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Evolution and structural behavior of historic masonry arch bridges: implications for conservation

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Abstract: Masonry arch bridges represent a unique synthesis of engineering efficiency and cultural heritage that has evolved over more than two millennia across different civilizations. Despite their historical relevance and continued widespread use, research on these structures often remains fragmented between historical evolution and structural engineering perspectives. This paper aims to address this gap by providing an integrated overview of the evolution, structural behavior, and conservation of historic masonry arch bridges, encompassing both Chinese and European heritage. The study reviews the evolution of arch bridges from early origins to the scientific era, then examines their typological and morphological features, highlighting the interplay between geometry, materials, and construction techniques. It analyses structural behavior and reviews current assessment and modelling approaches. Finally, it discusses conservation strategies and future perspectives, with emphasis on advanced materials, digital tools, and the renewed role of masonry arch bridges in contemporary infrastructure.

Keywords: historic bridges; masonry arch bridges; structural behavior; conservation; heritage infrastructure; structural assessment; modeling approaches

1 Introduction

Masonry arch bridges represent one of the most enduring and widespread structural typologies in the history of civil engineering. Developed over more than two millennia, they embody a unique convergence of structural efficiency, material optimization, and cultural expression. From the monumental infrastructures of the Roman Empire to the refined and innovative solutions developed in China, these structures have played a fundamental role in shaping transportation networks, urban development, and territorial organization across different civilizations [1].

Despite their apparent simplicity, masonry arch bridges encapsulate a highly sophisticated understanding of structural behavior, achieved long before the formalization of engineering science. Their design was historically based on empirical rules and geometric principles [2], yet many of these structures have demonstrated remarkable durability and resilience, remaining in service for centuries under evolving functional demands. Today, thousands of masonry arch bridges are still in operation worldwide, particularly in Europe [3] and China [4], where they continue to serve as both critical infrastructure and cultural heritage assets.

In recent decades, increasing traffic loads, aging processes, and environmental factors have raised significant concerns regarding their structural safety and long-term performance [5]. At the same time, their recognized historical, architectural, and symbolic value requires that any intervention be carefully balanced with conservation principles [6]. This dual condition – as both infrastructure and heritage – makes masonry arch bridges a particularly complex object of study, requiring the integration of historical knowledge, structural analysis, and conservation strategies [7].

However, existing research often remains fragmented. Historical studies tend to focus on the chronological and cultural evolution of arch bridges, while engineering research primarily addresses structural behavior [8], assessment methodologies [9], and strengthening techniques [10], often with limited reference to the broader historical context [1]. This separation hinders a comprehensive understanding of these structures and limits the effectiveness of conservation approaches.

This paper addresses this gap by providing an integrated review of the evolution, structural behavior, assessment methodologies, and conservation of historic masonry arch bridges. By combining historical analysis with structural engineering perspectives, it establishes a coherent framework linking construction techniques, mechanical principles, damage mechanisms, and preservation strategies. The novelty of the review lies in three complementary aspects. First, it provides a comparative examination of European and Chinese traditions. Second, it integrates engineering and conservation perspectives that are often treated separately. Third, it proposes a multilevel interpretative framework that organizes current knowledge and identifies future research directions.

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The paper is organized as follows: in section 2 a historical evolution of masonry arch bridges is provided, with both reference to Europe and China; section 3 examines the typology and morphology of masonry arch bridge; section 4 discusses the structural behavior of masonry arch bridges; section 5 provides an overview of modeling approaches; section 6 is focused on conservation issues; finally, in section 7 some final remarks are given.

2 Evolution of masonry arch bridges

The origin of the masonry arch remains uncertain and cannot be attributed to a single geographical area or historical period. Rather, it should be understood as the result of a gradual and convergent development across different cultures. Several evolutionary paths have been proposed, including the transformation of corbelled structures, the progressive use of wedge-shaped elements, and the transition from lintel-based systems to curved load-bearing forms [11].

These processes likely occurred independently in different regions, reflecting the adaptive capacity of early builders in response to material availability and construction challenges. Before the widespread adoption of true arches, various forms of pseudo-arches and corbelled structures were already in use, and archaeological as well as documentary evidence suggests that early arch-like configurations appeared in funerary and domestic architecture [12], gradually evolving toward more refined and structurally efficient forms [13]. In this context, the transition from polygonal or stepped configurations to continuous curved profiles represents a key milestone, enabling a more effective transmission of loads through compression [14].

The emergence of the masonry arch can therefore be interpreted as a progressive convergence of empirical knowledge, construction practice, and geometric intuition. Its fundamental structural advantage lies in the ability to transfer loads primarily through compression, making it particularly well suited to materials such as stone and brick, which are characterized by high compressive strength and negligible tensile capacity [15].

A systematic and large-scale development of masonry arch bridges is first clearly documented in the Roman period, when the expansion of the Roman road network, supported by a highly organized administrative system, created the conditions for the standardization and dissemination of construction techniques across vast territories. Roman engineers refined the use of ashlar masonry and introduced concrete as a filling material, achieving highly durable and reliable structures [16].

The semicircular arch became the predominant form, combined with well-defined construction practices involving arch rings, spandrel walls, and internal fill, while bridge geometries were characterized by robust proportions reflecting both empirical knowledge and construction constraints. The longevity of Roman bridges – many of which remain in use today – demonstrates the effectiveness of these design principles [1] (Fig. 1 and Fig. 2). Although the arch was not a Roman invention, Roman builders were the first to systematically exploit its structural potential, achieving a balance between materials, techniques, and structures.

