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On the thrust surface of unreinforced and FRP-/FRCM-reinforced masonry domes

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ABSTRACT

We employ a *r*-adaptive finite element model to search for a 'safe' thrust surface of a masonry dome, which minimizes the maximum tensile stress carried by the unreinforced portion of the material. A numerical procedure based on a Breeder Genetic Algorithm is employed to drive the movement of the nodes of a membrane model within a suitable design domain, which coincides with the region comprised in between the intrados and extrados of the dome in correspondence with the unreinforced portion of the structure. The presence of externally bonded Fiber Reinforced Polymer and/or Fabric Reinforced Cementitious Mortar reinforcements is accounted for by allowing the thrust surface to move outside the physical domain of the structure in correspondence with the reinforced regions. A benchmark example shows that the proposed procedure leads to detect if a masonry dome is safe or not, according to the master 'safe' theorem of the masonry vault theory. In addition it allows to optimally design reinforcement strategies that are aimed at preventing or mitigating crack damage, and increasing the load carrying capacity of the structure.

1. Introduction

The so-called modern vault theory by Heyman [1] consists of a limit analysis approach to the statics of masonry arches and vaults based on the following assumptions: (i) masonry has no tensile strength, (ii) masonry has infinite compressive strength, and (iii) sliding between masonry parts does not occur (*no-tension model*). It is well suited for curved structures where the effects of bending and shear stresses on the collapse mechanisms are usually less relevant than those played by in-plane tensile stresses [2,3]. The individual roles played finite friction between parts, infill, brick pattern and individual members, such as, e.g., the lantern, drum and buttresses, on the limit analysis of masonry vaults and domes is accurately described in Refs. [2,3] and references therein. In the case of masonry arches, the master 'safe' theorem of Heyman leads to search for a fully-compressive line of thrust (or funicular curve) of the applied loads, which is entirely contained within the intrados and the extrados of the structure ('static' or 'safe' theorem of the limit analysis of masonry arches, see Chapters 1 and 2 of Ref. [1]). Several extensions of the funicular curve method to 3D problems dealing with vaults and domes have been proposed over recent years, by using either continuous or discontinuous approaches. Continuous approaches typically make use of stress-function formulations of the equilibrium problem [4–6] or maximum modulus eccentricities surfaces [7,8], while discontinuous approaches describe the no-tension stress field through spatial force networks generated via 3D funicular constructions [9], the Thrust Network Analysis (TNA) [10,11], or the Lumped Stress Method (LSM) [12–15]. Continuous and discontinuous approaches based on stress-functions or the TNA are intrinsically restricted to parallel loading [4,13,11], while maximum modulus eccentricities surfaces call for fixed finite element models assuming given boundary conditions [8]. Under parallel loading, a stress function-based mesh adaption strategy based has been presented in Ref. [13], employing a convex hull predictor-corrector strategy.

A number of studies have shown that genetic/evolutionary algorithms are particularly useful in structural optimization problems [16–20]. In particular, such optimization strategies have led to

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show that funicular shapes of curved structures provide minimal compliance configurations [21]. Optimization through evolutionary algorithms was first developed in the 1960s and has since come to refer to a family of probabilistic search methods inspired by the principle of natural selection [22–25]. Evolutionary optimization algorithms have been shown to be well suited for problems where the solution space is multidimensional, multimodal, discontinuous, and noisy [26]. A Breeder Genetic Algorithm (BGA), is a specific type of evolutionary optimization algorithm, that employs a both stochastic and a deterministic selection scheme, in that the fittest "individuals" (solutions) are selected from a current generation and enter the "gene pool" to be recombined and mutated as the basis to form the new generation, fitter population, and arrive at an optimal solution [27–30].

