Preface

Many historically and artistically important masonry buildings of the world's architectural heritage are in dire need of maintenance and restoration. In order to optimize such operations in terms of cost-effectiveness, architectural impact and static effectiveness, accurate models of the structural behavior of masonry constructions are invaluable. The ultimate aim of such modeling is to obtain important information, such as the stress field, and to estimate the extent of cracking and its evolution when the structure is subjected to variations in both boundary and loading conditions.

Although masonry has been used in building for centuries, it is only recently that constitutive models and calculation techniques have been available that enable realistic description of the static behavior of structures made of this heterogeneous material whose response to tension is fundamentally different from that to compression.

Important insights on the mechanical behavior of masonry arches and vaults come from as far back as Leonardo [10], Hooke [58], Poleni [92] and many other authors (see [47], [9] and [10] for detailed references). Castigliano, in his famous paper on the Mosca bridge [23], and Signorini, in his studies on masonry beams [97], [98], showed both the possibility and necessity of taking into account the weak tensile strength of masonry material.

Subsequently, the success attained in applying linear-elastic calculations to iron and reinforced concrete structures elicited so much enthusiasm that the models sometimes came to be employed, in a rather arbitrary fashion, to the study of masonry constructions as well. This not only hampered research efforts to further the work begun in 19th century by Castigliano on developing proper calculation techniques for masonry structures, but also contributed to breeding scepticism regarding the very possibility of modeling the static behavior of masonry buildings. For many years the fundamental studies on materials not withstanding tension remained without practical application, until the sixties, when they were resumed in order to determine the collapse load of relatively simple masonry structures [61], [54].

More recently, the availability of ever more powerful computers and sophisticated numerical techniques for solving nonlinear problems has reopened the debate over the possibility and advisability of modeling restoration work on historical building with the aim of evaluating its effects on the structures' statics before its implementation.

Many authors have proposed determining the collapse load for masonry structures through rigid blocks models with different kind of interfaces [62], [64], and have applied these models to the study of vaults as well [86]. Elastic-plastic constitutive equations are widely adopted to model both the block units and mortar, as well as taking into account the anisotropy of masonry (see e.g. [65] and [66]). A comparison among elastic-plastic constitutive models adopting different yield criteria (Galileo-Rankine, Drucker-Prager, etc.) can be found in [45], and an application to the study of vaults is presented in [101]. Moreover, many proposed models use homogenization techniques to take the masonry's texture into account, even if their application is generally limited to the study of panels [81], [82], [104].

A constitutive equation widely adopted to model the behavior of masonry materials views them as nonlinear elastic materials with zero tensile strength and infinite compressive strength [41], [42] and [38]. Many authors have contributed to a better understanding of this constitutive equation and to detailing its capabilities [97], [98], [54], [56], [90], [28], [37], [93], [94] and [95]. This equation, which is known as the *masonry-like* or *no-tension* model, can, at least in certain aspects, realistically describe the mechanical behavior of masonry [12], [13], [76].

Despite the relative simplicity of the constitutive equation of *masonry-like* materials, explicit solution of equilibrium problems of any practical interest is nonetheless very difficult [7], [8], [80]. Therefore, in order to study real problems, it is necessary to resort to numerical methods. To this end, suitable numerical techniques have been developed [68], [1], [96]. The constitutive model has been generalized in order to take into account both masonry's bounded compressive strength and its weak tensile strength, and both the model and the associated numerical method studied have then been applied to the analysis of some buildings of historical and architectural interest [77], [75], [67], [78], [13], [12], [14], [74].

In this book we shall firstly provide a detailed description of the constitutive equation of the masonry-like materials, clearly setting out its most important features. In order to make the approach easier to follow, we shall first present the case of infinite compressive strength and zero tensile strength, and only afterwards address the modifications necessary to take into account the material's bounded compressive strength and weak tensile strength. Lastly, the approach to masonry-like materials under non-isothermal conditions is dealt with. The main properties of the constitutive equations presented here are proved for the general anisotropic case, though the stress tensor as function of the strain tensor has been calculated for the isotropic case only. Since the numerical techniques for determining an approximated solution to the equilibrium problem make use of the tangent stiffness matrix, the derivative of the stress with respect to strain is calculated explicitly. These issues are taken up in Chapter 2 using some basic concepts of tensor algebra and analysis, which are summarized in Chapter 1. This chapter is devoted to some basic results on the gradient and divergence of vector and tensor fields, as well as some less standard questions such as differentiation of eigenvalues and eigenvectors of a symmetric tensor with respect to the tensor itself.

Chapter 3 describes the equilibrium problem of solids made of a masonry-like material and presents a proof of the uniqueness of the solution in terms of stress. This result has been obtained in [4] and [46] under much more general hypotheses than those considered here. In fact, we preferred to formulate the results in such a way that their understanding did not call particular skills on functional analysis. Moreover, different variational formulations of the equilibrium problem are dealt with, and the equivalence between some of them proved.

Chapter 4 briefly describes the numerical method used to solve the equilibrium problem and implemented in COMES-NOSA, a finite element code developed at the Istituto di Scienza e Tecnologie dell'Informazione "A. Faedo" of the Italian National Research Council (CNR).

Chapter 5 is devoted to masonry arches and vaults. Although the limit analysis of masonry structures is not dealt with in this book, some basic results are recalled, as they are used later to interpret the results of some numerical analyses. The maximum modulus eccentricity surface (m.m.e.s) is then defined for masonry vaults; in our opinion, this can play a role analogous to that of line of thrust for arches and thus allows concise, effective rendering of the results of the finite element analyses, as well an evaluation of the safety of vaults.

In Chapter 6 we first present some simple equilibrium problems whose explicit solutions are known and compare the explicit solutions with the numerical ones obtained via the COMES-NOSA code. We then consider some different masonry structures. Although explicit solutions to the equilibrium problem are not available for such cases, we explicitly determine the value of the collapse load. Then, for the sake of comparison, the collapse load is calculated via numerical analysis by progressively increasing the load until convergence is not longer attainable.

Finally, Chapter 7 presents some applications. The first three cases deal with some important monuments with the aim of modeling eventual strengthening operations and assessing their effects on their static behavior. The fourth example, of a completely different nature, is a study of a ladle employed in the iron and steel industry. The analysis aims to determine the behavior of the refractory material lining the metallic vessel, which must hold molten steel.

Four appendices supplement the book. Some results concerning the constitutive equation of masonry-like materials in the two-dimensional case are listed in Appendix A and a brief description of the numerical method for the solution of the equilibrium problem in the non-isothermal case is given in Appendix B. Appendix C contains some information about the finite element code COMES-NOSA and lastly, Appendix D, written by Stefano Secchi, presents a graphical tool which can be used to process both input and output data for COMES-NOSA.

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The COMES-NOSA code and graphical tool described in Appendix D may be freely downloaded, together with the associated user manuals, from the Website http://www.isti.cnr.it/comesnosa. We wish to thank Silvia Degl'Innocenti and Andrea Pagni for their support in creating the Website and compiling the software documentation and Anthony Cafazzo for the care he took to improve the quality of the book's English.

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