Engineering Structures xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Probabilistic damage identification of a designed 9-story building using modal data in the presence of modeling errors

Iman Behmanesh [a], Babak Moaveni [b,*], Costas Papadimitriou [c]

[a] Department of Building Structures, WSP | Parsons Brinckerhoff, New York, NY, United States[1]
[b] Department of Civil and Environmental Engineering, Tufts University, Medford, MA, United States
[c] Department of Mechanical Engineering, University of Thessaly, Greece

ARTICLE INFO

Article history:
Received 9 September 2015
Revised 18 May 2016
Accepted 18 October 2016
Available online xxxx

Keywords:
Probabilistic damage identification
Modeling error
Bayesian FE model updating
Bayesian model class selection

ABSTRACT

Validity and accuracy of model based identification techniques such as linear finite element (FE) model updating are sensitive to modeling errors. Models used for the design and performance assessment of civil structures often contain large modeling errors for certain frequency ranges of response. In other words, modeling errors have unequal effects on different vibration modes of structures. Therefore, the performance of FE model updating for damage identification is sensitive to the type and the subset of data used and to the residual weight factors. This study proposes a process to mitigate the effects of modeling errors by selecting the optimal subset of modes and the optimal modal residual weights. Multiple model updating classes are defined based on different subsets of modes and different weight factors. Structural damage is then identified using Bayesian model class selection and model averaging techniques over the results of all the considered model updating classes. In addition, a new likelihood function is defined to allow damage identification without the need for calibrating a reference FE model. Performance of the proposed damage identification process and the new likelihood function is evaluated numerically at multiple levels of modeling errors and structural damage on the SAC 9-story steel moment frame. It is shown that the structural damages can be identified with negligible bias when the proposed likelihood and updating process is implemented.

1. Introduction

In the structural health monitoring research community, damage identification is defined as the process of determining: (1) existence of damage; (2) location of damage; (3) severity of damage; and (4) remaining useful life of structures [1]. Among many methods that have been proposed in the past two decades [2–4], finite element (FE) model updating methods are popular for damage identification [5–10] because they provide information about the existence, location, and extent of the damage, and because in some cases the updated FE models can be used for response prediction and damage prognosis. These methods have been applied for damage identification of several civil structures in recent years [11–14]. In the FE model updating methods, a set of structural model parameters, usually stiffness of substructures (groups of finite elements), are adjusted so that the model predicted quantities of interest best match those obtained from the test data. Note that the identifiability of structural damage depends on the sensitivity of measured data (or data features) to the damage [15]. Despite the fact that the natural frequencies of civil structures often have small sensitivity to local damage, they are commonly used for assessment of structural health and performance. This is mainly due to the facts that (1) they provide a global measure of structural dynamic properties and (2) they can be easily extracted from ambient or operational vibration measurements. Damage identification through FE model updating is usually performed in two steps: a baseline/reference model is calibrated from the initial FE model in the first step to match the data at the undamaged state of the structure, and in the second step, a second model is calibrated to represent the data of the structure at its current (potentially damaged) state. The difference between the two models indicates the location and extent of damage [12,13,16–18]. This damage identification process is summarized in Fig. 1.

The identification results obtained from the process shown in Fig. 1 depend on (1) the accuracy and completeness of the identified modal parameters used in the identification process and (2) the accuracy of the initial FE model. The accuracy of the identified modal parameters are mainly affected by measurement noise, esti-

* Corresponding author.
E-mail address: babak.moaveni@tufts.edu (B. Moaveni).
[1] Former Graduate student, Tufts University.

http://dx.doi.org/10.1016/j.engstruct.2016.10.033
0141-0296/

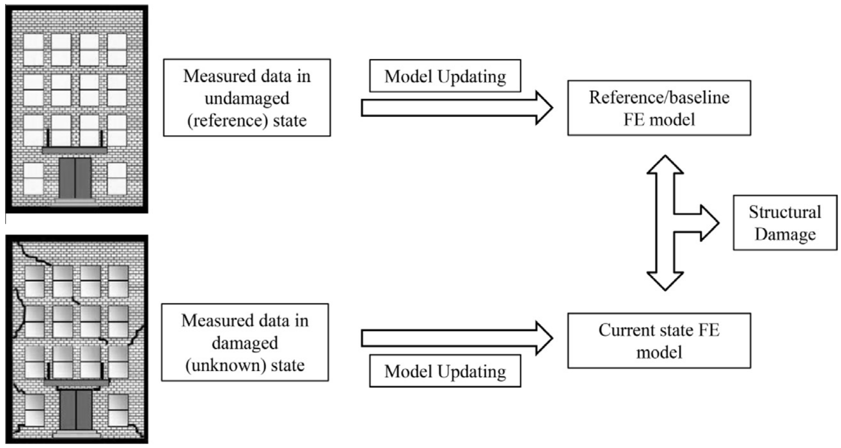

Fig. 1. Two-step damage identification process using FE model updating technique.

