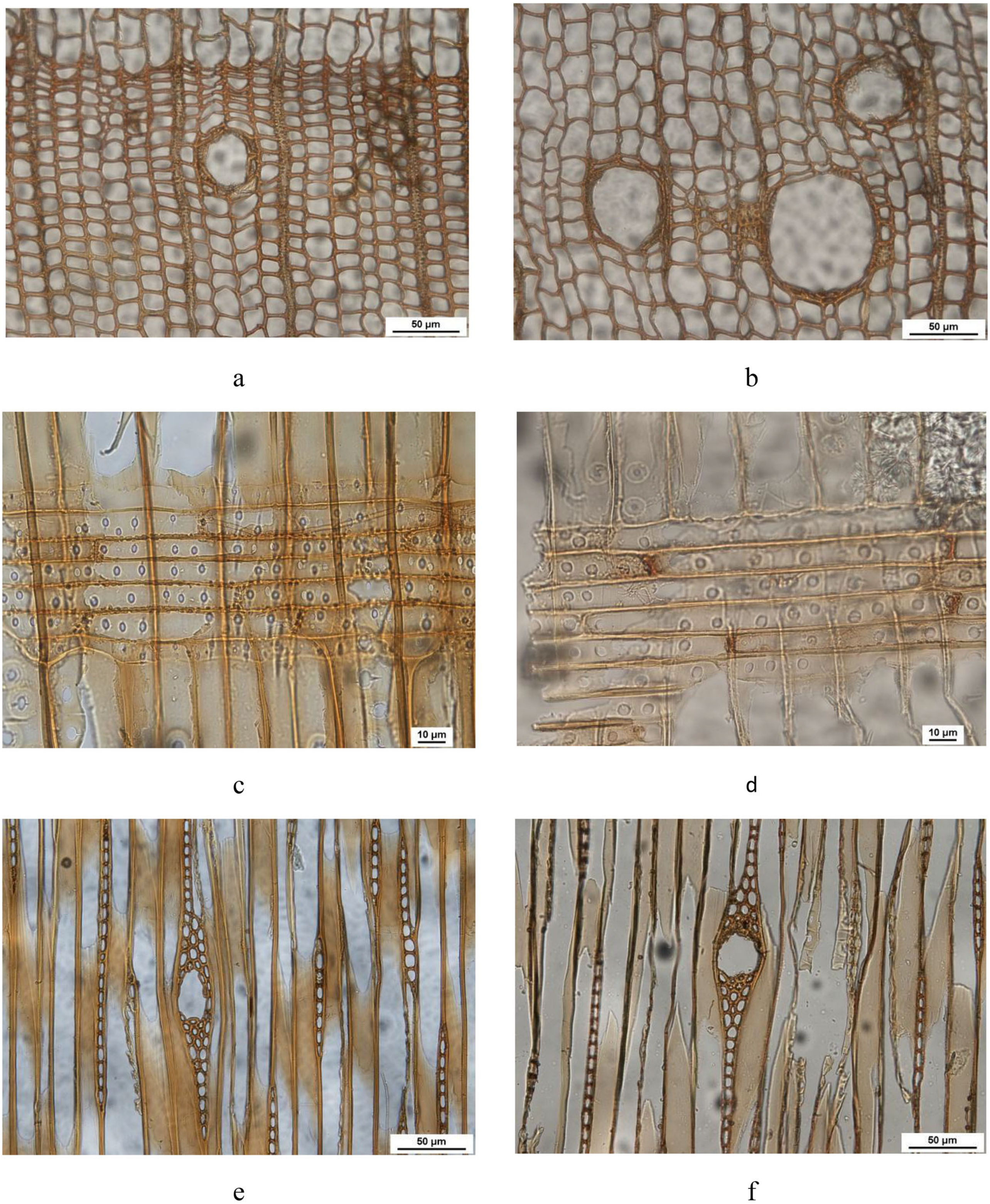

Fig. 2 | Anatomical structure of Group I wood. Identification result: *Larix* sect. *Multiseriales*. **a** Transverse Section, 200×: growth ring boundaries slightly distinct; gradual transition from earlywood to latewood; earlywood tracheids with thin walls and latewood tracheids with thick walls; axial intercellular canals. **b** Transverse Section, 200×: earlywood tracheids with thin walls; axial intercellular canals. **c** Radial Section, 400×, and **d** Radial Section, 400×: ray cells are isodiametric or slightly isodiametric, comprising ray tracheids and ray parenchyma cells; Cross-field pitting Taxodioid-type. **e** Tangential Section, 200×, and **f** Tangential Section, 200×: uniseriate ray and fusiform ray; radial intercellular canals.

(located at the upper or lower ends of ray parenchyma cells; low rays may consist entirely of ray tracheids) and ray parenchyma cells; inner cell walls of ray tracheids smooth with wavy outer edges, horizontal walls thick with numerous pittings and end walls distinct nodular thickenings (Fig. 2c, d); End walls of ray parenchyma cells distinctly pitted and horizontal walls distinctly pitted (Fig. 2c, d).

Cross-field pitting: Cross-field pitting between ray parenchyma cells and earlywood tracheids Taxodioid-type (2–4 pittings), which is a diagnostic characteristic of *Larix* sect. *Multiseriales* (Pinaceae) (Fig. 2c, d).

Intercellular canals: Both of axial intercellular canals (solitary, pore-like, concentrated in latewood and adjacent earlywood zones, numerous, with thick-walled epithelial cells) (Fig. 2a, b) and radial intercellular canals (located within fusiform rays, smaller than axial canals) (Fig. 2e, f) present, this is a key characteristic of Pinaceae genera such as *Pinus*, *Picea*, *Larix*, *Pseudotsuga*, and *Cathaya*.

The genus *Larix* (Pinaceae) is classified into two sections: *Multiseriales* and *Pauciseriales*. Sect. *Multiseriales* is characterized by isodiametric or slightly isodiametric ray cells and Taxodioid - type Cross-field pitting, whereas sect. *Pauciseriales* exhibits elliptical or long elliptical ray cells and Piceoid - type Cross-field pitting[10,14]. Microscopic observations and comparative analyses confirmed that Group I wood corresponds to *Larix* sect. *Multiseriales*.

