



Journal of Highway and Transportation Research and Development

Home page: www.sciopen.com/journal/2095-6215



Research progress on ancient Chinese bridges and typical restoration cases from a multidisciplinary perspective

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Abstract: Ancient bridges in China are significant testimonies to Chinese civilization, reflecting remarkable engineering ingenuity as well as rich historical and cultural values. They can be divided into various structural types including beam bridges, arch bridges, suspension bridges, and pontoon bridges. These bridges not only serve as physical evidence of the evolution of bridge structural forms and building technologies, but also act as important medias for cultural transmission. In recent years, with the increasing emphasis on the conservation of cultural heritage, researches on ancient bridges in China has gradually developed into an interdisciplinary issue encompassing archaeology, architecture, surveying and mapping, and cultural studies. In disciplines such as architectural history, hydraulic engineering history, and transportation history, ancient bridges have been recognized as a special type of immovable cultural relics, which attracted particular interest of study. This paper presents a systematic review of researches in these fields, summarize the major advances of studies in both China and other countries, analyzing existing key challenges and technical bottlenecks, and outline current research approaches and future trends. On this basis, together with recent technological innovations in the conservation of ancient bridges in China, the study further discusses the future directions for studying and protecting ancient bridges, providing theoretical basis and technical references for their scientific conservation and appropriate utilization.

Keywords: ancient Chinese bridges; cultural heritage conservation; multidisciplinary research; digital conservation; restoration techniques

1 Introduction

Mr. Mao Yisheng once remarked that “bridges represent a form of material construction that embodies culture” [1-2]. Ancient bridges represent an important category of cultural heritage, reflecting both technological development and socio-cultural evolution in human history. In China, a large number of ancient bridges have been preserved, covering various structural types such as beam bridges, arch bridges, suspension bridges, and pontoon bridges. These structures provide valuable evidence for understanding the historical development of bridge engineering and construction technologies.

Early studies on ancient Chinese bridges were mainly based on the compilation and interpretation of historical documents—such as Yingzao Fashi (Treatise on Architectural Methods) and Tiangong Kaiwu (The Exploitation of the Works of Nature)—as well as field investigations conducted by scholars in the fields of architectural history and engineering [3-18]. Among them, Liang Sicheng’s study *Open Spandrel Bridges of Ancient China—The An-Chi Ch’iao at Chao Chou, Hopei* [8] and Mao Yisheng’s work *History of ancient Chinese bridge technology* [11] made foundational contributions to the systematic study of ancient Chinese bridges. In particular, Mao Yisheng, widely regarded as a pioneer in the study of

the technological history of Chinese bridges, conducted extensive investigations and established a relatively comprehensive framework for understanding the development trajectory, structural types, and technological evolution of ancient bridges. His work *History of ancient Chinese bridge technology* provides a systematic synthesis of these aspects, while “Bridge Talk” (Qiao Hua) [12] further compiles a wide range of historical records and vernacular materials, promoting the dissemination and broader recognition of bridge history research. These studies laid the foundation for subsequent research, although they were largely descriptive in nature.

In recent decades, with the advancement of heritage conservation concepts and engineering technologies, research on ancient bridges has gradually shifted toward interdisciplinary approaches. Increasing attention has been given to structural performance evaluation, conservation and restoration technologies, non-destructive testing, and digital documentation. Emerging techniques such as laser scanning, UAV photogrammetry, and information modeling have significantly improved the accuracy and efficiency of documentation and analysis.

Despite these advances, several challenges remain. Existing studies are often fragmented across disciplines, and there is still a lack of systematic integration between historical research, engineering analysis, and conservation practice. In addition, in-depth in-

Received: 20 March 2026; **Revised:** 14 April 2026; **Accepted:** 16 April 2026

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DOI: 10.26599/HTRD.2026.9480093

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vestigations into structural mechanisms, long-term performance, and the application of digital technologies in practical conservation remain insufficient.

Therefore, a comprehensive review of the research progress on ancient Chinese bridges from a multidisciplinary perspective is necessary. This paper aims to systematically summarize existing studies, identify key challenges, and propose future research directions to support the scientific conservation and sustainable utilization of ancient bridge heritage.

2 Research on ancient Chinese bridges from an interdisciplinary perspective

Based on previous scholarly achievements, Chinese researchers since the modern era have conducted extensive and in-depth studies on the science and technology of ancient bridges in China from a variety of perspectives.

2.1 Conservation of ancient bridge heritage

2.1.1 The emergence and theoretical foundations of ancient bridge heritage value studies

In the field of cultural heritage studies, bridges have long been regarded primarily as transportation infrastructure or achievements of engineering technology, and their heritage attributes have received relatively limited attention. With the development of the World Heritage concept, scholars have gradually reexamined the value of bridges from a broader cultural heritage perspective.

Wan and colleagues [19] introduced the concepts of “heritage bridges” and “bridge heritage.” The theoretical origins of these concepts can be traced to the survey and research on historic bridges commissioned by UNESCO and conducted by ICOMOS in the 1990s, which resulted in the report *Context for World Heritage Bridges* [20]. This report was the first to systematically articulate the value characteristics and evaluation principles of bridges as heritage objects. It emphasized that bridge heritage should satisfy fundamental World Heritage requirements such as authenticity and integrity, thereby establishing a theoretical foundation for incorporating bridges into the World Heritage research framework.

Building upon this framework, Zhang and Wan [21], through a further interpretation of the report, pointed out that bridge heritage possesses characteristics within the World Heritage system that distinguish it from general architectural heritage. Its value is not only reflected in historical and artistic dimensions but also in aspects such as engineering and technological innovation, the integrity of structural systems, and the continuity of transportation functions. In addition, they summarized the principal categories under which bridge heritage has been inscribed on the World Heritage List.

However, their study is largely based on a secondary interpretation of the *Context for World Heritage Bridges* report, which limits its analytical depth and originality. While the authors emphasize the multi-dimensional value of bridge heritage, their framework remains predominantly descriptive and lacks a systematic methodological approach for evaluating or comparing these values across different cases. Moreover, although they highlight technological and functional aspects, the discussion does not sufficiently engage with broader socio-cultural or regional variations, particularly the underrepresentation of non-Western bridge heritage noted in the original report.

In recent years, Professor Zhang Fang of Southwest Jiaotong University and his collaborators [22–23] have comprehensively reviewed the research progress on bridge cultural heritage from perspectives including value recognition, conservation planning methodologies, and protection and utilization practices. Furthermore, through statistical analysis of the development of ancient bridge studies in China over the past two decades, they identified major

research trends and summarized the principal directions of research in the conservation of bridge cultural heritage.

Current research indicates that no individual bridge in China has been inscribed on the World Heritage List as a standalone cultural relic. Instead, most bridges have been included within broader heritage categories. For example, bridges along the Beijing Central Axis have been inscribed as part of an architectural ensemble, bridges within the Old Town of Lijiang are included under the category of historic towns and town centres, and bridges in the West Lake Cultural Landscape of Hangzhou are listed as components of a cultural landscape. These cases illustrate that bridges are generally incorporated into larger heritage contexts rather than being recognized independently within the World Heritage system.

2.1.2 Studies on the morphology of ancient bridges

An essential component of ancient bridge heritage conservation is the study of the morphological characteristics of historic bridges. Such research plays a crucial role in clarifying the formal features, technological characteristics, material usage, and construction details of ancient bridges in China. Consequently, this topic has long attracted sustained attention from scholars across multiple disciplines.

(1) Typological studies of ancient bridge forms

Liu [24] in a study published in 2012, proposed that ancient bridges in China can be broadly classified into four fundamental structural types: beam bridges, pontoon bridges, suspension bridges, and arch bridges. Over several millennia of bridge construction, ancient Chinese bridges underwent a gradual process of development, evolving from relatively simple and primitive structures to more sophisticated and technically refined forms. The origins of bridge construction in China can be traced back to the Spring and Autumn Period (770BC–476/403BC), followed by further development during the Qin (221–206 BC), Han (202 BC–220), and Three Kingdoms periods (220–280), when all four basic bridge types had already emerged and begun to take shape. Bridge technology reached a peak during the Sui (581–618), Tang (618–907), and Song (960–1279) dynasties, a period marked by significant technological breakthroughs and innovations across various bridge types. Subsequently, during the late imperial period up to the late Qing Dynasty, bridge construction largely inherited and continued traditional construction methods.

Similarly, Yang [25] argued that the development of ancient Chinese bridges followed a relatively continuous and internally coherent trajectory, forming a distinctive technical system. Historical records indicate that by the Spring and Autumn Period the initial stage of bridge development had largely been completed, with the fundamental forms of beam bridges, arch bridges, pontoon bridges, and suspension bridges already appearing in China. Among these, pontoon bridges and suspension bridges are generally considered to be bridge forms with strong indigenous characteristics. Early studies therefore established a historical evolutionary framework for ancient Chinese bridges based on the four principal structural types—beam, arch, suspension, and pontoon bridges—which has later become an important foundation for typological research on ancient bridges in China.

Building upon early typological studies, subsequent scholars have conducted numerous regional case studies, which have greatly enriched this framework and revealed the strong regional adaptability of ancient Chinese bridge forms. These studies also highlight the construction wisdom of adapting designs to local environmental conditions. In the northern plains, where river crossings often required durable masonry structures, stone arch bridges were widely constructed. For example, Baqiao Bridge in Xi'an is considered one of the earliest, largest, and longest-span multi-arch stone bridges known in China [24]. Similarly, the Zhaozhou Bridge in Hebei Province is recognized as the world's earliest surviving single-span open-spandrel stone arch bridge and one of the best-

preserved examples of its kind [26].

In southern Hubei and eastern Hubei, stone arch bridges are also highly representative, with a history dating back to the Song Dynasty. Bridge openings in this region were often designed with an odd number of arches, with single-span bridges being the most common, although three-, five-, and seven-arch bridges were also widely constructed. During the Ming and Qing dynasties, bridge forms became increasingly diverse, with structural types such as slightly curved slab arches, flat-shell arches, and double-curvature arches emerged [27–29].

