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Dynamic Identification of the Damage for a Parabolic Tuff Barrel Vault with Differential Settlements of the Supports

Anna Castellano[1], Aguinaldo Fraddosio[1], Jacopo Scacco[2], Gabriele Milani[2], Mario Daniele Piccioni[1]

[1] *Department of Civil Engineering Sciences and Architecture, Polytechnic University of Bari, Via Orabona 4, 70125, Bari, Italy, anna.castellano@poliba.it, aguinaldo.fraddosio@poliba.it, mariodaniele.piccioni@poliba.it*

[2] *Department of Architecture, Built environment and Construction engineering ABC, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133, Milan, Italy, jacopo.scacco@polimi.it, gabriele.milani@polimi.it*

Abstract **– The dynamic identification of structural damage for masonry constructions could play a crucial role for the preservation of architectural heritage. The interest is this experimental technique is motivated both by its non-destructive nature and by the possibility of assessing the damage at an early stage.**

In this context, this paper studies the damage identification of a full-scale parabolic tuff barrel vault subjected to differential settlements of the supports starting from vibration measurements.

The geometry of the vault (polycentric near parabolic shape) and the masonry material (Apulian tuff) have been chosen in order to be representative of some masonry vaults common in rural constructions of Apulia region.

I. INTRODUCTION

In order to preserve ancient masonry constructions, the Structural Health Monitoring (SHM) [1-2] and the damage identification techniques [3,4] based on non-destructive experimental approaches could be very effective. Indeed, only through the support of effective experimental investigations is possible to accurately characterize the internal features, the structural behavior, and the eventual damage of the construction and, on this knowledge base, to design appropriate and not disproportionate strengthening intervention, compliant with restoration rules.

In the last decades, dynamic based methods have been proposed for damage identification of large civil constructions [5-6], but there are few works concerning masonry structures [7-8], where major difficulties arise. Indeed, masonry structures have generally very large mass and stiffness, and consequently ambient vibrations are usually of small amplitude. Moreover, masonry structures are characterized by a non-linear response already for low stress levels, due to the negligible tensile strength resulting in a substantially unilateral behavior of joints. The above justify the need of further theoretical and experimental research, as testified by recent experimental papers appeared in literature and concerning the structural diagnosis of large masonry arched structures [9], the Operational Modal Analysis approaches for the dynamic identification of historical towers [10], the assessment strengthening interventions on masonry barrel vaults [11], the development of automated data analysis method for static structural health monitoring of historic masonry constructions [12], the correlation between the vulnerability and the activation of kinematic mechanisms and dynamic identification results [13] and the correlation between experimentally identified modal features and the damage progressively induced by horizontal settlements of the supports of a masonry arch [14].

In this vein, the present paper represents a contribution in experimental research on the response of damaged historical constructions in dynamic identification tests.

The source of damage here considered is represented by foundations vertical settlements. Notice that compared to horizontal settlements (see, e.g., [14]), vertical settlements are much difficult to be obtained in experimental tests in laboratory on large scale masonry models, but are representative of a class of structural disease very common for historical masonry buildings.

In particular, the vibration response of a polycentric near parabolic tuff barrel vault under differential settlements of the abutments has been experimentally examined.

The experiments, performed on a full-scale vault, required a quite complex setup, ad hoc designed [15-16]. The structural behavior of the masonry vault, as differential settlements of the abutments step by step was increased, was continuously monitored through several sensors placed in appropriate points of the intrados and extrados of the structure. Specifically, starting from the data acquired by 24 accelerometers, the damage progressively induced in the structure was dynamically identified based on the changes of modal frequencies and modal shapes.

During the test the vault has been subjected, in addition to the self-weight, to a distributed load representative of the weight of the infill.

Results obtained by reprocessing dynamic data show that the damage leads to a evident change in the modal features (modal frequencies and modal shapes) of the vault, indicating that the examined experimental technique could be very effective for the identification of the damage for curved masonry structures, and suggesting further directions of investigation in view of developing approaches also capable of characterizing and locating damage.

II. EXPERIMENTAL TESTS

A. Geometry and materials of masonry vault

The experimental tests on the full-scale masonry vault were performed at Laboratorio Ufficiale Prove Materiali “M. Salvati” of Polytechnic University of Bari.