Wood of *Larix* sect. *Multiseriales*, e.g., *L. chinensis*, *L. mastersiana*, *L. potaninii*, is lighter, softer, with a uniform structure, less susceptible to cracking, and more decay-resistant compared to that of sect. *Pauciseriales*[14], rendering it well-suited for secondary load-bearing components such as purlins, rafters that demand balanced mechanical performance, durability, and lightweight properties to reduce the upper structural load. These species are naturally distributed in the Qinling Mountains and Sichuan Province[15]. Nanyang's geographical proximity to the Qinling Mountains facilitated short-distance land transportation of this timber during the late Qing Dynasty and the Republic of China.

Group II Wood: *Pinus* subg. *Haploxylon*, sect. *Cembra*

Key anatomical characteristics of this wood Group (Samples No. 3, No. 15) are presented in Fig. 3:

Growth rings: Boundaries slightly distinct (Fig. 3a); gradual transition from earlywood to latewood (Fig. 3a).

Tracheids: Earlywood tracheids with thin walls (square, rectangular, or polygonal); latewood tracheids with thick walls (rectangular or square) (Fig. 3a, b); tracheid pitting in radial walls (in earlywood only) predominatly uniseriate; helical thickenings in longitudinal tracheids absent (Fig. 3c, d).

Axial parenchyma: Absent (Fig. 3a, b).

Ray type and composition: Two types consisting of uniseriate (5–15 cells in height) and fusiform (2–3 cells in width, 3–12 cells in height) (Fig. 3e, f); ray cells comprising ray tracheids (located at the upper or lower ends of ray parenchyma cells; low rays may consist entirely of ray tracheids) and ray parenchyma cells; inner cell walls of ray tracheids micro-dentate with wavy outer edges, horizontal walls thick with numerous pittings and end walls non - nodular thickenings (Fig. 3c, d); End walls of ray parenchyma cells smooth (unpitted) pitted and horizontal walls distinctly pitted (Fig. 3c, d).

Cross-field pitting: Cross-field pitting between ray parenchyma cells and earlywood tracheids Window-like-type (1–2 pittings), this is a diagnostic characteristic of *Pinus* (Pinaceae) (Fig. 3c, d).

Intercellular canals: Both of axial intercellular canals (solitary, pore-like, concentrated in latewood and adjacent earlywood zones, numerous, with thick-walled epithelial cells) (Fig. 3a) and radial intercellular canals (located within fusiform rays, smaller than axial canals) (Fig. 3e, f) present.

Pinus (Pinaceae) is classified into two subgenera: *Haploxylon* and *Diploxylon*. Within subg. *Haploxylon*, sect. *Cembra* is characterized by window-like Cross-field pitting, while sect. *Parrya* exhibits Pinoid-type pittings[10,11,14,16,17]. Microscopic analyses confirmed that Group II wood belongs to *Pinus* subg. *Haploxylon*, sect. *Cembra*.

Wood of *Pinus* sect. *Cembra*, e.g., *P. armandii*, *P. koraiensis*, is light, soft, delicate, easy to process, and moderately decay-resistant but low in strength[14], and is ideal for non-load-bearing/decorative components such as door, window frames, mullions that require fine carving and do not require high mechanical strength. *Pinus armandii* is distributed in southwestern Henan, Songshan Mountain, Zhongtiao Mountain (southern Shanxi), and the Qinling Mountains (southern Shaanxi)[14,15,18].

Group III Wood: *Cunninghamia lanceolata*

Key anatomical characteristics of this wood Group (Samples No. 8, No. 12) are presented in Fig. 4:

Growth rings: Boundaries distinct (Fig. 4a); gradual transition from earlywood to latewood (Fig. 4a).

Tracheids: Earlywood tracheids with thin walls (square, rectangular, or polygonal); latewood tracheids with thick walls (rectangular or square) (Fig. 4a, b); tracheid pitting in radial walls (in earlywood only) predominatly uniseriate; helical thickenings in longitudinal tracheids absent (Fig. 4c, d).

Axial parenchyma: Abundant (diffuse and tangential banded), this is a typical characteristic of Taxodiaceae (Fig. 4a, b).

Ray type and composition: Uniseriate (rarely biseriate, 5–10 cells in height) (Fig. 4e, f); only ray parenchyma cells (no ray tracheids, distinguishing it from Pinaceae), end walls smooth (unpitted) and horizontal walls distinctly pitted (Fig. 4c, d).

Cross-field pitting: Cross-field pitting between ray parenchyma cells and earlywood tracheids Taxodioid-type (2–4 pittings), this is a diagnostic characteristic of *Cunninghamia* (Fig. 4c, d).

Intercellular canals: Absent (Fig. 4a, b, e, f).

Insect infestation: Obvious insect holes in transverse sections (Fig. 4a), indicating weak insect resistance.

Group III wood is characterized by abundant axial parenchyma, no resin canals, rays composed solely of ray parenchyma cells, and Taxodioid-type Cross-field pitting—consistent with *Cunninghamia lanceolata*[10,14,16,19–21].

Although *Cunninghamia lanceolata* is a dominant species in southern China, Nanyang's location at the north-south climate transition (southern foot of the Funiu Mountains) supports its large-scale distribution in Tongbai, Xixia, and Nanzhao counties[14,15,18], enabling local material utilization. The wood's light weight, low shrinkage, and natural decay resistance attributed to aromatic compounds[14] make it suitable for rafters which requiring lightweight properties to reduce structural load and decay resistance to extend service life. However, sapwood is susceptible to insect infestation[14], as evidenced by insect holes in Fig. 4a, it is consistent with the severe eave rafter infestation observed in the Introduction. This finding provides a species-specific basis for targeted sapwood preservation in subsequent restoration.

Group IV Wood: *Quercus* subg. *Lepidabalanus*, sect. *Cerris*

Key anatomical characteristics of this wood Group (Samples No. 1, No. 16, No. 17: columns, beams) are presented in Fig. 5:

Growth rings: Growth ring boundaries are distinct (Fig. 5a).

