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Structural Assessment, Repair, and Strengthening of Masonry Arch Bridges: Modes of Operation and Open Issues

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Abstract: Masonry arch bridges represent a significant part of civil infrastructure, characterized by their longevity and historical value. However, many of these structures are facing critical challenges due to aging, environmental factors, and increased loading conditions. This paper provides a comprehensive overview of structural assessment, repair, and strengthening methods applicable to masonry arch bridges, emphasizing the necessity for effective risk mitigation strategies. The study first focuses on current assessment methodologies used to evaluate the structural integrity of masonry arch bridges under various load scenarios, including traffic, seismic, and hydraulic influences. It highlights the importance of acquiring a thorough understanding of the structure under investigation by utilizing advanced surveys and diagnostic techniques. Several analytical and numerical methodologies aimed at achieving accurate assessments are explored, outlining their advantages and disadvantages. The paper then discusses various repair and strengthening solutions that aimed at restoring and enhancing the performance and safety of these bridges, respectively. These include traditional approaches such as repointing and arch ring reinforcement, as well as modern techniques like fiber-reinforced cementitious matrix (FRCM) applications. Additionally, the traditional technique of post-tensioning is analyzed in a modern context for the strengthening of masonry bridges. The effectiveness of these methods is assessed based on the advantages and disadvantages of each technique, providing comparisons among the commonly used methods. Overall, the paper identifies open issues within the field, such as the need for standardized assessment protocols, the integration of sustainability considerations into repair strategies, and the development of innovative strengthening techniques.

Author keywords: Masonry arch bridges; Numerical models; Strengthening techniques

Introduction

Masonry arch bridges constitute a significant portion of the global railway and road infrastructural heritage. Estimating the exact number of masonry arch bridges worldwide is challenging, as there is no comprehensive global database tracking all such structures. According to a past approximate estimate, the European railway network alone contains approximately 200,000 masonry arch bridges, representing 50% of the total railway bridge stock.[1] This number is expected to rise to around 300,000 when masonry bridges in national road systems are included.[2] Statistical analyses in various national contexts suggest that these estimates may even underestimate the actual number of in-service masonry arch bridges. For instance, in the UK, there are about 40,000 masonry arch bridges across both railway and road networks; in Italy, nearly 10,000 masonry arch bridges exist solely along the railway network; and in Spain, the railway network includes over 3,000 masonry arch bridges.[3] Focusing on limited stocks of Italian road bridges, more recent estimates have again demonstrated the widespread presence of this structural typology.[4]

Assessing the structural condition of masonry bridges is essential to ensure the safety of road and rail infrastructure and to preserve their historical value. Bridge owners and managers are increasingly focused on developing management plans that involve identifying traffic load limits and defining appropriate interventions to mitigate damage and negative impacts from road and railway traffic, as well as those caused by exceptional actions. At the same time, masonry bridges are culturally significant structures of high historical value that require preservation and protection.[5]

Despite their widespread use and crucial role in infrastructural assets, it is important to note that this construction technique was mainly adopted until the first decades of the last century, relying on outdated traffic load models or even empirical criteria and mostly neglecting seismic actions.[6] Although this is generally not a critical issue for these massive structures—characterized by a low ratio of traffic loads to permanent loads—it does highlight the significant aging

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of in-service masonry arch bridges, many of which may not have undergone any maintenance or retrofitting throughout their service life. Moreover, it should be highlighted that since the construction of many of these bridges, the load, speed, and length of vehicles have significantly increased, resulting in substantial increases in internal stresses and an acceleration of structural degradation phenomena.[7]

Although masonry bridges have demonstrated high robustness and durability over time, they remain vulnerable to deterioration. This deterioration, resulting from the interaction of the structures with their surrounding environment, can lead to significant damage, such as erosion, loss of mortar joints, loss of bricks, and cracking (see Fig. 1), which compromises their load-bearing capacity.[8–12]

For instance, in Zizi et al.[13], a defect survey of several masonry arch bridges based on classifications from recent Italian Guidelines[14], revealed critical conservation states for these bridges, stemming from both natural and human-made causes. Given this, there is a clear need to promote and implement effective conservation strategies—including retrofitting solutions—to safeguard this extensive infrastructural heritage and ensure its continued functionality.

The proposed challenge is twofold: on the one hand, it involves developing reliable assessment methodologies to evaluate the actual capacity of these structures under various load scenarios, including traffic, seismic, and hydraulic loads; on the other, it requires proposing effective repair and strengthening solutions. This manuscript thoroughly addresses these two aspects, highlighting both recent and longstanding research trends, open issues, and potential future directions for effective risk mitigation concerning various factors (e.g., traffic, earthquakes, floods, etc.) impacting in-service masonry arch bridges.

Analysis and Assessment

Problem statement

Breaking down the uncertainties in the safety assessment of masonry arch bridges can be challenging for several reasons. Firstly, since these bridges were predominantly constructed up to the first half of the last century, detailed information about their construction details, such as original blueprints or the mechanical properties of the materials, is generally unavailable. Additionally, there is considerable complexity in understanding their response to both vertical (self-weight and traffic) and horizontal (seismic) forces due to the intricate interaction between different materials, such as fill material and masonry, as well as the inherent difficulties in analyzing arched structures made of poorly tensile-resistant materials. Given these factors, the problem can primarily be associated with two key issues: acquiring appropriate knowledge of the main structural and geometrical features and conducting reliable and robust analyses.

Besides these issues, as noted in the previous section, many masonry arch bridges may be affected by structural defects that compromise their ability to withstand various load sources. As a consequence, a detailed and reliable assessment must somehow account for these situations.

Knowledge of masonry arch bridges

The challenge associated with understanding masonry arch bridges for reliable structural and seismic safety assessments, as well as for structures in general, generally pertains to both geometry and materials. Investigation of geometry, in turn, involves two distinct aspects: defining the external and internal geometries. While the external geometry of a bridge can often be determined with relatively minimal effort, using either traditional methods (e.g., basic measurements with tapes, rulers, and plumb lines) or more advanced techniques (e.g., laser scanning and terrestrial and UAV-based photogrammetry, see Fig. 2),[15–19] investigating the internal geometry is often more complex.

For this purpose, nondestructive techniques, such as GPR,[20,21] or even minimally invasive methods, may not always provide sufficient accuracy to capture all the geometric features of these bridges (e.g., the complete stratigraphy of the backfill material). Thus, more invasive techniques, such as vertical coring from the rails or street level, could be adopted (Fig. 3).

