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An efficient indicator for structural damage localization using the change of strain energy based on static noisy data

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ABSTRACT

An efficient method is proposed to find multiple damage locations in structural systems. The change of static strain energy (SSE) due to damage is used to establish an indicator for determining the damage location. The SSE is determined using the static analysis information extracted from a finite element modeling. In order to assess the performance of the proposed method for structural damage detection, some benchmark structures having a number of damage scenarios are considered. Numerical results demonstrate that the method can accurately locate the structural damage when considering the measurement noise. The efficiency of the proposed indicator for finding the damage site is also compared with a modal strain energy based index (MSEBI) provided in the literature.

1. Introduction

Many structural systems may experience some local damage during their lifetime. If the local damage is not identified timely, it may lead to a terrible outcome. Therefore, damage identification is an essential issue for structural engineering and it has received a considerable attention during the last years [1–4]. Structural damage detection consists of three different levels aiming to identify the existence, localization and quantification of damage, respectively. After discovering the damage occurrence, damage localization is more important than damage quantification. Due to a great number of elements in a structural system, properly finding the damage location has been the main concern of many studies. In the last years, numerous methods have been proposed for accurately locating structural damage. Structural damage detection by a hybrid technique consisting of a grey relation analysis for damage localization and an optimization algorithm for damage quantification has been proposed by He and Hwang [5]. A two-stage method for finding the structural damage sites and extent through an evidence theory and a micro-search genetic algorithm has been introduced by Guo and Li [6]. The changes of modal flexibility matrix and modal strain energy of flexural members before and after damage have been used by Shih et al. [7] as a basis for locating the structural damage. Locating structural damage through an adaptive neuro-fuzzy inference system (ANFIS) has been utilized by Fallahian and Seyedpoor [8]. Damage detection using an efficient correlation based index and a modified genetic algorithm has been proposed by Nobahari and Seyedpoor [9]. A two-stage method for determining structural damage sites and extent using a modal strain energy based index (MSEBI) and particle swarm optimization (PSO) has been proposed by Seyedpoor [10]. Most of the methods developed for structural damage detection have been founded on using dynamic information of a structure that can be obtained slowly and expensively. However, the methods of structural damage detection employing static data are comparatively fewer, while static information can be obtained more quickly and cheaply.

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In this study, an efficient static data based indicator is introduced to estimate the damage locations in a structural system. The change of strain energy between healthy structure and damaged structure subjected to some static load cases is used to formulate an index for finding damage localizations. Various test examples with and without considering measurement noise are selected to assess the efficiency of the proposed index for accurately locating the damage. Numerical results reveal that the proposed index can identify the flawed elements in a damaged structure rapidly and precisely.

2. Strain energy based damage detection methods

Structural damage detection using non-destructive methods has received significant attention during the last years. The fundamental law is that damage will change the mass, stiffness and damping properties of a structure. Such a change would lead to changes in the static and dynamic responses of the structure. This enables us to identify the damage by comparing the response data of the structure before and after damage. Based on this concept, various methods have been introduced to identify the damage in structural systems. One of the most widely used methods is that one based on using the strain energy of a structure [7,10–12].

Assuming that a 2D beam-column is divided into n elements, the strain energy stored by an element due to the axial deformation $u(x)$ and flexural deformation $v(x)$ can be expressed as:

$$SE_i = \frac{1}{2}\int_{x_j}^{x_{j+1}} EA(x)\left(\frac{du}{dx}\right)^2 dx + \frac{1}{2}\int_{x_j}^{x_{j+1}} EI(x)\left(\frac{d^2 v}{dx^2}\right)^2 dx, \quad (1)$$

where EA and EI are the axial and flexural rigidity; x is a distance measured along the length of the structure; also, x_j and x_{j+1} delimit the element j.

Hypothetically, the damage occurrence in a structure results in a reduction of the stiffness of the structure which leads to increasing the strain energy and therefore can be used as an efficient indicator for damage detection.

In many studies for determining the strain energy, mode shape vectors have been considered instead of common displacements (static data). The strain energy of a structure determined by mode shape vectors as dynamic data is usually referred to as modal strain energy (MSE) and has been considered as a valuable characteristic for damage identification. Using a matrix notation, the modal strain energy of a structural element for ith mode shape can be expressed as [10]:

$$MSE_i = \frac{1}{2}\varphi_i^{\mathrm{T}} \boldsymbol{K}^e \varphi_i, \quad (2)$$

where $\boldsymbol{K}^e$ is the stiffness matrix of the element and ϕ_i is the vector of corresponding nodal displacements of the element in mode i.

Although, the use of dynamic data for structural damage detection has shown its high efficiency in comparison with using the static data, however, extracting the dynamic information of a structure may be a very expensive process. Therefore, in this study a static data based damage indicator is proposed and its performance is assessed when comparing with a dynamic data based indicator provided in the literature [10].

3. The proposed static strain energy based damage indicator

In this study, an efficient indicator based on the change of static strain energy is presented to accurately site the flawed elements of a damaged structure using a static analysis. The static analysis is a tool to determine the nodal displacements and internal forces of a structure subjected to static loads. It has the mathematical form of

$$\mathbf{K}d = f, \quad (3)$$

where $\boldsymbol{K}$ is the total stiffness matrix of the structure, d is a nodal displacement vector and f is the vector of nodal loads.

Due to nodal displacements, in each element of the structure strain energy is stored. The strain energy of a structure due to static loads is termed here as static strain energy (SSE) and can be considered as a valuable parameter for damage identification. The SSE of eth element for ith load condition of the structure can be expressed as:

$$sse_i^e = \frac{1}{2} d_i^{e^{\mathrm{T}}} \boldsymbol{K}^e d_i^e, \quad i = 1, ., nl, \; e = 1, \ldots, nte, \quad (4)$$

where $\boldsymbol{K}^e$ is the stiffness matrix of eth element of the structure and d_i^e is the vector of corresponding nodal displacements of the element e in load condition i. The total static strain energy of ith load condition of the structure can also be determined by summation of SSE of all elements nte, given by

$$sse_i = \sum_{e=1}^{nte} sse_i^e, \quad i = 1, \ldots, nl. \quad (5)$$