The examined barrel masonry vault was designed and built specifically to reproduce both the geometry and the materials of some vaults widespread in historical towns of Apulia (Italy).

In particular, the vault has a raised, polycentric profile, whose shape is more similar to the parabola than to the circumference [15-16]. The span is 346 cm and the rise 120 cm (Fig. 1).

Fig. 1. Tuff barrel masonry vault.

For the construction of the vault, the voussoirs were made by cutting blocks of the so-called “Apulian tuff”, coming from stone quarries of Gravina in Puglia. A lime-cement mortar with low mechanical properties very similar to the properties of mortars used in rural tuff constructions was employed for the joints.

The mechanical properties of materials have been determined by mechanical tests. In particular, according to UNI EN 772-1:2011 and UNI EN 1926:2007 standard compression tests on 6 cubic tuff samples having average mass density 1400 kg/m^3 were performed.

From the experimental results, it was possible to determine for the bricks the average compressive strength f_{bm}=2.25 MPa, the characteristic compressive strength f_{bk}=1.87 MPa and the average Young modulus E_m=637.39 MPa [17].

Moreover, according to UNI EN 1015-11:2007, compression and flexural tests (three-point bending tests) were performed on 6 prismatic samples of the mortar with average mass density 1883.98 kg/m^3.

Then, the flexural strength f_{mf}=1.91 MPa, the compressive strength f_{mc}=8.94 MPa and the average Young modulus E_m=6902.27 MPa of the mortar have been determined.

B. Experimental setup

A suitable experimental setup has been designed, allowing for the control of the vertical settlement of one of the two supports of the vault. In particular, the two supports of the vault were made by steel beams: one fixed, while the other could be moved by a hydraulic jack, allowing for imposing vertical displacements of one of the abutments of the vault. Two additional steel beams placed on the top lateral shoulders of the vault gave further constraints, avoiding rigid rotations of the whole structure.

During the tests, the mechanical response of the vault was continuously monitored through different sensors (Fig. 2) placed in suitable points of the vault and on supports [15-16]. In particular, 9 electrical strain gauges have been applied to the intrados of the vault along the middle axis (named SI1, …, SI9 in Fig. 2); 7 electrical strain gauges have been applied to the extrados of the vault along the middle axis (named SE1, …, SE7 in Fig. 2); 8 pairs of monoaxial accelerometers have been mounted at the extrados of the vault, with measuring directions oriented tangent and orthogonal to the vault, respectively, and placed symmetrically with respect to the middle axis of the vault (named A1, …, A8 in Fig. 2); 4 pairs of monoaxial accelerometers have been mounted at the abutments for acquiring the reference vibration signal (named A9, …, A12 in Fig. 2); 6 potentiometric displacement transducers have been connected by 6 plumb-lines to suitable points of the intrados of the vault (named P1, …, P6 in Fig. 2); 2 LVDT displacement transducers (named LVDT1, LVDT2 in Fig. 2) have been applied on the support steel beam capable of vertical displacements and controlled by the jack.

After the construction of the vault, 40 sandbags were placed on the shoulders of the vault in order to simulate the infill load (Fig. 3), with a total weight of 840 kg.

