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## Finite element model refinement of a reinforced concrete highway arch bridge based on Operational Modal Analysis

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### ABSTRACT

Nowadays, the use of operational modal analysis (OMA) plays a significant role in the health assessment of existing structures, as it allows the identification of modal parameters under operational conditions. By using these parameters as targets, numerical models can be calibrated to reduce modelling uncertainties and obtain a model that accurately represents current structural conditions. In this context, the Italian DM 204/2022 code recognizes the relevance of OMA to support the calibration of numerical models in view of the structural assessment of existing bridges. The case study analysed in the present paper focuses on a reinforced concrete highway arch bridge in Southern Italy. The development of a detailed FE model using Ansys Mechanical ADPL is presented. Then, the major uncertainties associated with numerical modeling are highlighted as well as the discussion on model refinement. Finally, the key insights gained from this application are summarized.

*Keywords: Operational Modal Analysis, model refinement, Finite Element Model, reinforced concrete, arch bridge*

### 1. INTRODUCTION

Italy features a wide range of bridges, including a significant number of reinforced concrete (r.c.) arch bridges built between the 1940s and 1960s. Bridges are essential for connecting communities, enabling transport and supporting economic activity. However, increasing traffic loads compared to original design values [1] together with ageing and degradation phenomena [2], have motivated significant research efforts in recent years on their accurate structural assessment [3,4], and these re-

