SIMULATION OF COMPLEX 3D BEHAVIOR OF MASONRY ARCH SYSTEMS

by

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Masonry structures constitute a large portion of architectural heritage all around the world in the form of post-lintel systems; walls, arches, vaults and domes in buildings and masonry arch bridges. Since it is such a dominant construction material, achieving realistic numerical models of complex masonry structures is of particular interest to better understand their structural behavior and avoid unnecessary or poor interventions.

This dissertation makes several contributions to the state of the art of modeling complex masonry arch systems.

First, in discontinuum analysis commonly used contact models in tension (tension cut-off) does not capture the complete response of the material and also does not include mode-I fracture energy which leads to the underestimation of the capacity. In this context, present dissertation proposes new contact models to be incorporated into the discrete element method (DEM) to more accurately simulate the tensile softening in quasi-brittle materials, such as masonry, with an emphasis on fracture mechanism and post-peak response. As an important novel contribution, the proposed computational models successfully represent the complete (pre- and post- peak) material behavior and realistically replicate the cracking mechanism.

Second, the discontinuum modeling strategy is extended to analyze the masonry arches and it is compared with different modeling strategies, namely limit state and sequential linear analysis. All numerical models are validated via experimental results and sensitivity analyses are performed on the mechanical properties of the material.

Third, a novel 3D representation of masonry arch bridges is achieved using mixed discrete-continuum approach and it is validated with several experimental studies. With this modeling strategy, two main contributions are achieved; first, triggering mechanisms for the out of plane failure of spandrel walls are established; second, the influence of soil backfill on the behavior and strength of the bridges is better understood through a comprehensive parametric study. Transverse effects, damage patterns and collapse mechanisms are discussed under different types of loading considering different arch bridge models, representing common geometrical properties in the northwest Iberian Peninsula. The analysis demonstrates the severe capacity reduction due to spandrel wall failures and the importance of soil backfill in the behavior of these systems. These observations were, only possible by utilizing the proposed mixed numerical modeling strategy. Hence, a better understanding of masonry arch bridge behavior is accomplished by taking into account the soil-structure interaction problem.

To my wife

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CHAPTER 1 INTRODUCTION

Throughout history, masonry arches were used to span relatively large distances as a common structural form dating back to the Roman Empire. Many of them are still in use in road and railway networks in Europe and the northeastern United States. Until the first half of the nineteenth century, the design and analysis of these structures had been performed by using empirical methods and common construction techniques (Brencich and Morbiducci 2007). With recent developments in modern mechanics and the increased computational capacity, more detailed structural analysis of masonry arches became possible. Notwithstanding that experimental studies of masonry arch systems require material sources and time for the construction of the scaled model of existing structures. This process may be costly and time intensive. Moreover, it may be difficult to replicate the existing conditions of a structure in the laboratory environment, since there are many uncertainties about the material properties, geometrical parameters, and boundary conditions. With the help of the advanced modelling techniques, full-scale representation of existing structures is possible, where various input parameters can be varied to understand the behavior an existing structure under various type of loadings in a time manageable manner.

In this chapter, a brief introductory about the masonry arch bridge components and up-to-date computational modeling strategies are presented. Then, the summary of the dissertation is given together with the contributions and significance of the present study.

1.1 Background and Motivation

A masonry arch bridges has a composite and highly heterogeneous structural form where all of the components interact with each other in a complex manner. The commonly used terminology for the components of a masonry arch bridge is given in Figure 1-1.

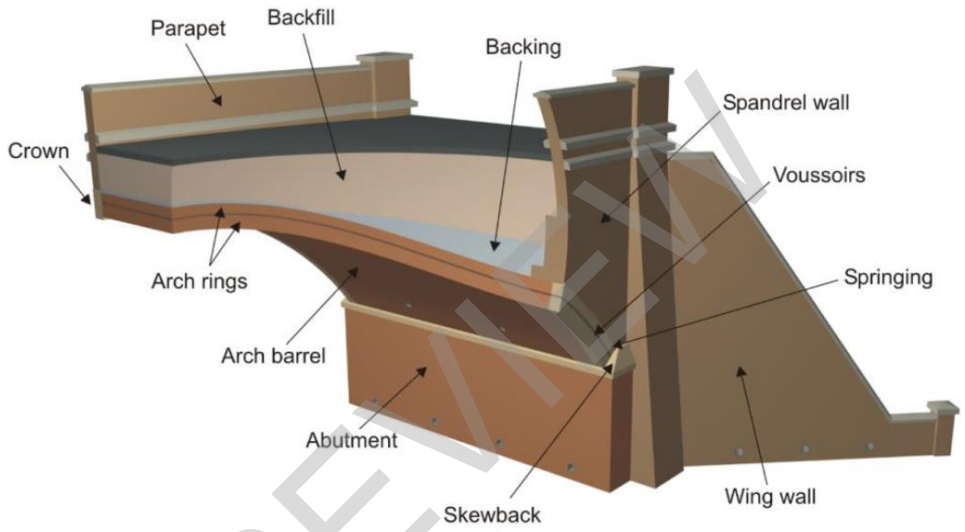

Figure 1-1. Masonry arch bridge terminology (Gilbert 2016).

