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Experimental and analytical analysis on a masonry arch strengthened with basalt FRCM

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Abstract

Italian cultural heritage is often characterized by innumerable structures built using few-known construction techniques. In the present work, an arch built with a technique typical of Southern Italy and dated back to the II Century after Christ was investigated. The construction technique used is the "fictile tubules" one. With the term "fictile tubules" it is possible to identify a cylindrical element of hollow conformation recognized as the first hollow brick of history. It was realized for the first time in the Roman provinces of North Africa and subsequently introduced in Italy where it is still used today in the rural zones.
In the present work, the results obtained during an experimental campaign conducted on an arch realized with this constructive technique will be exposed. In a first step, the arch was subjected to a static test characterized by a concentrated linear load applied in keystone, then, to the formation of the first cracks, the test was interrupted, and the arch was strengthened with Basalt-FRCM and tested until collapse. All the results obtained have been validated using an analytical approach.

Keywords: Cultural heritage, Masonry arch, Fictile tubules, Analytical check, Basalt-FRCM.

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1. Introduction

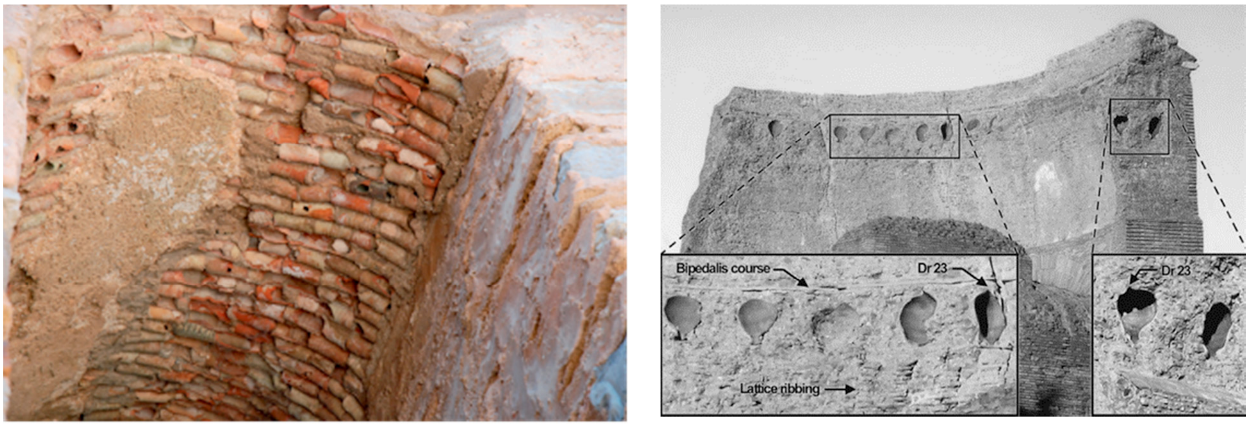
Ceramics include all products made by baked clay dough. Within this broad definition, porous and compact artifacts must be distinguished, each characterized by different surface treatments. Uncoated porous products go under the name “terracottas”, whereas those coated with transparent varnish or colored enamels are labelled “majolica”.

The widespread use of bricks, made with clay, for the construction of buildings at all times and in many geographical areas is due to their ease of manufacture, transportation, and maneuverability. Many writers of architectural treatises from the 13th and 14th centuries began to make a distinction between bricks and stones constructions in their books. The first were preferred for their durability and resistance, and were often called "cooked stones" (Alberti, 1485).

Vaulted and domed structures have always represented a brilliant technological innovation in the context of the evolution of building techniques (Rondelet, 1802). Compared with other techniques, these structures enabled to build roofing for large spaces by reducing the permanent weights and the thrust against the skewback wall of structures (Olivito et al., 2016 a). Moreover, ancient builders began to devise solutions that could lead to further weight reduction to vaults and domes. Some examples of lightened structures are dated between the 1st and 2nd century A.C., in the surroundings of Pompeii and Rome. The most important structure is certainly the Pantheon, whose dome consists of two opus ceamenticum made with different materials and is characterized by a lighter specific weight in the upper part (De Fine Licht 1974). Another technique to ensure the lightening of the vaults and domes is based on the use of “fictile tubules”, identified by researchers as the first hollow brick in history (Olivito et al. 2016 b).

