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Reliability-based assessment of existing masonry arch railway bridges

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HIGHLIGHTS

- Simplified full probabilistic analysis through Limitstate RING software.
- A sensitivity analysis is introduced to reduce the computational costs of the overall analysis.
- Statistical definition of resistance random variables involved in the limit state function.
- Analysis of a set of masonry arch bridges of small, medium and large spans.
- Comparison of the obtained reliability indexes of all bridges, justifying the influence of each variable.

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ABSTRACT

A great number of masonry arch bridges dates back to past centuries, being preserved by society due to their historical and still economic importance. Thereby, adequate preservation measures are required. Regarding masonry arch bridge's structural condition, it is relevant to consider its age, and consequently deterioration, and the fact that these bridges are submitted to loads higher than those for which they were conceived, being imperative to assess their structural performance. Regarding safety assessment requirements, there are different reliability levels, whose objectives are to analyse the ultimate load-carrying capacity and the serviceability performance.

This paper presents and discusses a framework that allows to determine the ultimate load-carrying capacity (Ultimate Limit State) of masonry arch bridges, using limit analysis and probabilistic approaches. Geometric and material data and load characterization, as well as inherent uncertainties will be also introduced. In order to determine the ultimate load-carrying capacity, the plastic theory will be employed, namely the limit analysis theorem, which is based on kinematic mechanisms. Since one of the main drawbacks of a probabilistic analysis is the required high computational resources, a sensitivity analysis is incorporated in order to reduce the analysis time. The presented framework is validated with an application to a set of existing Portuguese railway masonry arch bridges.

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1. Introduction

Masonry arch bridges (MAB) represent a significant portion of the transportation network (roadway and railway), playing an important role in the daily life of the majority of the European population [1]. Approximately 40% of the current railway bridge stock in Europe is composed by MAB, being an important link in the transportation network infrastructure [2]. Hence, it is imperative to assure whether these structures present the required levels of safety or if it is necessary to perform strengthening/replacement measures.

The safety assessment of existing structures, particularly bridges, is a remarkably complex thematic. Currently, not only most of ancient masonry arch bridges that are in service are submitted to higher loads than those for which they were built, but also the lack of maintenance and expected degradation caused by time and utilization, have aggravated their condition [3]. Moreover, the available funds for maintenance and repairs are limited, challenging the development of accurate and feasible methodologies that assure the condition and safety levels of existing bridges.

The safety assessment of existing structures has many similarities with the design process. The main difference lies in the fact that when a structures is being designed, the additional costs

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necessary to make the structure safer are minimal, since it is to be constructed. However, when a structure is being assessed, the required funds to make a structure safe might be huge, and should be only considered if worthy.

Another relevant obstacle that the safety assessment of existing bridges points out is that the available existing documentation, if available, is based on design methodologies, being inadequate for a reliability analysis and safety verification of existing structures, due to the fact that the associated uncertainties of an existing structure may be very different in intensity and nature from those recommended by current standards [3]. Most procedures for the safety assessment of existing structures are based on the partial safety factors method, being the structural safety assured by the application of calibrated safety factors to the characteristic values, according to the associated levels of uncertainty of the variables involved. Since the uncertainty related to a specific case study is not considered explicitly in the partial safety factor method, the safety classification may not reproduce the structural condition in a reliable manner, resulting sometimes in load limitations, expensive and unnecessary interventions or, even in some cases, in the replacement of the whole structure. On the other hand, by application of probabilistic methodologies significant funds have been saved in the field of intervention and reconstruction, preventing structures classified as unsafe to be repaired or, even demolished and replaced [4,5].

The development of safety assessment methods, simple to apply and that provide reliable results, is thus of utmost importance. Recently, it has been noticed a huge interest in probabilistic techniques that explicitly consider randomness in model parameters in order to quantify the reliability index more accurately.

