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Dynamic characterization of a severely damaged historic masonry bridge

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Abstract

The paper presents the preliminary results of an ongoing research on a masonry arch bridge in the neighborhood of Todi (Umbria, Italy). A multidisciplinary approach integrating geometric survey, dynamic testing and numerical modeling is presented aimed to assess the structural performance of the ancient bridge.

A photogrammetric survey based on high resolution images provided by UAV (Unmanned Aerial Vehicle) has been processed in order to obtain a 3D numerical model and to map the crack layout. Ambient and forced vibration tests have been carried out using laser vibrometer, radar interferometer and seismic accelerometers. Experimental data have been processed by operational modal analysis and the results have been compared with the numerical results given by a simplified model.

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Keywords: Masonry arch bridge, Dynamic identification, Experimental tests, Operational Modal Analysis, Image-based survey, Architectural heritage.

1. Introduction

The preservation of cultural heritage is of primary concern especially in all those countries where history delivered significant architectural heritage, which is exposed to the inherent degradation in time and to natural hazards (e.g. seismic loads). Within this context it is crucial to develop effective tools in order to characterize the significant structural parameters and to follow their evolution in time, considering both the complex geometry and the material heterogeneity denoting old masonry buildings [1–3].

The experimental work described in this paper follows a preliminary investigation on a single span masonry bridge located in the neighborhood of Todi (Umbria, Italy), whose actual conditions indicate the need of restoration procedures to limit the damage process and to avoid the loss of an important historical and architectural heritage (Fig.1). It is believed that the current condition is the result of several restoration processes over time built on the foundations of an old Roman bridge. For this reason the structure is also known as the ”Roman bridge”. Nevertheless, both the

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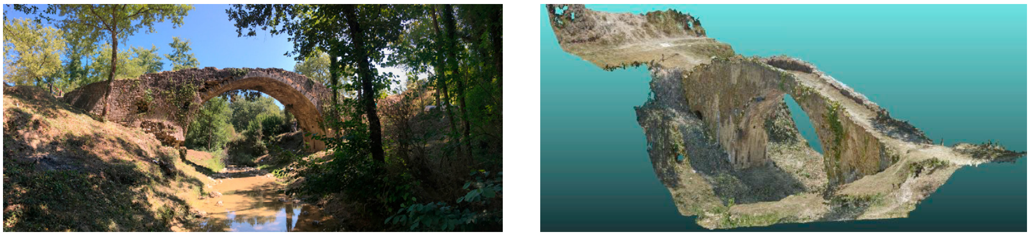


Fig. 1. The Roman bridge in Todi: (a) photo and (b) virtual 3D Model.

construction techniques and the materials are typical of the high Middle Age. Until the 19th Century the bridge was the only one crossing the Arnata river, becoming the only local transport route.

The bridge is a segmental polycentric arch structure with a span of 10.5 m and a rise of 4.23 m. The cross section width of the deck is variable with a minimum of about 3.56 m at the mid span and maximum value at the abutments.

The structure exhibits typical mechanical deterioration phenomena: longitudinal cracks below the vault (Fig.2(a)), material detachment in the voussoir (Fig.2(b)) as well in the spandrel wall and damage of the West (Fig.2(c)) and East abutment. The damage level of the masonry is even worsened by vegetation grown between the cracks of the stones.

A multidisciplinary approach is presented integrating an accurate geometrical survey based on high resolution image processing, dynamic testing, and Finite Element Method (FEM).

In the last years the possibility to perform 3D surveys of complex and unaccessible constructions is having a growing interest [4] together with the development of non-contact measurements for structural identification [5]. In this paper close range digital images were taken using UAVs, commonly known as drones, in order to map the crack layout of the bridge and to develop a consistent 3D numerical model. Furthermore, full-scale ambient and forced vibration tests have been carried out using nine contact high sensitivity seismic accelerometers and contactless techniques based on Laser Doppler Vibrometry and Radar Interferometry. Measurements of displacement, velocity and acceleration have been recorded in order to estimate dynamical parameters, mainly natural frequencies and mode shapes. The experimental results have been compared with those obtained with a FEM model reported in [6]. Research is still in progress to calibrate a suitable FEM model and to evaluate the effect of both the damage and the restoration measures on the dynamic structural features.

2. Photogrammetric survey and 3d Model from UAV technology

The size of the bridge as well as the morphological characteristics of the site made an optimal case study to perform architectural and geometrical survey based upon high resolution images provided by UAV technology. The framework used in this experimentation can be summarized in three main steps: operation planning, data acquisition and processing, post processing representations.