mation uncertainties, and changing environmental conditions [19,20]. The effects of these sources of uncertainty on model updating and damage identification results are well-documented in the literature. The effects of noisy measurements can be alleviated by using multiple sets of data and averaging as shown in [16,17]. Damage identification under environmental variability is discussed in [21–23]. Among the aforementioned sources of uncertainty, modeling errors can be regarded as the most influential factor and its effects on model updating results has been the subject of a few studies in the past [24–26]. Goller and Schueller [24] showed that FE modeling errors will increase the variance of prediction error parameters and will result in bias for model-predicted modal parameters even after updating. They suggested that the bias should be included in predictions from the updated FE model. Goulet and Smith [25] proposed model falsification instead of identification to overcome the difficulties of addressing modeling error uncertainties. They also discussed the biased-predictions of Bayesian model updating methods. Ching and Beck [26] stated that the inaccurate damage identification results of their experimental test are mostly due to modeling error effects. Haukass and Gardoni [27] discuss different sources of modeling errors such as discretization of finite elements, linear assumptions for material properties, geometrical uncertainties, or simplifications in boundary condition modeling.

This paper first investigates the effects of modeling errors on the damage identification results, and then proposes a two-step damage identification process to mitigate the effects of modeling errors. In the first step, the optimal subset of modes to be included in the FE model updating are selected using Bayesian model class selection technique [28,29] by defining multiple model classes each with different subsets of modes. In the second step, different weight factors are defined between the eigenvalue and mode shape errors. A set of damage identification results is estimated for each weight factor, and the final estimation is obtained by averaging all the results using Bayesian model averaging technique. The effect of weight factors between the eigenvalue errors and the mode shape errors were previously studied in [30,31].

The proposed first step is based on the hypothesis that using an optimal subset of modes for model updating will provide more accurate damage identification results compared to when using all contributing modes [32,33]. This can be justified by the fact that modeling errors (e.g., due to discretization) have different effects on different modes, i.e., FE models are non-uniformly valid within the frequency domain. Therefore, including certain modes in the updating process will negatively affect the updating and damage identification results. This hypothesis has often (almost always) been used in an ad-hoc manner in real-world applications of model updating for complex structures. In these applications, the higher vibration modes – where generally the modeling errors are larger – or certain identified modes that cannot be paired with the initial model are not included in the updating process. The proposed first step will exclude the modes with large estimation errors. It is worth noting that the influence of modes with large errors can be alternatively mitigated by considering relatively large standard deviations for their corresponding error functions in the likelihood.

Another challenge in formulating the damage identification process shown in Fig. 1 is the fact that modeling errors cause biased error functions, i.e., the updated model will not be an unbiased representation of the true system. To address this challenge, a new likelihood function is proposed that uses both data sets in the damaged and the undamaged conditions. By using this likelihood function, the structural damage can be identified using the initial FE model directly and there is no need to create the baseline/reference FE model. In practice, the initial models are created based on the best level of engineer's knowledge and material test data and therefore, significant modifications of the initial models to match the measured data at the undamaged state of the structure are unrealistic. These modifications can cause certain physical parameters of the model (e.g., stiffness, mass) fall outside acceptable ranges. This shortcoming is also addressed by using the proposed likelihood function.

The proposed model updating process and likelihood function are used for damage identification of a 9-story building based on its numerically simulated dynamic response. The considered test bed structure is the 9-story steel moment frame SAC building, designed for Los Angles, California [34]. The original model is modified to reflect different levels of realistic modeling errors. Performance of the proposed identification process is evaluated considering three levels of structural damages and three levels of modeling errors.

2. Proposed likelihood function

This section presents a summary of the Bayesian FE model updating formulations used in this study. More detailed formulations of the Bayesian model updating process can be found in seminal publications on this topic [18,26,32,35–39]. According to the Bayes theorem, conditional posterior probability distributions of updating parameters $\boldsymbol{\theta}$ (vector of structural model parameters) and $\boldsymbol{\sigma}$ (vector of standard deviations of the error functions) given the measured data $\mathbf{D}$ (identified modal parameters in this study) and the model class M can be obtained by: