MULTIDISCIPLINARY APPROACH TO THE STRUCTURAL ASSESSMENT OF A HISTORICAL MASONRY ARCH BRIDGE

B. Conde[1], D.V. Oliveira[2], L.F. Ramos[2], B. Riveiro[1], P. Arias[3], P.B. Lourenço[2]

[1]University of Vigo, Department of Materials Engineering, Applied Mechanics and Construction, Vigo, SPAIN.
[2]ISISE, University of Minho, Department of Civil Engineering, Guimarães, PORTUGAL.
[3]University of Vigo, Applied Geotechnologies Research Group, Vigo, SPAIN.

e-mails: bconde@uvigo.es, danvco@civil.uminho.pt, lramos@civil.uminho.pt, belenriveiro@uvigo.es, parias@uvigo.es, pbl@civil.uminho.pt

SUMMARY

In this paper, a multidisciplinary approach for the structural assessment of masonry bridges is presented. A real case study, the Vilanova Bridge located in Galicia, Northwest of Spain, is considered to the implementation of the methodology.

A comprehensive field survey, fully based on non-destructive testing techniques which integrates laser scanning, ground penetration radar and ambient vibration testing is proposed. It provides all the necessary geometric data to construct an accurate and detailed three-dimensional finite element model. The calibration of the numerical model is then carried out through the coupling with an optimization algorithm, which minimizes the discrepancies with respect to the experimentally obtained modal properties. A pushover analysis, adopting specific constitutive laws for masonry and fill material, is conducted to evaluate the structural performance with emphasis on out-plane response, damage distribution and estimation of collapse mechanism.

Keywords: *Masonry arch bridges, geomatic techniques, operational modal analysis, finite element model updating, nonlinear analysis.*

1. INTRODUCTION

Masonry arch bridges are complex three-dimensional systems whose structural behaviour is greatly influenced by the interaction between its different components. When developing numerical models for assessment purposes, a detailed information about the structural system is crucial for an accurate estimation. However, this is not an easy task due to the large uncertainties associated to this kind of constructions. Among others, the lack of geometrical and material data are the main drawbacks.

Concerning the geometry, masonry bridges are usually materialized in complex shapes. In most situations, drawings about the original design either does not exist or, even if they exist, might not actually represent the final construction due to damage and permanent deformations that might happened during its service life. Furthermore, the inner morphology of the bridge such as information about the spandrel walls and fill material, which plays a key role in the overall resistance and ultimate strength of the bridge, is very difficult to assess.

As for mechanical properties, which are essential for a reliable definition of appropriate constitutive laws within numerical models, they are hardly measurable. Large variability due to the use of natural materials, the effect of past interventions, mechanical degradation processes due to environmental effects and past loading events are, among others, the causes of its difficult characterization.

In this paper a multidisciplinary approach fully based on non-destructive testing techniques, and aimed to solve most of these difficulties, is proposed and applied to a real case study, the Vilanova masonry arch bridge located in the village of Allariz, Spain. For the geometric characterization both a detailed laser scanning and ground penetrating radar survey were conducted. Through their use, precise information about the external geometry of the bridge (including permanent deformations) as well as an estimation of the inner morphology (presence of backing, distribution of fill material and thickness of the spandrel walls) were achieved. A dynamic identification test campaign based on the operational modal analysis was also carried out, which allowed to characterize the dynamic properties of the bridge, namely their natural frequencies and mode shapes.

The overall information was then collected and used for developing a three-dimensional nonlinear finite element model. Within the model, each of the components was individually defined and suitably modelled. Masonry was treated in the context of a macro-modelling strategy and it was modelled adopting a total strain crack rotating model that accounts for the possibility of development of cracks in tension and crushing in compression. Fill material was modelled according to the classical Mohr-Coulomb yield criterion. The finite element model was calibrated resorting to an optimization procedure and on the basis of experimental modal properties. Finally, pushover analysis was conducted to evaluate the structural performance of the bridge.

