Construction and Building Materials 145 (2017) 336–346

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Limit analysis of vaulted structures strengthened by an innovative technology in applying CFRP

Laura Anania *, Giuseppe D'Agata

Department of Civil Engineering and Architecture, University of Catania, Italy

HIGHLIGHTS

- A new approach to lower bound limit analysis of CFRP reinforced masonry arch is discussed.
- The basic idea of the proposed approach is to carry out a series of lower bound limit analysis.
- The shear strength is constant and given by the Mohr-Coulomb friction law from the previous step.
- The methodology results in very good agreement with available original experimental data.

ARTICLE INFO

Article history:
Received 6 June 2016
Received in revised form 22 February 2017
Accepted 27 March 2017

Keywords:
Arch
Vaults
Masonry structure
Strengthening
FRP
Limit analysis
Lower bound
Seismic retrofitting
Non-associative friction flow rule

ABSTRACT

Masonry vaults represent one of the most seismic vulnerable element in an ancient building. It also generally does not possess an adequate capability of redistribution of the seismic action among the walls of the buildings.

Nowadays the preservation of the historic vaults is devolved to the application of advanced materials and new technologies on traditional structures. The evaluation of their effects has assumed a major relevance. From the analytical point of view, the plastic (limit) analysis methods are now commonly used to determine the ultimate load–carrying capacities of masonry arch The aim of the present paper is to discuss the efficiency of an analytical models validated by means of experimental investigations carried out on masonry arches reinforced with an innovative technology proposed by the same author and based on the use of CFRP strips, with a special configuration called as "Ω-wrap". This configuration allows the resulting CFRP reinforced ribbed vault to assume the necessary strength and membranal and flexural rigidity so as to ensure the aforementioned seismic action redistribution capability and to avoid local collapse of the vault. A theoretical prediction of ultimate strength was derived in agreement with the occurrences observed during the experiments (masonry crushing, FRP rupture, debonding, sliding along the mortar joint). To this aim, a novel incremental step-by-step lower bound limit analysis approach was developed taking into account for the shear failure mechanism at each mortar joint. The shear strength is evaluated by the Mohr-Coulomb friction law for the mortar joint and by other nonlinear Italian Code relations for CFRP Ω-Wrap reinforcement. In the approximated incremental analysis process the current value of the shear strength, depend on the compressive stress resulting from the previous step.

1. Introduction

Masonry vaults are usually highly vulnerable to seismic hazard, as demonstrated in the recent past by the collapses of many masonry churches during the Umbria Marche (1997–1998), l'Aquila (2009) and Amatrice (2016) earthquakes. It also generally does not possess an adequate capability of redistribution of the seismic action between the masonry piers of the buildings.

So, nowadays, the theme of the seismic retrofitting of historical buildings, in presence of these structural curved components, is playing an increasing role, in the field of the civil engineering, The need of designing efficient and non-invasive strengthening techniques in high hazard area seems to be almost immediately clear to all technicians involved in the reconstruction. Recently, the use of innovative methods based on the use of light but high resistance materials (as FRP strips) appears a more powerful solution than the conventional retrofitting methods such as external reinforcement with steel plates, surface concrete coating and welded mesh, which have proven to be impractical, time expensive

* Corresponding author.
E-mail address: lanania@dica.unict.it (L. Anania).

http://dx.doi.org/10.1016/j.conbuildmat.2017.03.212
0950-0618/

and add considerable mass to the structure. In this paper, only a brief resume of same relevant results obtained by means of a new methodology for approaching the limit analysis of the reinforced masonry vaults, limited to the case of the non-isolated Ω-WRAP system, is reported. But, despite the always increasing diffusion of those innovative strengthening technique only few numerical method are nowadays available. Furthermore, when dealing with vaulted masonry structures, structural analysis becomes more complex because of the interaction between membrane and flexural actions.

From the analytical point of view, with the development of computer based numerical methods, the FEM method is largely used to simulate the complex behaviour of the masonry arches and vaults even when associated to innovative material (Mahini et al. [1,2]). However, this kind of analysis is often very time expensive and the input parameters of the simplified theoretical constitutive models are difficult to calibrate experimentally. For this reason, other method is actually proposed in literature, for the structural analysis of the masonry vaults and arches. Among these, the one that is becoming increasingly important is the limit analysis (Heyman J. [3]). The method proposed by Livesley [4], is based on the resolution of the equations of static equilibrium for under a vertical, horizontal punctual load or a bending moment applied over each rigid voussoir of the arch. Later Sinha [5], Ferris and Tin-Loi [6], Orduna and Lourenço [7], Milani et al. [8], gave a more accurate contribute to limit analysis taking also into account the friction of the joint as well as including the approach based on the thrust network analysis (Block and Lachauer [9], Fraternali [10]).

