Motivation

Masonry arch bridges represent a large sample in the European bridge stock. Insufficient knowledge on their behaviour under scour condition, which is the collapse reason #1 in bridge failures, is a matter of concern for owners and managers. Better approaches are desired to monitor their structural integrity.

Main Results

In a comprehensive experimental campaign the feasibility to apply the IRIS Risk Paradigm with the IRIS damage detection methodologies has been demonstrated.
6-1 Introduction

This work presents a series of test campaigns performed on a masonry arch bridge model from 2006 to nowadays. The experimental model was mainly built to study the evolution of damage mechanisms related to the settlements of the central pier in twin-span bridges and to develop a suitable application of the diagnostic monitoring methodologies to the protection of historical bridges from scour.

In the last few years the model was subject to a wide gamma of characterization tests and analyses. The paper elucidates the knowledge course that has been chosen to investigate the model and how the various tests were planned and carried out.

During the realisation of the model, a set of preliminary tests was carried out, mainly on the bridge materials. In this phase also a hydraulic flume test on a further scaled model was performed to simulate the scour effect. Two finite element (FE) models were built in order to predict the behaviour of the experimental mock-up: the first model implements a linear constitutive law to compute the modal parameters and designing vibration tests, the second model uses a non-linear law for predicting crack patterns due to the settlement application. The second phase of testing concerned the dynamic characterization of the bridge model at different damage steps. Nine damage steps were planned to be applied through a settlement application device. At each step a wide set of vibration tests were carried out, using different excitation sources, such as ambient vibrations, sledge hammer impact and an electro-mechanical shaker. Through modal identification techniques, the modal parameters have been identified and monitored during the whole experimentation. The monitoring of modal parameters supported the design of a structural health monitoring system based on the outlier analysis [Ruocci, 2010; Worden et al., 2000].

Instantaneous fitting techniques [Ceravolo, 2004] allowed identifying punctual variations in the modal parameters during the application of the settlements [Quattrone et al., 2010]. Moreover, the forced vibration tests using a shaker allowed the detection of non-linear phenomena. Current works deal with the identification of non-linearity using instantaneous techniques [Ceravolo et al., 2010].

The scaled masonry bridge: notice the settlement application device under the central pier
6-2 The Masonry Arch Bridge Model

The 1:2 scaled model of the masonry arch bridge shown in F.6-1 was built in the laboratory of the Department of Structural and Geotechnical Engineering at the Politecnico di Torino. The prototype this model comes from is not an existing bridge but was designed taking into account common features, geometric proportions and historical design codes of a series of masonry arch bridges.

The model is a twin-arch bridge with a length of 5.90 m, a width of 1.60 m and a height of 1.75 m. The two arches are segmental arches with a radius of 2.00 m and an angular opening of 30°. Each span is 2.00 m long between the supports and the thickness of the arch is equal to 0.20 m. The mock-up was built with handmade clay bricks also scaled to 130×65×30 mm to respect the adopted modelling scale law. Low compressive strength elements were chosen and a mortar with poor mechanical properties was used to bound them in order to reproduce the typical materials of historical constructions.

The mid-span masonry pier, which was cut at a hypothetical middle-height section to allow the insertion of a settlement application system, is imagined to be placed inside the streambed and subjected to the scour of its foundation.

Hydraulic flume tests were carried out on a further scaled down model of the bridge pier in order to simulate the scour effects in the lab. The foundation settlements and rotations resulting from these investigations were then replicated on the bridge model by means of the four independent screws installed at the extremities of the settlement application system. The spherical plain bearings placed at the head of the screws allow the plate that supports the central pier rotating about axes parallel to the longitudinal and transversal directions of the bridge.

In order to simulate the streambed material surrounding the foundation of the central pier, a polystyrene mould was introduced. A polystyrene layer is used as interface between the pier and the settlement application device and a polystyrene ring surrounds the pier.