2. DESCRIPTION OF THE BRIDGE

The Vilanova Bridge is located at the Municipality of Allariz in the northwest region of Galicia, Spain (see Figure 1). Built to span the Arnoia River, it is believed that its origin date from the XIII-XIV centuries, although it is certainly difficult to establish precisely the date due to the numerous processes of restauration that it has experienced along time [1].

Nowadays, the bridge still conserves the use for it was originally conceived, giving support to the local road network of the village and indeed, presenting a relatively high transit traffic. Following the classical pattern of mediaeval bridges, the Vilanova Bridge presents a slightly sloped profile in elevation view with a nearly rectangular-straight shape in planar view. The river is spanned with two arches that rest over a unique pier. Attached to this pier, but not connected, are disposed both a cutwater in the upstream side as well as a kind of buttress in the downstream side.

The arches are constituted with a quite regular arrangement of voussoirs and dry joints, that is, no mortar is present between stone blocks. The average thickness is about 0.7 m. Regarding its main dimensions, the bridge present spans of 11.15 m and 10.94 m respectively, viewing the bridge from the downstream side and from left to right. The corresponding rises at mid-span are 5.32 m and 5.63 m. These dimensions bring a rise to span ratios (r/s) of 0.48 and 0.52, which enable to classify the arches as deep or semi-circular following the criterion proposed by [2]. The width of the bridge, measured along the intrados of the arches in the transversal direction, is 5 m with a free width of the road surface of about 4.40m.

Fig. 1. General view of the Vilanova bridge from (a) downstream side (b) upstream side.

3. EXPERIMENTAL CAMPAIGN

Aimed to obtain the external geometry of the Villanova Bridge in its present form, a high resolution laser scanning survey was conducted, see Fig. 2a. The equipment used was the Riegl LMS Z-390i. In the data acquisition stage and due to the dimensions of the bridge, six scanner positions were needed to entirely capture the whole external geometry. The final global point cloud was composed of 10.643.955 points with a nominal accuracy in the adjustment of 7 mm. For CAD model creation, several methodologies can be applied [3], herein as a compromise between accuracy and demanding effort, the method based on orthogonal views was used. Geometry of the FE model of the bridge was entirely defined in Autocad [4] software and then imported to Abaqus FEM package [5]. Through the process some approximations were made in noncritical areas to eliminate modelling difficulties and easy mesh definition, but special care was put to conserve critical features such as the case of permanent deformations already existing in the bridge. See for instance in Fig. 3 the geometry of one of the arches where a singular in-plane deformation detected during on-site survey was successfully captured by the laser scanning and incorporated into the CAD/FEM model.

The characterization of the inner structure of the bridge was achieved by means of the Ground Penetrating Radar (GPR) method [6], using a RAMAC/GPR system from MALÅ Geoscience. Three different frequencies and acquisition parameters were selected depending on the application and the data required. Using an 800 MHz antenna, the parameters selected for data acquisition were a total time window of 60 ns composed by 613 samples and trace interval of 0.02 sec. The data acquisition was performed in the vertical direction through the accessible parts of the bridge, which allowed obtaining the thicknesses of abutments and spandrel walls and distinguish the presence of backing inside the structure. Under this configuration, GPR profiles along the pathway of the bridge in the transversal direction, were also acquired to determine the paving thicknesses. Finally, in the longitudinal direction, 250 MHz (total time window of 220 ns, 568 samples, trace interval of 0.02 m) and 500 MHz (total time window of 100 ns, 677 samples, trace interval of 0.02 m) antennas were used to obtain additional information about the homogeneity and layering of the infill. As an example of the measurements performed, Fig. 2b shows the GPR data obtained through three different areas belonging to the abutments of the bridge, very close to the springings of the arches.