The present study deals with an adaptive finite element approach to the search for a 'safe' thrust surface of a masonry dome, which is either unreinforced, or reinforced through externally bonded Fiber Reinforced Polymer (FRP) and/or Fabric Reinforced Cementitious Mortar (FRCM) systems over a portion of the boundary [5,6,31–36]. We assume that the dome resists the external loads through a thrust surface contained in a given search domain, which exhibits zero or almost-zero tensile stresses over the unreinforced portion of masonry. An elastic finite element model is allowed to move within the search domain, utilizing a BGA to manipulate the coordinates of the mesh nodes within the prescribed bounds, and minimizing the maximum tensile stress suffered by the unreinforced masonry (fitness function). The proposed approach is able to handle arbitrary loading conditions, structural inhomogeneities (e.g., nonuniform material properties), and geometries. The modeling of FRP/FRCM reinforcements is carried out following Baratta and Corbi [5,6], on allowing the thrust surface to move outside the physical domain of the structure in correspondence with the reinforced regions. A benchmark example allows us to emphasize the technical potential of the

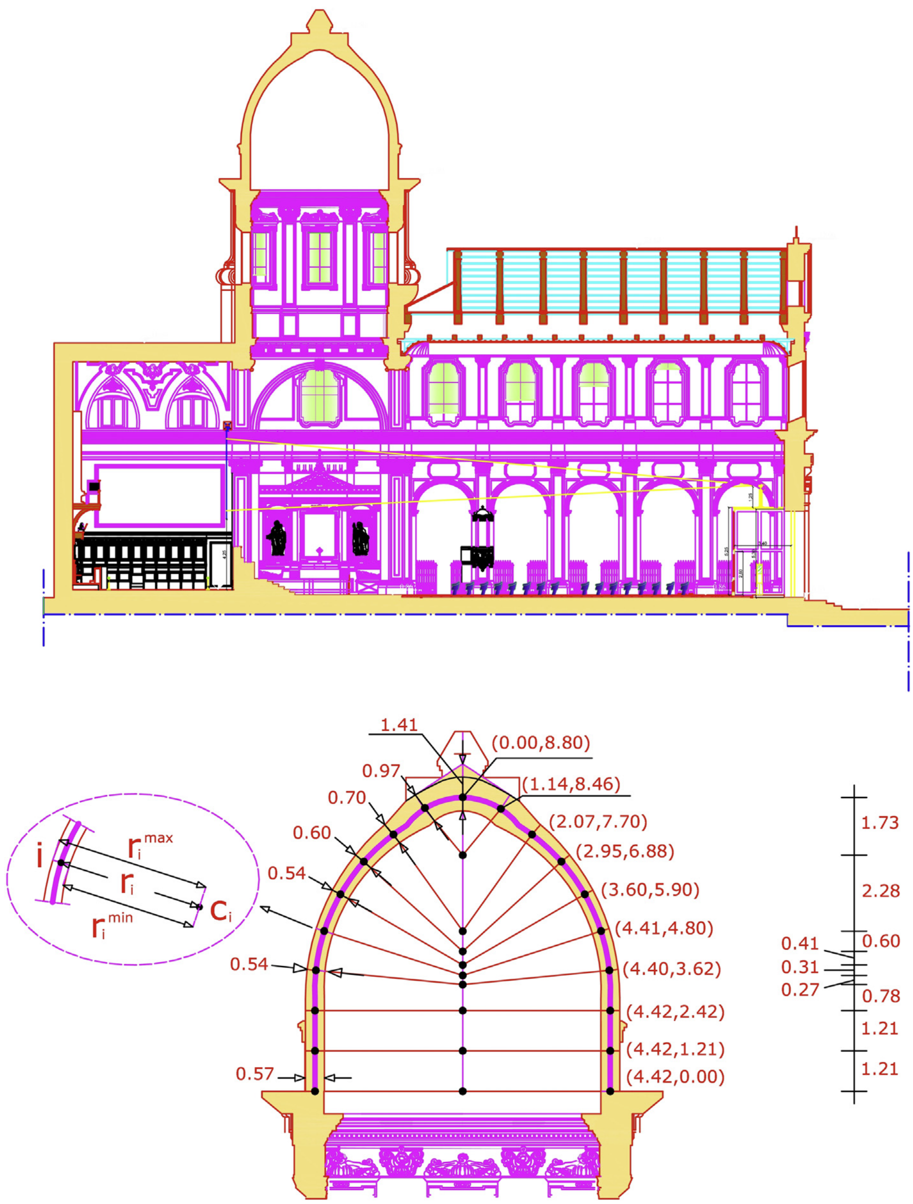

Fig. 1. Cross-section of the church of Santa Maria di Monteverginella in Naples (top) and zoom-in of the dome (bottom).