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Automated finite element model updating of a scale bridge model using measured static and modal test data

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ABSTRACT

Structural Health Monitoring (SHM) using nondestructive test data has become promising for finite element (FE) model updating, model verification, structural evaluation and damage assessment. This research presents a multiresponse structural parameter estimation method for the automated FE model updating using data obtained from a set of nondestructive tests conducted on a laboratory bridge model. Both stiffness and mass parameters are updated at the element level, simultaneously. Having measurement and modeling errors is an inevitable part of data acquisition systems and finite element models. The presence of these errors can affect the accuracy of the estimated parameters. Therefore, an error sensitivity analysis using Monte Carlo simulation was used to study the input–output error behavior of each parameter based on the load cases and measurement locations of the nondestructive tests. Given the measured experimental responses, the goal was to select the unknown parameters of the FE model with high observability that leads to creating a well-conditioned system with the least sensitivity to measurement errors. A data quality study was performed to assess the accuracy and reliability of the measured data. Based on this study, a subset of the most reliable measured data was selected for the FE model updating. The selected subset of higher quality measurements and the observable unknown parameters were used for FE model updating. Three static and dynamic error functions were used for structural parameter estimation using the selected measured static strains, displacements, and slopes as well as dynamic natural frequencies and associated mode shapes. The measured data sets were used separately and also together for multiresponse FE model updating to match the predicted analytical response with the measured data. The FE model was successfully calibrated using multiresponse data. Two separate commercially available software packages were used with real-time data communications utilizing Application Program Interface (API) scripts. This approach was efficient in utilizing these software packages for automated and systematic FE model updating. The usefulness of the proposed method for automated finite element model updating at the element level is shown by being able to lead to simultaneous estimation of the stiffness and mass parameters using experimental data.

1. Introduction

According to the American Society of Civil Engineers 2013 Infrastructure Report Card, “Over two hundred million trips are taken daily across deficient bridges in the nation’s 102 largest metropolitan regions.” One in nine, or below 11%, of the nation’s bridges are classified as structurally deficient, while an average of 607,380 bridges are currently 42 years old. Currently, 24.9% of the nation’s bridges have been defined as functionally obsolete [1]. The Federal Highway Administration (FHWA) estimates that the current cost to repair or replace the deficient bridges eligible under the Federal Highway Bridge Program is almost $76 billion [2]. Damage can accumulate during the life of the structure due to normal use or overuse and overloads. In the inspection process, many of the structure’s elements are not observable to the inspector since they are covered by non-structural elements or are not easily accessible, which can cause uncertainty in their final reports. To add more confidence in our current methods of inspection and to improve the maintenance of infrastructures, objective and quantifiable structural health monitoring is essential in this field.

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Implementing a damage identification strategy for aerospace, civil, and mechanical engineering infrastructures is referred to as Structural Health Monitoring (SHM). There are two main approaches to SHM: (a) non-model-based approach and (b) model-based approach [3]. Both approaches have been successfully used for damage detection in structural applications. The non-model-based approach relies on the signal processing of experimental data, while the model-based approach relies on mathematical descriptions of structural systems [4]. The alternatives to the non-model-based method include: modal analysis, dynamic flexibility measurements, matrix update methods and wavelet transform technique, which are used to determine changes in structural vibration to identify damage [5].

The model-based approach is usually implemented by using a computer model of the structure of interest, such as a Finite-Element Method (FEM), to identify structural parameters based on the measured test data. In the model-based method, the first step is to create the FE model based on the design calculations. In most cases the initial model cannot accurately predict the actual parameters and responses of the structure; this may arise from the simplification in the modeling process. The model-based methods are often used for structural evaluations at the element level. The recent advancements in data acquisition systems (DAQ) and sensor technology have significantly improved our confidence in nondestructive test (NDT) data. Measured responses of the structure based on the experimental data can be used to validate the initial structural model and to update the parameters of the assumed model. The model calibration process involves selecting a small number of model parameters that have uncertainty so that their values cannot be known a priori and using various procedures to find the values for which their measurements best match the model predictions [6]. A promising method is to minimize the residual between the predicted response from the initial model and the measured response of the actual structure according to the observed data sets. Different approaches, methods, and technologies for effective practice of structural health monitoring were surveyed in [7]. In this book, model calibration was classified based on the selection of parameters to estimate, available measured data, formulation of the objective function, an optimization approaches, and the level of uncertainties. Using a model-based approach allows modeling and estimating the physical properties using commercially available software to create and maintain the structural model.