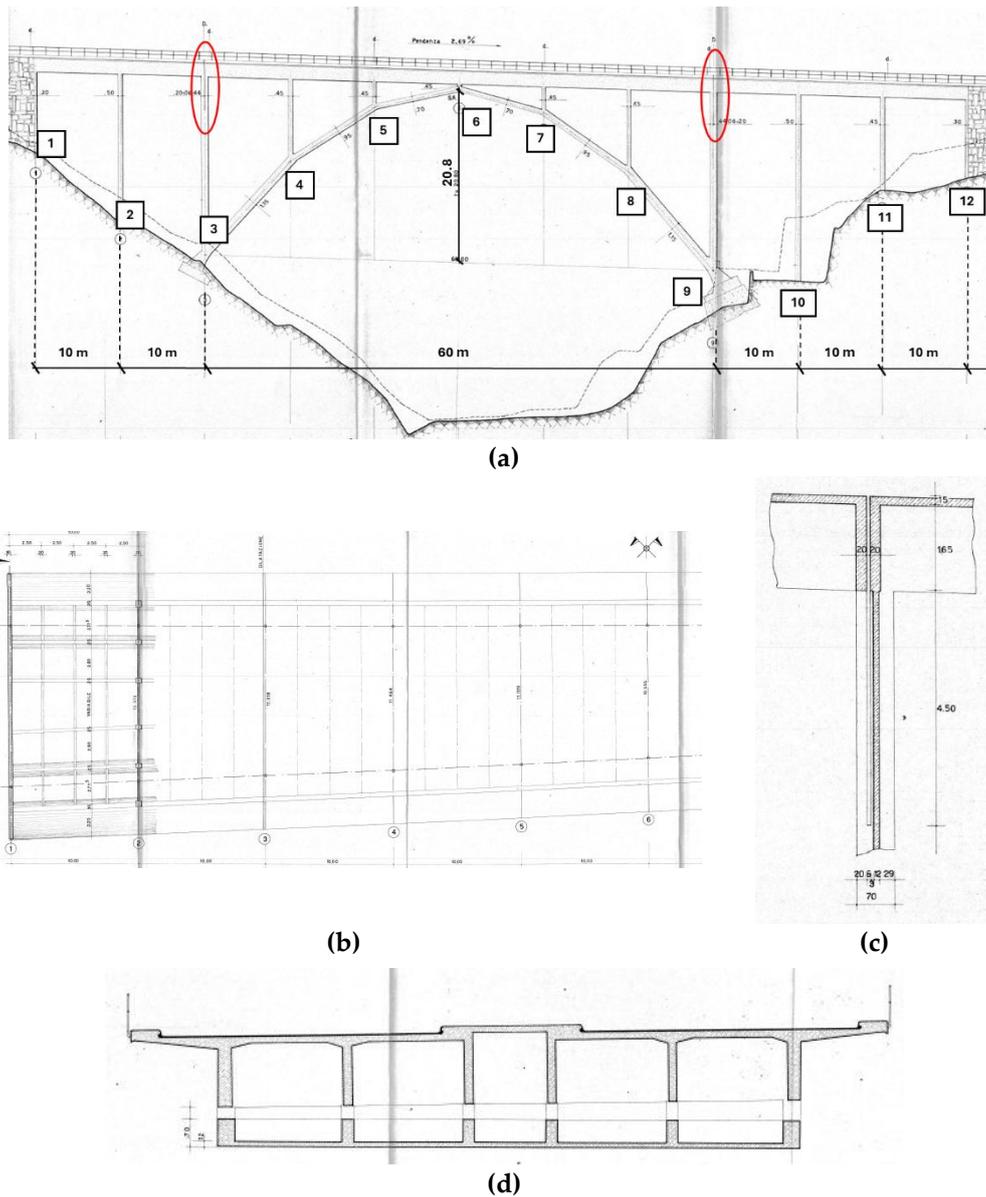
sulted in a regulatory framework entirely focused on the assessment and monitoring of existing bridges [5]. This code adopts a multi-level strategy for the assessment of existing bridges, through a classification system that quantifies the need for more in-depth analyses and investigations. In this framework, the combination of Operational Modal Analysis (OMA) with finite element model updating (FEMU) [6] is recommended for the accurate assessment and characterisation of the structural behaviour under operational conditions. OMA tests provide essential data, including natural frequencies and mode shapes, which are crucial for calibrating numerical models [7,8]. However, this approach is time-consuming and computationally expensive, so surrogate models are often used to solve the model updating problem [9–11]. Incorporating a surrogate model into the model updating process requires the definition of a simplified version of the original model in the form of a mathematical expression linking the modal parameters to the updating variables [12,13]. The present work addresses the refinement of a finite element model of a r.c. highway bridge, combining the data obtained from OMA tests with a surrogate model and a gradient-based algorithm to solve the model updating problem. The widespread presence of this type of bridge in Italy, and the fact that they were originally designed according to simplified assumptions, underscores the importance of evaluating their structural behavior under operational conditions.

