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Study of the interface behaviour between fictile tubules bricks and mortar: numerical and experimental analysis

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Abstract. This paper presents an investigation on the interaction between hollow clay bricks (*caroselli*) and mortar, aiming at obtaining frictional properties needed for a full description of the composite masonry material derived from these two constituents. A series of three-point bending tests is carried out on prism-shaped specimens representing typical arrangements of *caroselli* within mortar. Since no building code or guideline exists regulating this kind of tests, the specimens are built respecting the 1÷4 ratio between the transversal dimension and the length of the prism requested for mortar specimens subjected to three-point bending tests. The frictional properties of the interaction between the two constitutive materials are then derived through a series of back analyses concerning four different hypotheses on the actual degree of transmission of tangential stresses between *caroselli* and mortar. The numerical analyses are performed with the commercial finite element software ABAQUS. The obtained results sustain the experimental findings.

1. Introduction

The cultural heritage of different areas located around the Mediterranean Sea consists of several unique features and structural elements, often conceived to solve practical issues in the construction of buildings. A shining example is represented by a peculiar type of hollow clay bricks known as "fictile tubules". Three distinct categories can be generally identified with this definition - plain tubules, amphorae, and *caroselli* - depending on their geometrical characteristics and structural use. In particular, *caroselli* present a squat cylindrical shape, closed by a dome-like upper part, possibly provided with a small opening at the top [1]. They arguably originated during the 2nd Century A.D. in the Roman provinces of Northern Africa to bypass issues related to the shortage of wood needed to erect centrings [2]. In fact, they were used to build light-weight, self-supporting vaults and domes in several constructions, thus effectively overcoming the necessity of centrings during construction. The rough external surface of *caroselli* is characterised by an unevenness spiralling towards the upper part, which was created by the potter during the moulding phase to help each clay element adhering to the surrounding mortar.

2. Classification of hollow clay elements

Historically, a vast variety of hollow clay elements have been used to build domed and vaulted structures. For this reason, it is possible to create a classification based on their geometrical characteristics and different use in building techniques [3-4]. The larger category of hollow clay bricks consists of three general elements: tubules, amphorae and *caroselli*. The tubules are hollow, syringe-like elements manufactured so that they slot into each other (Figure 1). To guarantee the adhesion between these elements and the mortar, the external surface of the former is left rough. Over time, these tubules have taken different shapes, bulging in the central part or tapered on the end section. The most significant differences are observed in the length of the tip (upper end section) that allows alignment of the joint between multiple elements. The amphorae are ceramic elements strongly resembling the vessels

of the same name, whose shape is characterised by a bulging central section and a spindle-shaped bottom part. They present two handles tying the neck to the central part (Figure 2). Like the previous case, during the manufacturing phase the external surfaces are left rough to improve the adhesion with the mortar. Eventually, the fictile elements called *caroselli* are unusual structural elements made with clay (Figure 3) [5]. It is important to underline the fact that the name of these elements derives from a dialect term that identifies the moneybox, due to their geometry. This name is different and changes according to the geographical location of production. The term mostly used is *caroselli*, but there is trace of other names such as "pigniatelli", "caccavelli" or "bubbole" [1-6].

Figure 1. Example of tubule [5].

Figure 2. Example of amphora [7].

Figure 3. Example of *carosello* [2].

2.1. Construction with fictile tubules

During the construction phase, the tip of one tubule is inserted into the next element – characterised by a perforated base – thus ensuring the interlocking between adjoining elements (Figure 4) [8]. This technique allows the creation of arches joined side by side by lime mortar, so that a barrel vault can be erected without the use of traditional centring. The actual centring consists of a series of cordons compound of tubules inserted one inside another and following a generating curve, all converging in a keystone tubule that is uniquely produced without an apex (Figures 4-5) [9]. The vaults and domes constructed in this manner consist entirely of fictile tubules without the use of Roman concrete (*opus caementicium*).
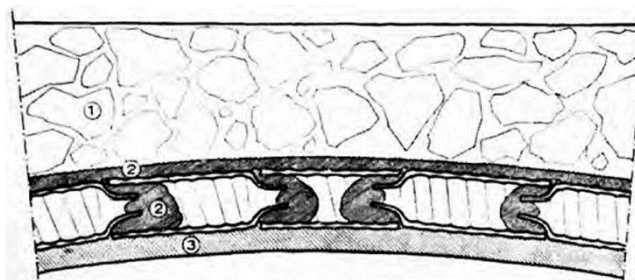

Figure 4. Draw of a keystone [10].

