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Parameter identification for damaged condition investigation on masonry arch bridges using a Bayesian approach

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ABSTRACT

In this work, an inverse analysis procedure adopting a Bayesian approach is proposed as a numerical tool to investigate the causes that have led a masonry arch bridge to be in a certain pathological condition. Within this framework, the damaged condition investigation is formulated as a parameter estimation problem. A nonlinear finite element model is developed, and the implementation of plausible loading scenarios together with possible initial undamaged configurations of the bridge is then carried out. Computer model predictions are subsequently compared against real, measured geometrical data. The aim of the identification problem is to obtain the distribution of the most likely values of the parameters of the mechanical model so that the numerical predictions reproduce with the highest accuracy the existing damage pattern. The posterior probability distributions of the unknown parameters are estimated via the use of simulation techniques, namely, the Markov chain Monte Carlo (MCMC) method. The computational burden associated with both the MCMC sampling procedure and the time-consuming numerical model is alleviated by the adoption of a Gaussian process emulator. The feasibility of the practical implementation of the method is tested on a real case study located in Kakodiki village on the island of Crete (Greece). The results indicate that reasonable inferences about the original geometry of the bridge, as well as possible damage loading scenarios, can be made, resulting in a nearly identical crack pattern with respect to the present damaged state. The possibility of exploiting the posterior distributions of the model updating parameters for subsequent structural assessment tasks is also shown, allowing probabilistic simulation outcomes from which a more reliable judgement of the actual bridge safety condition can be established. The application of the proposed methodology would result in a better understanding of the underlying mechanisms triggering damage while also providing useful guidelines for decision making, such as those related to the planning of adequate maintenance actions and the selection of optimal strengthening measures.

1. Introduction

The conservation of ancient masonry constructions is crucial. On the one hand, modern societies value and preserve the cultural legacy and the architectural heritage that they represent. On the other, many of these constructions still strongly contribute to the economy of different countries by continuing the use for which they were originally conceived, such as the case of masonry arch bridges in road and railway networks [1], or by supporting new activities, such as tourism. Therefore, it is important to provide useful tools and reliable methods that can contribute to extending the service life of these constructions and ensure optimal use of the resources required for the tasks of inspection, maintenance, and repair.

In the case of masonry arch bridges, due to their long existence accompanied in many instances by long in-service periods, it is likely that pathological problems, expressed in the form of permanent deformations and cracks or damage patterns, have emerged as a consequence of the diverse and intense loading conditions that these structures might have been subjected to [2]. In this scenario, one may be interested in obtaining as much information as possible about the most likely causes of the structure's present jeopardized condition so that the design of proper maintenance strategies or reinforcement, if needed, can be more efficient.

This issue, which quantifies and makes more precise structural health monitoring, can be mathematically expressed as a parameter identification problem, or inverse problem [3]. Within this theoretical framework, a computational model of the bridge is first developed, and then, several loading scenarios using different undamaged

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configurations are simulated. The aim of the back-analysis is to obtain suitable estimates for the parameter values of the mechanical model of the structure so that the numerical predictions match the existing damaged condition with the greatest possible accuracy [4].

One classical way of addressing the solution of an inverse problem is by combining a suitable parameterized numerical model with an optimization algorithm to minimize an objective function that measures the differences between the numerical predictions and measured data. For the study herein addressed, this approach has already been used in a previous work [5]. A significant number of applications of the deterministic (optimization-based) parameter identification approach in the case of masonry structures can be found in the recent literature, particularly for model calibration or model updating procedures; see, among others [6–9]. Some drawbacks associated with the use of optimization procedures are the issues of ill-conditionedness, non-uniqueness of the solution, and if gradient-based algorithms are adopted, the need to avoid the local minima of the objective function [10]. Indeed, the usual implementation of the approach does not consider potential errors of the experimental measurements, and commonly, there is the implicit assumption that the simulation model is an accurate representation of the physical phenomenon that is being modelled, which does not always hold true [11].

Thus, a possible alternative is the use of a probabilistic Bayesian approach, which allows overcoming the above drawbacks that may arise when adopting optimization-based methods [10]. The Bayesian approach is a sound theoretical framework for dealing with the different sources of uncertainty involved in inverse problems [12]. This encompasses the possibility of uncertainty quantification not only with regard to the model parameter values but also concerning the validity of the numerical model itself and the observation errors of the experimental data [13–15]. Using the Bayesian approach, the solution of the identification problem is a statistical inference procedure [16]. Bayes' theorem is employed to derive the posterior probability distributions of the uncertain parameters given initial knowledge about their possible range of values (i.e., the prior probability distributions) and the likelihood of the observed data. In the structural engineering domain, some recent relevant works based on the use of the Bayesian paradigm for solving inverse problems can be found, among others, in [10,17–19]. However, to the best of the authors' knowledge, the application of the Bayesian approach for parameter identification on masonry structures is scarce [20,21].

In this study, a Bayesian inference procedure is adopted for the inverse problem of estimating the most likely causes that have led a masonry arch bridge to be in a certain pathological condition. The practical feasibility of the proposed methodology is tested in a real case study, the Kakodiki Bridge, which is located on the island of Crete (Greece). The paper is organized as follows. Section 1 is the introduction. Section 2 describes the methodology proposed, which begins with a brief description of the Kakodiki Bridge in Section 2.1, continues in Section 2.2 with the details regarding the computational model and ends in Section 2.3, where the overall inverse analysis procedure is outlined together with the formulation of the parameter identification problem from a Bayesian perspective. In Section 3, the main results are presented and accompanied by a pertinent discussion; finally, the general findings are summarized in Section 4.

2. Methodology

2.1. Case study: Kakodiki bridge

The proposed methodology has been applied on a real masonry arch bridge located in Kakodiki village, on the island of Crete in Greece (see Fig. 1). The bridge was built in 1903 by the Cretan State and its heritage importance was officially recognized by the Greek government in 2005.

Currently, the bridge presents an important damaged state, with three major cracks having developed at the body of the arch (Fig. 2)

Fig. 1. Kakodiki Bridge: general view from the downstream side [4,5].

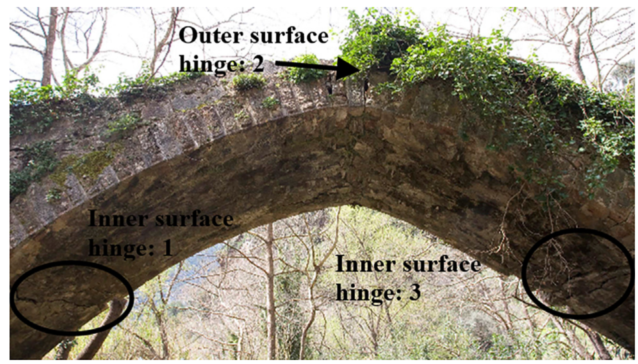

Fig. 2. Kakodiki Bridge: crack pattern in the arch, shown from the upstream side [4,5].

Fig. 3. Kakodiki Bridge: damage in one of the abutments, shown from the upstream side [4,5].

together with the presence of a significant deterioration at the abutments (Fig. 3). The cracks are placed approximately at a quarter of the span from both sides of abutments (hinge 1 and 3) and at the crown of the arch (hinge 2).

With the aim of gaining a thoroughly understanding of the actual state of the structure as well as for collecting the relevant geometric information needed in the subsequent numerical studies, both an in-situ visual inspection and a topographic survey were conducted. For an extensive photographic report as well as for a more detailed description of the bridge, the reader is kindly referred to the previous publications [4,5].