CASE STUDY ON UPDATING NUMERICAL MODELS OF MASONRY ARCH BRIDGES

Cristina Costa¹, António Arêde², Aníbal Costa³ and Elsa Caetano⁴

ABSTRACT

This paper aims at presenting and discussing the strategies for updating the finite element numerical modeling of a stone masonry arch bridge using operational modal analysis. A 3D detailed numerical model is used to perform the bridge modal analysis and the bridge modal identification is based on in situ measurements recorded during ambient vibrations tests.

The dynamic characteristics obtained through in situ measurements were estimated using analysis and signal processing software based on different techniques such as Peak Picking, Frequency Domain Decomposition (FDD and EFDD) and Stochastic Subspace Identification (SSI).

Keywords: Model updating, Operational modal analysis, Masonry arch bridges

1. INTRODUCTION

The structural assessment of masonry arch bridges has been assuming increasing importance in the field of management, maintenance and heritage preservation by the administration authorities. Modifications in initial loads and material degradation are sufficient grounds to seek for better understanding of structural behavior, to detect the critical zones of potential or actual structural damages and to implement appropriate plans of rehabilitation, repair and strengthening.

In this context, this work fits within a more comprehensive study focused on the calibration of analysis procedures for stone masonry arch bridges using 3D detailed finite element numerical models with the purpose of estimating the structural response under dead load and road traffic excitation [1] and [2].

Simulation of existing masonry structures by means of refined numerical models based on the finite element method requires that a great amount of geometric and material mechanical parameters are known. With this purpose, the discretization of masonry and infill structure took into account the

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dimensions of structural elements and specificities of materials and connections between components observed on the bridge.

To calibrate and validate the numerical bridge model, ambient vibration tests [3] and [4] were performed, from which the frequencies and vibration modes of the structure were estimated in order to be compared with similar parameters numerically obtained.

This procedure allowed updating the model parameters, by adjusting the elastic material characteristics, the geometric model and the boundary conditions, thereby numerically reflecting the experimental dynamic characteristics. The assigned material properties were also based on available results obtained from in situ and laboratory tests and on the results of both visual inspection and historical research.

2. BRIEF DESCRIPTION OF THE CASE STUDY

The St. Lázaro Bridge crosses the Leça river in Alfena, Valongo (nearby Porto) and it is a granite stone masonry bridge supposedly built in the Middle Ages [5]. The bridge is about 28 m long with two different perfect arches, one with 7.5 m span and a smaller one with 2.3 m. The deck is about 3.3 m wide and the pavement is made of granite slabs (Figure 1).

During the year 2008 the bridge was consolidated by cement grout injection in the backfill as well as by injecting and repointing the masonry joints with appropriate mortar.

The geometric characterization of components of structural masonry (arches, spandrels and pavement) and infill was based on 3D laser scanning survey techniques provided by the Municipality of Valongo [6].

The mechanical parameters used in numerical study were defined considering a set of experimental results obtained from laboratorial tests carried out on material samples representative of the structural behavior, obtained from other similar stone masonry structures, available in the literature [1], [2], [7], [8] and [9].

Apart from the measured geometric and material characteristics, the results of the visual inspections for the detection of cracks, settlement and excessive deformations and for the evaluation of the degree of material degradation before and after the intervention have also been taken into account. Complementarily, historic information on the bridge has been gathered, particularly on the activities involving rehabilitation, repair and strengthening, as well as other events leading to changes in the structural behavior [10] and [11].

Subsequently, the calibration of the numerical model was made by comparing the numerical results of the bridge dynamic characteristics and similar experimental results obtained through ambient vibration tests.
3. NUMERICAL MODEL OF THE BRIDGE

3.1. Finite element mesh

Numerical analysis of the bridge was performed by 3D structural modeling based on finite element (FE) method resorting to CAST3M software [12].

Masonry micro-modeling strategies were used for arches, spandrels and pavement considering the stone blocks discretized with solid elements, duly individualized through zero thickness joint elements allowing the interfaces between blocks (stone-to-stone joints) to be materialized.

The infill zone was discretized from the external geometry using solid elements. The interfaces between the infill material and the masonry structure of the arches, spandrels and pavement were discretized with joint elements using infill-to-stone joints.

3D models were defined using solid elements with 6 or 8 nodes and no thickness joints elements with 6 or 8 nodes.

Figure 2 shows the FE meshes of blocks and joints of the St. Lázaro bridge model.

![Figure 2 3D FE model of St. Lázaro bridge: a) solid elements and b) joint elements](image)

The boundary conditions were set using rigid supports to fix the displacements at the base of the bridge in contact with the riverbed. The same type of conditions was imposed at the base of the abutments.