Drone flights were planned in order to have a suitable number of superimposed high resolution images. Different data sets were used to obtain the complete layout of the whole structure, the plan view, the two elevations and the lower side of the vault. Markers were used for a proper image matching and alignment. The flight altitude was determined in order to obtain the target level of accuracy. Manual shots were taken to complete the image data sets,

Fig. 2. Structural details: (a) cracks on the vault, (b) material detachment from the voussoir and (c) damage of the West abutment.

which consisted of 307 snapshots. A final point cloud with more than 31 million points was developed (Fig.1(b)) and each pixel at the center of the original photo is able to represent a 5 mm portion of the bridge.

3. Laser doppler vibrometer and radar Interferometer measurements

3.1. Brief decription of the measuring system

The laser doppler vibrometer used in this work is a Polytec OFV 3001 - OFV 303, controller and sensor head, with resolution 0.25 nm, constant in the whole frequency range from 0 Hz to 250 kHz. In order to improve signal quality it was decided to use reflecting targets applied on the keystone section at the intrados of the arch.

The IBIS-FS ground based radar interferometer is characterized by a range resolution ΔR equal to 0.75 m. The test set up was completed adding two passive radar reflector along the measuring direction in correspondence of the arch keystone section. Fig.3(d) shows the laser vibrometer and the radar interferometer positions used in the experimental measurements. Since the two instruments measure along their line of sight the recorded data have been processed along the vertical direction.

A sampling frequency of 1000 Hertz was set for the laser vibrometer while 200 Hertz was set for the radar interferometer. Impulsive loading condition and periodically varying force were induced by jumps at the keystone section and by synchronous walking and running upon the entire span of the bridge, respectively. Ambient vibration test were also recorded but it was not possible to obtain significant information given the very low level of vibration. Loading conditions are summarized in Table 1.

3.2. Results of contactless measurements

Fig.4 shows the displacement time histories obtained by the laser vibrometer and radar interferometer. Two different loading conditions are highlighted: synchronized walking and single vertical jumping. Left panels refer to laser vibrometer, while right panels report radar interferometer measurements. Fig.5 shows the the power spectral densities estimated from 10 s of the displacement time histories for each loading condition. The left and the right panels report the results obtained from the laser vibrometer and radar interferometer measurements, respectively.

The main frequency values can be estimated performing a peak-picking in the frequency domain. These values are summarized in Table1 both for laser vibrometer and radar interferometer data. The results comparison shows that the radar interferometer measures seem to have a lower accuracy with respect to laser vibrometer measurements. It is

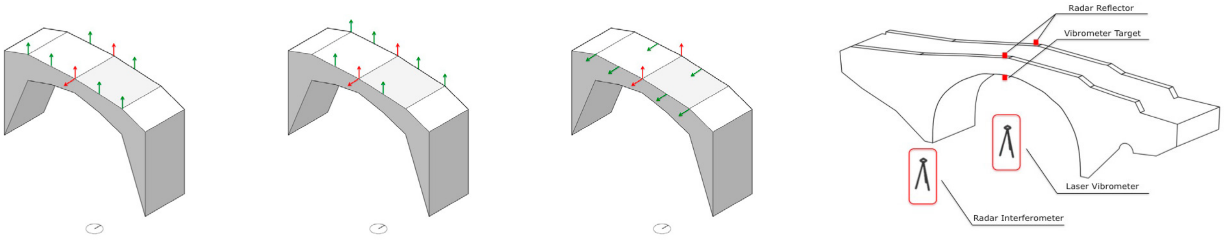


Fig. 3. Ambient vibration tests: accelerometer position in (a) Setup-1 (b) Setup-2 and (c) Setup-3. (d) Tridimensional view of the contactless measuring setup.

Table 1. Frequency values estimated from the laser vibrometer and radar interferometer displacement time history.

Loading Conditions	Laser Vibrometer	Radar Interferometer
c1: sinchronyzed walking	f_1 = 8.79 f_2 = 16.60	f_1 = 9.18 f_2 = 17.58
c2: single vertical jumping	f_1 = 8.79 f_2 = 16.85	f_1 = 9.32 f_1 = 17.72
c3: four people running	f_1 = 8.55 f_2 = 16.11	f_1 = 9.27 f_2 = 17.14
c1: single person running	f_1 = 8.55 f_2 = 16.60	f_1 = 9.13 f_2 = 17.72

