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Probabilistic-based assessment of a masonry arch bridge considering inferential procedures

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ABSTRACT

Considering the safety assessment requirements of masonry arch bridges, different levels of reliability, based on uncertainty, may be distinguished, whose core objectives are to accurately analyse the ultimate load-carrying capacity and the serviceability structural response. Within this framework, a simplified full-probabilistic methodology for the safety assessment of existing masonry arch bridges is proposed, which combines both structural analysis and Bayesian inference procedures. The proposed framework aims to determine the ultimate load-carrying capacity (Ultimate Limit State) of masonry arch bridges, by using probabilistic procedures and Limit States principles. Geometric, material and load characterization, as well as inherent uncertainties will be also considered. In order to determine the ultimate load-carrying capacity, a limit analysis approach, based on the mechanism method, will be employed. Due to the high computational costs required by a probabilistic safety assessment framework, a sensitivity analysis will then be introduced. The incorporation of new information from monitoring and/or testing will be performed by the application of Bayesian inference methodologies. Based on the information collected, two reliability indexes will be computed and compared, one with data collected from design documentation and literature and the other with data collected from testing, emphasizing the importance of testing and the advantages of Bayesian inference procedures. The probabilistic framework developed is tested and validated in a Portuguese railway masonry arch bridge from the 19th century.

1. Introduction

The highest expansion period of railway transport in Europe occurred in the early twentieth century [1]. Many of these bridges are over 100 years old, being the largest stock composed of masonry arch bridges (MAB) [2].

In Portugal, it was verified, between 1951 and 1973, the development of oriented programs for infrastructure maintenance [3]. Accordingly, MAB were renewed and/or strengthened for the new demands required by society's needs [4]. Nowadays, many in-service bridges are submitted to much higher loads compared to those used in their design project. In addition, maintenance investments in this field are scarce, and, therefore, an advanced deterioration process is commonly identified as a result of several years in use without intervention. Thus, it is of utmost importance to assess the performance of existing bridges, in order to ensure its safety [5].

Most procedures for safety assessment of existing structures are based on the partial safety factor method. The major disadvantage of this methodology is the non-explicit consideration of uncertainties, resulting in a safety assessment procedure that does not reproduce the assessed structure behaviour with liability [5,6]. Therefore, the development of safety assessment methods, which are easy to apply and give accurate results, is of extreme importance. Accordingly, some methodologies that explicitly consider the existing uncertainty when computing the reliability index were recently proposed [7,8].

In this work, a probabilistic-based assessment framework combined with Bayesian inference procedures is presented. As a first step, the bridge's geometry and material characterization are performed according to literature and design documentation, allowing to define the deterministic numerical model. Since the number of structural variables involved in safety assessment is typically high and, consequently requiring costly computational and time resources, a sensitivity analysis is introduced, being obtained the critical structural parameters. Thus, probability density functions (PDF) will be assigned only to these parameters. In order to

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compute the failure probability, simulation methods are used. Latin hypercube sampling (LHS) is chosen, due to its reduced required resources [9,10]. Some structural parameters may also present some correlation between each other. This correlation is considered by proper coefficients, according to literature. Thus, the developed framework combines a LHS sampling procedure with a built-in Iman and Conover algorithm [9,11], which allows the sampling of correlated random variables. After generating all numerical models, the results are then statistically analyzed. The structural analysis is performed through the Upper Bound (Kinematic) Theorem of Plasticity. The bridge's safety is evaluated by comparison of its resistance with the effect of loadings, being obtained the failure probability and corresponding reliability index.

Once data acquisition is common in safety assessment evaluations, Bayesian Inference procedures are introduced. Bayesian Inference procedures consist in updating and reducing the statistical uncertainty, through incorporation of gathered external data into the data analysis process. In the present paper, external data regarding geometry is collected by photogrammetric methods, being complemented by conventional measures. Additionally, material characterization tests are performed in order to gather masonry's physical and mechanical properties.

Lastly, the framework proposed in chapter 2 is applied and tested with an in-service Portuguese stone masonry arch railway bridge. The comparison of two reliability indexes, obtained before and after Bayesian updating, shows the importance of data acquisition when assessing MAB and that Bayesian inference is a key procedure to incorporate gathered data into the numerical analysis, providing a more reliable safety assessment.

