SAFETY OF MASONRY ARCH BRIDGES AGAINST FLOOD HAZARD

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SUMMARY

Although masonry arch bridges are very vulnerable to flooding, accurate procedures to systematically assess their performance when subjected to flooding actions have yet to be proposed. The present paper describes the development of a framework for the flood risk assessment of masonry arch bridges including accurate computational strategies for predicting the response of these structures to flood effects. The most critical types of loading associated with floods and the sources of uncertainty relevant to the problem are illustrated. Then the proposed framework is applied to a realistic case study showing the potential of the proposed three-dimensional mesoscale representation for masonry arch bridges under scour action.

Keywords: *Flood risk assessment, arch bridges, scour, hydrodynamic forces, buoyancy.*

1. INTRODUCTION

Masonry arch bridges represent the oldest type of bridge construction which also at present play a crucial role in transport networks around the world. These heritage structures have proven to be very durable, with a service life extending well beyond the design life of modern bridges. However, in the last decades, the combined effects of ageing/deterioration, scarce maintenance as well as the increase of traffic loading and natural/man-made hazards have resulted in a significant growth of the risk and rate of failure of these structures [1]-[3].

Although masonry arch bridges are very vulnerable to flood effects, no accurate procedures have been proposed thus far to systematically assess their performance when subjected to flooding actions. These include [4]: a) the hydrodynamic pressure on the submerged surfaces exerted by the water and floating debris, b) buoyant forces reducing the effective unit weights of submerged components and thus decreasing the compressive forces within the arch, and c) scour at the footings of piers and abutments, which is the most common cause of collapse due to the high vulnerability of arches to foundation settlements. To account for these effects in the safety assessment of arch bridges, a probabilistic approach is required given the inherent uncertainty in the occurrence of floods and their magnitude, and the limited accuracy of the models employed to predict flood effects.

The first part of this paper describes the development of the framework for the flood risk assessment of masonry arch bridges. The proposed framework accounts for the specific characteristics of the analysed structures, the most critical types of loading associated with floods, and the various sources of uncertainty relevant to the problem. It integrates the results of flood hazard analysis and structural vulnerability analysis to obtain more realistic risk estimates as compared to other approaches which consider only a design flood event with a given return period [5].

The application of the framework to real bridges also involves the development of accurate and efficient computational modelling strategies to evaluate the effect of flooding. In the final part of the paper, a realistic case study is considered to show the application of the proposed framework to the risk assessment against scour, which is the most critical hazard for bridges, illustrating the capabilities of an accurate three-dimensional (3D) mesoscale representation [6] of masonry arch bridges, which has been developed at Imperial College [7]-[10]. The proposed modelling approach allows for a realistic description of the non-homogeneous components of masonry arch bridges and the specific 3D loading characteristics representing scour conditions. Moreover, as opposed to limit analysis approaches [11], the proposed strategy enables performance assessments for different loading levels up to collapse.

2. CHARACTERIZATION OF FLOOD HAZARD FOR MASONRY ARCH BRIDGES

Water flow exerts different actions on arch bridges. First of all, it induces a significant hydrodynamic pressure on the submerged surfaces, resulting in horizontal forces which may become very high when the deck is also submerged [12]-[14]. Foundation capacities decrease when the water level increases due to the increased eccentricity of the vertical loads. Buoyant forces reduce the effective unit weights of submerged components, thus decreasing the load-carrying capacity of the bridge which strongly depends on the compressive forces within the arch due to the self-weight [15]. Large floating lumps/debris can impact the bridge causing local damage which can jeopardize the bridge integrity. Water flow results also in scour at the footings of piers and abutments which is the most common cause of collapse due to the high vulnerability of the arches to foundation settlements [16],[17]. The factors causing scour to develop are complex and differ according to the type of structure. Scour may occur as a result of natural changes of flow in the channel, as part of longer-term morphological changes to the river, or as a result of human activities, such as the building of structures in the channel or the dredging of material from the bed. Undermining the foundation can induce several negative effects which may jeopardize the integrity of arch bridge components or even global stability. These include (i) rupture of the foundation plinth due to the loss of support [18], (ii) failure of the foundation-soil system [19], (iii) cracking and mechanism formation due to angular rotation, (iv) subsidence, and/or (v) shift of the bridge pier's foundation [20]. Finally, it is worth noting that the low clearance offered by arch bridges makes them very susceptible to debris accumulation, and this may increase both scour development and hydrodynamic forces.