Vessels: Wood ring-porous, earlywood vessels 1–3 cells wide (round, oval, or elliptical), tyloses and deposits in vessels common, and latewood vessels irregular polygonal (Fig. 5a); latewood vessels in radial pattern (Fig. 5a, b); latewood vessels exclusively solitary (90% or more) and occasionally short radial multiples (2 vessels) (Fig. 5b); simple perforation plates; intervessel pitting alternate; helical thickenings in vessel elements absent (Fig. 5e).

Vasicentric tracheids: Present, surrounding earlywood vessels (Fig. 5c).

Axial parenchyma: Apotracheal axial parenchyma diffuse and diffuse-in-aggregates, axial parenchyma in narrow bands or lines up to three cells wide, rhomboidal crystals present (Fig. 5a–d).

Ground tissue fibers: Fibers very thick-walled with distinctly bordered pittings (Fig. 5c, d).

Ray type and composition: Rays of two distinct sizes consisting of narrow (uniseriate) and wide (larger rays commonly >10-seriate, ray cells are extremely tall, often exceeding the limits of the section) (Fig. 5a, b, e, f), this is a diagnostic characteristic of *Quercus* (Fagaceae); all ray cells procumbent (Fig. 5c–f).

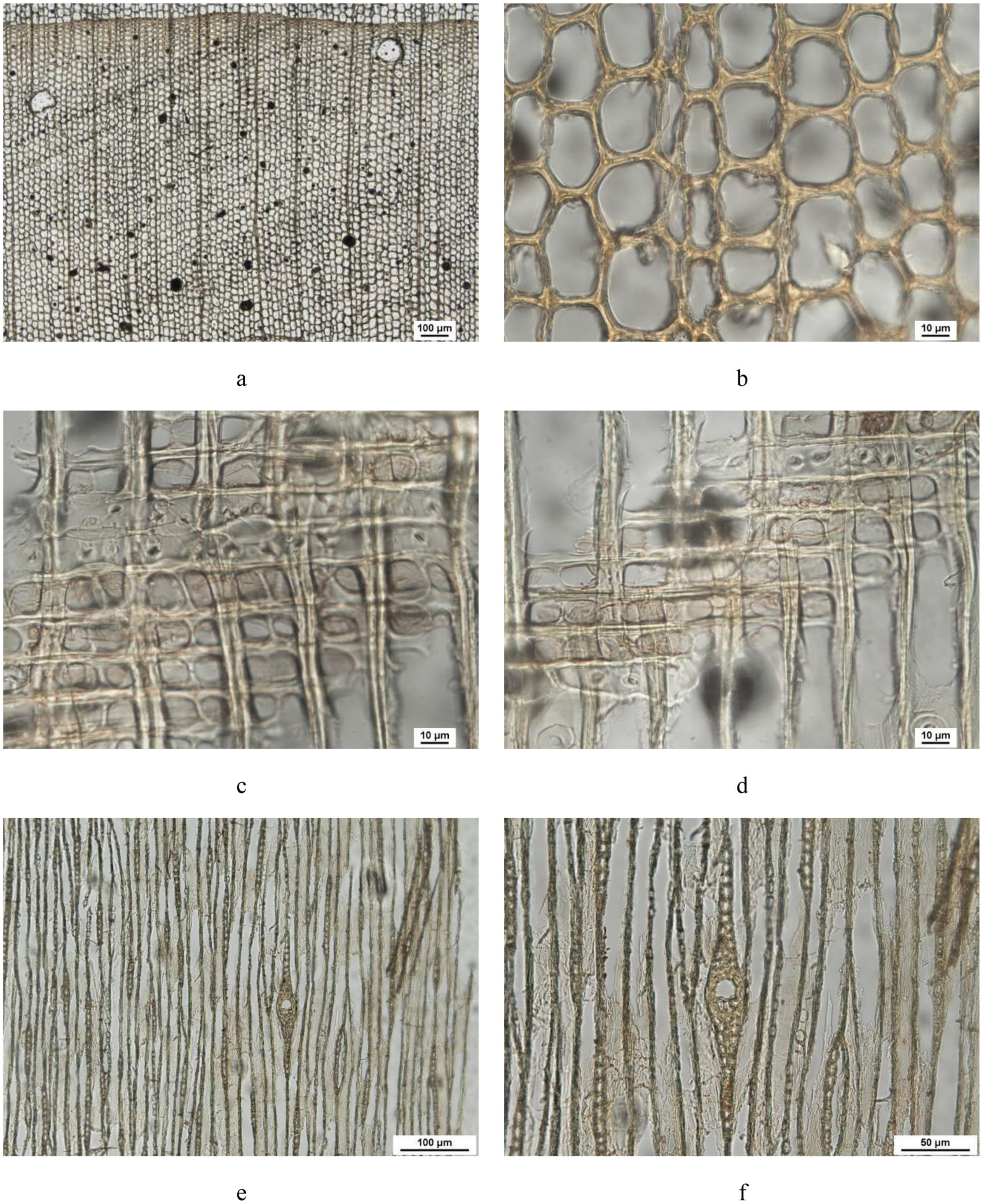

Fig. 3 | Anatomical structure of Group II wood. Identification result: *Pinus* sect. *Cembra*. **a** Transverse Section, 100×: growth ring boundaries slightly distinct; gradual transition from earlywood to latewood; earlywood tracheids with thin walls and latewood tracheids with thick walls; axial intercellular canals. **b** Transverse Section, 400×: earlywood tracheids with thin walls. **c** Radial Section, 400×, and **d** Radial Section, 400×: ray cells comprising ray tracheids and ray parenchyma cells; Cross-field pitting Window-like-type. **e** Tangential Section, 100×, and **f** Tangential Section, 200×: uniseriate ray and fusiform ray; radial intercellular canals.

Intercellular canals: Absent (Fig. 5a, b, e, f).

Quercus (Fagaceae) is classified into two subgenera: *Erythrobalanus* and *Lepidabalanus*. Within subg. *Lepidabalanus*, sect. *Cerris* is characterized by round/oval latewood vessels (few, thick-walled), minimal tyloses in earlywood vessels of heartwood, and wide, low, fusiform Ray composition; sect. *Prinus* exhibits irregular polygonal latewood vessels (numerous, thin-walled), abundant tyloses, and narrow, high, linear rays; sects. *Ilex* and *Suber* are diffuse-porous[14].