Following the decline of the Roman Empire, bridge construction in Europe experienced a period of stagnation; nevertheless, the knowledge of arch construction was preserved and gradually reintroduced during the Middle Ages [17]. Medieval bridges exhibit greater variability in geometry and construction, reflecting a return to more empirical approaches, in which pointed and segmental arches were introduced alongside semicircular forms and structural solutions were adapted to specific site conditions.

During the Renaissance, architectural and theoretical developments led to a renewed interest in proportion, geometry, and structural form [18]. Although major technological breakthroughs were limited, increasing attention was paid to the relationship between

Fig. 1 Roman arch bridges: Ponte St. Martin, Aosta Valley, Italy.

Fig. 2 Roman arch bridges: Segovia Viaduct, Spain.

arch shape and thrust, anticipating later scientific developments [19].

A decisive transformation occurred between the 17th and 18th centuries, with the emergence of structural mechanics and the first attempts to formalize the behavior of arches; engineers such as Perronet introduced more slender designs, reduced pier dimensions, and new arch geometries [20], marking the transition from empirical construction to scientifically informed engineering [21].

Parallel to the European tradition, China developed an independent and highly sophisticated approach to masonry arch bridge construction, which Chinese scholarship attributes to an autonomous and internally coherent evolution, rather than to transmission via the Silk Road from Parthia in the 1st century AD [22]. Early forms of arch structures can be traced back to ancient periods, with evidence of arch-like configurations in tombs and architectural elements, which progressively evolved into fully developed masonry arch bridges with distinct geometric and constructive characteristics [4].

Chinese arch bridges are notable for the diversity of arch axis shapes, including segmental, semicircular, elliptical, and more complex profiles, reflecting a refined understanding of structural behavior and a strong sensitivity to material optimization [23]. In contrast to the massive constructions typical of Roman bridges, many Chinese examples exhibit a lighter structural approach, with thinner arch rings and efficient load distribution systems. One of the most significant innovations is the use of openings in spandrel walls, which reduce weight and modify load paths, as exemplified by the Zhaozhou Bridge (Fig. 3 and Fig. 4). Additionally, construction techniques often relied on dry masonry or limited mortar use, combined with mechanical connections such as iron clamps. Adaptations to local conditions, including soft soils or navigational requirements, led to the development of specific solutions, including inclined foundations, multi-span configurations, and hump-backed profiles.

Alongside masonry arches, several other historic bridge typologies also developed in China [22]. These include timber arch bridges, typical of the Fujian and Zhejiang provinces, consisting of

Fig. 3 Chinese arch bridges: Zhaozhou Bridge, Hebei province, China.

Fig. 4 Chinese arch bridges: Baodai Bridge in Suzhou, Jiangsu province, China.

one or more wooden arches supported by stone piers and covered by a superimposed gallery [24]. Additionally, stone beam bridges, characteristic of the Fujian province, were constructed using massive stone beams assembled from blocks weighing several tons, achieving spans of up to ten meters and supported by continuous series of stone piers, forming structures extending for several hundreds of meters [25].

While Europe largely abandoned masonry arch construction in favor of reinforced concrete in the early 20th century, China continued to build masonry arch bridges well into the late 20th and early 21st centuries [1]; this extended tradition resulted in the construction of long-span masonry bridges of remarkable scale, demonstrating the continued evolution of the typology under different economic and technological conditions [4].

The transition from empirical construction practices to a scientific understanding of structural behavior represents a crucial phase in the evolution of masonry arch bridges. Beginning in the 17th century, the development of mechanics and materials science provided the theoretical foundations necessary to analyze and design structures based on physical principles rather than solely on experience [11]. The formulation of the basic laws of statics and elasticity enabled engineers to better understand the relationship between geometry, loads, and internal forces, introducing concepts such as thrust, equilibrium, and structural stability into bridge design. This shift led to the refinement of arch geometries, the reduction of material usage, and the optimization of structural performance.

By the 19th century, masonry arch bridge construction had reached its technical peak, supported by both empirical knowledge and emerging analytical methods [26]. However, the simultaneous development of new materials – particularly steel and reinforced concrete – gradually led to the decline of masonry as the dominant bridge-building material in Europe. Nevertheless, the extensive stock of existing masonry arch bridges and their proven durability ensured their continued relevance [3].

Today, this historical evolution provides essential insight into the behavior and performance of masonry arch bridges, as understanding how these structures were conceived, constructed, and refined over time remains fundamental for their assessment, conservation, and potential adaptation to contemporary requirements. From this perspective, the diversity of historical solutions should not be interpreted merely as a chronological sequence. Rather, it forms the basis of the typological and morphological configurations that characterize masonry arch bridges, whose recurring elements and variations are discussed in the following section.

3 Typology and morphology of masonry arch bridges

The long and articulated historical evolution briefly outlined in the previous section is reflected in the typological diversity of masonry arch bridges, which, despite significant regional variations, retain a set of recurring structural and constructive principles. Each bridge can thus be interpreted as the result of a balance between the persistence of consolidated construction practices–rooted in centuries of empirical knowledge–and their adaptation to local conditions. Within this perspective, the fundamental configuration of masonry arch bridges remains remarkably consistent. It is based on the interaction between a primary load-bearing element, the arch barrel, and a system of secondary structural components–such as spandrel walls, fill material, and foundations–that collectively define the global structural behavior of the bridge [27]. This interaction can be interpreted through a multilevel framework in which contextual conditions, technical solutions, and formal–functional outcomes are connected through bidirectional relationships (Fig. 5).

From a typological standpoint, masonry arch bridges can be classified according to geometric and morphological criteria, in conjunction with functional requirements and construction techniques [28]. A primary typological parameter is the number of spans, which reveals the interaction between site-specific constraints and the available technical solutions, as well as the evolution of construction practices over time. Single-span bridges are generally associated with limited crossings or with advanced structural solutions that enable greater spans, whereas multi-span bridges–composed of a sequence of arches supported by intermediate piers – represent the predominant configuration in both European and Chinese traditions [1]. In such cases, the arrangement of spans is determined not only by structural requirements but also by hydraulic and morphological constraints, including the need to accommodate fluctuating water levels and to reduce foundation stresses in weak soils [5].