Since uncertainty is an intrinsic characteristic of structural parameters, the statistical variability should be considered in structural analysis. Consequently, the application of deterministic approaches is improper to manage and treat uncertainty. When assessing masonry arch bridges, the major drawback is the lack of available information concerning materials, such as masonry, fill material and mortar, and structural behaviour, such as mathematical models that consider the interaction between spandrel walls, fill material, arches and joints. In addition, the lack of statistical information regarding material parameters makes the probabilistic assessment even harder to perform [6,7]. Further, some authors consider that uncertainty due to lack of knowledge about structural parameters enhances the employment of probabilistic approaches in order to treat uncertainty more accurately [8]. Considering the mentioned facts, the most reliable methodologies to assess existing bridges are the probabilistic ones [3,5]. Lately, probabilistic approaches have been employed and successfully performed in this area [3,6,7,9,10]. Ultimate load-carrying capacity (Ultimate Limit State – ULS) is typically obtained by the application of semi-empirical and numerical methods. Recently, non-linear methods have been employed as they contemplate the nonlinearity of structural material and the structural system, such as redundancy and robustness.

In this paper, a simplified full probabilistic analysis framework for reliability-based assessment of MAB, for predicting the ultimate load carrying capacity, is proposed. Firstly, the geometrical and material parameters, as well as inherent uncertainties, are presented. Then, a sensitivity analysis procedure is introduced in order to reduce the computational costs of the overall analysis, being the obtained critical structural parameters described through proper probability density functions (PDF) according to literature [9–11]. The structural analysis is then performed through the limit analysis approach. The developed framework is applied and proven with a set of masonry arch bridges of different spans (small, medium and large-span bridges), being the obtained reliability index of all bridges compared and discussed according to the influence of obtained critical parameters for each assessed bridge (geometric and material influences of each variable in the overall response) [11].

2. Masonry arch bridges

2.1. Description

MAB are gravity structures, which mean that their structural behaviour highly depends on geometry of the structural elements, but also on masonry and mortar properties and, not least, the fill material properties. Two types of materials are used in the construction of MAB: masonry and soil (fill material). The main characteristics of masonry are its heterogeneity, anisotropy, moderate compressive strength and reduced or null tensile strength. The fill material consists of agglomerates of various particle size materials placed over the masonry vaults [12].

MAB are tri-dimensional structures [13], being stresses distributed along longitudinal and transversal directions. In the longitudinal direction, the arch barrel is the main load-carrying element, supporting loads from the fill material and transmitting them to piers and abutments, which offer horizontal and vertical pressures for the arch. Also, spandrel walls at the edges of a bridge can stiffen the arch prior to failure, enhancing the ultimate limit strength, depending on their end restraint conditions [14,15]. The fill degrades and disperses live loads, transmitting its effects to the arch. In addition, the fill material effectively compresses the masonry in an arch, providing additional stability of the arch due to its self-weight (additional compression) and by a passive pressure that is generated when the arch suffers large deformations, resulting in an increase in the load-carrying capacity [14]. In the transversal direction, the spandrel walls are the elements responsible to support the pressures provided from fill material. Considering both stress distribution mechanisms, it is possible to verify that the structural behaviour is strongly dependent on the interaction between the fill, the spandrel walls, the arch and also by the connection of these two latter elements (arch and spandrel walls) [13].

The backing (or haunching) built over the arch barrel and on the top of piers or abutments, diminishes the effective span of the arch and results in a higher ultimate load-carrying capacity [16,17]. When assessing MAB of multiple spans, depending of the geometry of the piers, two possible collapse mechanisms may be obtained: local or global collapses. If piers are 'stocky' (i.e. thick in comparison to their height), it may safely be analysed as a series of isolated single spans. Otherwise, the whole MAB has to be analysed. Thus, the failure mode is highly dependent of the slenderness of the piers (height-to-width ratio) [15,17]. Fig. 1 presents the most relevant components of a MAB.

Regarding the possible failure modes, three main modes are typically considered: i) formation of a mechanism due to internal releases, such as plastic hinges or sliding planes, single arch bridges (Fig. 2a)) or multiple arches bridges (Fig. 2b)); ii) snap-through failure prior to the full formation of hinges, Fig. 2c); and iii) ring separation, in case of multi-ring MAB (Fig. 2d)). The failure mode due to crushing of material is not common, once the loss of structural stability usually appears before the material reaches its compressive strength [6,18,19]. The slippage at the foundations is also a typical failure mode but it involves geotechnical issues. These failure modes are highly dependent of the type of construction of the arch and if the applied load is static or cyclic [6,7,18]. In the present paper, only static loads will be analysed. A detailed and

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