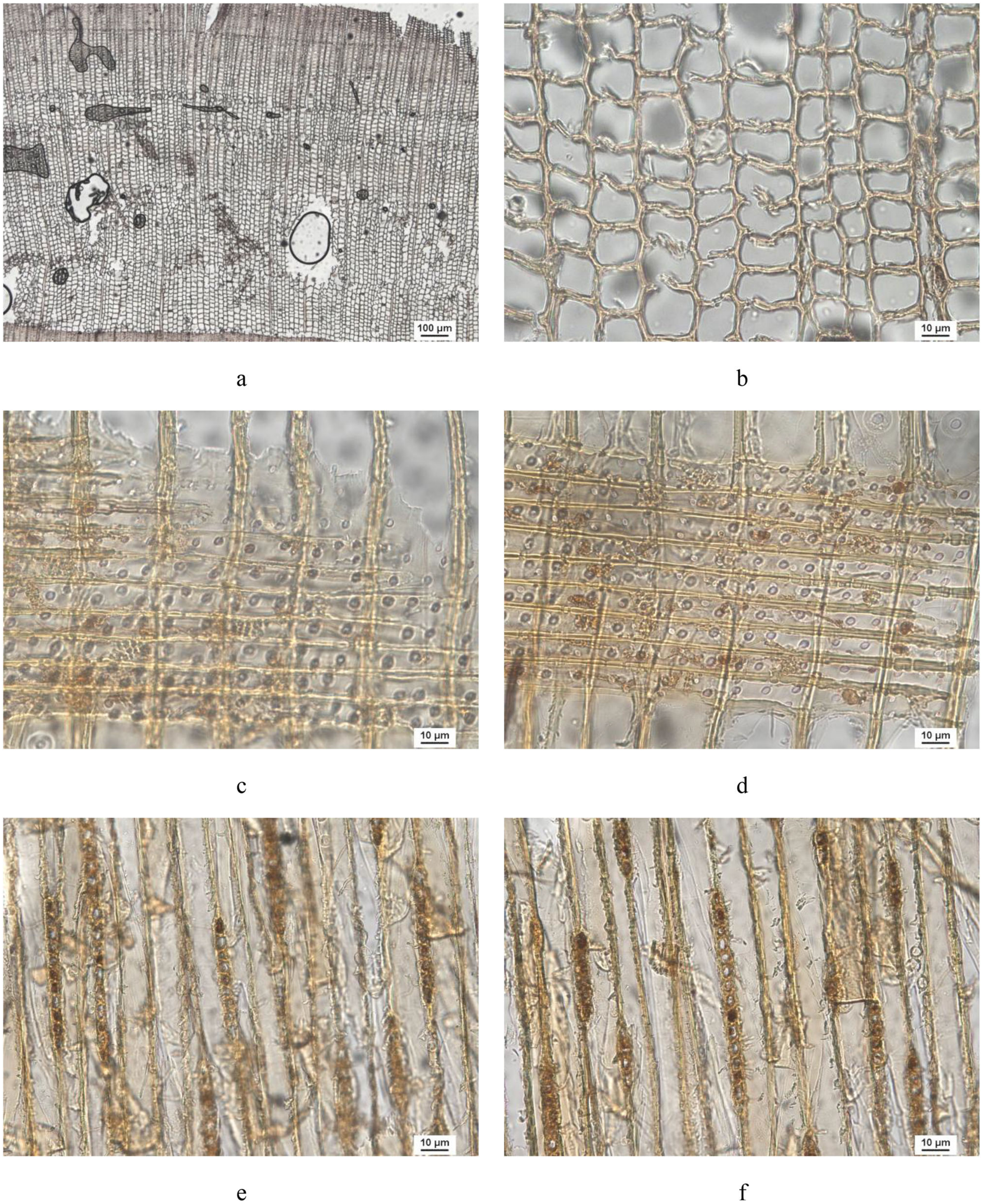

Fig. 4 | Anatomical structure of Group III wood. Identification result: *Cunninghamia lanceolate*. **a** Transverse Section, 100×: growth ring boundaries distinct; gradual transition from earlywood to latewood; earlywood tracheids with thin walls and latewood tracheids with thick walls; axial parenchyma diffuse and tangential banded; insect holes. **b** Transverse Section, 400×: earlywood tracheids with thin walls. **c** Radial Section, 400×, and **d** Radial Section, 400×: only ray parenchyma cells; Cross-field pitting Taxodioid-type (2–4 pittings). **e** Tangential Section, 400×, and **f** Tangential Section, 400× : uniseriate ray.

Microscopic comparisons confirmed that Group IV wood belongs to *Quercus* subg. *Lepidabalanus*, sect. *Cerris*[11,14,16,22–24].

Wood of *Quercus* sect. *Cerris*, e.g., *Q. variabilis*, *Q. acutissima*, *Q. chenii* has an air-dry density of 0.93 g/cm³, extremely high hardness and strength, and strong decay resistance[14], this is ideal for core load-bearing components such as columns that support the building's vertical load. However, it is susceptible to infestation by Anoplophora glabripennis and Lyctus brunneus[14]. *Quercus chenii* is widely distributed in Nanyang and

