Mechanical Systems and Signal Processing 85 (2017) 236–251

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Nonlinear model calibration of a shear wall building using time and frequency data features

Eliyar Asgarieh [a], Babak Moaveni [a,*], Andre R. Barbosa [b], Eleni Chatzi [c]

[a] Department of Civil and Environmental Engineering, Tufts University, Medford, MA, USA
[b] School of Civil and Construction Engineering, Oregon State University, Corvallis, OR, USA
[c] Department of Civil, Environmental and Geomatic Engineering, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland

A R T I C L E   I N F O

Article history:
Received 13 October 2014
Received in revised form
18 March 2016
Accepted 30 July 2016

Keywords:
Nonlinear structural identification
FE model updating
Time-varying instantaneous modal parameters
Unscented Kalman filter

A B S T R A C T

This paper investigates the effects of different factors on the performance of nonlinear model updating for a seven-story shear wall building model. The accuracy of calibrated models using different data features and modeling assumptions is studied by comparing the time and frequency responses of the models with the exact simulated ones. Simplified nonlinear finite element models of the shear wall building are calibrated so that the misfit between the considered response data features of the models and the structure is minimized. A refined FE model of the test structure, which was calibrated manually to match the shake table test data, is used instead of the real structure for this performance evaluation study. The simplified parsimonious FE models are composed of simple nonlinear beam-column fiber elements with nonlinearity infused in them by assigning generated hysteretic nonlinear material behaviors to uniaxial stress–strain relationship of the fibers. Four different types of data features and their combinations are used for model calibration: (1) time-varying instantaneous modal parameters, (2) displacement time histories, (3) acceleration time histories, and (4) dissipated hysteretic energy. It has been observed that the calibrated simplified FE models can accurately predict the nonlinear structural response in the absence of significant modeling errors. In the last part of this study, the physics-based models are further simplified for casting into state-space formulation and a real-time identification is performed using an Unscented Kalman filter. It has been shown that the performance of calibrated state-space models can be satisfactory when reasonable modeling assumptions are used.

1. Introduction

A large number of methods exist in the literature for identification of structural systems from measured dynamic data. Among these methods, finite element (FE) model updating has received increased attention in the structural health monitoring research community with the goal of reliable response prediction and performance assessment of civil structures. Physics-based FE models can directly use the available information from geometry and material behavior of a structural system and therefore can mitigate the effects of modeling error and uncertainty in the identification process [1–4]. Most of the FE model updating studies in the literature are restricted to linear model assumption [5,6]. In the

* Correspondence to: Department of Civil and Environmental Engineering, 200 College Ave., Medford, MA 02155, USA.
E-mail address: babak.moaveni@tufts.edu (B. Moaveni).

http://dx.doi.org/10.1016/j.ymssp.2016.07.045
0888-3270/

application of linear model updating, selected model parameters are tuned to match the extracted data features measured during the linear (low-amplitude) response of structures. Comparison of linear modeling parameters (often stiffness) before and after a damaging event, such as an earthquake, can be used for estimating the location and extent of damage in the structure. Successful application of linear FE model updating can be found in the literature for damage identification [7–12]. However, updated linear models are only useful for predicting the future response of structures to low amplitude excitations, and can lead to large errors when used for nonlinear response estimation [13,14]. In addition, most civil structures are inherently characterized by nonlinear behavior and therefore in an effort to avoid large modeling errors, nonlinearity should be taken into consideration [15]. To this end, nonlinear models are necessary for accurate and efficient prediction of structural response to moderate-to-high amplitude excitations.

