Crack identification with combined numerical simulation-intelligent optimization algorithms: a brief summary

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Abstract: Crack identification in structures is a typical inverse analysis problem, which is very crucial for the reliability evaluation of various structures. In recent years, the rapid development of numerical technologies and artificial intelligence algorithms has provided a new way for crack detection. Numerical methods are used as the forward analysis tools to solve crack problems, while intelligent optimization approaches are applied to identify crack geometries based on the data collected by forward modeling. In this paper, the research status of crack identification, with the combined typical computational tools and well-known intelligent optimization schemes, is briefly summarized.

1. Introduction
All kinds of engineering structures inevitably have cracks, holes and other defects due to the influence of many factors, such as construction quality, applied load and temperature change (Figure 1 shows some common defects in typical concrete structures). As a representative type of defect, the existence and evolution of cracks will lead to the decrease of structural bearing capacity, the degradation of serviceability and durability, and even lead to more serious consequences such as collapse, endangering the safety of life and property. Therefore, it is of great significance to detect and identify cracks in various structures quickly and accurately.

(a) Cracks at the bottom of a bridge (b) Localized voids in a column
Figure 1. Typical defects in concrete structures (pictures from internet)

Crack identification in structures is a typical inverse analysis problem to quantify crack geometries such as the location, size and type of cracks. At present, the most frequently adopted crack identification methods include manual detection technology, ultrasonic detection technology and image recognition technology, but these methods have some limitations. For example, manual detection technology is laborious and inefficient; ultrasonic detection technology will lead to inaccurate measurement under high temperature, and the image recognition method is easily affected by the environment.

In recent years, the rapid development of numerical technologies and intelligent optimization (IO) schemes provides a new way for crack detection and identification. In the collaborative numerical
modeling–IO approaches, the numerical methods are developed to perform forward crack simulation, upon which the required data is obtained and then used in the IO algorithm to further identify the crack configuration. In the following, we will give a brief review on the research status of representative numerical methods and IO schemes for crack modeling and identification.

2. Brief research status of numerical methods and IO schemes for crack modeling and detection

Theoretically, falling into the catalogue of inverse analysis, crack detection using numerical tools and IO schemes mainly includes two parts, i.e., forward analysis of cracked structures to obtain sampling data for IO and objective function minimization to identify crack geometries. In this section, a brief introduction to typical numerical methods for crack modeling is firstly presented; then, the widely adopted IO methods are given; finally, the applications of combined numerical tools and IO approaches for crack identification are described.

2.1. Typical numerical methods for crack modeling

2.1.1 Finite Element Method. The finite element method (FEM) originated in 1940, and its essence is to approximately transform the analysis of the continua into the study of finite elements through the discretization ideas. The merits of the FEM mainly contain: (1) suitable for problems with arbitrary geometric shapes and boundary conditions, materials/geometric nonlinearity; (2) easy coding and widely packed in many commercial software. However, the FEM also has some inherent defects for crack modeling. For example: (1) the finite elements must be consistent with the crack geometry, double nodes are necessary in crack discretization and very fine mesh is demanded around crack tips (see Figure 2(a)); (2) local remeshing around crack tips is required in crack propagation simulations. With the FEM, Fang et al.[2] proposed a coupling method of the state-based peridynamics and the FEM for crack propagation. Wang et al.[3] calculated the mesh stiffness of spur gear pairs with crack using the hybrid analytical-FEM approach.

2.1.2 Boundary Element Method. The boundary element method (BEM) was developed after the FEM. The outstanding advantages of the BEM include: (1) only the domain boundary needs to be discretized which can reduce the problem dimension and improve the solution efficiency; (2) the use of fundamental solution can ensure the accuracy of physical fields and their derivatives. However, there are also some difficulties in crack simulation with the BEM, e.g.: (1) conforming elements with the crack faces and bi-nodes are also required; besides, remeshing is necessary for propagating crack (see Figure 2(b)); (2) fundamental solution of the problem must be obtained, which is very complicated for nonlinear crack problems. Xie et al.[4] proposed a group of quadrilateral and triangular incompatible crack front elements for BEM to solve 3D crack problems. Mrose et al.[5] used the dual BEM for statistical inference of the equivalent initial flaw size in assembled plate structures.

2.1.3 Meshless Methods. In the meshless methods (MM), the approximate function is constructed based on a series of discrete points. Their major advantages are: (1) they are very suitable for complex problems involving large deformation and high gradients; (2) no elements are required in discretization and remeshing can be avoided for crack path tracking (see Figure 2(c)). However, they also have some disadvantages in crack simulation, e.g., (1) special criterion should be used to reflect the existence of crack; (2) there are some bottlenecks in numerical integration, boundary condition treatment and solution efficiency. Belytschko et al.[7] applied the element-free Galerkin method, a representative of MM, to simulate dynamic crack growth. Shao et al.[8] proposed a meshless method for 3D crack propagation based on phase field model.

