Structural Characteristics, Deterioration, and Conservation of Historic Timber Arch Covered Bridges: A Field-based Case Study in Shouning and Taishun Counties, China

Lei Liu, Qifang Xie, and Zhiqiang Qin *

Historic timber covered bridges are important examples of traditional timber engineering and cultural heritage in southeastern China. This study presents a field-based investigation of 10 historic timber covered bridges in Shouning County, Fujian Province, and Taishun County, Zhejiang Province, together with one contemporary reference bridge. The investigation documents structural characteristics, roundwood geometric variability, visible deterioration, connection anomalies, repair traces, and conservation and adaptive-use conditions. Field observations indicate that cracking, suspected biological deterioration, localized material loss, and joint anomalies should be interpreted in relation to the structural configuration and natural variability of timber members. Taper, unequal end diameters, and curvature may reflect intrinsic roundwood characteristics rather than service-induced deterioration. Steel hoops, rope restraints, and apparent replacement traces further highlight the importance of documenting previous interventions. The findings also emphasize the protective function of the covered superstructure and the need to consider moisture exposure in timber conservation. Based on the observed conditions and established heritage conservation principles, a four-level framework is proposed to integrate material protection, component and joint assessment, structural-system monitoring, and conservation management. The investigation provides a descriptive field baseline and bridge-specific conservation priorities without assuming statistically representative differences between construction periods or geographical regions.

DOI: 10.15376/biores.22.1.517-534

Keywords: Timber arch covered bridge; Field survey; Deterioration; Structural characteristics; Repair intervention; Conservation

*Contact information: School of Civil Engineering and Transportation, Northeast Forestry University, Harbin 150040, China; *Corresponding author: Zhiqiang Qin 1583249776@qq.com*

INTRODUCTION

Timber arch covered bridges are a distinctive form of traditional Chinese timber engineering, with surviving examples concentrated mainly in southern Zhejiang and northern Fujian. Their principal load-bearing system consists of two interlaced polygonal arch systems assembled from roundwood members, with a covered bridge house above the deck (Yang *et al*. 2012; Yang *et al*. 2019; Chen *et al*. 2022). The basic structural form of the timber arch covered bridge is shown in Fig. 1. The structural response of these bridges depends on interactions among overlapping members, joints, and supporting components.

The bridges also preserve traditional carpentry knowledge and living craft practices, giving them both engineering and cultural-heritage value (Yang *et al*. 2012; Chen *et al*. 2022).

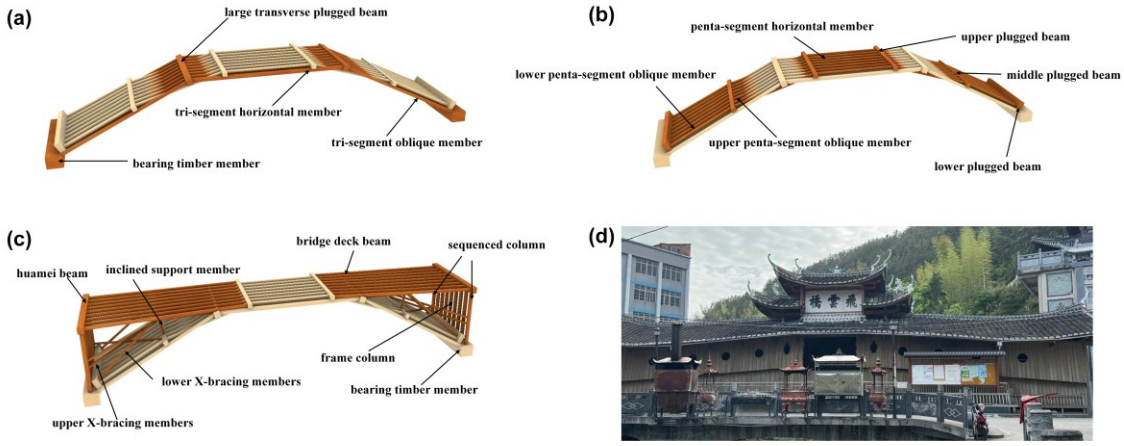


Fig. 1. Structural configuration of a timber arch covered bridge: (a) Tri-segment arch system; (b) penta-segment arch system; (c) assembled structural framework; and (d) overall view of Feiyun Bridge

Previous studies have substantially improved understanding of their structural behavior and safety. Mechanical and finite-element investigations have clarified the cooperative action of the woven arch systems (Yang *et al*. 2019), while quantitative methods have been developed for structural-safety evaluation and component importance (Han *et al*. 2022; Ye *et al*. 2024). Seismic- and wind-related studies have further highlighted the effects of site conditions, deterioration, structural configuration, and environmental actions (Gao *et al*. 2025; Song *et al*. 2025). For timber structures more broadly, decay, insect attack, moisture-related degradation, cracking, and section loss can reduce structural performance, while repair decisions must also consider compatibility, reversibility, and long-term effectiveness (Dewey *et al*. 2018; Degl'Innocenti *et al*. 2022; Nocetti *et al*. 2023; Rashidi *et al*. 2025).

For historic timber arch covered bridges, however, structural condition cannot be understood only from isolated mechanical analysis. Deterioration is distributed unevenly among members and joints, and field interpretation is complicated by the natural characteristics of roundwood. Taper, unequal end diameters, knots, and initial curvature may be part of the original material and construction practice rather than service-induced damage. At the same time, long-term maintenance leaves visible intervention traces, such as member replacement, metallic confinement, temporary restraint, or supplementary support. These physical conditions coexist with different present-day uses, ranging from everyday community circulation to heritage interpretation and tourism.

Existing heritage studies have discussed the reconstruction, cultural value, and continued use of timber arch covered bridges in the Min-Zhe (Fujian–Zhejiang) region (Chen *et al*. 2022; Yang *et al*. 2025), but multi-bridge field investigations that connect construction characteristics, deterioration, repair traces, and current conservation conditions remain limited. A field-based perspective is therefore useful for identifying recurrent condition problems, distinguishing original construction irregularities from later damage, and understanding how physical preservation interacts with maintenance and adaptive use.