A further level of typological differentiation concerns the geometry of the arch, which plays a fundamental role in defining both structural behavior and construction techniques [29]. Semicircular arches, widely adopted in Roman construction, are characterized by geometric simplicity and high structural reliability, whereas segmental arches– featuring a lower rise-to-span ratio – enable flatter deck profiles and reduced construction heights, and became increasingly widespread in later periods. Other configurations – including elliptical, polycentric, and pointed arches– reflect both regional traditions and progressive refinement of structural understanding. In particular, the wide variety of arch axis geometries observed in Chinese bridges reveals an advanced control of load distribution and material efficiency [23], while in European contexts the gradual adoption of shallow arches is closely associated with the development of theoretical mechanics and the pursuit of structural optimization [1].

Beyond overall geometric configuration, the morphology of masonry arch bridges is defined by a set of primary structural components, each contributing to the global structural behavior of the system [27]. The arch barrel constitutes the main load-bearing element, typically formed by one or more rings of carefully shaped voussoirs arranged along the intrados profile. Its geometry–defined

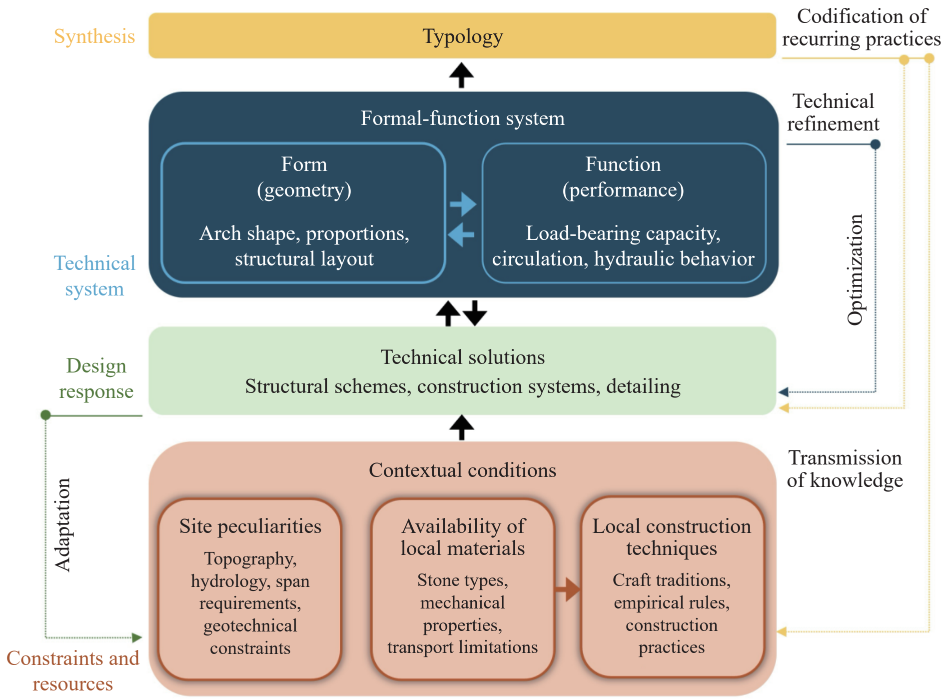

Fig. 5 Multilevel interpretative framework bridge typologies, illustrating the bidirectional interactions between contextual conditions, technical solutions, and formal–functional outcomes, and the emergence of typology as a synthetic construct.

by span, rise, thickness, and curvature-–governs the distribution of internal forces and the overall stability of the structure. Vertical loads are transmitted through the arch into horizontal thrusts, which are resisted by the abutments and, in multi-span bridges, by intermediate piers. These supporting elements must ensure sufficient load-bearing capacity and resistance to horizontal forces, often requiring substantial dimensions, particularly in earlier construction phases [17].

The spandrel zone represents a further key component, mediating between structural form and functional requirements. Composed of spandrel walls and backfill material, it plays an active role in structural performance: the backfill, often consisting of granular or rubble materials, contributes to load redistribution, confinement of the arch ring, and regulation of the thrust line [30], while spandrel walls, in addition to their retaining function, ensure both retention and structural continuity [31]. Variations in this zone – such as the introduction of voids or openings, particularly in Chinese bridges – can be interpreted as adaptive strategies aimed at optimizing weight distribution, stiffness, and load transfer mechanisms [32].

Material use constitutes a further key aspect in the typological characterization of masonry arch bridges, linking local resource availability to structural performance. These structures are typically constructed using locally available materials, including stone or brick masonry units bonded with mortar of varying composition and mechanical properties. High-quality ashlar masonry is generally reserved for the arch barrel and exposed structural elements, while less regular materials are used in the internal fill. Material selection is an expression of both mechanical requirements and local construction practices, contributing simultaneously to structural behavior and regional identity. In some traditions, particularly in many Chinese bridges, the use of dry masonry or limited mortar, combined with mechanical interlocking between blocks, represents an alternative approach to achieving structural integrity and durability [31].

The interaction between typology, geometry, and construction techniques is particularly evident in response to site conditions. Bridges built in steep valleys typically take the form of high multi-span viaducts with tall piers, allowing the development of gentle longitudinal gradients required for transportation systems. Conversely, wide river crossings or compressible soils favor solutions with fewer but larger spans, or the adoption of specialized foundation systems aimed at limiting settlements and controlling horizontal thrusts. The alignment of the bridge relative to the obstacle-whether orthogonal or skewed–introduces additional geometric and structural complexity, affecting both construction processes and structural response [33].