The evaluation of the performance of bridges against floods must account for the random nature of flood-induced actions. This entails the development of a probabilistic hazard model capable of describing the frequency of exceedance of the intensity of the single actions as well as their correlation. The model should also account for the fact that flood-induced actions on bridges may often concurrently interact with each other, e.g. the accumulation of debris against bridges might significantly affect the bridge hydraulics, the hydrodynamic forces and the scour at the bridge foundations, as well as the development of a scour hole may increase the hydrodynamic pressure on the bridge.

3. FRAMEWORK FOR FLOOD RISK ASSESSMENT

The proposed framework is very similar in concept to other frameworks that have been recently formalised for evaluating the risk of structures exposed to different natural and man-made scenarios including blast, fire, tsunami and wind scenarios (see [21]-[23] for a recent state-of-the art review). The main idea behind the development of these tools is to propose a general procedure for the evaluation of the performance of structural systems in terms of decision variables (DVs) such as risk of collapse, fatalities, repair costs, and loss of function, while accounting for all the possible sources of uncertainty that characterise the problem at hand. In this way, the structural risk can be efficiently defined in terms of variables of interest for stakeholders, decision makers, and the society.

The proposed risk assessment framework disaggregates the performance assessment procedure for bridge structures subject to the flood hazard into elementary phases that are carried out in sequence. The framework is summarised in the following expression:

$$\lambda_{DV} = \int_q \int_h \int_{ip} \int_{edp} \int_{dm} G_{DV|DM}\left(dv|dm\right) \cdot f_{DM|EDP}\left(dm|edp\right) \cdot f_{EDP|IP}\left(edp|ip\right) \cdot f_{IP|H,Q}\left(ip|h,im\right) \cdot f_{H|Q}\left(h|im\right) \cdot dDM \cdot dEDP \cdot dIP \cdot dH \cdot \left|d\lambda_{IM}\left(im\right)\right| \quad (1)$$

where $G(\bullet)$ = complementary cumulative distribution function, and $G(\bullet|\bullet)$ = conditional complementary cumulative distribution function; $f(\bullet)$ = probability density function, and $f(\bullet|\bullet)$ = conditional probability density function; IM = vector of intensity measures (i.e., parameters characterizing the environmental hazard); SP = vector of structural parameters (i.e., parameters describing the relevant properties of the structural system and non-environmental actions); IP = vector of interaction parameters (i.e., parameters describing the interaction phenomena between the environment and the structure); EDP = vector of engineering demand parameters (i.e., parameters describing the structural response for the performance evaluation); DM = vector of damage measures (i.e., parameters describing the physical damage to the structure), DV = vector of decision variables. By means of Eq. (1), the risk assessment is disaggregated into the following tasks: (1) hydrologic analysis, (2) hydraulic analysis, (3) interaction analysis, (4) structural analysis, (5) damage analysis, and (6) loss analysis (Fig.1).

It is worth noting that this decomposition, which is a statement of the Total Probability Theorem, is made possible through the fundamental Markovian assumption that the result of each analysis (e.g. *DV*), conditional on the result of the previous step of (*DM*), is independent from the other preceding steps of the analysis (i.e., *EDP*, *IP*, *H*, *IM*). Another assumption that needs to be introduced is that of stationarity, i.e. the conditional probabilities are the same and the relevant conditional distributions shown in these formulas are independent and identically distributed for successive flood events. This implicitly assumes that the system does not deteriorate/evolve, and that it is instantaneously restored to its original state after each flooding event. In this regard, it should be observed that while the hydrodynamic and buoyancy actions associated with the flood event can be assumed to renew at each flood occurrence by following the same conditional probability distribution, the scouring can be cumulative over the long term, and it may result by the succession of events of flooding of different intensity occurring over time. The quantification of the error induced by the assumption of stationarity on the conditional distribution of the scour depth given the conditioning hydraulic parameters (e.g., flow height, velocity) is currently under investigation.