The present study initially outlines the main findings of an extensive experimental program aimed at achieving a full knowledge of the bridge, which encompassed geometric surveys, destructive and non-destructive tests, as well as OMA in Section 2. Section 3 describes the development of the finite element (FE) model of the bridge by using ANSYS Mechanical ADPL. Lastly, Section 4 presents the outcomes of the model updating process, with the key insights gained from this work summarized in Section 5.

## 2. EXPERIMENTAL CAMPAIGN RESULTS

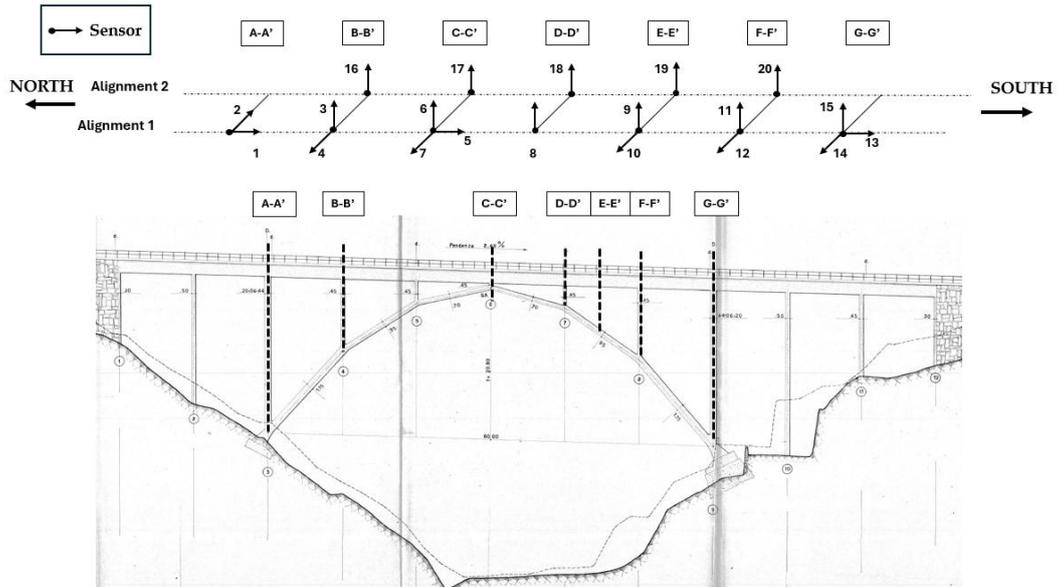
The structure under examination is a r.c. arch bridge. For confidentiality reasons, the analysed viaduct is not explicitly identified in this paper. The highway bridge was built in the 1950s. The arch-supported central part of the bridge deck and parts supported by the outer access viaducts are separated by two structural joints where the standard pillar sections are splitting in two. Extensive surveys and experimental tests were carried out to enhance the knowledge about the investigated structure and to set an accurate FE model. A thorough review of available documents and design drawings was conducted to develop the structural model of the viaduct. Among the analyzed original design documents there were the planimetric layout, elevations, deck profiles, arch plans and sections, construction details of the load-bearing components, and the reinforcement steel specifications. Examples of the original design drawing are shown in Figure 1. Furthermore, the original test certificates on materials at the time of creation have been recovered; they provide valuable information on the materials used in that period. In particular, compressive strength tests on cubic specimens were documented. In addition, destructive and non-destructive tests on various elements of the structure, such as the pillars, deck, beams and arch have been recently carried out to evaluate the current mechanical properties of the concrete. A detailed geometric survey has also been carried out to further assess the current state of the bridge. Additional investigations included carbonation tests on microcores, combined SonReb investigations and tensile strength tests on reinforcing bars extracted from structural elements. The results of this comprehensive investigation were made available for the present study. The average value of the compressive strength obtained from the tests, equal to 47,7 MPa, was used to obtain an initial estimate of the Young's modulus of concrete based on the following equation [14]:

$$E_c = 22000 \cdot [(f_{cm}/10)^{0.3}] \quad (1)$$



**Figure 1.** Original design drawings showing the deck profile and the locations of the structural joints (a), the deck plan (b), the structural joint section (c) and the deck and arch section (d).

