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Full-scale Dynamic Tests on Unreinforced and GFRCM-reinforced Apulian Tuff Masonry Arches

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Abstract **– The study of the dynamic behavior of masonry arches and vaults is of paramount importance for several reasons: the evaluation of the seismic capacity; the determination of failure modes; the determination of the ductility and of behavior factors; the design of effective strengthening interventions, like for example by employing Fiber Reinforced Cementitious Matrix (FRCM) composites. Despite this, the literature still lacks a sufficiently large number of contributions on this subject, especially for what concerns either experimental study or reinforced arches. In this context, this paper, starting from the data of full-scale dynamic tests performed on unreinforced and Glass-FRCM reinforced Apulian tuff masonry arches, proposes some interesting observations on the dynamic behavior of masonry arches.**

I. INTRODUCTION

Masonry arches and vaults are the most common and iconic structural elements of historical constructions, having a great structural relevance, but also a significant seismic vulnerability. The latter entails the risk of loss of important parts of the architectural and cultural heritage. Against this risk, it is necessary to develop efficient strengthening techniques for masonry structures.

In recent years, new reinforcement materials, more compatible with masonry substrates, have been developed: Fiber Reinforced Cementitious Matrix (FRCM) composites. A large part of the research papers concerning FRCM strengthening focuses on the analysis of the performance of the reinforcement especially with respect to the phenomenon of debonding [1-3] and on the effectiveness in terms of increasing of the strength of structural members like columns and masonry walls [4-6]. Also the issue of FRCM reinforced arches and vaults has been studied, especially by developing numerical modeling approaches [7] whereas and experimental analyses are substantially limited to the case of static loads [8-9]. Indeed, according to the author's knowledge in Literature there are few papers addressing the dynamic behavior of unreinforced and FRCM reinforced masonry arches and vaults, especially from the experimental point of view [10-11].

Indeed, also the issue of the dynamic behavior of unreinforced masonry arches and vaults has been scarcely covered by experimental studies, essential for validating the results of numerical [12] or static load tests [13].

Thus, further experimental research is needed either for deepening the dynamical behavior under seismic excitation of curved masonry structures, or for studying the effectiveness of FRCM reinforcements for the protection of these structures against seismic actions.

Moreover, it has to be underlined that also the developing of a suitable theoretical framework for describing the dynamic behavior of unreinforced and FRCM reinforced masonry arches and vaults is a subject still under research.

For the particular case of unreinforced segmental masonry arches, a theoretical reference paper is [14], where the dynamic behavior of an unreinforced arch made of masonry blocks under base motion is described as the rocking motion of rigid blocks constituting a four-link mechanism. The approach proposed in [14] is based on the classical Heyman's assumptions for the masonry material: zero tensile strength, infinite compressive strength, and no sliding between blocks, and leads back also the analysis of masonry arches to the model of rocking, successfully employed for describing the dynamic behavior of other classes of masonry structures.

The approach in [14] has been further developed by deepening issues like the influence of the base excitation, the change of the rocking arch mechanism at the inversion of the motion; moreover, numerical and experimental validations of the theoretical model (tests performed on small scale structures) have been proposed [15-17]. Finally, the issue of the effect of possible discrepancies between the real arch and the simplified model considered by the theory, like, e.g., the damage or geometrical irregularities, has been considered [18-19].

Here, some results of full-scale tests performed on an unreinforced and a Glass-FRCM (GFRCM) reinforced tuff masonry arch are discussed. The dynamic tests have been carried out by means of an innovative test bench [12] expressly developed and built for experimental studies of the dynamic behavior of masonry arches. The behavior of the arches during the tests was monitored through accelerometers and displacement transducers, positioned in suitable points of the structure.

Experimental results are discussed in the light of the predictions of the rocking arch theoretical model. Finally, a comparison of the dynamic response of the two tested tuff masonry arches in terms of maximum recorded base acceleration, base shear force and dynamic amplification factor was show. This comparison allows for highlighting some relevant effects of the FRCM reinforcement on the possible seismic behavior of the arch, concerning the seismic capacity increase but, on the other hand, compatibility issue with the rest of the construction, due also to the marked change in the kinematic mechanism.