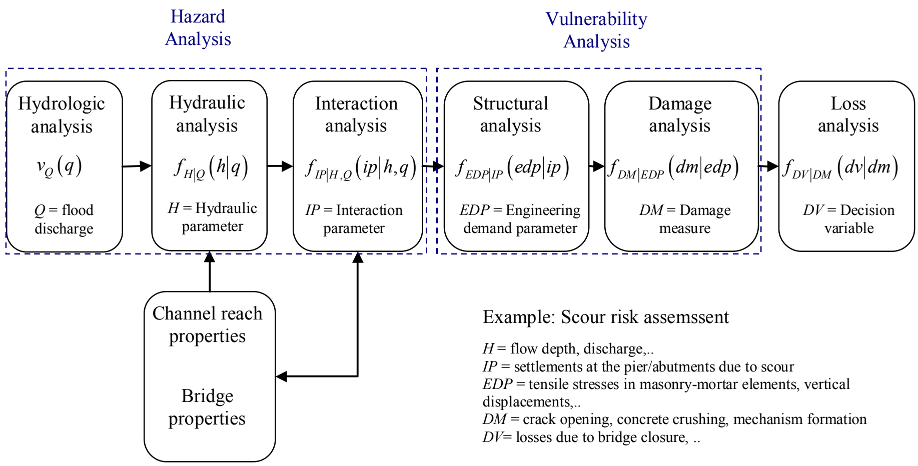

Fig. 1. *Illustration of the risk assessment framework.*

The combination of the first steps (1)-(3) of the framework allows the characterisation of the flood hazard in terms of the mean annual frequency (MAF) of exceedance for the IPs that are used as input for the structural analysis such as the hydrodynamic pressure, the buoyancy and the extent of the scour. Under the aforementioned assumption, it can be shown that also the IPs follow a Poisson distribution with a mean rate given by the combination of the results of steps (1)-(3). The combination of the results of steps (4)-(5) provides information on the structural vulnerability. This can be expressed in terms of fragility curves, which yield the probability of exceeding given damage or limit states vs. the values assumed by the IPs.

4. CASE STUDY

This section presents a case study, where the proposed flood risk assessment framework is applied to a realistic masonry arch bridge. The focus here is on pier scour, which is one of the most critical flooring actions, whose modelling has not received adequate attention to date.

4.1. Bridge and numerical model description

The analysed structure is a two-span arch bridge with a length of 8.50m (left to right abutment), a width of 3.20m and 2.275m height. The two arches are segmental arches with a radius of 2.00m, a rise of 0.536m corresponding to an angular opening of 30°, and a thickness of 0.40m. The multi-ring arches have headers connecting adjacent rings, thus preventing ring separation. A 1/2 scale physical model of the considered case study was tested at the Polytechnic University of Turin under scour-induced settlements [17].

A mesoscale approach [7]-[9] is adopted to describe the two masonry arches and the pier (Fig. 2a). In the mesoscale description, 3D elastic continuum solid elements are used to model the masonry blocks, while the mortar joints and brick-mortar interfaces are modelled by means of 2D nonlinear interface elements (Fig. 2b). Zero-thickness interface elements are also arranged in the mid-plane of all blocks to account for possible unit failure in tension and shear. This mesoscale approach enables the representation of any 3D arrangement for masonry including the complex bond pattern used in multi-ring and skew arches. The constitutive model for the interface element allows for the actual elastic deformations of mortar and brick-mortar interfaces using specific elastic stiffness values, which are functions of the component elastic properties and the joints dimensions. The inelastic response at the interfaces is simulated by means of a cohesive fracture model based on a multi-surface plasticity criterion. The response in tension and shear is described by an elasto-plastic contact law following a Coulomb slip criterion. On the other hand, a formulation that considers energy dissipation, de-cohesion and residual frictional behaviour is employed to describe cracks formation and propagation, where plastic work is used to determine the evolution of material parameters.