Figure 5. Detail of the joints of the fictile tubules [9].

2.2. Construction with amphorae

In historical buildings, amphorae are positioned inside the structure before casting the cement jet to ensure the formation of voids and consequently decrease the stress due to the dead loads [2].

These elements are found in different locations of historic buildings, typically included in masonry walls: for example, at the bottom of the wall, in the reins of the arches, in the filling of old concrete structures, and in the roofing [5]. They are used to lighten the weight of the roofs and the horizontal thrust on the perimeter walls. In the case of cavity walls, amphorae are also used to ensure internal ventilation. Famous examples are the mausoleum of Helena in Rome (Figure 6) where the amphorae are arranged in two lines, one running parallel above the other, and the bleachers of the Circus of Maxentius in Rome where the number of amphorae employed is almost equal to 9000 [11].

The positioning of the amphorae appears more effective in the case of the Temple of Minerva Medica (81-96, Rome), where they are arranged on top of the windows, easing the springing load [12]. In the case of architectural findings dating back to the early Christian era, especially in the Mediterranean area, the amphorae are placed on the thickness of vault with their opening visible on the intrados. In this case, they were used to improve the acoustics of the rooms [13].
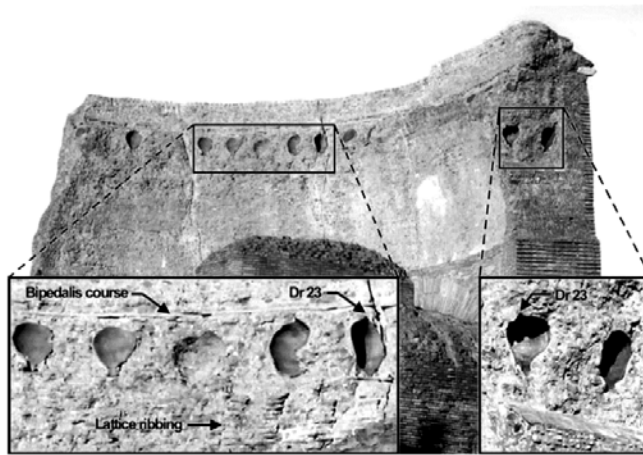

Figure 6. Mausoleum of Helena, Rome [14].

Figure 7. Cross vault built with *caroselli* [5].

2.3. Construction with caroselli

Caroselli are used to build barrel vaults, cross vaults, domes, floors, partitions, also serving decorative purposes [4]. Due to their unique shape, *caroselli* cannot not be inserted one inside another to build curved structures.

Conversely, they are placed in a vertical position on the centring or on a bed of bricks and then kept together with gypsum or lime mortar. In the case of barrel vaults, cross vaults or domes, *caroselli* are radially assembled following overlapping lines; their disposition over two lines is staggered in such a way that each *carosello* of the upper line is placed midway between two *caroselli* of the bottom line. In general, their lower base points downwards to form the intrados surface of the structure.

To complete the main structure, the completion jet is cast in two steps: the first consists in the actual casting of mortar, the second in the insertion of stone chips to better fill the voids between adjoining *caroselli*.

In the Italian southern region of Calabria there are several examples of barrel and cross vaults built with *caroselli*, especially in the small village of Bisignano (close to Cosenza) and the cities of Crotone, Soverato, and Monterosso Calabro (Figure 7). In the same region, *caroselli* are also part of a patented technique used to build a specific type of aseismic structures [15].

