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Effects of changing temperature in the vibration-based model updating of a masonry bridge

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ABSTRACT: FE model updating of structures is commonly based on the modal parameters evaluated in a single vibration test. Nevertheless, the influence of changing temperatures on modal parameters – especially on natural frequency – is well known. The paper presents an investigation on the effects of (temperature-induced) frequency variations on the estimate of the elastic properties of a historical masonry bridge. Firstly, documentary research, geometric survey, minor destructive tests and ambient vibration tests were performed. Subsequently, the numerical model of the masonry bridge is developed based on the collected data, and the updating procedure is performed by using the two sets of modal parameters identified in July 2018 (average temperature 30.4°C) and April 2021 (average temperature 13.2°C). The results show that the (temperature-induced) frequency decrease seems to affect more significantly the estimate of the Young's modulus of spandrels and backing.

1 INTRODUCTION

The calibration of FE models is fundamental to obtaining reliable results in the structural assessment of existing bridges and infrastructures. In the engineering practice, the modal parameters identified from vibration data are often used as targets for the model parameters adjustment (see e.g. Costa et al 2015, Pepi et al. 2021, Aytulun et al. 2022 for recent applications on masonry bridges); however, the influence of environmental factors (e.g. outdoor temperature) on modal parameters, and especially on natural frequencies, is well known and extensively documented in the scientific literature (Ramos et al. 2010, Saisi et al. 2015, Ubertini et al. 2017, Roselli et al. 2018). Consequently, when a FE model is calibrated for structural assessment purposes, it would be appropriate to consider that the identified structural parameters also result from specific environmental conditions and the related variability might propagate along the structural identification process.

Figure 1. The *Olla* bridge: (a) picture from the Stura River; (b) existing damages on the second arch.

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In the present paper, the effects of temperature-induced frequency variations on FE model updating of a historical masonry arch bridge are investigated. The selected structure is the *Olla* bridge, a masonry viaduct built in the second half of the 19th century in the northwest of Italy. High piers characterise the bridge; therefore, operational modal testing and analysis are well suited for evaluating its dynamic behaviour. Firstly, the numerical model is developed by integrating topographic survey, historical research, visual inspections and limited tests on materials. Subsequently, two ambient vibration tests are performed in different environmental conditions and the two different sets of identified modal parameters are used to estimate the optimal structural parameters. The presented results highlight that major variations of the optimal estimates are observed in the structural elements with lower compressive forces.

2 THE *OLLA* BRIDGE: DESCRIPTION AND PRELIMINARY ANALYSIS

The investigated structure (Figure 1a) – called *Olla* bridge (Borlenghi et al. 2023) – is a multi-span masonry arch bridge that crosses the Stura River between the small municipalities of Gaiola and Borgo San Dalmazzo. The structure is approximately 120 m long and comprises 5 arches, with a maximum span of 25 m, 4 piers and end abutments, with the tallest pier being 26 m high. Piers and abutments are in a good quality ashlar stone masonry, whereas arches and spandrel walls are in brick masonry.

The documentary research revealed the collapse of the central arch in 1944 (Figure 2) and the subsequent reconstruction in 1945.

The complete representation of the structure was obtained with the Terrestrial Laser Scan and topographic survey. The processing of the point clouds allowed the extraction of an accurate 3D model and a series of conventional 2D drawings from which the FE model was developed. In addition, the visual inspections highlighted the presence of local damages on the arches (Figure 1b) and diffused surface decay.

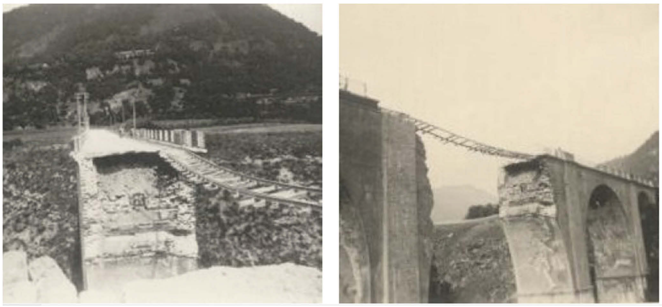

Figure 2. The collapse of the central arch occurred in 1944.

3 EXPERIMENTAL SURVEYS

The experimental survey on the *Olla* bridge included some Minor Destructive Tests (MDTs) to retrieve information on internal morphology and material distribution and two series of Ambient Vibration Tests (AVTs) to characterise the dynamic behaviour of the structure under different environmental conditions.