Within this framework, the typological and morphological configuration of masonry arch bridges can be understood as the result of an integrated and adaptive process in which geometry, materials, construction techniques, and environmental conditions are intrinsically interconnected. Such an integrated perspective is essential not only for interpreting the historical evolution of these structures, but also for guiding their structural assessment and conservation, as effective interventions require a comprehensive understanding of the relationships between structural form, construction processes, and performance [5].

The proposed interpretative framework, grounded in the relationship between form, construction, and context, provides a robust basis for understanding the structural behavior of masonry arch bridges, which is examined in the following section.

4 Structural behavior of masonry arch bridges

The typological and morphological characteristics discussed in the previous section provide the essential basis for understanding the structural behavior of masonry arch bridges, which is governed by the interaction between geometry, material properties, and construction techniques. Unlike modern structures designed to resist significant tensile stresses, masonry arch bridges rely almost entirely on compressive load transfer, exploiting the high compressive strength and limited tensile capacity of stone and brick. As a result, their structural performance is intrinsically linked to the ability to maintain compressive stress states within the masonry, ensuring that the internal force flow remains compatible with the geometry of the structure [34].

A key concept in the analysis of masonry arches is the equilibrium of forces through the development of compressive stress trajectories, commonly described by the thrust line. Under service conditions, loads are transferred from the deck to the arch barrel through the spandrel walls and the backfill. They are then directed toward the supports as inclined compressive forces. The position of the thrust line within the thickness of the arch is critical: as long as it remains within the masonry section, the structure can be considered stable; conversely, when it approaches or exits the boundaries of the arch ring, tensile stresses and potential cracking may occur, leading to the activation of collapse mechanisms [35]. This interpretation, rooted in limit analysis and the work of Heyman, provides a powerful and conceptually clear framework for assessing the safety of masonry arch bridges, particularly in conditions where material properties are uncertain or heterogeneous [36].

The structural behavior of masonry arch bridges cannot be understood by considering the arch barrel in isolation, as it results from the combined action of multiple components forming a complex three-dimensional system. The backfill plays a particularly significant role, contributing to load redistribution, enhancing the confinement of the arch ring, and influencing the position of the thrust line [30, 31]. Depending on its mechanical properties, degree of compaction, and geometry, the backfill may either improve structural performance or, in adverse conditions, contribute to uneven load transfer and localized stress concentrations [37]. Similarly, the spandrel walls participate in the global response by retaining the fill and interacting with the arch barrel, while the deck structure and parapets can introduce additional stiffness and load paths [38]. In multi-span bridges, the presence of piers introduces further complexity, as the interaction between adjacent arches affects the distribution of horizontal thrusts and the overall equilibrium of the structure [39].

Within this framework, masonry arch bridges typically exhibit a set of well-defined failure mechanisms [40], which are closely related to their limited tensile capacity [15]. Collapse is generally associated with the formation of a sufficient number of hinges within the arch, leading to a mechanism characterized by rigid body motion of the arch segments [41]. The location and sequence of hinge formation depend on the geometry of the arch, the distribution of loads, and the boundary conditions at the supports. Common damage patterns include cracking at the intrados or extrados, depending on whether the thrust line approaches the upper or lower boundary of the arch ring, as well as deformation or displacement of the supporting elements [42]. These mechanisms may be triggered or accelerated by various factors, including increased traffic loads, differential settlements of foundations, material degradation, or alterations to the original structural configuration [43].

In addition to these classical mechanisms, the structural behavior of masonry arch bridges is strongly influenced by long-term processes and external actions. Time-dependent phenomena such as creep, material weathering, and mortar degradation can progressively modify the internal stress distribution and reduce structural capacity [10]. Environmental factors, including temperature variations, moisture ingress, and hydraulic actions, may further contribute to deterioration processes, particularly in bridges exposed to aggressive conditions. Moreover, interventions carried out over time significantly alter the original load paths. Examples include the addition of fill, the replacement of deck systems, and the introduction of incompatible strengthening measures. These modifications may lead unintended and detrimental effects on structural performance [9].

The complexity of masonry arch bridge behavior is further increased by the inherent variability of materials and construction techniques, which often result in non-uniform mechanical properties and irregular geometries. This variability challenges the direct application of conventional analysis methods and requires the adoption of simplified yet robust modeling approaches capable of capturing the essential features of structural response [44]. In this regard, the conceptual framework provided by limit analysis remains particularly effective, as it allows the evaluation of structural safety based on equilibrium conditions and geometrical constraints, without requiring detailed knowledge of material properties [45]. At the same time, more advanced numerical approaches, such as finite element and discrete element methods, enable a more refined representation of material behavior and structural interaction, particularly in the presence of complex geometries or localized damage. While limit analysis is particularly effective for assessing global equilibrium and collapse conditions with limited input data, FEM and DEM approaches provide a more detailed representation of stress distribution, material behavior, and damage evolution, although at the cost of greater modeling complexity and data requirements.

Overall, the behavior of masonry arch bridges results from a delicate balance between geometry, materials, construction techniques, and boundary conditions [46]. Understanding this balance is essential not only for assessing structural safety, but also for guiding conservation and intervention strategies, as any modification to one component of the system may influence the global response. From this perspective, the integration of historical knowledge, morphological analysis, and structural modeling becomes a fundamental prerequisite for ensuring the long-term preservation and functionality of these structures, while respecting their cultural and material integrity.