3. Problem of adhesion observed in experimental tests

In a previous work, the structural behaviour of an arch built with *caroselli* was investigated [16]. This arch presents an internal span of 1.5 m, a width equal to 0.5 m and a thickness of 15 cm. The *caroselli* are here arranged in a staggered manner, with their circular base tangent to the intrados of the arch. Mortar joints of approximately 2 cm separate each row of elements. The arch is built using a wooden centring. After the completion of the arch, its upper side is covered with a final cast of mortar with a thickness of about 3 cm [6;16].

A possible equivalent isostatic scheme for the analytical model is the three-hinged arch. Two steel beams are fixed with a single bolt to two blocks of concrete at the base of the arch to prevent relative displacements during the test. Initially, only two hinges are supposed to be present at each base, leading to supposing a two-hinged arch as a feasible equivalent isostatic scheme. However, the keystone section rotates in a way that is not consistent with the previous hypothesis, which may be caused by a non-perfect adhesion between mortar and fictile tubules, as shown in the Figure 8. This figure shows how the cracks develop inside the mortar without affecting the fictile tubules, suggesting the analysis of this problem in the present work.

Figure 8. Developed of the cracks in the arch during the experimental test [13].

4. Experimental study/research

The aim of the experimental campaign is to investigate the interface behaviour between fictile tubules bricks and mortar. The experimental tests are carried out at the Materials and Structures Engineering Laboratory of Civil Department of University of Calabria.

4.1 Preparation of the specimens

The dimension of the investigated prism-shaped specimens is $48 \times 16 \times 15$ cm^3, respecting the 1:4 ratio between the transversal dimension and the length of the prism requested for mortar specimens subjected to three-point bending tests. The formworks are built in a specialised carpentry workshop and consist of multilayer wood panels. The connection between adjacent wood panels is ensured by iron screws that facilitate disassembly after 28 days of maturation of the mortar. Before casting the mortar in the prism-shaped specimens, the frameworks have been coated with a material that facilitates the form stripping.

The fictile tubules here used are labelled NFTs (New Fictile Tubules) since they are produced in a potter factory with innovative and faster techniques, and then refined on the potter's wheel. They are 13 cm high, their diameter is about 6 cm, and they present a thickness of 6 mm [3-5]. The mortar is characterised by a compressive strength of about 1.8 MPa and consists of 9 parts of sand, 2 of lime mortar and 1 of cement.

A total number of 11 fictile tubules is used for each prism-shaped specimen. The elements are arranged in a staggered manner as shown in Figure 9. Mortar joints of approximately 1.2 cm separate each element from the nearest ones (Figure 10). The beam is completed by casting a 2 cm thick layer of mortar to cover the tips of the fictile tubules (Figure 11).

Figure 9. Placement of the fictile tubules.

Figure 10. Mortar joints.

Figure 11. Final phase of the mortar casting.

4.2 Three-points bending tests

A series of three-point bending tests is carried out on three prism-shaped specimens to assess the actual degree of adhesion between mortar and fictile tubules. Given the similarities between these prism-shaped specimens and mortar specimens, the tests are performed in accordance with EN 1015/11 [17]. The three-point bending testing machine consists of three steel rollers: two are placed at the base of the specimen for support, the other is located on the upper side for the application of the displacement (Figure 12). This is applied at a uniform rate with a speed of 0.2 mm/min.

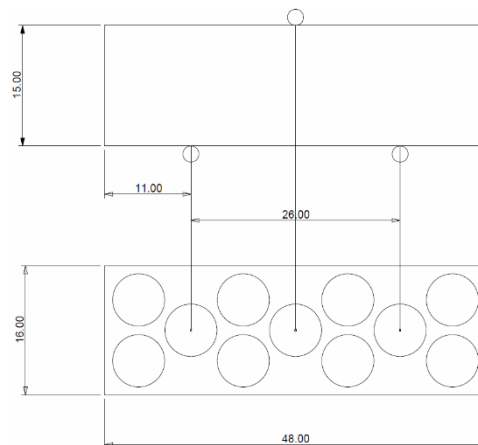**Figure 12.** Three-point bending testing machine.

