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Masonry arches reinforced with CFRP: an experimental and numerical investigation

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***Abstract* – Masonry constructions have received great attention from many researchers both from a theoretical and a practical point of view. This owing to the complex behaviour of the masonry material and the structural modelling problem of real constructions.**
Furthermore, this type of construction represents most historical and monumental constructions in the world, in terms of historical buildings, masonry arch bridges and monuments.
However, these constructions are deteriorating over time after being subjected to a prolonged exposure to unfavourable environmental conditions. It therefore becomes important to plan their strengthening to preserve these cultural heritages.
In this paper a numerical and experimental investigation of masonry arches is developed with an analysis of the effects of strengthening by means of advanced composite materials. The focus of the analysis concerns the effects on the strength and stiffness improvement of damaged masonry arches by strengthening with carbon fibre reinforced plastic.
An experimental investigation was developed aimed to study the behaviour of damaged solid clay brick masonry arches strengthened with carbon fiber reinforced plastic. In addition, a finite element model of the structure is developed accounting for the effective geometry of the brick–mortar components of the masonry arch and of the reinforcement layer.

I. INTRODUCTION

In order to create roofs or walkways characterized by substantial distances between the supports, that is, span larger than the size of the materials supplied, man has always created structures capable of overcoming these obstacles. Among these, the masonry arch, which, both from an aesthetic-architectural point of view, and due to its static capacity, has proven to be the most suitable construction for solving the aforementioned problem. Therefore, from the past we inherit infinite applications of such models, characterized by different geometries, whose choices are linked to the culture and knowledge gained by the different building peoples. In many practical applications, the arch has a semi-circular shape and is made up of blocks of stone or ashlars (figure 1). It is able to withstand the overlying loads through a regime of internal stress characteristics corresponding to a state of axial compression of the arch.

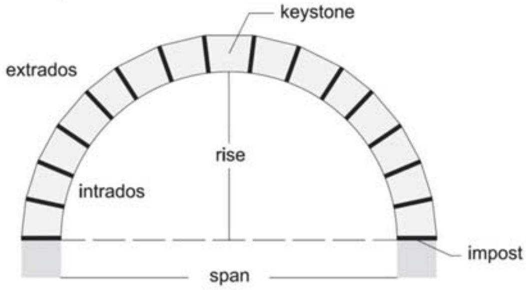

Fig. 1. Components of arch.

Leonardo da Vinci was the first to define the concept of the arch accurately and elegantly. “The arch is nothing else than a force originated by two weaknesses, for the arch in buildings is composed of two segments of a circle, each of which being very weak in itself tends to fall; but as each opposes this tendency in the other, the two weaknesses combine to form one strength”.
Subsequently, Hooke introduced the concept of catenary as a new static condition: “As hangs a flexible cable so, inverted, stand the touching pieces of an arch”.
Bernoulli, Huygens and Leibniz then provided mathematical formulations capable of representing the catenary. In this regard, it is important to underline that such an approach was applied by Poleni to verify the stability of the dome of St. Peter's in the Vatican.
Navier (1833) was the first to observe accurately the distribution of stresses at the interfaces between arch segments. To analyse the stress distribution over a cross-section, he introduced the thrust line concept, proving that the resulting line of action has to lie within the central core to ensure arch stability. Then, Mèry’s studies (1840) gained widespread recognition in the field of arch structures design. His method was based on the use of a