6-3 Preliminary Studies

The experimental investigations carried out on the masonry arch bridge model were divided into two different sessions. The first session was conceived to reduce the high uncertainties referring to the material properties and the structural behaviour of this complex structure. Several destructive tests were performed on samples collected during the construction of the mock-up in order to estimate the mechanical properties of the masonry material. The estimated parameters were then introduced into a numerical model of the bridge to obtain a preliminary calculation of the modal parameters. The information acquired in these preliminary analyses was helpful to plan the following dynamic tests and to interpret the first results of the modal identification. At the same time the hydraulic tests conducted on a reduced model of the central pier allowed to quantify the settlement to be applied.
6-3-1 Material Characterization Tests

Several tests were carried out in order to characterize the mechanical properties of the mortar and of the masonry used to build the model.

The characterization tests on the mortar samples were performed following the prescriptions proposed by the European standard code EN 998-2:2003 which were adapted to take into account the scaled measure of bricks. The collected samples belong to the M2.5 class of the European standard code EN 998-2:2003 which is one of the poorest in terms of mechanical properties.

The characterization tests on the masonry samples were performed following the prescriptions proposed by the European standard code UNI EN 1052-1, EN 052-3:2002 and the American standard code ASTM E 518-02. The masonry samples were adapted in order to resemble the shape of required test specimens while the testing procedures were followed strictly. The destructive tests performed on the masonry samples were:

- Axial compression on cubic samples
- Diagonal compression on cubic samples
- Shear test on masonry triplets
- Four point bending test on a segment of arch
### Results from the compressive tests, diagonal tests, shear tests and four point bending tests: average values ($\mu$) and standard deviations ($\sigma$)

<table>
<thead>
<tr>
<th>Test</th>
<th>$\mu$ [N/mm²]</th>
<th>$\sigma$ [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive tests: tensile strength</td>
<td>4.278</td>
<td>0.354</td>
</tr>
<tr>
<td>Compressive tests: Young modulus $E$</td>
<td>1451</td>
<td>472</td>
</tr>
<tr>
<td>Diagonal tests: tensile strength</td>
<td>0.304</td>
<td>0.088</td>
</tr>
<tr>
<td>Diagonal tests: shear strength</td>
<td>0.430</td>
<td>0.125</td>
</tr>
<tr>
<td>Diagonal tests: shear Young modulus $G$</td>
<td>940</td>
<td>436</td>
</tr>
<tr>
<td>Shear tests (0.1 kN pre-compression): shear strength</td>
<td>0.794</td>
<td>0.301</td>
</tr>
<tr>
<td>Shear tests (0.5 kN pre-compression): shear strength</td>
<td>1.013</td>
<td>0.188</td>
</tr>
<tr>
<td>Four point bending tests: $R$ modulus of rupture</td>
<td>0.22</td>
<td>//</td>
</tr>
</tbody>
</table>

### 6.3-2 Flume Tests

The hydraulic model was designed scaling the pier dimensions down so that the ratio between the length of the bridge and the width of the pier was maintained. The bottom section of the pier scaled model was connected with a hypothetic foundation base. The rectangular foundation was dipped into the bed material, whose uniform mean diameter was 0.80 mm. The pier was hung up and fixed to preserve any movement during the flume tests. The evolution of the soil profile produced by the induced scour was periodically monitored through a laser scanner acquired by a digital camera. The images taken during the tests were then automatically processed to define the portion of the foundation lateral face not covered by the bed material at each time step. The corresponding portion on the arch bridge model was freed from the polystyrene ring surrounding the bottom part of the pier to simulate the reduction of the lateral restrain at the foundation base.

Also the undermining effects were experienced in the flume tests, especially when the foundation base was not excessively dipped in the bed material. The erosion of the soil underneath the foundation, and consequently the loss of its bearing action, is simulated in the experimental model through the settlement application device previously described.

### 6.3-3 Numerical Models

A 3D numerical model of the arch bridge was realised in the ADINA Finite Element package to estimate and assimilate the modal parameters. The purpose was to better understand the dynamic behaviour of the structure and to accurately plan the following vibration analyses. In fact, the selection of the sensor location must be assessed carefully in order to allow a suitable resolution in the mode shapes for the highest number of identified modes. The model mainly consists of solid elements and spring elements able to simulate the polystyrene layer and the settlement application device. The mechanical properties have been inherited from the material characterization tests. The model is subdivided into a series of element groups, where each group includes all those finite elements which share common mechanical features or structural functions.
In order to predict crack locations, a numerical model of the masonry arch bridge [Invernizzi et al., 2009] was built in the DIANA FE package which was able to simulate the non-linear behaviour of masonry. The FE package implemented a smeared cracking law which incorporates a tension cut-off, tension softening and shear retention. After the results of the non-linear analysis, it was decided to add masses at the top of the central pier so as to take into account the weight of the missing part of the pier and to partially compensate the arch effect developed by massive abutments.
6-4 Experimental Test