Qin *et al.* (2026) investigated UAV-based defect detection, segmentation, quantification, and crack distribution in heritage timber arch bridges. Building on this work, the present study examines field observations from 10 historic timber arch covered bridges and one contemporary reference bridge in Shouning and Taishun Counties, focusing on structural characteristics, material deterioration, connection anomalies, intrinsic roundwood geometry, repair traces, and conservation conditions. Its main contribution is an integrated, multi-bridge account of these interrelated conditions and conservation recommendations tailored to the structural characteristics and continued use of traditional timber arch covered bridges.

The study addresses three questions: (1) What types of material deterioration, connection anomalies, and roundwood geometric irregularities are documented in the surveyed bridges? (2) Which observable features support a provisional distinction between intrinsic roundwood geometry and suspected service-related deformation, and where does uncertainty remain? (3) How can the documented conditions and previous interventions inform priorities for further inspection and conservation? These questions are addressed through qualitative field observations and literature-informed engineering interpretation.

STUDY AREA AND SURVEY METHODOLOGY

Study Area and Survey Design

The investigation focused on Shouning County in Fujian Province and Taishun County in Zhejiang Province, two localities within the Min-Zhe timber arch covered-bridge region (Yang *et al*. 2012; Chen *et al*. 2022). The primary dataset of the present paper was an intensive field survey of 11 bridges: 10 historic bridges and Qifeng Bridge, a contemporary reference structure in Shouning County. The investigated bridges constitute a purposive case-study sample rather than a statistically representative selection of historic covered bridges in either province.

Figure 2 summarizes the regional distribution of timber arch covered bridges and the field-survey routes used in the present study.



Fig. 2. The distribution of wooden arch bridges in Zhejiang and Fujian, and the locations of field surveys. Regional bridge-distribution information was adapted from W-Bridge (2026).

Surveyed Bridges

Seven historic bridges were surveyed in Shouning County: Xiangong, Dengyun, Risheng, Feiyun, Shangxiaodong, Dabao, and Liren Bridges. Three were surveyed in Taishun County: Beijian, Xidong, and Chiyuan Bridges. Qifeng Bridge in Shouning County was included as the single modern reference case. Because only one modern bridge was investigated, the historic-modern comparison is descriptive rather than statistical. The surveyed bridges and their roles in the present field investigation are listed in Table 1.

At each bridge, whole-bridge and close-range photographs were collected to document the woven arch system, deck and covered-house components, accessible joints, visible deterioration, geometric irregularities, and repair traces. Close inspection was limited to joints and connection regions that could be observed with sufficient clarity from accessible field viewpoints and the corresponding close-range photographs. Concealed tenon interfaces, obstructed contact surfaces, and connection regions without adequate visual access were classified as not assessable. Therefore, the absence of a recorded anomaly at an inaccessible joint was not interpreted as evidence of satisfactory joint condition.

Table 1. Bridges Included in the Primary Field Survey

Bridge	County	Construction and Reconstruction History	Reported arch span (m)	Structural configuration
Xiangong	Shouning	Origin attributed to the Ming Tianshun period	24.5	Historic woven timber arch
Dengyun	Shouning	Constructed in 1771 to 1773	Not verified	Historic woven timber arch
Risheng	Shouning	Not established	Not verified	Historic timber arch; details not verified
Feiyun	Shouning	Origin attributed to the Ming Tianshun period	Not verified	Historic woven timber arch
Shangxiaodong	Shouning	Not established	16.4	Historic timber arch; details not verified
Dabao	Shouning	Reconstructed in 1878	33.1	Historic woven timber arch
Liren	Shouning	Not established	Not verified	Historic timber arch; details not verified
Beijian	Taishun	Built in 1674; rebuilt in 1803	29.0	Historic woven timber arch
Xidong	Taishun	Built in 1570; rebuilt in 1745	25.7	Historic woven timber arch
Chiyuan	Taishun	Rebuilt in 1857	Not verified	Eight-shaped braced timber arch
Qifeng	Shouning	Completed in September 2024	36.6, single-arch span	Contemporary timber arch reference

Note: Construction and reconstruction information and reported spans were compiled from available documentary sources. The reported span values were not independently measured during this investigation and should not be assumed to represent consistently defined clear spans. Comparable member-dimension measurements were unavailable for the surveyed bridges.

The available documentation does not provide a complete joint-by-joint accessibility inventory. Accordingly, condition interpretations are restricted to the documented accessible regions, and no conclusion about the condition of inaccessible joints is drawn. Current use, tourism-related facilities, environmental management, and visible maintenance conditions were also recorded.

Field Inspection and Condition Classification

Structural configuration was documented separately from condition assessment. The field observations were organized into six categories: material deterioration, connection anomalies, geometric condition, roundwood characteristics, repair and strengthening traces, and conservation and use context (Table 2). To improve the consistency of qualitative condition assessment, each category was defined using observable physical indicators. A condition was considered visually identifiable when its characteristic features could be distinguished in accessible field views or photographs. Features that suggested deterioration but lacked sufficient diagnostic evidence were interpreted as suspected conditions, whereas concealed or insufficiently visible components were regarded as not assessable. These criteria were intended to support the identification and description of visible conditions rather than to establish quantitative damage severity or structural safety ratings (Cruz *et al*. 2015).