graphic procedure in order to check the thrust line in agreement with the stress limitations identified by Navier. Heyman [1-3] introduced some hypotheses for the determination of the admissibility domain of the masonry material. The three assumptions are reasonable approximations, but – as the same Heyman remembers – each is not strictly true and must be protected with reservations. Heyman does not introduce anything new but formalizes in a perfect way some hypotheses on the material, which formed the basis for the calculation of the arches in the XVIII and XIX century. These assumptions enable Heyman to frame the masonry action in the plastic theory and to formulate the famous safe theorem: "If any equilibrium state can be found, one for which a set of interval forces is in equilibrium with the external loads, and, further, for which every internal portion of the structure satisfies a strength criterion, the structure is safe". The three hypotheses are: (1) the masonry has no tensile strength; (2) the masonry has infinite compression strength; (3) sliding failure does not occur. As regards the first, it is an assumption that does not always adhere to the reality, but it is at safety benefit. It is strictly true only if the masonry is made by dry-stone blocks or with weak mortar. However, in most cases, the adherence between mortar and masonry blocks is negligible because the mortar may decay in time. Therefore, whatever is the ultimate tensile strength of the individual blocks, the masonry may be considered a non-resistant tensile material (NRT material). The hypothesis of infinite compression strength is a valid approximation only if the ratio between the average compression stress and the masonry compression strength is a negligible value compared to the unit. That is, the compression strength is not infinitely great, but if the ratio illustrated is sufficiently small, the hypothesis of infinite compression strength is justified.

As stated, man has therefore inherited infinite practical applications of masonry arches, some of which are of monumental importance and are still in use. Among these, it should be remembered the masonry bridges, many of which were built already in the centuries BC and up to more recent periods. In addition to undergoing natural deterioration, they have been damaged by prolonged exposure to the loads transmitted by traffic, which have intensified over the years.

Therefore, it is necessary to plan their consolidation, so as to continue to preserve and use these artefacts, representative of a fundamental cultural heritage. Therefore, the assessment of the structural safety status of such historical constructions becomes a current and relevant objective. In other words, a principal issue for such historical constructions, characterized by a certain geometry and load condition, is to determine their degree of safety and to improve their structural performance through a restoration.

In recent past decades, many studies have been conducted concerning the analyses of arch masonry structures and significant results have been achieved. In particular, an analysis of the historical development of the general themes of structural mechanics is conducted in earlier studies [4], focusing attention on arch and vaulted structures with respect to the main contributions given by different authors to reach a deep understanding of this type of structures. Como [5] made a wide study of historical masonry constructions, analysing the basic aspects of the masonry material structures both from a technological and a mechanical point of view. Then, arched, and diverse types of vaulted structures are studied also giving a useful understanding of the structural performance of some famous historical existing monumental constructions.

Today some structural models related to the mechanical behaviour of the interfaces between the masonry arch blocks are used. These models can refer to a softening behaviour of the interface, where an extremely low tensile strength of the material interface is assumed, or an interface behaviour of no tension type corresponding to a null value of its tensile strength [6]. In our developments the second type of interface, i.e., no tension interface is used. Different authors developed further studies of the masonry arch modelling. In particular, Kurrer [7] presented an interesting discussion on the history of the masonry arch theory, starting from the analysis of the rigid multi-body system of the masonry arch to elastic arch theory, followed by an outline of newer numerical engineering methods for analysing masonry arches. De Santis [8] investigated the structural response of masonry arch bridges under traffic loads and earthquakes, focusing the attention on the load-carrying capacity, where a relevant supporting experimental investigation on the mechanical response of historic brickwork under eccentric compression is also developed.

In order to improve the load carrying capacity of arch structures, reinforcement by composite material is a successful solution. In particular, reinforcement of arches is necessary, for example, to improve their ability to resist seismic actions or live loads increment owing to the upgrade of design codes. In addition, reinforcement becomes of fundamental importance to restore safety conditions after earthquake damage or structural degradation. The aspect of architectural preservation of the cultural heritage and monuments plays a key role in determining the strengthening technique. The employment of traditional materials in the strengthening of masonry structures always implies aesthetic problems and invasive processes that risk compromising the peculiar characteristics of the construction. So, the employment of advanced new materials, like composite materials, represents a power tool in addressing the rehabilitation of monumental ancient constructions and, in particular, in the strengthening of masonry arches. These new reinforcement techniques offer several advantages both from aesthetic and structural point of view, with a notable increasing of the ultimate load bearing capacity. So, a deep assessment of the structural and technological characteristics of the added reinforcing materials has to be conducted.

A large experimental campaign was developed by analysing the structural behaviour of reinforced and non-reinforced masonry vaults using diverse types of reinforcing composite material [9]. Furthermore, Sarhosis [10] provided an interesting review of evaluation methods for masonry arches.