Figure 13. Scheme of three-point bending test.

Figure 14 shows the load-displacement diagrams for the three considered specimens. In all three cases, the failure of the specimen occurs due to a single crack forming centrally and developing all along the height of the prism, which are shown in Figure 15, Figure 16, and Figure 17 for Specimens 1, 2, and 3, respectively. This crack develops inside the mortar, extending along the contact surface between the mortar and the fictile tubules, up to the top where the force is applied.
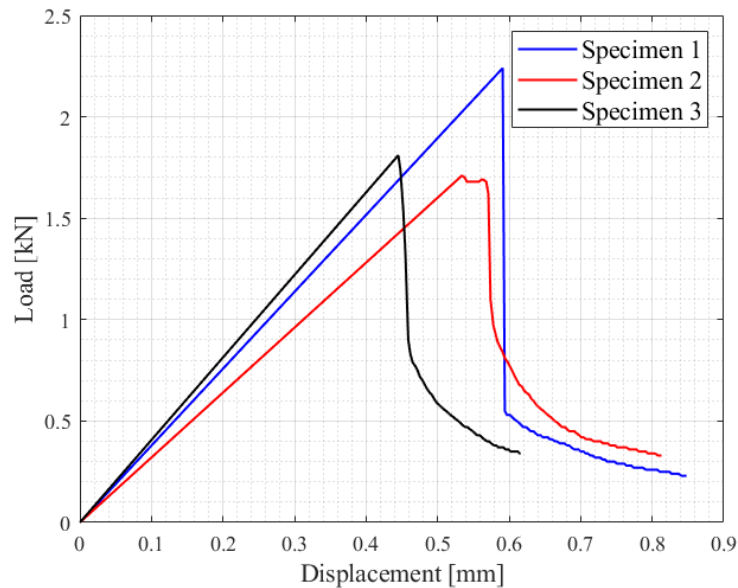
Figure 14. Load-displacement diagrams for the three specimens.

Figure 15. Development of the crack during the three-point bending test in the Specimen 1.

Figure 16. Development of the crack during the three-point bending test in the Specimen 2.

Figure 17. Development of the crack during the three-point bending test in the Specimen 3.

5. Numerical modelling of interface behaviour

The numerical analyses are carried out in the commercial finite element software Abaqus. The analytical model of one prism-shaped specimen is created as follows: first, the models of a single NFT and of the mortar *caldana* are separately generated, then 11 instances of the NFT model are assembled into the *caldana*.

The complete model is eventually meshed using tetrahedral finite elements. The finite element for the model of the prism-shaped specimen is shown in Figure 18, consisting of 8593 nodes and 28425 elements.
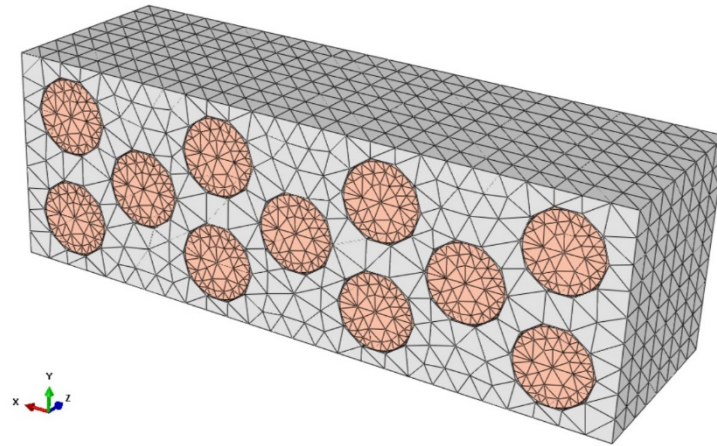

Figure 18. Finite element mesh for the analytical model of the prism-shaped specimen.