6-4-1 Experimental Test Programme

As previously stated, the main objective of the experimental test was to determine the capability of a structural health monitoring system, based mainly on dynamic measurements, to detect damage (such as scour at the bridge pier foundation). In this framework, dynamic testing ensures to identify a set of parameters to be monitored. A sensitivity analysis has been carried out on the parameters to choose the most reliable set to detect the damage. Several damage steps have been applied to the structure in accordance with hydraulic flume tests as shown in T.6-2.

T.6-3 shows the timeline of the experimental tests. Different excitation sources were applied to the bridge model: ambient vibrations (AV), impact hammer (IH) and an electro-mechanical shaker (S). Several physical quantities were monitored under the different excitations: acceleration measurements (ACC), strain deformation (SG and OPT) and temperature (T).

The experimental test involved three different experimental campaigns. The first campaign regarded the undamaged structure (October 2008 to March 2009): an extensive set of dynamic tests was carried out on the bridge model in order to characterize its “healthy” state (HS). Monitoring of dynamic properties of the bridge showed a decrease in the structure stiffness through the whole campaign. This may be due to the development of some rheologic phenomena, for instance the concrete block creep and the mortar shrinkage.

<table>
<thead>
<tr>
<th>Experimental test timeline</th>
<th>T.6-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Step</td>
</tr>
<tr>
<td>1st campaign</td>
<td>Oct. 2008</td>
</tr>
<tr>
<td>Nov. 2008</td>
<td>HS</td>
</tr>
<tr>
<td>Jan. 2009</td>
<td>HS</td>
</tr>
<tr>
<td>Feb. 2009</td>
<td>HS</td>
</tr>
<tr>
<td>Mar. 2009</td>
<td>HS</td>
</tr>
<tr>
<td>2nd campaign</td>
<td>Apr. 2009</td>
</tr>
<tr>
<td>DS1</td>
<td>AV, IH, S</td>
</tr>
<tr>
<td>DS2</td>
<td>AV, IH, S</td>
</tr>
<tr>
<td>DS3</td>
<td>AV, IH, S</td>
</tr>
<tr>
<td>DS4</td>
<td>AV, IH, S</td>
</tr>
<tr>
<td>3rd campaign</td>
<td>Sep. 2010</td>
</tr>
<tr>
<td>DS6</td>
<td>AV, IH, S</td>
</tr>
<tr>
<td>Oct. 2010</td>
<td>DS7</td>
</tr>
<tr>
<td>DS8</td>
<td>AV, IH, S</td>
</tr>
<tr>
<td>DS9</td>
<td>AV, IH, S</td>
</tr>
</tbody>
</table>
leading to strains incompatible with the stiffness of the arch barrels, which might have produced a partial detachment between the masonry abutments and the arch barrels.

The second campaign (April 2009) started after the application of additional masses on the central pier, in order to take into account the weight of the missing part of the pier. In the same campaign the first four settlement steps were applied on the upstream side of the pier. In addition, parts of the polystyrene ring were removed at each step to simulate the erosion of streambed around the foundation according to the hydraulic flume tests. Dynamic tests were conducted in correspondence with each settlement step.

During the latter campaign (September 2010 to October 2010) five further settlement steps were applied. In this phase the removal of the polystyrene ring continued until all the polystyrene was removed.

6-4-2 Experimental Setups

Dynamic vibration tests require a careful identification of an optimal sensor location. In order to achieve a good mode shape resolution, a heuristic approach was employed. The arch barrels were subdivided into eleven segments whose ends were assumed as measuring points for both the edge and the middle lines. Other six positions at the springing sections of the pier were materialized to capture the longitudinal displacements. The four mid-span sections of the arch barrels’ lateral faces and the two pier frontal faces were considered for the lateral and torsional modes. Finally, the two positions on the longitudinal spandrel walls at the middle section of the deck were added to identify the vertical modes.

