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An innovative framework for probabilistic-based structural assessment with an application to existing reinforced concrete structures

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A B S T R A C T

A novel framework for probabilistic-based structural assessment of existing structures, which combines model identification and reliability assessment procedures, considering in an objective way different sources of uncertainty, is presented in this paper. A short description of structural assessment applications, provided in literature, is initially given. Then, the developed model identification procedure, supported in a robust optimization algorithm, is presented. Special attention is given to both experimental and numerical errors, to be considered in this algorithm convergence criterion. An updated numerical model is obtained from this process. The reliability assessment procedure, which considers a probabilistic model for the structure in analysis, is then introduced, incorporating the results of the model identification procedure. The developed model is then updated, as new data is acquired, through a Bayesian inference algorithm, explicitly addressing statistical uncertainty. Finally, the developed framework is validated with a set of reinforced concrete beams, which were loaded up to failure in laboratory.

1. Introduction

Structural assessment comprises all activities required to evaluate the condition of structures for future use, in particular, regarding safety. During structural assessment of existing structures a wide range of sources of uncertainty can be identified. In order to consider them, reliability algorithms are commonly used. Structural safety is quantified through the reliability index, or the probability of failure, obtained from the comparison of resistance and effect of loads probability density functions (PDFs) [1–3].

Several authors have used probabilistic-based safety assessment procedures to assess existing structures, having shown that the conclusions can be dramatically different from those obtained using existing codes [4–10]. More recently, Bayesian inference was introduced to improve the quality of probabilistic models for both resistance and effect of loads, using data collected from the structure under analysis [11,12].

The use of nonlinear finite element analysis (NL FEA) methods in structural assessment procedures, although computational costly, enables a more realistic estimation of the structural response, both in service and ultimate limit states. Bergmeister et al. [13] introduced a probabilistic-based safety assessment concept for reinforced concrete structures that integrates NL FEA software with reliability-based algorithms.

For existing structures, the available information regarding used materials (e.g. class of concrete or steel) and geometry is always scarce. Moreover, the retrieval of samples for laboratory tests is often restricted. As a result, the applicability of Bayesian updating directly considering material and geometric properties has limited applicability. Therefore, some authors used model identification techniques to estimate structural parameters based on performance measures. A review of these procedures is provided in [14]. Accordingly, Novák et al. [15] developed a complex methodology for structural assessment of existing structures, which combines structural analysis and reliability algorithms with new modules for model identification.

In this paper, a novel framework for probabilistic-based structural assessment of existing structures is presented. This framework combines some of structural assessment techniques above outlined with a new methodology to identify optimal solutions, based on an evolutionary algorithm and a hybrid

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decision-making procedure, and a Bayesian inference tool, providing the objective treatment of uncertainties. In the first step, model parameters, in particular material (e.g. steel yield stress, concrete strength), geometric and mechanic properties are estimated considering a minimization procedure between observed performance and performance predicted using a non-linear finite element model (NL FEM). A convergence criterion is defined considering the expected accuracy of experimental and numerical data. The minimization procedure yields a set of near optimal solutions, from which the best model is selected considering the probability of each solution occurring based on previous knowledge. If deemed adequate, an expert judgment can be employed within this selection procedure. Once selected, the deterministic model is converted into a probabilistic model by considering randomness in model parameters, through the adoption of appropriate PDFs. Bayesian inference is then used to update each model parameter with new acquired data from material and geometric properties. This way, the statistical uncertainty is explicitly considered. Structural safety is respectively assessed in a continuous basis through this framework.

This framework can be classified, according to SAMCO report [16], as a level 5 assessment class (model-based assessment of existing structures), once it combines probabilistic simulation methods, with a stochastic NL FEM and data from testing and measurement of material properties and dimensions. Although this methodology can be applied to new structures, its application aims at better characterizing existing structures for which limited information exists. The effectiveness of both model identification and reliability assessment procedure, with an integrated Bayesian inference approach, is supported in the reliability of such data. Accordingly, the developed framework, which addresses different sources of uncertainties, is tested and validated with a set of reinforced concrete beams, which were loaded up to failure in laboratory. This controlled experiment is crucial since, unlike real structures, destructive tests can be extensively employed to evaluate the accuracy of the prediction.

