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Behavior of thin masonry arches repaired using composite materials

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ABSTRACT

The innovative technique described in this article is the result of the evolution of a traditional building technique (*tabicada* technique or tile vaulting method) belonging to the constructive Spanish tradition. This technique consists in the realization of thin masonry vaults by placing several layers of thin bricks alternated with coatings of hydraulic mortar. Since the use of a modern technology may improve the mechanical performance of the traditional materials, the proposed strengthening system is based on the combination of the typical features of *tabicada* technique with the high mechanical properties of the composite materials. In order to provide extra tensile strength to the vaulted structure, composite grids were inserted between the brick layers into the mortar coating as well as on the outer surface of the vaults. Seventeen arch specimens were tested under a monotonic vertical compression load applied at the keystone. The influence of the type of strengthening arrangements, arch thickness and properties of hydraulic mortars were investigated. Test results are presented and discussed considering the mechanical behavior of the specimens and the axial stress-axial strain relationships.

1. Introduction

The assessment of unreinforced masonry arches or vaults is difficult to undertake in practice [1]. A structural engineer is often confronted with a standing structure that seems to defy most of the rules of structural behavior as incorporated in modern building codes. The engineer must then choose between retrofitting the masonry structure according to a "modern" understanding of structural behavior or attempting to study its behavior on a more fundamental level.

In the first case, conventional retrofitting techniques [2,3], such as single- or double-sided jacketing with cast-in-situ reinforced concrete, grout injections or crack stitching ties, internal or external post-tensioning with steel ties, have proven to lead to an adequate increment in strength and stiffness, but are often short-lived, labor-intensive, and usually violate the aesthetic, conservation and restoration requirements.

Following a recognition of the drawbacks of those "retrofitting methods", a series of both national and international standards [4] were introduced in order to claim the principle of "minimal intervention that achieve adequate protection" by techniques avoiding indiscriminate interventions on structures belonging to the architectural heritage. It is worth noting that improving the load-carrying capacity by interventions that do not alter the original structural behavior and, at the same time, remain completely removable is often hardly possible. For this reason, the listed principles are intended, in general, as asymptotic concepts, meaning that they are targets not fully achievable by common technology. Traditional retrofit methods combined with innovative materials can be helpful in the matter, opening new scenarios for engineers [5–14].

The present experimental campaign places itself in the above described framework focusing the attention on an innovative technique which, as it will be deeply explained later in the paper, combines the tradition (since it is the result of historical evolution of a traditional building technique belonging to the constructive Spanish tradition) together with the modernity (since the use of composite materials).

Since the behavior these reinforced structures, is poorly understood, precautions must be taken to ensure the structural safety. In the absence of established standards or guidelines for the analysis of these systems, numerical models, developed with available documentation about the structure, and engineering judgment offer a viable solution.

In such a context, it should be noted how several researchers have developed analytical predictions of the ultimate strength of

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FRP (Fiber Reinforced Polymer) strengthened masonry arches. Some can simplistically be described as discrete block models, in which the contact properties between the FRP and masonry and between adjacent masonry blocks are modeled [15,16]. Other methods use a sectional analysis of the strengthened arch as their starting point [5,6,8]. This broad classification is rather crude: all of the previously proposed analysis methods combine aspects of mechanism failure and component failure to different extents, reflecting the possible failure modes in an FRP strengthened arch. The focus of the current paper is upon experimental work; hence, these analytical models are not explored in further detail.

Seventeen prototypes of tile arches were designed, assembled and tested in laboratory to compare their behavior up to collapse through the investigation of three different research variables: strengthening scheme, number of arch rings and mortar type.

2. Description of the strengthening techniques

The innovative technique here illustrated is the result of the evolution of a traditional building technique belonging to the constructive Spanish tradition (*tabicada* technique or tile vaulting method, [17,18]).