In water towns in the southern area of the Changjiang River (so-called Jiangnan district), where soft soil conditions and navigational requirements shaped bridge construction, bridges typically featured thin arches and slender piers to minimize obstruction to waterways. Because these regions also experienced high pedestrian traffic, pavilion bridges or small pavilions at bridgeheads were often constructed to provide resting spaces for travelers [30]. A notable example is Baodai Bridge in Suzhou, which is the longest ancient multi-arch stone bridge existing today.

Among these water towns, Shaoxing is well known as the “museum of ancient bridges in China” [31]. Its historic bridges include various structural types such as beam bridges, arch bridges, pontoon bridges and beam–arch composite bridges. It is also famous for having covered bridges, a kind of bridge covered by houses. These different types of bridges exhibit distinct characteristics in structural design, material selection, and construction techniques, reflecting the diversity and sophistication of ancient bridge-building technologies [32].

In the mountainous regions of Fujian and Zhejiang provinces, wooden arch covered bridges are commonly built. For instance, the covered bridges of Taishun county in Zhejiang province employ a woven timber arch structure capable of adapting to deep ravines and fast-flowing streams, while the roofed corridor protects pedestrians from sun and rain [33]. In the southwestern and Xizang regions, where deep valleys and turbulent rivers make pier construction difficult, suspension bridges are widely adopted. Ancient bridges in Xizang can generally be categorized into three main types: ancient suspension bridges (including rope slides, rattan-net bridges, and iron-chain bridges), ancient wooden bridges (such as single-log bridges, plank bridges, ladder bridges, cantilevered timber bridges, and simply supported wooden beam bridges), and ancient stone bridges (including stone slab beam bridges and stone arch bridges) [34].

(2) Local material use and environmental adaptation in ancient bridge construction

The construction of ancient bridges across different regions of China generally follows the principle of adapting to local conditions and utilizing locally available materials. In southern Hubei, where the terrain is characterized by hilly landscapes and rich mountainous resources, building stones such as tuff, limestone, bluestone shale, and granite are widely available. Consequently, ancient bridges in this region often employ softer stones such as tuff and limestone for constructing bridge piers and arch rings, while harder rectangular bluestone slabs were inserted as transverse beams [35]. In contrast, ancient bridges in Suzhou and Shaoxing frequently use granite and Wukang stone, reflecting local material traditions and construction practices [30, 32]. In the mountainous areas of Fujian and Zhejiang, abundant bamboo and timber resources facilitate the development of a mature system of timber arch bridges. In the Huizhou region, examples of bridges built with mixed masonry techniques combining brick, timber, and stone are also documented [36].

Collectively, these studies clearly outline the regional material landscape of ancient bridge construction, demonstrating that material selection of ancient bridges is closely linked to local environmental conditions, resource availability, and traditional building techniques.

Existing studies have gone beyond simply cataloguing the types of materials used in ancient bridges to further explore the relationships between material properties, structural forms, and durability. For example, it has been noted that softer stones such as tuff were commonly used for constructing the main body of bridge piers, whereas harder bluestone slabs were applied in key load-bearing components [35]. Similarly, researchers have recognized that the woven timber arch structure of wooden arch bridges enables the construction of large spans using relatively small timber elements, representing a sophisticated application of the mechanical properties of wood.

Nevertheless, much of the existing research remains largely descriptive and phenomenological in nature. Critical issues still require more systematic and in-depth investigation, particularly the ways in which material properties influence bridge lifespan and the choice of structural forms. These include the compressive strength and weathering resistance of specific stone materials, or the elastic modulus, durability, and treatment techniques of different timber species.

(3) Construction details of ancient bridges

Studies that focus specifically on the construction details of ancient bridges remain relatively limited in the existing body of research. Xia [35] studied ancient bridges in southern Hubei, noting that their masonry techniques reflect the broader tradition of brick–stone construction in the middle and lower reaches of the Yangtze River. Two principal masonry methods—segmented parallel masonry and longitudinally connected courses (commonly observed during the Ming Dynasty)—are both present. The bridge abutments are typically constructed with carefully dressed stone blocks forming the outer surface, while the interior is filled with stone fragments to enhance structural stability. In addition, boat-shaped pointed piers and cantilevered structural elements are widely used, demonstrating the continuation and refinement of traditional bridge-building techniques.

Liu and Lei [24] described the construction details of Baqiao Bridge built in the Qing dynasty, which is supported by stone frame columns (stone shaft columns) arranged in groups of six per row. The foundation adopts the “plum-blossom pile” technique, in which a central pile is driven beneath each column. The upstream pile is left approximately one chi higher, while the remaining piles are cut level. At the top of the columns, stone bearing plates are installed, with an iron column placed at the center of the plate to connect with the stone shaft. Eight additional protective piles are then driven around the structure before the installation of the upper beam framework. Lian and Xiao [37] conducted a comprehensive review of the progressive refinement of construction techniques in the three bridges of the Ming Tombs over different historical periods. Their study systematically analyzed several architectural components, including the construction of the arch-face stones, bridge deck paving, balustrades and ornamental posts, as well as the wing walls (cutwater walls).

2.2 Conservation and restoration technologies for ancient bridges

2.2.1 Reinforcement and repair techniques for ancient bridges

Structural reinforcement and repair technologies constitute essential measures for the conservation of ancient bridges. As many historic bridges have been in service for extended periods, various forms of deterioration have gradually emerged, including cracking, settlement, and material degradation. To ensure the continued safety and functionality of these structures, effective reinforcement and repair interventions are required. Such measures typically include structural strengthening, material replacement, and surface restoration, aiming to restore the load-bearing capacity of the bridge while preserving its structural integrity and aesthetic value.

In the field of conservation and restoration technologies, Professor Chun Qing of Southeast University has long been engaged in

research on architectural heritage conservation and has recently led thorough theoretical and engineering studies focusing on ancient bridges. His research mainly covers two major bridge types: timber arch covered bridges and stone arch bridges.

For timber arch covered bridges, Han and Chun [38] conducted a study on the Wenxing Bridge in Taishun as a representative case, investigating the wind-induced vibration response of traditional timber covered bridges under strong wind conditions. A finite element model was established using SAP (Structure Analysis Program) 2000 to analyze the dynamic characteristics of timber arch covered bridges, providing an important basis for evaluating wind-induced vibration performance and developing wind-resistance protection strategies for traditional timber bridges in China.

For stone arch bridges, Chun and collaborators [39] examined the Jinhu Bridge in Nanjing, a Ming Dynasty stone arch bridge, and developed a quantitative risk assessment method that considers the disaster-bearing mechanisms of ancient masonry arch bridges and timber covered bridges under deteriorated conditions. Their research included structural performance evaluation and component importance analysis, leading to the proposal of scientifically grounded conservation technologies specifically suited for Ming Dynasty stone arch bridges.

These research achievements are systematically compiled in Chun Qing's monograph *Conservation Technologies for Typical Architectural Heritage* published in 2015 [40]. The book includes a dedicated chapter on "Conservation Technologies and Case Studies of Timber Structural Heritage," which documents restoration practices of nationally protected heritage sites such as the Taishun covered bridges (including Wenxing Bridge). It establishes a comprehensive technical framework covering the entire process from condition assessment and structural evaluation to reinforcement and restoration interventions.

The research team led by Professor Chen Baochun at Fuzhou University has long been devoted to the study of the structural mechanisms and engineering value of traditional Chinese timber arch bridges, particularly the woven timber arch bridges of the Fujian–Zhejiang region. Their work has produced systematic achievements in areas including structural form analysis, mechanical theory, and traditional construction techniques.

As shown in Fig. 1, Liu and Chen [41] reviewed the development history and structural typologies of timber arch bridges, noting that the arch ribs of timber bridges mainly include timber rib arches, timber truss arches, and woven timber arches. Among these, the woven timber arch structure is a distinctive structural form found almost exclusively in China and preserved in relatively large numbers. Its structural behavior differs significantly from that of conventional two-dimensional or three-dimensional frame systems, making it of considerable significance for the study of structural mechanics and traditional engineering systems.

Further studies by Yang and Chen [42] conducted quasi-static tests on full-scale models of dovetail mortise–tenon joints used in woven timber arch bridges in the Fujian–Zhejiang region, as shown



Fig. 1 Chinese Timber Arch Bridges [41]. (a) Detail of Along the River During the Qingming Festival (Bian River Rainbow Bridge); (b) Fujian–Zhejiang Timber Arch Bridge (Xidong Bridge).

in Fig. 2. Based on the experimental results, they established a moment–rotation mechanical model that accounts for the effects of mortise–tenon gaps and tenon withdrawal displacement. The validity of the proposed model was verified through a combination of experimental testing and finite element analysis, which revealed the relationships between joint stiffness and influencing factors such as axial force and mortise–tenon gap size.

These studies provide important theoretical insights into the structural mechanisms of woven timber arch bridges and offer valuable scientific support for the conservation and restoration of traditional timber bridge heritage.

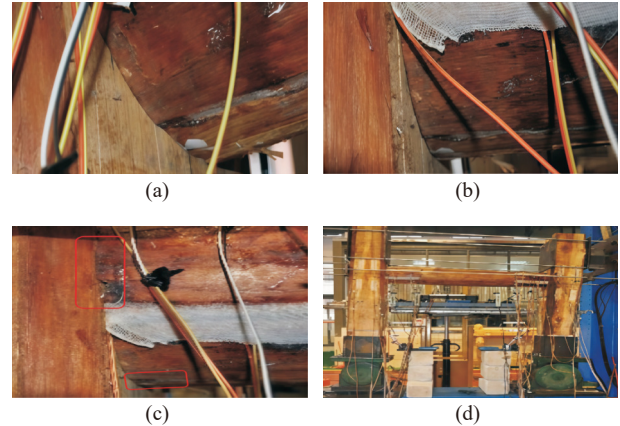


Fig. 2 Quasi-static test phenomena [42]. (a) Tight closure at the mortise base before the test; (b) Gap formed at the mortise base due to compression after the test; (c) Propagation of shrinkage cracks; (d) Large deformation of the component.