The horizontal displacements (longitudinal and transversal) of the spandrels and the infill were fixed at the vertical boundary of the abutments. The elements of the deck in contact with the abutments were set free on the remaining bridge structure.

3.2. Material properties

The material properties of solid and joint elements representing the bridge behavior in the elastic regime are summarized in Table 1. The linear elastic behavior of the volumetric elements used to simulate stone blocks, infill and macro-blocks is controlled in terms of elastic modulus (E) and Poisson's ratio (ν). The joint elements used to simulate linear elastic behavior of the interfaces between blocks (stone-to-stone joints) and the interfaces between the infill and the masonry (stone-to-infill joints) are controlled in terms of normal stiffness and shear stiffness (kn and ks). The unit weight (γ) of solid elements is also included in Table 1.

<table>
<thead>
<tr>
<th>Solid elements zones</th>
<th>E [GPa]</th>
<th>γ [kN/m³]</th>
<th>ν</th>
<th>Joint elements zones</th>
<th>kn [MPa/mm]</th>
<th>ks [MPa/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone blocks</td>
<td>35.0</td>
<td>26.0</td>
<td>0.20</td>
<td>Stone-to-stone joints</td>
<td>7.200</td>
<td>0.560</td>
</tr>
<tr>
<td>Infill</td>
<td>0.2</td>
<td>21.5</td>
<td>0.33</td>
<td>Stone-to-infill joints</td>
<td>0.529</td>
<td>0.282</td>
</tr>
</tbody>
</table>
The St. Lázaro bridge modeling aims at approximating the bridge response after the rehabilitation intervention recently made, therefore considering joints after repointing with mortar and the infill constituted (supposedly) by the original granular material and the material added through cement grout injections.

Since no specific laboratory tests were performed for St. Lázaro bridge materials, the results of laboratory tests performed on samples of materials used in other similar masonry structures [1], [2], [7], [8] and [9] have been considered to define and adjust the material parameters; afterwards, the material parameters (Table 1) were based on visual inspection and historical research on the bridge [10] and [11] and calibrated by ambient vibration tests carried out on the bridge after the rehabilitation intervention by comparing experimental dynamic characteristics (determined by dynamic tests) with those obtained by numerical modal analysis.

3.3. Numerical dynamic properties

The numerical dynamic properties of the bridge were achieved by performing linear modal analysis considering the bridge models and corresponding parameters presented in previous sections 3.1 and 3.2, therefore aiming at representing the current bridge conditions and approximating the numerical results of dynamic characteristics with the corresponding experimental results measured in dynamic tests.

The results of the bridge modal analyses in terms of frequencies, type of mode shapes and corresponding configurations are included in Figure 3.

![Numerical frequencies and vibration modes](image)

**Figure 3** Numerical frequencies and vibration modes
4. OPERATIONAL MODAL ANALYSIS

4.1. Ambient vibration tests

The ambient vibration tests were performed using three portable macro seismographs GSR from GeoSIG [13].

Each macro-seismograph allows recording acceleration signals in three orthogonal directions and assuming specific conditions of trigger and sampling rates. Time series of 480 seconds of reading duration were considered defining sampling rates of 100 Hz.

The digitizer and sensors’ operating conditions are set using specific software therefore it is necessary to use a portable computer which also permits transferring the records stored in the memory units of the macro-seismograph to the computer disk.

The campaigns addressed in this work were carried out in collaboration with the Laboratory of Vibrations and Structural Monitoring - ViBest FEUP (http://www.fe.up.pt/vibest).

The testing methodology consisted in successive vibration measurements in points of the bridge deck, illustrated in Figure 4a, corresponding to different cross sections of the bridge. Several series of measurements were performed following the sequence shown in Figure 4b, placing one seismometer at a fixed reference point (point 5U) and the other devices at other measurement points.

The reference point was selected considering that this point should not coincide with the nodes of the main vibration modes to be identified [14]. This information was obtained previously through preliminary result analysis of the bridge finite element modeling and other dynamic measurements performed before.

![Figure 4 Ambient vibration tests. a) Instrumented points. b) Set points and datasets](image)

4.2. Signal processing

Based on the acceleration measurements recorded during the ambient vibration tests, the analysis and signal processing ARTEMIS software [15] was used to estimate the natural frequencies and the mode shapes of the St. Lázaro bridge.

Resorting to ARTEMIS software, the determination of natural frequencies and vibration modes of the bridge were based on different techniques such as Peak Picking, Frequency Domain Decomposition (FDD and EFDD) or Stochastic Subspace Identification (SSI) [14], [16], [17] and [18]. Initially and using the Peak Peaking technique, the frequencies corresponding simultaneously to power spectra peaks and coherence values close to 1 have been identified. Moreover, the phase spectra between the measurement points were also analyzed for each frequency value.