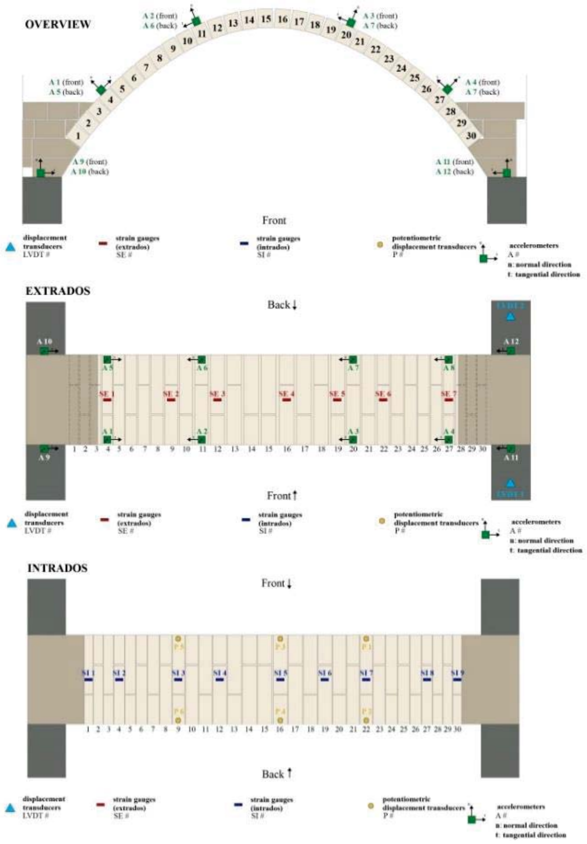

Fig. 2. Sensors placed in suitable points of the vault.

The test was carried out by applying gradually the differential settlements of the abutments by subsequent incremental steps in order to induce damage in the structure. At the end of each settlement step, first a visual inspection was performed in order to evaluate the emergence of cracks. Then, the dynamic response of the vault was acquired by the accelerometers using both Gaussian white noise signals generated by a high-power loudspeaker for exciting vibration of the structure, and the ambient vibration of the laboratory test hall.

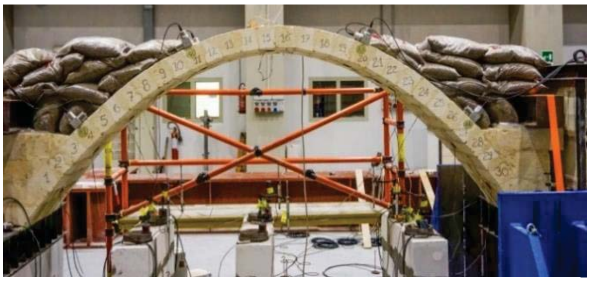

Fig. 3. Experimental setup.

C. Experimental results

The test was interrupted when cracks formed transforming the vault in a statically determined structure, thus capable of adapting to differential settlements of the abutments by rigid body displacements. This happened at the 11th step, corresponding to about 17 mm of relative vertical displacement of the abutments.

Fig. 4 The three crack hinges.

In particular, the cracking hinges due to the imposed differential settlements formed in positions compatible to those characterizing the collapse mechanism of a circular arch under vertical supports settlements without rotations of the abutments (the mechanism labeled “III” in [18]). In particular, an intrados cracking hinge formed in correspondence of the joint between voussoirs 23 and 24, and two extrados cracking hinges appeared in correspondence of the joint between voussoirs 14 and 15, and of voussoirs 11 and 10, respectively (Fig. 4).

According to the observations in [19], the slight differences from the cited mechanism in [18] are likely ascribable to the shape of the vault (that is parabolic rather than circular), by the different embrace angle and by the different thickness-to-radius ratio.

III. DAMAGE IDENTIFICATION

The damage identification is based on experimental data acquired by 24 seismic flexural accelerometers (PCB Piezotronics 393B05), with a bandwidth ranging from 0.7 to 450 Hz (±5%), a dynamic range of ±0.5 g, a sensitivity of 10 V/g, connected by coaxial cables to a data acquisition system with a 24 bit ADC. Ad hoc software in LabVIEW (2018) was developed to acquire the data.

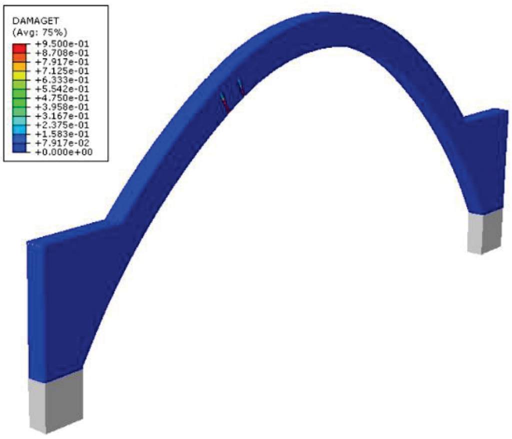

Fig. 4. Numerical model of the vault.

