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Experimental modal analysis and finite element model updating of a historical masonry arch bridge

M. Morici
School of Architecture and Design, University of Camerino, Ascoli Piceno, Italy

V. Nicoletti
Department ICEA, Engineering Faculty, Università Politecnica delle Marche, Ancona, Italy

G. Leoni
School of Architecture and Design, University of Camerino, Ascoli Piceno, Italy

F. Gara
Department ICEA, Engineering Faculty, Università Politecnica delle Marche, Ancona, Italy

ABSTRACT: This paper presents the experimental test campaign to calibrate a finite element model intended to evaluate the seismic vulnerability of the SS Filippo e Giacomo historical masonry arch bridge in Ascoli Piceno (Italy). The bridge has undergone very complex vicissitudes related mainly to exceptional river floods; it was partially rebuilt twice and other strengthening works were carried out over the time. The bridge, which is almost completely built with travertine blocks, has a total length of 146 m and follows a slightly curved path. Six arches, the main of which is semi-circular with span of 25 m and the others are lancet arches with span of about 8 m, support the carriageway that is about 8 m wide. The piers and abutments are founded on the bedrock and consequently some piers are deeply embedded in the sandy gravel deposit. A campaign of experimental tests was executed encompassing onsite measurements of stresses and modulus of elasticity, as well as laboratory measurements on specimens taken from the structures. Vibration tests were also carried out to evaluate the modal properties of the bridge. The acquired experimental data were used to calibrate a 3D Finite Element Model that has been developed considering the complex geometry of the bridge also including the deformable soil deposit. A very good consistency was achieved between experimental and theoretical behaviours.

1 INTRODUCTION

Evaluation of a historical masonry structure is a challenging task due to the numerous unknown factors surrounding the structure's actual conditions (Minnucci et al. 2022) (original structure, structural changes brought on by repair, enlargement, retrofit works, various construction systems, various materials, degradation and damages to the structure and materials, changes to the soil and foundation, etc.), as well as the complexity of modelling techniques and analysis methods (Pavia et al. 2021). In this regard, advanced measuring techniques are required to capture the true behaviour of the structure, particularly the mechanical properties of the structural materials and the overall dynamic behaviour, following a thorough study and geometrical and structural survey (Ragni et al. 2019).

Regarding the material survey, both conventional and cutting-edge techniques are accessible, however non-destructive procedures are typically favored when working with historically significant and priceless structures. A thorough material testing campaign may make it possible to fix a significant number of the key parameters used to define the structural finite element model. By employing modal identification methods and a variety of test types, such as forced, impulse, release, or ambient vibration testing, it is possible to empirically assess the structure's overall

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dynamic behaviour (Aras et al. 2011, Beolchini and Vestroni 1997, Benedetti and Gentile 1994, Nicoletti et al. 2023, Dall'Asta et al. 2022, Tubaldi et al. 2021). Since no artificial excitation is needed and the test can be conducted in operational conditions with minimal disruption to the structure's use, ambient vibration tests with the appropriate output-only modal identification methods have recently emerged as the preferred test typology for evaluating the modal parameters of full-scale structures, particularly historic ones. (Gentile and Saisi 2007, Nicoletti et al. 2022a) The updated improved finite element models, which are needed for structural verifications, as well as for the design of repair and retrofit works, may then be created based on the experimental modal parameters (De Sortis et al. 2005, Ahmadian et al. 1994, Mottershead et al. 1993, Nicoletti et al. 2022b, Gara et al. 2021, Cipriani et al. 2022).

The paper presents the experimental test campaign and the updating of the finite element model of the SS. Filippo and Giacomo Bridge over the Tronto River, in Ascoli Piceno, Central Italy. The bridge was constructed in the 14th century, after which it underwent several modifications for renovation, strengthening, modernization, and enlargement work. As a result of interactions between parts with varied mechanical properties and ages, the structural organism becomes very complicated. Given these uncertainties and the significance of the bridge, a precise examination of its current state was deemed necessary in order to create a reliable predictive finite element model that would be utilized to develop the seismic retrofit design. First, a geometric survey and historical analysis of the bridge were developed. In order to assess the quality of the travertine block masonry, both destructive and non-destructive in-situ testing for material characteristics were performed. In particular, the young modulus of some materials, which was initially defined according to standard values suggested by codes, was calibrated to fit the dynamic behaviour obtained experimentally. A refined 3D finite element model was developed using these data and tuned based on the experimental modal parameters.