Table 2. Condition Categories Used in the Field Survey

Category	Visual Identification Criteria
Material deterioration	Visible cracks, suspected decay, insect-associated holes, and local material loss
Connection anomalies	Suspected tenon withdrawal: visible relative withdrawal or reduction in apparent engagement; joint separation: open interfaces; suspected looseness: gaps or offsets; local dislocation: relative member misalignment
Geometric condition	Suspected deformation indicated by sagging, inclination, or distortion accompanied by displacement, crushing, or misalignment
Roundwood characteristics	Natural taper, unequal end diameters, knots, and curvature without clear evidence of structural distress
Repair/strengthening traces	Visible steel hoops, plates, bolts, ropes, apparent replacement traces, or supplementary supports
Conservation/adaptive use	Visible maintenance conditions, tourism facilities, signage, environmental management, and community use

Timber arch covered bridges in the Min-Zhe region traditionally relied on locally available wood. Available construction records and previous investigations indicate that Chinese fir (*Cunninghamia lanceolata*) was the predominant timber used in the main structural members, while harder pine timber was sometimes selected for some highly stressed or transverse load-transfer members. For example, Han *et al*. (2022) reported Chinese fir for most members of Wenxing Bridge and Chinese pine for its transverse plugged beams. In the present investigation, however, anatomical sampling and microscopic species identification were not performed for every member of the 11 surveyed bridges. Timber species were therefore not assigned solely from surface appearance, and the above material description represents the established regional construction practice rather than member-by-member laboratory confirmation.

Natural durability varies with wood species, tissue type, and exposure conditions. EN 350:2016 classifies wood durability against biological agents, distinguishing heartwood from sapwood (CEN 2016). Laboratory tests have reported some resistance of Chinese fir (*Cunninghamia lanceolata*) to brown-rot fungi, although substantial losses in mechanical properties may still occur (Li *et al*. 2019). Because species and heartwood/sapwood status were not verified for individual members, no specific EN 350 durability classes were assigned. Wood moisture content and microclimatic conditions were not directly monitored. Accordingly, insect-associated damage and suspected fungal decay were identified by visible symptoms only, without assigning insect taxa or decay types (*e.g*., brown rot, white rot, or soft rot) in the absence of biological or anatomical verification.

The visual condition survey followed a qualitative screening procedure informed by established guidance for the on-site assessment of historic timber structures (Cruz *et al*. 2015). Conditions were classified as directly visible, suspected, or not assessable according to the clarity and accessibility of the field observation. A feature was classified as directly visible when its defining physical characteristics could be distinguished during accessible field inspection or in the corresponding photographic documentation. Features suggesting deterioration but lacking sufficient diagnostic evidence were classified as suspected, whereas concealed or insufficiently visible regions were designated as not assessable.

Because calibrated dimensional measurements and baseline joint-displacement records were unavailable for all bridges, no retrospective numerical thresholds were established for crack width, tenon withdrawal, joint opening, or member misalignment. These operational criteria were intended to improve the consistency and transparency of qualitative documentation; their inter-observer reproducibility was not formally evaluated. Suspected tenon withdrawal was identified by visible withdrawal or reduced apparent engagement; suspected looseness by abnormal gaps, offsets, or positioning without mechanical verification; and local dislocation by relative offsets between connected members not reasonably attributable to original geometry.

Natural taper, unequal end diameters, knots, and smooth curvature were provisionally classified as intrinsic roundwood characteristics when no signs of structural movement were visible. Curvature or misalignment accompanied by abnormal sagging, joint displacement, local crushing, or relative movement was treated as a suspected service-related anomaly. Without as-built records or baseline measurements, this distinction remains an observational inference rather than a definitive reconstruction of original member geometry.

Data Analysis

The field evidence was examined qualitatively using the available photographic documentation and observations of accessible structural components. The analysis focused on representative condition types, construction variability, and visible intervention traces across the investigated cases. The available records do not constitute an exhaustive defect inventory of all members and connections. Qifeng Bridge was used only as a contemporary construction reference, and no inferential comparisons were made between construction periods or counties. No inferential statistical comparison was conducted between historic and contemporary bridges or between the two counties. Observed differences in construction, deterioration, maintenance, and current use are therefore interpreted as case-specific characteristics rather than representative regional patterns.

STRUCTURAL CHARACTERISTICS AND CONTEMPORARY REFERENCE OBSERVATIONS

Common Structural Characteristics of the Historic Bridges

Most of the historic bridges surveyed represent the characteristic Min-Zhe woven-arch tradition, although the structural configurations are not identical across all cases. The typical woven-arch system consists of interlaced tri-segment and penta-segment polygonal arch systems assembled from overlapping roundwood members. Chiyuan Bridge, in contrast, is classified as an eight-shaped braced timber arch (Yang *et al*. 2012; Yang *et al*. 2019; Chen *et al*. 2022). Transverse, deck, vertical, and covered-house components complete the superstructure. Although this construction logic is common, the bridges differ in member dimensions, roundwood geometry, local detailing, repair history, and the extent of component replacement. Representative overall views and principal structural systems of the surveyed historic bridges are shown in Fig. 3.

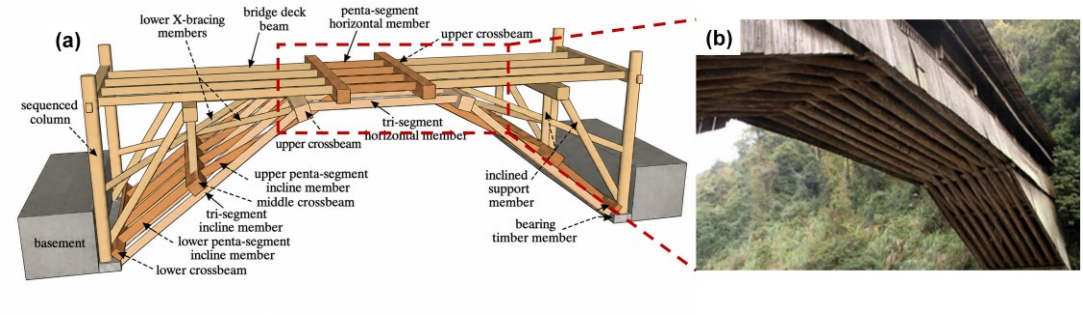


Fig. 3. Representative overall views and principal structural systems of the surveyed historic bridges

Roundwood Geometry and Construction Variability

Visual inspection revealed readily observable differences in roundwood geometry among some historic members, including taper, unequal end diameters, and curvature. These features may reflect natural tree geometry and traditional material selection rather than deterioration. However, systematic measurements of member diameters, taper ratios, and curvature were not obtained. Accordingly, the observed geometric variability is described qualitatively and is not interpreted as a quantified dimensional distribution.



Fig. 4. Examples of visually observed roundwood geometric variability: (a) apparent size differences among comparable members; (b) unequal apparent end diameters; and (c) curvature of a roundwood member. These observations do not establish whether the geometric features originated during construction or developed during service.

A curved or non-prismatic member was provisionally interpreted as an intrinsic geometric characteristic unless accompanied by evidence such as abnormal sagging, joint displacement, local crushing, or misalignment. This distinction is important for later deterioration analysis because dimensional non-uniformity is part of the historic construction record and should not automatically be interpreted as damage or poor workmanship. Representative examples of intrinsic roundwood geometric variability observed in the field are shown in Fig. 4.

Qifeng Bridge as a Modern Construction Reference

Qifeng Bridge, located in Kengdi Village, Shouning County, Fujian Province, was completed in September 2024. According to published construction records, the bridge has a single-arch span of 36.6 m and a width of 6.6 m. In the present study, it serves as a contemporary construction reference for the surveyed historic bridges. The comparison is restricted to directly observable features, including member regularity, dimensional consistency, overall alignment, and visible material condition. It is not intended to support general conclusions about the structural performance or durability of modern timber arch covered bridges.

Where the modern bridge shows more regular geometry, the difference may reflect contemporary material selection, processing, and construction control, whereas the historic cases preserve greater natural variability and accumulated maintenance history. These observations are interpreted as construction differences rather than as evidence of inherently superior structural performance or heritage value. Representative field comparisons of member geometry and structural arrangement between the historic bridges and the contemporary reference bridge are shown in Fig. 5.



Fig. 5. Illustrative field views of a historic timber arch covered bridge (a) and Qifeng Bridge (b, c). The photographs document visible structural arrangements from different viewpoints and are not used for quantitative dimensional comparison.

Implications for Deterioration Assessment

The structural observations establish the boundary for the deterioration analysis that follows. Natural taper, unequal end diameters, initial curvature, and local geometric variability were provisionally interpreted as intrinsic construction characteristics, whereas cracking, decay, insect damage, material loss, tenon withdrawal, joint separation, and abnormal deformation are treated as condition-related phenomena. Subsequent interpretation therefore relies on field context rather than geometric appearance alone.

DETERIORATION CHARACTERISTICS OBSERVED IN THE FIELD

Major Deterioration Types

The 11-bridge survey identified recurring material deterioration, connection anomalies, and geometric changes. Material-level observations included cracking, suspected fungal deterioration, insect-associated surface holes, and localized material loss. The responsible insect taxa and fungal decay types could not be reliably determined from visual evidence alone. Connection-related conditions included tenon withdrawal, visible separation, looseness, and local dislocation. Service-related bending or misalignment was recorded as a geometric condition only when field evidence suggested change beyond the original roundwood form.

Cracking was frequently observed during the field inspections, but the condition of the surveyed bridges cannot be adequately described by a single deterioration type. Suspected biological deterioration and local material loss may affect timber integrity, whereas joint withdrawal and separation may influence the interaction of connected members. The structural significance of each condition depends on its location, extent, structural role, and relationship with adjacent components. Representative examples are shown in Fig. 6.

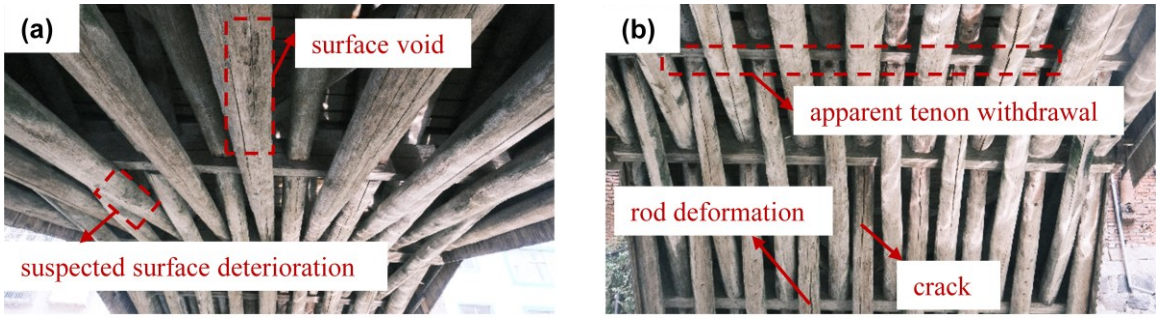


Fig. 6. Representative observed conditions in the surveyed bridges: (a) suspected surface deterioration and localized surface voids of undetermined origin; (b) visible cracking, apparent tenon withdrawal, and member curvature. The biological causes of the surface features and the origin of the curvature were not verified.

Cracking and Connection Anomalies

Cracks were observed in both principal woven-arch systems and in members with different orientations. Their appearance varied from relatively localized surface checks to more evident splitting associated with member ends, contact regions, or connection zones. Because the study relied on field observations rather than local stress measurements, crack locations were interpreted qualitatively and were not used to assign a unique mechanical cause.

Connection anomalies included tenon withdrawal, visible opening, local looseness, and relative displacement between connected members. These conditions are important because the structural behavior of the bridge depends on the interaction of many overlapping components. The structural significance of a joint gap depends on its location, residual engagement, contact conditions, and evidence of progression; apparent stability alone does not establish adequate force transfer.

