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Experimental and Numerical Analysis of a Two-Span Model Masonry Arch Bridge Subjected to Pier Scour

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Abstract A scaled model of a two-span masonry arch bridge has been built in order to investigate the effect of the central pile settlement due to riverbank erosion. The bridge model has been equipped with different Non Destructive Testing (NDT) instruments and subjected to incremental settlement of the pier. The evolution of the pier scour has been investigated experimentally by means of a hydraulic model and reproduced accordingly. The numerical interpretation of damage, carried out by finite element analyses, has been compared with the results of the Acoustic Emissions (AE) monitoring. Several ultrasonic emissions have been detected and main damage source areas have been localized.

Keywords: Masonry arch bridge, experimental model, dynamic tests, numerical modeling, acoustic emissions

Introduction

Masonry arch bridges are outstanding masterpieces which embody a priceless historical and architectural preciousness. These structures exploit their stiffness and geometric shape to sustain high gravity loads but are very vulnerable with respect to the loss of the bearings. Multi-span arch bridges crossing rivers are particularly exposed to this danger because of the flood peaks. The erosion of soil at the piers foundations due to scour leads to differential settlements which result to serious structural damage. In the last few years, several approaches have been attempted to detect the occurrence of scour and to monitor its evolution. However, most of the proposed monitoring technologies are concerned with the measure of the scour depth at the piers foundations and they provide poor information about the overall integrity of the bridge.

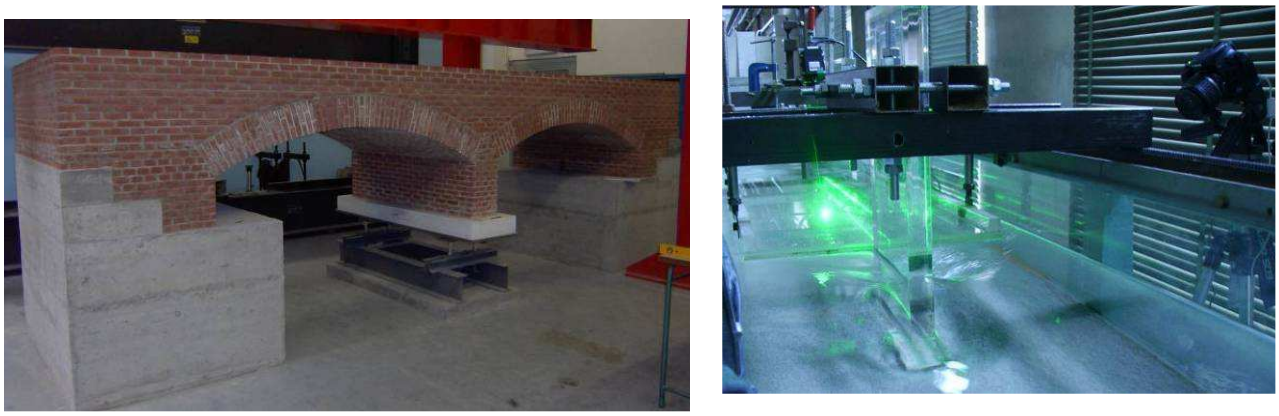
Structural and hydro-geological monitoring can be effectively integrated in a wider diagnostic framework, which could provide early warnings for the safety of the structure and its occupants in the cases of real danger. A further requirement for the monitoring and protection of historical structures is the minimum intervention on the original construction in order to respect their architectural and cultural value. This reason explains the choice of the sensing equipment which has been used to investigate the effect of the pier settlement introduced in the scaled model of the masonry arch bridge. The common characteristic of the accelerometers, fibre optic sensors, strain gauges and AE transducers employed in the experimental study is their slightly invasive nature. Moreover, the different NDTs acquisitions performed and coupled with the results of the numerical analyses allowed to increase the robustness of the integrity assessment.

The Scour Experimental Simulation on the Arch Bridge Model

The prototype the bridge model has been derived from is not a real existing bridge, but it has been designed according to the historical rules and the geometric proportions of ancient bridges. The theory of models has been employed to scale down the geometry to half of the prototype dimensions. The model is characterised by a length of 5.90m and it is 1.60m wide. It has been built with handmade clay bricks also scaled to 130x65x30mm to respect the adopted modelling scale law.

Strength and stiffness of masonry brick and mortar have been selected to better reproduce the poor mechanical properties of the materials commonly used in the real historical bridges construction.