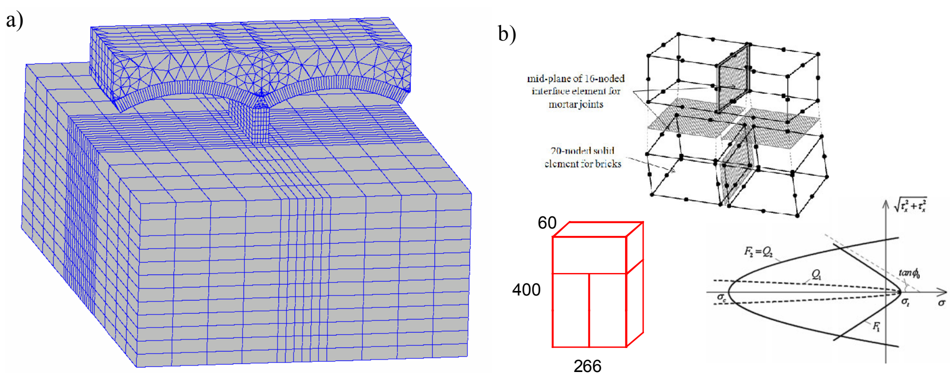

Fig. 2. *a) Bridge model and b) mesoscale modelling, brick unit and plastic surface.*

The backfill is modelled by employing 15-noded wedge solid elements whose constitutive behaviour is described by an elasto perfectly-plastic model based on the use of a smooth rounded hyperbolic Mohr-Coulomb failure criterion [8]. The discrete model with solid elements and nonlinear interfaces for the masonry arch and the continuous model for the backfill are connected by a non-conforming interface [10]. Finally, 16-noded interface elements accounting for the frictional interaction between the arch and the backfill material are defined in the arch partition. The two faces with 8 nodes coincide in the initial undeformed configuration.

In the proposed 3D numerical description for masonry arch bridges, the contribution of the spandrel walls is also taken into account using a simplified homogenised continuous model. The values of the material properties are taken from [8], where they have been calibrated against experimental results on masonry arches and bridges.

The foundation and the soil are described by 20-noded brick elements with linear elastic behaviour. In particular, the soil has a Young's modulus of 500 MPa and a Poisson's ratio of 0.2. A damage parameter is used to control indirectly the scour evolution by reducing the element stiffness, thus simulating the soil removal.

The numerical bridge model has been implemented in ADAPTIC [24] by employing a partitioned approach recently developed at Imperial College [25] allowing for an efficient parallel computation. In particular, the bridge model is described by a parent structure and by a set of super-elements representing the partitioned subdomains. Dual super-elements are used for modelling the partitions as separate processes, where two-way communication between each pair of dual parent/child super-elements allows effective parallelisation of the nonlinear structural analysis simulation [25]. The application and effectiveness in the use of this approach for the analysis of large masonry components is discussed in [7]. Figs. 3-4 show the partitioning scheme for the bridge model.

