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Review article

A review of methods for strengthening of masonry arches with composite materials

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ABSTRACT

Strengthening of existing structures have been widely investigated around the world with the aim to preserve historic heritage and monument. Traditional techniques are being abandoned in favour to composite materials considered as innovative. Several authors have recently investigated techniques using carbon fibre, glass fibre, steel rod or other fibre materials as strengthening material of masonry arches the last two decades.

This paper reviews the experimental campaigns conducted by several international researchers with the aim to bring new insights on the effectiveness of strengthening techniques using composite materials. A database of over 100 experimental tests have been analysed considering different arch parameters and interesting results on the role played by the position and the type of the reinforcement have be found.

1. Introduction

Masonry as construction material has been widely used around the world. First buildings with arched forms are attributed to Ancient and Near East civilizations 4000 BCE. They used stone or clay bricks to build corbel arches for underground structures such as drains. This technique will be considerably expanded throughout the Roman Empire where bigger structures like bridges and aqueducts will be constructed in masonry. Different forms of arches and vaults will be then introduced like segmental or semi-circular arches. In Europe, the introduction of ogive will be done during the construction of several bridges early centuries AC. Masonry became an architectural and structural system well diffused and adopted in many existing structures such as bridges and monuments. Since many of these existing structures were built long time ago, they are now suffering different type of damages either due to exceeding traffic loads or seismic events. It becomes important to assess them and plan their strengthening in order to preserve these cultural heritages.

Strengthening of masonry arches is adopted to either improve or restore their load carrying capacity. Specifically, reinforcement of arches is required for example, to improve their capacity to withstand earthquakes or live loads that have increased over the years from the original design conditions. Moreover, strengthening is essential for repairing structures that have suffered earthquake damages, settlement of foundations [1–4]. These events could induce essentially a loss of springing at the supports leading to different collapse mechanisms of the arch. Many authors focused their works on the discussion of the type of collapse mechanism and displacement capacity of masonry arches with spreading supports [5–8]. Instead, few works studied the interaction between inertia accelerations and relative displacement at the abutments as both the consequence of the earthquake in masonry arch structures. Numerical and experimental studies taking into account this interaction are required for the optimal design of the seismic retrofit of masonry structures.

The reinforcement of masonry arches can be achieved by means of several techniques. Traditional techniques for strengthening vaults and arches have been widely used in Europe and particularly in Italy many years ago. The common techniques found in literature are the use of steel bars or stirrups to increase confinement of masonry arches, the introduction of ties at the arch impost, the use of reinforced concrete hoods, the construction of internal spandrel walls to prevent thrust, the application of steel profiles at the arch intrados and the injection of cementitious mortar [9]. Due to the aesthetic incompatibility and to the extra self-weight and rigidity that these techniques could added to the structure, they are no longer used and are being replaced by new techniques.

Strengthening of masonry arches by means of composite materials is one of the most innovative techniques that can be used to increase or restore the structural capacity of these structures. The technique offers advantages over traditional reinforcement methods, as it does not modify the mass of the structure, does not significantly alter the rigidity of the arch [2,10,11], does not alter the static arrangement of the arch in service conditions and finally modifies the arch collapse mechanism.

The preservation architectural aspect of the cultural heritage and

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Nomenclature

Notation

V	shear force in section of vault
ds	length of portion of laminate
R_{frp}	sliding resistance due to FRP laminate
R_m	sliding resistance due to masonry
R	radius of curvature
T	tensile force in FRP
δs	infinitesimal length of portion of laminate
δϕ	infinitesimal angle
δN	infinitesimal axial force
CFRP	carbon fiber reinforced polymer
PBO-FRCM	polyparaphenylene benzobisoxazole- Fabric Reinforced Cementitious Matrix
SRG	steel reinforced grout
BTRM	Basalt Textile Reinforced Mortar
C-FRCM	Carbon-Fabric Reinforced Cementitious Matrix
SRP	steel reinforced polymer
GFRP	Glass Fibre Reinforced Polymer
L	arch length:
f	arch rise
S	arch thickness
b	arch depth
A_c	equivalent area of reinforcement
e	width of the reinforcement
ρ	$A_c/(b \times S)$ reinforcement ratio
L.T	load type
X_L	load position
P_u	maximum load of reinforced arch
α_P	$P_u/P_{u,0}$
$P_{u,0}$	maximum load of non-reinforced arch
μ	$(q_u - q_y)/q_y$ Kinematic ductility
q_u	maximum displacement at P_u
q_y	displacement at P_y
α_μ	μ/μ_0 (μ_0 = ductility of non-reinforced arch)
I	reinforcement at intrados;
E	reinforcement at extrados;
S.C.	static concentrated load
S.D.	static distributed load
H.L.	horizontal load