The main component of a masonry arch bridge is the arch barrel, or barrel vault, which may have varying cross-sections and arch curvatures (shallow, circular and pointed). It may be composed of single or multiple layers of masonry arches constructed with different bond patterns (running bond, stack bond, etc.). Each masonry arch bridge has unique construction details and morphology due to workmanship, local practices and material availability. These unique properties of the structure may yield to noticeable differences on the load carrying capacity and failure mechanism of the structure.

The soil backfill and spandrel walls are the other important load bearing components of a masonry arch bridge. The backing material is typically constructed with earthen materials, i.e. sand, clay or rubble stone. The spandrel walls are constructed of masonry, typically in similar style to the arch barrel, but may also be different. The spandrel wall contains the soil backfill and connects the arch barrel to the approach roads and abutments providing lateral support to the arch. Because of this, spandrel walls work like a retaining wall and are subjected to transversal earth pressures due to soil. In addition, spandrel wall thickness may change through the height of bridges, generally decreasing towards the top. The backfill provides two main advantages. First, it compresses the arch and increases the axial compression inside the arch barrel. This prestressed condition provides higher load carrying capacity. Second, it distributes the live loads on the load bearing arch form, which eliminates possible stress concentrations. Each of these structural elements provide unique characteristics to masonry arch bridges in terms of strength, stiffness and structural behavior. These contributions will be explored through the advanced modeling strategies in this dissertation.

There are different methods to analyze masonry arch systems, which vary depending on the level of accuracy and the knowledge of material properties. Sarhosis et al. (2016) divides current assessment methods into three main categories, *i)* semi-empirical models, *ii)* equilibrium-based models and *iii)* numerical models. The most practical and widely used semi-empirical technique is the MEXE method, developed in 20th century for quick assessment of load carrying capacity of masonry arch bridges. However, this approach does not consider the influence of arch geometry and spandrel walls. Furthermore, it overestimates the capacity of short span arch bridges, while it may provide conservative results for spans over 12 meters (Wang et al. 2013). On the other

hand, limit state analysis (LSA) is another practical and fast solution to estimate the failure load of masonry arch bridges. It requires few input parameters and it may provide a simple consideration of the passive and active earth pressures acting on the arch barrel. Although, simplified modeling of soil backfill yields less sophisticated numerical models, it may be under estimating the load carrying capacity of the structure. Furthermore, it may be essential to simulate other structural components of masonry arch bridges, i.e. spandrel walls. This concern arises when poor backing materials and damaged spandrel walls exist. Therefore, advanced three-dimensional numerical models are needed to capture full structural response. The finite element method (FEM) is one of the most popular numerical solutions which forms the foundation of the continuum-based modeling and thus far for masonry arch bridges. The continuum-based macro modelling approach offers practice-oriented option to professionals and engineers with different level of complexity, which can be applied to large scale models in 2D and 3D. However, localized cracks and joint openings may not be represented properly in continuous medium models and for accurate representation of masonry, more detailed micro-modeling solutions are required. In this context, discrete, or discontinuous, approaches have a clear advantage to simulate crack propagations and collapse mechanisms by considering weak mortar joints as a discontinuous displacement field. The main drawback of discontinuous finite element methods is the computational cost and large number of input parameters to characterize masonry as well as the priori knowledge of the discontinuities in the numerical model. Recently, discrete element method is applied on masonry arch structures as an alternative simplified approach to micro-modeling with FEM, by expanding masonry units, while maintaining the discontinuity characteristics at the unit/mortar interface (joints). In DEM models, joints are represented by zero-

thickness interfaces where linear/nonlinear joint constitutive models can be assigned. Hence, depending on particular concern of the research, the numerical approach may be modified, and necessary simplification can be made without interrupting the overall response of the structure.

1.2 Goals and Objectives

In present research, the complete mechanical behavior of masonry arch systems is investigated by means of different numerical modeling strategies. The overarching goal of this dissertation is to better simulate the masonry arch system incorporating discontinuum and continuum based computational modeling strategies. To achieve this goal, it is necessary to take into account following objectives.

1) To develop new contact models to be used in discrete element method.

Commonly used tensile contact constitutive models are not able to represent the complete (pre- and post-peak) response of the material and do not consider the fracture energy in the numerical formulation. As a result of that, newly developed linear and polynomial tensile contact softening models are implemented into a commercial discrete element code, called 3DEC. Next, the proposed contact models including tensile fracture energy are utilized in both detailed and simplified representations of the material. Using this method, the tensile response of unreinforced stack bonded masonry prisms and plain concrete, referred as quasi-brittle construction materials, are studied to capture their pre- and post-peak behavior of these materials via discontinuum type of analysis.

2) To compare the different modeling strategies in order to analyze the in-plane capacity of masonry arches.