II. DYNAMIC TESTS

A. Materials

The dynamic tests were carried out at Laboratorio Ufficiale Prove Materiali "M. Salvati" of Polytechnic University of Bari.

In particular, the tests were carried out on two segmental circular masonry arches representative of Apulia historical constructions. Both arches have span s=1600 mm (intrados radius R=800 mm), thickness t=240 mm, and angle of embrace β=180°.

The material of the voussoirs of the arches is typical of Apulia (is named "Apulian tuff"), and comes from stone quarries of Gravina in Puglia. Masonry blocks are connected by an ordinary cementitious mortar.

In order to characterize the mechanical behavior of the materials, compression tests on the tuff according to UNI EN 772-1:2011 and UNI EN 1926:2007, and compression and flexural (three-point bending test) tests according to UNI EN 1015-11:2007 standard on the mortar, were conducted (Tab. 1-2). In particular, the results obtained by compression tests on 6 samples of tuff with average mass density 1400 kg/m^3 are reported in Table 1, where f_{bm} is the average brick compressive strength, $f_{b,k}$ is the characteristic brick compressive strength, and E is the average Young modulus. Table 2 shows the results obtained by compression and flexural tests performed on 6 prismatic samples of mortar with average mass density 2070 kg/m^3, in terms of the average flexural strength f_{mf}, the average compressive strength f_{mc}, and the average Young modulus E.

Table 1. Compression test results on tuff samples.

f_{bc} [MPa]	C.o.V. [%]	$f_{b,k}$ [MPa]	E [MPa]
2.25	12.55	1.87	637.4

Table 2. Flexural (three-point bending) test and Compression test results on mortar samples.

f_{mf} [MPa]	C.o.V. [%]	f_{mc} [MPa]	C.o.V. [%]	E [MPa]
2.72	1.34	7.40	1.1	8.100

The reported data indicate that Apulian tuff is characterized by low compressive and tensile strengths. This causes the possibility that voussoirs break easily due both to crushing or fracture formation, questioning the validity of Heyman's assumptions, and determining possible variations of the geometry of the arch during a dynamic test. Moreover, the surface of Apulian tuff is very dusty, and this on one hand make it easier sliding between blocks, and on the other hand could compromise the effectiveness of FRCM reinforcements.

One of the two arches was strengthened at the extrados with a Glass Fabric Reinforced Cementitious Matrix (GFRCM) mortar Mapei Planitop HDM Restauro embedding a glass-fiber grid Mapei Mapegrid G220. The reinforcement layer is 5 mm thick. According to the manufacturer, the GFRCM mortar has characteristic compressive strength greater than 15.0 MPa, Young Modulus E=8000 MPa and initial characteristic shear strength f_{v0k}=0.15 MPa; the reinforcement grid is characterized by a tensile strength F_{t1}=45.0 kN/m, with Young Modulus of the fibers E=72000 MPa.

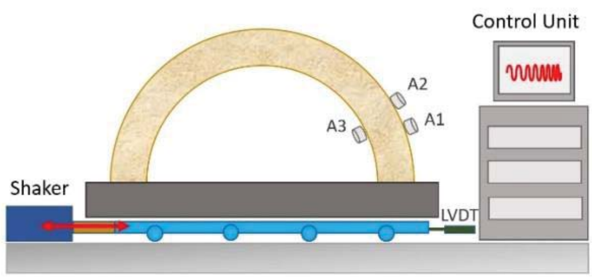

Fig. 1. Dynamic test setup

B. Setup

An innovative experimental setup was designed and built for dynamic tests on masonry arches [12]. The main components of the single degree of freedom (horizontal translation) dynamic test bench are (Fig. 1): a hydraulic dynamic Bosch Rexroth servo-actuator (maximum dynamic load ± 50 kN, maximum displacement ± 200 mm, maximum operative frequency of about 50 Hz); a steel bracket equipped with a load cell connecting the servo-actuator to a steel base frame; roller bearings, allowing the free sliding of the base frame.

