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"Afflictions" and "Remedies" of Wooden Arch Lounge Bridges

-- Investigation and Intervention of the Damage to the National Protected Site Shunde Bridge

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Abstract

Wooden arch lounge bridges in Zhejiang and Fujian provinces represent a unique heritage in the history of world bridge engineering. Their preservation faces ongoing challenges from both natural and anthropogenic factors. Focusing on the Shunde Bridge, part of the Chuzhou Lounge Bridges in Longquan City, Zhejiang Province-a national key cultural heritage protection unit-this paper addresses its structural safety crisis. Through comprehensive literature review, on-site investigation, and 3D laser scanning technology, a systematic survey and diagnosis of the bridge’s damages were conducted. The results reveal major deteriorations, including severe decay and insect infestation of key structural members of the wooden arch (e.g., three-joint seedlings), overall tilting and tenon dislocation of the lounge timber frame, and persistent leakage due to roofing system damage. Based on an analysis of the causes-natural aging, biological erosion, and limitations of prior interventions-and adhering to the principles of authenticity, integrity, and minimal intervention in cultural heritage conservation, this paper argues that partial repairs are insufficient to ensure the safety and value preservation of the heritage structure in its current state. Consequently, a systematic conservation and restoration design centered on "complete dismantling and major repair" is proposed. This study aims to provide a direct basis for eliminating fundamental safety risks to Shunde Bridge, while also offering a referential case for the holistic conservation practice of similar wooden heritage structures-from refined diagnosis to scientific intervention.

Keywords

Wooden Arch Lounge Bridge; Shunde Bridge; Damage Investigation; 3D Laser Scanning; Complete Dismantling and Major Repair; Cultural Heritage Preservation.

1. Introduction

The surviving wooden arch lounge bridges in the mountainous regions of southern Zhejiang and northern Fujian are a unique creation in the history of world bridge architecture, embodying distinct Eastern wisdom [1]. Their structural system of "compiling timber into an arch" not only represents an exceptional application of material mechanics and structural geometry by ancient craftsmen [2], but also carries the historical memory of regional social, economic, and cultural life[3]. Over time, these heritage structures, primarily built of wood and long exposed to the damp and rainy mountainous environment, continuously face multiple threats from natural forces, biological deterioration, and inappropriate human interventions. Their state of preservation is concerning, making systematic conservation work urgent [4].

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The theory and practice of cultural heritage conservation emphasize that any intervention must be based on a deep understanding of the heritage's "value" and a precise diagnosis of its "afflictions." The principles of "authenticity"[5], "integrity"[6], and requirements such as "minimum intervention"[7] and "reversibility" advocated in The China Principles for the Conservation of Heritage Sites constitute the core ethical framework for contemporary conservation work. Among these, "minimum intervention" is not an absolute principle. When a heritage structure faces severe safety risks and localized measures cannot provide a fundamental cure, "necessary intervention" based on thorough investigation and rigorous argumentation becomes the inevitable choice for prolonging the structure's life and preserving its core value. Scientific and systematic investigation serves as the crucial bridge linking value recognition to conservation action, determining the relevance, effectiveness, and rationale of any intervention.

This paper takes the Shunde Bridge, part of the Chuzhou Lounge Bridges, as its research object. Designated as a National Key Cultural Heritage Protection Unit in 2013, the bridge was originally built during the Daoguang period of the Qing Dynasty. Although it has been reconstructed after a fire and undergone several repairs throughout its history, recent inspections have revealed severe decay and fracture of key members in its wooden arch structure, highlighting significant structural safety risks. This has raised considerable concern within the local community and management authorities. Therefore, this study aims to: 1) Conduct a systematic investigation and precise diagnosis of the damages to Shunde Bridge by combining modern technological means with traditional methods; 2) Based on the investigation results and value assessment, argue for the urgency and direction of conservation intervention; 3) Propose a fundamental restoration design scheme to eliminate safety hazards and ensure the long-term preservation of this important cultural heritage. This research not only serves as the necessary engineering foundation for applying the correct "remedy" to Shunde Bridge's specific "afflictions," but the process from "refined diagnosis" to "scientific decision-making" is also expected to provide a methodological framework and practical example that can be referenced for the conservation of similar wooden heritage structures.