(a) (b)

Figure 1. Examples of damage on masonry arch bridges: (a) loss of mortar joints and bricks, and (b) longitudinal crack at the arch intrados

Moving to material characterization, two levels, again, can be distinguished for material parameters: linear (elastic) and nonlinear. As for linear parameters (i.e., elastic moduli), their determination can be performed with direct and indirect methodologies. Direct methodologies involve measurement through specific tests (e.g., sonic and ultrasonic tests, single or double flat jack tests, etc.). In contrast, indirect methodologies may include the dynamic characterization of overall structural behavior by measuring and elaborating recorded infinitesimal accelerations, velocities, or displacements to identify the main mode shapes, frequencies, and damping ratios of the structure (Operational Modal Analysis—OMA).

These can be profitably used in combination with multi-objective optimization processes,[22] aimed at reducing the differences in terms of frequencies and mode shapes (Modal Assurance Criterion—MAC) to calibrate unknown parameters. Several modal parameter identification procedures can be adopted when performing Operational Modal Analysis (OMA) of masonry arch bridges. Since measurements are generally taken under environmental and anthropic (traffic) unknown excitations, output-based procedures are commonly preferred.[23] Among the most widely adopted methodologies are Frequency Domain Decomposition (FDD)[24–26] (see Fig. 4), Enhanced Frequency Domain Decomposition (EFDD),[27–30] and Stochastic Subspace Identification (SSI).[31,32]

In this regard, it should be noted that for stiff structures characterized by high vibrational frequencies, such as stocky masonry arch bridges, dynamic identification can be far from trivial. Nonetheless, as outlined in Gonen and Soyoz,[33] due to their complexity and greater stiffness compared to standard shear-type buildings, dynamic identification of historical masonry structures poses a greater challenge. Therefore, it is advisable not to depend on a single method; instead, validation of the identification results should be conducted using alternative methods grounded in different principles.[34]

The issues related to the definition of nonlinear material parameters can be even more challenging. In particular, masonry, backfill material (generally a soil medium), and their interaction are characterized by strong nonlinearities. Despite the fact that it is well-known that a masonry arch is a mostly compressed element, failure in masonry bridges can generally occur due to tensile and shear stresses. This puts into evidence the need to accurately estimate these strengths[35–37] in order to obtain reliable results from the analyses, especially when influencing the analysis method adopted. This holds true also for fill material, which plays a fundamental role in the overall response of such a bridge typology.[38–41] Generally, backfill is modeled as a cohesive-frictional material (Mohr–Coulomb behavior), and thus the estimation of the parameters at hand is essential for a correct interpretation of the structural response under different types of loads. Another important issue is represented by the interaction between masonry and fill material.[39] In a recent study,[42] this interaction was experimentally investigated in detail, by providing ranges of reliable values of the ratios

Figure 2. Example of the survey of external geometry: (a) the Bridge on SP9 in Caserta Province and (b) point cloud elaboration based on UAV photogrammetry

Figure 3. Example of vertical coring (Bridge on SP9 in Caserta Province): (a) coring machine and (b) extracted material

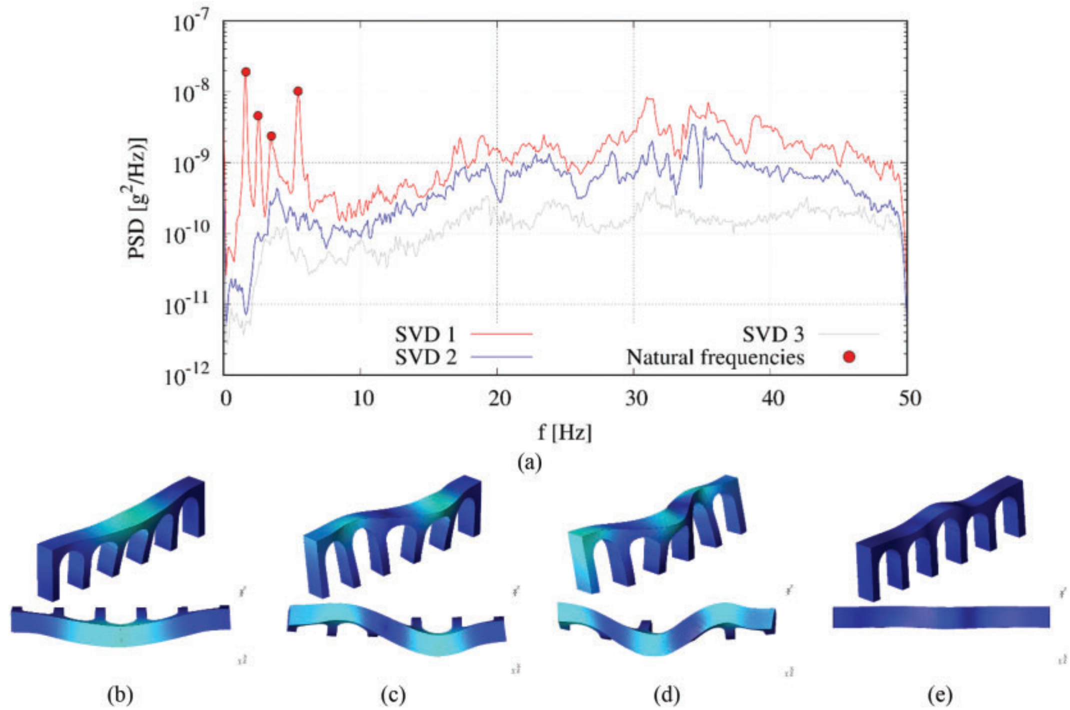

Figure 4. Example of OMA by means of FDD application: (a) identification of relevant frequencies by singular value plot, and (b–e) mode shapes of the first four frequencies (adapted from Zizi et al.[26])

between the interface angle of friction and the internal angle of friction of the backfill materials.

However, it should be highlighted that the parameters to be investigated must be selected to support the accurate calibration of the analysis model (described in further detail in the next subsection) to be adopted. For instance, when simplified models, such as kinematic or linear analysis, are adopted, an in-depth understanding of the mechanical properties of the masonry is generally not required. Conversely, it is essential to characterize the materials in terms of elastic moduli, strengths, and deformation capacities, and to verify the validity of the assumptions underlying the analysis, such as infinite compressive strength or the absence of sliding between structural components that define the collapse mechanisms.