The placement of the accelerometers in suitable points of the structure has been evaluated by a preliminary estimation of modal parameters obtained by 3D Abaqus FEM heterogeneous model where all the components of the structure (tuff bricks, mortar joints) have been separately modeled. The non-linearities are assigned taking advantage of the Concrete Damage Plasticity model (Fig. 4).

This numerical analysis was performed in order to better design the dynamic tests and to obtain a reference for the modal frequencies and shapes of undamaged and damaged masonry vault.

The performed dynamic tests aim at studying the variation of the modal properties of the vault as the damage progresses. Indeed, damage results in a degradation of the stiffness, and in a variation of the overall structural behavior due to hinges opening.

A very large quantity of data has been acquired but, for the sake of brevity, here are compared results obtained analyzing vibration data in the initial stage, before the damage, and in the final stage, when the maximum damage of the vault has been induced by the imposed differential settlements of the abutments.

For each of these two phases, the modal identification tests were carried out by employing 5 different dynamic excitations: 1) ambient noise of the laboratory test hall; 2) an artificial Gaussian white noise signal of frequency 55 Hz; 3) an artificial Gaussian white noise signal of frequency 110 Hz; 4) an artificial Gaussian white noise signal of frequency 145 Hz; 5) a an artificial Gaussian white noise signal of frequency 220 Hz. The excitations 2)-5) have been realized by using a frequency sound generator and a 100 mm loudspeaker mounted driven by a 300 W amplifier.

The data acquired during the identification tests were analyzed by using the software ARTeMIS Modal. As the first results, the modal features obtained from the white noise excitation of frequency 55 Hz and by applying the Enhanced Frequency Domain Decomposition (EFDD) approach, an improvement of the classical Frequency Domain Decomposition (FDD) technique, are presented in this paper.

In particular, in Tab. 1 the first 6 modal frequencies obtained from the numerical FEM model and the modal frequencies estimated by reprocessing dynamic data through ARTeMIS, relating both to undamaged vault (UV) and damage vault (DV) are reported.

First, it is possible to see that the modal frequencies determined by the numerical FEM model are in good agreement with those determined by structural dynamic identification, except for the highest modes (modes 5 and 6). This, in the case both of the undamaged and the damaged vault. In particular, for modes 5 and 6 the experimental frequencies are quite higher than the numerical ones. This discrepancy can be reduced by a model updating procedure, considered not essential for the present study since the substantial agreement of the first modes results.

Furthermore, by comparing data referred to the undamaged vault to those acquired for the damaged vault, it is possible to observe an evident reduction in the modal frequencies of the masonry vault induced by the damage. The above occurs both in numerical and experimental results.

Table 1. Modal frequencies [Hz] obtained from the numerical FEM model and ARTeMIS estimation for the undamaged (UV) and damaged (DV) vault.

Modes	UV FEM model	UV ARTeMIS estimation	DV FEM model	DV ARTeMIS estimation
1	3.128	3.498	3.079	3.498
2	6.806	7.497	5.797	6.497
3	16.107	15.493	13.748	12.994
4	19.748	19.991	16.256	14.993
5	24.954	30.986	20.044	29.987
6	25.813	43.481	24.016	41.181

From the quantitative point of view, Table 2 show the variation of modal frequencies both numerically and experimentally determined due to the damage. It is easily seen that the first modal frequency appears to be unsensitive to the damage, since it undergoes a very small variation in the numerically evaluated data, and no variations for the experimentally determined data. The frequencies of upper modes, from 2 to 4, are instead very sensitive to damage, undergoing reductions of the order of 15-25%, consistently with the degradation of the stiffness induced by the damage. Also modal frequencies 5 and 6 are affected by the damage, although in a less marked way.

Table 2. Variation of modal frequencies due to the damage [Hz]: results obtained from the numerical FEM model and from ARTeMIS.

Modes	FEM model	ARTeMIS estimation
1	1.57%	0.00%
2	14.83%	13.34%
3	14.65%	16.13%
4	17.68%	25.00%
5	19.68%	3.22%
6	6.96%	5.29%

In Fig. 5, the first 6 modal shapes of the undamaged (UV) and damaged (DV) vault, experimentally estimated using by ARTeMIS software, are shown.

