Computational Framework for Failure Analysis of Funicular Structures

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ABSTRACT

Funicular geometries, which are compression governing structural systems, are a significant part of our architectural heritage. To ensure the safety and serviceability of these historical infrastructures, where arches, vaults and domes are integral components, it is essential to have a comprehensive understanding of the structural behaviour of these geometries. Unlike conventional structural systems, the failure of funicular geometries is governed by the system equilibrium and geometric instability rather than strength exceedance. Further, the collapse behaviour of these structures is usually quantified either using simplified two-dimensional analytical approaches, which might not be representative, or using complex numerical models, which might be computationally expensive. To address this, a novel analytical approach is proposed, leveraging structural geometry and system equilibrium to quantify the collapse behaviour of funicular structures.

keywords: *funicular structures, rigid block, collapse mechanism, limit analysis*

1. Introduction

Funicular structures, such as arches, vaults, and domes, are primarily governed by compression. These structures are integral to architectural and structural design due to their efficient load-bearing capabilities. The design philosophies for these structures have evolved from historical methods to modern computational tools. Historically, the construction of these structures was guided by empirical rules and intuitive understanding. Builders relied on their experience and observations to construct stable and durable structures. This paper explores the load transfer mechanisms in funicular structures, traces the historical development of their design principles and analyses modern approaches to arrive at a simplified analytical approach for collapse analysis of funicular geometries. This aspect is critical as the available approaches for the analysis of these geometries are either computationally expensive (Cavicchi & Gambarotta, 2006; or are simplified to equivalent two-dimensional approaches (Block et al., 2006; Kooharian, 1952). In this context, a novel analytical approach is presented, based on kinematic analysis, which could quantify the collapse behaviour of these geometries by iterative application of the virtual work method.

2. Theoretical background

Even though arches, domes, and vaults are funicular structures, which are compression-governing structural systems, the load transfer mechanism is unique considering their distinct structural typology. The load transfer mechanism in an arch is achieved by the action of compressive forces developed in the arch cross-section, creating a horizontal outward force called thrust at the supports (Galassi et al., 2018). These loads are then transferred through piers and abutments to the foundation. Like arches, vaults also carry loads through compression, while the developed horizontal thrust is taken by buttressing. The governing load transfer mechanism in domes is also by compression, but the generated forces are three-dimensional, resulting in a combination of compressive and tensile forces.

3. Methodology

The research program is structured into three stages. Where in the initial stage, an analytical model based on kinematic analysis is developed to evaluate the interaction between in-plane and out-of-plane displacement components of funicular structures considering diverse structural demands such as seismic forces, superimposed live load and settlement of supports. This is validated by training of analytical models against numerical models and experimental testing based on machine learning-based algorithms. Finally, software considering the three-dimensional collapse behaviour of funicular structures is presented.

A displacement-based analysis procedure is developed which can be used to evaluate the structural behaviour considering the in-plane and out-of-plane deformations, satisfying equilibrium, under rigid block assumptions. As already established, the mechanism failure of a funicular geometry is by the loss of equilibrium rather than strength exceedance. Considering this condition, the generic equilibrium equation of a masonry arch bridge subjected to an external applied load, w_e can be written as(George & Menon, 2021):

$$W_G + \alpha W_E = W_I \quad (1)$$

Figure 1 illustrates the detailed process for determining the collapse configuration of the arch within a designated in-plane layer, denoted as L_i in Figure 8(b The framework is used for the case study of an arch bridge which collapsed by the settlement initiated by scouring. A 3D model of the same is created in a numerical tool and compared with the analytical framework. Based on the data collected, the developed framework will be used to predict the observed damage in a masonry arch bridge with existing damage. These results will be compared with a detailed numerical model for the bridge.

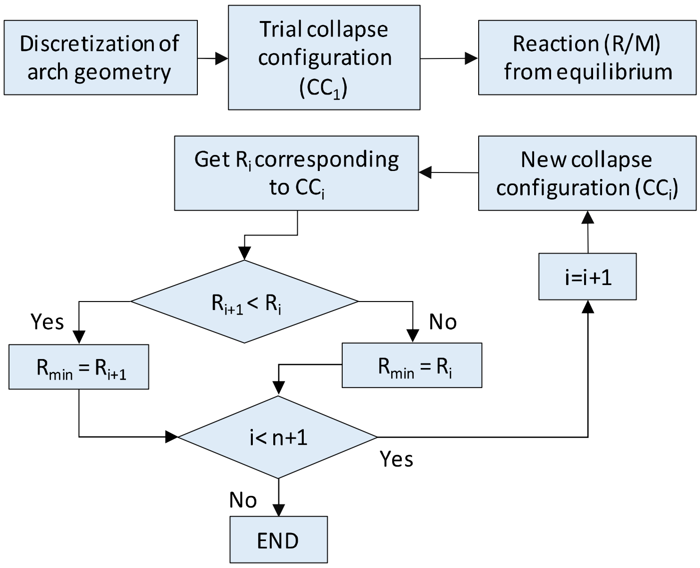

Figure 1 Flow chart to identify governing collapse configuration in a layer

The framework is used for the case study of an arch bridge which collapsed by the settlement initiated by scouring. A 3D model of the same is created in a numerical tool and compared with the analytical framework. Based on the data collected, the developed framework will be used to predict the observed damage in a masonry arch bridge with existing damage. These results will be compared with a detailed numerical model for the bridge.

4. Concluding remarks

The paper introduces a novel analytical procedure to enhance our understanding of the collapse behaviour of funicular structures. The developed methodology focuses on the inherent geometric stability and equilibrium of these structures, providing a robust method for assessing their safety. Further, the proposed methodology can quantify the 3D collapse behaviour of these structures; This approach is particularly relevant for historical structures, where preservation and accurate assessment are critical.

5. Reference

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