Flaw detection in concrete media using XFEM and an improved artificial fish swarm algorithm

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Abstract: A novel strategy is proposed in this paper for identifying and characterizing the irregular flaws in heterogeneous media. The optimization iterations are implemented by using the improved AFS algorithm and the corresponding forward analyses are solved by XFEM. A series of candidate sub-defects are employed to describe each flaw jointly. Each candidate is devised as a square void with the boundaries matched the XFEM meshes to avoid subdividing the enriched elements. The K-means cluster algorithm is utilized to narrow the searching space and output the number of flaws. A typical numerical example is conducted to demonstrate the proposed strategy. The result indicates that this strategy can identify the irregular flaw and it is potential to be applied in the evaluation of the civil and hydraulic structures.

1. Introduction
Detection of the internal flaws or damage regions hid in concrete is a fundamental part for ensuring the safety and reliability of structures [1]. In the process of structural monitoring, various non-destructive detection methods (e.g., ultrasound, radar imaging, laser scanning, infrared acquisition, etc.) have been extensively devised to track the locations, sizes, and shapes of flaws within structures [2-3]. While these techniques to roughly identify and quantify the properties of internal flaws have already been well developed, efficient and accurate reconstruction of flaws’ shape is an ongoing quest, especially for irregular flaws.

Thanks to the advantages of computational techniques, such flaws detection problems can also be devised as an inverse problem with a minimization/maximization process, wherein the objective functions correlate with the discrepancies between the measured and simulated responses (e.g., displacements, velocities, acceleration, etc.)[4]. XFEM is an attractive alternative for solving the discontinuous problem in flaw detection. Rabinovich et al. [5-6] utilized the combination of XFEM and the genetic algorithm (GA) to identify the cracks within flat membrane structures.Waisman et al. [7] and Chatzi et al. [8] employed the XFEM-GA combination to analyze regularly shaped flaws (e.g. straight crack, circular or elliptical void) in elastostatic problems, wherein the convergence robustness and accuracy were demonstrated. In the field of quantification of multiple flaws, Sun et al. [9] developed a quantified strategy via an additional parameter based on XFEM and an enhanced artificial bee colony (ABC) algorithm, wherein Nelder-Mead simplex accelerated the local convergence. A multiscale flaw detection scheme was presented later in [10] based on a discrete ABC algorithm and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method. Ma et al. [11] detailed the three-step optimization procedures by using a hierarchical...
clustering analysis (HCA). In addition, XFEM model-based schemes were also developed for flaw detection in heterogeneous medium [12] and piezoelectric structures [13]. Unfortunately, the shapes of flaws within civil and hydraulic structures are usually complex and irregular. While several studies were presented to track the irregular boundaries of flaws by splines, it is still an ongoing quest to describe the interfaces of the irregular flaw.

The aim of this paper is to present a two-step strategy for identifying and characterizing the irregular flaw in heterogeneous media based on the XFEM and an improved artificial fish swarm (AFS) algorithm. In this approach, the K-means cluster algorithm is utilized to narrow the searching space and output the number of flaws in Step 1. In Step 2, we employ a series of candidate sub-defects to describe each flaw jointly. The optimization iterations are completed by using the improved AFS algorithm and the corresponding forward analyses are solved by XFEM. A typical numerical experiment is employed to demonstrate the proposed approach.

2. Formulation of XFEM

Considering a linear elastic heterogeneous domain $\Omega \subset R^2$ with inclusions, voids and cracks, we employ XFEM to discretize the domain. The approximated displacement field $u^h$ in XFEM can be written as:

$$\begin{align*}
    u^h(x) &= \sum_{i \in I} N_i(x) u_i + \sum_{i \in I^e} N_i^e(x) \phi_i(x) a_i
\end{align*}$$

where $N_i$ and $N_i^e$ denote the shape functions. $u_i$ and $a_i$ represent the FEM displacement vector and additional nodal vector of the enriched DOFs, respectively. $I$ and $I^e$ are the corresponding sets of all nodes and the enriched nodes with the relation of $I^e \subset I$. $\phi_i(x)$ is the enrichment function.

In the two-dimension forward analysis of the heterogeneous media, several versions of enrichment functions in XFEM have been studied and demonstrated and the results indicated the enrichment functions away from the discontinuous interface needs to be a constant [14]. The enrichment function value for capturing inclusion is expressed via Eq. (2). The enrichment function seems like a ridge centered on the inclusion interface and has zero value on the elements that are not crossed by the interface.

$$\begin{align*}
    \phi_i(x) &= \sum_{i \in I} N_i^e(x) \phi_i - \sum_{i \in I} N_i^e(x) \phi_i
\end{align*}$$

In Eq. (2), $\phi_i$ denotes the level set function value of the enriched node. If the node lies inside the void $V(x) = 0$, and $V(x) = 1$ if the node is in the exterior of the void. In order to describe the discontinuities (e.g. cracks, voids, and inclusions), we assume that the crack is a narrow void and void is a soft inclusion. Thus, we obtain a unified form of the displacement field approximation in XFEM:

$$\begin{align*}
    u^h(x) &= \sum_{i \in I} N_i(x) u_i + \sum_{i \in I^e} N_i^e(x) \left[ \sum_{i \in I} N_i^e(x) \phi_i - \sum_{i \in I} N_i^e(x) \phi_i \right] a_i
\end{align*}$$