5 Assessment and modeling approaches

Based on the structural principles outlined above, a range of assessment and modeling methods has been developed to capture the structural response of masonry arch bridges at different levels of detail [47]. Given the large number of existing bridges, often characterized by limited available data and significant variability in construction, these methods must balance accuracy, robustness, and practical applicability. Within this framework, approaches span from simplified analytical methods [48] to advanced numerical simulations [49], each associated with specific assumptions, advantages, and limitations (see Table 1).

Among these, limit analysis represents one of the most widely adopted and conceptually effective approaches for the assessment of masonry arch bridges [50]. Based on the assumption that masonry has negligible tensile strength and infinite compressive capacity, this method evaluates structural safety through equilibrium conditions and the admissibility of thrust lines within the geometry of the arch [51]. By identifying potential collapse mechanisms associated with hinge formation, limit analysis allows the estimation of load-carrying capacity without requiring detailed knowledge of material properties [52]. Its relatively low computational demand and clear physical interpretation make it particularly suitable for preliminary assessments and for the analysis of large bridge stocks [53], also in the presence of damage and material degradation [54], taking into account three-dimensional effects and the interaction with backfill and other structural components [55]. However, its simplified assumptions may limit its ability to capture complex behaviors.

In order to overcome some of these limitations, finite element methods (FEM) have been extensively applied to the analysis of masonry arch bridges [49]. These approaches enable a more complete and detailed representation of material behavior, including nonlinearity [56], cracking and damage evolution, as well as the interaction between different structural components [37, 57]. Depending on the level of refinement, FEM models may treat masonry as a homogeneous continuum or adopt advanced constitutive laws capable of simulating anisotropy and progressive failure, although at the cost of increased modeling complexity and data re-

Table 1 Comparison of the main assessment and modeling approaches for historic masonry arch bridges.

Method	Fundamental assumptions	Advantages	Limitations	Typical applications
Limit analysis	No tensile strength; unlimited compressive strength; equilibrium-based approach	Simple interpretation; limited input data; suitable for historic structures with uncertain properties; directly related to collapse mechanisms	Does not explicitly model material damage evolution; limited representation of complex interactions	Preliminary assessment; collapse analysis; evaluation of safety margins; conservation-oriented studies
FEM	Continuum representation of materials and geometry	Detailed stress and deformation analysis; versatile; suitable for complex geometries and loading conditions	Requires extensive material characterization; results sensitive to modeling assumptions; computationally demanding	Detailed structural assessment; strengthening design; seismic analysis
DEM	Structure represented as interacting discrete blocks	Effective for modeling discontinuities, crack propagation, and collapse mechanisms; suitable for representing masonry discontinuities and collaps behavior	High computational cost; calibration often complex; large number of parameters required	Collapse simulations; seismic response; investigation of damage evolution
Hybrid FEM–DEM approaches	Combination of continuum and discrete modeling	Captures both global behavior and local failure mechanisms	Increased modeling complexity and computational effort	Advanced research applications; complex damage scenarios

quirements [58]. Moreover, FEM allows the inclusion of complex boundary conditions, staged construction effects, and variable loading scenarios, including seismic actions [59], making it a powerful tool for detailed assessment [60] and design of interventions [61]. Nevertheless, the reliability of FEM analyses strongly depends on the availability and calibration of material parameters, which are often uncertain in historical structures, and on the quality of the geometric representation.

An alternative modeling strategy is provided by discrete element methods (DEM), which explicitly represent masonry as an assembly of interacting blocks [62]. This approach is particularly effective in capturing discontinuities, joint behavior, and large displacements, making it well suited for the analysis of collapse mechanisms and post-cracking behavior [63]. DEM models can simulate the opening, sliding, and rotation of individual elements, providing insight into failure processes that are difficult to reproduce with continuum approaches [64–65]. However, this increased level of detail is associated with higher computational costs and the need for detailed information on block geometry and contact properties, which may limit its applicability in small-scale assessments.

In recent years, hybrid and multi-scale approaches have been proposed to combine the advantages of different modeling strategies [66–67]. These methods may integrate simplified global models with localized detailed analyses, or couple continuum and discrete representations to better capture both overall structural behavior and local damage phenomena. At the same time, the increasing availability of digital survey techniques–such as laser scanning and photogrammetry–has improved the accuracy of geometric models, enabling more reliable simulations [68].

More recently, digital twins have attracted growing interest as a potential tool for the management of historic masonry arch bridges [69], enabling the integration of geometric surveys, numerical models, structural health monitoring data, and maintenance records within a unified digital environment [70]. In parallel, machine-learning techniques [71] and probabilistic assessment frameworks [72] are increasingly being adopted to improve damage detection [73], risk assessment [74], and predictive maintenance strategies.

Despite these advances, the choice of an appropriate modeling strategy remains strongly dependent on the objectives of the analysis, the available data, and the required level of accuracy. Consequently, different approaches should be regarded as complementary rather than alternative tools. Within a review perspective, it is important to emphasize that no single method can be considered universally applicable to all conditions (Fig. 6). For this reason, a hierarchical and integrated use of different modeling techniques is often the most effective strategy, allowing the combination of robustness, efficiency, and accuracy in the assessment of masonry arch bridges. Simplified approaches such as limit analysis remain essential for rapid assessment and for understanding the fundamental mechanics of masonry arches, while more advanced numerical methods provide deeper insight into complex structural behaviors and support the design of targeted interventions. The comparative characteristics of the principal modeling approaches are summarized in Table 1. For a more comprehensive discussion, readers are referred to the recent systematic review by Grillanda et al. [75], which provides an extensive overview of numerical approaches for the analysis of masonry arch bridges.