Mao and colleagues [43] investigated a stone arch bridge located on a mountainous highway as a case study. Through visual inspection and load testing, they evaluated the bridge's deterioration conditions and service performance, and subsequently proposed targeted reinforcement measures. The results demonstrated that appropriate strengthening interventions can effectively improve the service performance of historic bridges.

Zheng [44] conducted a study on Tongji Bridge in Yuyao, Ningbo city, Zhejiang Province. By integrating digital and intelligent technologies, they combined field monitoring data with mathematical modeling to analyze the deformation behavior and damage mechanisms of the arch bridge. Based on these analyses, they identified scientifically grounded and technically feasible conservation and restoration strategies for the historic bridge.

2.2.2 Non-Destructive Testing (NDT) techniques for ancient bridges

Due to their long service history, complex structural systems, and prolonged exposure to natural environments, ancient bridges face significant challenges in the assessment of structural stability and reliability. Traditional evaluation methods often struggle to accurately capture the true structural response of these bridges, particularly when key parameters are difficult to determine. With the increase in traffic loads and the intensification of structural aging, the inspection, assessment, and strengthening of ancient bridges have gradually become essential measures for ensuring their safe operation.

In recent years, non-destructive testing (NDT) technologies, geometric surveying techniques, and numerical simulation methods have been widely applied in the evaluation and conservation of ancient bridges. These approaches enable the acquisition of structural condition information with minimal disturbance to the bridge, making them essential tools for the safety assessment of ancient bridges [45–46].

For typical historic bridge types such as stone arch bridges and timber covered bridges, a range of techniques has been introduced

to obtain high-precision data on geometry, materials, and structural behavior. Ground-penetrating radar (GPR) has been widely used to detect internal voids, cracks, and masonry compactness in historic stone bridges. Wu [47] for example, verified through engineering case studies the effectiveness of GPR in identifying internal voids and cracks, while Zhang and Qiao [48] applied this technique to evaluate the masonry compactness of the Bazzi Bridge in Shaoxing. Laser scanning and UAV-based photogrammetry have been employed to document bridge geometry with high accuracy, while modal testing has been adopted to evaluate the stiffness and dynamic characteristics of stone arch bridges. In addition, multidisciplinary approaches combining geometric surveying, dynamic testing, and numerical modeling have increasingly been used to analyze the structural performance of historic bridges [49–50].

Other NDT methods have also been applied to address specific assessment needs. Ultrasonic pulse velocity (UPV) testing can identify internal defects in materials and evaluate the compactness of masonry by analyzing variations in wave propagation velocity [51–52]. Acoustic emission techniques allow real-time monitoring of structural damage and localization of damage sources. Sonar technologies, on the other hand, have been applied to detect scour and settlement of underwater foundations. For example, Chen [53] used multibeam sonar and side-scan sonar to perform three-dimensional reconstruction and damage identification of the underwater foundations of an ancient stone arch bridge. Radiographic imaging techniques can be employed to identify internal structural characteristics and defects [54].

Beyond condition inspection, recent studies have further integrated NDT results with numerical modeling and probabilistic analysis to support scientific decision-making in bridge conservation. For instance, Gong [55] proposed a structural reliability assessment method for stone arch bridges that integrates non-destructive testing techniques with probabilistic analysis. By deriving key structural parameters through field testing and incorporating them into numerical models, their approach provides a new technical pathway for the scientific assessment and conservation of ancient bridge structures.

2.2.3 Structural performance assessment of ancient bridges

Structural performance assessment is a crucial step in ensuring the safe operation and long-term service ability of ancient bridges. By systematically evaluating their structural performance, potential safety risks can be identified in a timely manner, allowing appropriate conservation and intervention measures to be implemented. Such assessments typically involve static analysis, dynamic analysis, and reliability analysis, among other approaches, with the aim of obtaining a comprehensive understanding of the current structural condition of historic bridges.

Jiao et al. [56] used Wanning Bridge in Beijing as a prototype and developed a three-dimensional finite element model incorporating cohesive interfaces, based on experimentally calibrated mechanical parameters of stone blocks and mortar joints, as shown in Fig. 3. Using this model, they systematically investigated the effects of voussoir arrangement, arch-ring thickness, and friction coefficient, as well as long-term deterioration factors such as differential settlement, horizontal displacement, and mortar-joint loss, on the ultimate load-bearing capacity and failure modes of the bridge. The results verified the effectiveness of the cohesive interface model in simulating the damage evolution and failure mechanisms of mortar joints in historic stone arch bridges, providing important references for the load-bearing capacity assessment of ancient masonry arch bridges.

Hua et al. [57] conducted a detailed investigation and summary of the arch masonry construction methods commonly used in ancient Chinese stone arch bridges. Based on this survey, they developed finite element models for four typical arch masonry configurations to analyze their failure modes and load-bearing capacities. Their study further examined the influence of the friction coefficient on the failure patterns and ultimate bearing capacity of these typical arch structures, providing valuable insights into the structural behavior of traditional stone arch bridges.

Wang [58] investigated the field inspection and safety evaluation of stone arch bridges. Through a combination of finite element analysis and reliability analysis, the load-bearing capacity and overall safety of stone arch bridges were assessed. The study indic-

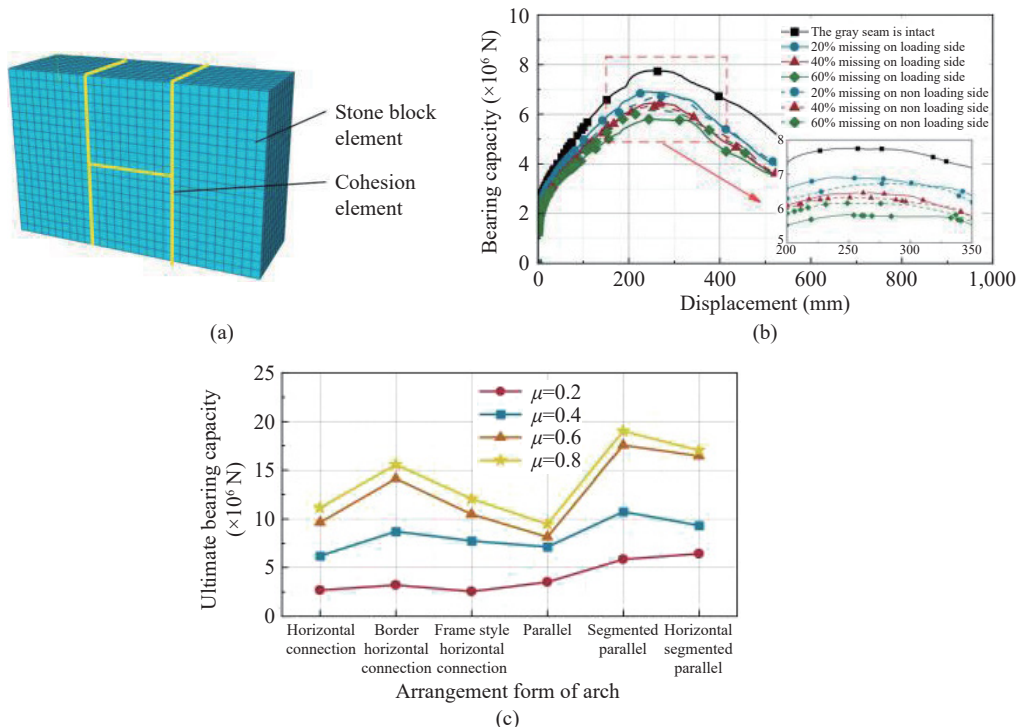


Fig. 3 Finite element model of Wanning Bridge in Beijing [56]. (a) Overall three-dimensional finite element model; (b) Bearing capacity displacement curve of frame type transverse arch under gray joint deficiency disease; (c) Horizontal comparison of arches with different arch stone-mortar friction properties.

ated that, during long-term service, many stone arch bridges exhibit insufficient load-bearing capacity due to factors such as material aging and environmental influences. Zhao [59] proposed a non-destructive stiffness assessment method for stone arch bridges based on modal testing. By identifying modal parameters under ambient excitation, they evaluated the stiffness condition of stone arch bridges. This approach provides a new methodological perspective for the structural assessment and conservation of historic bridges.

2.3 Disaster risk and structural safety of ancient bridges

2.3.1 Fire effects on ancient bridges

Wood, as a natural construction material, has a long history of application in engineering practice. Timber bridges, constructed primarily with wood as the main structural material, were once an important category of ancient bridge forms. Even today, timber bridge structures continue to retain a certain degree of practical value and application in modern bridge engineering [60]. In addition to their use in beam bridges, timber has also been widely applied in the construction of arch bridges, gradually evolving into several structural forms over the course of historical development, including timber rib arches, timber truss arches, and woven timber arches [61].

The remains of timber arch covered bridges in China are widely distributed across multiple regions, including Southeast China, Southwest China, Central South China, Northwest China, North China, and the Jiangnan region. In spatial terms, these bridges have gradually formed six relatively concentrated distribution belts of covered bridge heritage. Among them, Fujian and Zhejiang provinces represent the core area where the largest number of ancient timber arch covered bridges are preserved. Benefiting from abundant forest resources, a warm and humid climate, and a dense river network, this region has maintained the most concentrated clusters of traditional timber arch covered bridges in China and remains the principal distribution center of this distinctive bridge type.

Due to the susceptibility of timber structural materials to decay and their relatively limited durability, only a small number of early timber bridges have survived to the present day. According to the statistical data shown in the Fig. 4, most of the existing timber arch bridges were either originally constructed during the Qing Dynasty or underwent major reconstruction or restoration during that period. These bridges account for approximately 53.9% of the total number of surviving examples.