Such a constructive method, proposed separately or in addition to other techniques (such as tie-rods or massive piers), consists in the realization of thin vaults by laying several layers (typically two or three) of flat rectangular tiles or thin bricks (called *rasillas*) alternated with layers of mortar mainly based on gypsum [19–21]. These tiles are so arranged as to cover or "break" the joints of adjacent layers: doing this in diagonal fashion assures right-angle breaking of all joints (Fig. 1). Furthermore, it should be noted that the elements of these vaults are not held together by the friction produced by the contact of the elements against each other under the force of gravity, as in the case of the conventional vaults; instead the tiles are simply "stuck" together by a mortar so tenacious that tiles will ordinarily break or split before the mortar parts. The action of the vault approximates to that of a sheet of plywood whose wood laminations will split before the adhesive bond gives way. The mortar is not simply a bed for the joints of large stone voussoirs; it is a thick blanket around and amongst the tiles so that the whole becomes, as it were, a sort of concrete made with an aggregate of highly regular pieces-the tiles. This gives reinforced elements that, in spite of their thickness, significantly lower than that of traditional masonry arches or vaults, enable masonry vaults to carry substantial tensile stresses, eliminating their greatest mechanical shortcomings at an acceptable cost.

Under this point of view the addition of composite materials represents a natural evolution of the aforementioned construction technique. By preventing the hinge opening, the addition of composite strips or fabrics into the mortar bed joints as well as on the outer surface of the vaults (*Reinforced tabicada* technique, Fig. 2) may provide extra tension strength to the curved structure, thus increasing its load carrying capacity. More specifically, while the outer layer of GFRP (Glass Fiber Reinforced Polymer) mesh (i.e., that installed on the extrados surface, Fig. 2b) gives, due to the larger distance from the neutral axis, the main contribution in preventing the arch soffit from hinging, the inner layers (i.e., those interposed between the layers of bricks, Fig. 2a) – even if less effective – are able to prevent both the extrados and the soffit of the arch from hinging.

Furthermore, regarding the thrusts, which the vault exerts on the walling, it should be noted that the proposed strengthening method does not substitute classic operations (tie-rods on the haunches or abutments). Since the addition of composite strips or fabrics may be applied in conjunction with the traditional techniques of tie-rods, it is, in fact, possible to compensate the thrust induced on the bearing walls thus providing extra displacement capacity with respect to the unreinforced structure.

Within this context, in spite of the use of thin vaults as a support element have become obsolete since the beginning of the 20 century, there is a practical purpose concerning their recovery as a strengthening elements for a specific structure, namely the brick "*in folio*" vault (made of flat solid bricks arranged in a single skin and usually used as the ceiling of a room or other enclosed spaces), that characterize the historical buildings in a large part of Central Italy [19]. With respect to the traditional retrofitting methods which are aimed to relieve the existing vault from any contribution (e.g., jacketing with cast in situ reinforced concrete or shotcrete), the proposed strengthening system is based on the idea of giving to the original "*in folio*" vault a fundamental importance as an element contributing to the static equilibrium of the global structural system. According to the hypothesis at the basis of the *tabicada* technique, instead of excluding the structural functionality of the pre-existing thin vault, the latter becomes a structural part of the new, multi-layered vaulted configuration.

This gives a promising technique that may represent a new opportunity to restoring ambit, since it is aimed at integrating the masonry rather than transforming it and compatible with the preservation of the building materials.

3. Materials characterization

3.1. Hydraulic mortar

Specimens were constructed using two types of hydraulic lime mortar. The first type (type 1) was chosen with the aim of

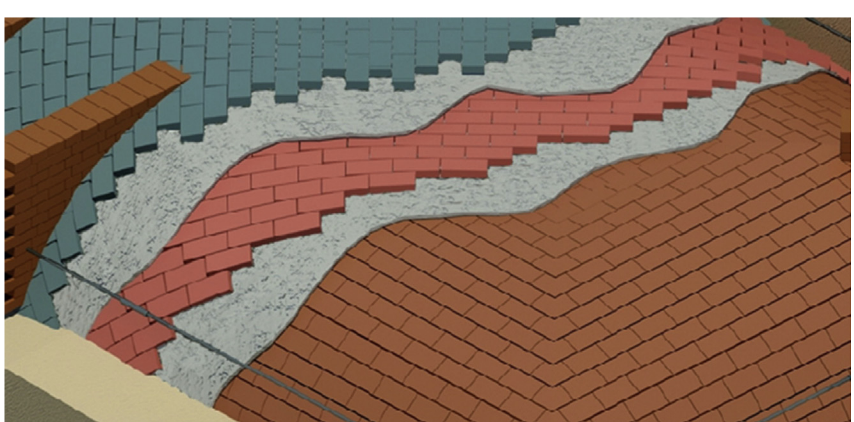

Fig. 1. *Tabicada* technique.