Fig. 2. GFRCM reinforced arch

Masonry arches were built on steel beams and constrained to them by welded steel elements. For the tests, these beams were mounted on the steel base frame of the test bench (Fig. 2)

To monitoring the dynamic response of the arches under the effect of the base motion, 3 uniaxial accelerometers were mounted on each arch (Fig. 3), labeled as follows: A1 on the extrados in correspondence of the center of the voussoir 14; A2 on the extrados in correspondence of the joint between voussoirs 13 and 14; A3 on the intrados in correspondence of the center of the voussoir 14.

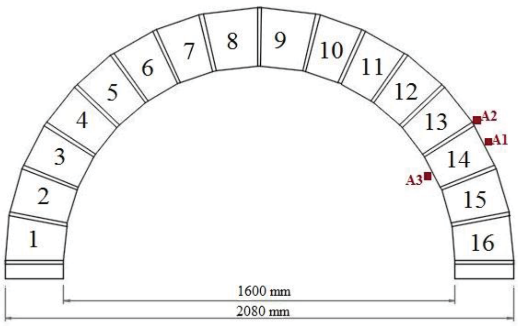

Fig. 3. Position of the accelerometers

The displacements of the base frame were monitored by a LVDT transducer, and the base shear force has been measured by the load cell embedded in the text bench.

Each arch was subjected to a dynamic excitation represented by a harmonic motion of the base frame with fixed nominal amplitude of 1 mm, and variable frequency from 0 to 8.00 Hz. Clearly, fixed the displacement amplitude, as the frequency increases, also the acceleration amplitude increases. The variation of the frequency has been executed by incremental steps of 0.25 Hz, and the duration of each step was about 30 s. High-speed video recordings have been performed during the tests.

For reprocessing experimental data, an ad hoc LabView software was developed.

III. EXPERIMENTAL RESULTS

A. Unreinforced Masonry Arch

According to what it is possible to observe from the video recordings of tests, the unreinforced arch behaved substantially like a rigid body for frequencies below 6 Hz: no cracks were observed.

A little above 6 Hz, two systems of four cracking hinges progressively formed, and the unreinforced arch transformed in a rocking mechanism, according to theoretical predictions in [7].

In Fig. 4 (down), the four hinges related to the first and the second half cycle of motion, respectively, have been indicated.

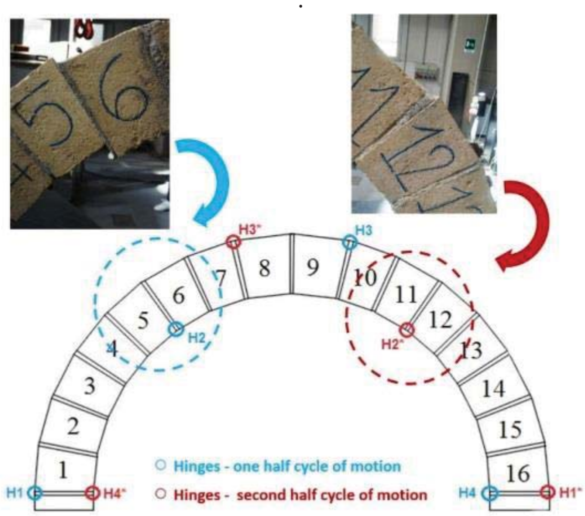

Fig. 4. Collapse mechanism of unreinforced arch

In particular, in the first half cycle of motion, the hinges H1 between the base masonry element and voussoir 1, H2 between voussoirs 5 and 6, H3 between voussoirs 9 and 10, and H4 between voussoir 16 and the base masonry element formed. In the second cycle of motion, the hinges were: H1* between the base masonry element and voussoir 16, H2* between voussoirs 11 and 12, H3* between voussoirs 7 and 8, and H4* between voussoir 1 and the base masonry element. Further increasing the frequency of the forced basis oscillations, the clapping between the faces of the cracked joints gave rise also to sliding displacements (Fig. 4, up).

Furthermore, when the frequency of 7 Hz was reached, significant openings of the hinges and evident sliding between the voussoirs were observed, as well as out-of-plane motions due to the unavoidable asymmetries and defects of the construction. Therefore, in order to prevent a catastrophic collapse, the test was stopped.

The maximum recorded base acceleration was 0.480 g, corresponding to a base shear of about 716 N.