2. Historical Evolution, Form, and Value Reassessment of Shunde Bridge

2.1 Historical Evolution and Construction History

The construction history of Shunde Bridge forms an integral part of its physical remains, documenting key events throughout its lifespan. According to documentary research and inscribed records, the bridge was originally built in the 20th year of the Daoguang reign of the Qing Dynasty (1840 AD). It was destroyed by fire in the 3rd year of the Republic of China (1914 AD) and subsequently rebuilt the following year. This reconstruction established the primary basis of the current bridge structure. The inscription on the ridge purlin, which reads "Newly constructed with the ridge beam raised on the Xinchou day, Ximao hour, the thirtieth day of the tenth month (Yiyou year) in the 4th year of the Republic of China (October 30, 1915)," provides conclusive evidence for this date.In the latter half of the 20th century, the bridge's Buddhist shrine was damaged during the "Cultural Revolution" period and was later restored in 1980. Entering the 21st century, the bridge's protection status has been progressively elevated: it was designated as a Provincial-Level Cultural Heritage Protection Unit in 2005 and was upgraded to a National Key Cultural Heritage Protection Unit in 2013. During this period, a major restoration project was undertaken in 2008, involving the replacement and reinforcement of some timber elements. However, approximately fifteen years after this restoration, new and severe damages have re-emerged, highlighting the long-term and complex nature of conserving wooden heritage structures.

2.2 Architectural Form and Structural Characteristics

Shunde Bridge (Figure 1) is located in Yangshun Village, Pingnan Town, Longquan City, spanning the Mei River on an east-west axis. The existing bridge has a total length of 36 meters and a width of 4.84 meters. Originally featuring a lounge with 17 bays, one bay at the eastern end was demolished and reconstructed due to road construction. Its core value is embodied in the unique "timber-weave

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arch" structural system. This system consists of two layers: the lower layer is an A-shaped arch frame (known as sanjiemiao, or three-section seedlings) composed of three long logs, while the upper layer is a five-segmented polygonal arch frame (known as wujiemiao, or five-section seedlings) formed by five slightly shorter logs. The turning points of the arch frames are tightly connected by transverse large timbers called niutou (bull's head), integrating them into a cohesive whole. Bridge deck planks are laid flat over the arch frames, upon which the lounge structure is built. This technique, centered on mortise-and-tenon joints, achieves a stable arch form through the interlocking, compression, and mutual restraint of timber members, representing an outstanding example of ancient bridge engineering. The lounge structure employs a post-and-lintel (tailiang) framework with a flush-gable roof, covered with small black tiles. Its overall form is simple, rustic, and substantial, blending harmoniously with the surrounding mountainous landscape.

Figure 1. Shunde Bridge(self-drawn)

2.3 Multi-Dimensional Value Assessment

From the perspective of heritage conservation theory, the value of Shunde Bridge can be interpreted at a deeper level.(1) Historical and Technical Value: Shunde Bridge serves as a material witness to the construction techniques of wooden arch bridges in the mountainous regions of southern Zhejiang from the Qing Dynasty to the Republican era. Its preserved original fabric, traces of historical repairs, and a surviving "Bridge Construction Contract" (Figure 2) from the Daoguang period of the Qing Dynasty together constitute a multidimensional documentation for studying the history of bridge architecture, craftsmen's organizations, construction customs, and local socio-economics in the region. Its timber-weave arch structure itself is a technical heritage of high scientific significance.(2) Artistic and Cultural Value: The bridge exhibits well-proportioned form and robust, powerful structural members, showcasing an unadorned aesthetic grounded in material and structural logic. Although the Buddhist shrine in the central bay has experienced vicissitudes, its spatial arrangement reflects the social function of lounge bridges as nodes of faith and cultural activity.(3) Social and Emotional Value: As a vital link on the historic trail connecting Qingyuan and Longquan, and currently serving as a daily passage and spiritual sustenance for villagers, Shunde Bridge carries profound community attachment and collective memory, which form the source of its enduring cultural vitality.