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 performed in the Autumn of 2018. Six coring samples were taken from the following elements: 2 on the arches, 2 on the spandrels and 2 on the deck (Figure 3a). The tests revealed that the arches are constituted only by brick masonry while the spandrels are a mixture of stone and brick masonry. The fill consists of compacted soil and pebbles. The thickness of the asphalt over the fill is equal to 20 cm.

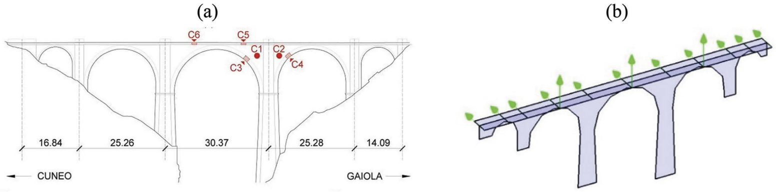

Figure 3. (a) Layout of the samples coring; (b) Sensor layout adopted for the AVTs.

Overall, the adopted measuring devices for the AVTs included 14 high-sensitivity piezoelectric accelerometers (WR model 731A, 10 V/g sensitivity and ±0.50 g peak) and a multi-channel acquisition system with 4 DAQ modules (NI 9234, 24-bit resolution, 102 dB dynamic range and anti-aliasing filters). In addition, each accelerometer was connected with a 1-meter cable to a power unit/amplifier (WR P31) to improve the performance of the acquisition chain: the power unit/amplifier was aimed at providing a constant current to power the accelerometer's internal amplifier, signal amplification and selective filtering.

Regarding the dynamic testing, a preliminary prompt test was performed with a single triaxial geophone (SARA GEOBOX SS45), revealing that the fundamental vibration mode of the structure involved the transversal motion of the deck. Therefore, the sensor layout for both tests was arranged to guarantee a complete representation of the lateral mode shapes and a partial reconstruction of the vertical ones (Figure 3b): the transversal response was recorded in 11 measuring points, while the vertical response was measured in 3 points (i.e. the centre of the three major arches). The tests were performed with one lane open to vehicular traffic.

The sampling frequency adopted in both AVTs 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 with time windows of 2400 s using the covariance-driven Stochastic Subspace Identification technique (SSI-Cov, Peeters & De Roeck 1999). The reader can refer to (Cabboi et al. 2017) for full details on the applied SSI-Cov procedure.

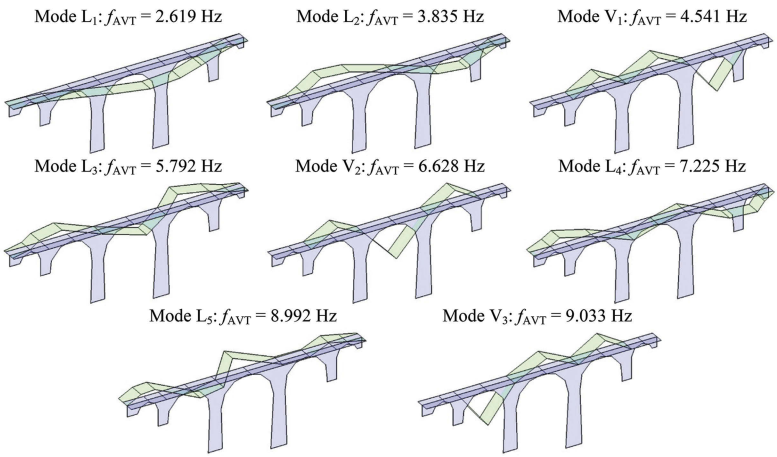

Figure 4. Modal identification from Dataset 1, July 2018: L denotes the dominant lateral vibration modes, and V denotes the dominant vertical vibration modes.

The first dynamic test was performed on July 31st, 2018, with an average temperature of 30.4°C, while the second dynamic test was performed on April 22nd, 2021, with an average temperature of 13.1°C. Overall, 5 transverse and 3 vertical vibration modes are identified in both tests for the frequency range of 0-10 Hz. The identified mode shapes are shown in Figure 4. It should be noticed that: (a) the transverse modes exhibit an increasing number of half-sine waves and inflexion points; (b) each identified vertical mode is characterised by the dominant deformation of one of the three longer spans, respectively.

The comparison of identified natural frequencies is shown in Table 1. The decrease in the outdoor temperature among the two tests is equal to 17.3°C, and the corresponding average reduction of natural frequencies is equal to 4%.