Numerous theoretical and numerical analyses have recently been performed to define a structural modelling capable of capturing the structural behaviour that can be deduced from experimental assessments. The objective of this research is to establish numerical codes useful for a comprehensive examination of the complex structural behaviour of masonry structures and to assist in the design of masonry strengthening systems.

In this paper an experimental study of brick masonry arches for both unreinforced and reinforced arches is developed. The experiments undertaken relate to the applying of a progressively increasing vertical point load until a state of crack deformation corresponding to a pre-failure condition of the un-reinforced arch is reached. Next, arch strengthening is applied, and load continues until the collapse of the reinforced arch is achieved. Moreover, a nonlinear finite element analysis was conducted accounting for the actual geometry of the arch, by considering the masonry as a no-tension material. This behaviour was implemented by assuming that a unilateral contact with friction is present at the interface between bricks and mortar in the nonlinear 3D-FEM arch model. Obtained results show a good agreement between experimental and numerical results. This enables a suitable analysis of data obtained to be conducted and interesting considerations to be made on the structural behaviour of masonry arches reinforced with composite material.

II. EXPERIMENTAL PROGRAM

A series of arches was created with semi-circular generatrix of internal radius 800 mm, thickness 120 mm and depth 500 mm.

The arches were made of solid brick masonry and cement mortar in the laboratory on a reinforced concrete base with the double aim of ensuring a constraint for the arch of the continuous support-type, allowing a safer and more manageable handling for the structure built.

The mechanical properties of the materials constituting the masonry were obtained by standard compression and indirect three-point bending tensile tests and are shown in Table 1, where:

- ν is the Poisson's ratio;
- E_c is the Young's modulus;
- σ_c is the ultimate compressive strength.

For the creation of the arch models to be subjected to experimental testing, solid 250 × 120 × 60 mm bricks were used, arranged in shear so as to reduce the thickness of the mortar joints.

Table 1. Mechanical properties of masonry materials

Material	σ_c [Mpa]	E_c [Mpa]	ν
Mortar	10	14,278	0.108
Brick	17	5,921	0.108

A. Experimental equipment

The experimental tests were conducted in the Large Models Laboratory of the Department of Civil Engineering of the University of Calabria using a contrasting frame, specially made, composed of four uprights made from two U120 steel beams, welded and anchored to the ground and connected to each other by four U120 crossbeams placed at the top. The test jacks run on the lower wing of an IPE200 steel beam, properly welded to two U120 transverse beams bolted to the uprights at 152 cm from the ground (figure 2).

Fig. 2. Contrast frame model.

The various elements are connected by high-strength bolts belonging to class 8.9 (tensile strength = 784.53 N/mm2, yield strength = 706.08 N/mm2), tightened with a torque wrench. The frame was reinforced by means of two flat profiles 20 mm thick and 100 mm wide and anchored to the ground to limit deformations.

The loads were imposed by means of hydraulic jacks placed in the key section ($\alpha = \pi/2$) and on the kidney section ($\alpha = \pi/4$); each of the hydraulic jacks was mounted in series with a load cell to detect the load value and the load history was recorded for each location studied, which for the sake of brevity is not reported. The experimental strategy can be considered quasi-static as the loading process was imposed with load increments at low speed to avoid dynamic effects, as well as the unloading after reaching the predetermined applied force value was always performed at low speed.

In order to detect and record the absolute and relative displacements of the points of the structure subjected to

experimental testing, a set of measuring devices consisting of 11 centesimal gauges and 9 inductive displacement transducers were used. The loads were imposed by means of hydraulic jacks placed in the key section ($\alpha = \pi/2$) and on the kidney section ($\alpha = \pi/4$); each of the hydraulic jacks was mounted in series with a load cell to detect the load value and the load history was recorded for each location studied, which for the sake of brevity is not reported. The experimental strategy can be considered quasi-static as the loading process was imposed with load increments at low speed to avoid dynamic effects, as well as the unloading after reaching the predetermined applied force value was always performed at low speed.
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B. Experimental phases

A thorough experimental program was investigated, divided into two phases: in the first one, the arch model was subjected to loading on sections $\pi / 2$ and $\pi / 4$, with load increments of 200 N up to a value of 2,000 N; in the second phase, in order to verify the bearing capacity of the vault model, the section was loaded in key up to cracking. Each loading step was performed at low speed to prevent dynamic deformation effects due to the application of the loads. In addition, after reaching the predetermined applied load value, the unloading was always performed at low speed. Subsequently, the arch samples were restored by applying strips of CFRP to both the extrados and intrados, repeating the two test phases in the same way to analyse the behaviour of the reinforced structure compared to the non-reinforced one. As verified through laboratory tests, the mechanical and geometric characteristics of the FRP composite are shown in table 2.