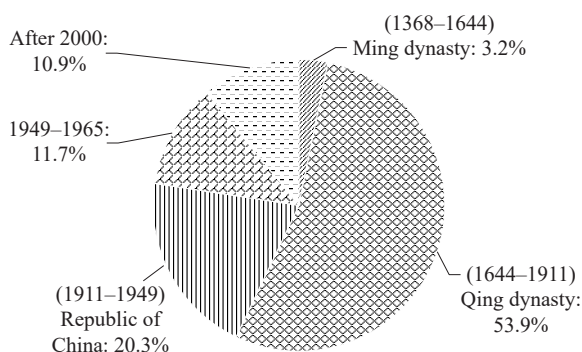


Fig. 4 Construction period distribution of Fujian-Zhejiang timber arch bridges [61].

Existing timber covered bridges are generally confronted with severe fire hazards, and as the degree of material aging increases, their fire resistance performance declines significantly. In recent years, the number of timber arch covered bridges in the Fujian-Zhejiang region has continued to decrease. In addition to demolitions resulting from adjustments in urban and rural develop-

ment, natural disasters such as fires and floods have also been major contributing factors. Among these threats, fire incidents occur relatively frequently and often cause particularly severe damage. Consequently, fire prevention has become both a key priority and a major challenge in the conservation of timber arch covered bridges.

In recent years, the timber arch covered bridges of the Fujian-Zhejiang region, known for their distinctive structural forms, have attracted increasing scholarly attention. Chen [62] conducted a systematic investigation and statistical analysis of fire incidents involving timber arch covered bridges in this region, examining factors such as ignition causes and the extent of damage. On this basis, they carried out a comprehensive evaluation of the effectiveness of existing fire prevention measures and proposed forward-looking strategies for improving fire protection. Furthermore, from the perspective of spatial fire risk management, the study suggested dividing the bridge environment into three fire prevention zones, including the upper and lower spaces of the bridge structure, the spaces between multiple spans, and the areas between the bridge and surrounding forests or buildings, in order to enhance targeted fire prevention and control strategies.

Cao [63] employed a comprehensive index evaluation method to systematically analyze the fire risk of timber covered bridges in the Taishun region. They established a risk assessment index system incorporating multiple dimensions, including the hazard level of disaster-inducing factors, the sensitivity of the disaster-forming environment, the vulnerability characteristics of the heritage structure, and the adaptability of fire management and response capacity. The results indicated that human fire-use activities and the fire-resistance rating of structural materials are the primary factors influencing the level of fire risk.

In the same year, Pan and Liu [64] conducted a systematic evaluation of the fire-prone environmental sensitivity of timber covered bridges by integrating multi-source data. They developed an assessment model based on a CRITIC-entropy (Criteria Importance Through Intercriteria Correlation-entropy) combined weighting method, providing a more scientific basis for fire risk management and decision-making in the conservation of timber covered bridges. Their study selected six representative timber covered bridges in Taishun County, Zhejiang Province as empirical cases, promoting a shift in heritage safety management from post-disaster response to proactive risk prevention.

However, the study samples were all concentrated in the Taishun region, which limits the representativeness of the findings. In terms of both sample size and preservation environment, the selected cases may not fully reflect the overall conditions of timber covered bridge heritage in other regions of China. Furthermore, the complex and dynamic environmental conditions in which timber covered bridges are situated—together with significant regional variations in natural and socio-cultural contexts and the difficulty of accurately quantifying transient environmental factors—introduce additional constraints on the generalizability of the evaluation results.

Fan and Chen [65] proposed a digital reconstruction approach that integrates three-dimensional laser scanning with BIM-based parametric modeling to develop digital twin models of timber arch covered bridges. On this basis, they further combined BIM with the Fire Dynamics Simulator (FDS) to simulate and analyze the mechanisms of fire propagation and corresponding fire prevention strategies.

The outcomes of this research not only facilitate the digital documentation and information management of timber arch covered bridges, but also enable quantitative analyses of fire spread, thereby providing valuable data support for preventive conservation. Moreover, these approaches offer important technical support for the long-term safety operation, monitoring, and management of historic timber bridge heritage.

2.3.2 Flood effects on ancient bridges

For covered bridges, flood-induced damage is primarily concentrated in the bridge structure itself. Under the impact of strong water flow, covered bridges with insufficient overall stability and limited component load-bearing capacity often struggle to withstand external forces, making them highly susceptible to overturning or

structural collapse. In 2016, severe flooding triggered by Typhoon Meranti caused significant destruction in the Fujian–Zhejiang region, where three covered bridges recognized as “national heritage-level” structures were washed away by floodwaters. Fig. 5 shows a comparison of the Xuezhai Bridge, Wenzhong Bridge, and Wenxing Bridge before and after the flood disaster.

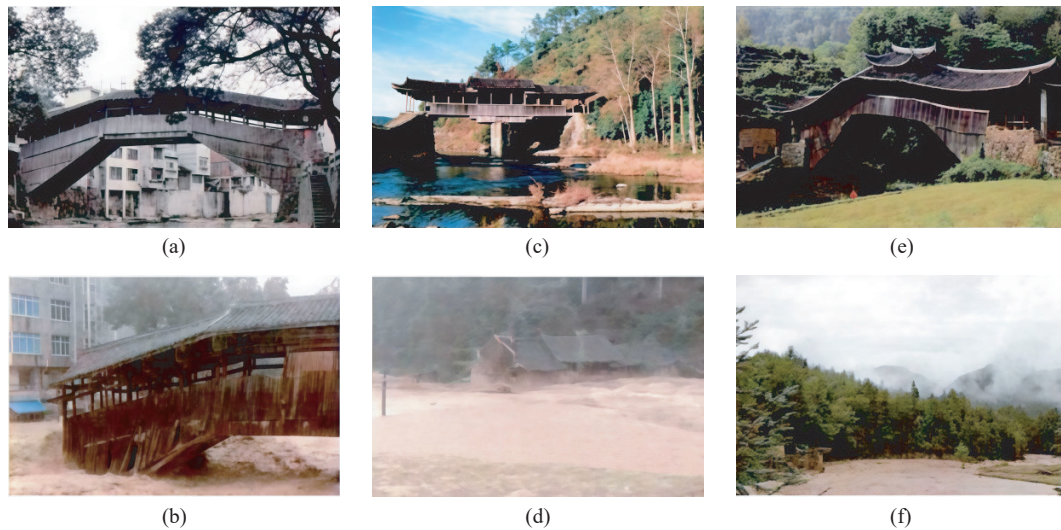


Fig. 5 Comparison of “nationally significant” Taishun covered bridges before and after the flood disaster [66].

(a) Xuezhai Bridge-before flood; (b) Xuezhai Bridge-after flood; (c) Wenzhong Bridge-before flood; (d) Wenzhong Bridge-after flood; (e) Wenxing Bridge-before flood; (f) Wenxing Bridge-after flood.

The frequent occurrence of flood-related damage highlights the urgent need for systematic research on the flood resistance of timber arch covered bridges. As a key structural component designed to protect these bridges from wind and rain, wind–rain boards play an important role in their structural behavior. Zhang [67] established a mechanical calculation model of a timber arch covered bridge using the finite element software SAP2000, and conducted comparative analyses under different flood frequency scenarios for bridges with and without wind–rain boards. The results indicate that the presence of wind–rain boards significantly increases the lateral and vertical loads acting on the bridge. Moreover, flood impacts can weaken the stabilizing effect generated by the self-weight of the structure, potentially inducing uplift of the bridge body and the disengagement of mortise–tenon joints, which may ultimately lead to overall structural instability or collapse.

Fan and Zhao [66] further noted that certain ancient bridges incorporated targeted flood mitigation concepts during their design and construction. For example, the Yongqing Pingliang Bridge in Taishun features pointed bridge piers on the upstream side, which help disperse and reduce the direct hydraulic impact of floodwaters on the piers, thereby mitigating hydrodynamic forces. Similarly, the Lanxi Bridge in Qingyuan, which was destroyed by flooding in the 48th year of the Qianlong reign of the Qing Dynasty, was reconstructed with improvements aimed at enhancing structural stability. To increase the structural self-weight, a sand–gravel layer was added above the bridge deck, topped with cobbles and reinforced with stone slabs, thereby improving the bridge’s flood resistance and overall structural stability.

Masonry arch bridges, characterized by their elegant structural form and relatively high load-bearing capacity, have long been widely constructed and utilized in countries such as China, Italy, and France, with many examples continuing to function within transportation systems after several centuries of service. However, under the context of climate change, the frequency and intensity of flooding events have been increasing. Coupled with the prolonged service life of these bridges and the gradual deterioration of their

structural performance, the risk of failure in masonry arch bridges has significantly increased, potentially resulting in serious casualties and substantial economic losses [68].

Jiang and colleagues [69] pointed out that the failure of masonry arch bridges under flood conditions is not caused by a single factor, but rather represents a complex dynamic evolutionary process. Fundamentally, such failures arise from the coupled interactions among three key components: the disaster-bearing system (the masonry arch bridge itself), the disaster-forming environment (such as geological and climatic conditions), and the disaster-inducing factor (flood events).

In addition, the damage of ancient bridges in flood environments is often closely associated with foundation scour. Liang [70] through analyses of several representative historic bridge cases, pointed out that flood-induced damage generally results from the combined effects of hydraulic impact and riverbed scour, with scour being a critical factor influencing the long-term service safety of bridges. When water flow accelerates around bridge piers and generates local vortices, the riverbed soil is gradually eroded, leading to the formation of scour holes and a consequent reduction in the stability of bridge foundations.

To address this issue, various scour protection strategies were developed in traditional bridge engineering practice. These include the construction of cutwaters (pointed upstream pier noses) to alter the flow field around piers, the use of riprap foundations to enhance the riverbed’s resistance to scour, and the installation of pile rows upstream of bridge piers to dissipate hydraulic energy. These measures reflect the empirical understanding of hydrodynamic effects in ancient engineering practice, and their underlying protective concepts continue to provide valuable references for modern bridge foundation protection and the conservation of historic bridges.