Masonry arch bridge modeling

The topic related to masonry arch bridge modeling is quite wide, and in the following, a brief overview is provided. To the authors' knowledge, the first pioneering studies date back to the 1950s–1960s, when Kooharian and Heyman applied the principles of plastic analysis to concrete and masonry arches, respectively.[43,44] In particular, under the assumptions of infinite compressive and zero tensile strengths of the voussoirs that compose the arch and perfect adherence between the voussoirs themselves, Heyman estimated a geometrical safety factor by constructing the line of thrust (i.e., limit analysis). Limit analysis-based methods, with either a static or kinematic approach, found notable application in the scientific literature for the estimation of the load-carrying (both vertical and horizontal) capacity of masonry arch bridges, as well as arches in general.[45–54]

Despite requiring moderate computational effort, limited material information, and being easy to use, classic limit analysis approaches have some limitations. For instance, they often neglect both out-of-plane mechanisms and backfill effects, are unable to provide stress and strain outputs, and rely on strong and simplified hypotheses about masonry behavior.

To overcome these limitations, various authors have proposed updates to the original problem formulations. For example, in Cavicchi and Gambarotta,[55] the authors introduced an arch-fill interaction model to account for the effects of backfill material properly. In Drosopoulos et al.,[56] the foundational assumptions of limit analysis were expanded to allow for tensile and/or sliding separations of the voussoirs. The issue of rigid-block definitions in kinematic approaches was explored extensively in Nodargi and Bisegna,[57] where the authors proposed a closed-form solution that considers the direction of separation lines. Additionally, finite compressive strength was introduced by several authors, including Caporale and Luciano[58] and Clemente and Saitta.[59] More recently, three-dimensional models were also developed using rigid-block analysis (Fig. 5) to capture the three-dimensional behavior of masonry structures.[60]

A notable example of both commercial and academic software for the assessment of masonry arch bridges based on limit analysis is RING (see Fig. 6), developed by the Sheffield University team led by Prof. Gilbert.[62]

Since its initial release, the software has been substantially updated, and its current version can account for

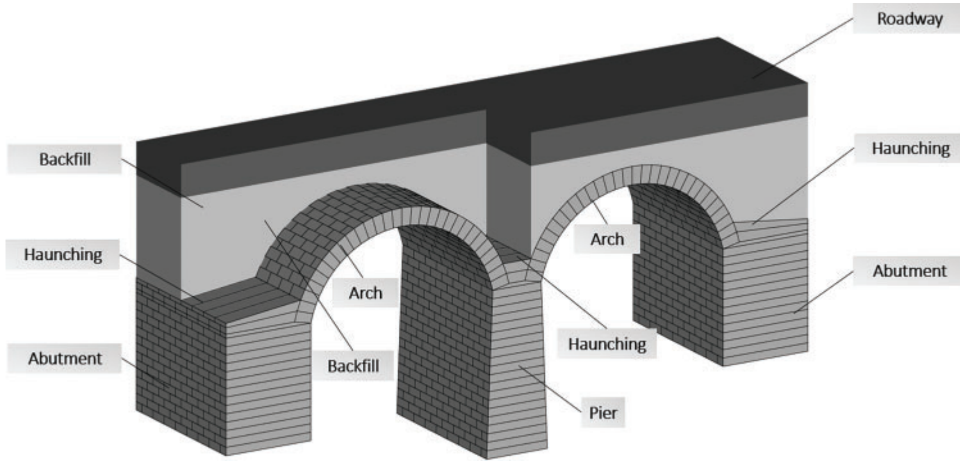

Figure 5. Three-dimensional modeling of a masonry arch bridge using rigid-block analysis (adapted from Niero et al.[61])

backfill influence, ring separation, non-infinite compressive strength, and sliding phenomena.

Transitioning from limit analysis-based methods to numerical ones, two main approaches are commonly distinguished for masonry structures: micro-(or meso-) scale and macroscale models.[63] Micro-models can be employed within the framework of both finite element (FEM) and discrete element (DEM) methods. Both require precise calibration of material parameters and involve significant computational effort, especially for complex analyses such as those necessary for three-dimensional masonry arch bridges, where the masonry and the fill material are represented as a series of blocks connected by advanced nonlinear interaction laws. Within FEM microscale models, a further distinction is made between detailed and simplified approaches. Whereas the detailed approach explicitly models mortar joints and contacts as distinct elements, the simplified approach represents them implicitly as a single contact layer. Notable examples of micro-modeling approaches applied to masonry arch bridges, or masonry arches in general, can be found in Bićanić et al.;[64] Ferrero et al.;[65] Tubaldi et al.;[66] Zhang et al.[67]. In this context, it is worth mentioning the studies conducted by Prof. B.A. Izzuddin and his team at Imperial College London (UK), which were implemented in the academic software ADAPTIC[34,68,69] (see Fig. 7).

Similarly, the Discrete Element Method (DEM)[70] can be reliably used for assessing masonry arch structures. However, its application remains largely confined to research purposes rather than practical engineering activities.[39,71–73]

Closely related to the concepts underlying the discrete element method (DEM) is the applied element method (AEM). This approach models interactions between small elements using spring stiffness and damping coefficients, rather than relying on contact mechanics. It enables the explicit modeling of crack initiation, propagation, and structural collapse. One of the few, if not the only, examples of AEM applied to masonry arch bridges can be found in Farneti et al.,[74] where the authors successfully reproduced the outcomes of a prior experimental study by adopting this modeling strategy.

An extension yet simplification of DEM and micro-modeling FEM approaches is represented by the discrete macro-element method (DMEM). With this modeling approach, instead of modeling every single component at a micro level, structural elements are treated as discrete blocks or "macro elements." This allows for an accurate representation of the overall behavior while reducing the computational load compared to traditional FEM or DEM. A successful example of DMEM used for analyzing masonry arch bridges is the HiStrA software[75] (see Fig. 8), initially implemented by the team at the University of Catania led by Prof. I. Caliò. It has recently found notable applications among academics and practitioners, particularly at the Italian national level.

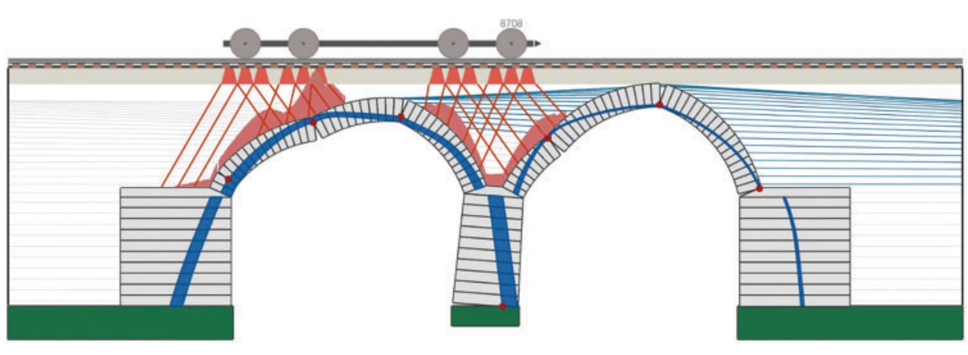

Figure 6. Example of limit-state-based analysis with RING[62]