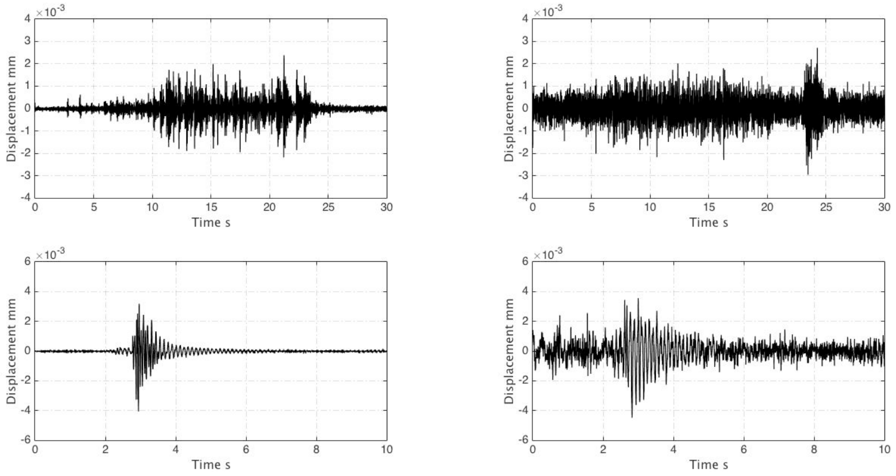


Fig. 4. Displacement time histories from the laser vibrometer (left panels) and radar interferometer (right panels) for sinchronyzed walking (upper panels) and single vertical jumping (lower panels).

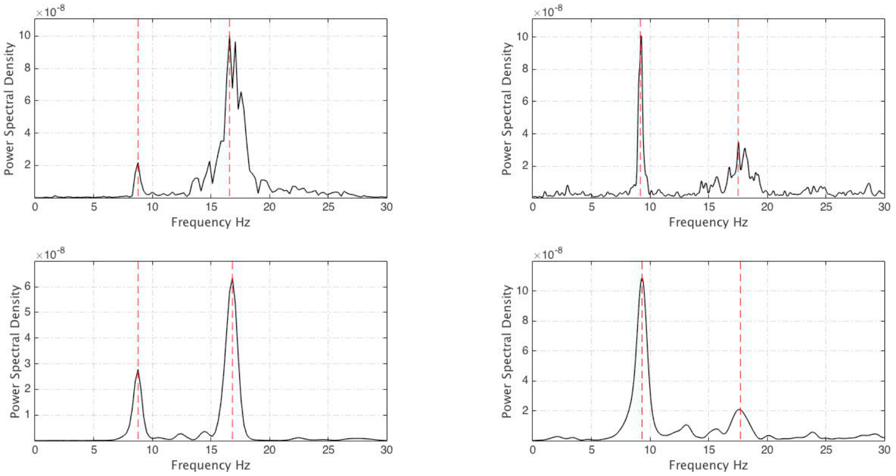


Fig. 5. Power spectral densities estimated from the laser vibrometer (left panels) and radar interferometer (right panels) measurements for synchronized walking (upper panels) and single vertical jumping (lower panels).

worth to notice that the frequency values obtained with all the type of excitation are slightly different because of the accuracy of the signal processing.

4. Operational Modal Analysis

The dynamic characterization in terms of natural frequencies and corresponding modal shapes has been performed by Operational Modal Analysis (OMA) using vibration response in operating conditions using classical contact measurements.

4.1. Measurement procedure

The dynamic response of the masonry arch bridge has been measured using nine uni-axial accelerometers model PCB 393B12 (10V/g sensitivity) located in different positions in order to obtain three different setups, to be used for the identification of vertical, horizontal and torsional vibration modes. The three sensor layouts are reported in Fig.3(a),(b) and (c).

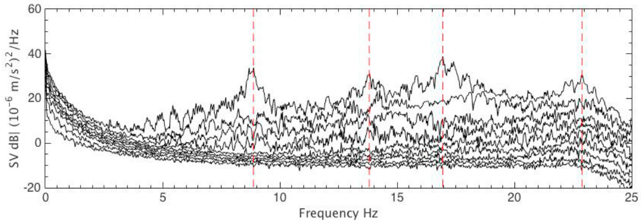


Fig. 6. Singular value of Setup 1: peak picking and dominant frequencies.

The testing methodology consisted in three different measurements, each recording 900 s time series with sample rate of 1653 Hertz. This value is due to the anti-aliasing filter when the sample rate is fixed at 1000 Hertz. Three sensors have been installed in correspondence of the keystone section of the arch as a reference system for the analysis: two sensors are placed in the downstream section, giving measurements in both vertical and transversal direction while the third sensor is placed in the upstream section giving measurements in vertical direction (red arrows in Fig.3(a),(b) and (c)).