The sampling frequency was fixed to a value of 400 Hz to acquire the signals produced by both ambient noise and impact hammer excitations, using an instrumented hammer. A 180 second time lap was adopted for the ambient noise acquisitions. Several impacts were acquired in a 60 second period, even if only one impact per acquisition was used in the dynamic identification. The hammer impacts were applied to the same sensor positions along the longitudinal, transversal and vertical directions of the bridge model in order to properly excite a large set of the modes estimated by the numerical modal analysis. Two setups were used for each vibration test in order to capture the higher number of natural modes. Each setup consisted of 18 channels leading to 36 instrumented positions (F.6-5).
Forced vibration tests were performed by using a shaker TIRA TV 51220, capable of supplying a rated peak force of 200 N. The force applied was acquired by using a mechanical impedance sensor PCB Piezotronics 288D01 (measurement range ±222.4 N pk). Five types of excitation tests were carried out:

- Random: random excitation in a 10 to 100 Hz band
- Sweep sine: linear chirp from 10 to 100 Hz
- Shock: impulsive excitation
- Resonance: sine excitation at resonance frequencies
- Sine: sine excitation from 10 to 100 Hz, with 1 Hz resolution

**Accelerometers**

The selected sensors for the dynamic tests performed on the structure were capacitive accelerometers. The employed dynamic acquisition system was composed of a set of 18 monoaxial PCB Piezotronics accelerometers with a sensitivity of 1 V/g, a measurement range of ±3 g, a broadband resolution of 30 μg and a weight of 17.5 g. The accelerometers were connected through coaxial cables to the LMS Difa-Scadas data acquisition system which also provided the signal amplification. The acquired signals were recorded on the hard drive of a laptop computer interfaced with the data acquisition system and running a specific signal acquisition software.

**Strain Gauges**

The responses of the arch barrels to the settlement application were measured by means of a set of 16 120 Ω resistive strain gauges 160 mm long and 10 mm wide. The length of the strain gauges 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 at 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...
The distribution of the strains throughout the first three steps resulted unchanged and a progressive increase of the deformations was recorded.

**Optical Fibres**

Fibre optic technology is widely used to measure different structural quantities. In particular, Fibre Bragg Gratings (FBGs) are simple sensing elements, which can be photoinscribed into a silica fibre and exploit all the advantages normally attributed to fibre sensors. They are suited to measure strain to a $1 \mu\varepsilon$ resolution they are insensitive to electrical alterations. The strain sensors employed in this work are based on the so-called “patch sensor” technology [Bassam and Ansari, 2008]. Twelve patch sensors were directly glued on the structure in order to measure the strain in correspondence with the masonry joints. The measured reduction in the positive strain moving from the upstream to the downstream side of the bridge agrees 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 on the bridge pier along the vertical direction. 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 F.6-7 the cumulative strain produced by the progressively induced settlement of the pier support is plotted.

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**Cumulative measured pier strain related to the first five settlement steps**

F.6-7

![Graph showing cumulative measured pier strain](image-url)
6-5 Data Analysis and Assimilation

The first step of the data analysis consisted of an experimental modal analysis. It was decided to employ two techniques working in the time domain due to the great spectral resolution they offer and their modal uncoupling capability. The Eigenvalue Realization Algorithm (ERA) was used to analyse the free decay responses, whilst ambient vibration signals called for a Stochastic Subspace Identification (SSI).

6-5-1 Modal Parameters and Symptom Evolution

The estimation of both natural frequencies and dampings did not show a monotonic trend during the different campaigns. F.6-8 shows the trend of the first four natural frequencies. It is noteworthy that, whilst in second campaign the trend of the first frequency is almost monotonic and highlights stiffness degradation (mainly related to the boundary conditions of the pier), in the third campaign the interpretation of the curve is more complex. Firstly, the first frequency increased up to 19.23 Hz, this meaning that relaxation made the pier settle, increasing the boundary condition stiffness. In fact, after DS4, the pier was almost completely suspended. Secondly, this phenomenon mainly governs the first modal shape, as it can be seen from the 2nd and 4th natural frequencies which retain their values almost equal between the 2nd and the 3rd campaign. A good agreement between the experimentally identified and numerically calculated mode shapes was observed (F.6-9). However, their changes with the applied damage states were minor compared to natural frequencies and damping rates.