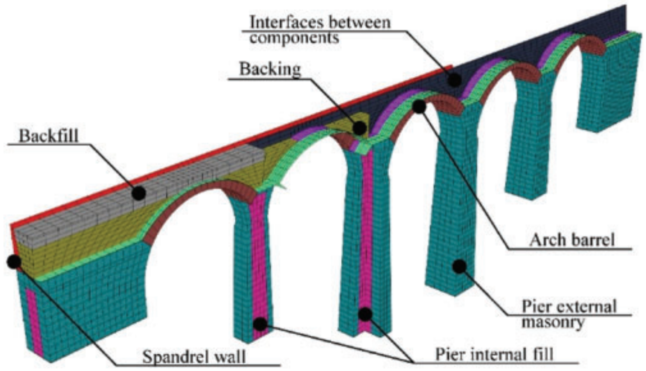

Figure 7. 3D FEM modeling with a mesoscale approach of a masonry arch bridge in ADAPTIC[34]

Finally, it is important to acknowledge the macro-modeling approach within the finite element (FE) analysis framework, where the behaviors of masonry and fill materials are represented by isotropic or orthotropic homogeneous continua that exhibit nonlinear behavior with varying strengths and ductility capacities depending on the direction of the applied stress. Despite its widespread use among researchers and practitioners, accurate calibration of the parameters governing the highly nonlinear response of masonry arch bridges is essential. An example of this issue related to masonry structures is discussed in Zizi et al.,[76] where the authors attempted to reproduce a set of laboratory tests on masonry panels subjected to shear-compression loads using three different commonly employed masonry material descriptions with a macro-modeling approach. Similarly, when applied to masonry bridges, several parameters can significantly affect the structural response[77] (see Fig. 9). Examples of macroscale models adopted for masonry bridges can be found, among others, in Bayraktar and Hökelekli,[78,79] Mentese et al.,[80] Özmen and Sayın,[81] Pantò et al.,[34] and Reccia et al.[82]

Within FEM frameworks, the extended finite element method (XFEM) enhances the traditional modeling approach by incorporating additional mathematical functions to address discontinuities, such as cracks and complex material interfaces, without requiring the mesh to conform to their geometry. This makes XFEM particularly well-suited for scenarios involving preexisting cracks and applications focused on analyzing crack propagation. A comprehensive review of crack modeling using this approach is provided in Branco et al.,[83] while in Yazdani and Habibi,[84] an application to masonry arch bridges is presented.

Repair and Structural Strengthening

To ensure the functionality and preservation of masonry bridges, it is essential to undertake timely repairs and retrofitting interventions. To this end, various strategies can be implemented: preventive, remedial, and strengthening measures. Preventive measures aim to maintain the condition of the structure through routine maintenance activities and continuous monitoring, thereby preventing the occurrence of significant damage or deterioration. On the other hand, remedial techniques seek to repair any existing damage to restore functionality and structural integrity. Finally, strengthening strategies focus on enhancing the load-bearing capacity of the structure to accommodate new requirements or to increase its structural safety[5,85–87] The choice of intervention strategy must be made based on the specific characteristics of the structure and its level of damage. Intervention techniques may include traditional and/or innovative methods; however, the materials used must always be compatible with the existing masonry, thereby ensuring integration as a constituent part of the new structural arrangement.

Repair interventions

One of the most widely employed repair techniques for masonry structures is joint repointing, which involves injecting mortar into deteriorated joints to enhance structural cohesion and improve the overall durability of the structure. This technique also mitigates water infiltration, thus helping to prevent further deterioration processes. Proper execution of joint repointing is essential to ensure uniform mortar distribution and to avoid excessive pressure that could damage the masonry. Additionally, selecting mortars compatible with the original materials is crucial; hydraulic lime-based mortars are often preferred due to their chemical and mechanical compatibility with historic masonry. An example of this restoration technique is found in the São Lázaro Bridge (Fig. 10) near Porto, Portugal, where the joints were repointed with bastard mortar composed of lime, cement, and aggregate.[5]

Additionally, deep repointing (to a depth of 70–80 mm) has been demonstrated to enhance the shear strength and stiffness of masonry structures significantly.[88]

In addition to joint repointing, another commonly used repair technique is the injection of fluid mortar into cavities and cracks within the masonry. This method improves material continuity and facilitates the transfer of internal stress, leading to an overall enhancement in structural performance. As with joint repointing, it is essential that the injection mortar be compatible with the original masonry; therefore, lime-based mortars that are sufficiently fluid to penetrate into the structure's cavities are typically preferred. This technique repairs the structure without altering its external appearance or disrupting the traffic flow above. However, it does not allow precise control over the exact volume of cavities or voids filled. For this reason, it is often used in conjunction with other structural strengthening measures, as demonstrated in the cases of the Portuguese bridges Segura, Real, Formigosa, Pedrinha, Caninhas, Sancheira, and Remondes.[5] Furthermore, in cases where masonry units are missing or exhibit significant material loss, replacement may be necessary. It is essential that the new blocks closely match the existing ones in terms of dimensions, shape, and material characteristics.

Another method of repair involves the replacement of backfill material, which is necessary when its mechanical properties have degraded, leading to an increase in the horizontal pressure exerted on the spandrel walls. This intervention stabilizes the spandrel walls without impacting the overall aesthetics of the structure. Typically, the replacement of backfill material is accompanied by structural reinforcements such as reinforcing straps or concrete slabs. For instance, in the case of the Marillais Bridge in France,[89] which experienced settlement of the central pier, rehabilitation was achieved by substituting the backfill material with concrete, complemented by the anchoring of steel bars in a damaged area. However, this technique requires significant excavation and reconstruction efforts, and it can lead to disruptions of traffic and services, as well as potentially impacting the drainage system.[9] In addition to these methods, other repair techniques, such as the restoration of road pavement and the improvement of the drainage system, can also be employed to enhance the overall integrity of the structure and prevent water infiltration.

Traditional strengthening interventions

One of the most traditional strengthening techniques for increasing the load-bearing capacity of masonry bridges involves thickening the existing masonry arch with new layers of bricks. This method effectively enlarges the load-bearing cross-section of the arch, thereby enhancing its structural capacity. However, during the application of this technique, it is crucial to properly connect the original masonry with the new layer to ensure stress transfer, allowing both elements to work together. An example of arch thickening has been implemented in the Sandro Gallo Bridge.[6,90]

In addition, when it is possible to remove the backfill material and suspend traffic, it is feasible to further improve the bridge's load-bearing capacity by constructing internal spandrel walls on the extrados of the arch. These elements, if adequately anchored to the existing masonry, counteract deformation within the arches, prevent the formation of longitudinal mechanisms, and assist in load distribution, thereby also improving the seismic resistance of the structure. This strengthening system has also been utilized in the Rio Moline Bridge,[6,90] preserving its external appearance and maintaining structural integrity.