Table 2. - Characteristics of the FRP composite.

Matrix	Epoxy resin
Width	50 mm
Thickness	1.2 mm
Specific weight	1,600 kg/m^3
Tensile Strength	> 2,400 MPa
Elastic Modulus	≥150,000 MPa
Ultimate Elongation at break	>14%
Fiber content	>60%

III. NUMERICAL FINITE ELEMENT MODEL

Let us consider the masonry arch represented in figure 3, where the masonry elements can be made up of stone elements or other types, such as those in solid clay brick.
The arch is acted upon its own weight and an additional point load F. For small values of the load F, the thrust line will safely lie within the masonry arch. As the load F is increases, this thrust line will move further and further away from the midline of the arch, until at a certain value of F it can only be contained just inside the masonry.

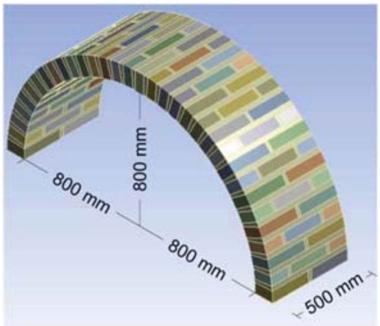

Fig. 3. The masonry arch scheme.

This limiting stage is shown in figure 4, where the line thrust reaches the intrados and the extrados surfaces at four locations. At each of these locations, a unilateral hinge is formed, and the four hinges transform the stable arch into a collapse mechanism.

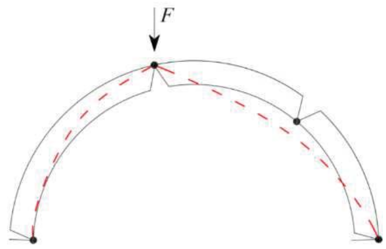

Fig. 4. Collapse mechanism of the masonry arch.

The kinematics and the trajectories of the thrust line of the arch change if a composite material is applied on the intrados or extrados (figure 5).

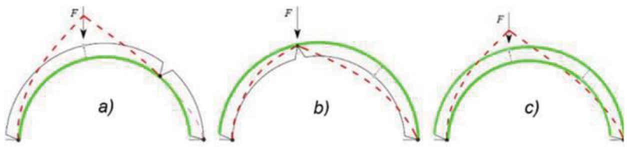

Fig. 5. Thrust line of reinforced masonry arch subject to its own weight and an additional point load. Reinforcement placed on: a) the intrados; b) the extrados; c) both the intrados and the extrados.

In fact, the added composite material is able to prevent the opening of the hinges, where the tensile strength of the composite material itself is mobilised. The presence of composite material reinforcement sheets also determines a change of the collapse kinematics with respect to that occurring in the case of not strengthened arches, where a hinging mechanism is found. Specifically, in the case of reinforced arches the collapse mechanism is associated with the damage of the masonry components, the composite material or both the masonry and composite elements, like masonry and/or composite failure or composite delamination. As also reported in Wang [11], it is observed that the compressive strength of the brick is quite higher than that of the mortar and from laboratory tests it is also observed that the brick has an elastic behaviour at a quite elevated level of stress. Furthermore, as regards the mortar, if a nonlinear behaviour is assumed, only a small effect of the inelastic properties on the load-displacement relationship emerges, as shown by Wang, where a Drucker-Prager nonlinearity was studied.