Natural frequencies of the first four modes through the various damage steps (damage step 0 corresponds to the healthy state of the bridge)
Left side: 2nd campaign, right side: 3rd campaign
Experimental Testing of a Masonry Arch Bridge Model Subject to Increasing Level of Damage

Experimental and numerical modal shapes

Mode 1: 35.9 Hz
1st vertical

Mode 2: 37.2 Hz
1st longitudinal

Mode 3: 37.6 Hz
1st lateral

Mode 4: 46.5 Hz
1st torsional

Results of the curve-fitting procedure for the first vibration mode: spectrogram of a filtered signal (top), modal frequency instantaneous estimate (middle), damping instantaneous estimate (bottom)
6-5-2 Study of the Transient after the Application of Settlements

Diagrams such as those represented in F.6-8 pose important problems regarding the real capacity of current diagnostic tools to distinguish between changes in linear parameters induced by damage and other rheologic and indirect actions, including relaxation, ageing etc. In order to derive information about the evolution of the modal parameters throughout the settlement application, the dynamic response was represented in the time-frequency domain by the Choi-Williams transform [Choi and Williams, 1989]. A non-stationary behaviour was detected relative to highly coupled modes in the high-frequency range.

In order to further investigate the transient phenomena, an instantaneous estimation of the modal parameters associated with the Frequency Response Function (FRF), was carried out. The implemented methodology follows the optimization procedure proposed by [Ceravolo, 2004]. F.6-10 shows the results of the curve fitting procedure used to calibrate the modal parameter estimates. This allowed detecting the decreasing and increasing variation of the natural frequency and the damping ratio of the first identified mode, respectively. The increase in relative damping is fictitious here, being associated with the assumption of viscous damping.

6-5-3 Non-Linearity Tests

The tests conducted with the electro-dynamic shaker allowed investigating the presence of non-linear phenomena. Interesting results were found in the resonance tests with different excitation levels. F.6-11 clearly shows the presence of super-harmonics in the resonance test of the first natural frequency, which become particularly intense at the higher sine-excitation test (100 N).

Super-harmonics of the first natural frequencies manifest themselves at higher excitation levels

![Diagram showing super-harmonics](image-url)
These non-linear effects will be subject of further studies, such as non-linear identification using an evolution of a recently developed technique [Ceravolo et al., 2010]. In order to characterize the non-linear behaviour of the bridge, a static test will be performed in the same locations where the shaker was used. This will allow quantifying the tangent stiffness matrix related to an associated theoretical oscillator.

6-5-4 Structural Health Monitoring

An SHM methodology was developed using outlier analysis [Worden et al., 2000] in order to exploit its limited computational effort, the damage sensitivity and the result accuracy. The choice of a data-driven approach for damage detection was forced by the complexity and uncertainties of the structure, which prevented the definition of a reliable numerical model. The difficulties to incorporate the noise effects, which are unavoidable in the vibration measurements, motivated the adoption of a stochastic approach. Several outlier analyses were carried out both in the time and in the frequency domain [Ruocco, 2010]. An on-line outlier analysis procedure was also developed and the flow-chart of its algorithm is presented in F.6-12.

By way of example, F.6-13 shows the result for the outlier analysis carried out at the measurements of the second campaign. The acquired signals were analysed in the frequency domain in terms of transmissibility functions. Small portions of the spectra were selected by means of a genetic algorithm and used as inputs to compute the statistical
distance assumed as damage index. All the sets concerning the measurements acquired after the introduction of the settlement steps are above the threshold which defines the in-control field. This result proves the accuracy of the damage detection method and the sensibility of the selected features.

6-6 Conclusions and Perspectives

This work has documented the extensive test campaigns carried out on a scaled masonry arch bridge subject to progressive damage steps. The experimental tests covered the span of three years and the data analysis is still in progress. The final prospect is the development of new vibration-based SHM approaches. This paper, in particular, describes the whole test programme in its various stages and strives for marking out a definite experimental path, as well as for outlining new plans and perspectives for SHM.
References