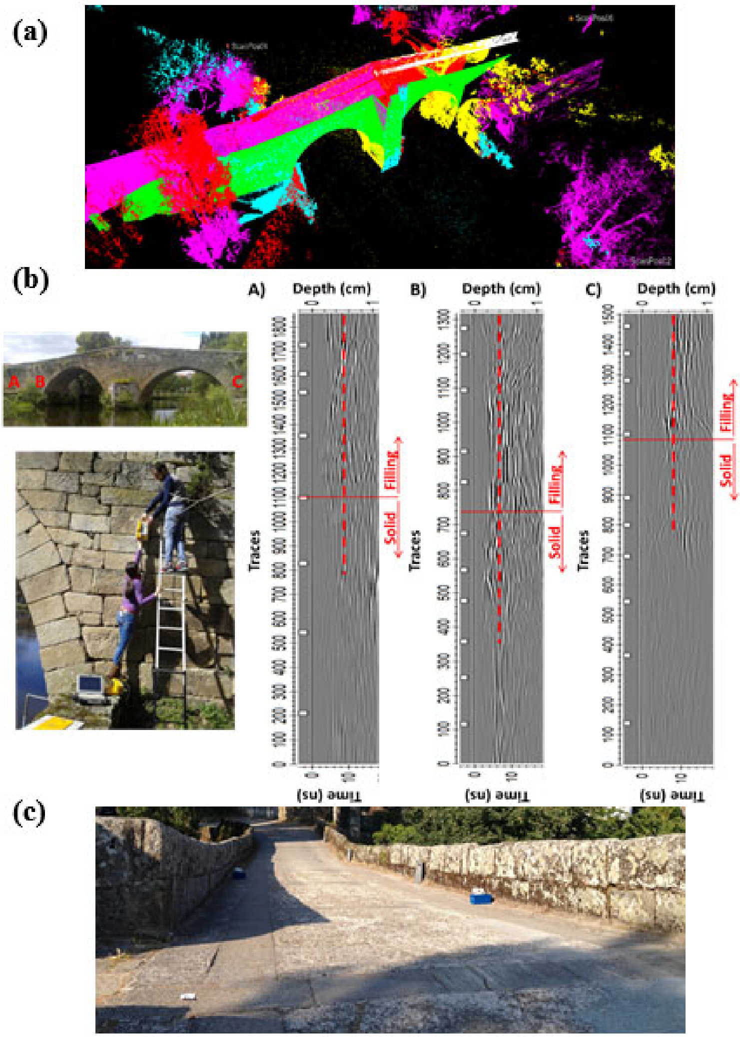

Fig. 2. In-situ non-destructive characterization (a) Point cloud from TLS survey (b) GPR survey (c) ambient vibration test.

Besides the geometric survey, also dynamic identification tests based on operational modal analysis were carried out during the experimental campaign. The fundamental goal was to obtain the most relevant modal parameters of the bridge, i.e. their natural frequencies and mode shapes, to understand how it dynamically behaves and to further proceed with the calibration of the numerical model [7]. Three portable triaxial macro-seismographs GeoSIG-GSM Plus [8], working under GPS time synchronization, were used to register the accelerations of the structure in the vertical, horizontal and longitudinal directions, see Fig. 2c. All the measurements were carried out under the ambient excitations, such as traffic or human walking induced vibrations. Twenty-five points distributed along the deck of the bridge and divided into twelve series of measurements were considered. In each one of these setups, an acquisition time of 15 min with a sampling rate of 200 Hz were adopted. The signal processing was performed using the ARTeMIS Modal software and the Enhanced Frequency Domain Decomposition (EFDD) technique was applied to estimate the modal parameters of the bridge. The first six modes of vibration could be satisfactory identified from ambient vibration tests.

4. FINITE ELEMENT MODEL DEVELOPMENT AND CALIBRATION

The overall information obtained during the experimental campaign was gathered and used as a basis for developing a three-dimensional finite element model of the bridge in the commercial code Abaqus. An overall image of the FE model including mesh discretization is shown in Figure 3. A twenty-node quadratic brick element with reduced integration was used for all the components involved in the model. Accordingly, the total number of elements, nodes and degrees of freedom were 12852, 60243 and 180729 respectively.

For the calibration of numerical model of Vilanova Bridge, the minimization of the differences between the experimental and numerical dynamical properties was taken into account. The objective function originally proposed by [9] was adopted, as follows:

$$\pi = \frac{1}{2}\left[W_f \sum_{i=1}^{n} \left(\frac{f^2{}_{i,num} - f^2{}_{i,\exp}}{f^2{}_{i,\exp}} \right)^2 + W_\theta \sum_{j=1}^{m} \left(\theta_{j,num} - \frac{\theta_{j,\exp}}{\left|\theta_{\exp,ref}\right|} \right)^2 \right] \quad (1)$$

where π is the objective function to be minimized according to the residuals formed by the relative error between the numerical $f_{i,num}$ and experimental frequencies $f_{i,\exp}$ as well as the differences between the numerical $\theta_{i,num}$ and experimental $\theta_{i,\exp}$ mode shapes. In this equation, n and m denote the number of frequencies and mode shapes considered in the updating process, while w_f and w_θ are the corresponding weighting matrices.

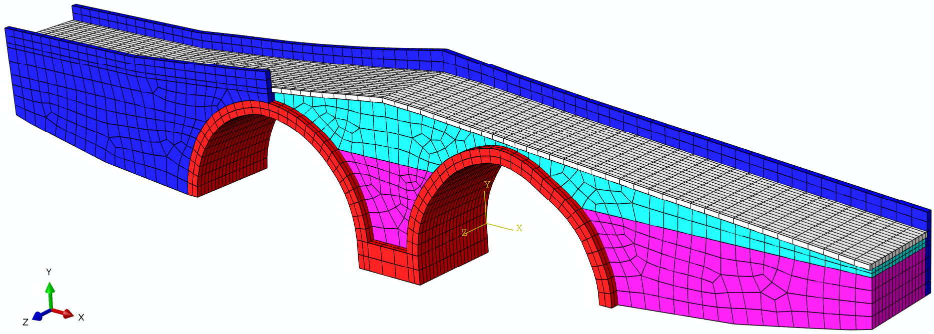

***Fig. 3.** General view of the FE model of Vilanova bridge.*

Five different updating parameters were considered, i.e. Young's modulus of masonry employed in arches, Young's modulus of masonry employed in spandrel walls and abutments, Young's modulus of pier, Young's modulus of infill and Young's modulus of backing. For the updating procedure, the first four natural frequencies and mode shapes of the bridge were taken into account.

The optimization problem was solved in the context of a non-linear least squares formulation with the use of the Trust Region Reflective iterative algorithm. In all optimizations run, lower and upper bounds were imposed to all updating parameters to avoid obtaining unrealistic values. Regarding to the degrees of freedom (DOF) involved in the characterization of mode shapes, 24 measured points in the experimental setups along the deck of bridge were considered, which renders a total of 72 DOF according to the transversal, longitudinal and vertical directions.

Due to the fact that gradient based optimization algorithms, such as the one used in this study, are prone to being trapped into local optima of the objective function, five optimizations analysis assuming different initial values of the updating parameters were carried out, aiming to explore the search space and assessing the possibility of reach global optimum. In general, rather good results were obtained, with an average MAC (Modal Assurance Criterion) value of 0.96 and average frequency errors of about 0.99%.

Moreover, from the obtained results, the variables seem to converge to a close set of values, which might indicate that a global minimum was attained. Only for one optimization case, the results deviated substantially and the reason was the change of order between the third and fourth modes, which leads to a MAC value of 0.48 and an average frequency errors of 2.27%. For the best solution, the final updated variables are reported in Table 1. The results are shown in Table 2 in terms of frequencies and mode shapes, as well as their comparison against experimental data. Finally, Figure 4 shows the comparison between experimental and numerical mode shapes after FE model updating.