2.1.4 Extended Finite Element Method. The extended finite element method (XFEM) was proposed by Belytschko and Black[9] in 1999. The XFEM is a neo-numerical method developed based on the standard FEM and very powerful in discontinuous analysis. The superiorities of the XFEM for crack problems mainly lie in: (1) the mesh can be independent of the crack geometry and therefore crack
growth trajectory can be captured without remeshing (see Figure 2(d)); (2) high accuracy can be achieved on coarse mesh due to the use of crack tip enrichment functions. However, when modeling multiple-branched and intersecting cracks, the determination of jump functions in the XFEM is relatively complex. Li et al.[10] introduced the basic theory and implementation steps of XFEM and also its application in crack problems. Surendran et al.[11] adopted the XFEM to study fatigue crack growth.

![Figure 2. Typical discretization of cracked domain by the FEM, BEM, MM and XFEM](image)

2.2. **Representative intelligent optimization algorithms**

2.2.1 **Genetic Algorithm.** Genetic algorithm (GA) is a global probabilistic search method that combines biology, computer science and artificial intelligence. Its basic principle can be summed up by “the survival of the fittest”, which means that the good individuals are retained and the bad individuals are eliminated. After continuous updating, the final results will gradually approach the optimal results. The main advantages of GA are as follows: (1) it is suitable for complex optimization problems, and the global optimal solution of the optimization problem can be obtained; (2) the algorithm is independent of the solution domain; (3) it possesses strong robustness. The main shortcomings include slow convergence speed, poor local search ability and many control variables. Shen et al.[12] used GA to identify cracks in plane frame structures. Wu[13] put forward the basic idea of bridge structural health monitoring system based on GA and neural network.

2.2.2 **Particle Swarm Optimization.** Different from GA, the particle swarm optimization (PSO) algorithm modifies the individual action strategy through the information sharing among groups and the summary of individual experience, and finally finds the optimal region in the complex search space. PSO has the advantages of easy to understand, easy to code, fewer parameters and faster convergence. But it also has some disadvantages, such as low precision and easy divergence. Abolbashari et al.[14] analyzed and identified multiple cracks of FGB based on PSO and neural network. Li et al.[15] used the laser scanning of PSO neural network to quantitatively evaluate the depth of surface crack.

2.2.3 **Artificial Bee Colony algorithm.** Artificial bee colony algorithm (ABC) is a novel global optimization algorithm based on swarm intelligence proposed by Karaboga and Basturk[16]. It was inspired by the bee colony through the individual division of labor and information exchange and cooperation to complete the task of honey collection. The advantages of the ABC algorithm are mainly reflected in the following points: (1) multi-role division mechanism; (2) cooperative work mechanism; (3) simple operation, few control parameters, high search accuracy and strong robustness. However, the result of this algorithm is limited to the local optimal solution rather than the global optimal solution, and the intermediate stagnation problem is easy to occur in the working process. K.J et al.[17] applied the ABC to the combinatorial optimization of truss structure. Ding et al.[18] proposed an improved ABC
and used it to identify cracks in beam structures.

2.2.4 BP Neural Network. The error-back-propagation (BP) neural network was proposed by the scientific team of Rumelhart and Mcelland [19]. It is a multilayer feedforward network with signal forward propagation and error reverse transmission, and it is also one of the most widely used neural network models at present. It is a neural network composed of an input layer, one or more hidden layers and an output layer. BP neural network has strong nonlinear mapping ability, self-learning and adaptive ability, generalization and fault tolerance ability, and also have the advantages of simple structure, stable working state, easy hardware implementation and so on. Its defects mainly cover: (1) easy to fall into local minimization; (2) slow convergence speed; (3) accuracy sensitive to the network structure. Zhao [19] analyzed the evolution law of fatigue crack based on GA-BP neural network. Wang et al. [20] used GA-BP neural network to characterize the cracks in ferromagnetic steel.

2.3. Crack identification based on collaborative numerical analysis-intelligent optimization method

With the successful application and rapid development of artificial intelligence technology, many scholars have combined IO algorithms with numerical analysis methods to identify cracks. Zhang et al. [21] proposed a quantitative crack identification method based on multivariate wavelet FEM and PSO. Hattori and Saez [22] took neural network, self-organization algorithm and BEM to identify cracks in magnetoelastic materials. Rabinovich et al. [23] used XFEM and GA algorithm to obtain the time information of the input signal arriving at the measuring point to identify the cracks in the structure. Wang et al. [24] constructed a defect back analysis model using the XFEM and GA. Khatir and Wahab [25] combined XFEM and extended isogeometric analysis method with the PSO and Jaya algorithm to predict crack location. Jiang and Du [26] utilized the XFEM and ABC algorithm to establish the back analysis model of internal defects (inclusions) and cracks. Sun et al. [27] proposed a multi defect detection method based on dynamic XFEM and improved ABC.

3. Discussion and conclusions

In this paper, we briefly presented the applications of typical numerical methods and intelligent optimization algorithms in crack modeling and identification. For more elegant comparison, the advantages and disadvantages of the associated numerical approaches and IO schemes are, respectively, summarized in Table 1 and Table 2.

