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Application of genetic algorithm in crack detection of beam-like structures using a new cracked Euler–Bernoulli beam element

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ABSTRACT

In this paper, a crack identification approach is presented for detecting crack depth and location in beam-like structures. For this purpose, a new beam element with a single transverse edge crack, in arbitrary position of beam element with any depth, is developed. The crack is not physically modeled within the element, but its effect on the local flexibility of the element is considered by the modification of the element stiffness as a function of crack's depth and position. The development is based on a simplified model, where each crack is substituted by a corresponding linear rotational spring, connecting two adjacent elastic parts. The localized spring may be represented based on linear fracture mechanics theory. The components of the stiffness matrix for the cracked element are derived using the conjugate beam concept and Betti's theorem, and finally represented in closed-form expressions. The proposed beam element is efficiently employed for solving forward problem (i.e., to gain accurate natural frequencies of beam-like structures knowing the cracks' characteristics). To validate the proposed element, results obtained by new element are compared with two-dimensional (2D) finite element results as well as available experimental measurements. Moreover, by knowing the natural frequencies, an inverse problem is established in which the cracks location and depth are identified. In the inverse approach, an optimization problem based on the new beam element and genetic algorithms (GAs) is solved to search the solution. The proposed approach is verified through various examples on cracked beams with different damage scenarios. It is shown that the present algorithm is able to identify various crack configurations in a cracked beam.

1. Introduction

Existing cracks in structures present serious threats to suitable performance of structures. The material fatigue may be considered as the primary reason for the failure of structures. Therefore, the methods that may detect and localize the cracks in structures have been the theme of many researches available in the literature.

Computational and experimental studies have proved that the presence of cracks results in some changes in the vibration properties of these structures, mainly as the structures lose their original stiffness due to the presence of crack [1,2]. As a result, the monitoring of vibration properties changes over time may provide widely used nondestructive approaches for evaluating damage severities and computing the remaining structure life. Therefore, representation of reliable models for the mechanical behavior of cracked elements may play an important role in this relation.

A suitable mesh of finite elements may provide a detailed model of the crack and its surrounding zone. Many finite element analyses have been presented to simulate crack's initiation and propagation under applied loading (see for example [3,4]). The use of such methods usually requires re-meshing the crack tip region. In other words, these methods need considerable computational efforts to precisely model the stress singularity at the crack tip. Furthermore, the crack extension procedures are computationally time-consuming and difficult. For some applications on the other hand, the global behavior of a cracked structure is of principal importance, while the local behavior of the structure in the vicinity of the cracks' tip may be ignored. Inverse problems are samples of these applications, in which cracks' location and depth are needed when searching for potential cracks. In such applications, it is required to simulate the crack effects without actually modeling the crack itself. In this relation, different analytical methods have been applied to illustrate the dynamic behavior of cracked beams. One of the methods has modeled the crack by reducing the corresponding section modulus [5], while another one has reported a model, in which the cracked sections were replaced by a rotational spring [6]. Chondros et al. [7] have presented a complete

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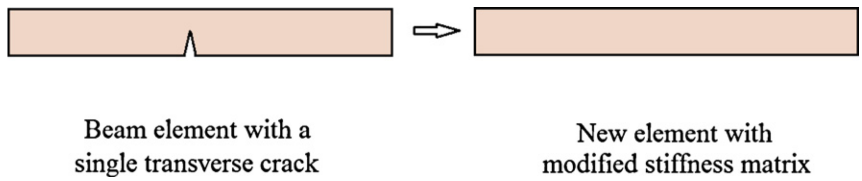

Fig. 1. Conceptual description of the new beam element with a single transverse crack: the crack is removed from the physical model with modifying the stiffness matrix.

vibration behavior of a cracked beam faced with single- or double-edge open cracks, in which the theory of fracture mechanics was used to describe the local flexibility of cracked section.

Various methods for solving crack identification problem were usually based on the variation of natural frequencies [8–10], measuring of dynamic flexibility [11], and comparison of mode shapes [12]. Among these crack identification methods, change of natural frequencies is more effective, inexpensive, and fast tool for non-destructive testing [8]. Comprehensive literature reviews are available in the field of structural damage detection [8,13,14] in which the vibratory behavior of beams with multiple cracks for forward [15–19] and inverse [20–24] problems are among the most important problems in the last two decades.

An inverse problem may be considered as the location and size detection of the beam's cracks. Actually, the conventional mathematically based methods (i.e., hard-computing methods) are not so efficient in solving inverse problems. Biologically inspired soft-computing methods are based on nature's problem-solving strategies. Soft-computing methods have capabilities which are appropriate for solving inverse problems in engineering [25]. Currently, these methods consist of evolutionary computational models (such as genetic algorithms) [26–28] and various neural networks [29–31] among others.

In this paper, an approach for crack detection of beam-like structures, based on a new macro beam element which includes single embedded transverse crack with any depth, is developed. In this element, the crack's effect is introduced by modifying the stiffness matrix of the element. The components of the stiffness matrix represented in closed-forms expressions are developed using the conjugate beam concept and Betti's theorem. The proposed macro element is used for obtaining natural frequencies and eigenvectors of the beam-like structures knowing the cracks' characteristics. For modeling beam-like structures with an arbitrary number of cracks, the required number of new macro element may be embedded easily. Afterwards, with knowing the natural frequencies and eigenvectors, an inverse problem is established, in which the cracks' location and depth are calculated. In the inverse approach, an optimization problem according to the new macro element and GAs is solved to search the solution. In this approach, the inverse problem is addressed as a minimization problem with the fitness function being the differences between the actual outputs and the relevant computed outputs from a candidate beam crack configuration. Using the available results of 2D finite element analysis as well as experimental data, some numerical examples are tested to verify the performance of the proposed algorithm.

2. New cracked finite element

Consider an Euler–Bernoulli beam element with a single- or double-sided open crack as depicted in Fig. 1. As shown in this figure, the presence of the crack is introduced by modifying the stiffness matrix of the element. In this method, the entire beam element is divided into two beam segments, and the crack position is considered as the separation point. It is also assumed that the cracks remain open during the analysis. Furthermore, we assume that the entire beam element has a uniform cross-section except at the crack section. The cracked section is modeled as a local flexibility, which may principally be assumed as a rotational mass-less spring.

The equivalent spring stiffness for a single-sided open crack based on the theory of fracture mechanics is given [32] as

$$K = \frac{Ewh^2}{72\pi f(\eta)}, \tag{1}$$

in which η represents a non-dimensional crack-depth ratio as

$$\eta = \frac{d}{h}, \tag{2}$$

where d is the crack depth, w represents the beam width, E is the modulus of elasticity, h denotes the beam depth, and

$$f(\eta) = \begin{array}{l} 0.6384\eta^2 - 1.035\eta^3 + 3.7201\eta^4 - 5.1773\eta^5 \\ +7.553\eta^6 - 7.332\eta^7 + 2.4909\eta^8 \end{array}. \tag{3}$$

Similar equations may be found in [32] for a double-sided open crack.

In this paper, for the beam element of length L, the crack is considered as rotational mass-less spring which connects two adjacent elastic sound/uncracked segments, whose moment of inertia are denoted by I (see Fig. 2). The spring is defined by its location, αL from the left end of the beam element, where α denotes non-dimensional crack position index ($0 \leq \alpha \leq 1$). The spring stiffness, K, is computed

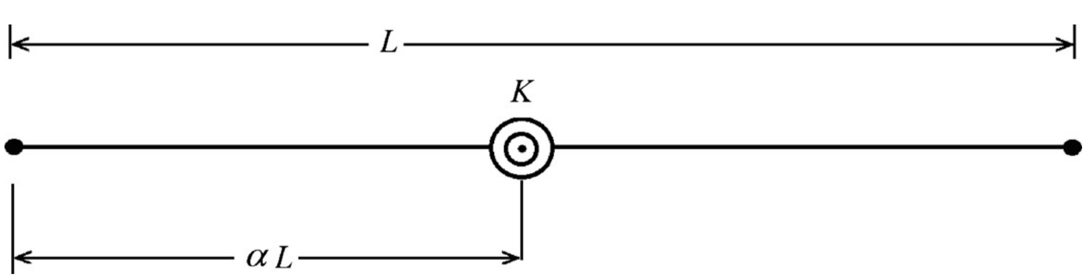

Fig. 2. The new beam element with a single transverse crack modeled by rotational mass-less spring.