Determining and Tuning Models of a Masonry Bridge for Structural Assessment

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Abstract. The paper describes a procedure aimed at developing FE models suitable to the seismic assessment of masonry viaducts. The modeling strategy is based on architectural research, non-destructive or minor-destructive tests, operational modal testing and surrogate-based model updating. In more details, the adopted methodology involves the following steps: (i) preliminary investigations including historical research, geomatic survey and local tests on materials; (ii) operational modal testing and analysis; (iii) FE modeling based on the available geometry and selected assumptions; (iv) choice of the uncertain structural parameters of the FE model; (v) identification of the optimal parameters by minimizing the difference between the model responses and the experimental responses using surrogate models.

The 19th-century Olla bridge (Gaiola, Italy) is used to exemplify the proposed approach. The investigated structure turns out to be of special interest because the use of a limited number of sensors allows the identification of a relatively large number of normal modes. Consequently, the installation of a dynamic monitoring system on the bridge has been scheduled.

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Keywords: Masonry bridges · Ambient vibration tests · FE model updating · Non-destructive inspections

1 Introduction

Masonry arch bridges were the dominant structural typology in bridge design until the first half of the 20th century, when reinforced concrete gradually substituted brick and stone masonry. Despite the age of construction, many masonry bridges are still in use, representing essential infrastructures for the European roadway and railway networks. In recent years, due to their key role and uncertain state of preservation, masonry bridges have received increasing attention from the scientific community, resulting in a series of experimental investigations and numerical studies (see, e.g., [1–3]).

In this context, documentary research and limited material tests, together with Operational Modal Analysis (OMA) and Finite Element Model Updating (FEMU), can be applied to develop reliable numerical models that can be used in the seismic assessment. The proposed approach is composed by the following steps: (i) preliminary investigations including historical research, geomatic survey and local tests on materials; (ii)

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operational modal testing and analysis; (iii) FE modeling based on the available geometry and selected assumptions; (iv) choice of the uncertain structural parameters of the FE model; (v) identification of the optimal parameters by minimizing the difference between numerical and experimental responses using surrogate models. It is further noticed that, if the optimal model does not match specific criteria of convergence – such as an appropriate correspondence between numerical and experimentally identified natural frequencies – the procedure restarts from different modeling assumptions or from a different set of updating parameters. The 19th-century *Olla* bridge (Fig. 1) is used to exemplify the proposed approach.

Fig. 1. The Olla bridge: view from the Stura river.

2 Description of the Olla Bridge

The *Olla* bridge (*Ponte dell'Olla* in Italian, Fig. 1) is a multi-span masonry arch bridge built in the second half of the 19th century over the Stura river. It carries the State Route no. 21 (SS21, i.e., the roadway connecting the city of Cuneo with the French border) between the municipalities of Gaiola and Borgo San Dalmazzo in the northwest part of Piedmont, Italy. Due to its position, the bridge has a strategic role for the economy of the area since it is the only entry to the Stura di Demonte Valley for trucks and commercial vehicles.

The structure is approximately 117 m long and has a maximum height over the river of about 42 m. It is composed of five masonry arches, almost symmetrically distributed and with spans of 10, 20, and 25 m, respectively. Piers and abutments are in a good quality ashlar stone masonry while arches and spandrel walls are in brick masonry. The documentary research started in the archive of the local Authority that was responsible for the design (the *Genio Civile*) but the original drawings were not found. Therefore, various construction details on the internal morphology of the structure were initially assumed according to the historical construction handbooks of Curioni [4] and then eventually modified in establishing the FE model.

In order to obtain a complete representation of the existing structure, a topographic survey was performed in September 2018 [5] using a total station (Leica TCRA 1203) and a laser scanner (Leica C10). Hence, the survey relied on different techniques, integrating local and global measurements, ensuring a 360° coverage of the bridge complexity. The 3D model resulting from point clouds was used to extract a series of 2D drawings from which the FE model was developed. It is worth noting that once a point cloud is available, it is possible to extract an unlimited number of 2D sections for future applications.

The historical research revealed that, during the Second World War, the central arch of the bridge was heavily damaged and collapsed. According to Taricco [6], the structure was detonated by the partisans on July 13th, 1944 to isolate the valley from the German army. The bridge was repaired starting from September 1945 [6], and the central arch reconstructed; however, no specific records were found on the execution of the intervention.

3 Experimental Survey

The experimental survey performed on the *Olla* bridge included Ambient Vibration Tests (AVTs) and Minor Destructive Tests (MDTs).