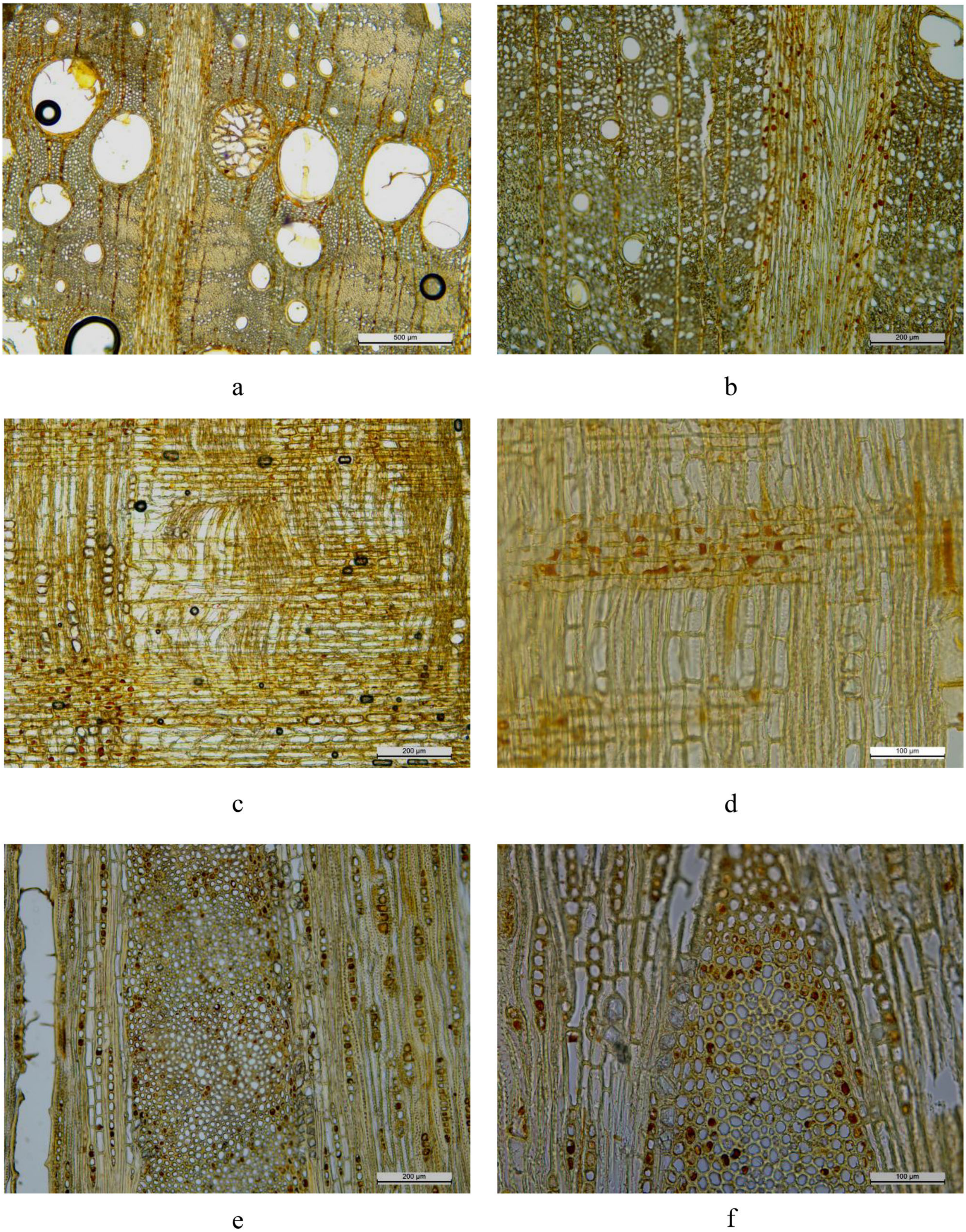

Fig. 5 | Anatomical structure of Group IV wood. Identification result: *Quercus* sect. *Cerris*. **a** Transverse Section, 40×: growth ring boundaries distinct; wood ring-porous, tyloses and deposits in earlywood vessels common; latewood vessels exclusively solitary, and in radial pattern; apotracheal axial parenchyma diffuse and diffuse-in-aggregates, axial parenchyma in narrow bands or lines up to three cells wide; rays of two distinct sizes—narrow and wide. **b** Transverse Section, 100×: latewood vessels exclusively solitary, and in radial pattern; apotracheal axial parenchyma diffuse and diffuse-in-aggregates, axial parenchyma in narrow bands or lines up to three cells wide; rays of two distinct sizes—narrow and wide. **c** Radial Section, 100×, and **d** Radial Section, 200×: vasicentric tracheids surrounding earlywood vessels; rhomboidal crystals present in axial parenchyma; all ray cells procumbent. **e** Tangential Section, 100×, and **f** Tangential Section, 200×: rays of two distinct sizes—narrow (uniseriate) and wide (>10-seriate rays).

southwestern Henan[14,15,25]. Column base decay observed in field investigations is attributed to long-term moisture exposure rather than insufficient decay resistance, highlighting the need for moisture-proof treatment in restoration.

Group V Wood: *Ulmus* sect. *Madocarpus*

Key anatomical characteristics of this wood Group (Samples No. 10, No. 14, No. 18: columns, beams) are presented in Fig. 6:

Growth rings: Growth ring boundaries are distinct (Fig. 6a).

Vessels: Wood ring-porous, earlywood vessels 1–3 cells wide (round, oval, or elliptical), tyloses and deposits in vessels common, and latewood vessels irregular polygonal (Fig. 6a); latewood vessels in tangential bands (Fig. 6b); latewood vessels clusters common and occasionally short radial multiples (2 vessels) (Fig. 6b); simple perforation plates (Fig. 6c); intervessel pitting alternate (Fig. 6c); helical thickenings only in narrower vessel elements, this is a diagnostic characteristic of *Ulmus* (Ulmaceae) (Fig. 6c, d).

Vasicentric tracheids: Absent.

Axial parenchyma: Abundant, mainly paratracheal axial parenchyma: axial parenchyma vasicentric in earlywood zone, and axial parenchyma bands more than three cells wide in latewood zone (Fig. 6a, b).

Ground tissue fibers: Fibers are very thick-walled with distinctly bordered pittings (Fig. 6c, d).

Ray type and composition: Larger rays commonly 4- to 10-seriate (Fig. 6a, b, e, f); all ray cells procumbent (Fig. 6c–f).

Intercellular canals: Absent (Fig. 6a, b, e, f).

Insect damage features: The transverse-section shows distinct insect holes (Fig. 6a), indicating weak insect resistance.

The genus *Ulmus* (Ulmaceae) is classified into two sections: *Madocarpus* and *Microptelea*. sect. *Madocarpus* (air-dry density ~0.65 g/cm^3) is lighter than sect. *Microptelea* (~0.90 g/cm^3) and is distinguished by its ring-porous vessels, well-developed spiral thickenings on latewood vessel walls, and multiseriate non-storied rays. Microscopic comparative analysis confirmed that Group V wood belongs to *Ulmus* sect. *Madocarpus*[11,14,16,22,23,26–30].

