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An effective computational approach based on XFEM and a novel three-step detection algorithm for multiple complex flaw clusters

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ABSTRACT

This paper presents an effective computational approach comprised of forward and inverse analyses for detection of multiple complex flaw clusters in elastic solids. A three-step detection strategy is introduced for inverse analysis, whereas extended finite element method (XFEM) is adopted for forward analysis. The use of XFEM is to avoid re-meshing during the change of flaw geometries. The three-step detection strategy involves: firstly, an optimization method that couples an improved discrete artificial bee colony algorithm and hierarchical clustering analysis (IDABC-HCA) is used to capture subdomains containing flaws with limited measure points in the global domain; secondly, additional measure points are introduced locally within each captured subdomain, where the number of flaws and the rough geometry of each flaw are quickly determined with the IDABC-HCA; finally, true geometries of flaws are obtained on the basis of the rough geometries by the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method. To save computational time, “Queue and Kill” method is proposed to actively identify and eliminate the improper candidate flaws and/or flaw clusters. Three numerical examples of multiple flaw detection that include simple and complex flaw geometries are analyzed. The results demonstrate that the proposed approach can effectively detect multiple complex flaw clusters without prior information of the flaw number.

1. Introduction

Flaws or defects such as cracks and voids greatly affect mechanical behavior of materials and performance of their structures and components. They are often the main sources that lead to critical failure and malfunction of such structures. In order to assess the reliability and durability of the structures, it is crucially important to identify flaws by using a nondestructive identification method. In the past decades, several experimentally nondestructive detection methods, such as ultrasonic testing, radiographic testing, laser scanning detection, image-based detection, acoustic emission, optical holography testing, and infrared detection, have been introduced and employed to identify flaws in structures [1–7]. However, an efficient method for accurate identification of flaws by means of the experimental approaches is still missing. It is challenging since many existing methods are limited to laboratory settings and specific flaw conditions, and some others are sometimes unable to provide accurate information of flaws including the locations, sizes, and shapes, as discussed in [8]. This paper is concerned with an effective computational approach comprised of forward and inverse algorithms, which is proposed to accurately detect multiple flaws in elastic solids.

Computational models can accurately identify variety of flaws under general settings, and the flaw detection methods based on numerical methods in terms of both forward and inverse analyses are increasingly attractive. Generally, in the forward analysis, the response of a system with flaws is predicted by an user-defined model; while in the inverse analysis, a set of parameters characterized flaw boundaries are determined by optimization techniques, in which the discrepancy between the measured and predicted responses are quantified by an object function. Solving such an inverse problem of flaw detection is performed iteratively where each iteration requires a forward solution with an updated flaw parameter set. The set of parameters characterized flaw boundaries varies during the iterative process towards a convergence, which is the best fit value as the simulated system response best matches the measurements. Therefore, the predicted flaw geometry in sim-

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ulated system continuously changes during the iterative process. This operation urgently requires re-meshing of the considered domain to create new meshes aligned with the flaw boundaries in the standard finite element method (FEM), which is a straightforward tool for the forward problem. In addition, solving inverse problem also requires tremendous number of iteration steps. Since the meshing procedure for complex flaw shape or multiple flaws is a highly time-consuming task, the re-meshing of structures in the optimization scheme becomes critical, and thereby, significant computational efforts are unavoidable. On the other hand, meshfree methods [9–12], which do not require re-meshing, have been coupled with optimization techniques and adopted in nondestructive evaluation applications to iteratively solve inverse problem [13]. Although meshfree methods are potential for some particular problems, their high computational cost generally restricts their applicability to practices. Boundary element method (BEM) can avoid costly re-meshing of the forward problem, so it is attractive in flaw identification problems [14–18]. However, applying BEM to arbitrary shapes of flaws is still challenging.

Extended finite element method (XFEM) is a powerful numerical method for discontinuities using the concept of enrichments, by which the geometry of discontinuities is independent of finite element mesh [19]. Hence, XFEM is becoming popular for forward analysis with arbitrary discontinuities. A large number of studies have been conducted to improve or apply the original XFEM for variety of engineering problems [20–35]. Particularly, XFEM has recently been coupled with optimization techniques to tackle flaw detection problems. Rabinovich et al. [36] developed a computational scheme based on a combination of XFEM and a genetic algorithm (GA), which successfully detects cracks in flat membranes subjected to static excitation. They later extended their scheme of crack detection to transient response of flat membranes subjected to a short-duration signal [37]. Waisman et al. [38] applied the XFEM-GA detection algorithm to analyze elastostatic problems with different types of flaws, and demonstrated the convergence robustness and accuracy under the conditions of substantial sensor numbers and sufficiently large flaws. For the detection of arbitrary flaw shapes, the XFEM-GA algorithm was then improved by Chatzi et al. [39], in which a new GA was introduced to accelerate the convergence of the scheme and alleviate the entrapment in local optima. Jung et al. [40] developed an identification procedure based on a gradient-type optimization method and dynamic XFEM to identify scatterers (e.g., cracks, voids, and inclusions) embedded in elastic heterogeneous media, and investigated various deployment patterns for multiple sensors to alleviate the potential manifestation of multiple solutions to the inverse problem. Their work was also extended to identify the location and arbitrary shape of single scatterer by defining internal boundaries with cubic splines [41]. For smart piezoelectric structures, Nanthakumar et al. [42,43] proposed a computational XFEM-multilevel coordinate search strategy and level sets to identify straight cracks, elliptical voids, and multiple voids.