So, for the arch studied here, brick and mortar were modelled as elastic materials and the interface between brick and mortar was modelled by introducing the contact elements provided in Ansys, named 'frictional'. Specifically, it is assumed that the contact between these two parts is a nonlinear unilateral frictional contact, in the sense that the contact surfaces can freely separate in orthogonal direction and present a sliding with resistance according to the friction coefficient μ.

The geometry of the Ansys model takes its starting point from that defined above. The arch is then defined through a 3D modelling as shown in figure 6, where the brick unit and mortar were modelled using the solid186 element, which is defined by a higher order 3D 20-nodes solid element that exhibits quadratic displacement behaviour.

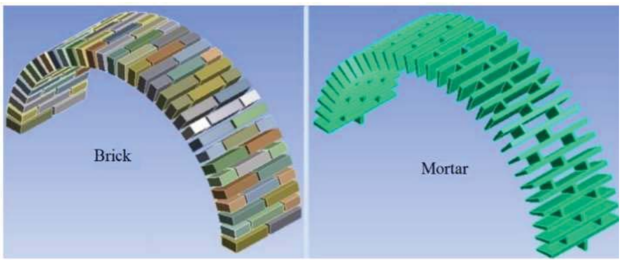

Fig. 6. The 3D arch model.

The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The unreinforced model is firstly analysed, followed by the reinforced one, where the geometrical and mechanical properties of the laboratory tests are employed. A numerical investigation was conducted preliminarily to analyse the effects of the friction parameter μ on the structural behaviour of the arch. As a result, the more appropriate realistic value μ = 0.40 was used.

A. Unreinforced arch model

Numerical analysis was performed by assuming that the arch model is subjected to its own weight and the following additional point load: a) point load F at the key; b) point load F at the kidneys.

The displacement-controlled loading technique was used to capture the softening behaviour of the structure. In our numerical applications the displacement-controlled loading step was 0.1 mm/step.

The force-displacement diagram shown in figure 7 refers to case a, where the arch is subjected to its own weight and an additional point load F acting at the key section. This figure shows the displacement v at the key versus the point load F. It can be observed that at the maximum load value F = 5.0 kN, the corresponding displacement at the key section is v = 1.0 mm, which agrees with the experimental one: v = 0.92 mm. Moreover, similar agreement is found with respect to the maximum load carrying capacity.

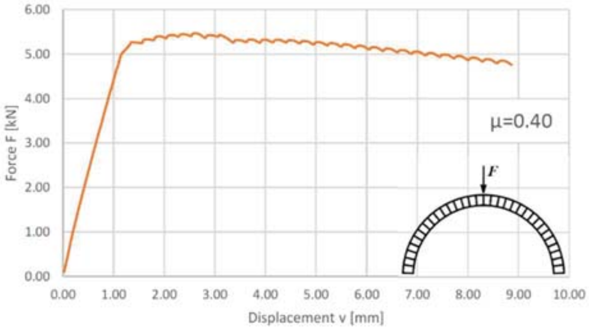

Fig. 7. Unreinforced arch: force-displacement diagram of the key section.

In fact, the experimental value of the limit load F = 5.2 kN, reached at cracking state of incipient collapse, agrees with that found by the numerical model (F = 5 kN).

Obviously, a more pronounced nonlinear behaviour of the arch is observed if a point load acting at the kidney section is considered, where a more limited load carrying capacity emerges.

B. Reinforced arch model

The arch model was reinforced with two 1.2 mm thick CFRP layers arranged at the intrados and extrados, with mechanical properties shown in Table 2. The geometry of the Ansys 3D-FEM model is shown in figure 8.

The FEM model used offers the possibility of updating the geometry of the structure as a function of the time evolution of the deformation state. So, it was possible to insert the reinforcement at a predefined load level. In particular, the additional CFRP layer was applied at the cracking deformation state corresponding to that just before the incipient collapse of the arch.