Wood of *Ulmus* sect. *Madocarpus*, e.g., *U. macrocarpa*, *U. pumila*, exhibits high hardness, excellent wear resistance, superior tangential compressive and bending strength, and esthetically pleasing grain patterns[14], making it a preferred choice for core load-bearing components such as columns, beams responsible for transmitting vertical and horizontal structural loads. *Ulmus macrocarpa* is widely distributed in southwestern Henan, while *U. pumila* is extensively cultivated as a local species in Nanyang[14,15]. However, consistent with prior research[14], this wood Group exhibits weak insect resistance, as evidenced by the distinct insect holes observed in transverse sections (Fig. 6a). This finding underscores the necessity of targeted insect-proof treatments, e.g., injection of environment-friendly insecticides during the restoration process to mitigate further biological deterioration.

Discussion

Based on the comprehensive identification results, the timber selection for the wooden components of the Sunjialou Cultural Relic Building exhibits dual core characteristics of functional adaptation and regional resource dependence, which collectively reflect the profound construction wisdom of Nanyang craftsmen during the late Qing Dynasty and the Republic of China.

Functional adaptation is reflected in precise matching of wood properties and component functions. A highly significant correlation was observed between the intrinsic properties of selected timbers and the functional requirements of building components, embodying the traditional construction philosophy of selecting materials based on their properties. High-strength, decay-resistant hardwoods such as *Quercus* sect. *Cerris*, *Ulmus* sect. *Madocarpus* were strategically employed for core load-bearing components. Specifically, *Ulmus* sect. *Madocarpus* exhibits an air-dry density of 0.65 g/cm^3, a bending strength of 80–90 MPa, and a tangential compressive strength of 32–40 MPa; in contrast, *Quercus* sect. *Cerris* possesses a higher air-dry density (0.90 g/cm^3), a bending strength of 97–140 MPa, and a tangential compressive strength of 44–61 MPa[14]. These mechanical properties fully meet the stringent load-bearing requirements of core structural elements, ensuring the long-term structural stability. Decay-resistant, lightweight softwoods with straight grains such as *Larix* sect. *Multiseriales*, *Cunninghamia lanceolata* were selected for secondary load-bearing components. Their lightweight nature effectively reduces the overall structural load imposed on the core system, while their inherent decay resistance inhibits fungal colonization and decomposition, thereby extending the service life of these components. Easily workable, fine-textured softwoods such as *Pinus* sect. *Cembra*, specifically *P. armandii* were prioritized for non-load-bearing/decorative components. The light and soft texture of Pinus armandii facilitates intricate carving and processing, enabling the realization of elaborate decorative patterns that align with local folk esthetic preferences.

Regional resource dependence is embodyted in the utilization of local or near-source materials. The timber selection in the paper strictly adheres to the time-honored principle of “local or near-source material utilization”, which is closely linked to the regional resource endowments and transportation conditions of the era. Local material utilization, such as *P. armandii*, *Cunninghamia lanceolata*, *U. macrocarpa*, and *Q. chenii* are either native species or widely cultivated in Nanyang and southwestern Henan. The adoption of local timbers eliminated the need for long-distance transportation, significantly reducing construction costs and minimizing material during transit. Near-source material utilization, i.e., *Larix* sect. *Multiseriales* is naturally distributed in the Qinling Mountains, which are geographically adjacent to Nanyang. During the late Qing Dynasty and the Republic of China, this timber could be transported via short-distance overland routes, making it a practical near-source alternative when local softwood supplies were insufficient for secondary load-bearing components. This characteristic not only reflects the dependence of Nanyang’s modern construction supply chain on local forest resources, e.g., Funiu Mountains, Tongbai Mountains but also confirms the constraining influence of transportation capacity on timber selection in ancient construction practices. Collectively, these findings provide critical tangible evidence for reconstructing the regional construction techniques and resource utilization patterns of modern-era architecture in southwestern Henan.

This study systematically identified the timber species of wooden components in the Sunjialou Cultural Relic Building through microscopic anatomical observation and taxonomic comparison, timber species composition was clarified. This research systematically establishes the timber species pedigree of the building’s wooden components, filling the gap in current knowledge of the material composition for this heritage site.

Dual-core selection principles are also explained. The timber selection for the Sunjialou Cultural Relic Building is characterized by distinct functional adaptation and regional resource dependence. Functional adaptation reflects the rational construction logic of traditional craftsmen, while regional resource dependence embodies the tradition of local or near-source material utilization during the late Qing Dynasty and the Republic of China. The dual core selection principles indicates efficient resource utilization strategies and the practical wisdom of regional craftsmen.

The research results provide guidance for subsequent restoration and replacement. The identification results clarify the original timber species for each functional component, providing a robust scientific foundation for adhering to the principles of minimum intervention and authenticity protection in restoration work. To avoid restoration failure caused by inappropriate species selection, the following recommendations are proposed in accordance with Article 7.2.1 of “*Technical Standard for Maintenance and Strengthening of Ancient Timber Structures*”(GB/T 50165—2020)[31]. One is priority to original species. For columns and beams, prioritize the use of *Quercus* sect. *Cerris* and *Ulmus* sect. *Madocarpus*, supplemented by targeted insect-proof and moisture-proof treatments; for purlins and rafters, select *Larix* sect. *Multiseriales* and *Cunninghamia lanceolata*, with emphasis on sapwood preservation, e.g., traditional tung oil coating, application of modern environment-friendly preservatives; for doors and windows, prioritize *P. armandi* to ensure consistency in processing performance and