Fictile tubules are cylindrical clay bricks with a hollow conformation that provides thermal insulation and ensures lightness in the structural elements. This well serves the purposes of thermae and kilns, since heat dispersion affects their functionality. Fictile tubules were usually either embedded in mortar in staggered manner or assembled with a female-male coupling system. (Tiberti et al. 2017 a).

These constructive elements assumed different sizes and shapes in according to the geographic areas where they were made (Olivito et al. 2016 b). During the research of sites characterized by construction made with fictile tubules carried out in the Mediterranean area, it was possible to identify three different types of these particular bricks: the amphorae, fictile tubules and “*caroselli*”. All types of fictile tubules were made by the potter that used the clay as raw material. The different clay used, that changed in according to the geographic area, assigned at these elements different colors and mechanical strength. This diversification depends on the mineralogical composition of the clay and the presence of iron oxide and calcium oxide inside them (Scuro et al 2018 a).



(a) (b)

Fig. 1. (a) Barrel vault built with fictile tubules, Cartagine (Scuro 2012); (b) Mausoleum of Helena, Rome (Lézine, 1954).

Fictile tubules are characterized by a syringe shape with the point being a truncated cone. During the construction phase, the point was inserted into the next element – characterized by a perforated base – thus to ensure the interlocking with each other. The structures with this technique was made by juxtaposition of arches (Fig. 1.a) (Scuro 2012).

The amphorae were characterized by shapes similar to those employed for creating the ceramic vases of the same name. They were positioned inside the structure before casting a cement conglomerate jet to ensure the formation of voids and consequently decreasing of the stress (Fig. 1.b) (Lézine, 1954).

The technique used to make the scale model is the caroselli one. It differs from the other because it uses a radial and staggered arrangement of the elements over a centering and was completed with a cement conglomerate jet colled *"caldana"* (Tiberti et al. 2017 b).

2. Experimental test

The masonry arch used for the experimental campaign has an internal span equal to 1500 mm, a width of 500 mm and a thickness of 150 mm. *Caroselli* are arranged in a staggered manner, with their circular base tangent to the intrados. Mortar joints of approximately 20 mm separate each row of elements (Fig. 2). The arch was built using a wooden centring and two concrete blocks. The blocks were fixed to the ground for supports and connected with two steel beams. After the arch was completed, a final cast of mortar, of about 30 mm, was placed on it. The wooden centring was carefully removed after thirty days.

Fig. 2. Phase of realization of the masonry arch.

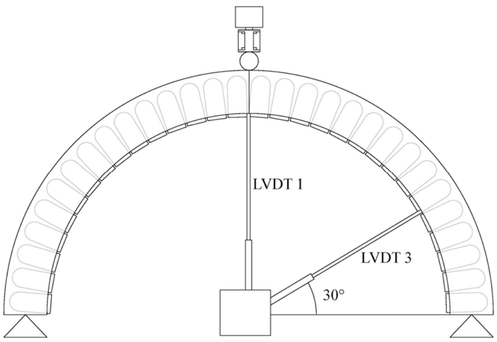


Fig. 3. Static test scheme

The static test was conducted using a manual hydraulic load cell. The load was applied to a steel beam welded to a cylindrical element, aligned to the keystone section. Four displacement transducers were used in order to measure vertical displacement of the arch (Fig. 3). The test was stopped when the first cracks were occurred in the structure. The maximum value of the force recording during the test was equal to 6.4 kN (Tiberti et al. 2017 c).