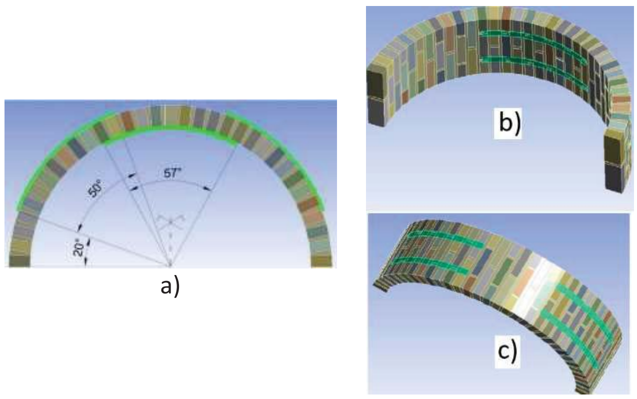

Fig. 8. Reinforced arch – 3D Ansys model: a) front view, b) bottom 3D view, c) top 3D view.

With reference to the point load F acting at the key of the arch, figure 9 shows the force-displacement diagram, from which one can observe both the stiffness and the strength increasing following the application of the CFRP reinforcement. As previously found, the maximum load carrying capacity of the unreinforced arch is represented by the maximum load value F = 5.2 kN. The reinforcement was applied to the deformed arch at the cracking deformation state corresponding to that just before the incipient collapse of the arch, at the load value F = 5.2 kN. At the load level F = 16 kN, the corresponding displacement of the key section is v = 2.0 mm, comparable with the experimental one of v = 1.9 mm.

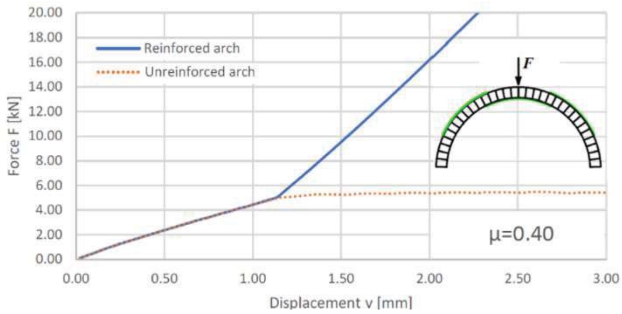

Fig. 9. F-v diagram of the key section.

Finally, figure 10 shows the diagram relating to the displacement exhibited by the points of the right and left kidney in the case of force applied to the right kidney.

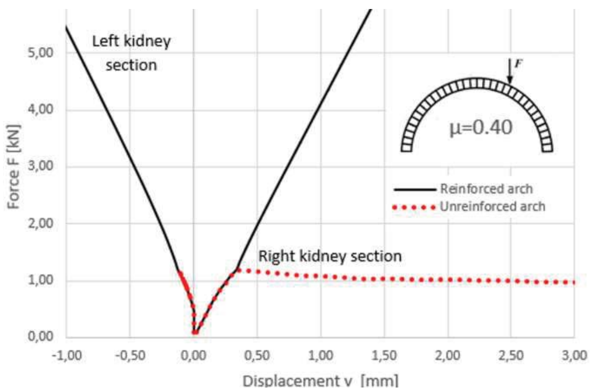

Fig. 10 F-v diagram of the kidney sections.

IV. CONCLUSIONS

This paper deals with experimental and numerical research on masonry arches reinforced with advanced composite material. The focus of the present analysis concerns the effects on the strength and stiffness improvement of damaged solid clay brick masonry arches by strengthening with carbon fiber reinforced plastic. The study involved the re-working of data obtained in the literature from the main destructive tests carried out by applying incremental vertical point loads. Experimental and numerical results here developed show that it is possible to deduce general conclusions on the parameters that most influence the general behavior of the structure and particularly the significant improvement of the load-carrying capacity of masonry arches due to the application of composite material reinforcements. To obtain realistic damage conditions of the unreinforced arch, a preloading was applied to reach a cracking deformation state corresponding to that just before the incipient collapse of the structure. Subsequently, strengthening layers of CFRP were applied at both intrados and extrados just after damage, and then the arch was retested to analyze the behavior of the reinforced structure compared to the non-reinforced one. The proposed model appears appropriate for the prediction of the load-carrying capacity with reasonable accuracy and for the simulation of the overall behavior of the structure and the prediction of the load-deformation relationship. So, it could be used as a satisfactory tool for the analysis of masonry arches and can represent a good reference point for further developments.

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