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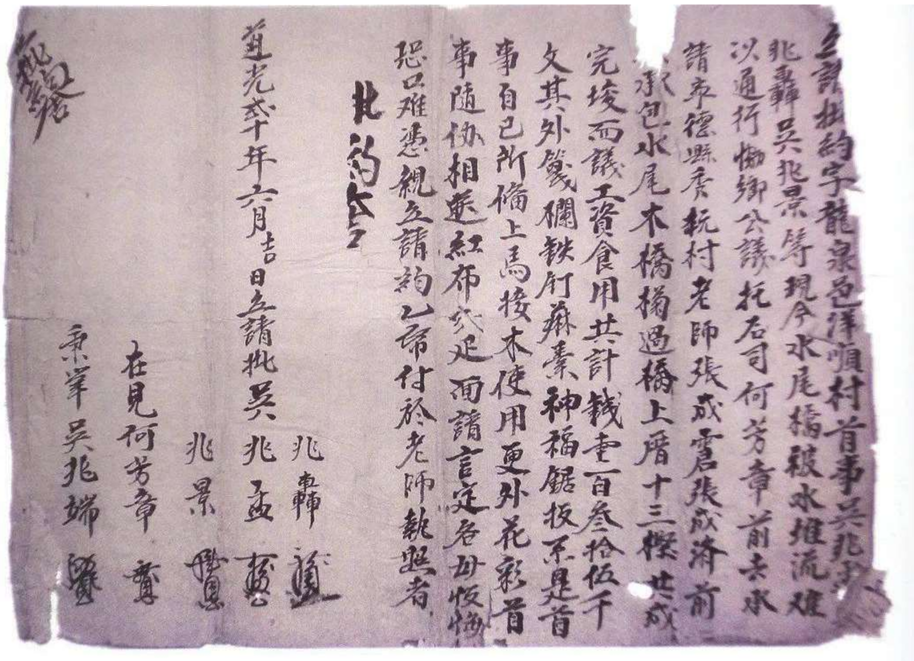
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Figure 2. Approximate bridge in Shunde Corridor in June 1920 (provided by the Longquan City Cultural Heritage Protection Center)

3. Systematic Investigation and Diagnosis of Damage based on Multi-Source Data

3.1 Investigation Methods and Technology Integration

To achieve precise diagnosis of Shunde Bridge's complex structure, particularly its concealed sections and irregular surfaces, this investigation employed a method integrating traditional survey techniques with modern 3D laser scanning technology. The application of a 3D laser scanner (Trimble TX8) was a key technical approach in this project. Its working principle involves high-speed laser ranging and angular measurement to non-invasively capture a massive set of three-dimensional point cloud data from the surface of the target object. This technology fundamentally overcomes the limitations of traditional single-point measurement, enabling the rapid, comprehensive, and precise recording of the bridge's true three-dimensional form, including millimeter-level information on various deformations, displacements, and defects.

