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Automated finite element updating using strain data for the lifetime reliability assessment of bridges

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ABSTRACT

The importance of improving the understanding of the performance of structures over their lifetime under uncertainty with information obtained from structural health monitoring (SHM) has been widely recognized. However, frameworks that efficiently integrate monitoring data into the life-cycle management of structures are yet to be developed. The objective of this paper is to propose and illustrate an approach for updating the lifetime reliability of aging bridges using monitored strain data obtained from crawl tests. It is proposed to use automated finite element model updating techniques as a tool for updating the resistance parameters of the structure. In this paper, the results from crawl tests are used to update the finite element model and, in turn, update the lifetime reliability. The original and updated lifetime reliabilities are computed using advanced computational tools. The approach is illustrated on an existing bridge.

1. Introduction

Currently, there is a gap between SHM and bridge inspection and management methods [1]. Whereas SHM has focused primarily on damage detection, bridge managers are focused on answers to serviceability and safety issues [2]. Further, methods for processing raw data obtained from SHM, to make them usable in validating and/or updating structural reliability, are lacking. Some recent studies have focused on channeling the information provided by SHM into better assessment of the structural response effect [3–8]. For instance, the records of strain collected at a structural detail can be used to obtain statistics of the live load effect at this detail. However, translating the SHM data into resistance-related information is not straightforward. Whether it is strain, acceleration, or displacement, the records of data obtained by SHM do not directly provide information about the structural resistance parameters. Therefore, a proper processing of the SHM data for generating resistance-related structural parameters is essential.

Lifetime structural reliability is used to predict the safety of aging structures over their service life. In general, lifetime reliability assessment is conducted in two steps by (a) computing the initial reliability based on design values for the load effects and structural parameters (e.g., component dimensions) and (b) accounting for the effects of time on these load effects (i.e., demand increase) and structural parameters (i.e., aging process) in order to predict the reliability over time. Environmental stressors are the primary factors that drive the aging process. Structural aging and its effects present challenges for bridges and other civil engineering structures [9–15]. For example, corrosion plays a significant role in reducing the reliability of bridges over time by reducing the cross-sections of the components [16–18]. Prediction of the section loss due to corrosion is made possible with available corrosion prediction models [19,20]. The uncertainty of such models and the compounding effect of this uncertainty over time make it necessary to validate site specific conditions for optimal decision making. As proposed in this paper, validating the resistance parameters of an aging structure for updating its lifetime reliability is a process that can be performed through updating the input variables of the finite element model of this structure.

Finite element model updating is a process in which the input parameters of the finite element model are tuned such that the responses obtained from the finite element analysis become in agreement with those provided by SHM. Even though the common global structural responses adopted in finite element model updating are dynamic, e.g. natural frequencies and mode shapes, in this paper, the static strain results from crawl tests are used to update the finite element model and, in turn, update the lifetime reliability of the structure. In this paper, the finite element updating is preceded by structural identification in which the boundary conditions of the finite element model are identified to concur closely with those of the real structure. The finite element updating is then conducted using an automated optimization technique known as Particle Swarm.

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Using advanced computational tools, the point in time reliability index and the cumulative time failure probability are computed and updated. Based on this data, the lifetime functions of the structural components are generated. The approach is illustrated on a bridge in the state of Wisconsin, USA.

The computations of this paper are performed using a workstation with dual quad core Intel® Xeon® processors and 8 GB of RAM. Softwares used include ABAQUS [21] for finite element modeling, VisualDOC [22,23] for optimization, MATLAB [24] for post-processing of ABAQUS results and Latin hypercube sampling [25], CALREL [26] for instantaneous reliability computations, and RELTSYS [27] for computing the cumulative-time failure probability. It is emphasized that the procedure presented in this paper is not exclusive to the use of the software and hardware mentioned. For instance, many finite-element analysis softwares are commercially available and can be used for the computations performed by ABAQUS in this study. Furthermore, the specific methods and algorithms for which the softwares are used for each computation step are either explained in sufficient detail or mentioned with the available references throughout the paper.