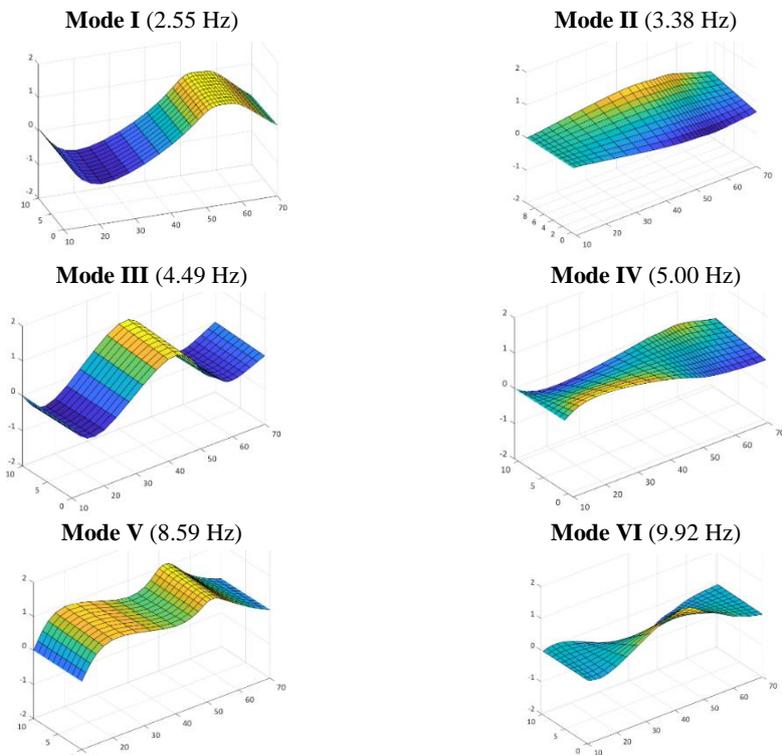
The investigation program also included an OMA test aimed at identifying the bridge's fundamental modes, considered as the basis for improving the model accuracy. The vibration response of the structure was measured at night under no traffic conditions. Well-established OMA methods such as Frequency Domain Decomposition [15] and Covariance Driven Stochastic Subspace Identification [16] have been applied for modal parameter estimation. The OMA test employed 20 IEPE accelerometers, characterized by a sensitivity of 10.0 V/g, a full-scale range of  $\pm 0.5$  g, and a bandwidth from 0.1 to 200 Hz. Data acquisition was performed using programmable hardware with 24-bit resolution and an integrated analog anti-aliasing filter, managed through the commercial software S2-DDA [17]. Sensor placement was carefully planned to ensure the observability of the expected structural modes. The record of the ambient vibration response of the bridge was 3600 s long. A schematic outline of the sensor layout is shown in Figure 2. Six modes were clearly identified, including longitudinal (L), transverse bending (TB), vertical bending (VB) and torsion (T) modes, as reported in Table 1. The graphical representations of the identified mode shapes are shown in Figure 3.



**Figure 2.** Sensor layout.

**Table 1.** Experimentally identified modes.

Mode	Natural frequency [Hz]	Mode shape
I	2.55	L
II	3.38	TB
III	4.49	VB
IV	5.00	T
V	8.59	VB
VI	9.92	T



**Figure 3.** Experimental mode shapes.

### 3. FINITE ELEMENT MODEL OF THE BRIDGE

The FE model of the bridge was set by means of ANSYS Mechanical APDL after a careful review analysis of the original design drawings and the results of the in-situ investigations presented in the previous section. Shell elements were used to model the slab and the arch; the walls connecting the columns were also modeled by shell elements, while unidimensional elements were employed to model the columns, the beams of the deck, and the arch ribs. A rigid body constraint was applied to each structural joint at the end of the pier bifurcation. Additionally, due to the pavement, a mass was incorporated as a distributed mass (area mass) on the bridge. Fixed boundary conditions were applied at the base of the structure. The initial FE model of the bridge is shown in Figure 4. Given the importance of proper mesh refinement to achieve accurate results, a mesh convergence analysis was carried out to ensure that the model produces consistent outcomes as the mesh dimensions decreases. The results of the mesh convergence analysis showed a stabilization of the results when the number of elements reached 16318 (Figure 5).