If it is not possible to interrupt traffic, an existing masonry bridge can be strengthened by injecting material at the base of the arch within the fill. The injected material increases the compressive forces exerted on the arch, resulting in the activation of plastic hinges in positions different from those expected and a reduction in the net span of the

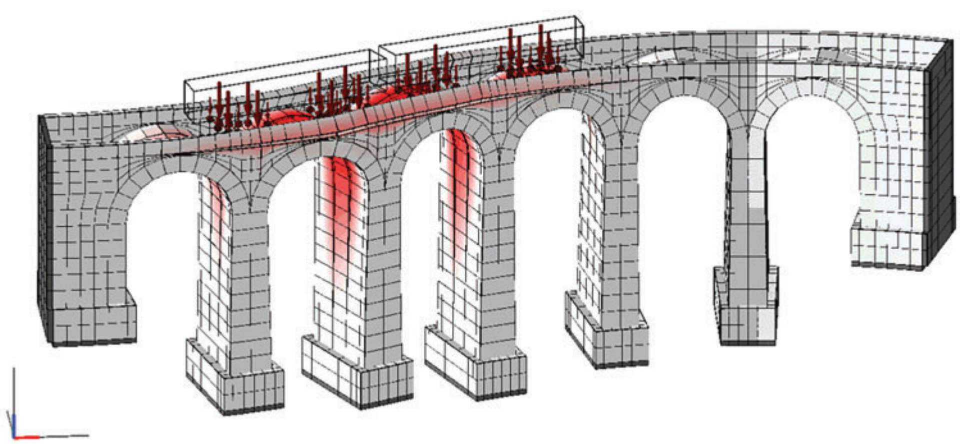

Figure 8. 3D DMEM modeling of a masonry arch bridge in HiStra

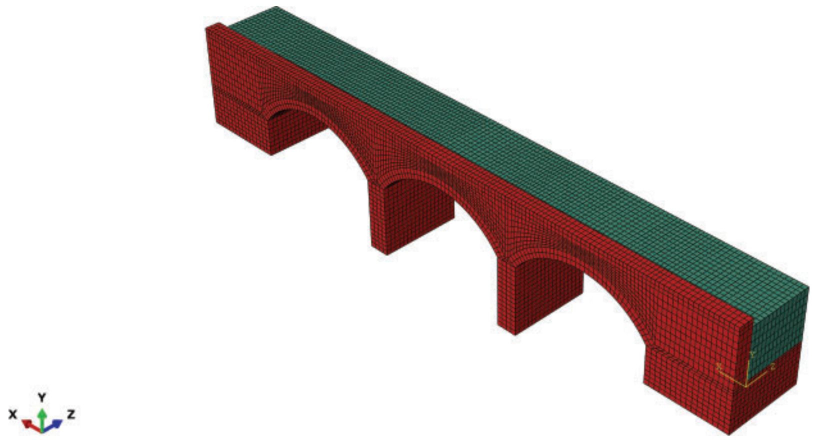

Figure 9. 3D FEM modeling with a macroscale approach of a masonry arch bridge (half model) (adapted from Zizi et al.[77])

Figure 10. Examples of joint repointing on the Sao Lazaro bridge[5]

arch itself.[91,92] Other traditional strengthening techniques encompass the construction of an RC slab on the extrados of the arch,[93] the application of RC jacketing at the intrados of the vault, anchorage with steel bars and prefabricated steel liners at the intrados of the vaults, the implementation of a continuous reinforced concrete deck (Fig. 11a), as well as arch reinforcement with shotcrete (Fig. 11b) and the seismic upgrading of masonry arch bridges (Fig. 11c). An example of the latter method is the masonry bridge over the Magra River in Villafranca,[94] which underwent rehabilitation and strengthening after the flooding of the Magra River.

FRCM strengthening intervention

Although the traditional interventions described above enhance the load-bearing capacity of masonry bridges, they can also lead to increased stiffness and mass. For this reason, over the past 15 years, new strengthening techniques utilizing fiber-reinforced cementitious matrix (FRCM) systems[95,96] have been introduced for masonry constructions. The advantages of these materials include their lightweight nature, high strength and stiffness, corrosion resistance, flexibility, and rapid application. Additionally, the cementitious matrix exhibits significant heat resistance, allows vapor permeability, and can be applied at low temperatures and on wet surfaces. Therefore, the application of FRCM materials to the intrados or extrados of masonry arches represents a particularly advantageous technique that, in the case of intrados application, can even be executed while the bridge remains in service.[97–102]

From a structural perspective, the application of FRCM strengthening significantly enhances the flexural strength of the arch and, consequently, of the masonry bridge. It is important to note that bridge mechanisms can develop when more than three hinges are formed; typically, four hinges occur under nonsymmetric loading relative to the arch's crown, whereas five hinges develop under symmetric or distributed loads along the arch.[5] Therefore, considering the most critical condition of a bridge loaded at one-quarter of the span, as depicted in Fig. 12a, it is possible that sufficiently increasing the applied load could activate a four-hinge collapse mechanism. In contrast, when the arch is strengthened at the extrados (Fig. 12b), the third hinge cannot develop freely due to the presence of tensile-resistant material that prevents its formation. Consequently, a greater load will be required for the development of kinematic hinge mechanisms. This also implies the potential for the thrust line of the structure to exit the thickness of the arch at the failure condition, as the structure strengthened with FRCM material exhibits tensile resistance. Conversely, when strengthening is applied to the intrados of the arch (Fig. 12c), the formation of the second hinge at the intrados is prevented due to the tensile resistance of the strengthening, and the thrust line of the bridge exits the arch section at this point. If the strengthening is extended beyond the arch's springing, ensuring sufficient bond lengths, the opening of the fourth hinge will also be prevented, further enhancing the capacity of the structure. Finally, when strengthening is applied to both the intrados and the extrados of the arch (Fig. 12d), a combination of the previously described effects is achieved, significantly increasing the capacity of the bridge.

However, the application of the FRCM system to the extrados is not a commonly used technique, as it necessitates the removal and replacement of large quantities of material (filling and pavement), resulting in traffic disruption. Therefore, strengthening the intrados is preferred despite being in a more vulnerable situation due to the risk of detachment. Fig. 13 illustrates the increase in tensile strength obtained in the bending moment (M)–axial force (N) diagram.