6 Damage mechanisms and conservation strategies

From a restoration perspective, historic masonry arch bridges represent a particularly complex field of intervention, characterized by the coexistence of cultural, structural, and functional values. Bridges are infrastructures still in use, whose significance lies simultaneously in their material authenticity and in their capacity to perform their original function. This dual nature introduces a fundamental tension between the conservation of the historic fabric and the need to ensure structural safety, serviceability, and, often, functional continuity. They constitute a well-established field within restoration practice, owing to their essential configuration, in which formal, structural, and material components are closely interrelated, thus providing an effective ground for testing and refining conservation tools and approaches.

Beyond their architectural and structural expression, it is precisely the infrastructural nature of these works that introduces further challenges. As Fiorani observes, “Unlike conventional monuments, infrastructures are engineering artefacts primarily defined by their functional performance. Referring to a bridge as a monument emphasizes its historical, aesthetic, and constructive qualities, whereas the term ‘monumental,’ when applied to infrastructure, highlights its scale and its capacity to organize and transform the surrounding territory” [76]. Accordingly, historic bridges should be understood as complex and multi-layered systems rather than isolated architectural or archaeological artefacts. They must be interpreted within a landscape framework, where the expansion of scale generates specific conservation challenges, requiring integrated and multi-scalar approaches.

Within this framework, conservation is not limited to the preservation of material remains but must engage with the understanding of structural behavior. Intervention strategies should be guided by principles capable of reconciling structural safety with the preservation of cultural values and their effectiveness depends on the ability to interpret the bridge as an integrated system, in which geometry, materials, construction techniques, and historical transformations are strictly interrelated.

The deterioration of masonry arch bridges is a complex and progressive process resulting from the interaction of multiple factors acting over time. Rather than being attributable to a single cause, deterioration arises from the combined effects of mechanical actions, environmental exposure, material aging, and human interventions, which together influence both the physical integrity and structural performance of the construction.

When properly maintained, masonry bridges generally exhibit a high structural capacity, often exceeding standard service loads [77]. From a mechanical standpoint, damage is commonly associated with the development of tensile stresses and crack formation, often linked to changes in load conditions or boundary constraints.

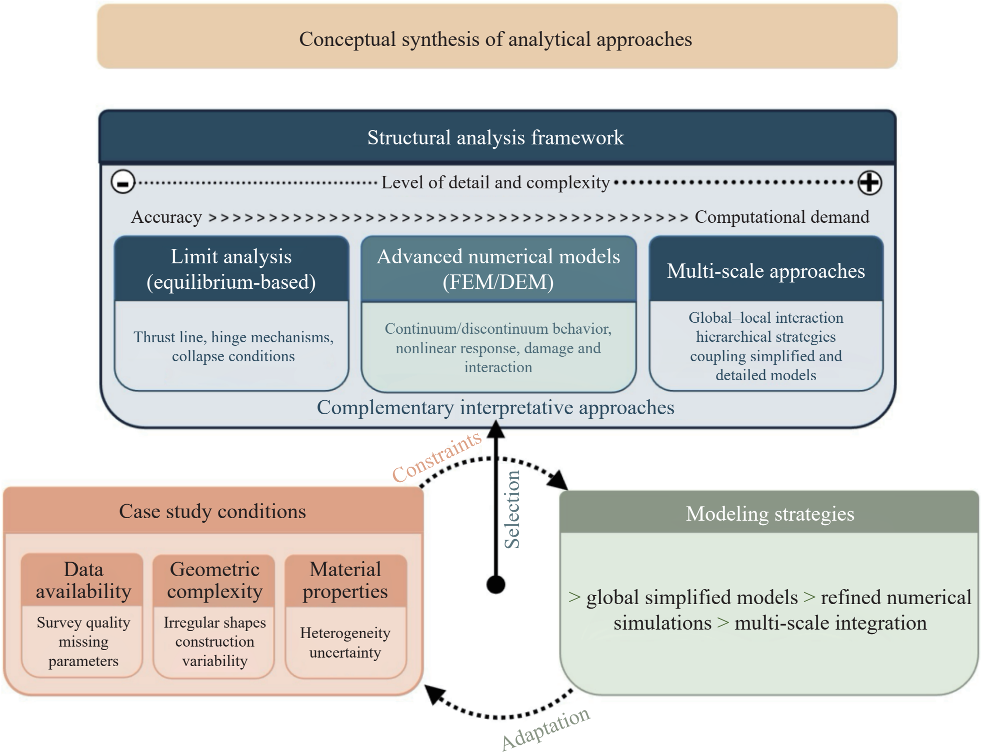

Fig. 6 Conceptual framework of modeling strategies for masonry arch bridges, illustrating the progression from simplified analytical methods to advanced numerical and multi-scale approaches, and their dependence on data availability, geometric complexity, and material properties. The diagram emphasizes the complementary and adaptive use of different methods across scales.

Increased traffic loads, differential settlements, and alterations to the original configuration may lead to stress redistribution and shifts in the thrust line, resulting in cracking at the intrados or extrados of the arch barrel, deformation of the arch profile, or displacement of supporting elements. In multi-span bridges, interactions between adjacent arches further complicate stress distribution, producing interdependent damage mechanisms [78]. Certain components are particularly vulnerable, notably the spandrel walls, which act as retaining structures and are therefore prone to sliding, bulging, or overturning, often as a consequence of changes in loading conditions or boundary constraints [79].

Environmental degradation also plays a critical role. Weathering of stone and brick, mortar decay, moisture ingress, and freeze–thaw cycles progressively reduce material cohesion and mechanical performance. Water represents one of the most significant agents of decay, whether due to inadequate drainage, infiltration through the deck, or hydraulic action at the foundations. Hydraulic effects – such as foundation scour, sediment accumulation, vegetation growth, and debris – can significantly alter flow conditions and increase vulnerability during flood events [77].

Biological factors further contribute to deterioration through vegetation growth and root penetration, which accelerate joint degradation and facilitate water ingress. These processes often act in synergy with environmental and mechanical factors, intensifying decay mechanisms.