Two distinct material models are used to simulate the behaviour of the constituents. NFTs are modelled with the "brittle cracking model" available in the Abaqus library, which is suitable for brittle materials such as clay. It is based on the assumption of infinitely resistant compressive behaviour, whereas the tensile behaviour can be formulated as function of the tensile strength and mode I fracture energy. The elastic parameters and mechanical properties used for modelling the NFTs are listed in Table 1, and they are based on values whose reliability in representing the behaviour of NFTs has been assessed in a previous work [5].

Table 1. Elastic parameters and mechanical properties for modelling the NFTs.

Parameter	Value
Young's modulus	3900 MPa
Poisson's ratio	0.15
Tensile strength	3 MPa
Mode I fracture energy	0.087 N/mm

Conversely, mortar is modelled with the "concrete damaged plasticity model" also available in the Abaqus library, which is conceived for quasi-brittle materials such as concrete and mortar as well. It assumes distinct behaviours in compression and tension, and the latter can still be formulated as function of the tensile strength and mode I fracture energy. Also, it allows the modelling of damage in the material, both in compression and tension. The elastic parameters and mechanical properties used for modelling mortar are listed in Table 2, and they are again based on values whose reliability in representing the behaviour of mortar has been assessed in a previous work [5].

Table 2. Elastic parameters and mechanical properties for modelling mortar.

Parameter	Value
Young's modulus	190 MPa
Poisson's ratio	0.2
Tensile strength	0.6 MPa
Mode I fracture energy	0.018 N/mm
Strain corresponding to damaged material	0.5

The interface behaviour between NFTs and mortar is assessed by creating 11 interactions in Abaqus, one for each NFT. These interactions connect the contact surfaces between one NFT and the surrounding mortar. The interface behaviour is modelled considering four cases, each representing a possible configuration in terms of transmission of tangential stresses. All the cases are created by setting a specific "tangential behaviour" in the formulation of the interaction property, and they are listed in Table 3.

Table 3. Description of the four considered cases for modelling the interface behaviour between NFT and mortar.

Case	Description
Frictionless	No transmission of tangential stresses
Friction 0.3	Transmission of 30% of tangential stresses
Friction 0.6	Transmission of 60% of tangential stresses
Rough	Complete transmission of tangential stresses

The three-point bending test is simulated with an analysis in Abaqus/Explicit. The three steel rollers are not modelled for sake of simplicity. The rollers at the base are substituted by one hinge and one roller (to represent an isostatic scheme), while the velocity applied on the upper roller is directly applied to the mid upper section of the model.

The load-displacement diagrams for the four cases are shown in Figure 19, where they are compared against the envelope of the experimental data. It is evident how only the case labelled "Friction 0.6" is

able to grasp the actual interaction between NFTs and mortar. The first two cases are not capable of reaching the lower bound of the experimental envelope, whereas the last case overestimates the stiffness of the specimen. Figure 20 displays the analytical crack development for the case "Friction 0.6", which is consistent with that observed in reality for the three specimens.
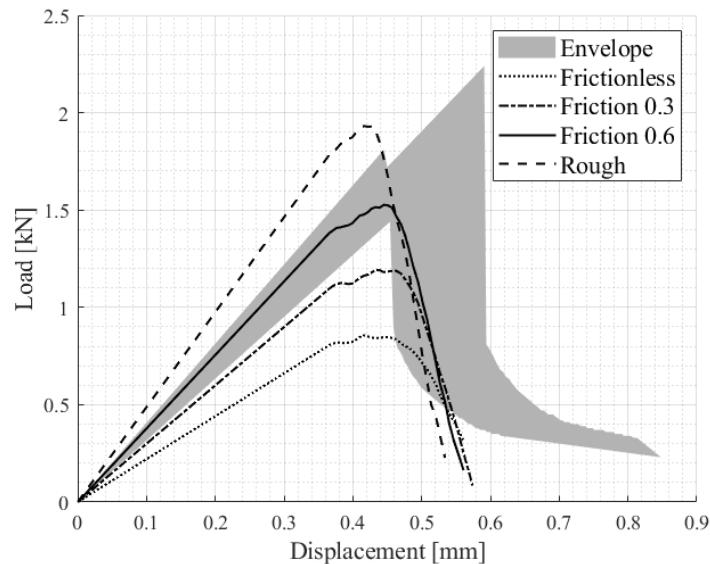

