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Structural damage identification built on a response surface model and the flexibility matrix

L.T. Stutz [a,*], I.C.S.S. Rangel [a], L.S. Rangel [a], R.A.P. Corrêa [b], D.C. Knupp [a]

[a] Graduate Program in Computational Modeling, Polytechnic Institute, Rio de Janeiro State University, Nova Friburgo, RJ, 28625-570, Brazil

[b] Post-Grad in Computational Modeling in Science and Tecnology, Fluminense Northwest Institute of Higher Education, Fluminense Federal University, Santo Antônio de Pádua, RJ, 28470-000, Brazil

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ABSTRACT

The present work is concerned with the inverse problem of structural damage identification. The damage state of the structure is continuously described by a cohesion field, spatially discretized by the finite element method, and a response surface model (RSM) is considered to provide a polynomial relation between the nodal cohesion parameters and elements of the flexibility matrix of the system. Here, the inverse problem of damage identification is posed as an optimization one, where the objective is to minimize, with respect to the nodal cohesion parameters, the squared norm of the difference between an experimental response vector, composed with elements of the flexibility matrix obtained from a modal test on the supposed damaged structure, and the corresponding one predicted by a RSM. The Particle Swarm Optimization method was considered for solving the resulting inverse problem of damage identification. A simply supported Euler-Bernoulli beam, with three different damage scenarios and the synthetic experimental mode shapes corrupted with two different levels of noise, was considered in the numerical assessment of the proposed damage identification approach. The numerical results show that the proposed approach, built on a RSM of the flexibility matrix, presented results comparable with those obtained with the approach built on the FEM of the structure and it also presented an extremely higher computational performance.

1. Introduction

Finite element models (FEMs) are widely used to predict the dynamic behavior of engineering structures [1]. However, due to parameter uncertainties, simplifying modeling assumptions, inaccurate boundary conditions and other sources of errors, the predictions of an initial FEM of a structure often differ from its experimentally measured responses. Therefore, in order to obtain more accurate predictions, one may update the uncertain parameters of the FEM of a structure based on its measured responses [2–4].

The FEM updating is generally formulated as an inverse problem of parameter estimation. Besides, in the specialized literature, most of the proposed approaches defines the inverse problem as an optimization one, where a set of unknown parameters is sought in order to minimize an arbitrary error function, which is defined as the difference between some output or matrix of the FEM of the structure and the experimentally obtained ones [2,3]. Within this framework, the special problem of damage identification is a subject of main concern in the scientific and engineering communities. Structural damage identification

* Corresponding author.
E-mail addresses: ltstutz@iprj.uerj.br (L.T. Stutz), isilva@iprj.uerj.br (I.C.S.S. Rangel), lrangel@iprj.uerj.br (L.S. Rangel), rosileneportella@id.uff.br (R.A.P. Corrêa), diegoknupp@iprj.uerj.br (D.C. Knupp).

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is an essential issue for determining safety reliability and remaining lifetime of aerospace, civil and mechanical structures [5]. Among the damage identification approaches, a special attention is devoted to nondestructive ones built on the dynamic behavior of the structures [5–7]. In this context, different methods, based on impulse response functions, frequency responses, modal parameters or the flexibility matrix, have been succeeded in practical damage identification problems [8–12].

The solution of an inverse problem of damage identification, directly formulated with a FEM, may become extremely time consuming when dealing with complex structures. With the aim at obtaining computationally more efficient approaches, in the formulation of the inverse problem, the actual FEM of the structure may be replaced by a surrogate model. The response surface model, radial basis functions, Kriging model and neural networks are some examples of surrogate models considered in FEM updating problems [13–16].

The response surface model (RSM) is a surrogate model that provides explicit relations, generally of polynomial type, between a given set of parameters and responses of interest [17]. Polynomial response surfaces are commonly adopted due to the simplicity of the required computations and to their closed-form algebraic expressions. Second order polynomials have been shown to be more adequate for most engineering problems and they have succeeded in different damage identification ones. In the context of damage identification, the RSM provides relations between parameters describing the damage state of the structure and responses supposed to be sensitive to them. Natural frequencies of the structures [16,18], the natural frequencies and mode shapes [19], a combination of static deflections and natural frequencies [20], and some metrics computed from time domain data [21–23] have already been considered in RSM formulations.

The present work is concerned with the formulation of a damage identification approach built on the RSM and the flexibility matrix. Here, the damage state of the structure is continuously described by a cohesion field, spatially discretized by the finite element model, and the RSM is considered for providing polynomial relations between the cohesion parameters and elements of the structural flexibility matrix. Therefore, the corresponding inverse problem of damage identification is defined as a minimization one, where the aim is to find the vector of nodal cohesion parameters that minimizes the squared norm of the difference between the experimental response vector, composed with elements of the flexibility matrix obtained from a modal test on the supposed damaged structure, and the corresponding one predicted by a RSM. As the flexibility matrix may be written as a function of the modal parameters of the structure, an experimental flexibility matrix may be obtained from standard modal tests. Besides, an accurate estimate for the experimental flexibility matrix may be computed from the lower frequency modes of the structure. The Particle Swarm Optimization method was adopted for solving the resulting inverse problem of damage identification [24]. To the best of the authors knowledge, this is the first work that formulates the damage identification problem built on a RSM of the flexibility matrix.

The reminder of the paper is organized as follows. Section 2 presents the theoretical background required for the formulation of the damage identification problem built on the RSM and on the structural flexibility matrix. Hence, Section 2 presents the continuum damage model adopted in the present work, the flexibility matrix as a function of the modal parameters of the structure and a brief description of the response surface modeling. Section 3 presents the formulation of the inverse problem of damage identification. The Particle Swarm Optimization method is presented in Section 4. Section 5 presents the numerical assessment of the proposed damage identification approach on a simply supported Euler-Bernoulli beam for different damage scenarios and noise levels. Finally, the concluding remarks are presented in Section 6.

2. Mathematical modeling

This section presents the basic concepts related to the proposed damage identification approach built on a response surface model of the flexibility matrix: The definition of the cohesion parameter, which is the parameter adopted to continuously describe the damage state of the structure; the relation between the stiffness matrix of a finite element of the structure and the cohesion parameter; the spatial discretization of the cohesion field; the definition of the structural flexibility matrix and its relation with the modal parameters of the structure; and, finally, the fundamentals for deriving the response surface model of the flexibility matrix.

2.1. Continuum damage model

In the present work, the damage state of the beam is related to the cohesion parameter β, which, at a point x along the beam, is defined as

$$\beta(x) = \frac{E(x)I(x)}{E_0 I_0}, \tag{1}$$

where $E(x)$ and $I(x)$ are, respectively, the Young modulus and the second moment of area of the beam, at the point x, and E_0 and I_0 are, respectively, the corresponding nominal values of these parameters [25,26]. Therefore, according to Eq. (1), the cohesion field is defined as the ratio between the actual bending stiffness along the beam, $E(x)I(x)$, and the corresponding nominal one, $E_0 I_0$. It is assumed that $0 \leq \beta \leq 1$, where $\beta = 0$ represents a local rupture and $\beta = 1$ represents an absence of structural damage.

Considering Eq. (1), the stiffness matrix of a finite element of a Euler-Bernoulli beam may be written as