Decay, Insect Damage, and Material Loss

Visible evidence of biological deterioration was documented in the surveyed bridges, including surface discoloration, localized material loss, and holes consistent with insect-associated activity. Wood-destroying insects relevant to timber structures include termites and wood-boring beetles, although their damage characteristics and ecological requirements differ. In the present survey, the observed surface holes could not be reliably attributed to particular insect taxa because no diagnostic insect specimens or species-specific gallery characteristics were documented. In particular, the available observations do not establish whether termite activity was present in the affected members. The recorded features are therefore described as insect-associated damage of undetermined origin rather than as confirmed termite or beetle attack.

Similarly, visible surface deterioration does not necessarily reveal the internal extent of biological damage or permit reliable differentiation among fungal decay types. Where internal deterioration or loss of effective cross-section is suspected, targeted diagnostic testing may be necessary before conclusions about residual structural capacity are drawn (Riggio *et al*. 2018; Rashidi *et al*. 2021; Degl'Innocenti *et al*. 2022; Nocetti *et al*. 2023).

The covered superstructure reduces direct rainfall exposure, although localized wetting may still occur near roof defects, drainage paths, and connection interfaces. Because bridge-specific leakage conditions were not systematically documented, the observed timber deterioration cannot be attributed directly to roof leakage. The potential role of moisture is discussed further in the following section.

Geometric Change and Interpretation Limits

The survey confirmed that apparent curvature must be interpreted cautiously. Some members are naturally tapered or curved, whereas others may have experienced service-induced deformation. Evidence such as abnormal sagging, joint displacement, local crushing, or loss of alignment relative to adjacent components provides a stronger basis for identifying structural deformation than curvature alone.

This distinction reduces the risk of overestimating damage in historic bridges. It also highlights the value of repeated geometric monitoring: one-time inspection can document the current shape, but only repeated measurements can reliably determine whether a geometric irregularity is stable or progressive.

PROBABLE DETERIORATION MECHANISMS

The field observations identified recurrent forms of deterioration but do not by themselves establish causation. The mechanisms discussed below are therefore treated as probable contributors based on bridge configuration, observed condition, and established knowledge of timber deterioration and traditional timber joints (Riggio *et al*. 2018; Yang *et al*. 2019; Rashidi *et al*. 2021; Brimblecombe and Richards 2022; Zhang *et al*. 2022; Zhang *et al*. 2024).

Environmental and Biological Effects

Termites and wood-boring beetles are potential biological hazards to timber structures, but the surface features documented in this survey were not diagnostically linked to either group. Temperature and moisture availability may influence insect activity;

however, the available records do not establish whether winter freezing or local moisture conditions affected biological deterioration in the investigated bridges (Lebow *et al*. 2012).

Decay and insect attack may reduce the effective timber section even when visible surface evidence is limited (Rashidi *et al*. 2021; Degl'Innocenti *et al*. 2022; Nocetti *et al*. 2023). Their structural significance should therefore be assessed together with exposure conditions and non-destructive testing if necessary. The scope of this evaluation excludes ongoing moisture data and internal section-loss analysis, so environmental and biological explanations remain qualitative mechanism-based interpretations.

Mechanical Demand and Member Cracking

The woven arch transfers load through overlapping member groups and local contact regions, consequently individual members may experience combined axial force, bending, bearing, and connection restraint rather than a single simple stress state (Yang *et al*. 2019). Such mechanical demand can contribute to crack development, particularly where force transfer is concentrated near contacts or joints.

Natural material characteristics may further influence local response. Taper, knots, grain deviation, initial curvature, and drying checks introduce geometric and material heterogeneity. Visible cracking should therefore be interpreted as the possible result of interacting mechanical demand, material variability, and environmental cycling rather than being assigned to one cause solely from appearance.

These mechanical actions are discussed as general theoretical mechanisms that may contribute to cracking in woven timber-arch systems and should not be interpreted as confirmed causes of individual cracks observed in the surveyed bridges.

Joint Looseness and Local Splitting

Traditional timber connections can develop gaps and looseness through shrinkage, repeated relative movement, local bearing, and long-term service. Experimental studies of mortise-tenon joints show that gaps and looseness can reduce rotational stiffness and moment resistance and can promote pull-out or inclination-related damage (Zhang *et al.* 2022; Zhang *et al.* 2024).

These mechanisms provide a plausible basis for interpreting the observed joint separation and tenon withdrawal, but the present survey does not quantify joint stiffness, engagement depth, or internal contact condition. The significance of an individual joint anomaly should therefore be assessed together with residual engagement, associated member movement, and local material condition.

Intrinsic Geometry Versus Service-Induced Deformation

Historic roundwood members may naturally taper, have unequal end diameters, or possess initial curvature. These features form part of the original material and construction practice and should not be classified as deterioration solely because the member is non-prismatic or curved. Service-induced deformation is more plausibly indicated when geometric change is accompanied by abnormal sagging, joint displacement, crushing, loss of alignment, or progressive movement.

REPAIR AND STRENGTHENING TRACES

Observed Interventions

The primary field survey identified visible evidence of previous interventions, including steel hoops around timber members and rope restraint within the covered bridge space. Apparent replacement traces and other local interventions were noted where differences in timber appearance, workmanship, connection details, or surrounding context were visible. However, the available field records did not permit systematic verification of the number, exact structural positions, or replacement dates of such members. These observations are therefore treated as possible intervention traces rather than as a complete quantitative inventory of apparent replacement traces.

Steel hoops and rope ties were documented as visible interventions. Their intended functions and structural contributions could not be established from photographs alone. Their presence records a maintenance response, but visual inspection alone cannot determine the actual force, residual capacity, or long-term effectiveness of the intervention. Representative repair and strengthening traces observed during the field survey are shown in Fig. 7.