In the context of designing a strengthening system using a fiber-reinforced cementitious matrix (FRCM) for existing bridges, it is essential to consider that the effectiveness of such strengthening may be reduced compared to isolated arches. This discrepancy arises from the fact that the axial forces in real bridge arches are typically greater due to the presence of filling materials, which can alter the distribution of stresses. Consequently, as shown in Fig. 14, it is necessary to account for the fact that the effectiveness of the FRCM strengthening system diminishes as the value of the compression force increases, highlighting the importance of careful consideration in the design process to ensure optimal performance and structural integrity.

The increase in load-bearing capacity of the bridge strengthened with FRCM can be demonstrated using the Principle of Virtual Work (Fig. 15).

Assuming an asymmetrical loading configuration, the approximate positions of the four plastic hinges are defined. Once the virtual displacement δ_P at the point of application of the external load on the structure is determined, the collapse multiplier λ of the bridge is calculated by applying the Principle of Virtual Work (1), as shown in (2):

$$\boldsymbol{L_W + \lambda P \delta_P = L_{FRCM} + L_I} \tag{1}$$

$$\boldsymbol{\lambda P = (L_{FRCM} + L_I - L_W)/\delta_P} \tag{2}$$

where L_W, L_{FRCM}, and L_I represent the work contributions of the self-weight, the FRCM strengthening system (which, as an internal work contribution, aligns with L_I), and the internal stresses, respectively. The failure load λP is therefore directly proportional to the resistant contribution provided by the FRCM system. Consequently, as the strength of the

FRCM system increases, the load-bearing capacity of the strengthened structure also improves.

Post-tension strengthening intervention

Post-tension is a traditional strengthening technique for masonry arches and vaults, which can also be applied in a modern context as a retrofit method for masonry bridges.[103–107] This method employs post-tensioned steel cables connected to either the intrados or extrados of the arch. The extremities of these cables are then anchored to the existing structure or to an external foundation system, in cases where mechanisms involving the bridge piers or abutments may develop.[108–110] Post-tension is an active strengthening system: once the cables are tensioned, they transmit stabilizing forces to the arch in an approximately radial direction, inducing beneficial axial compression and centering of the thrust line. This technique thus significantly increases the ultimate load capacity of masonry bridges when the primary failure mechanism is flexural.[111] Additionally, it provides an increase in the ultimate shear capacity, as the heightened compression enhances the limit frictional strength. To calculate the increase in load-bearing capacity of a masonry bridge strengthened with a post-tensioning system, the Principle of Virtual Work (Fig. 16) can be used (3).

Assuming the previously defined asymmetrical loading configuration, a failure mechanism consisting of four plastic hinges is defined. Given the virtual vertical displacement δ_P at the point of application of the external load on the structure, the collapse multiplier of the bridge is calculated as shown in (4):

$$\boldsymbol{L_W + L_{PT} + \lambda P \delta_P = L_I} \tag{3}$$

$$\boldsymbol{\lambda P = (L_I - L_{PT} - L_W)/\delta_P} \tag{4}$$

where L_I, L_{PT}, and L_W represent the work contributions of the internal stresses, the post-tensioning system (the sign depends on the definition of work), and the self-weight, respectively. Also, in this case, the collapse load λP is directly proportional to the resistant contribution provided by the post-tension, which thereby enhances the structural capacity compared to its unstrengthened configuration. Post-tension is advantageous as a strengthening method because it operates as a system parallel to the existing structure, enhancing both its strength and overall ductility without altering the mass and stiffness distribution. This aspect is crucial when strengthening bridges located in seismic zones, where inappropriate interventions could make the structure more vulnerable to earthquakes. Finally, if the post-tensioning system is applied to the intrados of the arch, an existing bridge can be strengthened without interrupting traffic.

Open Issues

Open issues in analysis and assessment

The problem related to the reliable assessment of masonry arch bridges can be mainly attributed to the knowledge of the main structural and geometrical features and analysis issues, as well as their interaction. It cannot be asserted that certain analytical methodologies are inherently better or more reliable than others; rather, each methodology has its own advantages and disadvantages, and its application should be aligned with the specific purpose of the analysis. In this regard, it is important to emphasize that the knowledge

Figure 11. Examples of traditional strengthening techniques: (a) reinforcement of half-slab on the Borbera bridge;[91,112] (b) arch reinforcement with shotcrete on the Remondes Bridge;[5] and (c) rehabilitation and seismic upgrading of the masonry arch bridge over the Magra River in Villafranca[94]