2 CASE STUDY: THE SS. FILIPPO AND GIACOMO BRIDGE

2.1 *General description*

In Ascoli Piceno town, the SS. Filippo and Giacomo bridge rises in a less urbanized area and spans the Tronto River in a modest straight valley located between two loops. The bridge highest height is almost 20 m, and its overall length is 146 m. The bridge is constructed between two rock escarpments, one of which has a significant slope (Figure 1). The left escarpment has a rather high slope (52°) whereas the right one is less sloping (31°). The gorge is characterized by a sandy gravel deposit on the right riverbank, with variable thickness up to 10 m, whereas the sandstone bedrock is outcropping at the left riverbank.

Figure 1. Aerial view of the SS Filippo and Giacomo bridge.

The bridge consists of six arches. The main one, which is semicircular in shape and has a span of around 25 meters, crosses the river during its normal flow. The remaining five arches have a span of roughly 8 meters and are lancet-shaped. During unusual floods, the river occupies the right bank where all of the piers are located. With a curve close to the left abutment, the plan route is mainly rectilinear. The bridge was widened in the first part of the 20th century using a double series of pensile semicircular tiny arches, with spans of approximately 4 m, supported by stone corbels. The two-lane road is about 6 m wide and is bordered by two sidewalks of about 1 m width. With the exception of the 20th-century pensile arches and the interior lighting chambers, the bridge is entirely constructed of travertine stones.

2.2 *Bridge damages during the centuries*

The current SS. Filippo and Giacomo bridge's appearance is the result of a complicated series of incidents that transpired during its almost 600-year history (Figure 2).

The previous bridge, which was built in the second part of the XIV century, was most likely made up of four semicircular arches. A flood that occurred in 1453 severely damaged it, resulting in the collapse of three arches on the right side, likely as a result of the river flowing down the canyon on that side at the time, as may be inferred from geological studies.

The reconstruction of the bridge began about 1464; the portion that had survived was left intact, while the piece that had fallen was reconstructed using lancet arches with shorter spans than the original ones. The requirement to shift the pier spacing without changing the height or the original top level led undoubtedly to the selection of lancet arches. It is believed that the five new arches have not undergone any significant changes as of right now. The major arch that had survived the first flood collapsed as a result of a second exceptional flood that took place in 1528. This was rebuilt beginning in 1545 and using two parallel barrel-vaults. The downstream vault, which is about 3 m wide, has remained largely unchanged, while the upstream vault, which has a variable width, underwent a significant vertical settlement (of about 0.4 m). The vault was finally rebuilt in 1667 by installing wooden and iron ties intended to tighten together the two parts. A poorly designed wall collapsed in 1721 due to a fresh flood (probably a wing wall or a part of the abutment at the left riverbank). In 1794, a cutwater was constructed to safeguard the main pier. Between 1835 and 1836, the two arches supported by the main pier were repaired. In order to make maintenance of the structure easier, two barrel-vaults were constructed at the conclusion of these works rather than reinstalling the earth fill at the extrados of the main arch. The spandrel walls of the bridge support the two vaults. Between 1849 and 1850, work was done to lessen the slope of the upper road. The spandrel walls were lifted and filled with dirt after transverse ties were put two meters from the previous top level to support the structure. In order to enlarge the roadway, the final curve was changed by adding side travertine corbels with various spans up to 1 m. These corbels were subsequently joined by 0.30 m thick brick arches. During this phase, a new arrangement of interior lighting rooms was constructed over the main arch; the rooms are spaced equally between the external pensile arches to allow for the installation of stone corbels in the walls dividing the rooms. Each chamber has an orthogonal vault to the previously realized lower level. The bridge's current configuration was determined by the last significant intervention, which took place in 1932. By using a series of pensile arches similar to those previously mentioned, the remaining portion of the bridge is widened.