The nonlinearity in FE models of civil engineering structures is often modeled via assignment of appropriate hysteretic material properties to groups or clusters of elements. Therefore, for calibration of such nonlinear FE models, it would suffice to estimate the time-invariant parameters of the hysteretic constitutive law, rendering such a formulation particularly convenient for model updating purposes. Few applications of nonlinear FE model updating exist in the literature [16–20]. The accuracy of calibrated nonlinear models gravely depends on the choice of data features used in the updating process and modeling assumptions. In this paper, the effects of four types of data features in the updating process are investigated. In addition, some of the common difficulties of updating nonlinear models of complex systems such as ill-conditioning and lack of identifiability are studied. The role of modeling error/uncertainty is also studied on the accuracy of identification results by considering models with different constraints and hysteretic material behaviors. The case study analysis is performed on the simulated response of a seven-story shear wall building using a detailed FE model of the test structure, which was calibrated manually to match the recorded test data. Nonlinear FE models of the structure are calibrated by minimizing an objective function defined as a measure of the discrepancy between data features of the forward simulation models and their simulated counterparts using the simulated annealing (SA) global optimization method [21].

In the case of using non-physics based models, several methods exist in the literature for nonlinear model calibration. Among these methods, adaptive methods such as Kalman or Particle filters have been used successfully for real-time nonlinear identification [22–30]. In these applications, nonlinearity is modeled using analytical phenomenological material models such as the Bouc-Wen model [31–34]. Although this framework has been applied successfully in many cases and promising results are reported, its applicability is hindered by problems such as large modeling errors in the considered state-space models (such as oversimplification of models, wrong boundary conditions and constraint assumptions, and incompatible nonlinear models) and difficulty of applying these models to more complex structural systems with large number of degrees-of-freedom [35]. In this paper, the applicability of an Unscented Kalman filter [36,37] algorithm is demonstrated for identifying two nonlinear state-space models of the test structure relying on different modeling assumptions. The effects of these modeling assumptions on the performance of the implemented Kalman filter are investigated.

The work presented herein is formulated as follows. Section 2 briefly describes the test structure, the detailed FE models used for response simulation, and the simplified FE models applied for identification. Section 3 presents the model updating process, the updating results, and the performance of the applied models for structural identification. In Section 4, simplified state-space models are identified by the Unscented Kalman filter and it is shown that more realistic modeling assumptions can significantly improve the accuracy of the real-time identification. Finally, in Section 5 the major points of this research are highlighted and conclusions are drawn.

2. Test structure and FE models

2.1. Detailed FE model used for simulating the "measured data"

The test structure was a full scale seven-story reinforced concrete shear wall building section (Fig. 1a), and consisted of a web wall as the resisting mechanism against lateral loads, a flange wall for transverse stability, a post-tensioned column that provided torsional stability, and four gravity columns for supporting the weight of the floor slabs. The structure was tested on the shake table of the University of California at San Diego (UCSD) in 2006 through base excitations of increasing intensities. More details about the structure and dynamic tests can be found in [38]. In this paper, the response of the test structure to be used in identification is numerically simulated using a refined nonlinear FE model of it. The nonlinear FE model (Figs. 1b and 2) was developed in OpenSees [39] – based on the knowledge from the geometry and material properties of the test structure – and was calibrated manually to represent the measured response of the test structure to a large earthquake shake table excitation. The FE model consists of 509 nodes, 198 elastic beam-column elements, 35 nonlinear beam-column elements with fiber cross-sections, and 315 linear elastic shell elements. The nonlinearity is defined as uniaxial stress–strain relations at fiber cross-sections in nonlinear beam-column elements, using Giuffre-Menegotto-Pinto [40] and Popovics [41] material models for simulating the nonlinear behavior of reinforcing steel bars and concrete, respectively. In the FE model, the web walls are modeled using four beam-column elements connected in series per story, and each beam-column fiber element is discretized into four fiber-sections (connected through Gauss-Lobatto integration points) each containing multiple uniaxial fibers. The flange walls are modeled by a single beam-column element per story, in which four integration points are defined for each element. To improve the efficiency of the FE model, other parts of the structure are assumed to have linear elastic behavior and are modeled using elastic beam-column elements and linear