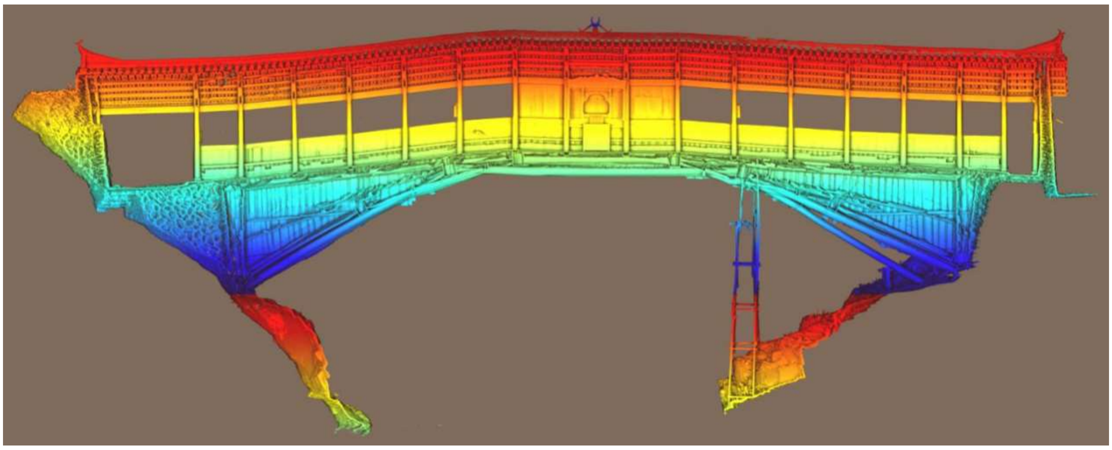

Figure 3. Schematic diagram of the 3D model slices of the Shunde Bridge timber woven arch (self-drawn)

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The data processing workflow included: on-site multi-station scanning, fully automated registration of point cloud data, noise removal and cropping, culminating in the generation of a high-precision 3D model (Figure 3). The advantages of this model are: 1) Objectivity and Accuracy: It provides a non-tamperable three-dimensional digital archive; 2) Quantifiable Analysis: Through model sectioning, it allows for precise measurement of member tilt, settlement, and crack dimensions ; 3) Visualized Diagnosis: It intuitively reveals overall deformation trends and correlations between localized damages. This establishes an unprecedented and reliable data foundation for subsequent structural safety assessment and restoration design.

3.2 Diagnosis of Damage in the Structural System

(1) Wooden Weave Arch Structure:The investigation revealed that the wooden weave arch, particularly the "three-section seedling" system which serves as the primary load-bearing component, suffers from the most severe damage, posing a direct threat to the overall structural safety. Sliced data from the 3D scan clearly shows significant issues with the eastern and western sets of inclined seedlings: The lower section (approximately 1 meter) of the eastern inclined seedling (A-5) has decayed, and component A-2 exhibits a 70% insect infestation rate throughout its length; the root section of the western inclined seedling (C-1) also shows approximately 1.2 meters of insect-induced decay (Table 1). More critically, signs of cracking and tenon withdrawal have appeared at the mortise-and-tenon joints connecting the inclined seedlings to the "bull's head" timbers. As shown in Figure 7, there is a crack of about 10mm at the junction between the western bull's head timber and the inclined seedlings C-3 and C-4, with some bull's head timbers themselves exhibiting mid-section cracks of 5-10mm. These damages, located at key load-bearing nodes, significantly compromise the integrity and load-bearing capacity of the wooden arch structure and constitute the core cause of the bridge's structural risk.

Table 1. Status of Damage to Key Timber Components of the Wooden Arch(self-drawn)

Western Inclined Seedling (C)	Bull's-head Timber	Lower Horizontal Seedling (B)	Bull's-head Timber	Eastern Inclined Seedling (A)
C-8: Condition relatively good	During the 2008 restoration, iron bands were added at both the northern/southern ends and the middle of the bull's-head timbers. Currently, cracks exist at the middle section and at the tenon joint with the inclined seedlings, measuring 5~10mm.	B-8: Condition relatively good	During the 2008 restoration, two flat iron bands were added to each end of the bull's-head timber; a steel plate (10mm thick) was also added underneath. The plate has mortises for installing the inclined seedlings. Cracks are observed on the upper side of the bull's-head timber.	A-8: Restored in 2008, raised 0.2m with a stone masonry base.
C-7: Replaced in 2008		B-7: Condition relatively good		A-7: Condition relatively good
C-6: Condition relatively good		B-6: Condition relatively good		A-6: Condition relatively good
C-5: Condition relatively good		B-5: Condition relatively good		A-5: Lower 1m insect-damaged and decayed; upper tenon decayed.
C-4: Condition relatively good		B-4: Condition relatively good		A-4: Condition relatively good
C-3: Condition relatively good		B-3: Condition relatively good		A-3: Condition relatively good
C-2: Condition relatively good		B-2: Condition relatively good		A-2: 70% insect infestation throughout
C-1: ~1.2m root section insect-damaged and decayed; upper half has central longitudinal crack depth < 1/3 diameter.		B-1: Condition relatively good		A-1: Replaced in 2008