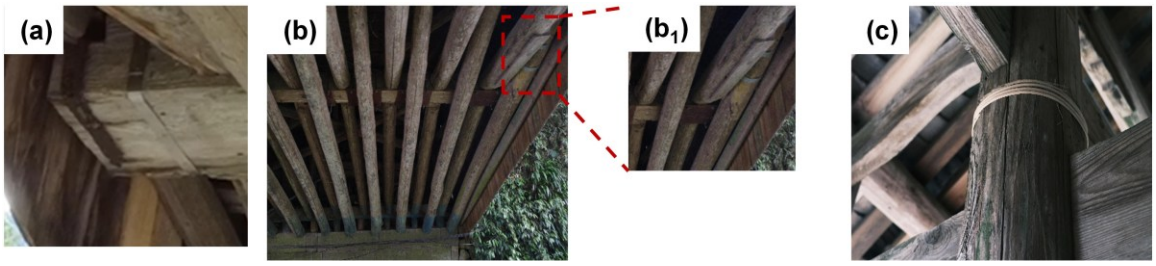


Fig. 7. Representative repair and strengthening traces observed during the field survey

Conservation Implications of Local Repair

Repair of heritage timber structures should balance structural safety with retention of historic fabric. Intervention decisions should consider deterioration mechanism, residual capacity, structural role, reversibility, inspectability, and compatibility with the original timber (Dewey *et al*. 2018; Riggio *et al*. 2018; Rashidi *et al*. 2021, 2025). A reinforcement that restrains one damaged zone may also alter local stiffness or moisture behavior and should therefore be evaluated together with the adjacent material.

Visible repair traces are best treated as part of the bridge's maintenance history rather than as proof of successful or unsuccessful strengthening. Recording the location, type, date if known, material, and subsequent condition of each intervention would provide a more reliable basis for future maintenance assessment.

CONSERVATION AND ADAPTIVE-USE CONDITIONS

Conservation Context of the Surveyed Bridges

The surveyed bridges remain embedded in different use contexts. Some continue to function mainly as local circulation or community spaces, whereas others are more closely integrated with heritage interpretation and tourism. Conservation requirements

therefore extend beyond material condition to include routine maintenance, drainage, environmental management, visitor access, and the ability to conduct periodic inspection.

The surveyed bridges exhibit different current-use contexts. Some show visible facilities associated with tourism or heritage interpretation, whereas others continue to support local circulation and community activities. These differences are described as characteristics of the investigated cases rather than as evidence of broader geographical patterns.

Management Implications

Tourism-oriented conservation can provide funding, public visibility, and incentives for environmental improvement. However, tourism-related interventions and adaptive use should remain compatible with the authenticity, historic fabric, and continued cultural function of the heritage structure, in accordance with established conservation principles (ICOMOS 2017). Conversely, lower-intensity tourism can preserve a stronger relationship with local life while offering fewer resources for systematic inspection and rapid intervention.

A balanced strategy should therefore link physical conservation with use management. Bridge-specific condition files, standardized photographs, intervention records, and periodic inspection would make it easier to distinguish stable defects from progressive change. Local users can also contribute valuable observations of leakage, new splitting, insect activity, or unusual movement between professional inspections.

MULTI-LEVEL CONSERVATION RECOMMENDATIONS

The field evidence indicates that deterioration cannot be managed effectively at a single scale. A practical conservation framework should connect material condition, component and joint behavior, structural-system response, and long-term management.

The proposed conservation framework is consistent with, and intended to complement, established principles for the conservation of historic timber structures rather than to replace existing standards. The ICOMOS Principles for the Conservation of Wooden Built Heritage (2017) emphasize prior investigation, minimum and compatible intervention, retention of historic fabric, documentation of interventions, and continued monitoring. Similarly, GB/T 50165-2020 provides a technical framework for the investigation, monitoring, assessment, maintenance, repair, and strengthening of historic timber structures in China. The four levels adopted in the present study—material, component/joint, structural system, and management—should therefore be understood as an organizational framework for applying these established principles to the surveyed bridges rather than as a new universal conservation standard.

The contribution of the present field survey is to identify typology-specific priorities for Min-Zhe timber arch covered bridges. In particular, the interlaced woven-arch system requires attention to overlapping roundwood members, contact regions, and traditional joints whose local condition may affect cooperative load transfer. The survey also highlights the need to distinguish intrinsic roundwood taper and curvature from suspected service-induced deformation, to document previous interventions such as steel hoops and rope restraints together with their structural context, and to consider the protective role of the covered superstructure, including roof integrity, drainage, and moisture-prone connection regions. These field-derived priorities translate general

conservation principles into inspection and maintenance considerations specific to the construction characteristics of timber arch covered bridges.

Material Level

At the material level, conservation should prioritize moisture control, inspection of suspected biological deterioration, and systematic documentation of cracking and local material loss. Particular attention should be given to maintaining the protective function of the covered superstructure through regular inspection of roofing elements, roof joints, drainage paths, exposed timber ends, and moisture-prone connection and support regions. Where leakage, inadequate drainage, or persistent dampness is identified, the source of moisture should be addressed before repeated localized repair is undertaken. If internal deterioration or section loss is suspected, targeted non-destructive or minimally invasive testing can supplement visual inspection (Riggio *et al*. 2018; Rashidi *et al*. 2021; Degl'Innocenti *et al*. 2022; Nocetti *et al*. 2023).

Where concealed or internal deterioration is suspected, visual inspection may be supplemented by targeted non-destructive or minimally invasive techniques. Stress-wave and ultrasonic methods can be used as screening tools to identify anomalous wave-transmission behavior associated with internal discontinuities or degraded zones, whereas resistance drilling can provide localized information on internal density loss and material deterioration (Machado *et al*. 2015). Resistance drilling is minimally invasive rather than strictly non-destructive. These techniques were not applied in the present investigation and are recommended only for subsequent targeted assessment of members requiring more detailed diagnosis.

Component and Joint Level

Inspection should focus on cracked members, damaged end or contact regions, and joints showing withdrawal or separation. Joint assessment should consider engagement, crushing, displacement, and adjacent member condition. Replacement or strengthening should preserve the original load-transfer logic as far as practicable.