The bridge model shown in Fig.1 (a) is characterised by two masonry arches which are supported by two masonry abutments and a central pier built with the same masonry. The pier was cut at half of the height to allow the insertion of a mechanical device used to apply the differential settlements. The missing weight of the lowest half of the central pier and its foundation was reproduced by means of a load concentrated on the bridge deck above the pier. A more detailed description of the structural elements which compose the bridge model can be found in the literature (Ruocci et. al. 2009).



(a) (b)

Figure 1: The masonry arch bridge model (a) and the hydraulic flume test

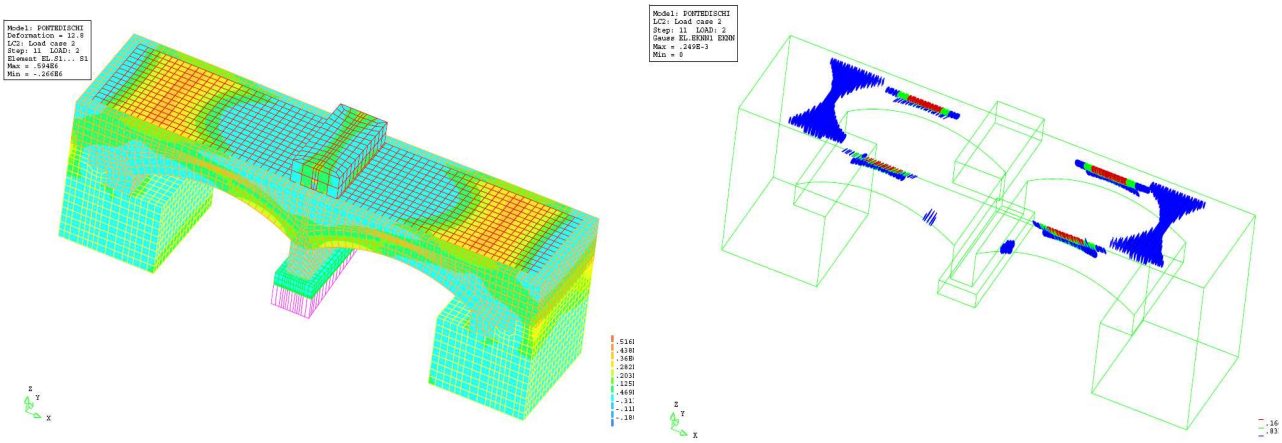
The simulation of the scour effects on the bridge model has been preceded by some flume tests carried out on a further scaled down model of the pier. The experiment illustrated in Fig. 1(b) allowed to monitor the evolution of the pier scour and to assess the extent of the phenomenon. The snapshots of a laser beam projection on the streambed soil acquired throughout the test and digitally post-processed provided an approximation of the differential settlements of the pier due to the scour erosion. The experimental results were then reproduced in the structural model acting on the four screws of the settlement application system, which allow to apply any kind of displacement and rotation. Four differential settlement steps were applied in order to introduce damage states of increasing extent in the structure. Only the two screws placed at the upstream side of the bridge were turned while the other two were kept fixed. The maximum settlement of each step was measured by displacement transducers placed at the vertexes of the steel plate which supports the pier. The applied four steps were set equal to 0.5, 1.0, 1.0 and 1.5mm, respectively. The polystyrene ring, which surrounds the bottom of the pier and whose density was selected to properly correspond to the foundation soil characteristics, was progressively removed with the settlement steps application in order to simulate the loss of the confinement effect throughout the erosive process.

Numerical Analyses

A numerical model of the bridge was prepared using the DIANA Finite Element (FE) package. The linear and nonlinear analyses that were performed allowed to better understand the dynamic behaviour of the arch bridge, to verify its response to the settlements application and to estimate the more likely damaged areas. The numerical predictions proved to be extremely helpful to identify the most damage sensitive symptoms, to optimally place the sensing units on the structure and to properly arrange the acquisitions.