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Lounge Timber Frame: The lounge structure exhibits an overall tilting trend toward one side, with widespread phenomena of column bending and beam-tenon withdrawal. Analysis indicates that this deformation results from the long-term cumulative effect of multiple factors. Firstly, the structure is built on a foundation with a significant height difference (0.51 meters between the east and west abutments), creating inherent unbalanced stresses (Figure 4). Secondly, although the 2008 restoration involved a "complete disassembly and repositioning" of the lounge frame, the inherent deformation of the wooden arch itself was not fully rectified. After the reapplication of roof loads, wood creep (elastic stretching) under sustained load, coupled with new settlement, led to the progressive accumulation of deformation over the following decade. This tilting of the timber frame further exacerbated the loosening of mortise-and-tenon joints (Figure 5), creating a vicious cycle.

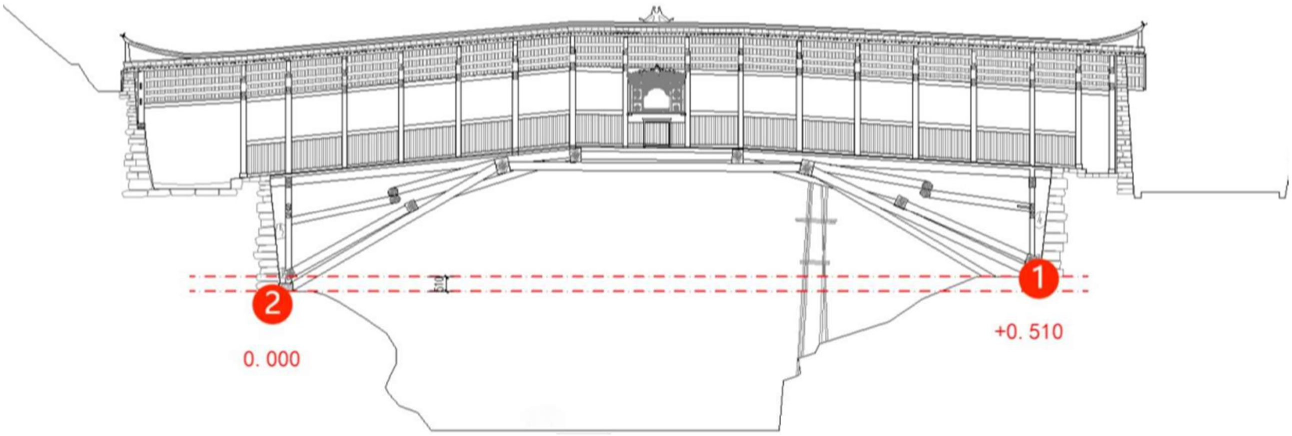

Figure 4. Cross-sectional view of Shunde Bridge (self-drawn)

Figure 5. Left: Middle cowhead misalignment at the upper west end of a three-segment seedling; Right: Cowhead cracking on the west side of a three-segment seedling (drawn by the author)

3.3 Damage to the Enclosure System and Decorative Elements

The roofing system is severely deteriorated, with cracked and missing tiles leading to direct rainwater infiltration. Persistent leakage has caused widespread dampening of the underlying wooden substrate (rafters, fascia boards), resulting in moldering and decay (Figure 6). This not only accelerates timber degradation and adds to the load, but the damp environment also fosters conditions for wood-decay fungi and insect infestation, creating a detrimental synergistic effect with the structural damages.