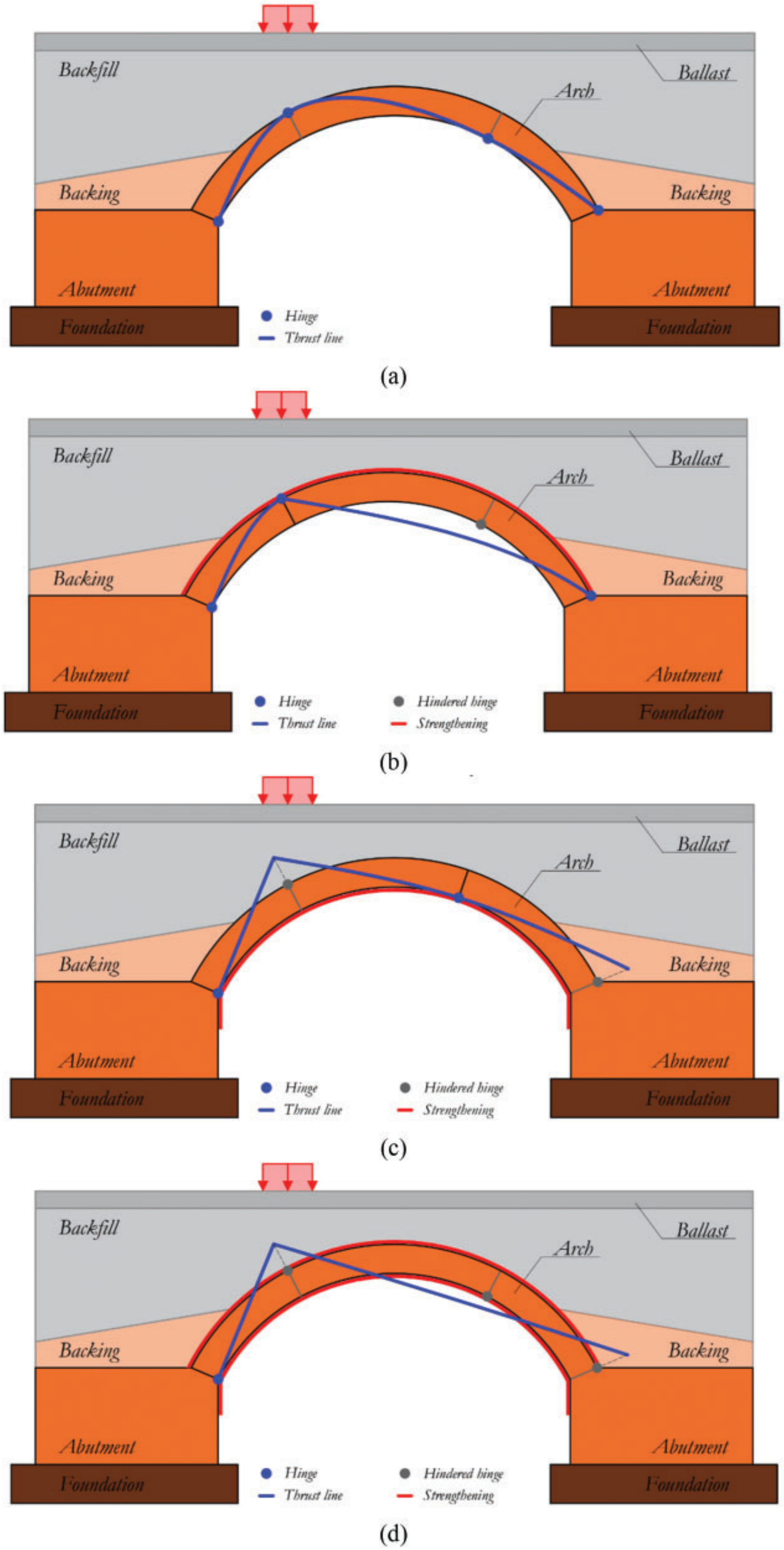

Figure 12. Representation of the arch thrust line in the case of: (a) unstrengthened bridge; (b) bridge strengthened at the extrados; (c) bridge strengthened at the intrados; and (d) bridge strengthened at the intrados and extrados

process should be oriented toward the proper calibration of the analysis model to be adopted, which should therefore be selected in advance. For instance, in the case of simplified models (e.g., kinematic analyses based on limit analysis concepts), a detailed understanding of the mechanical properties of the masonry is generally not required. However, it will be necessary to characterize the materials in terms of elastic moduli, strengths, and deformation capacities, as well as to verify the appropriateness of the assumptions underlying the analysis.

In the case of more refined analyses, including nonlinear behaviors of the materials, despite their wide adoption, at least for research and academic purposes, the main challenge is generally represented by the selection of numerical values to assign to the characteristics governing the nonlinear behavior of materials in a three-dimensional field (e.g., tensile strength and post-elastic behavior), which generally play a fundamental role in response assessment. Consequently, the use of highly detailed models is suggested only if accompanied by equally detailed knowledge of the structure, including the experimental estimation of characteristics typically not addressed by standardized tests.

Another issue directly addressed in this overview is represented by the modeling of preexisting damage conditions, which may be typical in ancient structures such as the ones under consideration and cannot be disregarded. Thus, expert judgment is always required to understand the effects that degradation or even cracking phenomena could have on the capacity of the structure.

From an operational perspective, the primary challenge in the analysis and assessment of masonry arch bridges undoubtedly lies in the absence of guidelines or even codes providing standardized and reliable methodologies for accurate evaluation. In this regard, the entire civil engineering community (including both researchers and practitioners) must make a concerted effort to propose reliable unified approaches that encompass the various analytical methodologies extensively discussed in this manuscript.

Open issues in repair and structural strengthening

The repair and strengthening of masonry arch bridges is a complex process requiring deep knowledge of existing materials and careful evaluation of applied techniques. One of the main challenges concerns the use of materials compatible with those already in place. Historic masonry is often composed of natural materials with unique chemical and

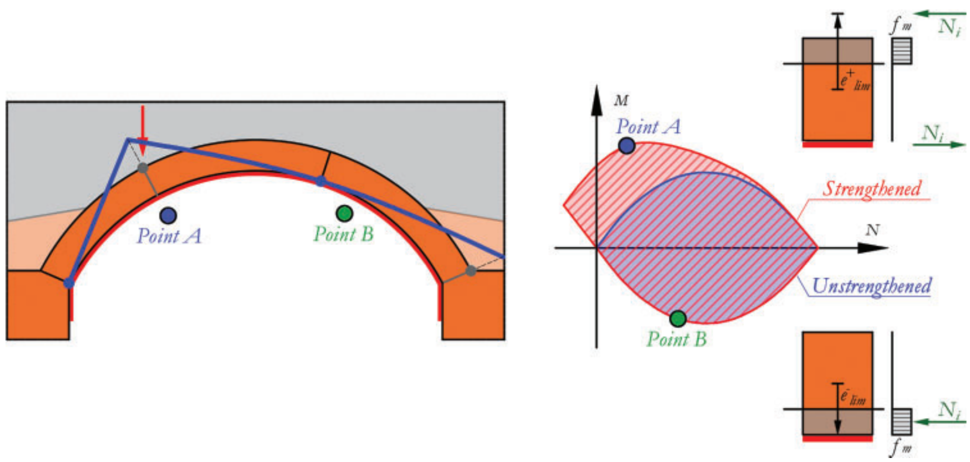

Figure 13. M–N interaction diagrams of the cross-section of the unreinforced arch and the arch reinforced with the FRCM system at the intrados

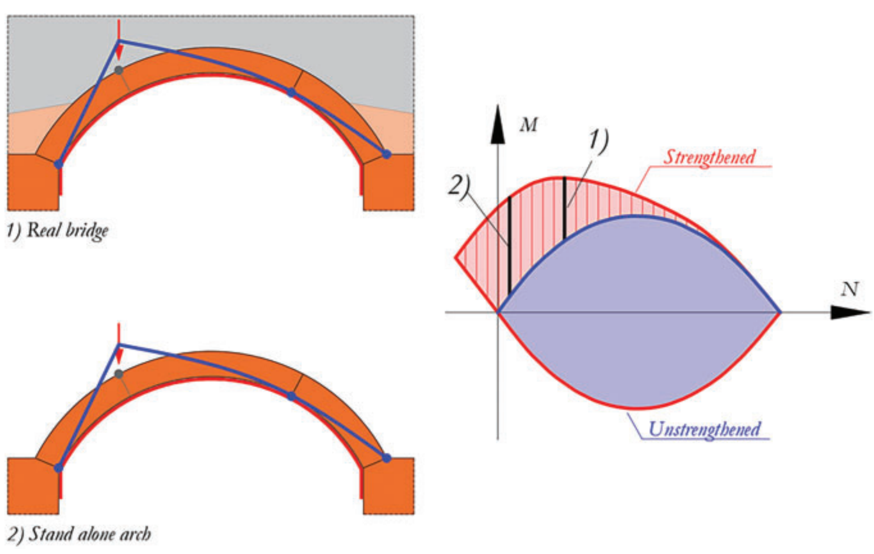

Figure 14. Effect of applying FRCM strengthening to the intrados in 1) real arches compared with 2) stand-alone arches