2.3.3 Seismic effects on ancient bridges

As ancient bridges generally have relatively small spans and many no longer serve as primary transportation infrastructure, their

seismic response is often considered limited. In addition, the lack of detailed structural documentation has resulted in comparatively few studies focusing on their seismic performance. Nevertheless, seismic loads can still induce structural vibrations and additional internal forces, which may lead to cracking of structural members, failure of connections, or even overall structural instability. Therefore, research on the seismic performance and resilience of ancient bridges remains of significant importance.

In recent years, some studies have begun to focus on the seismic response and reinforcement strategies for ancient bridges. For example, Lü [71] investigated the Yongning Ancient Bridge by developing a finite element model to analyze its seismic dynamic response and to compare structural performance before and after reinforcement. The results showed that appropriate strengthening measures can enhance the structural stiffness and stability of the bridge, while significantly reducing displacement and stress responses under seismic loading.

In addition, numerical simulations and post-earthquake damage investigations have been employed to analyze the seismic response characteristics of ancient bridges. Zeng [72], taking the Gongchen Bridge on the Beijing–Hangzhou Grand Canal as a case study, developed a finite element model coupling the arch bridge, surrounding water body, and site conditions to investigate the dynamic response under hydro–rock interaction conditions. The results indicated that the presence of a water environment can amplify structural stress and displacement, with the junction between the abutment and the secondary arch ring, as well as the bridge deck at the arch crown, identified as the primary structural weak points.

In terms of post-earthquake field investigations, An and colleagues [73], during a cultural heritage damage survey following the 2021 Luxian M6.0 earthquake in Sichuan Province, found that the overall seismic damage to ancient bridges was relatively minor. Observed damage mainly included cracking of bridge deck slabs, surface spalling of the deck, and displacement of abutment foundation stones, while severe structural failures were rare. These findings suggest that traditional stone bridges possess a certain degree of seismic resilience under low to moderate seismic intensities.

2.4 Digital technologies and information modeling for ancient bridges

Ancient bridges are characterized by complex structural forms and diverse construction techniques, while also facing issues such as the absence of original design drawings, long-term service, and multiple phases of repair and modification. To achieve accurate documentation and systematic conservation of these structures, researchers have increasingly introduced digital technologies in recent years, including three-dimensional laser scanning, photogrammetry, and information modeling. The application of these technologies has promoted a shift in ancient bridge studies from traditional experience-based descriptions toward more refined, data-driven research approaches.

2.4.1 Digital data acquisition technologies for ancient bridges

In the digital documentation of ancient bridges, three-dimensional laser scanning technology is often referred to as a form of “reality capture” technology. Owing to its advantages of high precision, non-contact measurement, and the capability of capturing detailed spatial information (“what you see is what you get”), it has been widely applied in the digital study of historic bridges. Three-dimensional laser scanning technology, commonly known as LiDAR (Light Detection and Ranging), originated in the late 1960s from the development of laser radar technology in the United States. Initially applied in aerial remote sensing, the technology was later gradually adapted for ground-based three-dimensional scanning and promoted in the field of terrestrial surveying. Its application in engineering fields such as architecture and bridge documentation can be traced back to the early 1990s [74].

LiDAR is an active remote sensing technology that acquires pre-

cise three-dimensional spatial information by emitting laser pulses and measuring the time taken for the reflected signals to return. Through this process, the technology can accurately capture the three-dimensional coordinates of target objects, enabling the generation of high-resolution spatial datasets for structural documentation and analysis.

During the process of three-dimensional laser scanning measurement, the scanner itself is typically taken as the origin for establishing a spatial coordinate system. As shown in Fig. 6, within this coordinate system, the X - and Y -axes lie on the horizontal scanning plane and are perpendicular to each other, while the Z -axis is oriented vertically to the horizontal plane. Based on this framework, the scanner determines the spatial position of target points by measuring the angular orientation of the emitted laser beam together with the corresponding distance information, thereby enabling the accurate acquisition of three-dimensional coordinates.

During operation, the laser scanner acquires the slope distance S from the scanned point to the instrument center, together with the corresponding horizontal angle α and vertical angle β . Based on these parameters, the three-dimensional coordinates of the scanned point in the scanner coordinate system can be expressed as follows:

$$x = S \cos\beta \sin\alpha \quad (1)$$

$$y = S \cos\beta \cos\alpha \quad (2)$$

$$z = S \sin\beta \quad (3)$$

where, α is the horizontal angle of the scanned point relative to the instrument coordinate system; β is the vertical measurement angle; S is the spatial distance from the instrument center to the target point.

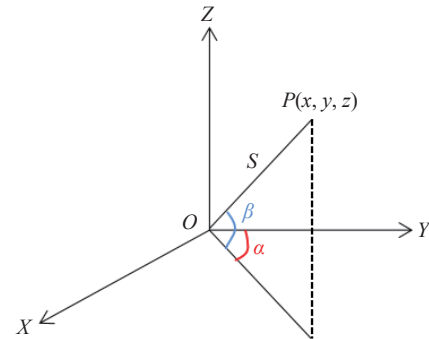


Fig. 6 Schematic diagram of the measurement principle of 3D laser scanning technology.

Li et al. [75] conducted a study on the stone bridges along the Sacred Way of the Ming and Qing imperial tombs in China, employing three-dimensional laser scanning technology to obtain high-density point cloud data of both the overall bridge structure and its detailed components. Based on these data, they analyzed the design principles, structural behavior, and evolutionary characteristics of the historic bridges, providing a reliable data foundation for the accurate surveying and conservation of ancient bridges. The results demonstrate that laser scanning, as a non-contact measurement technique, can effectively avoid physical disturbance to fragile stone components and is therefore particularly suitable for documenting historic bridges with high cultural heritage value.

Similarly, Liu [76] utilized terrestrial laser scanning technology to collect detailed three-dimensional point cloud data of an ancient stone arch bridge. Through processes including multi-view point cloud registration, noise removal, and data simplification, they successfully constructed a three-dimensional solid model of the bridge. This approach not only enables the efficient acquisition of the geometric characteristics of ancient bridges, but also provides

comprehensive data support for their structural monitoring, reinforcement, and restoration.

However, for certain ancient bridges where spatial occlusion and complex structural components limit the effectiveness of laser scanning, Jiang et al. [77] pointed out in their review study that photogrammetry can serve as an important complementary technique to laser scanning. By reconstructing three-dimensional information from photographic images, photogrammetry enables the accurate 3D representation of bridge components, thereby improving the completeness of digital documentation for historic bridge structures.

With the development of unmanned aerial vehicle (UAV) technology, UAV photogrammetry has gradually become an important method for acquiring three-dimensional data of ancient bridges. This approach employs UAVs as aerial platforms equipped with digital cameras and sensors such as GNSS (Global Navigation Satellite System)/IMU (Inertial Measuring Unit), enabling the rapid and flexible acquisition of high-resolution ground images.

Pan et al. [78], taking heritage bridges in China as research objects, proposed a semi-automated structural surface reconstruction method based on point cloud data derived from UAV photogrammetry. Their method achieved high-precision three-dimensional reconstruction of the main bridge components, thereby demonstrating the feasibility and efficiency advantages of UAV-based technologies for the digital documentation of ancient bridges.

In practical applications, some scholars have adopted multi-source data fusion strategies to improve the completeness and reliability of digital datasets. For example, Fan et al. [79] selected the Bazi Bridge in Shaoxing (as shown in Fig. 7) as a case study and combined UAV oblique photogrammetry with three-dimensional laser scanning to acquire comprehensive datasets, thereby establishing a complete, accurate, and long-term digital archive of the historic bridge.



Fig. 7 Digital modeling results of Bazi Bridge in Zhejiang [79].

Similarly, Fu [80] conducted research on the Wangchun Bridge in Ningbo, integrating UAV-based laser scanning to obtain point cloud data of both the bridge structure and its surrounding environment. Based on these data, they constructed a comprehensive three-dimensional model and proposed a framework for the “digital preservation of ancient bridge architecture throughout its entire life cycle,” enabling systematic integration of bridge information and facilitating public presentation and dissemination. Shan et al. [81], taking the Baling Bridge in Weiyuan County as an example, used three-dimensional laser scanning technology to collect and process point cloud data of the historic bridge. Based on these datasets, they further explored the application of digital conservation methods for the preservation and documentation of the bridge.

2.4.2 Point cloud-based geometric and information modeling methods for ancient bridges

After acquiring three-dimensional point cloud data, researchers have increasingly focused on how to transform these datasets into structural models that can be used for analysis and management. Xiong et al. [82] conducted early research on automatic modeling based on 3D laser scanning data, proposing a method for automatically generating BIM models from point clouds. Their study found that, after applying supplementary processing to occluded regions, the automatically generated models exhibited good geometric consistency with manually constructed ground-truth models, demonstrating the feasibility of automated point cloud-based BIM recon-

struction.

For typical historic bridge structures such as stone arch bridges, Deng et al. [83] proposed a structural parameter identification method based on three-dimensional laser scanning point clouds. In their study, an automatic arch-axis extraction algorithm was developed and successfully applied to the Lugou Bridge in Beijing. The results demonstrate that this approach can efficiently and accurately identify key geometric parameters, such as arch span and rise, thereby providing quantitative data to support the structural assessment and conservation of ancient arch bridges.

With the introduction of information modeling concepts, the application of BIM, BrIM (Bridge Information Modeling), and HBIM (Historic Building Information Modeling) has gradually increased in the study of ancient bridges. Yao [84] conducted a digital modeling study of the Guangning Bridge in Shaoxing by integrating three-dimensional laser scanning technology with BIM modeling. Their research demonstrates that the combination of 3D laser scanning and BIM technologies not only improves modeling accuracy but also provides more comprehensive information support for the conservation and restoration of historic bridges.