2. Probabilistic-based structural safety assessment of masonry arch bridges

The probabilistic-based structural assessment framework proposed here departs from a deterministic numerical model. Then, the influence of each structural parameter is evaluated by a sensitivity analysis. Afterwards, the MAB structural performance is assessed according to a reliability assessment procedure, by incorporating randomness into structural parameters. Later, Bayesian Inference techniques are employed to update the initial PDFs, by considering the collected information from visual inspection, characterization tests and/or monitoring systems. After the updating process, a set of numerical models are respectively computed, being obtained the failure load factors. This way, it would be possible to compute the resistance PDF before and after the inferential procedure.

2.1. Masonry arch bridge structural behaviour

MAB construction is not currently practiced, but many of these structures are still in service and playing an important role in the railway network. These type of structures were conceived as gravity structures for which mass and geometry were the design criteria [12,13]. Fig. 1 presents the typical elements and typology of masonry arch railway bridges [14]. The arch is the structural element responsible for transposing the span and transferring the loads from the fill material to abutments and piers, while the fill material disperses the live loads, confers additional compression to the arch and provides passive pressure when the arch tends to move against it, enhancing the ultimate load-carrying capacity. In the case of multi-span MAB, piers' geometry is conditioning since they may be involved in the collapse mechanism due to their slenderness, resulting local or global collapse mechanisms [13,15]. Thus, MAB structural behaviour is highly dependent on the interaction between the fill material, arches and piers [16], which is presented in detail in [17–21]. A detailed review and description of MAB failure modes, load effects and geometrical and material issues is presented elsewhere [17,22–24].

2.2. Data acquisition

Data acquisition is very important due to the fact that safety assessment of MAB depends on the liability of the input parameters. Hence, if possible, it is important to perform geometric and material characterizations to obtain geometry details, current physical and mechanical parameters, thus improving the predicted safety level assessment [12,13].

2.2.1. Visual inspection

The first inspection method to gather data for condition assessment should be visual inspection. The external visual inspection includes the identification of structural changes (e.g. settlements, deformations), missing geometric characterizations (e.g. piers thickness and height or arch width and thickness), defects (e.g. cracks), deterioration (e.g. masonry or ballast deterioration, mortar loss) and damaged structural elements due to accident situations (e.g. impact loads). Visual inspection may be complemented by non-destructive tests (NDT), being possible the detection of micro cracks, damages sources and progression [25]. A complete description of these methods is presented in [25].

2.2.2. Geometry

The first step in order to create a numerical model is the definition of the MAB geometry. The project documentation is usually lost or, in case it exists, rarely present any drawings of construction details. There are several techniques to perform geometry surveys of MAB. The most used methods are: (i) conventional methods, such as tape measure, level or laser meter; (ii) terrestrial laser methods, such as 3D laser scans; and (iii) photogrammetric methods, such as close range photogrammetry (under 100 m from the structure) and specific software. These methods may complement each other.

When performing MAB geometry characterization, it is important to give special attention to the following elements, since they are the most relevant geometrical parameters in the overall structural behaviour [15,17,22]: (i) arch thickness and width; (ii) fill depth at arch crown; (iii) rise at mid-span; and (iv) span-length. These parameters are typically described by a Normal PDF [12,17,22]. According to measurements performed by [17,22], a coefficient of variation (CoV) of 10% and 5% may be assigned to describe the variability of the thickness and width of the arch, respectively. Regarding the piers thickness and height, since literature is very scarce and this geometric detail is vital for defining the collapse mode of multiple-span MAB (local or global) [12,13], it is assigned a CoV of 10% as in the case of arch thickness [12,13]. All these parameters are here assumed to be described by a Normal PDF [12,13,17,22].

2.2.3. Materials

Besides the geometric configuration, which plays a very important role on stability, the structural behaviour of MAB is highly dependent of the mechanical properties of the materials, namely masonry and fill material [12,15,17,18]. Moreover, the type and quality of materials used for the arch, piers and fill material may be different even in the same MAB. The main characteristics of masonry are its heterogeneity, anisotropy, moderate compressive strength and reduced tensile strength [26], while the homogeneity of the fill material depends on the materials used [23].

NDT are the most used ones to characterize structurally MAB components. When selecting the most suitable material characterization tests, priority should be given to those that provide