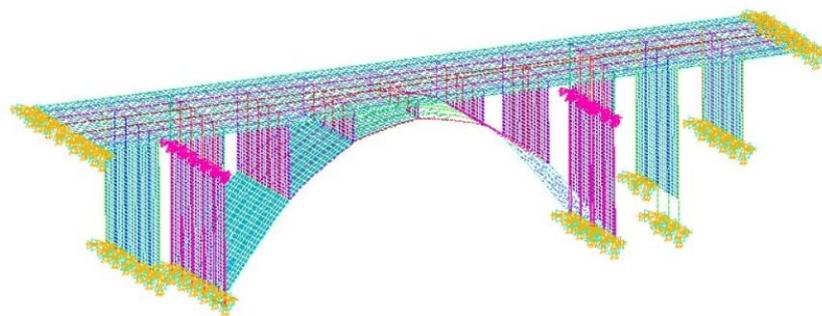


Figure 4. Finite element model of the bridge

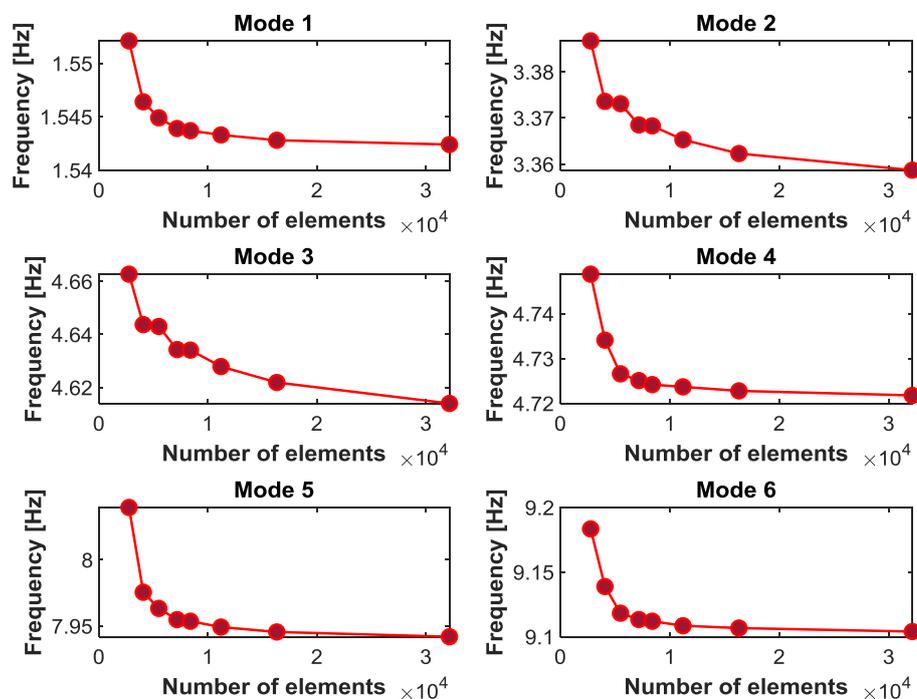


Figure 5. Mesh convergence analysis

In view of FE model updating, the correlation between the modal properties of the initial model of the bridge and the corresponding experimental estimates was quantified. The results, presented in Table 2, show a notable discrepancy for the first mode in terms of both natural frequency scatter and Modal Assurance Criterion (MAC) value, and a reversal between the third and fourth modes with respect to the experimental data. Given the longitudinal nature of the first mode, and the significant underestimation of its corresponding natural frequency compared to the experimental value, particular attention was paid to the accurate modeling of the interaction between the arch and the outer viaducts across the transverse joints.

**Table 2.** Comparison between experimental (EXP) and numerical (FEM) modal properties for the initial model.

Mode	$f_{EXP}$ [Hz]	$f_{FEM}$ [Hz]	MAC	$f_{scatter}$ [%]
I	2.55	1.54	0.79	-39.50
II	3.38	3.36	0.98	-0.52
III	4.49	4.72	0.98	5.18
IV	5.00	4.62	0.94	-7.56
V	8.59	7.95	0.96	-7.50
VI	9.92	9.11	0.91	-8.20

#### 4. MODEL UPDATING: RESULTS AND DISCUSSION

Updating of the initial FE model of the bridge has been carried out by applying the Douglas-Reid method [18] in order to establish a simplified mathematical relationship between the numerical modal properties, on one hand, and the updating variables, on the other hand. The search for the optimal solution of the updating problem exploited an automated optimization algorithm of the gradient-based type. The robustness of the solution was confirmed by testing different initial points. The objective function to minimize is given in Equation 2.

$$J_{f,I} = \frac{1}{2} \sum_{i=1}^M \left( \frac{f_i^{DR} - f_i^{EXP}}{f_i^{EXP}} \right)^2 \quad (2)$$