After that, two B-FRCM strips each of 100 mm width were applied at the extrados of the arch (Olivito et al. 2017 c) (Fig 4 a,b). In order to measure the strains on them, four strain gauges were used at 45° section. (Fig. 4 c) (Lamonaca et al. 2018). Then, the test was repeated on the reinforced specimen until collapse.

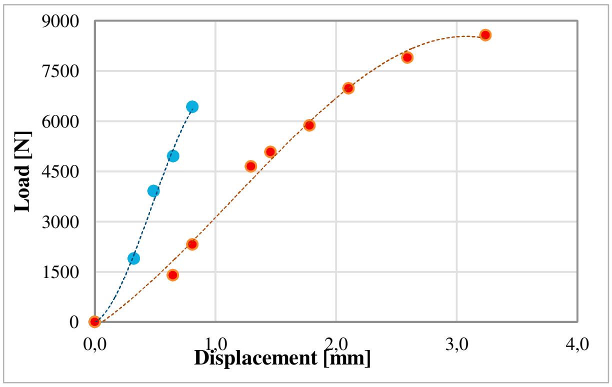

(a)


(b)

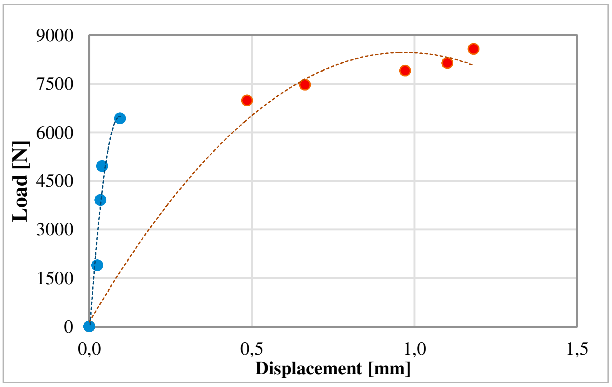

(c)

Fig. 4. (a)-(b) Masonry arch strengthened with basalt FRCM (c) Application of strain gages

The application of B-FRCM strips were used for repairing the cracks while strengthening the extrados surface of the arch, but it did not avoid the formation of two new hinges during the following test (Cevallos, 2015). Here, failure occurred in a slower way, reaching a maximum load equal to 8571 N. Considering the weaker role of mortar in the behavior of an arch, the cracks occurred in the mortar joints, without damaging the *caroselli*. The load-displacement comparison of curves obtained for the non-strengthened arch (in blu) and strengthened arch (in red) are showed in Fig. 5.



(a)



(b)

Fig. 5. Load-displacement diagrams: (a) 30° section of the intrados of the arch; (b) Section on intrados along the keystone.

3. Analytical checks

In order to obtain a validation of static tests conducted on the scale model, an analytical verification was carried out by solving an isostatic arch scheme characterized by a concentrated load located in keystone. The equivalent isostatic scheme used is the three-hinge arch. Two steel beams were fixed to the blocks of concrete at the base of the arch with a single bolt, in order to prevent displacement during the test. This condition was assumed in the analytical model with the presence of two hinges. Instead, the non-perfect adhesion between mortar and fictile tubules in keystone caused a rotation due to the load, as reported in previous work (Tiberti et al 2019) (Scuro 2017).

The isostatic scheme was solved by imposing the value of the concentrated load equal to first cracking load, achieved experimentally. The values of the internal reactions were obtained and the normal stress, shear stress and bending moment diagrams were calculated in order to identify what is the part of the model most stressed.