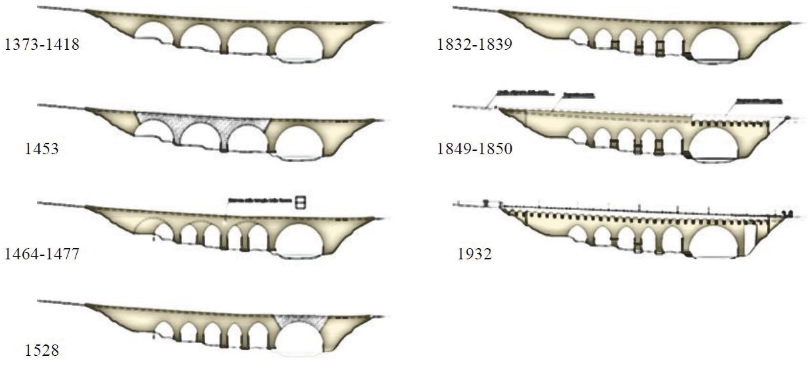


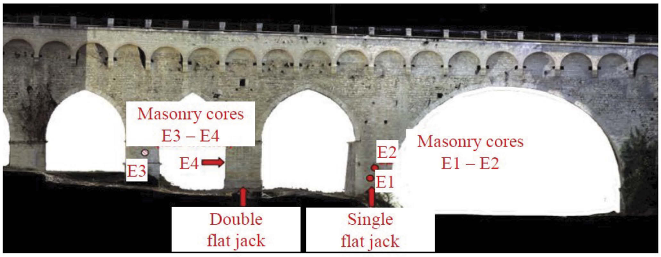
Figure 2. Bridge damages and reconstructions over centuries.

3 EXPERIMENTAL CAMPAIGN

3.1 *Tests on construction materials*

On-site experiments, including two tests using single flat jacks and one test using double flat jacks, were used to characterize the construction materials. Additionally, three compression experiments on travertine specimens obtained via masonry coring, were carried out. Locations for sampling and testing are reported in Figure 3.

Masonry coring allowed for the observation that the pier structure is made up of a significant internal rubble stone infill that is characterized by the presence of water in the lower parts, as well as an external curtain that is made of Ascoli Piceno travertine square blocks and has a variable thickness. Compressive tests carried out on the three specimens gave scattered results with minimum strength 16.9 N/mm^2. The double flat jack test carried out at the base of pier P2 provided a linear behavior in the stress range investigated (up to about 4 N/mm^2), characterized by Young modulus of about 6600 N/mm^2. At the bases of piers P1 and P2, single flat jack tests were conducted to estimate the stress status in the exterior brickwork curtains. As anticipated, the stress state for pier P1 is greater than that for pier P2. In particular, the normal vertical stress in pier P1 is approximately 1.3 N/mm^2, whereas that for pier P2 is around 0.5 N/mm^2. Testing was not done for the inner vaulted rooms masonry since it was clear through examination and laser scanner survey that it is a solid brick masonry. Nonetheless, it is important to note that, with the exception of the mass, these elements are not anticipated to have a substantial impact on the structure's overall behaviour. The two kinds of masonry constituting the bridge structure can be classified according to catalogs reported in design guidelines and standards (Decree 17/01/2018, Circular 21/01/2019), and the main characteristics are reported in Figure 3.



	Curtains of stone square-shaped blocks with poor core	Bricks with lime mortar
E [N/mm^2]	1680 - 2240	1200 - 1800
G [N/mm^2]	546 - 658	400 - 600
w [kN/m^3]	22	18

Figure 3. Experimental campaign and estimated properties of the construction materials.

3.2 *Ambient vibration tests and operational modal analysis*

The accelerations of the deck recorded during ambient vibration measurements, which are mostly caused by traffic, wind, and microtremors, are used to experimentally determine the modal characteristics of the bridge, including natural frequencies, damping ratios, and mode shapes. Eight low noise piezoelectric uniaxial accelerometers, a 24-bit data collecting device, and coaxial cables are used to conduct the testing.

Many tests were used to determine the bridge overall dynamic behaviour, but only those helpful to explore the transversal behaviour are described and analyzed in this work. The chosen measurement setup is seen in Figure 4a and consists of 8 accelerometers that are positioned in the middle of each span and measure in a transversal direction. The minimum sampling rate for the utilized data collecting equipment was 2048 Hz, and time histories measuring 1000 seconds in length were obtained. According to Cantieni (2005), this length of time gives adequate data to accurately determine the modal parameters, and a collection duration greater than about 1000–2000 times the fundamental period is advised (in this case a value of about 2.5 Hz was obtained by preliminary measurements, which leads to 400-800 s). Before performing the operational modal analysis all the recorded data were processed by means of suitable signal processing techniques: trend removal, low pass filtering (to eliminate the contribution of high frequencies and to avoid aliasing phenomena) and down-sampling at 51.2 Hz, in order to decrease the amount of data and make faster the successive analyses.

Based on the accelerations collected during the ambient vibration test, the modal parameters are estimated using the Covariance-Driven Stochastic Subspace Identi-fication (SSI-Cov). This approach converts the second-order system of differential equations that describes the dynamic issue into a first-order system using a stochastic state-space model (Juang 1994, Van Overschee & De Moor 1996). Depending on the model order employed in the state-space model, the SSI-Cov enables the estimate of a variety of modes. The stabilisation diagram (Figure 4b) allows the separation of the physical modes from the spurious ones, allowing the identification of the stable modes, i.e., natural frequencies, damping ratios, and mode shapes that remain consistent as the model order increases. In this work models with up to 40 order are used and the modes are considered to be consistent if, when increasing the model order one by one: natural frequency variation is less than 1%, damping ratio variation is less than 2%, and MAC between the modes is greater than 98%.

In the frequency range of 2–6 Hz, Table 1 lists the natural frequencies with the pertinent damping ratios, and Figure 5 displays the normalised modal shapes derived using the SSI–Cov approach. These modes are the transversal modes typical of a masonry bridge of this type.

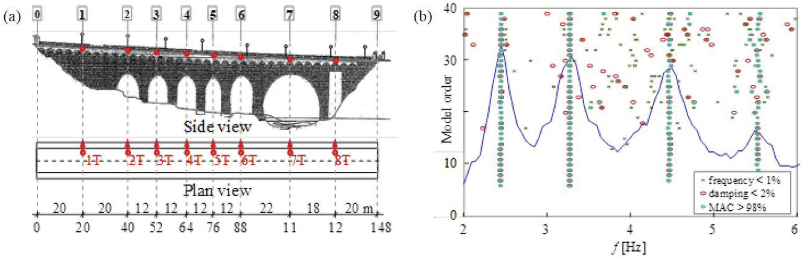


Figure 4. Ambient vibration tests: (a) sensor configuration, (b) stabilization diagram from SSI-Cov.

Table 1. Experimental modal parameters.

Mode	f [Hz]	ξ [%]	Mode shape
1	2.46	2.11	1st transverse
2	3.30	2.97	2nd transverse
3	4.54	2.54	3rd transverse
4	5.61	2.50	4rd transverse

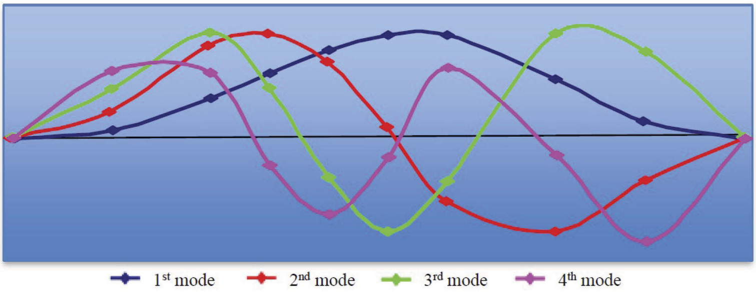


Figure 5. Experimental mode shapes.

4 NUMERICAL MODELLING

4.1 *Finite element model of the bridge*

Utilizing data from the laser scanner survey, a model for the overall structural analysis has been developed in Straus7. To account for the specific geological arrangement and capture the impacts of soil-pier interaction, the 3D model contains an appropriate area of the soil deposit with varying depth (Figure 6). A mesh of 4-node tetrahedral elements with linear interpolation shape functions is used to create the finite element model (Tetra4). By importing a closed poly-surface that approximates the geometry discovered by the laser scanner survey, the mesh is automatically generated. All internal chambers and the earth fill are modelled in order to accurately reflect the true stiffness and mass distribution of the structure. This avoids over-refinement of the mesh owing to features that do not directly affect the general behaviour of the bridge. The maximum length imposed to the element edge is 1.0 m, while it is extended to 4.5 m for the elements of the soil deposit. The deposit foundation and the structural portions engaging with the sand stone formation are both fixed with restraints. The model has a total of 75,204 degrees of freedom and is made up of 120,545 elements. All of the materials, including soil deposits and earth fills, are regarded as being linear elastic and isotropic.

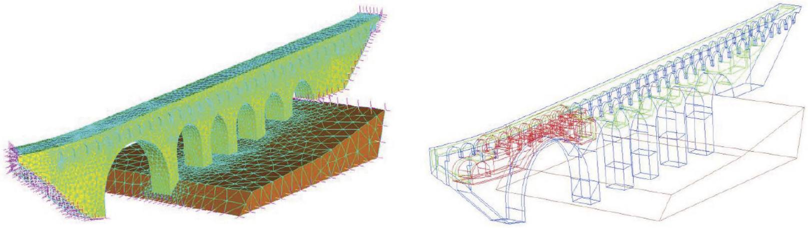


Figure 6. Finite element model of the bridge (Straus7).

4.2 *Finite element model updating*

By matching the experimental modal parameters with numerical ones pertinent to the finite element model previously stated, the mechanical parameters of the finite element model are calibrated adopting the manual tuning technique. Figure 7 displays the first four mode shapes that were achieved by calibrating the model by merely altering the elastic modulus of the travertine masonry that makes up the structure. Moreover, the comparison among the first four experimental and numerical mode shapes is reported as well, while Table 2 reports the percentage errors relevant to the frequencies and the approximation of the mode shapes by means of the Modal Assurance Criterion (MAC) (Allemang and Brown 1982). The parameters achieved at the end of the updating procedure are reported in Table 3. The soil parameters are supposed based on available geotechnical tests, while infill materials are hypothesized.

Table 2. Comparison between experimental and numerical modal parameters after the model updating.

	Frequency [Hz]			
Mode	Experimental	Numerical	Error [%]	MAC [%]
1	2.46	2.42	1.55	98
2	3.30	3.45	-4.67	95
3	4.54	4.87	-7.34	93
4	5.61	6.23	-10.99	86

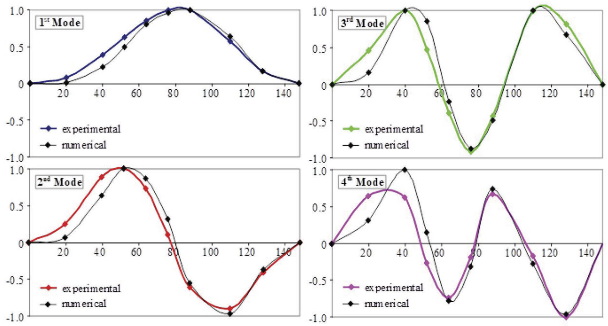


Figure 7. Comparison between experimental and numerical mode shapes.

Table 3. Comparison between experimental and numerical modal parameters after the model updating.

Material	E [N/mm^2]	G [N/mm^2]	W [kN/m^3]
Travertine masonry	7000	2414	22
Brick masonry	1282	427	18
Earth fill	666	238	18
Soil deposit	666	243	19

5 CONCLUSIONS

A finite element model of a mediaeval masonry bridge with distinctive geometry resulting from extremely complicated historical vicissitudes, has been calibrated through an experimental test campaign that has been presented. The bridge is built on a sand-stone deposit that is outcropping at the abutments and rises in a canyon. The bridge is made up of six separate arches, each supported by piers that extend up to 10 meters into the river deposit of sandy-gravel soil. The piers are built on a sand-stone formation. In order to create a model that included all significant aspects of the original building, including the interior lighting rooms highly asymmetrical geometry and the pensile arches built to widen the highway, a laser scanner survey was essential.

The onsite tests permitted to evaluate the main mechanical characteristics of the materials and to estimate the stress state in critical sections of the piers. The operational modal analysis, used to detect the dynamic behavior of the bridge, was decisive for tuning a finite element model capable of predicting the overall behavior of the bridge.

The calibrated model very well reflect the dynamic behaviour of the real bridge and it could be a fundamental support in the numerical analyses required for the bridge safety verifications.

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