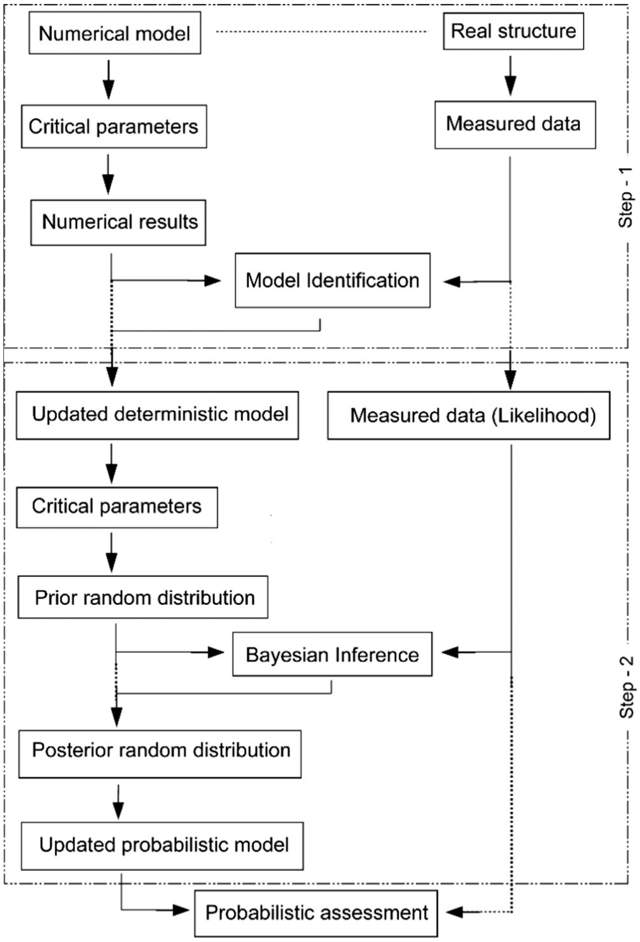

Fig. 1. Probabilistic-based structural assessment algorithm [14].

2. Probabilistic-based structural assessment

The proposed probabilistic-based structural assessment methodology can be divided in two main steps, Fig. 1. In the first step a deterministic analysis is used to estimate the most important model parameters, based on the combination of numerical methods and experimental data. This procedure, denoted as model identification, searches for expected values of material, geometric and mechanic structural properties. This data is then used to define the probabilistic distributions of structural parameters, used in the reliability assessment of the structure.

The main objective of model identification procedure is to obtain the most likely values of model parameters, consistent with observed structural performance. Within this procedure, numerical results are fitted to collected data from real structure, by adjusting model parameter values. This procedure is accomplished by using an optimization algorithm, with the objective of minimizing the difference between obtained numerical results and measured data, expressed by a fitness function. The optimization procedure stops when the improvement in this function is equal or lower than a threshold value. The main result of this procedure is a structural model that can, with acceptable accuracy, predict the structure performance.

The aim of reliability assessment of the structure is to evaluate its condition for future use, considering randomness in model parameters. In order to do that, a prior distribution is assigned to each model parameter. This distribution may be then updated through a Bayesian inference procedure, with complementary data obtained by visual inspection, non-destructive tests or permanent monitoring systems. A posterior distribution is respectively computed, being obtained an updated performance indicator for the structure under evaluation.

The main drawback of this methodology is its computational cost. In order to surpass this, an initial sensitivity analysis is recommended. The main objective of this analysis is to identify the parameters with a higher impact on the overall structural behavior. This analysis consists in evaluating the fitness function variation with each input parameter. An importance measure, b_k, is obtained for each parameter, expression (1),

$$b_k = \sum_{i=1}^{n} (\Delta y_k / y_m)/(\Delta x_k / x_m) \cdot \mathrm{CV}\ [\%] \tag{1}$$

with Δy_k the variation in structural response due to a deviation of Δx_k in input parameter mean value x_m, y_m the average response, n the number of generated parameters and CV the parameter coefficient of variation.

2.1. Model identification

In a first step, and according to Fig. 1, model identification is performed to obtain an updated deterministic numerical model. During this procedure, model parameters are obtained from an automatic adjustment process to measured data (Fig. 2). In the model identification procedure, unknown variables were taken as uncorrelated.