The AVT was performed on July 31st, 2018, with one lane open to traffic; the acceleration responses of the bridge were measured in 11 selected points belonging to the downstream side of the deck. As represented in Fig. 2, the sensor layout was aimed at guaranteeing a complete representation of the lateral mode shapes (11 transversal sensors) and a partial reconstruction of vertical ones, deploying 3 vertical sensors placed in the centre of the major arches, where the maximum modal displacements were expected.

During the test, 14 piezoelectric accelerometers with a 10 V/g sensitivity were used. The sampling frequency adopted was equal to 200 Hz, which is more than enough for the considered structure whose dominant frequencies are below 10 Hz. Therefore, low pass filtering and decimation were applied to down-sample the data to 40 Hz, obtaining a Nyquist frequency of 20 Hz.

The modal identification was performed by applying a fully automated algorithm, based on the Covariance-based Stochastic Subspace Identification (SSI-Cov) method [7] and developed within a previous research [8]. Overall, 5 lateral and 3 vertical vibration modes are identified in the frequency range of 0–10 Hz (Fig. 3).

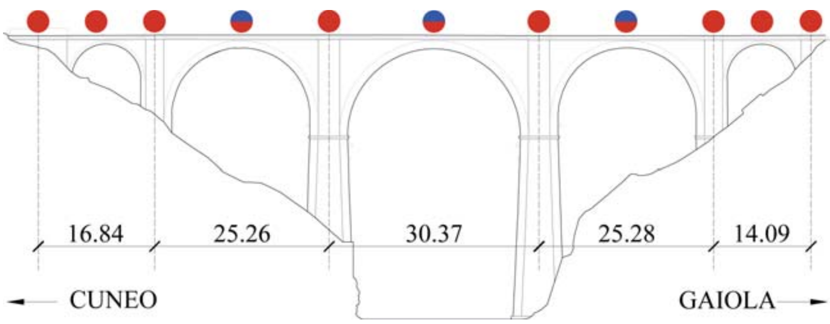

Fig. 2. Sensors layout during the AVT (dimensions in m): the red and blue dots refer to transverse and vertical sensors, respectively.

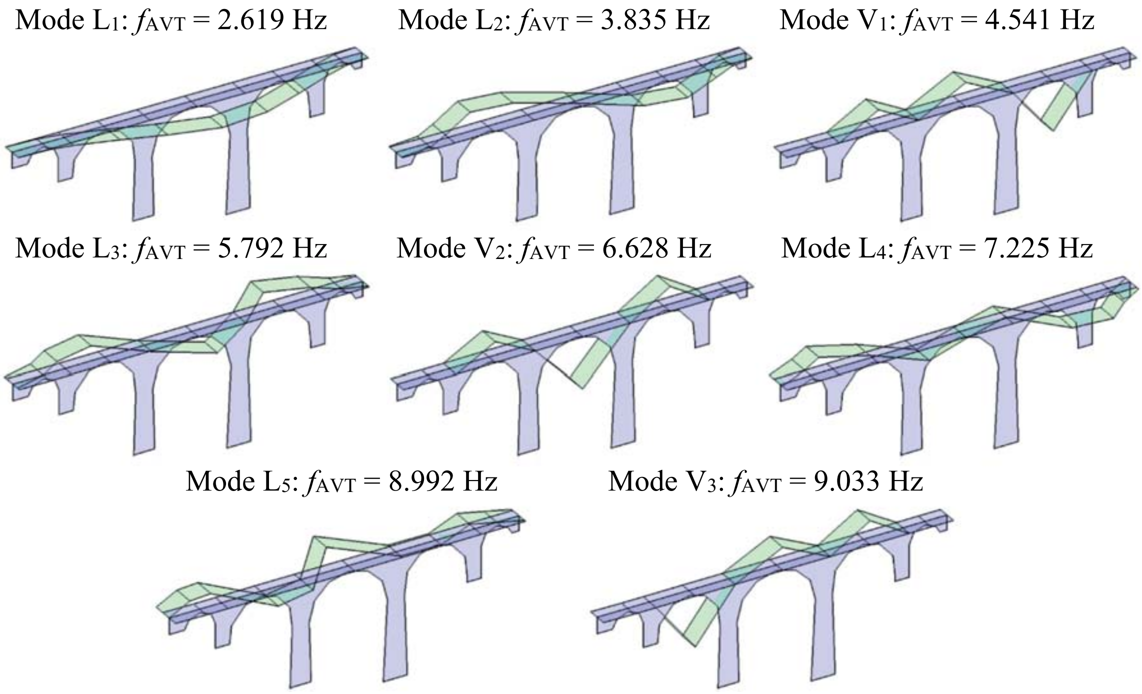

Fig. 3. Identified vibration modes (L = dominant lateral, V = dominant vertical).