Table 1. *Values of material properties obtained after FE model updating.*

Updating Variables	Young`s Modulus [MPa]	Specific Weight [Kg/m^3]
Arches	2660	2500
Spandrel Walls/Abutments	1000	2500
Pier	3000	2500
Backing	176	2000
Infill	100	1700

Table 2. *Comparison between experimental and numerical frequencies and mode shapes after FE model updating.*

Mode Shape	f_{Exp} [Hz]	f_{Num} [Hz]	Error [%]	MAC [%]	Mass part in X [%]	Mass part in Y [%]	Mass part in Z [%]
1st	4.76	4.71	1.04	0.98	0	0	32.21
2nd	6.05	6.10	0.81	0.95	0	0	0.069
3rd	6.74	6.82	1.20	0.96	47.78	0	0
4th	7.71	7.64	0.92	0.97	0	0	22.56

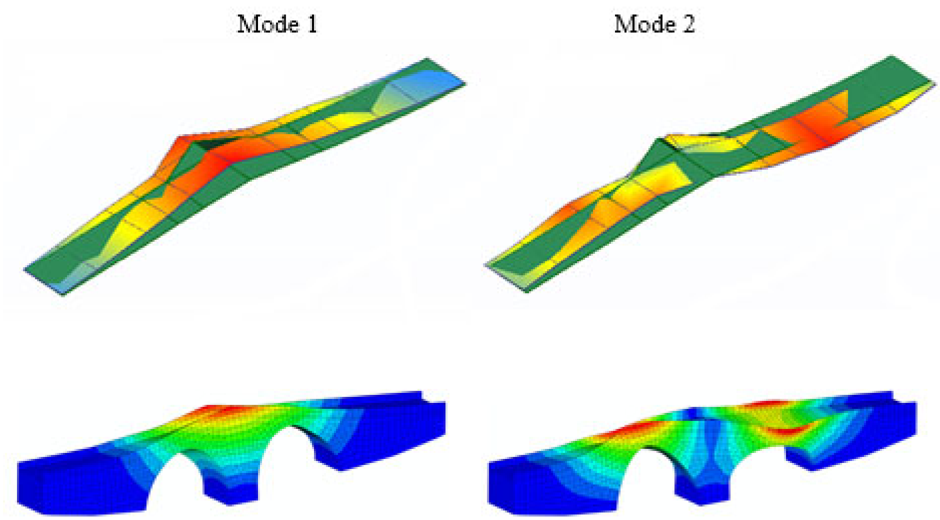

Fig. 4. *Comparison between experimental and numerical mode shapes of the first four modes after FE model updating.*

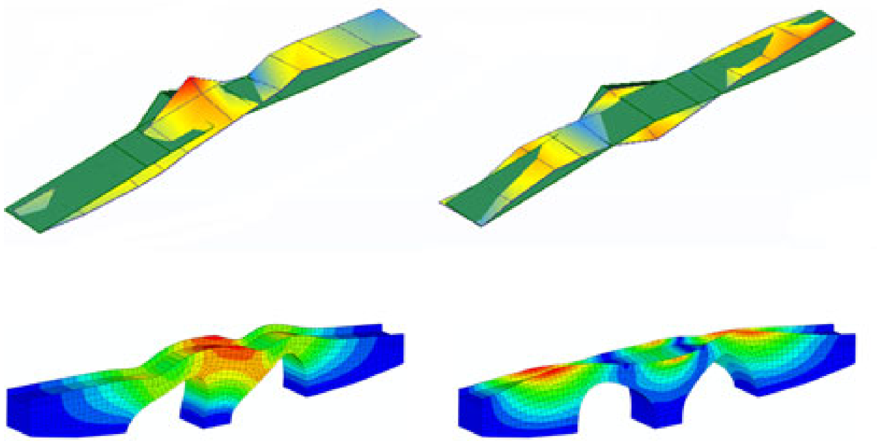

Fig. 4. (Continued).