Beyond the aforementioned XFEM-based schemes, Sun et al. [44] reported a new computational scheme based on the XFEM and an enhanced artificial bee colony (EABC) algorithm to detect and quantify multiple flaws in structures through a limited number of strain measurements. Since the EABC algorithm provides a robust, efficient, and fast way to solve the non-unique inverse problems without prior knowledge on the number of flaws, this algorithm further improves the XFEM-GA detection algorithms. A novel multiscale algorithm was then developed for nondestructive detection of multiple flaws in structures within an inverse problem typesetting [45]. The main idea of the multiscale algorithm is to employ a two-step optimization scheme, where rough flaw locations are firstly determined, and fine tuning is then applied in the localized subdomains to obtain global convergence towards the real flaws. A guided Bayesian inference approach for detection and quantification of multiple flaws in structures without prior knowledge on the number of flaws was described by Yan et al. [46]. In their work, the errors and measurement noises are explicitly considered, and the flaws are approximated by circular-shaped voids. More recently, Sun et al. [47] presented a sweeping window method for detecting multiple flaws with a dense arrangement of sensors using an explicit dynamic XFEM and absorbing boundary layers. The sweeping window method involves two phases, in which pre-analysis phase is used to identify the rough damage region, and post-analysis phase is for identification of the true flaws. Zhang et al. [48] combined Nelder–Mead and Quasi-Newton optimization methods and a dynamic XFEM to identify cracks, and their obtained results show that dynamic loads are more effective for crack detection problems compared to the static ones.

To emphasize the focus of the present study, a concept of ‘‘flaw cluster” is firstly introduced for a convenience in representation. The flaws, which are adjacent each other yet far from the others, are defined as a flaw cluster. A flaw cluster that contains only one flaw is regarded as a simple flaw cluster, while the others are complex flaw clusters. Although the problems that consist of several simple flaw clusters and/or one complex flaw cluster have been accomplished by several researchers [43–47,49], the existing methods however suffer disadvantages as they are not able to effectively detect multiple complex flaw clusters, i.e., hierarchy of flaws. The precise detection of multiple complex flaw clusters is still challenging, particularly for heterogeneous materials including widely-used concrete and metals, which inherently contain a large number of voids and cracks with complex cluster configurations. In addition, since many civil and mechanical structures built by such heterogeneous materials have large sizes, enormous number of sensors are required to detect multiple complex flaw clusters in such large structures by the existing methods. Therefore, it is crucially important to develop effective approaches for detection of multiple complex flaw clusters in large structures.

The main objective of the present study is to introduce a novel detection scheme particularly suitable for multiple complex flaw clusters in large structures. Unlike existing approaches, we develop a three-step optimization framework, which serves for the inverse analysis. The developed three-step approach is deceptively simple yet effective, and it is explained here. In the first step, each complex flaw cluster is quickly captured by a subdomain with limited measure points and iterations by employing a combination of an improved discrete artificial bee colony algorithm (IDABC) and the hierarchical clustering analysis (HCA), i.e., IDABC-HCA. In the second step, additional measure points are introduced locally into each captured subdomain; and the number of flaws and the rough flaw geometries are then determined by using the IDABC-HCA method and divide-and-conquer strategy. In the third step, based on these obtained flaw geometries, the Broyden–Fletcher–Goldfarb–Shanno (BFGS) method is then applied, which helps for a fast convergence to the true flaws. On the other hand, the XFEM is adopted in this work to deal with forward problem, which aims to dramatically alleviate the meshing cost and avoid the re-meshing during optimization process. In our XFEM scheme, both circular and elliptical enrichments are used for approximating arbitrary shapes of flaws.

Three numerical examples of multiple flaw detection that include simple and complex flaw geometries are analyzed. The proposed strategy can quickly capture the subdomains containing flaw clusters with a small quantity of sensors and accurately identify the true flaws by locally introducing additional sensors into the subdomains, and thereby, is effective. Hence, compared with the previous works, the new development can save a considerable number of iterations and sensors to achieve the same goal, and it