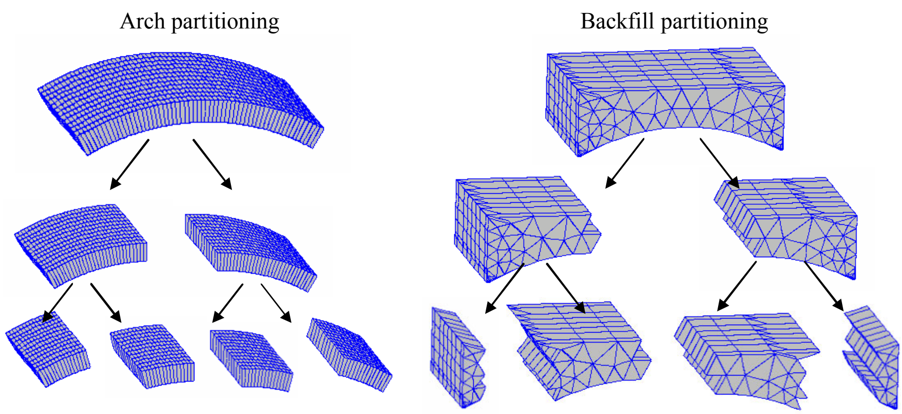

Fig. 3. *Superstructure partitioning.*

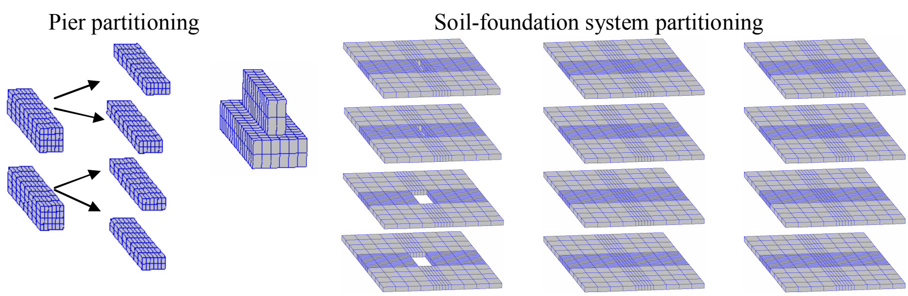

Fig. 4. *Substructure partitioning.*

4.2. Scour risk assessment

This section illustrates some preliminary results of the analyses carried out to evaluate the influence of scour on the bridge collapse probability. The vulnerability analysis of the bridge against scour is carried out for the collapse limit state, which is analytically defined as $G(s)=\lambda_c(s)-\lambda$, where λ_c denotes the value of the vehicle load multiplier inducing collapse, s is the scour depth, and λ is the multiplier value of the acting load. In the analysis, the vehicle load consists of a single axle load of nominal value 400 kN, and it is described in a simplified manner by assigning a set of nodal forces over an area centred at midspan of the first span of length 0.44 m (along the longitudinal bridge axis) and width of 3.2 m. Obviously, a more rigorous analysis should consider the most critical location for the vehicle load. The multiplier λ is assumed to follow a normal distribution with a coefficient of variation of 0.10.

The collapse condition is evaluated by performing the structural analysis first under the scour action, then under the vertical loads for increasing values of the multiplier λ until failure. The scour action is simulated by progressively degrading the soil element stiffness located within the scour hole. The geometric domain of scour is defined by an inverted pyramid. The upstream surface has a slope corresponding to an angle equal to the soil friction angle (ϕ=30°), the downstream one has a slope corresponding to $\phi/2$, whereas the lateral surfaces have a slope corresponding to $3/4\phi$. The maximum scour depth s is assumed to be located along the vertical plane containing the upstream pier surface. Having discretized the soil domain with solid brick elements, only the elements whose centroid is higher than the scour limit surface are considered to be scoured. The maximum level of scour depth considered is 1.2m below the bottom of the foundation.

Fig. 5a shows the deformed shape of the bridge after reaching the maximum scour level. It can be seen that the scouring action involves a rotational mechanism at the base of the pier, with non-uniform vertical displacements along the pier base. Fig. 5b shows the plastic work of the tensile and shear stresses on the masonry interfaces for λ=0.21, which is a value close to collapse. The vertical loads induce significant bending in the shallow arch, both in the longitudinal and in the transverse directions, thus leading to cracking in both the longitudinal and vertical head joints. The arch-backfill interface also experiences significant damage.