B. GFRCM Reinforced Masonry Arch

In the dynamic test performed on the reinforced arch, by increasing the frequency of the base motion the opening of cracks was observed first around 5 Hz. In particular, cracks between the base masonry element and voussoir 1, between voussoirs 5 and 6, between voussoirs 8 and 9, and between the base masonry element and voussoir 16 formed (Fig. 5, down).

Above 6 Hz, sliding between voussoirs 8 and 9 started, and shortly thereafter also sliding between voussoir 16 and the base masonry element was observed. Above 7 Hz the latter became marked, and also the debonding of the FRCM reinforcement from the extrados of voussoir 9 occurred; furthermore, voussoir 9 began to translate downwards due to the sliding at the joints with voussoirs 8 and 10 (Fig. 5, up). At the maximum test frequency of 8 Hz the GFRCM reinforcement was still capable to hold together the voussoirs, preventing the collapse of the arch. However, the opening and the sliding of joints, visible form Fig. 5, were so marked that the collapse of the arch would have occurred for slightly higher base accelerations. At the end of the test, a maximum base acceleration 0.873 g was recorded, corresponding to a base shear of about 1370 N.

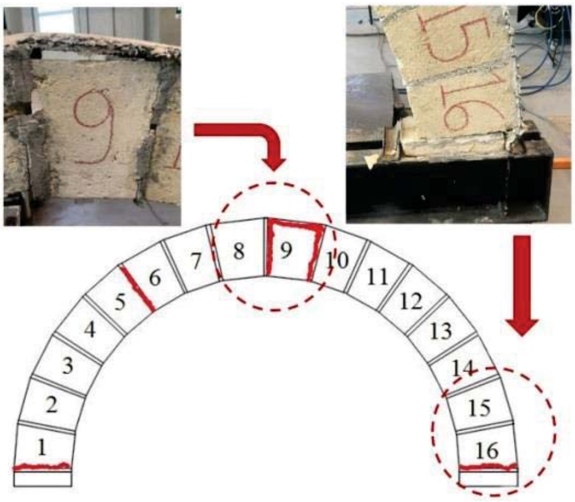

Fig. 5. Collapse mechanism of GFRCM reinforced arch

C. Discussion

Fig. 6 shows a comparison of the results obtained by dynamic tests on the unreinforced (black line) and the reinforced arch (red line), respectively, in terms of dynamic amplification factor, computed as the ratio of the acceleration recorded by the accelerometer A1 and the base accelerations. Notice that whereas the direction of the acceleration measured by the accelerometer A1 is not horizontal (see Fig. 3), the above ratio, and especially the change of it during the experiment, is indicative of the existence of amplification phenomena, and of the variation of the amplification properties of the arch as its structural behavior changes under the increasing base acceleration.

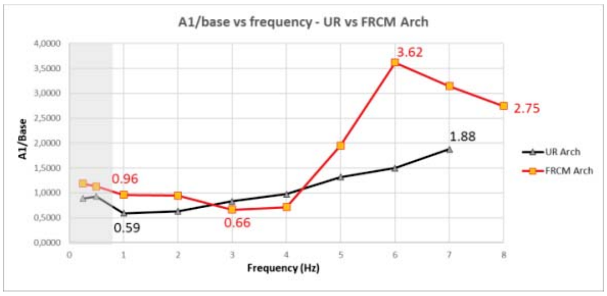

Fig. 6. Dynamic amplification factor UR Arch vs GFRCM Arch – A1

According to the rocking arch theory [5-8], based on Heyman's assumptions, the unreinforced arch should behave like a rigid body before the acceleration for the activation of the mechanism, corresponding to the limit capacity identified by limit analysis. In particular, by applying the approach in [20], a collapse load multiplier for uniform horizontal acceleration λ=0.437g has been obtained (Fig. 7), higher than the actual acceleration for the activation of the mechanism observed in the experimental test, about 0.395 g.