The analytical study performed in the section at 45 ° shown that both the bending moment and the normal stress assumed maximum values (Scuro et al. 2018). This cross section shows in figure 6, composed by only mortar, coincides with the part of the arch where the first crack appeared during the static test and it was investigated as a section subject to great eccentricity with the following equations:

$$I_n = S_n d_n \tag{1}$$

$$I_n = \frac{bx_c^3}{3} + \frac{n_{ct} b\left(h - x_c\right)^3}{3} \tag{2}$$

$$S_n = \frac{bx_c^2}{2} + \frac{n_{ct} b\left(h - x_c\right)^2}{2} \tag{3}$$

$$d_n = e - \frac{h}{2} + x_c \tag{4}$$

I_n is the moment of inertia of the cross section investigated, n_{ct} is a homogenization factor of the mortar that is equal to 0.5, S_n is a first moment of area calculated by imposing the distance from the neutral axis x_c, and d_n is the distance between the point of application of normal stress and the neutral axis as shown in Fig.6.

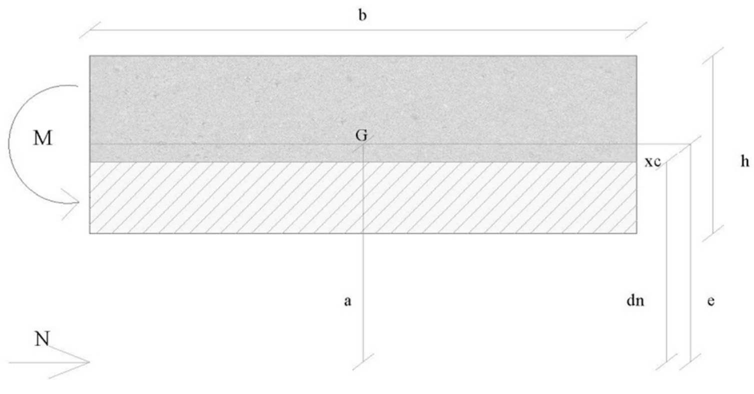


Fig. 6.Unreinforced section investigated

The value of the bending moment, that caused the development of the first cracks in the extrados of the section at 45°, is evaluated with the equation 5, where σ_t is the tensile strength of the mortar.

$$M_{ct} = \frac{\sigma_t I_n}{n_{ct}\left(h - x_c\right)} \tag{5}$$

From the value of M_{ct}, it is easy to obtain the value of the load (F) with equation 6.

$$F = \frac{2M_{ct}}{r\left(sin(\alpha) + cos(\alpha) - 1\right)} \tag{6}$$

The Load (F), analytically estimated, is equal to 6252 N, and it is 200 N lower than that obtained experimentally.

During the test, the composite collapses not by debonding between the matrix and the fiber but by the breakage of the latter. For this reason, the analytical check on the strengthened section was carried out considering the strain of the fiber equal to the maximum strain recommended to international technical standard.

The section investigated is the same analyzed for the check carried out on the non-strengthened model.

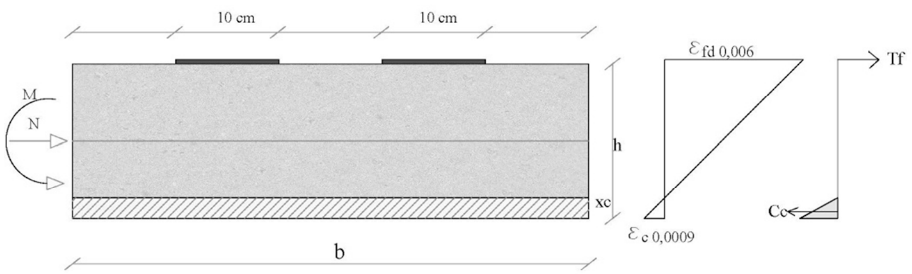


Fig. 7.Reinforced section investigated

The maximum strain attributable to FRCM reinforcement at the design stage, ε_{fd}, has been calculated from the equation 7 as expressed in the technical standard CNR DT 200 R1:2013.

$$\varepsilon_{fd} = min\left\{\eta_a \frac{\varepsilon_{fk}}{\gamma_f} ; \varepsilon_{fdd}\right\} \tag{7}$$