monument plays an important role to determine the strengthening technique. For this reason, the less invasive technique is to be considered for both the use of traditional and innovative technique. In fact, for traditional technique, the use of non-compatible material usually generates the flaw of the original structure while the use of epoxy resin in the composite material can lead to the humidity concentration until the cracks formation or failure of the structure [12].

Beside experimental researches, numerous theoretical studies have also been developed in recent years to determine structural models able to analytically and/or numerically simulate the experimental results. The aim of these studies was to provide mathematical tools to support the design of masonry strengthening systems that can provide reliable results and take into account the different possible types of collapse. These theoretical studies have primarily adopted three different calculation approaches: The finite and discrete element method [13–15] and limit analysis [15–21].

The simplest and most basic method of seismic analysis is the limit analysis, which despite being a simple structural calculation method, provides results that well describe the seismic behaviour of the masonry arch structure. In order to apply limit analysis, three assumptions should be made: the masonry has an infinite compressive strength, the tensile strength of the masonry is neglected and sliding within masonry elements is not allowed.

This paper presents and summarises the main data obtained from destructive laboratory tests carried out on reinforced arches using composite materials. The tests analysed in detail refer to the application of incremental vertical concentrated load until reaching failure conditions. It was then possible to perform a statistical analysis of data obtained and make interesting considerations on the structural behaviour of masonry arches reinforced with composite material.

2. Collapse mechanism of masonry arch

Researches carried out in recent decades on the strengthening of masonry arches with composite materials essentially focused on determining which materials can offer the best performance from a structural, economic and compatibility standpoint. Consequently, several research experiments have associated the structural performance achieved by strengthening masonry arches with different composite materials. Specifically, the main composite materials used are summarized in the Table 1.

Several experimental campaigns performed on both unreinforced and strengthened masonry arches and vaults describe the collapse mechanism of unreinforced arches as a consequence of the formation of four or five alternate hinges on the structure. In particular, a limited crushing of the masonry elements occurs firstly at the compressed part of the arch and the collapse becomes possible if hinges occur in an adequately number to create mechanism [22]. When the hinges are formed, they subdivide the arch structure in different blocks. A pinned system is then created at the boundary of each block that can rotate independently whether the load is symmetrical or asymmetrical [23]. Since the tensile strength of masonry is relatively low, the collapse of the masonry arch is linked to the position of the thrust line. As long as the thrust line remains inside the arch thickness, the arch is only compressed [24]. By increasing external loads, the structural behaviour changes and cracks initiate leading to the formation of first hinge. Some authors found that the first hinge appears at the extrados part of the arch while the second appears at the intrados. The failure happens thus as a consequence of the development of two other hinges near both the left and right abutments of the arch [9,24]. Fig. 1a shows the collapse mechanism of a masonry arch subjected to a concentrated load located at one third of its span length. As it can be seen (Fig. 1a), four hinges are formed and the thrust line is internal into the arch and tangential to the hinge points. When composite material is bonded to the surface of the arch, the collapse mechanism changes and the thrust line can be external with respect to the arch thickness (Fig. 1b–d). The tensile

Table 1
List of composite materials with both reinforcement materials and matrix.

Composite materials	Reinforcement materials	Matrix
PBO-FRCM	Polyparaphenylene benzobisoxazole	Cementitious mortar
CFRP	Carbon fibre	Polymer
BTRM	Basalt textile	Cement-free primer mortar (PM)
BTRM	Basalt textile	Cement-free primer mortar (PM)
B-FRCM	Basalt fibre	Cement-lime mortar
C-FRCM	Carbon fibre	Cement-lime mortar
SRP	Steel cord	Polymer
GFRP	Glass fibre	Polymer
GTRM	Glass textile	Cementitious mortar