4 FE MODELLING AND UPDATING CONSIDERING ENVIRONMENTAL EFFECTS

In a previous study (Borlenghi et al. 2020), a simplified model of the *Olla* bridge was developed to investigate the contribution of backing and spandrels in the dynamic response of the structure in operational conditions. The simplified model emphasised the importance of the stiffening effects given by the structural elements above the arches. Nevertheless – due to the simplified nature of the model – a good experimental-numerical correlation was obtained for the lateral modes while an imperfect correlation was obtained for the vertical modes. Consequently, the 3D FE model herein presented reproduces as closely as possible the external geometry of the bridge with reasonable assumptions on its internal morphology. Therefore, spandrels, backing and fill material have been modelled along with arches, abutments and piers, considering a perfect connection among each structural element.

4.1 *Development of the FE model*

The 3D FE model of the bridge was developed in the ABAQUS software using ten-node tetrahedral elements (C3D10). The regular distribution of masses, the accurate description of geometrical details and the negligible mesh sensitivity on natural frequencies were obtained using a relatively large number of elements. Overall, the FE model consists of 45604 tetrahedral elements with 211818 degrees of freedom and an average mesh size of 1.15m.

Regarding the adopted geometry, the geomatic survey allowed the definition of all external dimensions with high accuracy; in contrast, the thickness of aches, the thickness of spandrels, and the height of backing were identified with a multi-step procedure. The characteristics of the internal morphology were initially assumed from historical research and then verified with local tests. For the spandrels, it was possible to assume a constant thickness equal to 1.0 m, while for the arches, the thickness visible from outside corresponds with the internal one. Due to the limited length of the drilling machine, no information on the backing was retrieved from the local tests. Consequently, the height of the backing was directly assumed from the construction handbook of Curioni (1873) and then validated with the FEMU procedure.

Furthermore, the main assumptions regarding the definition of the numerical model are herein listed: (i) the effect of soil-structure interaction was neglected, and the boundary conditions of piers and abutments were assumed fixed; (ii) all the materials were considered isotropic; (iii) the Poisson's ratio of masonry materials was held constant and equal to 0.15; (vi) the weight per unit volume of each structural component was held constant and equal to 20 kN/m^3 for the piers and abutments, 17 kN/m^3 for the arches, 19 kN/m^3 for the spandrels, 21 kN/m^3 for the base of the central piers, 18 kN/m^3 for the backing, and 16 kN/m^3 for fill. In view of the clear presence of superficial rocks at the river level (Figure 1a), the base nodes of piers and abutments were assumed as pinned. Similarly, the longitudinal translation of the abutments was restrained.

Different materials were considered for each structural element: (a) piers and abutments are built in ashlar stone masonry, (b) arches are in solid brick masonry, (c) spandrels are characterised by a first layer of bricks, and then rough-cut stones, (d) the bases of two central piers are in regular ashlar stone masonry, (e) the backing – as shown in the historical pictures of Figure 2 – is in masonry, (f) the fill is made up of loose soil and pebbles. In addition, the information coming from the historical research was considered: the central arch was rebuilt after the second world war, and so it was for the backing above the nearby piers. Consequently, different material properties were considered for the central arch (rebuilt in 1945) and the backing over the central piers. Figure 5 summarises the adopted elements with constant material properties.

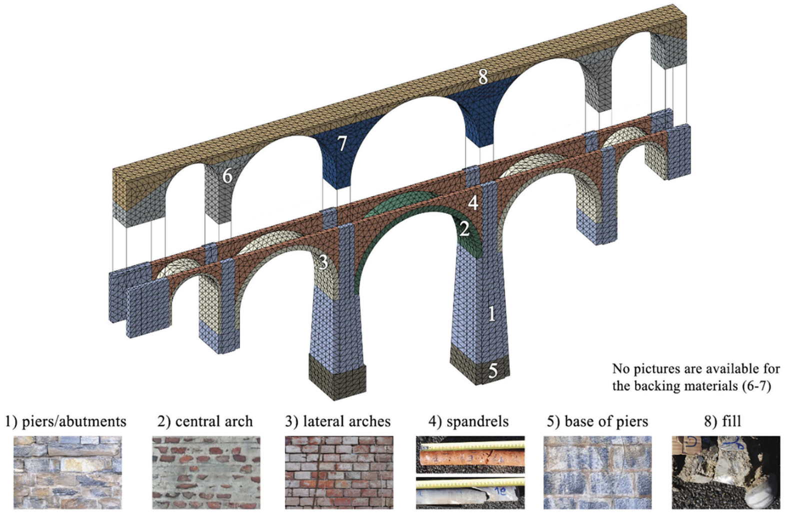

Figure 5. FE model of the Olla bridge with the indication of different materials.

4.2 *FE Model Updating (FEMU)*

Firstly, the (frequency) sensitivity of the selected Young's modulus was checked: all the parameters have a certain influence on the natural frequencies, with the only exception of the fill material. Due to its low sensitivity, the Young's modulus of fill was set equal to 0.30 GPa like a gravels/sand well-graded.

Subsequently, the selected structural parameters were manually updated until an acceptable solution was reached. The adopted values of the Young's modulus are the following: 16.5 GPa for the piers and abutments, 4.50 GPa for the arches, 15.0 GPa for the spandrels, 22.0 GPa for the base of the central piers, and 2.0 GPa for the backing. A one-to-one correspondence of the experimental-numerical modes was obtained, providing a preliminary verification of the main modelling assumptions. However, a maximum frequency discrepancy (DF = 100· $(1 - f_i^{\,FEM}/f_i^{\,AVT})$) equal to 7.4% showed the need for model updating.

The adopted FEMU procedure was implemented in MATLAB environment and it is based on the Douglas-Reid method (Douglas & Reid 1982) with the Particle Swarm Optimisation (PSO) algorithm: 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:

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

where f_i^{AVT} are the i-th experimentally identified natural frequency and $f_i^{*}(\mathbf{x})$ are the i-th polynomial approximations (Douglas & Reid 1982) of the numerical natural frequencies, expressed as functions of the **x** updating parameters. The interested reader can refer to Borlenghi et al. 2023 for full details on updating procedure.

4.3 *Discussion of the effects of environmental parameters on optimal models*

Table 1 shows the comparison between the experimentally identified and numerically estimated natural frequencies in the two considered ambient conditions: July 2018 with a T_{mean}=30.4°C and April 2021 with a T_{mean}=13.1°C. In both cases, an excellent

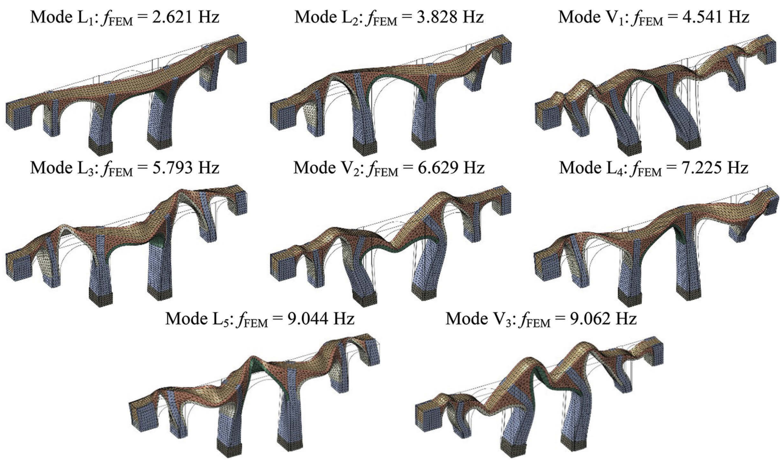

Figure 6. Vibration modes of the updated FE model (modal data from July 2018).

experimental-numerical correlation is obtained with an average frequency discrepancy DF of 0.15% and 0.57%, respectively, and an average mode shape correlation MAC of 0.95 in both cases. As expected, the numerical natural frequencies follow the variations of the experimental ones, with an average decrease equal to 4%, while the mode shapes exhibit negligible changes.

Table 2 lists the optimal estimates of the updated structural parameters of the two models. The differences between the Young's modulus of the central and lateral arches, as well as the one of the backing, are motivated by the reconstruction of 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 a better-quality stone masonry with respect to 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.

The decrease in temperature between July 2018 and April 2021 implies a decrease in natural frequencies, which, in turn, determines an average reduction in Young's modulus equal to 8%. In detail, Table 2 shows the percentage of decrease for each parameter. The Young's modulus of piers, abutments, central arch, the base of central piers, and the backing of central piers exhibits a variation of less than 2%, while the Young's modulus of lateral arches shows a decrease of about 4%. However, major variations of the Young's modulus estimate are observed for spandrels and lateral backing.

The interpretation of structural parameter variations due to temperature-induced frequency changes is not straightforward. The natural frequencies of the *Olla* bridge tends to increase with increased temperature. Similar behaviour has been observed in long-term monitoring of masonry towers (Ramos et al. 2010, Saisi et al. 2015, Ubertini et al. 2017), as well as, from the repeated dynamic testing of a masonry viaduct (Roselli et al. 2018). The most accepted explanation is that the thermal expansion of materials induces the closure of micro-cracks, minor discontinuities or mortar gaps (defects typically present in masonry elements). Hence, the temporary compacting of the masonry induces a temporary increase of stiffness and natural frequencies, as well. In addition, small gaps and micro-cracks are expected to be more frequent in structural element with a low level of compressive stresses. It is worth noting that spandrels and backing are bearing less compressive forces than piers and arches. Consequently, it might be expected that the relatively high temperature measured during the first test of July 2018 generated a significant stiffening effect on backing and spandrels due to the expansion of masonry material and the consequent closure of micro-cracks, resulting in an apparent higher elastic modulus.