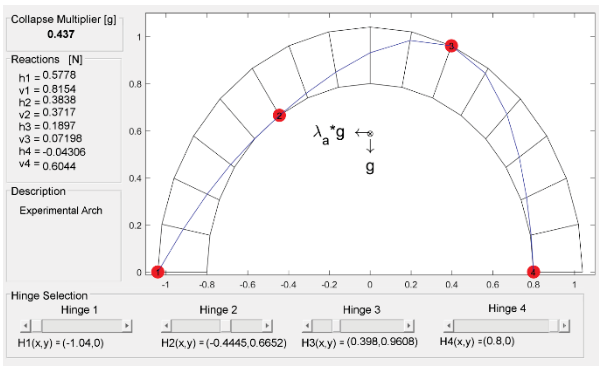

Fig. 7. Determination of the limit horizontal acceleration

In addition to the above discrepancy, according to the theoretical predictions no amplifications should have been observed below the acceleration threshold for the activation of the mechanism (corresponding to a frequency little above 6 Hz), since the arch should have behaved like a rigid body. Instead, it is seen from Fig. 6 that for low frequencies accelerations on the arch are substantially smaller than those at the base, whereas after 4 Hz the dynamic amplification factor increases quite smoothly towards the not negligible value 2.

In the case of the reinforced arch, no theoretical predictions are available. From experimental data in Fig. 6 it is possible observe that down to frequency of about 4 Hz the dynamic amplification factor gradually decreases from about 1.18 to about 0.72; after 4 Hz a sudden increase is observed, with a quite high peak of about 3.62 at 6 Hz. Finally, a decrease of the dynamic amplification factor occurs, until the value 2.74 recorded at 8 Hz.

In both cases (unreinforced and GFRCM reinforced arch) similar values and trends of the dynamic amplification factor have been observed by analyzing data acquired by the other two accelerometers.

IV. CONCLUSIONS

Dynamic tests on Apulian tuff masonry arches, one unreinforced and one reinforced at the extrados by GFRCM composites, have been performed under a base excitation consisting in a harmonic motion with constant amplitude and increasing frequency.

The material of the arch reproduce some features of Apulian vernacular construction but, above all, is characterized by mechanical strengths and surface conditions capable of putting into crisis the validity of the classical Heyman's assumptions, on which are founded the available theoretical models on the dynamics of segmental arches.

The observed dynamic behavior of the unreinforced arch confirms most of the qualitative aspects of the theoretical behavior of the rocking arch [5-8], although the hypothesis of rigid blocks is less justified due to low strengths of Apulian tuff compared to those of other traditional stones used in masonry constructions. This justifies some quantitative discrepancies in terms of the value of the base acceleration threshold for the activation of the mechanism and of the dynamic amplification factor.

After the formation of the mechanism, the dynamic behavior shows some important deviations from that predicted by the theoretical model: in particular, the collapse is driven especially by the sliding between blocks, instead of by the opening of flexural hinges. Therefore, it is necessary to represent the experimentally observed behavior by developing suitable numerical models capable of considering the loss of contact at interfaces, the impacts, and the sliding of the block forced by the pulse motion. Also, the influence on the dynamic behavior of the elastic deformability of the blocks and of the rounding of the edges of the block due to the impacts and to the low tensile strength of the material should be considered in view of estimating proper values of dynamic amplification factor. A final remark concerns the observed collapse base acceleration, still exceeding the value identified by limit analysis, indicating that limit analysis can provide a safe design format for the examined class of structures.

For the GFRM reinforced arch, the presence of the reinforcement yields a substantial increase of the capacity of the arch to withstand dynamic actions consisting in base motions. Moreover, the reinforcement is very effective in preventing the separation of voussoirs, and then in obstructing partial or global collapses of the arch. On the other hand, the arch loses the capacity of transforming in a rocking mechanism, that in some cases allows for better interactions with the supporting structures, also under seismic actions. The significant increase in the seismic capacity due to the reinforcement, enhanced by the curved shape of the structure, and then the great increase of the shear force transmissible to the supports in some cases may reveal counterproductive: indeed, if the rest of the construction is not suitably reinforced as well, the reinforcement applied on the arch may prevent the partial collapse of the arch but may trigger the global collapse of the whole construction or of a significant part of it. Also in this case, the experimental behavior have to be further investigated by means of suitable numerical models, accounting for the non-linear behavior of the materials and the dynamic loads.

In both cases of unreinforced and reinforced masonry arches, a crucial issue to be deepened is the dynamic amplification factor, since a correct estimate of the amplification properties of the structure is needed for determining the actual seismic capacity.

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