2.4.3 Applications and development trends of digital models in ancient bridge conservation

Digital models constructed through scanning technologies and information modeling have been increasingly applied in the structural assessment, restoration design, and long-term management of ancient bridges. Through digital modeling, the structural characteristics of historic stone arch bridges can be accurately documented and analyzed, providing a scientific basis for subsequent conservation and restoration interventions.

Zheng and Ding [85] developed an information management system for ancient bridges, through which traditional paper-based archival records were digitized into electronic archives. This system enables the implementation of simplified assessments and management of historic bridge information.

Xiang [86], taking a historic three-span stone arch bridge as a case study, conducted detailed measurements of its external geometric dimensions and reconstructed the arch axis profile. Based on these measurements, the plan, longitudinal, and transverse dimensional drawings of the bridge were produced. In addition, the current condition and structural defects of the bridge were systematically investigated and evaluated. On this basis, modern structural analysis theories were applied to estimate the potential load-bearing capacity of the bridge, thereby providing an important basis for its safety assessment and conservation decision-making.

Jiang [87] proposed a reverse modeling method for ancient stone arch bridges based on UAV imagery and contour extraction techniques. In their study, multi-view sequential images of the bridge were captured using UAVs, and a three-dimensional reality-based model of the stone arch bridge was constructed using Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms. Subsequently, an improved Canny edge detection algorithm combined with a polygon approximation method was applied to achieve automated identification of the bridge surface contours. In the same year, Jiang et al. [69] also provided a comprehensive review of the failure mechanisms, monitoring techniques, and protective measures for masonry arch bridges under flood conditions, emphasizing the importance of non-destructive testing, digital twin technologies, intelligent monitoring, and low-intervention protection techniques. These studies not only provide technical support for the digital modeling of historic stone arch bridges, but also offer theoretical foundations for their structural performance assessment and conservation.

Liu et al. [88], through the case study of the Tongjing Bridge project, verified the feasibility of integrating three-dimensional laser scanning with BIM technology in the construction of digital archives for ancient bridges. They pointed out that this technical

approach facilitates the systematic acquisition and long-term preservation of bridge information. Song et al. [89] selected the Dagong Bridge in Wuxi as their research object. By employing three-dimensional laser scanning to obtain point cloud data and establishing a finite element model, they carried out structural verification and assessment of the bridge's current condition. The results indicate that laser scanning technology offers significant advantages in the evaluation of ancient bridges, including non-contact measurement, high accuracy, and high efficiency.

2.5 Interpretation and dissemination of the heritage values of ancient bridges

2.5.1 Aesthetic value of ancient bridges

In recent years, scholars have produced a considerable body of research on the imagery and cultural representation of ancient bridges. Among these works, the bridge studies monographs *Poetic and Pictorial Bridges* by Yang Yu and He Xuhui [90] and *Bridges in Poetry* [91] are particularly representative. Taking the stories and cultural narratives behind bridges as their central theme, these works adopt interdisciplinary perspectives spanning engineering, literature, and aesthetics. Through this approach, they vividly illustrate the structural beauty, poetic imagery, and pictorial qualities of bridges, while also revealing the aesthetic characteristics and spiritual connotations of bridges across different historical period.

Research on the aesthetic value of ancient bridges in China mainly focuses on aspects such as architectural form, decorative motifs, and environmental imagery. Yang [92] argues that many ancient bridges in Zhejiang adopt symmetrical layouts and straight central axes, presenting a sense of simplicity and structural elegance. Stone arch bridges, characterized by graceful curves and slender arches, create a visual effect of lightness, while their reflections on the water surface generate an aesthetic of "interplay between reality and illusion." In addition, multi-span arch bridges, together with their reflections in the water, form circular visual compositions that evoke a distinctive poetic atmosphere typical of the Jiangnan region.

The decorative aesthetics of ancient bridges are manifested in the integration of pattern beauty, artistic conception, and craftsmanship. Through refined carving techniques and a wide variety of thematic motifs, these decorations form an artistic system with strong visual appeal. The carved motifs commonly include animal patterns, plant patterns, and auspicious symbols [93]. Moreover, such decorative elements often incorporate diverse aspects of traditional Chinese culture, including Confucian ethics, Daoist beliefs, Buddhist concepts, and folk auspicious symbolism [32, 93, 94].

2.5.2 Cultural value of ancient bridges

Many ancient bridges in China possess not only remarkable technological achievements but also profound cultural value. Beyond serving as transportation facilities that allow pedestrians to cross rivers and replace ferry crossings, bridges have long been closely connected with everyday life, influencing various aspects of people's material and spiritual activities. In ancient times, the areas around bridgeheads often functioned as marketplaces, social gathering spaces, resting spots, and scenic viewpoints, where people would converse, enjoy the surroundings, or bid farewell to travelers. As a result, bridges became places imbued with deep cultural sentiment and collective memory [95].

Ancient bridges spanning valleys and rivers were sometimes regarded as symbolic passages between the human world and the spiritual realm, and in folk beliefs they were frequently associated with legends of immortals, thereby becoming a material manifestation of Daoist cultural traditions [96]. Bridge names in ancient China were often closely related to local legends and historical narratives—some poetic and uplifting, others melancholic—reflecting local customs such as marriage traditions, fertility beliefs, and

communal values, and offering insights into the spiritual world of local communities [97].

The naming of ancient bridges also embodies rich cultural connotations. Xia [35] argued that the names of ancient bridges in southern Hubei often convey emotions, historical memories, or social values, functioning as symbols and carriers of regional culture. Dong [32] observed that the names of ancient bridges in Shaoxing are frequently associated with local place names, historical allusions, and folk customs, reflecting local cultural values. He [98] noted that the naming of ancient bridges in Chibi embodies local humanistic traditions and folk psychology, and summarized five major naming categories:

(1) Commemorative names, honoring bridge builders or historical figures.

(2) Aspirational names, expressing auspicious wishes such as longevity or peace (e.g., Wanshou or Yongning).

(3) Toponymic names, derived from village or river names.

(4) Religious or ritual names, associated with temples or deities (e.g., Dragon King Bridge or Guanyin Bridge).

(5) Descriptive names, depicting visual imagery or scenery (e.g., Wohong Bridge or Baichun Bridge).

Tu [99] examined the role of ancient bridges in Shaoxing within the Eastern Zhejiang Canal system, emphasizing that these bridges possess not only engineering significance but also outstanding cultural and artistic value. From a phenomenological perspective, Jiang and Dai [100] analyzed the cultural meaning of covered bridges, arguing that they are not merely transportation structures but also integral components of local lifeworlds. Similarly, Gong [101], taking three ancient bridges in Huizhou as case studies, explored their typological characteristics and cultural connotations from a historical and cultural perspective, concluding that Huizhou ancient bridges serve as important material carriers of Huizhou culture.

2.5.3 Social value of ancient bridges

Ancient bridges in China also embody significant social value. Professor Tian Lin of the China Academy of Cultural Heritage, from an architectural perspective, has led projects such as the *Survey and Archival Compilation of Ancient Bridges in Beijing* and the *Architectural Surveying of Ancient Bridges along the Beijing Section of the Grand Canal*. Through these projects, systematic investigations were conducted on 78 historic bridge sites comprising 88 individual bridges in Beijing. In his related monographs [102–103], Tian Lin established a theoretical framework encompassing architectural heritage value assessment, surveying and documentation technologies, and conservation design methodologies. This framework emphasizes a scientific, full-process approach, covering stages from value identification and condition investigation to conservation planning and construction documentation.

This theoretical and technical system also provides valuable references for the conservation of architectural heritage such as ancient bridges. For instance, through systematic surveying and typological analysis, structural and construction data of bridges can be obtained, enabling the establishment of comprehensive archival records that integrate historical information with structural characteristics. On this basis, scientifically grounded restoration strategies can be formulated. Such an approach forms an important theoretical and technical pathway that connects heritage investigation and research with practical conservation implementation in ancient bridge preservation.

Zhang and Tian [104] further examined the heritage value and conservation strategies of ancient bridges along the Shandong section of the Grand Canal. They proposed conservation principles that avoid excessive reconstruction while emphasizing moderate repair and appropriate presentation, highlighting the interactive relationship between ancient bridges and their surrounding environments. These studies provide both theoretical and practical founda-

tions for the holistic conservation of ancient bridges and offer methodological references for the recognition and evaluation of ancient bridge heritage value at a regional scale.

Liu [105] examined bridge imagery depicted in Han Dynasty pictorial reliefs, systematically analyzing the forms and structural characteristics of timber bridges represented in these materials. Their study revealed several technical features of Han Dynasty timber bridges, including structural forms such as the “braced arch” system. These construction methods not only reflect the technical expertise and creative ingenuity of ancient craftsmanship traditions, but also provide valuable inspiration for contemporary timber structural design.

In addition, Li [106] conducted research based on bridge images from the Han Dynasty, summarizing the typological classifications and structural characteristics of bridges from that period. Their findings highlight the important role of bridges within ancient transportation systems and regional connectivity, underscoring their significance in facilitating social and economic interactions in early Chinese society.

Jiang [107] studied the wind-and-rain bridges in Hunan Province, classifying them into two main categories: stone arch covered bridges and stone-pier timber-beam covered bridges. Their research analyzed the architectural structural characteristics and cultural connotations of these bridges, pointing out that wind-and-rain bridges function not only as transportation infrastructure but also as important symbols of local culture.

In the following year, Jiang [108] further investigated mortise-and-tenon stone beam bridges in southern Hunan, examining their structural forms, origins, and construction periods, as shown in Fig. 8, and highlighted the role of mortise-and-tenon connections in enhancing the structural stability of these bridges, demonstrating the sophistication of traditional construction techniques.

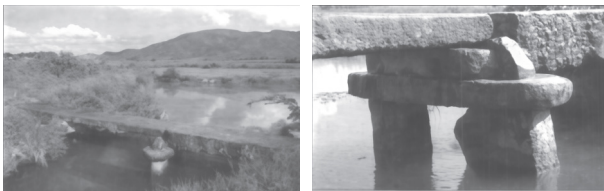


Fig. 8 Wugu No. 2 Bridge, Hunan Province [108].