To account for the presence of expansion joint devices, some springs were introduced in the model along the cross-section of the structural joint, whose stiffness was obtained from private communication about the results of several tests carried out on similar devices in an industrial context. Additionally, due to the presence of concrete curbs on both sides of the carriageways, an extra set of four springs was added to account for their stiffness contribution. The stiffness of the curbs was considered as an updating variable, because of visible cracks suggesting a partial contact due to occurrence of tensile stresses in the concrete. Two extreme scenarios are considered to set the range values of variation of longitudinal stiffness for each spring: i) zero stiffness, indicating no contact between the curb sections across the crack, and ii) complete contact, where the axial stiffness is calculated based on the full cross-sectional area of 0.09 m<sup>2</sup> and the secant Young's modulus of concrete, as estimated in Section 2. In addition to the spring stiffness, the concrete Young's modulus was selected as second updating parameter, given the significant dispersion of the mechanical properties of concrete observed from the in-situ tests. It is well known the elastic modulus of concrete depends on its main components and, in particular on the type of aggregates. Therefore, the value reported in Section 2 can decrease by up to 30% or increase by up to 20% [14]. Thus, the range of variability of the Young's modulus of concrete was defined by taking into account these uncertainty bounds.

In addition to the previously described model, the stiffness contributions at the joints have been also modeled in a simplified way by considering a set of eight parallel springs distributed across each structural joint, without distinguishing the contributions of expansion joints and concrete curbs. The initial value of the joint stiffness was defined based on the results of the previous updating in a way that the total stiffness of the parallel springs in this model was equal to the total stiffness after the previous updating.

Table 3 summarizes the model updating results for the first (subscript 1) and second (subscript 2) model.

**Table 3.** Comparison between experimental and numerical modal properties after model updating.

Mode	$f_{ini}$ [Hz]	$f_{upd,1}$ [Hz]	$f_{upd,2}$ [Hz]	MAC <sub>1</sub>	MAC <sub>2</sub>	$f_{scatter,1}$ [%]	$f_{scatter,2}$ [%]
I	1.54	2.65	2.66	0.94	0.93	4.11	4.39
II	3.36	3.52	3.52	0.97	0.97	4.06	4.03
III	4.72	4.78	4.79	0.93	0.99	6.55	6.61
IV	4.62	4.98	4.99	0.93	0.92	-0.39	-0.24
V	7.95	8.15	8.14	0.96	0.96	-5.16	-5.24
VI	9.11	9.33	9.32	0.91	0.91	-5.97	-6.05

The results of the first model updating correspond to updated variable values of 36559 MPa for the concrete Young's modulus and 214303 kN/m for the axial stiffness of the curbs, while they correspond to updated variable values of 36498 MPa and 107789 kN/m for the concrete Young's modulus and the spring longitudinal stiffness, respectively for the second model updating. The results of model updating are consistent with each other, confirming the reliability of the solution and the agreement with the experimental results. While the total stiffness of the structural joints remains basically unchanged, and the natural frequencies are little affected by the stiffness distribution along the structural joint, an improvement in the MAC value can be observed for the third mode when the contributions of concrete curbs and expansion joints are not distinguished.

## 5. CONCLUSIONS

The present study has described an application of OMA and model updating to enhance the knowledge about the dynamic behavior of a r.c. highway arch bridge in Italy. The investigated structure, 50 years old, is representative of a frequently adopted structural typology in Italy after the World War II now requiring accurate studies to assess possible structural deficiencies with respect to either static and dynamic loading. The creation of a detailed finite element (FE) model by ANSYS Mechanical ADPL, and its calibration based on the outcomes of an extensive experimental program have been presented and discussed highlighting how a model representative of the actual structural behavior under operational conditions has been obtained. The results show the relevant contribution to the stiffness of expansion joints and lateral concrete curbs, at least at low amplitude vibrations.

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