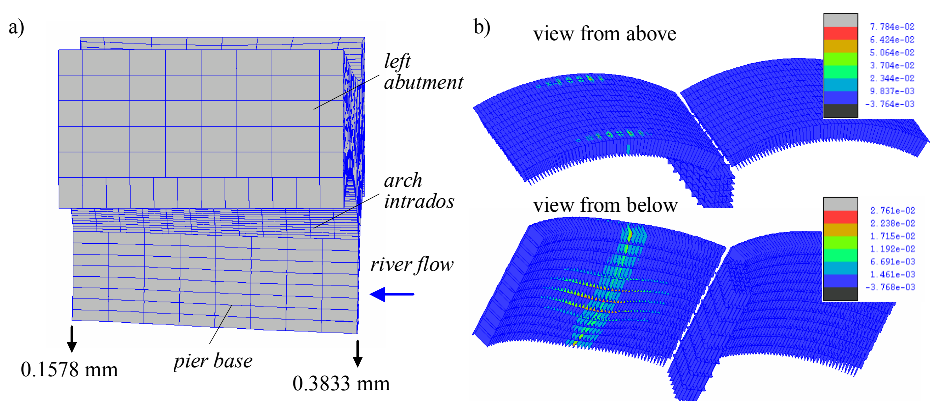

Fig. 5. *a) Deformed shape after scouring action (s = 1.2m), b) plastic work of the tensile and shear stresses.*

Fig. 6a plots the relation between the vertical load multiplier and the midspan displacement of the first span for the cases corresponding to no scour and to a scour depth *s*=1.2m and Fig. 6b reports the probability of collapse vs. the mean value of the load multiplier. It can be seen that the scour influences significantly the collapse limit state, and that the mean value of the collapse multiplier is close to 2 for the case of no scour, and to 1.72 for the scoured bridge case. The analysis shown can be repeated for different levels of maximum scour depth to obtain the scour vulnerability curve, providing the probability of limit state exceedance vs the scour depth. The information on the scour vulnerability can then be integrated with those of the scour hazard to obtain an estimate of the scour risk and of its effects on the bridge reliability.

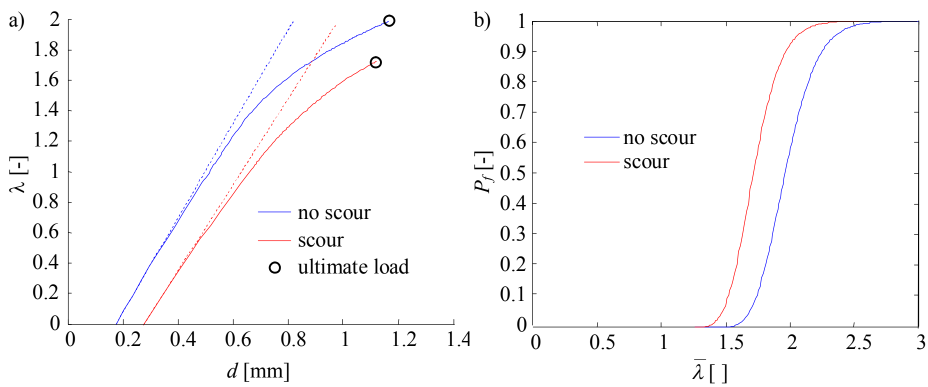

Fig. 6. *Load multiplier vs. midspan vertical displacement curve (a), and probability of collapse vs. mean load multiplier* $\bar{\lambda}$ *(b) for the cases corresponding to no scour and scour depth s=1.2m.*

5. CONCLUSIONS AND FUTURE RESEARCH

The present paper describes a probabilistic framework for the flood risk assessment of masonry arch bridges, integrating information on the most critical actions associated with the flood hazard analysis with those of structural vulnerability analysis. The paper also illustrates the computational strategy which is currently being developed by the authors for the numerical analysis of the structural response of masonry arch bridges subjected to flooding actions. A realistic case study is considered to illustrate the application of the proposed framework to scour risk assessment. It is shown that an accurate 3D model, including the foundation and the surrounding soil, can be used to describe the rotational mechanism induced by the scour action at the base of the pier, allowing the prediction of transverse bending in the arch induced by scour combined with vertical loading. Future studies will address the impact of other critical actions induced by floods on masonry arch bridges, the influence of the uncertainty of the model parameters on the risk estimates, and also the development of simplified and efficient modelling strategies leading to a reduction of the computational cost. S

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