Table 1. Comparison between experimental and numerical natural frequencies considering different environmental conditions: July 2018 with T_{mean}=30.4°C and April 2021 with T_{mean}=13.1°C.

	July 2018				April 2021			
	OMA	Optimal model			OMA	Optimal model		
Mode Id.	f_{AVT} (Hz)	f_{FEM} (Hz)	DF (%)	MAC (−)	f_{AVT} (Hz)	f_{FEM} (Hz)	DF (%)	MAC (−)
L_1	2.619	2.621	-0.07	0.998	2.555	2.570	-0.61	0.997
L_2	3.835	3.828	0.18	0.994	3.700	3.687	0.35	0.995
V_1	4.541	4.541	-0.01	0.976	4.235	4.246	-0.28	0.972
L_3	5.792	5.793	-0.02	0.989	5.554	5.553	0.02	0.991
V_2	6.628	6.629	-0.02	0.995	6.477	6.441	0.56	0.995
L_4	7.225	7.225	-0.01	0.902	6.789	6.908	-1.75	0.909
L_5	8.992	9.044	-0.57	0.794	8.605	8.631	-0.31	0.784
V_3	9.033	9.062	-0.32	0.951	8.671	8.697	-0.30	0.938

$DF = 100\cdot(1 - f_i^{FEM}/f_i^{AVT})$

Table 2. Summary of the structural parameters identified from model updating considering different environmental conditions: July 2018 with T_{mean}=30.4°C and April 2021 with T_{mean}=13.1°C.

		Optimal model A (July 2018)	Optimal model B (April 2021)	
No.	Structural elements	E_A (GPa)	E_B (GPa)	ΔE/E (%)
1	Piers/abutments	16.10	15.81	1.8%
2	Central arch	7.73	7.63	1.2%
3	Lateral arches	3.23	3.10	4.3%
4	Spandrels	16.85	12.00	28.8%
5	Base of central piers	27.49	27.34	0.5%
6	Backing lateral piers/abut.	1.38	1.13	17.6%
7	Backing central piers	4.56	4.49	1.7%

$\Delta E/E = 100\cdot(E_A - E_B)/E_A$

5 CONCLUSIONS

The paper illustrates the effects of different environmental conditions on the model updating procedure of a historical masonry viaduct called *Olla* bridge.

The investigations in the *Olla* bridge included documentary research, geometric survey, minor destructive tests and ambient vibration tests. Particularly, the AVTs were performed in different environmental conditions: the first test was performed in July 2018 with an average temperature of 30.4°C, and the second test was performed in April 2021 with an average temperature of 13.2°C. Based on the information collected onsite, a 3D FE model was developed, and the uncertain structural parameters were estimated using the modal parameter identified in the two dynamic tests.

In summary, the following conclusions can be drawn:

- The onsite visual inspections highlighted the presence of local damages on the arches and diffused surface decay;
- During both dynamic tests, 5 lateral and 3 vertical vibration modes were identified in the frequency range of 0-10 Hz;
- The outdoor temperature variation between the two tests (July 2018 and April 2021) is equal to 17°C;
- The percentage of variation in natural frequencies between the two tests has an average of 4%, a maximum of 6.7% for mode V_1 and a minimum of 2.3% for mode V_2;

- The Young's modulus of selected structural elements is estimated for both environmental conditions, showing an average variation of 8%;
- The Young's modulus of spandrels and lateral backing is the most affected by the changes in environmental conditions, with a decrease of 29% and 18%, respectively;
- The more pronounced variation in the elastic modulus of spandrels and backing is most likely related to the expansion of masonry material and the consequent closure of micro-cracks and small gaps during the hot season.

The reported results have demonstrated the importance of accurately evaluating the temperature effects for model updating purposes in masonry structures: the apparent stiffening effect given by the high temperatures of the hot season can lead to an over-estimation of the elastic properties of structural elements characterised by low loading levels. However, the apparent increase of stiffness is negligible for the main load-baring elements, i.e. arches and piers. Consequently, the influence of testing conditions (and consequently of temperature-induced frequency variations) is conceivable negligible in the structural safety assessment of the investigated bridge.

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