

## Chapter 12

# Validation of the Discrete Element Method for the Limit Stability Analysis of Masonry Arches

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### ABSTRACT

*This chapter revisits the limit equilibrium analysis of masonry arches when subjected to gravity and lateral loads. Firstly, the major contributions during the last three centuries either with geometric or energy formulations are discussed, and subsequently, the performance of the Distinct Element Method (DEM) is examined against rigorous solutions. Analytical solutions with the use of energy methods are presented for the assessment of the stability of masonry arches with circular or elliptical shapes under various load conditions, including gravity, lateral inertial loading or earth pressures. The DEM is implemented in all loading cases and reproduces the analytical results with remarkable accuracy. The DEM is used either for a direct correlation with the classic limit analysis that assumes that the joints of the masonry blocks do not transmit tension, masonry blocks are rigid and incompressible and do not slide at the joints, or by permitting sliding with the adoption of Coulomb sliding failure between the joints.*

### INTRODUCTION

During the last three decades we have witnessed a growing interest regarding the preservation of our cultural heritage and the retrofit of historic structures. The long history of these structures, most of them built out of masonry, is partly due to their sound structural configuration, the advanced level of construction practices and the quality of building materials. At the same time, the long loading history on these structures ranging from ground settlements to earthquake excitations has resulted in the accumulation

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of a variety of deformations which are responsible for a prevailing stress field that its current state may be challenging to assess.

In view of the challenge to assess the actual local stresses in a historic structure, which through the centuries has suffered a variety of deformation, an “elastic stress” analysis becomes less attractive; whereas, the pre-twentieth century “limit equilibrium” analysis has become again increasingly popular (Sinopoli et al., 1997; Foce & Aita, 2003; De Luca et al., 2004; among others).

Figure 1 summarizes the modelling strategies for masonry structures. Continuous modelling is mainly represented with Finite Element Analysis (linear and nonlinear), while discontinuous modelling is represented with Limit Analysis (classic and advanced formulation) and Discrete Element Method (DEM).

Below we present an overview of the major contributions for the analysis of limit stability of masonry arches during the last three decades together with the latest developments of limit analysis, including DEM.

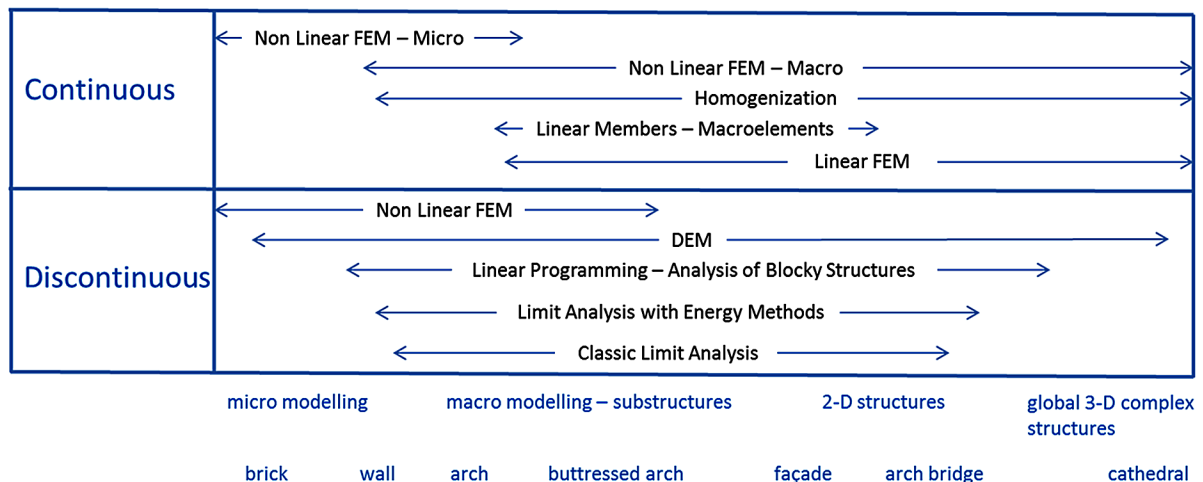
## BACKGROUND

### Stability Analysis of Masonry Arches: The Early Concepts

Robert Hooke (1675) was apparently the first to propose a rational rule for sizing masonry arches by describing the analogy in the load path between a “hanging chain”, which forms a catenary in tension under its own weight, and a masonry arch which stands under compression. This analogy conceived by Hooke is expressed in the literature “As hangs the flexible line, so but inverted will stand the rigid arch” (Heyman, 1998; O’Dwyer, 1999; Block et al., 2006).

Due to its zero tensile strength, the masonry arch acts only in compression; therefore, according to Hooke’s analogy, it is expected to satisfy equilibrium if its finite thickness can accommodate the shape of an inverted “hanging chain” which acts only in tension (Gregory, 1697). The shape of the catenary (the “hanging chain”) is a physically realizable load path which keeps the constituents of the one-dimensional chain (rings) in equilibrium. In the two-dimensional masonry arch, the physically realizable load path is

*Figure 1. Modelling strategies for masonry structures*



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