5. STRUCTURAL ASSESSMENT

To perform the non-linear static (pushover) analysis, the mesh of FE model was imported to Diana software [10]. The non-linear behaviour of masonry was modelled by adopting the total strain crack rotating model (TSCRM), which describes the tensile and compressive behaviour of the material with one stress-strain relationship and assumes that the crack direction rotates with the principal strain axes. A post-peak exponential softening for tensile behaviour and parabolic hardening followed by post-peak parabolic and exponential softening for compression were chosen. Both, tensile and compressive fracture energies, together with the characteristic crack length of the element, were taken into account to avoid mesh sensitivity results. For the 3D solid elements used in this study, the characteristic crack bandwidth was established as the cubic root of the volume of the element.

For all the masonry components of the Vilanova bridge, the masonry compressive strength was considered equal with a value of 2 MPa, which lies in the range of 200 to 1000 proposed by [11] for the relation between the Young's modulus and compressive strength of masonry. The compressive fracture energy was obtained following the recommendations of [12] by adopting a ductility factor of 1.6 mm, which represents the ratio between the fracture energy and the ultimate compressive strength, and which is also the recommended value for a compressive strength lower than 12 MPa. Finally, the masonry tensile strength was assumed equal to 5% of the compressive strength and an average value of 0.1 N/mm was adopted for the mode I fracture energy.

As for infill and backing, both were modelled as a cohesive-frictional materials according to the Mohr-Coulomb yield criterion. As expected, a stiffer behaviour of the backing was received from the calibration procedure, thus indicating the presence of a higher quality material. In agreement, a friction angle of 30º with a cohesion of 20 kPa were adopted for backing, whereas a friction angle of 20º with a cohesion of 20 kPa were chosen for the infill, according to the existing literature [2, 13] and the on-site inspections. Acknowledging the relevance of a sensitivity analysis, a preliminary parametric analysis was carried out considering two different scenarios. Model A, considering an associated flow rule (dilatation angle equal to the friction angle) and without limiting the tensile stresses developed in both materials, and model B, considering a non-associated flow rule (dilatation angle equal to 0) and adopting a tension cut-off value equal to the cohesion [14].

The boundary conditions were applied in agreement with the bridge's surrounding medium. That is, at the base of the arches, abutments and pier, all the degrees of freedom were restrained in the three principal directions. The vertical movement at the base of the backing as well as the longitudinal movements at both ends (also for the infill) were constrained. Finally, at both sides of the abutments, the movements in the longitudinal and transversal directions were also prevented. Pushover analysis was carried out under conditions of constant gravity load, applying a load pattern proportional to the mass in the transversal direction (z axis). Only the positive direction was considered due to the almost symmetry of the structure. The regular Newton–Raphson method, combined with arc-length control and the line-search technique, was adopted to obtain the solution of the nonlinear problem.

Figure 5 shows the capacity curve obtained for both models. The load factor, defined as the ratio between the horizontal load and total weight of the bridge, versus the displacement of a control point placed at the spandrel wall was 0.37g and 0.36g for models A and B, respectively.

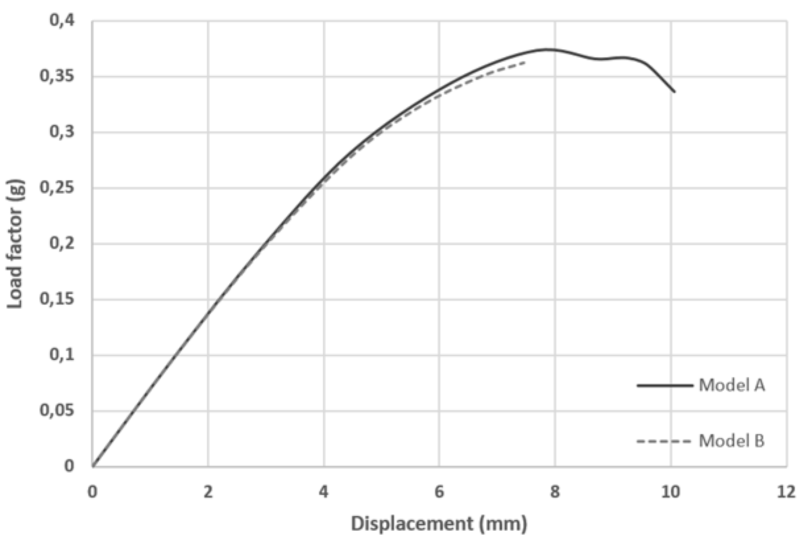

Fig. 5. *Capacity curve of the pushover analyses in transversal direction for models A and B.*

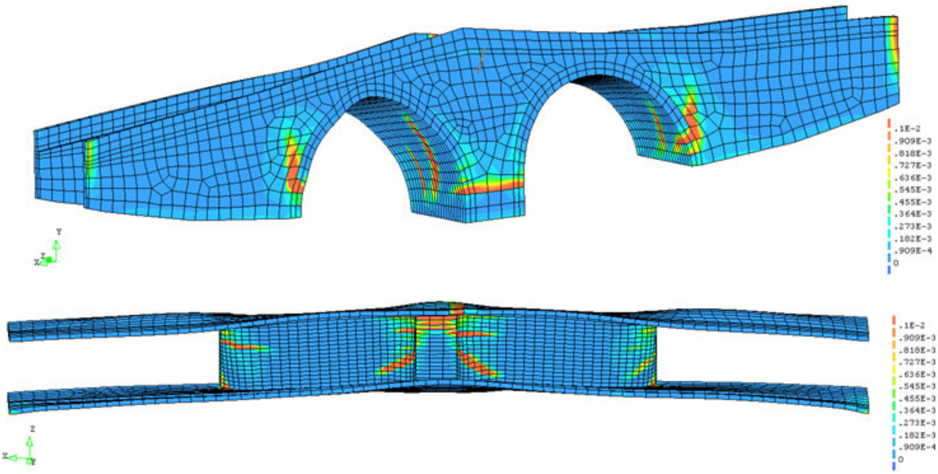

Fig. 6. *Collapse mechanism of Model A from pushover analysis with representation of maximum principal strains (as an indicator of cracking).*

Figure 6 shows the contour plot of maximum principal strains in the bridge for model A, which are assumed as an indication of cracking. The failure of the structure is related to the formation of flexural-shear hinges at the springings of the arches with the abutments, the connection of arches with the pier as well as diagonal cracking along the barrel vaults. Vertical cracking to some extent was also observed at the spandrel wall from upstream side. No significant differences were received from Model B in terms of predicted failure mechanism, and the variations were mainly related to a less intensive damage distribution (cracking) at the arches, which in turn is mainly related to the less ductile response of this model when assuming a non-dilatant behaviour for the fill and backing, which prevents the damage propagation at the arches in the post-peak part of the capacity curve.

6. CONCLUSIONS

In this paper a multidisciplinary approach to study masonry arch bridges was proposed. To develop the methodology, a real case study, the Vilanova masonry arch bridge located in the village of Allariz (Spain) was considered.

The on-site inspections of the structure related with visual damage examination were complemented with a battery of non-destructive surveying methods aimed to gain a deep insight into the unknown constructive details of the bridge. As a matter of fact, masonry bridges are materialized in complex and irregular shapes which demands accurate methodologies able to provide both precise information about the external geometric configuration as well as an adequate knowledge about the inner composition. In this research, both issues were successfully addressed by using laser scanning technology and ground penetrating radar.

Still, additional uncertainties which could substantially deviate real behaviour of the structure from numerical predictions, may remain. Accordingly, inverse analysis approaches based on available data about the system dynamic response could be adopted to estimate unknown input parameters of numerical models. The parameter identification problem, or sometimes simply referred as model calibration, was defined by comparison of the numerically predicted and experimentally obtained dynamic properties of structure. To that purpose, an ambient vibration test was performed to estimate the natural frequencies and mode shapes of the Vilanova bridge.