Figure 19. Load-displacement diagrams of the four interaction cases plotted against the envelope of the experimental data.
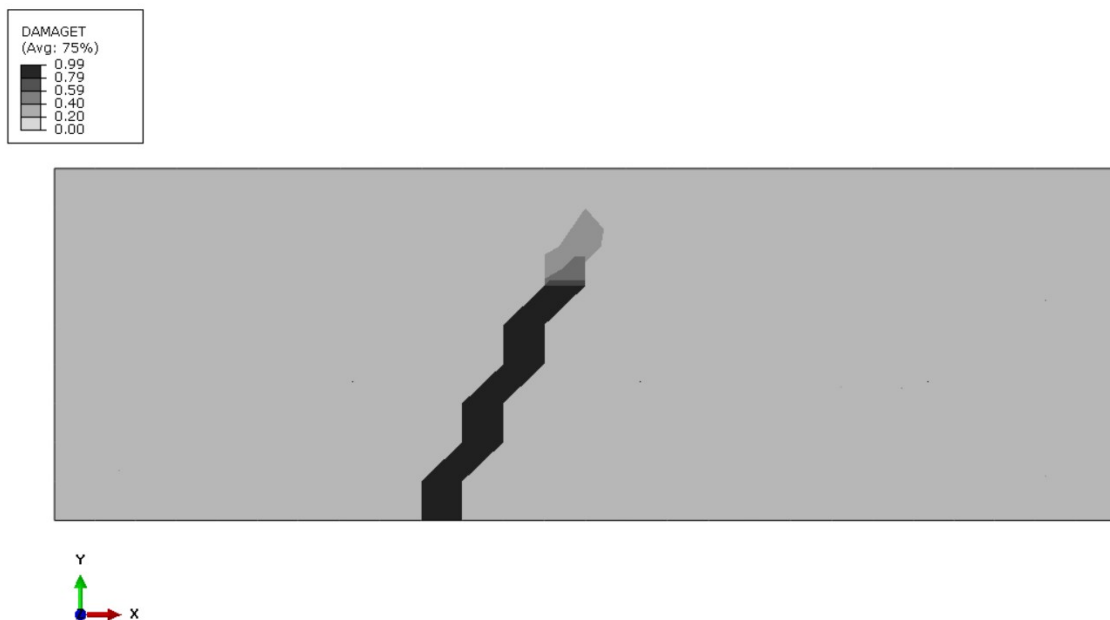

Figure 20. Development of the crack during the analytical three-point bending test for the interaction case "Friction 0.6".

6. Conclusions
In this work, the interface behaviour between hollow clay bricks called fictile tubules and mortar has been investigated. The investigation has been performed through a series of three-point bending tests on

three specimens, which consist of 11 fictile tubules embedded in mortar. The specimens are prepared assuring consistency with the 1:4 ratio between the transversal and longitudinal dimensions of the specimens used in three-point bending tests of mortar. The experimental results are then used as the basis for a series of back analyses carried out in the finite element code Abaqus, where four different cases of frictional properties are investigated. It is observed that the working hypothesis of non-perfect adhesion between tubules and mortar is correct, and that the actual interaction behaviour is well replicated by setting a 60% of transmission of tangential stresses between mortar and tubules.

In the follow-up of this paper, the newfound frictional properties will be applied to the analytical model of the arch to further corroborate the validity of these parameters assessing their suitability to simulate the outcome of the static vertical test on the arch itself.

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