The geometric characteristics of the bridge were accurately reproduced in the model. The mechanical properties of the materials were derived from some characterisation tests carried out on mortar and masonry samples collected during the bridge construction. The destructive tests included direct compression and diagonal compression on masonry cubes, four point bending tests on masonry arches and shear tests on bricks triplets. The main mechanical parameters obtained were

the Young's modulus E, the Poisson ratio ν, the tensile strength f_t, the compressive strength f_c, and the tensile fracture energy G_F. These parameters were used to describe the mechanical nonlinearity introduced in the FE analyses. A smeared cracking model, which incorporates tension cut-off, tension softening and shear retention was selected both for masonry and concrete. This approach allowed predicting the nucleation and propagation of cracks for increasing prescribed displacements. The model mesh was built with about 18000 three-dimensional quadratic brick elements connected by approximately 82000 nodes. The linear differential settlement was imposed to the central pier after the dead load application and progressively incremented till a largest value of 20mm. The contours of the principal tensile stress depicted in Fig. 2(a) show that the highest values interest the arches intrados nearby the central pier, as well as the extrados of the concrete slab on the bridge deck in the sections close to the abutments. Strain gages and fibre optic sensors were deployed in these regions to measure the evolution of the strain with the settlements steps application. Also the pier was monitored in order to detect the decompression it could have experienced because of the change in the boundary conditions. The nonlinear analysis allowed to identify the locations of cracks nucleation and to predict their propagation. From Fig. 2(b) the correspondence between the crack openings and the areas characterised by the highest tractions is clearly recognisable. This result proved the ability of the pier settlements to affect the structural integrity of the construction and consequently the seriousness of the scour effects on masonry arch bridges. The acquired information provided also the term of comparison for the experimental localisation of the AE sources.



(a) (b)

*Figure 2: Tensile principal stress contours (a) and smeared crack pattern (b) for the maximum differential settlement (20*mm*)*

Two modal analyses were performed prior and after the settlement application, respectively. Both the analyses were linear but in the second the damage propagation is taken into account considering the secant stiffness matrix in the computation. The shift of the eigenfrequencies towards lower values was seen to be the most significant effect due to the settlement application and confirms the decrease of the global stiffness of the bridge produced by damage. The results of the modal analyses are collected in Table 1.

Table 1 : Shift of the eigenfrequencies due to the settlement application

Eigenmode	*Undamaged eigenfrequency* [Hz]	*Damaged eigenfrequency* [Hz]
1	27.1	15.3
2	32.4	25.0
3	35.9	25.3

Experimental Analyses

The large number of sensing technologies employed in this work provided a wide range information about the structure and its health state. The robustness and the variety of acquired information are essential requirements for monitoring systems aimed at the improvement of the knowledge level of the historical constructions extremely affected by uncertainties. In the following sections the most interesting results obtained by the experimental investigations carried out on the arch bridge model will be presented.

Strain Gages The responses of the arch barrels to the settlements application were measured by means of a set of 16 120Ω resistive strain gages 160mm long and 10mm wide. The length of the strain gages allowed to cross at least five bricks and thus to obtain a representative information of the masonry behaviour. The transducers were divided into two sets and were uniformly distributed on the intrados of the arch barrels at the upstream side of the bridge model. As expected from the numerical analyses, the settlement application led to tensile strains in the central portion of the bridge and compressions in the lateral parts. The distribution of the strains throughout the first three steps resulted unchanged and a progressive increase of the deformations was recorded. In Fig. 3 the maximum strain drifts measured after each settlement step application are shown. The contribution of each successive step is depicted with a colour of the histogram bars varying towards darker tonalities.

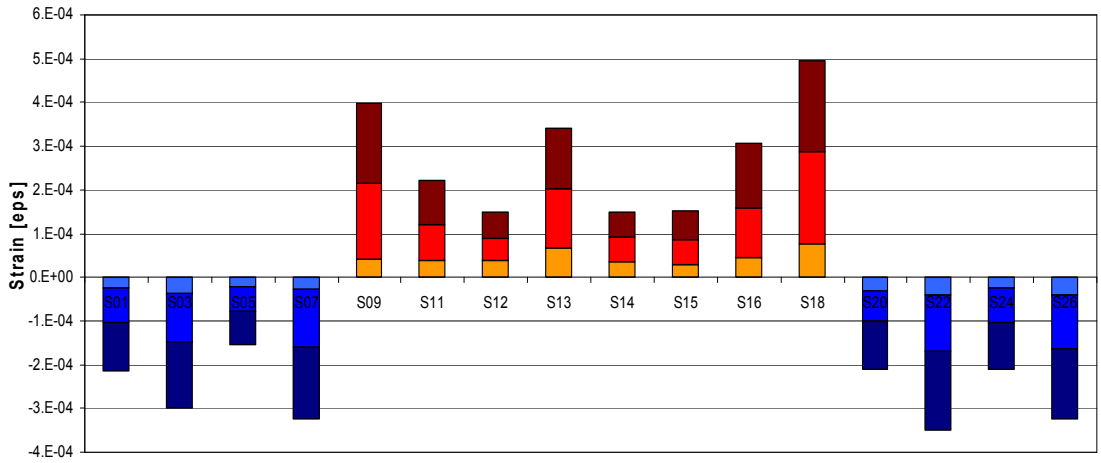


Figure 3: Maximum strain drifts measured by the strain gages after each settlement step