Subsequently, the MDTs – consisting of limited coring tests – were performed to obtain information on arches, spandrels and fill. Due to the limited extension of the core drill machine, no information on the backing was obtained. The coring tests were executed in Autumn 2018. Six coring samples were taken from the following elements: 2 on the arches, 2 on the spandrels and 2 on the deck. The tests revealed that the arches are made only by brick masonry, whereas stone and brick masonry was adopted in the spandrel walls. The fill – as expected – is constituted by compacted soil and pebbles. The thickness of the asphalt, over the fill, is equal to 20 cm.

4 FE Modelling and Updating

The structural contribution of spandrels and backing is often not clear and hard to determine. Therefore, the standard approach in modelling masonry bridges considers the arches as the main load-bearing structure [1], neglecting the role of the other parts that form the deck (spandrels, backing and fill).

In a previous study [9], a simplified model was developed for the *Olla* bridge to clarify the contribution of non-structural components in the bridge dynamic response. The simplified model emphasised the importance of considering the stiffening effect given by the elements above the arch. Nevertheless, due to the simplified nature of the model it was impossible to match both lateral and vertical response.

The three-dimensional FE model herein presented reproduces as closely as possible the actual geometry of the bridge. Therefore, spandrel walls, backing and fill have been modelled along with arches, abutments and piers and the material properties of each structural element was updated according to the adopted FEMU procedure.

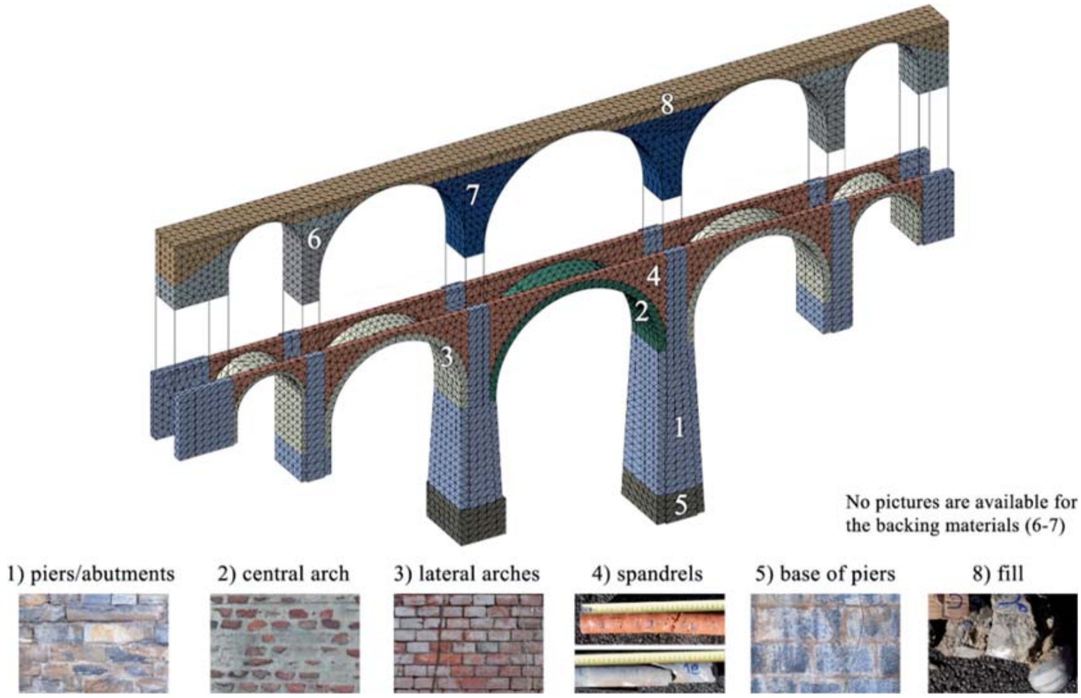

Fig. 4. FE model with the indication of different materials.

The 3D model was developed with the FE code ABAQUS using ten-noded tetrahedral elements (C3D10). A relatively large number of elements were employed to obtain a regular distribution of masses, a good description of geometrical details, and to avoid frequency sensitivity to mesh size. Overall, the numerical model consists of 45604 tetrahedral elements with 211818 degrees of freedom and an average mesh size of 1.15 m (Fig. 4).