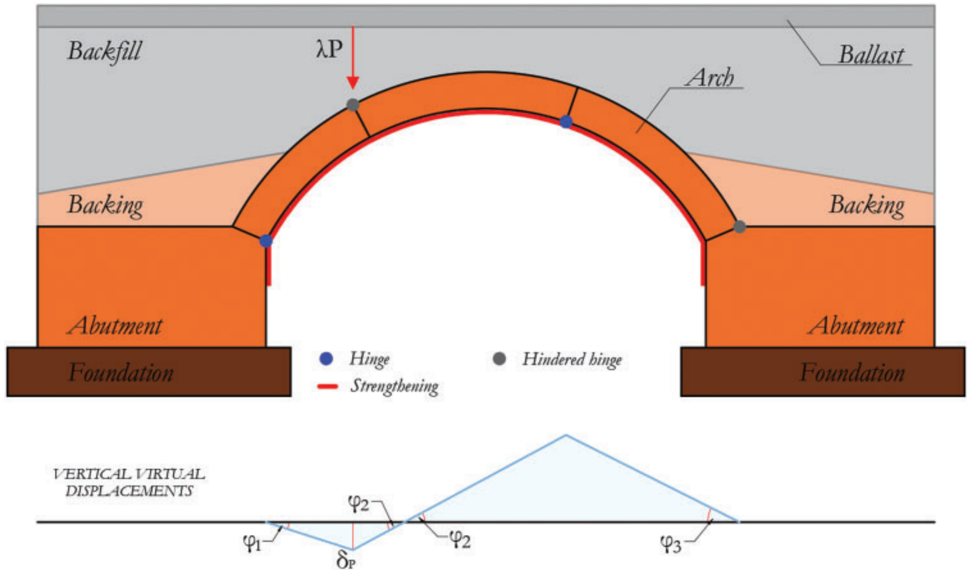

Figure 15. Vertical virtual displacements for a bridge strengthened with the FRCM system

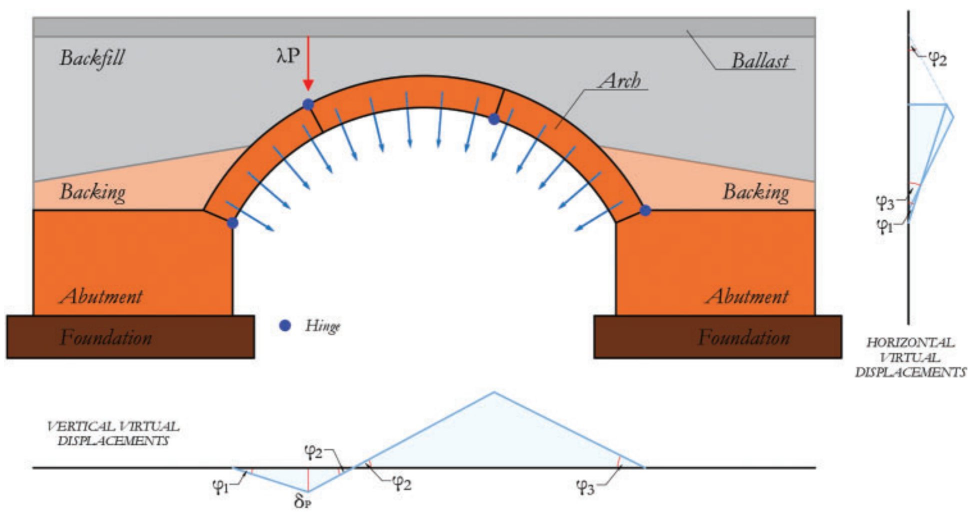

Figure 16. Horizontal and vertical virtual displacements for a bridge strengthened with a post-tensioning system

physical properties, tied to the geographic and temporal context of the construction. The use of modern materials that are incompatible can alter the original chemical composition, triggering degradation processes such as accelerated moisture-related phenomena or the formation of harmful salts. This issue necessitates a meticulous selection of repair materials that not only respect the original chemistry of the structure but also ensure adequate mechanical behavior and long-term durability.

Another critical aspect is the impact that certain interventions can have on the stiffness and mass of the structure. Modifying the distribution of stiffness can alter the dynamic behavior of the structure and its response to external actions, such as static and dynamic loads or seismic events. Additionally, the increase in structural mass resulting from some strengthening interventions can amplify the effects of dynamic stresses, increasing inertial forces and, consequently, the risk of damage during extreme events.

A further crucial consideration is the use of active and passive systems for structural strengthening, which interact with the existing structure to enhance its performance. These systems can operate in parallel with the original masonry or activate only in response to specific stresses, such as extreme loads or seismic events. Their application must be carefully calibrated to respect the integrity of the structure and preserve its historical and cultural value while simultaneously improving safety conditions.

In conclusion, the repair and strengthening of masonry arch bridges requires an integrated approach that balances safety, efficacy, and sustainability, while preserving the historical integrity of the structure.

Conclusions

This paper has provided a comprehensive examination of the structural assessment, repair, and strengthening of masonry arch bridges, which are vital components of our civil infrastructure. As these structures face increasing challenges from aging, environmental factors, and evolving loading conditions, the need for effective assessment and mitigation strategies has never been more critical.

The analysis underscores the importance of utilizing advanced diagnostic and assessment methodologies to evaluate the condition and capacity of masonry arch bridges accurately. By integrating various analytical and numerical techniques, practitioners can gain a more nuanced understanding of the factors affecting these structures, thereby enabling informed decision-making regarding maintenance and rehabilitation.

Furthermore, the exploration of both traditional and modern repair and strengthening solutions reveals that a multifaceted approach is necessary to enhance the performance and longevity of masonry arch bridges. The techniques explored offer promising avenues for intervention, especially when tailored to specific deterioration mechanisms.

Despite these advancements, several open issues remain within the field. The need for standardized assessment protocols is imperative to ensure consistency and reliability across different contexts. Additionally, incorporating sustainability considerations into repair and strengthening strategies will be crucial for the long-term viability of these historical structures.

Future research should focus on developing innovative strengthening techniques and refining existing methodologies to address the unique challenges posed by masonry arch bridges. By fostering collaboration between researchers, practitioners, and policymakers, the resilience of these structures can be further enhanced.

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