Fiber Optic Sensors Fiber Optic technology is widely used to measure different structural quantities. In particular, Fiber Bragg Gratings (FBGs) are simple sensing elements, which can be photo-inscribed into a silica fiber and exploit all the advantages normally attributed to fiber sensors. They are suited to measure strain to a 1 resolution and to operate also in hostile environments.
The strain sensors employed in this work are based on the so-called 'patch sensors' technology (Ansari and Bassam 2008), where the FBGs are sandwiched between two thin sheets of polyimide, kept together with two-components glue. The sensibility of the FBGs and the strain transmission were ensured by using sheets with thickness around few microns. Twelve patch sensors were glued directly on the structure, in order to measure the strain in correspondence of the masonry joints. The measured reduction in the positive strain moving from the upstream to the downstream side of the bridge agree with the results of the numerical analyses. However, the most encouraging result for a future early warning application on real bridges was provided by the sensor glued along the vertical direction on the bridge pier. This sensor was able to detect the decompression of the pier due to the removal of the base support from the first step application. In Fig. 4 the cumulative strain produced by the progressively induced settlement of the pier support is plotted. It is worthy to stress that the increasing trend of the measured strain observed in the first two steps reduces in the third and finally vanishes in the fourth. This indicates that, while for a total settlement of 1.5 mm still exists contact between the pier and the base support, between 1.5 and 2.5 mm the detachment of the pier from the support occurs.

Table 2: Experimentally identified modal frequencies

Eigenmode	*Undamaged frequency* [Hz]	*Damage step 0 frequency* [Hz]	*Damage step 1 frequency* [Hz]	*Damage step 2 frequency* [Hz]	*Damage step 3 frequency* [Hz]
1	18.94	18.67	19.03	18.37	16.66
2	30.65	29.42	30.05	28.88	28.17
3	36.23	34.81	35.85	34.37	31.76
4	40.93	39.30	40.21	39.30	37.72
5	51.95	49.85	50.93	48.56	47.25
6	52.91	51.07	52.60	50.57	51.29

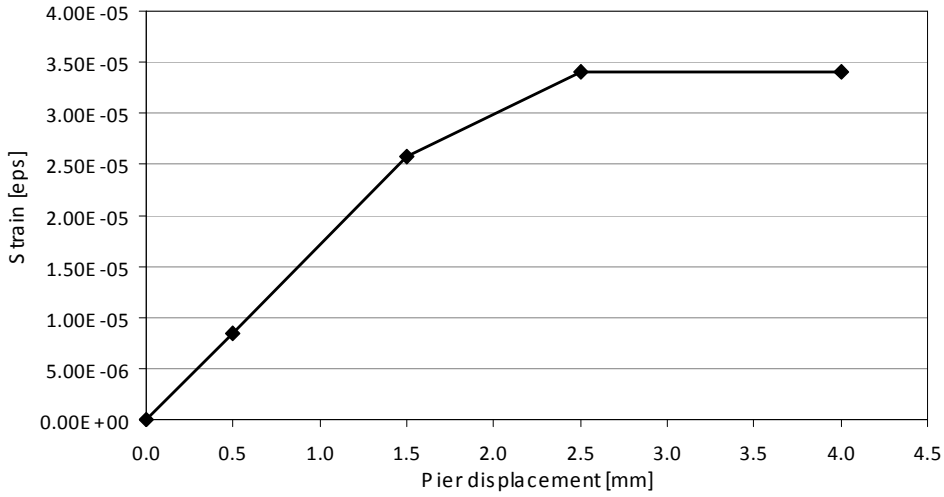
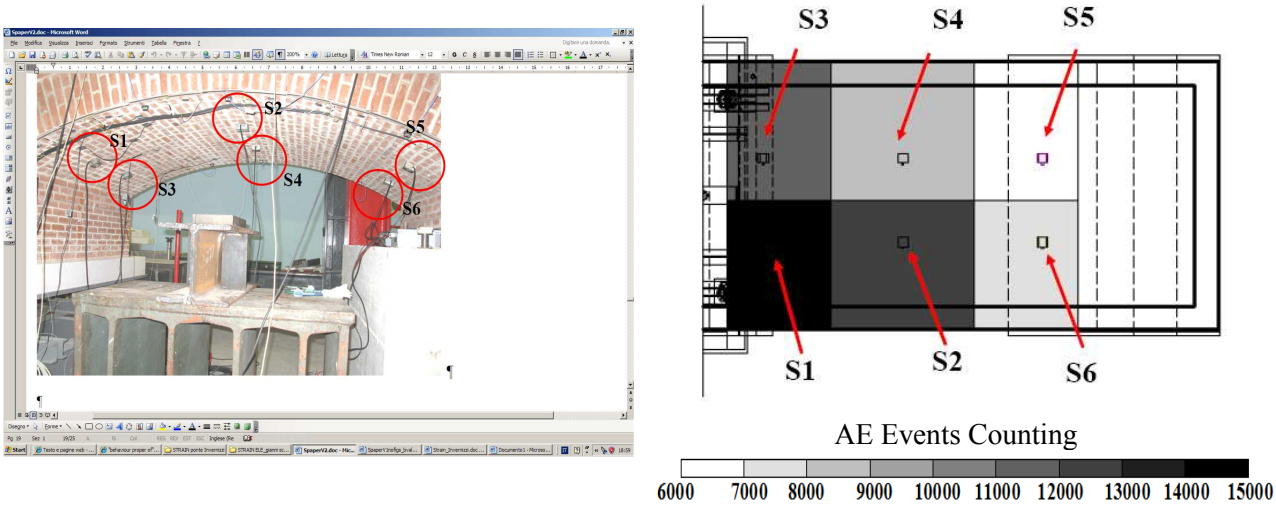


