Engineering Structures 76 (2014) 339–358

Contents lists available at ScienceDirect

Engineering Structures

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

Advanced numerical models for the analysis of masonry cross vaults: A case-study in Italy

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ARTICLE INFO

Article history:
Received 26 December 2013
Revised 14 June 2014
Accepted 15 July 2014
Available online 8 August 2014

Keywords:
Masonry cross-vaults
Case study
Non linear FE model
Infill role
FRP strengthening

ABSTRACT

Aim of the present paper is the analysis of a series of existing masonry cross vaults exhibiting meaningful structural deterioration and diffused crack patterns, by means of an advanced non-linear and limit analysis software.

The approach utilized is a non-standard and non-commercial one and bases both for the non-linear and limit analysis procedure on a FE discretization of the domain by means of rigid infinitely resistant wedges, where all the non-linearity is concentrated on interfaces between adjoining elements.

When dealing with the non-linear code, a sequential quadratic programming scheme is used at each iteration in order to deal with the deterioration of mechanical properties of interfaces, provided that the actual non-linear behavior is approximated by means of a linear piecewise constant function.

Several numerical simulations are performed varying constraint conditions, material properties, infill modeling and presence of FRP strips as reinforcement devices, comparing and discussing in detail the results obtained.

From simulations results, it is found that the approach commonly used in practice to study cross vaults by means of the assemblage of single arches is not always reliable, providing failure loads and mechanism quite different from the real ones. Furthermore, similarly to what occurs for masonry arch bridges, it is found that the role played by the infill is crucial and that, depending on the actual mechanical properties of the infill, both the failure mechanisms and the collapse load may vary significantly.

1. Introduction

The analysis of masonry vaults under both gravity loads and horizontal seismic action is still an open issue that deserves great consideration by specialized technicians.

Double curvature masonry structures in the form of arches, bridges, cross vaults and cupolas constitute a considerable percentage of the historical built heritage: for this reason, their study – mainly based on graphical statics – goes back to the early 18th century. Among the others, the approaches based on 1D equilibrium equations for the study of masonry domes and proposed by Bouguer (1734), Coulomb (1773), Bossut (1778) and Mascheroni (1785), are worth noting.

Anyway, what was clear from the beginning, was that non-linearity appears very early on curved masonry elements, even in presence of self-weight and with very low tensile stresses.

Taking into account such important feature, a considerable improvement in the analysis of spherical domes was achieved when Levy (1888) proposed a graphical analysis aimed at finding the circle on which circumferential forces vanish. For an exhaustive history of the theories of masonry vaults we refer the reader to the comprehensive treatise by Benvenuto [1].

Exception made for some particular cases either where geometric and load symmetry may help in simplifying the problem or for single curvature structures (arches), and despite the considerable wide spreading of Finite Elements programs, it can be affirmed that, at present the models available to practitioners for a fast and reliable analysis of curved structural elements beyond the elastic limit are a few, see for instance the indications provided by Como [2], Paradiso and Tempesta [3], Mark et al. [4], Heyman [5–7] and Huerta [8].

Limit analysis theorems associated with FEs, both in the static and kinematic version, are still the most effective and widespread procedure to estimate the collapse loads of one dimensional arches [9–14]. In a similar way, cupolas may be treated as well, but only under the quite restrictive condition of axi-symmetric loads

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http://dx.doi.org/10.1016/j.engstruct.2014.07.018
0141-0296/

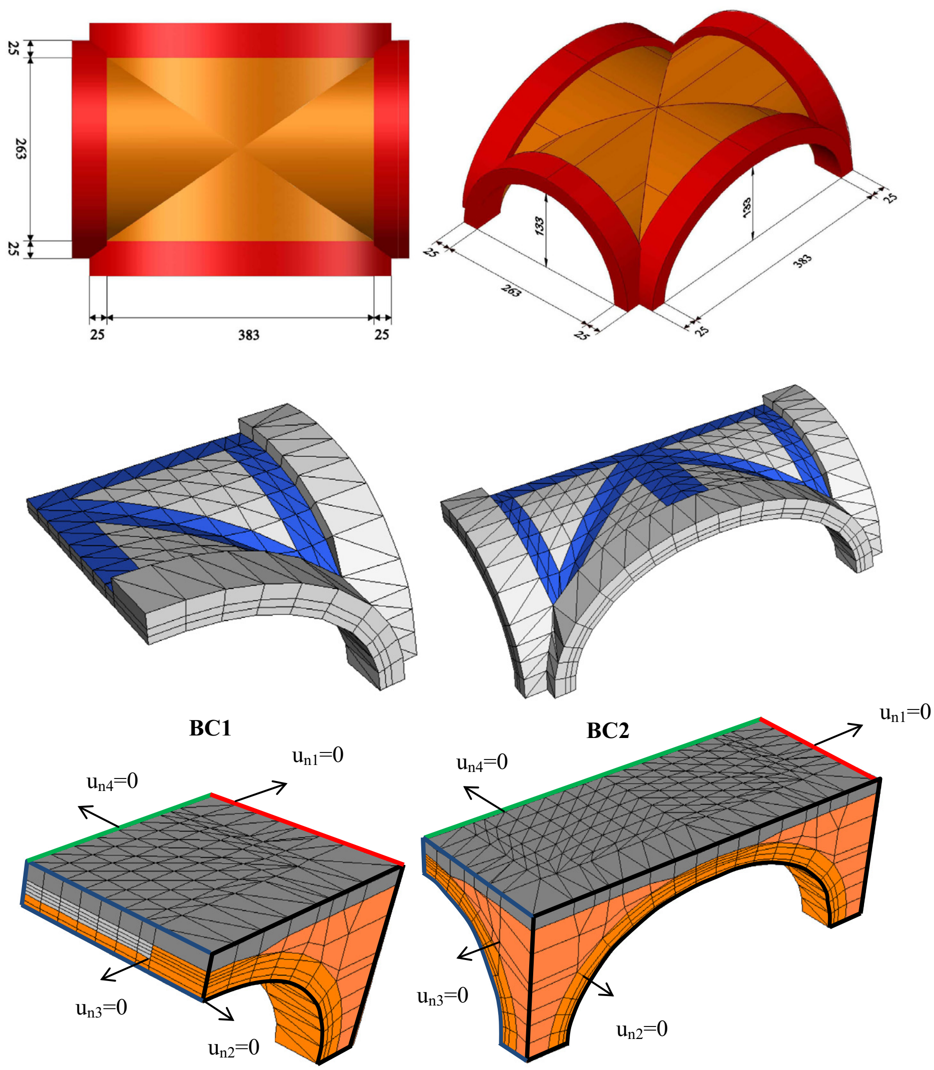

Fig. 1. Top, plan and perspective view of the rectangular cross vault analyzed (dimensions in centimeters). Center, first and second boundary condition configurations BC1 & BC2 without infill, FE discretization. Bottom, first and second boundary condition configurations BC1 & BC2 with infill.

Fig. 2. Ground floor planar view with identification of the position of the vaults.

[14–17]. Exception made for some special cases, the extension of automated approaches for complex geometries, general load conditions, reinforced arches and structures interacting with the infill still remains a challenging topic [18–22], despite experimentation in the field is putting at disposal a huge amount of experiences and evidences [23–25]. In absence of dedicated software, the most