2. Structural identification and finite element updating

Structural identification may be defined as the art of analytically conceptualizing, modeling, designing experiments for measuring, and quantifying structural behavior as well as the phenomena affecting it, in order to make engineering decisions [28]. Application of structural identification provides the most reliable manner of characterizing a structure for analysis and decision-making as it goes through its life-cycle [29]. A finite element model is an idealization of a real structure. Often, the true boundary conditions of the structure and the connectivity between its members are hard to conceptualize and highly uncertain. Ideal supports that provide full or no fixity to the degrees of freedom at certain nodes are rationally assumed to provide a practical alternative for exactly capturing the support conditions. More rationally, supports with partial fixities are assumed and modeled by springs with translational and/or rotational stiffnesses at some supports. In this approach, the different combinations of boundary conditions create multiple models for analytically representing the structure. Monitoring measurements from controlled loading tests provide an excellent tool for identifying which of these candidate structural models is closest to reality, i.e., provides the closest responses to those obtained from monitoring measurements. Once the structure is identified in this step, the selected model is calibrated by finite element updating techniques to further reduce the discrepancies between the structure and its model [30].

Finite element updating techniques date back to 1967, when ground vibration test data were used to determine the structural influence coefficients of a structure [31]. Ever since, a multitude of algorithms and methods for finite element updating have been developed. These can be categorized according to different classes. Zimmerman [32] classified finite element updating techniques into optimal matrix update algorithms, sensitivity methods, control-based eigenstructure assignment techniques, and minimum rank perturbation theory. Schlune and Plos [33] classified them as manual tuning, direct methods, and iterative methods. Brownjohn and Xia [34] classified them into one step (global methods) and iterative (local methods). The choice of the method to be used is dependent on whether the system matrices or the structural parameters are selected for updating [35].

Typically, the finite element model updating is conducted for the sake of using the updated finite element model itself with more confidence in further analysis and decision-making. The objective in this paper, however, is different. After updating, the updated finite element model itself will not be used anymore. What will be used are the updated parameters of this model. In other words, the objective is to calibrate the parameters of a structure by updating its finite element model. Then, these updated parameters are used to compute a new updated lifetime reliability for the structure.

In this paper, an iterative parametric updating method is used. In iterative parametric updating methods, the model updating problem is posed as an optimization problem that is solved iteratively [33]. Sensitivity methods or optimization algorithms are used to conduct this task. Owing to the advances in modern computational tools, automated optimization-based finite element updating methods are becoming increasingly popular [30,36–40]. In optimization-based methods, an objective function is formulated as a form of the differences between the analytical and experimental results. In this paper, the objective function is formulated as the root mean square error (RMSE) expressed as [30]

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_{i,c}-x_{i,m})^2}{N}} \tag{1}$$

where $x_{i,c}$ is the value measured at the ith measurement point, $x_{i,m}$ the corresponding value computed using the finite element model, and N the number of measurements (i.e., responses) considered. This objective function is minimized in order to bring closer together the analytical and experimental responses. This is achieved by iteratively and systematically modifying the parameters of the model using an optimization algorithm.

Optimization algorithms are either gradient or non-gradient (direct) methods. In gradient methods, the search direction is determined using knowledge of the first and/or second derivatives of the objective function. In most cases, the derivatives have to be calculated numerically. In contrast, direct methods make use of only the objective function and constraints. They have lower risk of getting trapped into a local minimum, but may need a very high number of iterations. Among the direct methods, simulated annealing and genetic algorithms have been used in finite element applications [30]. In this paper, the direct non-gradient optimization technique particle swarm is used.

The primary measurements of responses used in most previous finite element updating work are vibration data [30]. It seems reasonable to select global responses that are affected by the overall resistance of the structure and all of its parameters for the finite element updating. However, there is no reason to exclude static measurements like strains and deformations [33]. In fact, static measurements have been used for finite element updating [30,41–52].

When static response measurements are used, displacements are considered more reliable for finite element updating since they are affected more by a significant portion of the model parameters and less by local stress concentrations. Measuring displacements on full-scale structures, however, can be a difficult task; a frame of reference must be established [42]. Although strain gages are not perfect, like any other measuring device, there are sufficient advantages to merit their use in many situations particularly for large structures whose displacement would require considerable labor to measure [42]. In this paper, strain measurements from crawl tests over a bridge are considered as the response on which the structural identification and finite element updating are based.

3. Selection of parameters

Complex and large scale structures are generally composed of a large number of elements, each being defined by a number of