Structural-System Level

Local defects should be interpreted within the woven load path. Repeated measurements of arch alignment, deck level, and selected component endpoints can help distinguish stable irregularity from progressive deformation. Where changes affect principal load paths or global geometry, structural analysis or load testing may be required.

Management and Adaptive-Use Level

Each bridge should maintain an updated condition record containing component identification, standardized photographs, deterioration location, intervention history, and follow-up observations. Inspection frequency can be risk-informed, with previously repaired or visibly deteriorated locations receiving greater attention. Tourism and new facilities should support conservation without compromising structural safety, authenticity, or community use.

Inspection-to-Intervention Sequence

A staged inspection-to-intervention procedure is recommended: (1) routine field inspection; (2) condition classification; (3) targeted measurement or non-destructive/ minimally invasive testing where necessary; (4) structural assessment of critical defects;

(5) selection and implementation of appropriate maintenance, repair, strengthening, or replacement measures; and (6) post-intervention monitoring. The central principle is that intervention should follow diagnosis rather than visible appearance alone. The proposed multi-level conservation framework is summarized in Fig. 8.

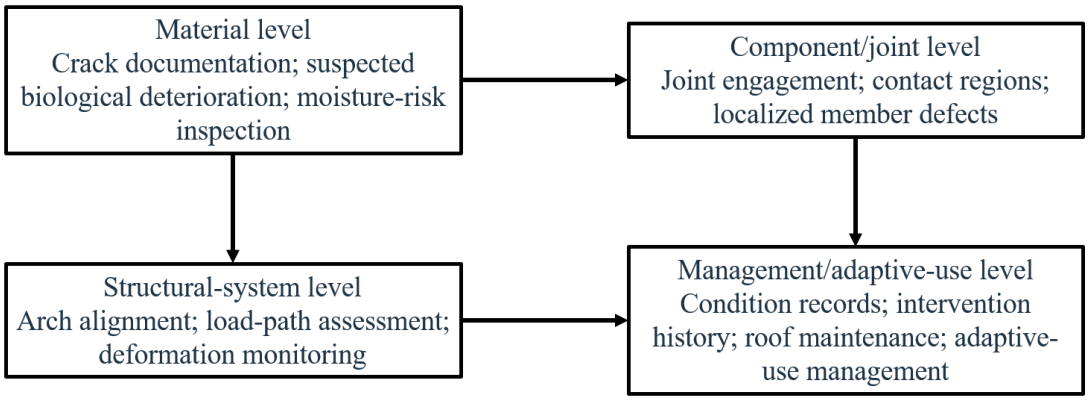


Fig. 8. Proposed multi-level conservation framework for timber arch covered bridges

CONCLUSIONS

1. An intensive field survey of 10 historic timber arch covered bridges and Qifeng Bridge was conducted in Shouning and Taishun. The survey documented structural configuration, roundwood variability, visible deterioration, repair traces, and conservation and current-use conditions across the investigated bridges.
2. The field survey documented several forms of material deterioration and connection anomalies beyond visible cracking. These included suspected fungal deterioration, insect-associated surface holes, localized material loss, tenon withdrawal, joint separation, and apparent looseness. Although termites and wood-boring beetles are relevant biological hazards for timber structures, the available observations did not permit identification of the insects responsible for the recorded surface features. Geometric irregularities must also be interpreted in relation to the natural taper and initial curvature of roundwood members rather than being automatically classified as service-induced deformation.
3. The field investigation provides a descriptive baseline for documenting material deterioration, connection anomalies, and geometric irregularities in the surveyed bridges. Although the available observations do not permit unique causal attribution or quantitative separation of individual deterioration mechanisms, the resulting documentation provides a basis for targeted follow-up inspection, repeated monitoring, and more detailed structural assessment.
4. Steel hoops, rope restraints, apparent replacement traces, and other local repairs record the maintenance history of the bridges. Their effectiveness cannot be judged from appearance alone; conservation decisions should consider residual timber condition, structural role, compatibility, reversibility, moisture behavior, and subsequent monitoring.

5. Conservation conditions vary among the surveyed cases, from stronger tourism and interpretation contexts to continued community-oriented use. A multi-level strategy is therefore recommended, integrating material protection, component and joint inspection, structural monitoring, documented intervention history, and management of tourism and community use.

ACKNOWLEDGMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest

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

REFERENCES CITED

Brimblecombe, P., and Richards, J. (2022). "Moisture as a driver of long-term threats to timber heritage-Part II: Risks imposed on structures at local sites," *Heritage* 5(4), 2966-2986. https://doi.org/10.3390/heritage5040154

CEN (2016). "EN 350:2016 — Durability of wood and wood-based products — Testing and classification of the durability to biological agents of wood and wood-based materials," European Committee for Standardization, Brussels. EN 350.

Chen, S., Yang, Y., Shen, Z., and Javanmardi, A. (2022). "Reconstruction of Min-Zhe wooden arch bridges and its legitimation as tangible and intangible heritage," *International Journal of Architectural Heritage* 16(12), 1779-1796. https://doi.org/10.1080/15583058.2021.1908444

Cruz, H., Yeomans, D., Tsakanika, E., Macchioni, N., Jorissen, A., Touza, M., Mannucci, M., and Lourenço, P. B. (2015). "Guidelines for the on-site assessment of historic timber structures," *International Journal of Architectural Heritage* 9(3), 277-289. https://doi.org/10.1080/15583058.2013.774070.