Once the geometry of the numerical model is established, the selection of the structural parameters to be updated is the next key issue. To prevent the ill-conditioning of the inverse problem and to improve the robustness of the updated parameter estimates, the following aspects were considered: (i) the number of updating variables was kept smaller than the experimental parameters used as targets; (ii) only the uncertain structural parameters were updated; (iii) the sensitivity of natural frequencies to the different parameters was checked and low-sensitivity structural parameters were not updated.

Overall, 8 regions with constant material properties were identified based on visual inspections and coring tests (Fig. 4): (1) piers and abutments; (2) the central arch (reconstructed in 1945); (3) lateral arches; (4) spandrels; (5) base of central piers; (6) backing over the abutments and the lateral piers; (7) backing over the central piers (partially reconstructed in 1945); (8) fill.

In addition, the following assumption were adopted: (a) the effect of soil-structure interaction was neglected; (b) all the materials were considered isotropic with constant mass density and Poisson's ratio (see Table 1); (c) the spandrels were assumed 1.0 m thick and (d) the Young's modulus of fill material was not adjusted due to its low sensitivity. In view of the clear presence of superficial rocks at the river level, the base nodes of piers and abutments were assumed as pinned. Similarly, the longitudinal translation of the abutments was restrained.

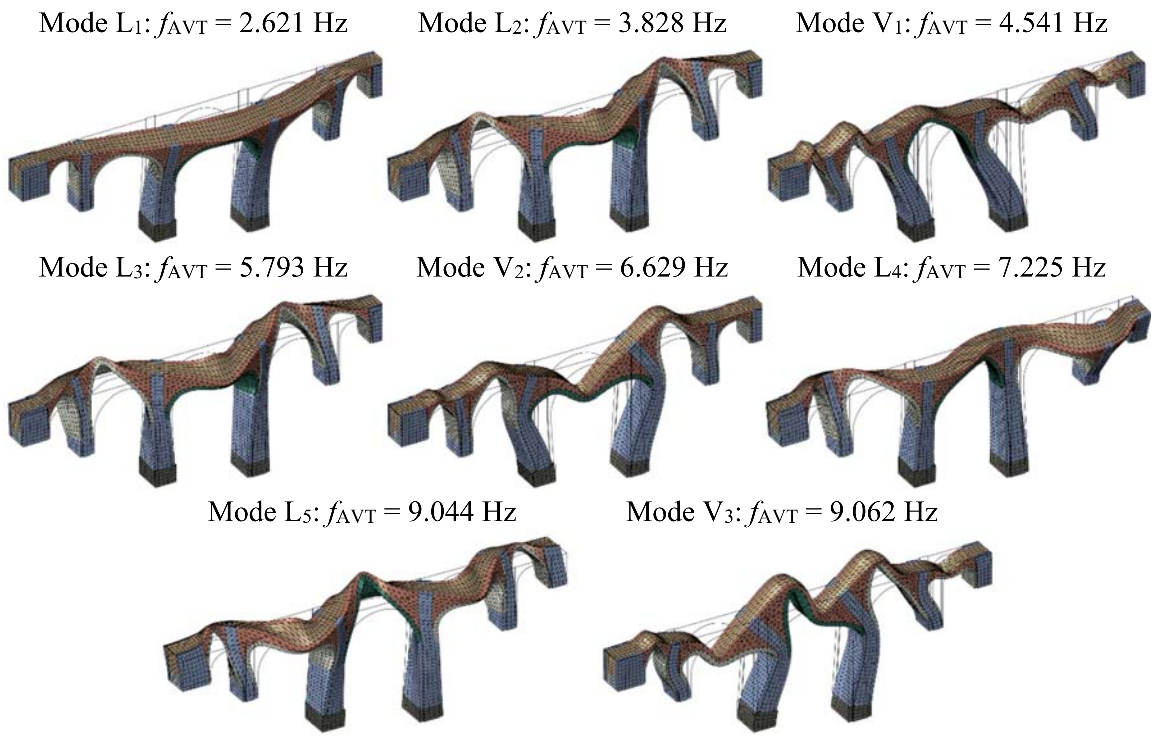

Fig. 5. Lateral (L) and vertical (V) vibration modes of the optimal (updated) FE model.

An initial FE model (Base model) was developed to check the similarity between experimental and numerical modal parameters. As shown in Table 1, the Young's modulus of arches and backing was assumed equal to 4.5 GPa and 2.0 GPa respectively. Table 2 illustrates the imperfect correlation with the experimental results, showing a maximum frequency discrepancy (*DF*) of 7.4%. However, the one-to-one correspondence of the experimental-numerical modes seems to provide a sufficient verification to the main model assumptions.