A further source of damage arises from past interventions that have altered the original structural conception. The introduction of incompatible materials, excessive stiffening of deck systems, or inappropriate strengthening techniques may modify load paths and generate stress concentrations. Although often intended to improve performance, such interventions may lead to unintended effects, including stiffness imbalances and new cracking patterns.

The diversity of deterioration processes described above highlights the need for conservation strategies specifically calibrated to the nature and causes of damage. Different deterioration mechanisms affect distinct bridge components and compromise structural performance in different ways. Consequently, effective conservation requires not only the identification of damage but also an understanding of the relationship between deterioration processes, structural behavior, and intervention objectives. Rather than applying standardized strengthening solutions, conservation measures should be selected according to the specific vulnerabilities identified through assessment and monitoring.

The conservation of masonry arch bridges should therefore be grounded in principles that balance structural safety, material authenticity, and heritage values. Minimal intervention, material compatibility, reversibility, and respect for heritage authenticity are widely recognized as fundamental criteria in the conservation of masonry structures. From a structural perspective, this implies favoring interventions that maintain or restore the original load-bearing mechanisms, rather than replacing them with fundamentally different systems.

As highlighted by Boothby, masonry arch bridges, when properly maintained, often exhibit a structural capacity exceeding standard service demand, and structural failure is relatively uncommon [77]. Consequently, intervention strategies should be based on a careful assessment of actual conditions rather than on presumed inadequacy. Assessment is often affected by significant uncertainties, including the absence of original drawings and limited knowledge of geometry and material properties. For this reason, load-carrying capacity is frequently estimated through engineering judgment, supported by visual inspection and indirect indicators of structural performance. Despite these limitations, assessment remains essential for identifying damage mechanisms and defining appropriate conservation strategies.

From this perspective, conservation cannot be reduced to a purely technical issue but must be approached as a multidisciplinary process involving structural engineering, materials science, and heritage conservation.

Intervention strategies should be calibrated according to the identified damage mechanisms and guided by the principle of minimum necessary action. From an operational perspective, conservation measures may be broadly classified into three categories: preventive maintenance, localized repair and stabilization, and structural strengthening.

Damage associated with material degradation, such as mortar loss, stone weathering, or biological colonization, is generally addressed through maintenance-oriented measures including repointing, replacement of severely deteriorated elements, vegetation removal, and improvements to drainage systems. These actions aim to preserve material integrity while preventing the development of more severe structural problems.

Conversely, damage affecting the structural response of the bridge requires interventions specifically targeted to the underlying cause. Cracking related to differential settlements may require foundation stabilization or underpinning, while instability of spandrel walls may be mitigated through localized consolidation, reconstruction of retaining functions, or improvement of drainage conditions. Hydraulic problems associated with scour and erosion typically require measures aimed at reducing foundation vulnerability and restoring adequate flow conditions.

When load-related deficiencies or significant structural vulnerabilities are identified, strengthening interventions may become necessary. In such cases, the selected techniques should preserve, as far as possible, the structural conception and original structural behavior of the bridge.

The choice among these approaches depends on the nature and severity of the identified damage, as well as on the heritage significance and functional requirements of the bridge. For example, the rehabilitation of the San Gallo Bridge involved the thickening of the existing arch ring through a new masonry layer combined with CFRP reinforcement, increasing the load-bearing capacity while maintaining the original structural behavior of the bridge [80].

The relationship between the most common damage mechanisms, their structural implications, conservation objectives, and typical intervention strategies is summarized in Table 2.

Beyond technical considerations, the extent of intervention should also reflect the heritage significance of the bridge. Structures of exceptional historical, architectural, or landscape value may justify more conservative approaches, privileging repair and maintenance over extensive replacement or strengthening measures. In many cases, effective conservation can be achieved through relatively simple and non-invasive measures, particularly when deterioration is addressed at an early stage. Maintenance plays a crucial role in long-term performance, although it is often irregular and reactive. Planned interventions–such as repointing of joints, replacement of deteriorated elements, crack repair, and vegetation control–are frequently carried out only in response to visible damage, contributing to progressive deterioration [77]. Proper water management is essential, particularly in relation to moisture infiltration and foundation instability caused by scour.

Localized interventions may include masonry consolidation, crack stitching, stabilization of spandrel walls, and improvement of drainage systems. Where foundation problems are present, interventions may involve underpinning or measures aimed at improving soil conditions and reducing hydraulic vulnerability. In cases where strengthening is required, solutions should be compatible with the original materials and structural behavior. Fig. 7 illustrates a representative conservation intervention on the Roman bridge of Porto Torres (Sardinia). Masonry repair, reintegration of missing stone elements, and repointing were adopted to address material decay, loss of continuity and localized deterioration of the arch intrados while preserving the original structural configuration and historic fabric [81]. Depending on the identified vulnerability, interventions may include grouting of internal voids, crack stitching, reinforcement of arch barrels, stabilization of spandrel walls, or strengthening through fiber-reinforced composite systems. Recent developments have focused on less invasive techniques, including FRP, FRCM, and CRM systems, stainless steel reinforcement, and advanced grouting methods [82]. These approaches can improve structural performance while limiting alterations to the historic fabric; however, their application requires careful evaluation in terms of compatibility, reversibility, durability, and long-term behavior.

The integration of monitoring systems and non-destructive investigation techniques has become an essential component of con-

Table 2 Relationship between damage mechanisms and conservation strategies.