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Figure 6. Left, damaged roof tiles with leaves blocking drainage; right, rotted eaves with water leaks, rafters damp and moldy (self-drawn)

3.4 Comprehensive Analysis of Damage Causes

The deterioration of Shunde Bridge is the result of systemic degradation. (1) Natural Factors: The local high-humidity environment, combined with cycles of wet-dry and thermal fluctuations, causes repeated expansion and contraction of the timber. This promotes cracking and the loosening of mortise and tenon joints. Persistent rainwater infiltration is the primary cause of wood decay. (2) Biological Factors: Insect infestation (e.g., termites) directly causes internal hollowing and a sharp decline in the timber's strength. (3) Human and Temporal Factors: The historical reduction of one end of the bridge (the eastern end) to accommodate traffic altered the original structural force equilibrium. Although the 2008 restoration addressed a number of visible issues at the time, its intervention in the core timber arch system was limited. It failed to completely correct underlying deformations, and the newly replaced components themselves are subject to aging. The interplay of these multiple factors has led to an accelerated progression of damage in recent years.

4. Justification of the Conservation and Restoration Design Scheme

4.1 Conservation Philosophy and Principles

In response to the critical condition of Shunde Bridge, this restoration design adheres to the following core principles: ensuring the structural safety of the heritage structure and public safety is the paramount prerequisite; the fundamental objectives are to eliminate the root causes of deterioration and halt the progression of damage, while preserving to the greatest extent possible its historical fabric and the full spectrum of value-laden information it carries.

At the operational level, the design strictly follows the guidance of The China Principles for the Conservation of Heritage Sites, upholding: (1) Authenticity: Striving to retain original components during repairs, especially those reflecting historical craftsmanship and period information; replacement components must adhere to the original form, traditional craftsmanship, and original materials. (2) Minimum Intervention and Necessary Intervention: Under normal circumstances, "minimum intervention" is the golden rule. However, when localized, minor measures can no longer prevent the accelerated loss of heritage value or eliminate major safety risks, a rigorously justified "thorough intervention" becomes the necessary and responsible form of "minimum intervention." The proposed "complete dismantling and major repair" is precisely the inevitable choice under this logic. (3) Reversibility and Distinguishability: Newly added reinforcement measures should be reversible where possible, avoiding obstacles to future conservation; necessary replacement components should be clearly marked with their date and be distinguishable.

4.2 Defining the Restoration Project: Justification for a Complete Dismantling and Major Repair

Based on the aforementioned diagnosis, it is clear that the core load-bearing wooden arch system of Shunde Bridge has suffered severe damage, and the overall tilting deformation of the lounge structure is a manifestation of deeper structural issues. Traditional localized methods such as lever-based

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straightening, repacking, or localized reinforcement can neither restore the strength of severely decayed components nor correct the destabilized structural system. Persisting with a "treat-the-symptom" approach of partial repairs would not only fail to address the fundamental safety hazards but could also introduce new stress concentrations through inappropriate intervention, accelerating the structure's decline. Therefore, this restoration project must be defined as a "complete dismantling and major repair." This entails the planned, comprehensive disassembly of the bridge structure to allow for thorough inspection, root-cause elimination of deterioration, and systematic restoration of the foundation, wooden arch, and lounge systems, ultimately achieving safe repositioning and long-term stability of the structure.

4.3 Design of Core Restoration Measures

Disassembly, Investigation, and Documentation: First, the entire lounge structure will be completely dismantled. All components will be numbered, documented, and assessed. Subsequently, the wooden arch system will be disassembled in a planned sequence, enabling the most detailed investigation to precisely determine the condition of each member.

Foundation Treatment: The east and west abutment foundations will be inspected. Loose or displaced foundation stones will be repositioned and stabilized to ensure a solid base.

Restoration of the Wooden Arch: This is the core of the restoration. Key components such as three-section seedlings, five-section seedlings, and bull's-head timbers with insect damage or decay exceeding safety limits will be replaced strictly according to original specifications and traditional craftsmanship. For components with cracks that can be retained, traditional techniques (e.g., resin injection, adding metal bands) will be used for reinforcement. All mortise-and-tenon joints will be refitted to ensure tight engagement. During reassembly, 3D scan data will serve as the benchmark for precisely correcting the arch's geometry and restoring its intended mechanical form.