Additionally, carrying out also the Enhanced Frequency Domain Decomposition (EFDD) and Frequency Domain Decomposition (FDD) of the spectral density matrix, a set of eigenvalues in the same number of the acceleration records was obtained for each frequency. The peaks of the eigenvalues spectra of the spectral density matrix were then identified as corresponding to the system natural frequencies.
The results from the application of the EFDD and FDD techniques to the acceleration records obtained on the St. Lázaro bridge are shown in Figure 5, in terms of the average spectrum of the normalized singular values, where the peaks of the spectrum provide information on the values of the dominant frequencies during the vibration tests (associated with the vertical lines in Figure 5).

![Figure 5 Average of the normalized singular values](image)

Thereby, the singular vector, associated with each singular value of the spectral density matrix, configures a vibration mode whose terms represent relative magnitudes to the reference point. This information provides the visualization and animation of the amplitude and phase of the identified vibration modes using the ARTEMIS program.

The corresponding modal configurations for St. Lázaro bridge are shown in Figure 6. The analysis of the vibration mode amplitude associated with the natural frequencies 7.73 Hz and 15.71 Hz (1\textsuperscript{st} transversal mode and 1\textsuperscript{st} vertical mode, respectively) show a good agreement with the results predicted in the numerical model, presented in section 3.3 (see Figure 3). However, for the remaining vibration frequencies, the identification of the mode shapes revealed some difficulties, also found by applying the SSI technique [2].

![Figure 6 Identified frequencies and mode shapes using the EFDD technique](image)

Within the St. Lázaro bridge modal identification performed through ViBest, free vibration tests have also been carried out. As a result it was possible to identify the bridge natural frequencies and the directions of component of the corresponding vibration modes using techniques developed in time domain [19]. In this case, due to the high structural stiffness, the dynamic excitation was achieved by a jump performed by four people on the deck and a race held by the same number of people.

Good agreement was found between the values of the natural frequencies identified using the three techniques, as well as good approximation between mode shapes, particularly, in what concerns the
direction of the modal components with higher amplitude (more excited), which leads to conclude that the first, second and fourth identified modes are (mainly) transversal modes, the third mode corresponds to a modal configuration with (mainly) longitudinal components and the fifth mode shows essentially vertical components.

The results of numerical and experimental dynamic characteristics are summarized in Table 2 where the latter columns indicate the range of the identified natural frequencies and corresponding mode types considering the most excited modal components in both frequencies (EFDD and SSI) and time domain techniques.

Table 2 St. Lázaro bridge dynamic characteristics numerically calculated and identified in situ

<table>
<thead>
<tr>
<th>Numerical frequencies [Hz]</th>
<th>Experimental frequencies [Hz]</th>
<th>Type of vibration mode</th>
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<tbody>
<tr>
<td>7.7</td>
<td>7.70 – 7.80</td>
<td>1st transversal</td>
</tr>
<tr>
<td>11.7</td>
<td>10.47 – 10.60</td>
<td>2nd transversal</td>
</tr>
<tr>
<td>12.9</td>
<td>12.70 – 12.96</td>
<td>1st longitudinal</td>
</tr>
<tr>
<td>14.1</td>
<td>14.20 – 14.47</td>
<td>3rd transversal + torsion</td>
</tr>
<tr>
<td>15.5</td>
<td>15.37 – 15.71</td>
<td>1st vertical</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

Throughout the previous sections some details were presented concerning the operational modal analysis using ambient vibration tests for updating the numerical model of a stone masonry arch bridge. Micro-modeling strategies have been used to define the bridge 3D numerical model considering the actual geometry and material properties of the bridge.

Model calibration, particularly the elastic material parameters, was performed by comparing the numerical dynamic characteristics with similar experimental parameters calculated with basis on ambient vibration testing.

The performance of ambient vibration tests and the results obtained therefore constituted a fundamental step for the mechanical characterization of the case study and calibration of the adopted numerical models. Using relatively simple test procedures with no interferences in the behavior or in the operation of the bridge, it is possible to obtain a great deal of information about the structure, in particular on its stiffness. Estimation of the dynamic characteristics, such as the natural frequency and mode shapes, is achieved with relative easiness through commercial software, designed for signal processing and modal analysis. However, the complete characterization of the vibration modes reveals itself more complex.

This difficulty arises from the large stiffness of this type of structures and, because of it, in the recorded signals the noise components are very high when compared with the low amplitudes of the acceleration. On the other hand, the dynamic testing of this type of structures is still not frequent, therefore procedures and equipment involved in testing (which are often adjusted to flexible structures such as long span bridges built in reinforced concrete) may not be as well adapted for the studied case.

ACKNOWLEDGEMENTS

This work includes researches with financial support from FCT through the research unit CEC (Construction Studies Centre of FEUP).

REFERENCES