The overall information was collected and used for developing a three-dimensional finite element model of the structure, where each of its components was individually defined and suitable modelled. Afterwards, FE model was coupled with an optimization algorithm, which, through the minimization of the differences between modal responses, enabled to calibrate the mechanical parameters of the bridge in the elastic range. Satisfactory results were obtained for the first four frequencies and modes considered, with an average frequency error of 0.99% and average MAC value of 0.96. Indeed, since a gradient based optimization algorithm was chosen, various optimizations analysis assuming different initial values for the updating variables were performed to ensure reliability in parameter identification.

The structural assessment of the bridge was carried out through a nonlinear static (pushover) analysis in the transverse direction, which is typically the most vulnerable one, aiming at identifying critical areas as well as potential failure mechanisms related with the out-of-plane response of the structure. Overall, considering the low seismicity of the region as well as the results obtained from a reasonable set of mechanical properties, the Vilanova Bridge seems to present an acceptable level of performance. Still, further studies might include carrying out additional analyses taking into account different load cases in order to gain a broader perspective of the actual condition of the bridge. It is also pointed out also the interest of performing a comprehensive sensitivity analysis to investigate the changes in structural response regarding to the variation of masonry and soil material properties.

ACKNOWLEDGEMENT

Authors would like to acknowledge Dr. Mercedes Solla for the valuable technical contributions to this work as well as for making available the relevant data about GPR prospection.

REFERENCES

[1] ALVARADO S, DURÁN M, NÁRDIZ C., *Puentes históricos de Galicia*. Colegio Oficial de Ingenieros de Caminos, Canales y Puertos, Xunta de Galicia, Santiago de Compostela, 1989, Spain (in Spanish).

[2] OLIVEIRA DV, LOURENÇO PB, LEMOS C., Geometric issues and ultimate load capacity of 0masonry arch bridges from the northwest Iberian Peninsula, *Eng Struct, 32*, 2010, pp. 3955–3965.

[3] RIVEIRO, B., CONDE-CARNERO, B., ARIAS, P., Laser Scanning for the Evaluation of Historic Structures. In Asteris, P. G., & Plevris, V. (Eds), *Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures (2 Volumes)*, Hershey, PA, IGI Global, 2015, pp. 765-794.

[4] Autodesk, 2016. AutoCAD. ⟨http://www.autodesk.com/products/all-autocad⟩. Last visit: 02.02.16

[5] ABAQUS. Theory manual, version 6.12; 2012.

[6] ANNAN, P., *GPR Principles Procedures and* Applications, Sensors and Software Inc. 2003.

[7] Ramos LF., *Damage identification on masonry structures based on vibration signatures*, PhD thesis, Guimarães, 2007, University of Minho.

[8] GMSplus User Manual, GeoSIG Ltd. (http://www.geosig.com). Last visit: 02.02.16.

[9] A. TEUGHELS, *Inverse modelling of civil engineering structures based on operational modal data*, Ph.D. Thesis, 2004, Catholic University of Leuven.

[10] DIANA, DIsplacement method ANAlyser, CD-ROM, Release 9.6. Netherlands, 2015.

[11] TOMAZEVIC M., *Earthquake-resistant and design of masonry buildings,* 1999, London, Imperial College Press.

[12] P. B. LOURENCO, 2009, *Recent advances in masonry structures: Micromodelling and homogenization, In Multiscale Modeling in Solid Mechanics: Computational Approaches,* ed. U. Galvanetto & M.H. Ferri Aliabadi, Imperial College Press: London, pp. 251-294.

[13] CAVICCHI A, GAMBAROTTA L., Two-dimensional finite element upper bound limit analysis of masonry bridges, *Comput Struct*, 84, 2006, pp. 2316–2328.

[14] MILANI, G., LOURENÇO, P.B. 3D non-linear behaviour of masonry arch bridges, *Computers and Structures 110-111*, 2010. pp. 133-150.