Figure 4: Cumulative measured pier strain related to the settlement steps

Vibration Measurements An extensive campaign of dynamic tests was performed on the arch bridge model subjected to settlement steps of increasing extent. The purpose was to experimentally investigate the symptoms already detected from the numerical simulations. The vibration acquisitions were carried out on the undamaged state of the model and then repeated after the application of each settlement step. A set of 18 capacitive accelerometers was placed in the positions of the bridge which presented the largest displacements in the numerical modal analyses. The impacts of a sledge hammer applied in several points of the structure and along different directions were used to excite properly the modes of vibration and to enhance the quality of the free decay responses. The signals acquired with a sampling rate equal to 400Hz were processed by means of the modal identification technique called Eigensystem Realisation Algorithm (ERA) (Juang and Pappa 1984). The results of the experimental modal analysis are collected in Table 2. The eigenfrequencies of the first 6 identified modes are presented for the undamaged state and the following damage steps. The damage state 0 refers to the removal of the first portion of the polysterene ring but does not entail the application of a settlement step. In agreement with the results of the FE analyses, the identified modal frequencies are significantly affected by the central pier settlements and resulted to be reliable symptoms of the occurrence of damage due to scour.

AE Monitoring The cracking process taking place in some portions of the masonry vault during the loading test was monitored using the AE technique. Crack advancement, in fact, is accompanied by the emission of elastic waves, which propagate within the bulk of the material. These waves can be captured and recorded by transducers applied to the external surface of the structural elements.

The AE measurement system used by the authors (ATEL device) consists of six piezoelectric (PZT) transducers and six control units. The PZT transducers exploit the capacity of certain crystals to produce electric signals whenever they are subjected to a mechanical stress.



(a) (b)

Figure 5: Positioning of the AE transducers (a); Number of AE counts in each competence area (b)

The AE sensors were placed at the intrados of one of the bridge vaults, in order to cover six almost equal competence areas (Fig. 5a). The cumulative AE curves emphasize the different amount of events in the different competence areas. The AE counting is displayed by shaded grey diagrams in Fig. 5b. The regions with the larger amount of AE counts correspond correctly to the most fractured areas visually detected (Invernizzi et al. 2010).

Conclusions

A laboratory scaled model masonry bridge has been built for the experimental analysis of the pier scour phenomenon. The amount and shape of the differential settlement due to the pier scour was experimentally evaluated by means of hydraulic tests. During the application of the differential settlement, the bridge was monitored with several non-destructive techniques, including Acoustic Emission, Optical Fibres and Dynamic Identification. The monitoring was coupled with a detailed nonlinear finite element simulation that allowed for a better interpretation of experimental results.

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