Wu [109] examined the timber arch covered bridges in Qingyuan from the perspective of folk culture, discussing traditional practices such as taboos and ritual ceremonies associated with timber bridges, as well as the symbolic role of water-gate bridges (shuikou bridges) in village layouts, where they are often regarded as symbols of prosperity and wealth.

Zhang [110] argued that timber arch covered bridges are not merely physical architectural structures, but rather spatial cultural creations rooted in regional life traditions. Their existence reflects multiple cultural dimensions, including agricultural culture, architectural culture, religious beliefs, Confucian values, and regional traditions, serving to meet the folk customs, daily practices, and spiritual needs of communities across different historical periods.

He [98] analyzed the ancient bridges of Chibi located along historic routes, noting that these bridges were closely associated not only with agricultural culture, but also with tea-horse trade culture and post-road (courier route) culture. As such, they functioned as important nodes within ancient transportation systems and international trade networks.

Liu [111] further suggested that ancient bridges in Hunan embody rich layers of cultural meaning: they preserve folk traditions expressing aspirations for prosperity, contain ecological wisdom rooted in harmony with nature, retain historical memories of commerce and exchange symbolized by the idea that bridges connect the world, and create a spatiotemporal arena where past and present

interact. As a result, these bridges have become important settings for contemporary cultural tourism and heritage interpretation.

From an engineering perspective, the construction techniques of ancient bridges reflect the technological capabilities and craftsmanship of historical societies, and they continue to provide valuable inspiration for modern bridge design. Zhang [112] pointed out that the Zhaozhou Bridge (Fig. 9), with its single-span stone arch of 37 m, adopts a segmental arch and open-spandrel structure. This design not only reduces material consumption and lowers the bridge deck gradient, but also allows floodwaters to pass through the auxiliary openings during high-flow events, thereby enhancing hydraulic performance. Such features demonstrate the remarkable structural innovation and engineering ingenuity embodied in ancient Chinese bridge construction.



Fig. 9 Zhaozhou Bridge.

2.6 Conservation systems and management mechanisms for ancient bridges

The holistic conservation of ancient bridge heritage refers to an approach that not only focuses on the preservation of the bridge itself but also emphasizes the protection of its surrounding cultural landscape and ecological environment. Ancient bridges should not be viewed merely as isolated architectural relics; rather, they are integral components of the broader environmental and cultural context in which they exist. Therefore, holistic conservation requires that, while protecting the bridge structure, equal attention be given to safeguarding the natural and cultural environments associated with it, thereby ensuring a harmonious coexistence between the historic bridge and its surrounding landscape.

Chen [113] taking the timber arch covered bridges of the Fujian–Zhejiang region as the research object, provided a targeted interpretation of the principle of authenticity in bridge heritage conservation, drawing on multiple international cases of World Heritage bridge conservation. Their study argues that, as engineering heritage with strong functional attributes, the authenticity of bridge heritage should not be narrowly understood as the absolute immutability of form and materials. Instead, it should be evaluated in relation to the core value elements of the bridge, including its distinctive structural system, traditional construction techniques, and the social functions it carries. On this basis, the authors propose that necessary disaster prevention, fire protection, and structural reinforcement measures applied to non-core components do not constitute a substantive loss of authenticity; rather, such interventions contribute to the long-term preservation of the heritage value of bridges.

Cui and Chun [114] developed a conservation and restoration framework for Putang Bridge, proposing scientifically grounded methods for its repair and protection. The results of this study provide valuable references for the conservation of ancient masonry arch bridges.

Long [115] examined the conservation of timber arch bridges from the perspective of cultural landscape heritage, emphasizing the importance of a holistic conservation approach. They argued that the preservation of timber arch bridges should not be limited to

protecting the bridge structure alone, but should also encompass the overall settlement environment and landscape context in which the bridges are situated.

Zhu [116], focusing on ancient bridges along the Grand Canal, proposed a multi-dimensional evaluation framework for bridge heritage that considers historical value, cultural value, and scientific value. Based on this evaluation approach, they further suggested corresponding management and conservation measures, providing a practical pathway for the development of a heritage value assessment system for historic bridges.

Jia [117], in their article *On the Current Situation and Countermeasures for the Conservation of Ancient Bridges in China*, discussed the heritage value and significance of ancient bridges, analyzed the current state of ancient bridge conservation in China, and proposed recommendations for implementing sustainable conservation strategies for historic bridge heritage.

3 Case studies of typical ancient bridge restoration

3.1 Wanning Bridge

Wanning Bridge is located on Di'anmenwai Street in the northern section of the Beijing Central Axis, spanning the Yuhe River. It is an important surviving stone arch bridge originally constructed during the Yuan Dynasty. In 2013, the Chengqing Upper Sluice (including Wanning Bridge) was designated as a National Key Cultural Relics Protection Unit, and in 2014 it was inscribed on the World Cultural Heritage List as part of the Grand Canal heritage. As the only intersection between the Beijing Central Axis and the Grand Canal, Wanning Bridge possesses both engineering significance as a bridge structure and historical and cultural value within the urban landscape, making it a representative case in the conservation and restoration of ancient bridges in China.

Wanning Bridge was first built in the fourth year of the Zhiyuan reign of the Yuan Dynasty (1267 CE). It is a single-span solid spandrel stone arch bridge with a semicircular arch ring. The upper structure adopts a frame-type transverse masonry arrangement. The bridge measures approximately 33 m in length, 20.5 m in width, and 7.3 m in span. The structure consists of several components, including the foundation, arch ring, bridge deck, balustrades with ornamental posts, wing walls (yan-chi walls), and water-suppressing stone beasts. The bridge retains architectural elements from multiple historical periods, including the Yuan, Ming, Qing, and Republican eras.

The bridge is primarily constructed from bluish-white stone and white marble, with an arch-ring thickness of approximately 900 mm, giving the structure a robust and stable overall form. Among the four water-suppressing stone beasts located at the corners of the wing walls, the northeastern sculpture bears the inscription “September, Zhiyuan 4”, identifying it as an original Yuan Dynasty component of considerable archaeological significance.

According to the pre-restoration condition survey, the overall structural condition of Wanning Bridge was assessed as “good” (technical grade B). Nevertheless, several issues related to material deterioration and later external interventions were identified. As shown in Fig. 10, these included weathering, cracking, and mortar joint loss in the stone materials; localized water seepage in the arch ring, posing a risk of freeze–thaw damage; alligator cracking and rutting in the asphalt pavement on the bridge deck; modern pipelines and masonry foundations attached to both sides of the arch intrados; mortar loss and vegetation growth on parts of the wing walls; and uneven surface weathering of the water-suppressing stone sculptures.

The causes of the observed deterioration are mainly attributed to long-term loading effects, natural weathering, rainfall erosion, and freeze–thaw cycles, as well as modern human interventions and alterations carried out in recent decades.

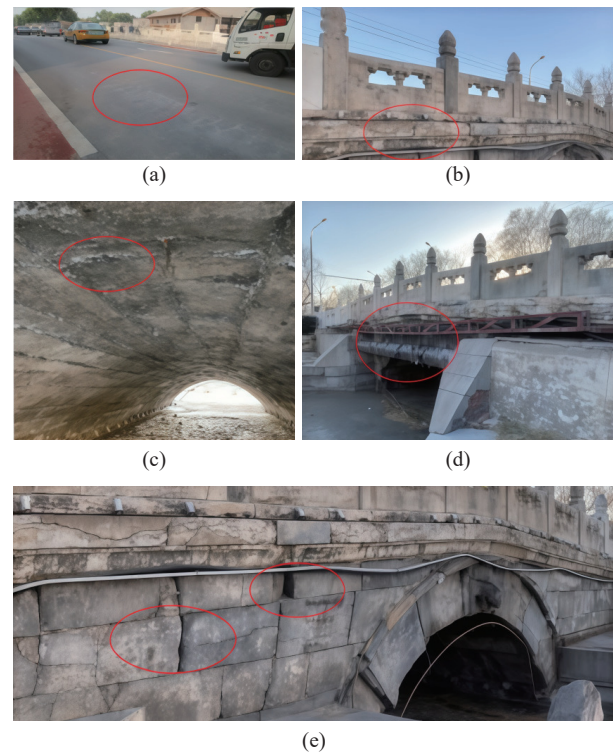


Fig. 10 Bridge deterioration conditions. (a) Rutting and alligator cracking on the bridge deck pavement; (b) Weathering of stone materials in the railings and balustrades; (c) Water seepage at the arch intrados with stone spalling and cracks; (d) Right wing wall partially obstructed; (e) Mortar joint loss on the left wing wall.

During the present restoration project, a range of modern diagnostic technologies were employed to conduct a systematic assessment of the bridge structure. These methods included: three-dimensional laser scanning to acquire detailed geometric information of the bridge; ground-penetrating radar (GPR) to detect the internal structure of the bridge deck pavement and arch ring; non-metallic ultrasonic testing to evaluate the mechanical properties of the stone materials; static and dynamic load tests to assess the structural load-bearing capacity; and traffic-induced vibration monitoring to analyze the impact of vehicular loads on the bridge structure.

As shown in Figs. 11–13, the inspection results indicate that the bridge foundation remains stable, and the arch ring shows no structural cracks, distortions, or displacements. Overall, the bridge meets the current safety requirements for use. However, the long-term impact of motor vehicle loads poses potential risks to the durability of the bridge structure.

The restoration project adhered to the conservation principles of “minimum intervention,” “reversibility,” and “authenticity protection.” The main restoration measures included: partial removal and restoration of the bridge deck pavement to improve the waterproofing and drainage system; sealing and repointing of cracked stone materials; cleaning of surface contamination and application of protective treatments; removal of pipelines and incompatible installations attached to the arch intrados; realignment of displaced drum-shaped stone elements (baogushi); and the implementation of traffic control measures, including flow restriction and load limitation, to reduce motor vehicle access.