Damage mechanisms	Structural effects	Conservation objective	Intervention strategies
Material decay and mortar loss	Loss of material integrity and local resistance	Preservation of materials	Repointing, stone replacement, surface treatments
Moisture and water infiltration	Loss of material cohesion and progressive deterioration	Control of moisture-related deterioration	Drainage improvement, waterproofing
Differential settlements	Cracking, deformation, and thrust-line alterations	Structural stabilization	Underpinning, soil improvement
Spandrel wall instability	Bulging, sliding, and local instability	Structural consolidation	Masonry repair, localized strengthening
Scour and hydraulic action	Loss of foundation support and differential movements	Hydraulic protection	Scour countermeasures, riverbed stabilization
Increased traffic loads	Excessive stresses and reduced safety margins	Capacity enhancement	Structural strengthening and load redistribution techniques

Fig. 7 Roman Bridge of Porto Torres (Sardinia), Arch intrados: pre-and post-intervention comparison.

Left: condition prior to intervention, showing widespread material degradation, loss of stone elements, joint discontinuities, and localized decay phenomena. Right: condition after intervention, with restoration of masonry continuity, reintegration of missing elements, and overall improvement in the surface and structural integrity of the intrados.

temporary conservation practice. These tools allow the detection of early-stage damage, the assessment of structural behavior over time, and the verification of intervention effectiveness, supporting a preventive and knowledge-based approach.

Recent research is also exploring the integration of digital twins, machine-learning algorithms, and probabilistic assessment frameworks with structural health monitoring systems, enabling predictive conservation strategies and more informed risk-based management of historic masonry arch bridges. For instance, sensor-based monitoring networks have been successfully implemented on historic masonry railway bridges to track structural performance over time and support preventive maintenance strategies [83]. These developments suggest a progressive shift from reactive interventions toward preventive and knowledge-driven conservation strategies based on performance assessment.

7 Future perspectives and conclusions

The analysis presented in this paper highlights how masonry arch bridges, far from being merely relics of past construction practices, represent a living heritage in which historical knowledge, structural efficiency, and contemporary challenges converge. Their long-term performance demonstrates the effectiveness of construction techniques developed through empirical processes and later refined through scientific understanding, while their continued presence within modern infrastructure networks underscores their functional resilience. At the same time, the increasing demands imposed by contemporary traffic, environmental changes, and evolving safety standards call for a renewed and integrated approach to their assessment, conservation, and management.

Building upon the understanding of evolution and structural behavior discussed in this paper, future developments are likely to focus on the integration of advanced materials and innovative strengthening techniques with traditional construction systems. High-performance materials, such as fiber-reinforced composites and ultra-high-performance concretes, offer new possibilities for enhancing structural capacity while minimizing visual and material impact. However, their application must be carefully evaluated in relation to compatibility, durability, and reversibility, in order to avoid compromising the long-term integrity of historic structures. In this context, the challenge is not simply to increase structural resistance, but to do so in a way that respects and preserves the original structural logic of masonry arch bridges.

Equally significant is the role of digital technologies in improving knowledge, assessment, and decision-making processes. The increasing use of high-resolution survey techniques, including laser scanning and photogrammetry, enables the creation of accurate geometric models that capture the complexity of existing structures. When combined with advanced modeling approaches and monitoring systems, these tools allow for a more informed understanding of structural performance, the identification of critical conditions, and the development of targeted intervention strategies. The integration of data-driven approaches and digital twins represents a promising direction for the long-term management of bridge assets, particularly in the context of large infrastructure networks.

From a broader perspective, the future of masonry arch bridges is closely linked to the evolving relationship between infrastructure and heritage. These structures should not be regarded solely as objects to be preserved, but as active components of contemporary landscapes, capable of accommodating new functions and contributing to sustainable mobility systems. In this sense, the reuse and adaptation of existing bridges, when compatible with their structural and historical characteristics, can represent a viable alternative to replacement, reducing environmental impact and preserving cultural value. This perspective is particularly relevant in the context of current energy and resource transitions, where the conservation of existing infrastructure aligns with broader sustainability objectives.

The comparative perspective between European and Chinese traditions further emphasizes the potential for cross-cultural exchange and knowledge transfer. While Europe offers a vast heritage of historic masonry bridges requiring conservation and adaptation, China provides examples of more recent developments and continued experimentation with masonry arch construction. Bringing these experiences into dialogue can contribute to the development of more comprehensive and innovative approaches, capable of addressing both preservation and contemporary engineering challenges.

The principal contribution of this review is the development of an integrated perspective on historic masonry arch bridges, encompassing their historical development, structural behavior, assessment approaches, and conservation strategies. The multilevel interpretative framework presented in Fig. 5 synthesizes this perspective by bringing together European and Chinese experiences, as well as engineering and heritage-conservation approaches, within a common structure. In doing so, it helps organize existing knowledge and identify future research priorities.

In conclusion, masonry arch bridges should be understood as complex systems in which history, structure, and technology are deeply interconnected. Their effective conservation and continued use require an integrated approach that combines historical awareness, structural understanding, and advanced analytical tools. By bridging the gap between past and present, and by aligning conservation practices with future-oriented perspectives, it is possible to ensure that these structures remain not only testimonies of engineering heritage, but also active and meaningful components of contemporary infrastructure systems.

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Author contribution statement

Emanuele Reccia: conceptualization, investigation, methodology, writing-original draft, writing-review & editing, supervision. Shujie Chen: conceptualization, investigation, writing-original draft. Zlatko Šavor: conceptualization, investigation, writing-original draft. Cong Li: conceptualization, investigation, writing-original draft. Valentina Pintus: conceptualization, investigation, methodology, writing-original draft, writing-review & editing.

Data availability statement

All the data that are used in this research will be made available upon reasonable request by the first author.

Use of AI statement

During the preparation of this research, we used ChatGPT to improve grammar and readability. After using this tool, we reviewed and edited the content as needed and take full responsibility for content of the publication.

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