So, limit analysis with a strong reduction in the number of material parameters is capable of providing limit multipliers of loads, failure mechanisms. As a matter of fact, the reinforcement by means of FRP should require a non linear complex damaging models capable of taking into account both the typically brittle behaviour due to FRP delamination and the tensile cracking of the mortar joints, while limit analysis is based on the assumption of a perfect plasticity of the constituent compounds (Baratta & co. [11]). Anyway, limit analysis is an useful instrument for the design purpose as suggested by CNR-DT 200 Italian Code [12] and [13].

In the follow, an approximated methodology for approaching the lower bound limit analysis of masonry arch (and barrel vaults), reinforced by CFRP is illustrated. It is based on the central idea of carrying out a series of lower bound limit analyses. In each of them shear strength is assumed constant and given by the Mohr-Coulomb limit at the corresponding compression force, in each mortar joint, resulting from the previous step.

In this way the associated flow rule holds at each step for the shear failure mechanism without dilatancy.

The analytical approach is also capable of taking into account the shear mechanisms according to the dowel effect at the interface between masonry and CFRP. So, an incremental procedure was carried out in which for each single step the limit analysis problem was solved considering a constant value of the shear resistance derived taking into account the normal stress at the previous step according to Coulomb law. The proposed limit analysis method was implemented in Mathematica software to carry out numerical simulation of the experimental test conducts on the scaled barrel vault samples, described above (See Fig. 1).

To this aim, a new technology for the retrofitting of masonry vaults by means of CFRP, proposed by Badalà et al. [14] and named Ω-WRAP is studied under analytical and experimental investigation.

The basic idea of the "Ω-Wrap" system is to give high stiffness to the CFRP strips by wrapping it around a high resistance mortar core cast and molded in site (Fig. 1).

This reinforcement, placed at the extrados of the vault, allows preserving the precious frescoes that commonly, in the historic masonry buildings, adorn the intrados.

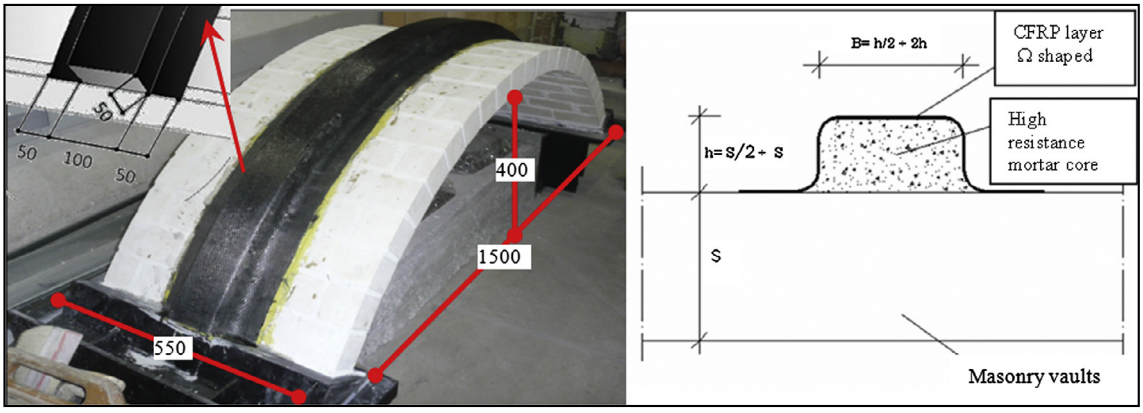
In addition, it presents a higher resistance against delamination respect to the canonic FRP – strip based reinforcement, as considered in the technical document CNR-DT 200/2004, for two orders of reasons:

- The extrados curvature positively affects the delamination resistance due to the onset of compression normal stresses. See Basilio et al. [15], D'Ambrisi et al. [16], Malena & De Felice [17], Fagone et al. [18];
- The global bending stiffness of fiber-reinforced rib increases its resistance against shear induced out of plane peeling (Fig. 2);

It is also under evaluation the effectiveness of another version of the proposed innovative reinforcement system, named Isolated-Ω-Wrap.

This variant provides for the interposition of a neoprene bearing between the extrados of the vaults and the fiber reinforced concrete rib.

This bearing, with a thickness of a few millimeters, continuously placed throughout the length of the leader of the vault and having the same width of the reinforcement, is expected to allow the vault to freely deformed under daily thermal-hygrometric gradient. On the contrary, remaining unchanged the sewing effect on the collapse hinges, and the cinematic confinement effect and thus the resistance against accidental and seismic loads. Some first results about this system is available in Anania [19].



(a) Model of the barrel vault tested, dimensions in [mm]; (b) Ω-Wrap reinforcement

Fig. 1. a) Model of the barrel vault tested, dimensions in [mm]; b) Ω-Wrap reinforcement.