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Mechanistically-informed damage detection using dynamic measurements: Extended constitutive relation error

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ABSTRACT

Model-based damage detection entails the calibration of damage-indicative parameters in a physics-based computer model of an undamaged structural system against measurements collected from its damaged counterpart. The approach relies on the premise that changes identified in the damage-indicative parameters during calibration reveal the structural damage in the system. In model-based damage detection, model calibration has traditionally been treated as a process, solely operating on the model output without incorporating available knowledge regarding the underlying mechanistic behavior of the structural system. In this paper, the authors propose a novel approach for model-based damage detection by implementing the Extended Constitutive Relation Error (ECRE), a method developed for error localization in finite element models. The ECRE method was originally conceived to identify discrepancies between experimental measurements and model predictions for a structure in a given healthy state. Implementing ECRE for damage detection leads to the evaluation of a structure in varying healthy states and determination of discrepancy between model predictions and experiments due to damage. The authors developed an ECRE-based damage detection procedure in which the model error and structural damage are identified in two distinct steps and demonstrate feasibility of the procedure in identifying the presence, location and relative severity of damage on a scaled two-story steel frame for damage scenarios of varying type and severity.

1. Introduction

Many forms of structural failures in steel frames can be attributed to damage in connections, such as shear failure of bolts, excessive bearing deformation at the bolt-hole and edge tearing or fracture of the connection plate [10,24]. One particular damage type is the self-loosening of bolts which leads to the loss of the clamping force in the bolted connection [27,41]. The loss of structural redundancy from such damage in connections can considerably reduce the load-carrying capacity of a steel frame system, especially when the damaged connection is a critical component of the load path [35]. Hence, early detection of connection damage is essential for structural engineers and infrastructure managers to ensure timely rehabilitation and repair of steel frame structures.

Model-based damage detection is now deemed an effective method for identifying, localizing and determining the severity of damage in structural systems [26,40]. In this approach, a numerical model, typically a finite element (FE)

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Nomenclature

$\boldsymbol{M}$	discrete mass matrix of order N,
$\boldsymbol{K}$	discrete stiffness matrix of order N,
$\ddot{\boldsymbol{x}}$	acceleration time response vector
$\boldsymbol{x}$	displacement time response vector
$\boldsymbol{f}$	time-dependent excitation force vector
λ_z	the z^{th} eigenvalue
$\boldsymbol{y}_z$	the z^{th} eigenvector
$\boldsymbol{u}$	mode shapes extracted from experimentally measured data
$\boldsymbol{v}$	numerically calculated displacement field
E_z^2	the extended constitutive relation error for the z^{th} experimentally identified eigensolution
$\boldsymbol{u}_z^e$	the z^{th} identified eigenvector on the n experimentally measured DOFs
$\boldsymbol{u}_z$	expansion of the z^{th} identified experimental eigenvector $\boldsymbol{u}_z^e$ to the N model DOFs
$\boldsymbol{v}_z$	static displacement field evaluated for the FE model due to the inertial loading $\lambda_z^e \boldsymbol{M}\boldsymbol{u}_z$
$\boldsymbol{H}$	transformation matrix
N	total number of degrees of freedom in finite element model
n	number of experimentally measured degrees of freedom
m	number of modes
$\boldsymbol{K}_R$	reduced stiffness matrix of finite element model
α	weighting factor
λ_z^e	the z^{th} experimentally identified eigenvalue
$\boldsymbol{K}_i$	stiffness matrix of the i^{th} subdomain
$\boldsymbol{K}_j^{ele}$	sparse matrix containing the stiffness matrix of the j^{th} finite element
$\boldsymbol{S}_i$	the set of element matrices belonging to the subdomain i
$E_{z,i}^2$	residual energy that represents the model error for the i^{th} subdomain of FE model
$\boldsymbol{R}_h$	relative displacement vector between mode shape vectors of the healthy structure and corresponding static displacement field predicted by the FE model
$\boldsymbol{R}$	relative displacement vector between mode shape vectors of the damaged structure and corresponding static displacement field predicted by the FE model
$I_{D,i}$	damage indicator for the i^{th} subdomain
$ECRE_i$	residual energy for the i^{th} subdomain that represents the difference between the healthy and damaged structure.

representation, is developed based on the properties of the undamaged system and then updated with respect to the measurements obtained from the damaged system. Damage detection is based on the premise that the changes imposed on the model during the updating process reflect the damage in the system. Over the last three decades, a variety of FE model calibration schemes have been implemented for model-based damage detection. For instance, the earliest techniques entailed calibrating the individual terms within stiffness and mass matrices. Although this approach made it possible to obtain global matrices that reproduced the measured modal parameters identically [5,7], the resulting matrices were not guaranteed to maintain structural connectivity and the suggested changes in the model were not always related to actual damage (in worst cases the changes were not even physically meaningful)[1] [18]. These direct methods were followed by the emergence of indirect (also known as parametric) methods, which focused on updating the parameters of the model and thus, preserved the physical meaning of imposed corrections [21,32–34,4]. The parametric method, when implemented for damage detection, typically involved solving an optimization problem where a cost function that represents the discrepancy between the FE model of the undamaged system and the experimental measurements from its damaged counterpart was minimized by manipulating the damage-indicative parameters. This cost function was defined through a user-selected metric, often based on mathematical norms, such as Euclidean distance [14,38,9] or p-norms [31], without explicitly taking the knowledge regarding the mechanistic behavior of the system into account. This parametric approach was most commonly applied using non-destructively measured vibration modes [28,39]. In most applications, however, the practical constraints on the number of measurement degrees of freedom (DOFs) limited the number of identified vibration modes resulting in an ill-posed inverse-problem [20]. In the context of damage detection, ill-posed inverse-problems lead to multiple plausible solutions (i.e. more than one possible damage scenario), a concept widely referred to as non-uniqueness [6].

These approaches for model calibration as applied for damage detection mentioned are based only on the outputs of computer models (natural frequencies, mode shapes, modal forces, etc.). In contrast, the Extended Constitutive Relation Error (ECRE) based damage detection integrates the mechanistic principles (e.g. load-displacement relationships) underlying the behavior of the system during the comparison of model predictions against experiments [12,15,25,30]. In the traditional ECRE approach, the model error localization procedure involves pinpointing the contributions of each element to the global error considering both model and experimental errors [29]. The proposed ECRE-based damage detection involves calculating the residual energy in each element of the FE model of the undamaged structure using experimental measurements collected from the damaged structure. A damage indicator is then obtained by normalizing the residual energy to the total energy in each element of the FE model. Thus, the damage indicator reveals the damaged elements by pinpointing

[1] In these applications, the objective was to improve the feedback control loop and hence accurate representation of the structural connectivity was not implemented.