The comparison between UV and DV results shows that the first modal shape is scarcely affected by the damage that, on the contrary, induces a variation of the shape of higher modes, particularly evident starting from mode 3. This is motivated from the fact that the more complex modal shapes, characterized by a higher number of nodal points, are more affected by the damage especially when it consists in the local opening of hinges.

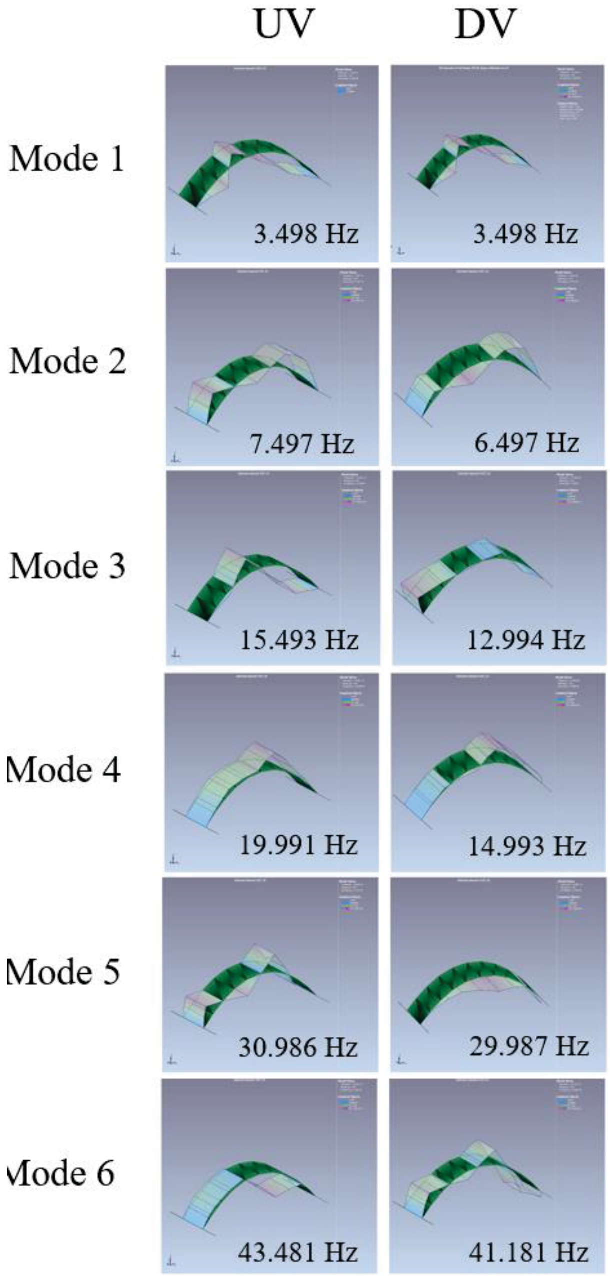

Fig. 5 Experimentally determined shapes for the first principal modes – undamaged (UV) and damaged (UV) vault.

Similar differences between the modal features (modal frequencies and modal shapes) of the undamaged and damaged vault have been obtained with reference to artificial excitations 3)-5). But reprocessing dynamic data obtained with ambient excitation 1) yields to less clear results.

IV. CONCLUSIONS

Some preliminary results of a dynamic damage identification test performed on a full-scale parabolic tuff barrel vault are presented and discussed. In particular, the damage is induced by differential support settlements.

Experimental results show that the damage leads to a evident lowering of modal frequencies and to a variation of modal curvature shapes between the damaged and undamaged masonry vault, especially for modes higher than the fundamental one.

In particular, the possibility of observing large variations of the modal frequency induced by the damage is very interesting, since the modal frequency are much easier to be identified with respect to modal shapes. Thus, the obtained results indicate that the examined experimental approach could be very effective for the non-destructive damage detection for masonry constructions, also at an early stage.

In addition, the observed variation of modal shapes indicates the direction for further investigations aimed at identifying and locate the damage, by following approaches similar to those proposed in [7] and [20].

Future developments of the technique include the utilization of advanced numerical modelling based both on limit analysis accounting also for settlements [21]-[24] and advanced FE non-linear simulations with homogenized materials [25]-[26].

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