In the equation number 7, ε_{fk} is the characteristic collapsing deformation, while ε_{fdd} is the maximum deformation in the reinforcement system during the intermediate detachment from the masonry support. γ_f is the partial coefficient of the FRP material to be used for design while η_a is the environmental conversion factor for various exposure conditions and has been assumed to be 0.85.The maximum deformation of the reinforcement system is calculated by the identification of the design value of the specific fracture energy, provided by the following equation:

$$\Gamma_{fd} = \frac{k_b k_g}{FC}\sqrt{f_{bm} f_{btm}} \tag{8}$$

k_g is a correction coefficient calibrated on the basis of experimental test results, expressed in mm and depending on the type of masonry, which in the case of in situ impregnated reinforcements for brick structures is worth 0.031 mm, FC is the confidence factor, f_{bm} and f_{btm} are, respectively, the values of compressive strength and tensile strength of the material that composed the section under investigation.

k_b is a geometric correction coefficient, b_f and b are respectively, the width of the reinforced element and that of the reinforcement.

$$k_b = \sqrt{\frac{3-\frac{b_f}{b}}{1+\frac{b_f}{b}}} \tag{9}$$

The design tension of the reinforcement causing the end-coupling is calculated by the equation 10 where $\gamma_{f,d}$ is a partial coefficient valid between 1,2 and 1,5 at the designer's discretion, E_f is the normal elastic modulus of the fiber, t_f is the equivalent thickness of the reinforcement and Γ_{fd} is the fracture energy.

$$f_{dd} = \frac{1}{\gamma_{f,d}}\sqrt{\frac{2E_f\Gamma_{fd}}{t_f}} \tag{10}$$

$$f_{dd,2} = f_{dd}\alpha \ (1,0 \le \alpha \le 2,0) \tag{11}$$

$$\varepsilon_{fdd} = \frac{f_{dd,2}}{E_f} \tag{12}$$

The minimum value of the strain obtained and used in the analytical check it is equal to 0.00632.

The cross section shows in figure 7, composed by only mortar, coincides with the part of the arch where the FRCM collapsed during the static test, it was investigated and was calculated the position of the neutral axis with the following equations where E_m is the value of the elastic modulus of the mortar, N_{ed} is the compressive stress calculated from the equivalent static scheme and A_f is the area of the reinforcing fiber.

$$\frac{1}{2}bx_cE_m\left(\frac{\varepsilon_{fd}}{h-x_c}x_c\right) - A_fE_f\varepsilon_{fd} = N_{ed} \tag{13}$$

The value of x_c is equal to 20.2 mm, and the value of the bending moment, that caused the collapse of the FRCM was calculated with the following equation:

$$M_{rd} = \frac{1}{2}bx_cE_m\left(\frac{\varepsilon_{fd}}{h-x_c}x_c\right)\left(\frac{h}{2}-\frac{x_c}{3}\right) + A_fE_f\varepsilon_{fd}\frac{h}{2} \tag{14}$$

From the value of M_{ct}, it is easy to obtain the value of the load that induced the collapse ($F_{collapse}$)

$$F_{collapse} = \frac{2M_{rd}}{r\left(sin(\alpha)+cos(\alpha)-1\right)} \tag{15}$$

The value of the load calculated during the analytical check is equal to 8541 N and differs from that obtained experimentally by only 30 N.

4. Conclusion

The paper deals with a historical construction technique typical of the Mediterranean area and in particular of the regions of south Italy as Calabria and Puglia. This technique is characterized by the use of special hollow clay bricks called fictile tubules. For the aim of this work, experimental and analytical analyses were conducted in order to evaluate the behavior of an arch built with fictile tubule bricks.

The experimental results obtained for the not strengthened arch and for the strengthened arch were validated by an analytically approach based on the study of the section at 45° mostly stressed during the test. In the first case, the difference between the experimental and analytical value is equal to about 200 N, while for the second case it is 30 N.

In future works, a numerical model of the reinforced arch will be created with a software based on finite elements in order to investigate the behavior of this structure with the application of FRCM.

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