4.2. Signal processing - FDD and EFDD

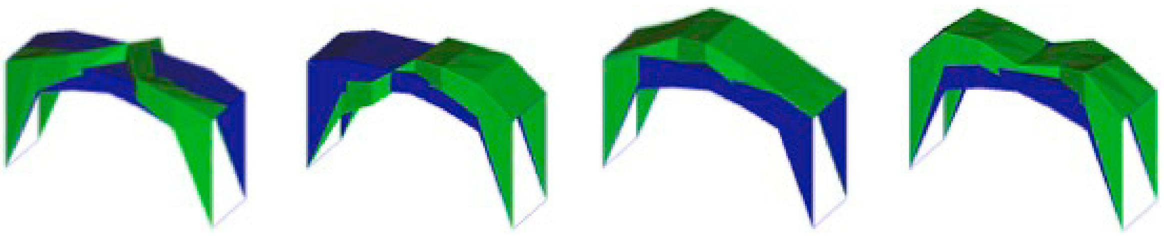
Since the power spectral density spectrum estimated from the raw acceleration data show a significant content in the range of frequencies lower than 20 Hertz and considering the results of the spectral analysis on the laser vibrometer and radar interferometer data, the ambient vibration data have been processed with a decimation of order 30, a low pass filter of order 3 with a cut-off frequency equal to 27.548 Hertz.

Natural frequencies and vibration modes of the masonry arch bridge were estimated using the Frequency Domain Decomposition approach (FDD and EFDD). Figures 6 and 7 show the singular values of the spectral density matrices of setup 1 and the estimated natural frequencies and mode shapes, respectively.

5. Remarks and discussion

The experimental results in terms of natural frequencies and related mode shapes presented in the previous section have been compared with the numerical results given by a 3D finite element model proposed in a previous work [6]. In this paper, the simplified preliminary numerical model was based on a geometrical survey carried out by direct methods. Materials were characterized by historical research and visual inspections and the italian code was used to select the values of the mechanical and physical parameters of the numerical model given the lack of specific laboratory tests. The damage of the bridge was considered spread all over the structure, selecting suitable values of the elastic (E) and the shear (G) moduli. Figure 8 shows the results of the numerical modal analysis.

It is worth to note that the preliminary FEM model in [6] was calibrated on the single point laser vibrometer measurements so that only the natural frequencies could be used. Thus, no information were available on the experimental mode shapes. As expected the comparison between the results in Figures 7 and 8 shows a good agreement between



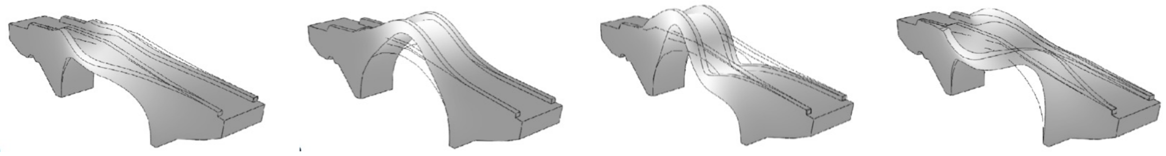
(a) First Out of Plane Mode f_1 = 8.79 Hertz

(b) First In Plane Mode f_2 = 13.81 Hertz

(c) Second In Plane Mode f_3 = 16.95 Hertz

(d) Third In Plane Mode f_4 = 22.81 Hertz

Fig. 7. Experimental frequencies and vibration modes.



(a) First Out of Plane Mode $f_1^{FEM} = 9.43$ Hertz

(b) First In Plane Mode $f_2^{FEM} = 14.19$ Hertz

(c) Second In Plane Mode $f_3^{FEM} = 15.36$ Hertz

(d) Second Out of Plane Mode $f_4^{FEM} = 15.96$ Hertz

Fig. 8. Numerical frequencies and vibration modes from [6].

the experimental and numerical natural frequencies. The same cannot be said when comparing the mode shapes. In particular, the first and second experimental in plane modes are inverted with respect to the corresponding numerical modes. This is consistent also in higher order mode shapes. Point cloud of Figure 1(b) is being used to obtain a more accurate FEM model, which takes into account the significant geometric irregularities given by the degradation process of the masonry arch bridge. These irregularities can be responsible of the found differences between the numerical and experimental dynamic behavior.

6. Conclusion

The results of dynamic investigations on an ancient severely damaged masonry arch bridge were presented in this paper. In particular, contact and contactless non destructive tests were performed using high sensitivity piezoelectric accelerometers, a laser vibrometer and a radar interferometer. The vibration tests were aimed both to compare effectiveness of different measurement techniques on such constructions and to perform dynamic structural identification. A preliminary comparison between the experimental OMA results and a simplified numerical FEM model demonstrated the need to take into account the effect of the damage on the geometry of the structural system. Work is in progress in developing a more accurate 3D model of the arch bridge using the geometrical survey obtained by the UAV technology and photogrammetry technique. The experimental tests will be repeated at the end of the on going restoration process in order to investigate the change of the dynamic properties with the structural strengthening. This will give useful information on the effect of severe damage on masonry arch bridges.

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