3. The improved artificial fish swarm algorithm

The artificial fish swarm (AFS) algorithm is a heuristic intelligence algorithm, which is inspired by the natural behavior of a fish swarm when searching for high quality food sources, and has been applied in the analysis of optimization problems [15]. The optimization procedure is defined as: foraging the best possible food source by the artificial fish swarm to satisfy the error criteria of the objective function. In order to make the sub-defects’ boundaries match the meshes, we modified the optimized strategies of the AFS algorithm. The initial candidates are generated as follows:
where $v_i$ is the $i$-th solution candidate of $v$, for $i=1,2,\ldots,np$, $np$ denotes the number of candidates. Each candidate is represented by a vector $v_i = \{v_{i1}, v_{i2}, \cdots, v_{in}\}$, where $m$ denotes the total number of parameters to be optimized. $\mu_i$ denotes a $m$-column random vector with the value distributed in $[0,1]$. $v_i^{\text{min}}$ and $v_i^{\text{max}}$ represent the lower and upper bounds of the candidate $v_i$ in the feasible space, respectively. $U_i$ is the mesh unit size and $[\ast]$ denotes the round function, for example $[2.3]_\text{int}=2$ and $[2.6]_\text{int}=3$.

The prey, swarm and follow phases of the improved AFS algorithm are performed according to the updating strategies of Eq. (5), Eq. (6) and Eq. (7) respectively as follows:

\begin{align}
v_i &= v_i + U_i \left[ 2 (\mu_i - 0.5) (v_k - v_i) U_i^{-1} \right]_\text{int} \\
v_i &= v_i + U_i \left[ 2 (\mu_i - 0.5) (v_c - v_i) U_i^{-1} \right]_\text{int} \\
v_i &= v_i + U_i \left[ 2 (\mu_i - 0.5) (v_b - v_i) U_i^{-1} \right]_\text{int}
\end{align}

where $v_k$ is a random neighborhood candidate of $v_i$, with $k \neq i$. $v_c$ and $v_b$ are the center and the current best candidates, respectively. The optimization is conducted to assess the qualities of candidates. Once a candidate can’t be improved after a given times of iterations, the random phase performs.

## 4. Flaw detection scheme

Herein, we utilize several candidate sub-defects to characterize the damage region or irregular flaw jointly. Each sub-defect is represented by a square void with three parameters $s_i = \{x_i, y_i, l_i\}$. The main advantage of this approach is that the enriched elements are not need to subdivide and calculate the enrichment integration by adjusting the defect boundary to match the mesh. The computational effort would be reduce significantly in the flaws iteration especially when the number of iteration step is tremendous. Such unknown parameters vector that used to track internal flaws can be writes as:

$$v = \{s_1, s_2, \cdots, s_n\}$$

where $n$ is the number of candidate sub-defects. The corresponding objective function defined as follows:

$$O(v) = \sum_{i=1}^{n} \|u^m - u^f(v)\|^{\frac{1}{p}}$$

The scheme of the flaw detection is devised into a two-step process. In Step 1, we generate the initial solutions and make the candidate sub-defects match the mesh via Eq. (4). The candidates are updated gradually by assessing the qualities via Eq. (9). A clustering analysis is conducted for the candidates by the K-means method. Then, we obtain a confidence interval of the potential flaws, as well as a narrowed searching space. In Step 2, the candidate sub-defects are regenerated in the narrowed space based on Step 1. Finally, the target flaws are captured by using the improved AFS algorithm and the shape is described by these sub-defects jointly.

## 5. Numerical example

In this section, we conduct a detection of three irregular flaws to demonstrate the performance of the proposed scheme based on the mesoscopic numerical model of concrete. The mesoscopic model is obtained from the CT slices of concrete specimens in laboratory. A 2D square plate with a length of 200 mm is considered as shown in Figure 1. The corresponding Young’s modulus and Poisson’s ratio are $E=2.2 \times 10^{10}$ Pa and $\nu=0.167$, respectively. This plate is simulated as a plane-stress problem with a uniform
mesh of 40×40 elements for the forward XFEM analysis. The bottom edge is restricted by rollers, while the top edge is drawn by a uniform pressure $P$. There are three irregular flaws within the structure. Numerical displacements of the plate with the target flaw are calculated to substitute the measured values in the detection problem, as shown in Figure 2. Twelve sensors are installed uniformly on the three edges to acquire the displacement response.

In the iterative process, a set of candidate sub-defects are initialized randomly within the parameter bounds of $x_i \in [20,180]$, $y_i \in [20,180]$ and $l_i \in [5,50]$. Figure 3 shows the typical snapshots of the detection process of the irregular flaw. The result indicates that the proposed detection strategy can yield good results. The irregular flaws can be captured by sub-defects jointly as the iterations proceed gradually. Figure 4 presents the convergence process for the detection problem of three irregular flaws. The final objective function value is $4.85 \times 10^{-4}$. 

Figure 3. Detection processes of three irregular flaws
6. Conclusions
This paper presents a novel strategy for identifying and characterizing the irregular flaw in heterogeneous media based on the XFEM and an improved artificial fish swarm (AFS) algorithm. The key idea is to employ a series of candidate sub-defects to describe each flaw jointly. Each candidate is represented by a square void to make the boundaries match the XFEM meshes. The computational effort would be reduce significantly in the flaws iteration especially when the number of iteration step is tremendous. The K-means cluster algorithm is utilized to narrow the searching space and output the number of flaws. The optimization iterations are completed by using the improved AFS algorithm and the corresponding forward analyses are solved by XFEM. A typical numerical experiment is employed to demonstrate the proposed approach. The result indicates that the proposed detection strategy can identify the irregular flaw and it is potential to be applied in the evaluation of the civil and hydraulic structures.

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