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Computer modelling of masonry cross vaults strengthened with fiber reinforced polymer strips

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ABSTRACT

Masonry arches and vaults often need repair and/or strengthening because of damage which can occur due to such factors as material degradation, forced displacements of supports or increase of service loads, which can finally cause their failure. A possible solution for preventing failure or to reinforce already cracked arches or vaults can be properly applied FRP composites – strips or sheets. The basis of analytical and numerical models of FRP and masonry, as well as some results of selected 3D numerical calculations of masonry cross vaults strengthened with FRP strips are presented in the paper.

1. Introduction

Masonry cross vaults are very important structural elements of many historical buildings of heritage value. These vaults are vulnerable to cracking and other dangerous failure mechanisms under certain loading conditions. Traditional reinforcement techniques as, for example, additional structures suspending or relieving existing vaults or surface strengthening using steel elements, may guarantee an adequate increment in strength, stiffness and ductility, but are often short lived and labor extensive. Besides, the additional elements can be mounted to convey expansion forces or to strengthen existing braces or struts. As an alternative to such solutions, composite materials can be applied in case of a necessity to considerably increase the load-bearing capacity of a strengthened structure. The main advantage of this material is high strength in relation to its mass and also its simple technique of application.

In the last few years great interest has been devoted to the reinforcement of masonry arches and vaults as a result of a growing necessity to repair heritage structures, either damaged due to natural disasters or because of the exhaustion of their bearing capacity after years of exploitation. In fact, for example, aramid fiber reinforced composites were adopted to restore the vaults of the Basilica di S. Francesco d'Assisi [1] and the Chiesa di San Filippo Neri, in Spoleto [2], destroyed by earthquakes.

Numerical analysis of structures reinforced in such a way is an important and complex problem. For example, Como et al. [3] applied the limit analysis theorems in order to evaluate the collapse of reinforced arches, and Olivito and Stumpo [4] proposed a numerical and experimental analysis of vaulted masonry structures subjected to a moving load. Chen [5]

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presented a method to calculate the limit load-bearing capacity of masonry arch bridges strengthened with fiber reinforced polymer (FRP). Foraboschi [6] presented mathematical models for studying the possible failure modes of masonry arches and vaults with FRP reinforcement.

Briccoli Bati and Rovero [7], and also Aiello et al. [8] developed experimental investigations on reinforced masonry arches, emphasizing that the application of sheets or laminates of composite materials significantly increases the strength of the structure, modifying the collapse mechanism and the corresponding collapse load. Experimental tests and finite element analyses of masonry arches made of blocks in dry contact and reinforced by FRP materials have been developed by Luciano et al. [9], demonstrating the effectiveness of strengthening. Ianniruberto and Rinaldi [10] investigated the influence of the presence of FRP on the collapse behavior of a structure when reinforcements are placed at the extrados or at the intrados of the arch.

It can be emphasized that the collapse of masonry elements is generally induced by the opening of fractures due to limited strength in tension. The presence of FRP reinforcement, placed in the tensile zones of the masonry structure, inhibits the opening of the fractures; thus, a compression state can occur for bent elements, and failure due to crushing can be activated. As a consequence, a suitable masonry model for reinforced masonry should take into account the possibility of collapse due to compression, i.e. a limited compressive strength for the masonry material should be considered.

Strengthening methods based on carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composite materials have favorable effects on the structural response and load bearing capacity [11–16]. FRP composites may bring an important load bearing contribution by compensating the lack of tensile capacity of brick masonry elements. Application of FRP strips over the inside and outside surfaces of the cross vaults can prevent the cracks opening and the formation of hinges prior to collapse of the structure. However, reinforcement cannot prevent masonry from cracking. So cracks may also form at a reinforced boundary, but cannot open because the reinforcement closes them.

Application of FRP strips increases the load-bearing capacity of the vault, although the following types of failure can appear [6]:

- crushing;
- sliding;
- debonding of the connecting layer;
- FRP rupture.

From the review of investigations carried out in the world [17–24] it is possible to state that the problem of reinforcing cross vaults by means of composite strips is widely analyzed, but there are still some details that need examination, such as modelling the process of FRP strip delamination from masonry surface.

In addition to their material and structural characteristics (low weight, corrosion resistance, high tensile strength and low thermal expansion coefficient) FRP stripes and sheets are generally simple in execution, also in difficult operative conditions, they offer a wide range of possible applications in different situations of damage. Their disadvantages are lack of fire resistance and relatively high cost. Despite that most of the traditional reinforcement methods used for masonry structures strengthening guarantee an adequate increment in strength, stiffness, and ductility, they very often are short-lived and labor intensive, and, usually, do not ensure esthetic requirements or conservation and restoration needs what is sometimes crucial for monumental structures and is perfectly fulfilled by FRP materials.

In the proposed initial finite element (FE) model and presented selected examples it was assumed that none of the above mentioned failure situations occurs. The objectives of this paper are the following:

- to develop and assess a numerical FE model for the analysis of unreinforced and FRP-reinforced vaults;
- to verify the enhancement of the response of vaults strengthened with FRP before failure occurs, compared to not strengthened ones;
- to analyze proper ways of application and localization of FRP strengthening to masonry vaults.

2. FRP material model

The material of FRP strips is assumed to be linear elastic and orthotropic until fiber tensile strength is achieved at which the rupture of fibers can occur [25]. Design of FRP reinforcement should ensure that the FRP system is always in tension. In fact, compression of FRP is unable to increase the performance of the strengthened masonry member due to its small area, compared to that of compressed masonry. Moreover, FRP in compression may be subjected to debonding due to local instability. In this analysis a perfect bond between materials was assumed.

3. Masonry material model

Due to the specific construction which represents a brick masonry in recent years have been developed and tested different ways of modelling the behavior of masonry structures. In these models the effort was put on the best definition of the most important feature of the masonry, which is its heterogeneity, resulting from a combination of ceramic components (units) and mortar (joints). In the analyses two main concepts of numerical modelling of the masonry are widely applied [26–30]. The first one is called two-material model or micro-modelling, the second is referred to as macro-model or equivalent material modelling.

In micro-models two materials – masonry units and mortar joints, are considered separately and are described by their own constitutive laws. In this approach blocks are modeled with continuum elements, while joints are simplified with interface elements. So, in structural analysis using FEM, the masonry structure is divided into high number of finite elements having different constitutive laws what leads to high computational effort because of generation of great number of finite elements.