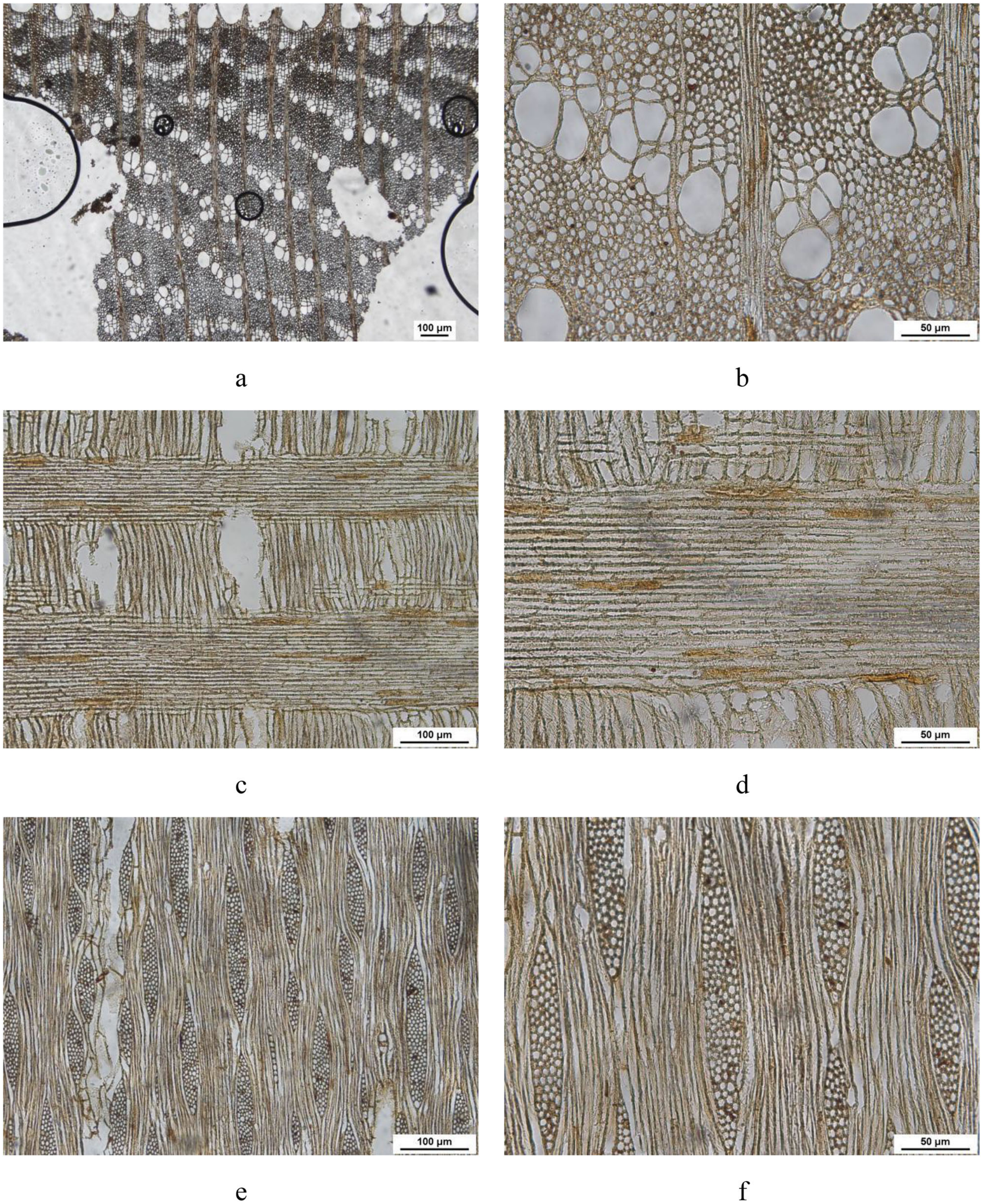

Fig. 6 | Anatomical structure of Group V wood. Identification result: *Ulmus* sect. *Madocarpus*. **a** Transverse Section, 100×: growth ring boundaries distinct; wood ring-porous; latewood vessels clusters common, and in tangential bands; apotracheal axial parenchyma diffuse and diffuse-in-aggregates, axial parenchyma in narrow bands or lines up to three cells wide. **b** Transverse Section, 200×: latewood vessels clusters common, and in tangential bands; apotracheal axial parenchyma diffuse and diffuse-in-aggregates, axial parenchyma in narrow bands or lines up to three cells wide. **c** Radial Section, 100×, and **d** Radial Section, 200×: helical thickenings only in narrower vessel elements; simple perforation plates; all ray cells procumbent. **e** Tangential Section, 100×, and **f** Tangential Section, 200×: larger rays commonly 4- to 10-seriate.

decorative effects. The other is scientific selection of alternative species. In cases where original species, e.g., high-quality large-diameter *Larix* sect. *Multiseriales*, *Quercus* sect. *Cerris* are scarce, alternative species should be selected in accordance with Tables 7.2.1-1 and 7.2.1-2 of "*Technical Standard for Maintenance and Strengthening of Ancient Timber Structures*" (GB/T 50165—2020)[31]. The selected alternatives must have strength grades not lower than those of the original components, and priority should be given to species within the same genus with equivalent mechanical properties, e.g., substitute species for *Quercus* sect. *Cerris* should be selected from the *Quercus* genus with comparable density and strength.

In summary, this study provides a scientific basis for the precise restoration of wooden components in the Sunjialou Cultural Relic Building and serves as a representative case study for constructing timber species databases, restoring regional construction techniques, and investigating resource utilization patterns of modern-era ancient architecture in southwestern Henan. It holds significant reference value for the conservation and restoration of similar ancient wooden structures across China.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to the confidentiality requirements of cultural heritage protection units of Nanyang City but are available from the corresponding author on reasonable request.