Robert-Nicoud et al. [8] performed the model calibration of the Lutrive Highway Bridge in Switzerland, a 395 m three span bridge with a maximum span of approximately 130 m, based on static measurements such as deflections, rotations, and strain. Bodeux and Golinval [9] successfully applied the Auto-Regressive Moving Average Vector (ARMAV) method to identify frequencies and mode shapes of the Steel-Quake benchmark, a two story steel frame structure. Koh et al. [10] presented a combination of genetic algorithms (GA) and local search techniques to identify structural parameters using vibration measurements. Hybrid structural identification methods were performed to estimate the structural parameters of a structure with 52 unknown parameters. Huang et al. [11] performed the system identification of the dynamic properties of a three-span box-girder concrete bridge using the Ibrahim Time-Domain (ITD) technique based on the free vibration test results of the bridge. Structural identification procedure was successfully applied on a three-span post-tensioned reinforced concrete (RC) highway overpass by Morassi and Tonon [12] based on modal analysis and FE model updating. Several other researchers have tackled different model updating techniques and their applications on various structures, such as Wang et al. [13], Mosavi et al. [14], Brownjohn et al. [15], Jaishi et al. [16] and Ancich [17].

Along with the analytical studies, a feasible way to verify a new methodology for structural health monitoring and system identification is to apply it first to a scale model structure. Therefore, many different test structures have been utilized for verification of SHM methods. In one of these studies, Catbas et al. [18] stated: “the main purpose of constructing this laboratory model was to close the gap between very simple laboratory tests and the field tests.” To provide an abstract representation of a short to medium span highway bridges, the University of Central Florida (UCF) benchmark was designed to have the lower natural frequencies in the range of 1–50 Hz, similar to full scale short to medium span bridges. The UCF benchmark was used in the experimental validation of various methodologies by different researchers such as Scianna and Christenson [19], and García-Palencia and Santini-Bell [20]. Although scaling is not the focus of this research, more information on scaling problem with respect to geometrical dimensions and material properties is given by Harris and Sabnis [21].

1.1. Objective, scope and contributions of this research

The main objective of this study is to develop a robust multiresponse structural parameter estimation method for the automated FE model updating. The proposed method is verified using data obtained from a set of nondestructive tests conducted on the UCF grid. In the present work, experimental data quality criteria was established and implemented to reduce the measurement errors in the model calibration process. To lessen modeling error, an accurate FE model was created with all the details including geometry, section properties, and boundary conditions. Error sensitivity analysis was performed using simulated damage cases to estimate the parameters with least sensitivity to measurement errors and also to determine the most observable parameters in presence of measurement errors. In these simulations, various grouping of elements with the same properties were used to reduce the number of unknowns, and then ungrouping was utilized to reduce the modeling errors. In this process a set of observable and error tolerant unknown parameter groups was selected for the purpose of FE model calibration using experimental data. Multiresponse parameter estimation based on the static and modal data collected from the UCF grid was used to calibrate the finite element model such that it can reflect the actual behavior of the structure more closely. The modal data includes the natural frequencies and the corresponding mode shapes whereas the static data includes displacement, rotation and strain, which have been used in this study. Selecting an observable and error tolerant set of unknown structural parameters and using the best subset of measured data led to successful simultaneous estimation of stiffness and mass parameters. To overcome the probable ill-conditioning in solving system of equations, which can result in poor parameter estimation, four different types of normalizations were applied at various levels of the proposed method. Using these normalizations enabled the usage of multiresponse parameter estimation method based on static and modal experimental data. A novel statistical normalization method based on the quality of the measured static data, instead of only applying weight factors, was used to provide a robust parameter estimation methodology.

The major contributions of this research presented for the first time are: (1) use of measured static and dynamic data for multiresponse parameter estimation, (2) implementation of real-time communication between two separate commercial software packages for automated finite element model updating, (3) development of NDT data quality analysis to reduce measurement errors, (4) implementation of a novel statistical normalization method based on the quality of the measured static data for use in parameter estimation methodology, (5) use of Monte Carlo analysis to