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Model-reference damage tracking and evaluation of hysteretic structures with test validation

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ABSTRACT

A data-driven damage tracking and evaluation method for earthquake-excited hysteretic structures is proposed in this study. The model reference tracking concept is introduced to quantify the shifts of the model status due to the damage developments, and a logistic framework is then designed with the employment on monitoring data from both healthy and damaged conditions of the instrumented structures. The linear behavior modeling of the objective structure is adopted for generating the reference signals and calculating the tracking errors of structural responses. A tracking error-based damage sensitive index in a normalized form is then presented for the simultaneous and combined quantification on the peak, cumulative and residual damage effects within the little knowledge on non-linear characteristics. Comprehensive results from the numerical simulations of a single degree-of-freedom degradation model and the experimental investigations on several large-scale reinforced concrete columns are studied and discussed for the illustration of the tracking and quantification performances of the proposed data-driven evaluation method.

1. Introduction

Health monitoring of infrastructures subjected to disastrous events such as earthquakes constitutes an important task for structural engineers, with the most emphasis on structural performance and damage. Generally, the damage detection capability in a continuous and data-driven manner is referred to as one of the major objectives for structural health monitoring (SHM), and such monitoring-based evaluation processes can benefit the quantitative assessment of earthquake-resistant design practices, the enhanced understanding of large-scale and real-world structural behavior, the necessary post-earthquake rapid evaluation of structural safety and vulnerability to future earthquakes [1,2].

Distinguished from the operational monitoring of in-service systems, strong hysteresis and deterioration behaviors are experienced and potentially defined as structural damages for the seismic-excited structures [3], such as micro-cracks with opening and closing behaviors, reinforced concrete (RC) components with strength and stiffness degradation, and steel members with yielding and buckling. Recently, performance-based earthquake engineering (PBEE) and structural health monitoring (SHM) are two emerging aspects for performance assessment of earthquake-damaged structures. The PBEE develops engineering demand parameters (EDP) for predicting the damage of significance for different performance levels

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[4]. Meanwhile, the SHM implemented in earthquake engineering is focused on the identification and assessment of structural hysteresis and nonlinear damages by using seismic monitoring data [5].

Currently, the available and mostly-used damage indicators by the outcomes of PBEE may consist of softening indices with the equivalent linearization, the peak quantities related to ductility, the cumulative quantities relevant to dissipated energy, and the combination of ductility and dissipation in the Park-Ang (PA) model and relevant damage indices [6–10], and specifically, the comparison of three different damage indices, including the methods of Banon and Veneziano, Park and Ang, as well as the linear cumulative law of fatigue, have been extensively analyzed in the study [11]. Recently, the linear cumulative rule for fatigue damage has been integrated with the statistic response process in [12], and to evaluate the seismic damage of building structures, some novel damage indices based on the static analysis [13] and modes of linear vibration [14] for a nonlinear system have also been investigated. Inspired from the existing damage indices in seismic studies, the quantitative evaluation of nonlinear damage or hysteresis behavior is challenging and complicated due to the comprehensive contributions from the instantaneous, cumulative and residual damage effects, which correspond to the peak deformation, the dissipated hysteresis energy, and the residual drift, respectively. Accordingly, the novel damage-sensitive data features with the focus on these damage effects and developments may constitute one major challenge for the SHM applications in earthquake engineering.

Correspondingly, the vibration-based SHM is mostly focused on developing data-driven damage indicators [15–17], wave propagating-based analysis [18], and model updating methods for dynamical systems [19]. In the case of real-world diagnosis, most remarkable progress has been made in modal analysis on recorded structural responses [20–22]. However, the direct utilization of modal properties for further nonlinear damage evaluation may be questionable. Representative concerns and evidences include the lacked strong correlation to stiffness degradation [23], the uncertain peaks of transfer function due to yielding [24], and the conceptual drawback because of linear system theory [25]. Hence, the response-based assessment in the time domain may be a potential and feasible choice for quantitative damage evaluation of hysteretic structures [26]. Especially, the damage occurrence, location and severity are the long-term used objectives for damage detection in SHM, and in the context of earthquake-damage structures, the progressive development of nonlinear damage during the mainshock and aftershocks may be an additional valuable aspect [27] to be tracked by using the measured data during the strong excitations.

In terms of nonlinearity evaluation, recent progress has been reported on the parametric identification of hysteresis systems with the Bouc-Wen model by Chatzis et al. [28], Charalampakis and Dimou [29], Chatzis and Chatzi [30] and Wang and Lu [31], and was systematically reviewed by Chang et al. [32]. However, the identification and modeling of structural hysteresis may not be able to directly quantify the structural damages regarding peak and cumulative effects. In the purpose of nonlinear damage evaluation, the following issues may be desired to be incorporated: (1) the definition of structural hysteresis as damage, distinguished from the SHM studies adopting linear stiffness reduction; (2) the simultaneous and comprehensive evaluation of peak, cumulative and residual damage effects and the good correlation with the hysteresis development and PBEE indices (i.e. Park-Ang model), different from the studies using modal identification; (3) the little prior-knowledge of structural hysteresis terms as nonlinear model-free evaluation, alternative from the parametric identification studies with the prior-assumed hysteretic model. To the best knowledge of the authors, there are few publications that have simultaneously and fully addressed these issues, and the damage feature with these characteristics may become real-world implementable and valuable for post-earthquake assessment.

In this paper, a data-driven damage tracking and evaluation methodology is proposed with a novel damage-sensitive feature, incorporating the concept of model reference tracking. The concept and basis of the data-driven method is firstly presented, and the formulations and the designed procedure is then illustrated and discussed. Illustrative examples, including numerical simulation adopting one single degree-of-freedom (SDOF) degradation model and experimental investigations employing several large-scale reinforced concrete columns subjected to cyclic loading and seismic excitations, are utilized for demonstrating the real-time tracking and evaluation capability of the proposed method on nonlinear and hysteresis structures.

2. Methodology

2.1. Model reference concept

Usually in PBEE, the performance evaluation of structural hysteresis is dependent on the material property and physics-based damage indicators, which is physically straightforward and clear in concept, such as using material strain and stress, peak and residual deformation, and energy dissipation [33]. However, the implementation of such damage models is successful in the case of numerical modeling with every-level detailed information perfectly known, and partially feasible for the shake table testing with dense measurement data but may become relatively restrained in the real-world seismic monitoring studies due to the inevitable practical issues. The numerical model-based damage evaluation may not be fully reliable for large-scale physical structures with respect to the modeling uncertainty due to incomplete and uncertain structural information [34], the incomplete monitoring data [35], and the observed variation of the prediction results by different research teams as illustrated in the RC column blind prediction contest [36]. Hence, the data-driven modeling and evaluation has been recently presented for structural behavior modeling [37] and post-event damage diagnosis [38], which may provide an alternative way for nonlinear damage tracking and evaluation.