The adopted FEMU procedure was implemented in the MATLAB environment and it is based on the Douglas-Reid method [10] with the Particle Swarm Optimisation (PSO) algorithm [11]: the updating parameters are iteratively corrected in a constrained range until a stable minimum solution for an objective function is found. Particularly, the following objective function was adopted:

$$J(\mathbf{x}) = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{f_{AVT,i} - f_i^*(\mathbf{x})}{f_{AVT,i}} \right| \tag{1}$$

where $f_{\mathrm{AVT,i}}$ is the i-th experimentally identified natural frequency and $f_{\mathrm{i}}^{*}(\boldsymbol{x})$ is the *i*-th polynomial approximation [10] of the numerical natural frequencies, expressed as functions of the $\boldsymbol{x}$ updating parameters.

Table 1 lists the optimal estimates of the uncertain parameters of the model. The differences between the elastic moduli of the central and lateral arches, as well as the one of the backing, are motivated by the different years of construction: as shown by the historical analysis, the central arch was rebuilt in 1945. As demonstrated by the coring tests, the spandrels are made of bricks externally and stone internally, justifying the high values elastic modulus obtained. Finally, the base of the central piers is built in stone masonry of better quality than the rest of the piers and, moreover, the optimal elastic modulus conceivably accounts for the stiffening effect provided by the compacted soils surrounding the piers.

Table 1. Summary of the identified structural parameters.

No.	Structural elements	Assumed properties		Base model	Optimal model
		ν (-)	γ (kN/m^3)	E (GPa)	E (GPa)
1	Piers/abutments	0.15	20	16.50	16.10
2	Central arch	0.15	17	4.50	7.73
3	Lateral arches	0.15	17		3.23
4	Spandrels	0.15	19	15.00	16.85
5	Pier foundations	0.15	21	22.00	27.49
6	Lateral backing	0.15	18	2.00	1.38
7	Central backing	0.15	18		4.56
8	Fill*	0.3	16	0.30	0.30

* non-updated parameter

Table 2. Comparison between experimental (SSI-Cov) and numerical frequencies.

Mode		Exp. (SSI)	Base model		Optimal model	
No.	Type	f_{AVT} (Hz)	f_{FEM} (Hz)	DF (%)	f_{FEM} (Hz)	DF (%)
1	L_1	2.619	2.56	2.2	2.621	−0.07
2	L_2	3.835	3.83	0.3	3.828	0.18
3	V_1	4.541	4.53	0.2	4.541	−0.01
4	L_3	5.792	5.80	−0.2	5.793	−0.02
5	V_2	6.628	6.14	7.4	6.629	−0.02
6	L_4	7.225	7.45	−3.2	7.225	−0.01
7	L_5	8.992	9.17	−2.0	9.044	−0.57
8	V_3	9.033	8.64	4.3	9.062	−0.32
	DF_{ave} (%)	–	–	2.46	–	0.15
	DF_{max} (%)	–	–	7.35	–	0.57

5 Conclusions

The paper focuses on the OMA-based structural identification of the *Olla* bridge of Gaiola, Piedmont region, northwest Italy. The occasional brick fall from one of the arches had caused concerns on the state of preservation of the structure by the Local Authorities, motivating the following research programme. The investigations included documentary research, geometric survey, minor destructive and ambient vibration testing, and FE modelling and updating. The following conclusions can be drawn:

1) The documentary research revealed the construction period and designer, along with a series of historical pictures of the central arch collapsed in 1944;
2) During the AVT, performed with one lane open to traffic, 5 lateral and 3 vertical vibration modes were identified in the frequency range of 0–10 Hz;
3) Notwithstanding the initial 3D model represented accurately the geometry retrieved from geomatic survey, a relatively poor correlation with the actual natural frequencies was obtained ($DF_{\text{ave}} = 2.46\%$, $DF_{\max} = 7.35\%$);
4) On the contrary, as shown in Fig. 5, applying the FEMU procedure and considering the effects of the reconstruction of 1945, an excellent correlation with the experimental results was obtained ($DF_{\text{ave}} = 0.15\%$, $DF_{\max} = 0.57\%$), highlighting the importance of backing and spandrels in the representation of the dynamic response of masonry bridges.

To complete the structural assessment of the *Olla* bridge, full-scale load tests and additional minor-destructive and non-destructive tests on materials should be performed in near future.

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