In addition, a digital model of the bridge was established using BIM technology, providing digital support for construction supervision as well as long-term operation and maintenance management.

3.2 Yongtong Bridge

As shown in Fig. 14, Yongtong Bridge is located over the Tonghui River in Chaoyang District, Beijing, and was originally



Fig. 11 On-site laser scanning operation.

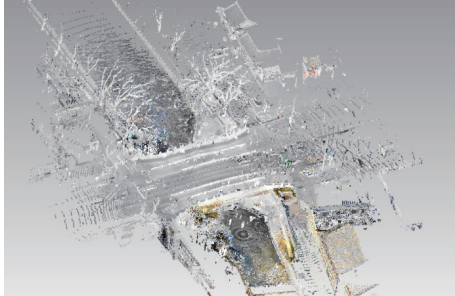


Fig. 12 Raw point cloud data.

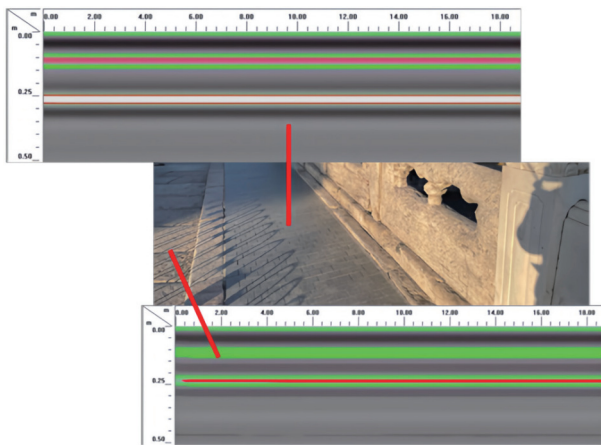


Fig. 13 Results of ground-penetrating radar scanning.



Fig. 14 Yongtong Bridge.

constructed during the Ming Dynasty. It is one of the relatively well-preserved ancient stone arch bridges along the Grand Canal. Due to the effects of long-term traffic loading and natural weathering, the bridge gradually developed several deterioration problems, including stone damage, loosening of masonry components, and aging of the bridge deck pavement.

To preserve this important cultural heritage site, the Beijing municipal government initiated a conservation and restoration project for Yongtong Bridge in 2021. The project involved systematic structural inspections and detailed condition assessments, followed by the formulation of a comprehensive conservation and restoration plan for the bridge.

During the restoration process, the project strictly adhered to the conservation principles of “minimum intervention” and “repairing the old as the old.” The asphalt pavement on the bridge deck was removed, and the traditional stone slab pavement was restored. In addition, misaligned masonry and damaged stone blocks were repaired or replaced where necessary, and the mortar joints of the bridge structure were reorganized and reinforced.

By 2023, the restoration project had been largely completed, effectively eliminating potential structural safety risks while restoring the historical appearance of the bridge. At the same time, digital surveying and documentation techniques were employed to systematically record the bridge’s structural and heritage information. In 2024, the restored Yongtong Bridge was reopened to the public, achieving an integration of cultural heritage conservation and the interpretation of Grand Canal cultural heritage.

3.3 Anping Bridge

As shown in Fig. 15, Anping Bridge is located between Anhai Town in Jinjiang City and Shuitou Town in Nan’an City, Quanzhou, Fujian Province. It was originally constructed in the eighth year of the Shaoxing reign of the Southern Song Dynasty (1138 CE). The bridge is recognized as the longest existing ancient cross-sea stone beam bridge in China and constitutes an important heritage component of the World Cultural Heritage site “Quanzhou: Emporium of the World in Song–Yuan China.”

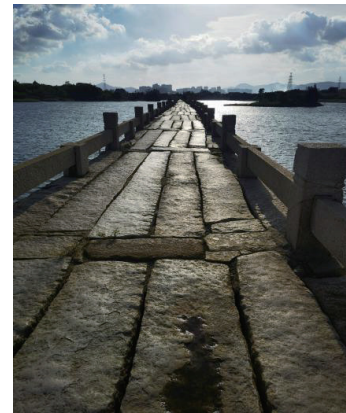


Fig. 15 Anping Bridge.

With a history of more than 800 years, the bridge has long been exposed to the harsh marine environment, as well as geological changes and natural weathering processes. As a result, a range of structural issues have gradually emerged, including uneven bridge deck slabs, differential settlement of bridge piers, detachment of railings, and localized cracking of structural components. These deterioration phenomena highlight the urgent need for systematic conservation and restoration measures to ensure the long-term preservation of the bridge.

To strengthen the protection of this cultural heritage site, the Quanzhou municipal authorities initiated a conservation and restoration project for Anping Bridge. In July 2025, the Jinjiang Municipal Bureau of Culture, Sports and Tourism, together with the People’s Government of Anhai Town, officially announced the launch of a pilot restoration section for the Jinjiang segment of Anping Bridge. The experimental restoration section extends approximately 79.8 m and involves nine bridge piers, with construction scheduled from July 2025 to May 2026. During the construction

period, parts of the bridge deck were temporarily closed to the public, while structural repair and foundation reinforcement works were carried out.

During the restoration process, technicians first dismantled the bridge deck slabs and railings, and each component was individually numbered, photographed, and recorded to ensure accurate reinstallation during reconstruction. Subsequently, cofferdams were constructed to remove accumulated silt around the bridge piers, allowing for the repair and reinforcement of the pier foundations. The restoration work followed the conservation principle of “minimum intervention,” striving to employ original materials, traditional construction techniques, and authentic structural forms wherever possible. At the same time, the project documented and studied traditional Song Dynasty construction techniques, such as the “sleeping timber foundation” (shuimu chenji) method used in bridge construction. This approach aims to restore the structural safety of the bridge while preserving its historical information to the greatest extent possible.

4 Conclusions

In summary, scholars both in China and internationally have achieved substantial progress in the study of ancient Chinese bridges, particularly in areas such as historical document compilation, typological research, structural engineering analysis, cultural value interpretation, and conservation and restoration practices. These efforts have gradually established a multidisciplinary research framework grounded in archaeology and architectural history, while being strongly supported by structural engineering methods and digital technologies. In recent years, with the rapid development of technologies such as three-dimensional laser scanning, UAV photogrammetry, BIM-based information modeling, and digital twin systems, the capacity for digital documentation and structural analysis of ancient bridges has been significantly enhanced. These technological advances provide increasingly accurate data foundations for morphological identification, structural performance evaluation, and decision-making in conservation and restoration projects.

Despite the substantial body of research on ancient Chinese bridges, several limitations can be identified in existing studies. First, many studies remain descriptive and lack in-depth quantitative analysis of structural behavior and performance. Second, interdisciplinary integration is still insufficient, with limited interaction between historical research, engineering analysis, and conservation practice. Third, although digital technologies have been increasingly applied, their use is often confined to documentation rather than being fully integrated into assessment, monitoring, and decision-making processes. Furthermore, long-term performance evaluation and resilience analysis under environmental and loading conditions remain underexplored. Future research on ancient bridges may be further expanded in the following directions:

(1) Strengthening systematic surveys and database construction for ancient bridge heritage.

China possesses a large number of ancient bridges with a wide geographic distribution; however, systematic and standardized databases for ancient bridge documentation remain relatively insufficient. Future efforts should promote nationwide surveys and digital documentation programs for ancient bridges. By integrating historical documents, surveying and mapping data, structural parameters, and deterioration information, it is possible to establish a comprehensive heritage database and information management platform for ancient bridges. Such a system would provide long-term and stable data support for both academic research and conservation practice.

(2) Deepening research on structural mechanisms and long-term service performance.

Many ancient bridges have remained in service for several cen-

turies, and their mechanical behavior, material degradation processes, and deterioration evolution are often complex. Future research should combine experimental investigations, numerical simulations, and field monitoring techniques to systematically analyze the structural responses and damage evolution patterns of ancient bridges under loading conditions, environmental influences, and hazard events. Such studies will provide more reliable theoretical foundations for structural safety assessment and scientifically based reinforcement strategies.

(3) Promoting deeper integration between digital technologies and conservation practice.

At present, the application of digital technologies in ancient bridge research is still largely concentrated on three-dimensional surveying and model reconstruction. Future studies should further extend the use of digital technologies to structural analysis, disaster simulation, structural health monitoring, and operation and maintenance management. For example, digital twin technologies could enable real-time monitoring and predictive analysis of structural conditions, thereby providing intelligent technical support for the long-term conservation of ancient bridges.

Overall, with the continuous advancement of heritage conservation concepts and digital technologies, research on ancient bridges in China is gradually shifting from traditional document-based and typological studies toward digitalized, systematic, and engineering-oriented approaches. Through ongoing interdisciplinary collaboration and technological innovation, future studies will be able to more comprehensively reveal the engineering ingenuity and cultural value embodied in ancient Chinese bridges, thereby providing stronger theoretical foundations and technical support for their scientific conservation, sustainable utilization, and cultural transmission.

Acknowledgements

The authors gratefully acknowledge the reviewers and editors for their valuable comments and constructive suggestions, which greatly improved this manuscript.

Funding

This work was funded by the Beijing Social Science Foundation Planning Project (No. 23GLB019). This support was gratefully acknowledged.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

Chiyu Jiao: Conceptualization of the study, acquisition of funding, provision of resources, supervision of the research process, and critical revision of the manuscript. Liuqing Yang: Drafting of the original manuscript, development of the research methodology, data collection and organization, and formal analysis. Xiumei Shen: Participation in manuscript preparation, data organization and analysis, and assistance with the research process. Shujie Chen: Conceptualization of the study, provision of research resources, supervision of the research progress, and revision of the manuscript.

Data availability statement

Data will be made available on request.

Use of AI statement

During the preparation of this manuscript, the authors used

Deepseek to enhance the grammar and readability of the text. The authors carefully reviewed and edited the content afterward and assume full responsibility for the final manuscript.

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