Restoration of the Lounge Frame: Tilted or bent columns and beams will be straightened or replaced. Loose mortise-and-tenon joints will be repaired. The lounge timber frame will be reassembled according to its original configuration.

Restoration of the Roofing and Enclosure System: The roof's wooden substrate will be comprehensively inspected and repaired. Decayed rafters and sheathing boards will be replaced. The small black tile roof will be re-laid using local traditional techniques, with improved drainage to ensure waterproofing. Damaged weatherboarding will be repaired or replaced.

Treatment of Previous Interventions: Reinforcement elements added during the 2008 restoration, such as iron bands and steel plates, will be assessed. Parts that remain effective and cause minimal intervention to the heritage fabric will be retained; parts that are ineffective or potentially causing new damage to the timber will be carefully removed or replaced.

5. Conclusion and Reflections

5.1 Conclusion

Through an in-depth investigation of the nationally protected Shunde Bridge, part of the Chuzhou lounge bridges, this study systematically revealed and substantiated the core deterioration it currently faces: severe biological infestation and material degradation of the key load-bearing members within its wooden arch, and the consequent overall structural tilting and instability of the lounge structure. These issues represent the result of systemic decay stemming from the combined effects of natural erosion, biological attack, and the limitations of past interventions. The research indicates that, in the bridge's current state, any localized or superficial repair measures are insufficient to ensure its long-term safety and the preservation of its values. Therefore, this paper proposes and justifies the urgency and necessity of implementing the fundamental intervention of a "complete dismantling and major repair," and has developed a systematic restoration design scheme centered on restoring structural safety to its proper state and addressing the root causes of deterioration.

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5.2 Reflections

The conservation practice for Shunde Bridge provides a vivid case study for reflecting on several theoretical issues in the conservation of wooden heritage:

(1) The Dynamic Relationship between Preventive and Remedial Conservation: The case of Shunde Bridge highlights the critical importance of regular, precise condition monitoring (preventive conservation). The emergence of safety-threatening damage merely a decade after the 2008 major repair underscores the need to establish routine, detailed inspection and monitoring mechanisms for key wooden heritage structures, shifting the paradigm from "emergency rescue repairs" to "foresighted maintenance."

(2) The Choice of Intervention Extent:This case profoundly illustrates the dynamic connotation of the "minimum intervention" principle. When a heritage structure is in a "critically endangered" state, the "minimum" approach that best preserves its value may indeed be a thorough "surgical" intervention. This demands that conservators possess both precise diagnostic capabilities and the decision-making courage rooted in a clear understanding of the structure's value.

(3) Technique Transmission and Material Durability: The conservation of wooden arch bridges involves not only repairing a structure but also transmitting a set of craftsmanship. Ensuring the authentic transmission of traditional construction techniques during restoration, while scientifically addressing the inherent challenge of wood's limited natural durability (e.g., exploring environmentally friendly and efficient preservative treatments), remains a long-term endeavor.

(4) The Role of Modern Reinforcement Technologies:Evaluating and reflecting on modern metal reinforcements used in past repairs can aid in exploring alternative reinforcement materials and methods that better align with conservation ethics (e.g., reversibility, compatibility).

The "afflictions" and "remedies" of Shunde Bridge represent not only a rescue engineering practice for a specific national key protected site but also an empirical study on the systemic decay mechanisms and intervention strategies for wooden heritage. By integrating historical research, 3D laser scanning, and on-site investigation, this study has completed a full workflow from value reassessment and precise damage diagnosis to the scientific justification of a conservation plan. This case demonstrates that the conservation of wooden heritage is a comprehensive disciplinary practice integrating material science, structural mechanics, traditional craftsmanship, and conservation ethics. Its significance extends beyond the restoration of a single structure, providing a valuable reference for the complete conservation practice-from refined diagnosis to scientific intervention-for similar wooden heritage assets.

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