Degl'Innocenti, M., Nocetti, M., Kovacevic, V. C., Aminti, G., Betti, M., Lauriola, M. P., and Brunetti, M. (2022). "Evaluation of the mechanical contribution of wood degraded by insects in old timber beams through analytical calculations and experimental tests," *Construction and Building Materials* 339, article 127653. https://doi.org/10.1016/j.conbuildmat.2022.127653

Dewey, J., Burry, M., Tuladhar, R., Sivakugan, N., Pandey, G., and Stephenson, D. (2018). "Strengthening and rehabilitation of deteriorated timber bridge girders," *Construction and Building Materials* 185, 302-309. https://doi.org/10.1016/j.conbuildmat.2018.07.064

Gao, X., Chun, Q., and Han, Y. (2025). "Wind pressure distribution characteristics of ancient Chinese timber lounge bridges based on the wind tunnel test," *Journal of Wood Science* 71, 9. https://doi.org/10.1186/s10086-025-02182-4

Han, Y., Chun, Q., and Wang, H. (2022). "Quantitative safety evaluation of ancient Chinese timber arch lounge bridges," *Journal of Wood Science* 68, 4. https://doi.org/10.1186/s10086-022-02011-y

ICOMOS. (2017). *Principles for the Conservation of Wooden Built Heritage*. Adopted by the 19th ICOMOS General Assembly, New Delhi, India, 15 December 2017.

Lebow, S., Kirker, G. T., White, R. H., Amburgey, T., Barnes, H. M., Sanders, M., and Morrell, J. (2012). "Guide for in-place treatment of wood in historic covered and modern bridges," *General Technical Report FPL-GTR-205,* USDA Forest Service, Forest Products Laboratory, Madison, WI. https://doi.org/10.2737/FPL-GTR-205

Li, S., Gao, Y., Brunetti, M., Macchioni, N., Nocetti, M., and Palanti, S. (2019). "Mechanical and physical properties of *Cunninghamia lanceolata* wood decayed by brown rot," *iForest* 12(3), 317-322. https://doi.org/10.3832/ifor2922-012

Machado, J. S., Riggio, M., and Descamps, T. (eds.) (2015). "Combined use of NDT/SDT methods for the assessment of structural timber members — State of the art report," COST Action FP1101, UMONS, Université de Mons. ISBN 978-2-87325-094-2.

Ministry of Housing and Urban-Rural Development of the People's Republic of China. (2020). GB/T 50165-2020, Technical Standard for Maintenance and Strengthening of Ancient Timber Buildings. Beijing, China.

Nocetti, M., Mannucci, M., and Brunetti, M. (2023). "Automatic assessment of insect degradation depth in structural solid wood elements by drilling resistance measurements," *Construction and Building Materials* 366, article 130273. https://doi.org/10.1016/j.conbuildmat.2022.130273

Qin, Z., Xie, Q., Li, Z., and Wang, C. (2026). "Accurate detection/segmentation and quantification of structural defects in heritage timber arch bridges," *Structures* 93, article 113055. https://doi.org/10.1016/j.istruc.2026.113055

Rashidi, M., Noori Hoshyar, A., Smith, L., Samali, B., and Siddique, R. (2021). "A comprehensive taxonomy for structure and material deficiencies, preventions and remedies of timber bridges," *Journal of Building Engineering* 34, article 101624. https://doi.org/10.1016/j.jobe.2020.101624

Rashidi, M., Mousavi, V., Rayegani, A., and Devitt, J. (2025). "Development of a decision support framework for timber bridge remediation," *Results in Engineering* 27, article 106917. https://doi.org/10.1016/j.rineng.2025.106917

Riggio, M., D'Ayala, D., Parisi, M. A., and Tardini, C. (2018). "Assessment of heritage timber structures: Review of standards, guidelines and procedures," *Journal of Cultural Heritage* 31, 220-235. https://doi.org/10.1016/j.culher.2017.11.007

Song, H., Chun, Q., Han, Y., and Zhang, C. (2025). "A novel quantitative evaluation method for seismic safety of ancient Chinese timber arch lounge bridges," *Journal of Wood Science* 71, article 66. https://doi.org/10.1186/s10086-025-02239-4

W-Bridge. (2026). *Public Information Platform for Timber Arch Covered Bridges*, Available at: http://w-bridge.wiki/#/ (accessed 19 September 2026).

Yang, C., Hu, Y., Su, Q., Li, X., and Zhu, M. (2025). "Empirical methods for recognizing and evaluating cultural heritage value of timber-arched lounge bridge from the perspective of cultural memory," *Journal of Asian Architecture and Building Engineering* 24(5), 3575-3592. https://doi.org/10.1080/13467581.2024.2399689

Yang, Y., Nakamura, S., Chen, B., and Nishikawa, T. (2012). "Traditional construction technology of China timber arch bridges," *Journal of Structural Engineering* A 58A, 777-784. https://doi.org/10.11532/structcivil.58A.777

Yang, Y., Nakamura, S., Chen, B., and Nishikawa, T. (2019). "Mechanical behavior of Chinese woven timber arch bridges," *Engineering Structures* 195, 340-357. https://doi.org/10.1016/j.engstruct.2019.05.068

Ye, L., Wang, B., and Shao, P. (2024). "Structural safety assessment method for ancient Chinese timber arch lounge bridges," *International Journal of Architectural Heritage* 18(2), 177-193. https://doi.org/10.1080/15583058.2022.2134063

Zhang, B., Xie, Q., Li, S., Zhang, L., and Wu, Y. (2022). "Effects of gaps on the rotational performance of traditional straight mortise-tenon joints," *Engineering Structures* 260, article 114231. https://doi.org/10.1016/j.engstruct.2022.114231

Zhang, B., Song, X., Xie, Q., and Xue, J. (2024). "Seismic behavior of looseness-induced inclined mortise and tenon joints in ancient timber structures: Experimental tests, multi-scale finite element model, and behavior degradation," *Engineering Structures* 318, article 118680. https://doi.org/10.1016/j.engstruct.2024.118680

Article submitted: September 22, 2026; Peer review completed: October 24, 2026; Revised version received: October 29, 2026; Accepted: November 5, 2026; Published: November 18, 2026.
DOI: 10.15376/biores.22.1.517-534