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References

1. Li, R. et al. Combining microscale ATR-FTIR and chemometrics to interpret degradation characteristics of earlywood, latewood, and compression wood in waterlogged archaeological pine wood. *npj Herit. Sci.* **12**, 387 (2024).
2. Kiliç, N. Determining the condition of waterlogged archaeological woods and iron nails from the yenikapı 17 shipwreck using multiple analytical techniques. *npj Herit. Sci.* **13**, 64 (2025).
3. Chu, S. et al. Degradation condition and microbial analysis of waterlogged archaeological wood from the second shipwreck site on the northwestern continental slope of the South China Sea. *npj Herit. Sci.* **13**, 10 (2025).
4. Alfredsen, G. et al. Characterisation of wood decay and fungal diversity in cultural heritage cable car pylons in Svalbard. *npj Herit. Sci.* **13**, 463 (2025).
5. Felle, T. K., Emmerich, L., Humar, M. & Brischke, C. Impact of fungal decay on the structural integrity of wood. *Eur. J. Wood Wood Prod.* **84**, 1–10 (2026).
6. Wang, P., Li, S., Macchioni, N., Palanti, S. & Milani, G. Comprehensive evaluation method of historical timber structural building taking Fujiu Zhou house as an example. *Forests* **12**, 1172 (2021).
7. Liu, B., Fu, Y. J., Ma, X. X., Lu, Y. & Wang, L. Relationship between wood species selection and biological diseases of ancient building wooden components in severe wood biological diseases area. *Sci. Silvae Sin.* **57**, 108–121 (2021).
8. Yang, Y. et al. Study on the identification and the extent of decay of the wooden components in the Xichuan Guild Hall ancient architectures. *Int. J. Archit. Herit.* **16**, 405–414 (2022a).
9. Yang, Y., Li, B., Liu, Y. Q., Zhang, W. Q. & Wang, C. B. Identification of tree species and extent of material deterioration of wood components in the Yangjia Courtyard ancient building. *For. Prod. J.* **73**, 82–93 (2023).
10. Yang, Y. et al. Wood utilized for wooden components in ancient buildings of Tingbao Yang's former residence. *IAWA J.* **45**, 535–552 (2024).
11. Yang, Y., Ji, H. D., Li, B. & Liu, Y. F. Identification of the wood species and relationship between the wood species selection and the occurrence of biological diseases in wooden components within ancient wooden-structure building of Songyun Temple. *Int. J. Archit. Herit.* **19**, 1870–1882 (2025).
12. Richter, H. G., Grosser, D., Heinz, I. & Gassib, P. E. IAWA list of microscopic features for softwood identification. *IAWA J.* **25**, 1–70 (2004).
13. Wheeler, E. A., Baas, P. & Gasson, P. E. IAWA list of microscopic features for hardwood. *IAWA J.* **10**, 219–232 (1989).
14. Cheng, J. Q., Yang, J. J. & Liu, P. *Atlas of Chinese Woods* (China Forestry Publishing House (in Chinese), 1992).
15. National Technical Committee on Wood Standardization of China. *Names of Chinese Main Woods (GB/T 16734-1997)* (China Standards Press (in Chinese), 1997).
16. Giachi, G. et al. Identification of wood from Roman ships found in the docking site of Pisa (Italy). *J. Cult. Herit.* **23**, 176–184 (2017).
17. Zhang, H. Y., Shen, D. W., Zhang, Z. G. & Ma, Q. L. Characterization of degradation and iron deposits of the wood of Nanhai I shipwreck. *Herit. Sci.* **10**, 202 (2022).
18. Editorial Committee of Flora of China, Chinese Academy of Sciences. *Flora of China* Vol. 7 (Science Press, (in Chinese), 1978).
19. Yang, Y. et al. Evaluation of the decay levels of wooden components in arcade buildings in the ancient town Chikan via polarized light, fluorescence and FTIR spectra. *Wood Res.* **67**, 545–557 (2022b).
20. Wang, X. Y., Chen, W. W., Liang, Y. H. & Li, N. S. Physical and chemical degradation characteristics of waterlogged archaeological wood from the Wenzhou No.1 shipwreck. *Herit. Sci.* **13**, 520 (2025).
21. Gao, Q. H., You, J., Liao, X. M. & Wang, Z. G. Identification and analysis of ancient ship wood excavated at Nantong Hydraulic Site. *BioResources* **18**, 5028–5040 (2023).
22. Yang, Y. et al. Internal cause analysis of damage of wooden components in Danxia Temple ancient architectures: tree species. *Wood Res.* **66**, 297–308 (2021).
23. Dong, M. Y. et al. AMS 14C dating and wood identification in ancient timber structures in Shanxi Province, China. *J. Archaeol. Sci. Rep.* **13**, 361–371 (2017).
24. Yeon, J. A. & Park, W. K. Species identification of wooden elements used for Daewungjeon Hall in the Bukjijangsa Temple, Daegu, Korea. *J. Korean Wood Sci. Technol.* **41**, 201–210 (2013).
25. Editorial Committee of Flora of China, Chinese Academy of Sciences. *Flora of China* Vol. 21 (Science Press (in Chinese), 1979).
26. Dong, M. Y. et al. Wood used in ancient timber architecture in Shanxi Province, China. *IAWA J.* **38**, 182–200 (2017).
27. Zhang, W. H. et al. Identification of the wood from chariots unearthed at the Yaoheyuan site in Ningxia and related issues. *Archaeol. Cult. Relics* **8**, 124–128 (2025).
28. Mayinuer, A. H. G. L., Feng, D. J. & Zhao, J. F. Identification of unearthed woods from timber components of stilt-style architecture at Hemudu site. *J. Northwest For. Univ.* (in Chinese) (in press). https://link.cnki.net/urlid/61.1202.s.20250605.1735.002 (2025).
29. Macchioni, N. et al. Timber structures of florence cathedral: wood species identification, technological implication and their forest origin. *Forests* **14**, 1733 (2023).
30. Wang, R. H., Shang, Y. P., Cheng, Y. M., Pan, B. & Jiang, H. G. Wood utilization and cultural integration indicated by woodware excavated from ancient Turpan, Xinjiang. *Herit. Sci.* **13**, 184 (2025).
31. Ministry of Housing and Urban-Rural Development of the People's Republic of China, State Administration for Market Regulation of the People's Republic of China. *Technical Standard For Maintenance and Strengthening of Ancient Timber Structures (GB/T 50165-2020)* (China Architecture & Building Press (in Chinese), 2020).

Author contributions

X.H.Q.: writing-original draft preparation; W.T.Z.: writing-original draft preparation; M.X.F.: writing—original draft preparation; X.H.L.: experiment operation; T.Y.X.: experimental operation; Z.Y.L.: experimental operation;

H.D.J.: data interpretation; B.L.: data interpretation; Y.Y.: reviewing and editing. All authors read and approved the final manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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