### Table 1 Advantages and disadvantages of numerical methods for crack modeling

| Methods | Advantages | Disadvantages |
|---------|------------|---------------|
| FEM | Suitable for problems with complex geometric shapes and boundary conditions, materials/geometric nonlinearity. | Required conforming elements with the crack faces; required remeshing for crack evolution; demanded fine mesh around crack tip. |
| BEM | Low solution cost and high accuracy. | Remeshing and fundamental solutions are required. |
| MM | No elements; without remeshing when tracking crack path; suitable for large deformation and high gradients problems. | Required special criterion to represent cracks; bottlenecks in numerical integration and boundary condition treatment; high computational cost. |
| XFEM | Non-conforming meshes permitted; high accuracy on coarse mesh. | Troublesome determination of jump functions for multiple-branched and intersecting cracks modeling. |

### Table 2 Advantages and disadvantages of IO algorithms

| Algorithm | Advantages | Disadvantages |
|-----------|------------|---------------|
| GA | Suitable for complex optimization problems; can obtain global optimal solution; independent of the search ability; many control | Slow convergence speed; poor local search ability; many control |


solution domain; strong robustness. variables.

PSO Easy to understand; easy to code; few parameters; fast convergence. Low precision; easy divergence.

ABC Multi-role division mechanism; cooperative work mechanism; simple operation; few control parameters; high search accuracy; strong robustness. Local optimum solution; easy to produce intermediate stagnation problem.

BP Strong nonlinear mapping ability; self-learning and adaptive ability; powerful generalization and fault tolerance ability. Easy to fall into local stagnation; slow convergence speed; accuracy sensitive to the network structure.

From Table 1 and 2, we can find that each numerical method/IO scheme has its own merits and defects. Although the combined numerical tools-IO algorithms have been widely applied in crack identification, there are still many issues to be further resolved, from the aspects of accuracy, efficiency, robustness, etc. For example:

(1) More advanced numerical tools are expected to perform forward crack modeling in complex engineering problems. For this purpose, the coupling of the existing approaches (e.g., coupling of the BEM and XFEM for crack simulation in semi-infinite space) may be a solution.

(2) More meticulous studies on the application scope of existing IO schemes are demanded. On these grounds, the combinations of different schemes (e.g., combined GA-BP algorithm) may be excellent keys to optimal crack detection. Besides, the development of new schemes with higher accuracy, efficiency and robustness is also crucial and urgent.

(3) The seamless and smart coordination among the numerical methods and the IO schemes should be further investigated to improve the self-adaption ability of the identification process.

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References
[1] Amit, K.C., Kim, J.H. (2008) Interaction integrals for thermal fracture of functionally graded materials. Eng. Fract. Mech., 75(8): 2542-2565.
[2] Fang, G., Liu, S., Fu, M., et al. (2019) A method to couple state-based peridynamics and finite element method for crack propagation problem. Mech. Res. Commun., 95: 89-95.
[3] Wang, Q., Chen, K., Bo, Z., et al. (2018) An analytical-finite-element method for calculating mesh stiffness of spur gear pairs with complicated foundation and crack. Eng. Fail. Anal., 94: 339-353.
[4] Xie, G., Zhou, F., Li, H., et al. (2019) A family of non-conforming crack front elements of quadrilateral and triangular types for 3D crack problems using the boundary element method. Front. Mech. Eng-Pre., 14(3): 332-341.
[5] Morse, L., Khodaei, Z.S., Aliabadi, M.H. (2020) Statistical inference of the equivalent initial flaw size for assembled plate structures with the dual boundary element method. Eng. Fract. Mech., 238: 107271: 1-23.
[6] Memari, A., Azar, M.R.K. (2018) Quick and robust meshless analysis of cracked body with coupled generalized hyperbolic thermo-elasticity formulation. Eng. Anal. Bound. Elem., 90: 47-62.
[7] Belytschko, T., Organ, D., Gerlach, C. (2000) Element-free Galerkin methods for dynamic fracture in concrete. Comput. Method Appl. M., 187(3): 385-399.
[8] Shao, Y.L., Duan, Q.L., Qiu, S.S. (2020) Consistent element-free Galerkin method for three-dimensional crack propagation based on a phase-field model. Comput. Mater. Sci., 179: 109694: 1-18.
[9] Belytschko, T., Black, T. (1999) Elastic crack growth in finite elements with minimal remeshing.
[10] Li, L.X., Wang, T.J. (2005) Extended finite element method (XFEM) and its application. Adv. Mech., 35(01): 5-20. (in Chinese)

[11] Surendran, M., Natarajan, S., Palani, G.S., et al. (2019) Linear smoothed extended finite element method for fatigue crack growth simulations. Eng. Fract. Mech., 206(1): 551-564.

[12] Shen, C.W., Tang, X.B., Yu, K.B. (2000) Genetic Algorithms for Identifying Cracks in Planar Rigid Frame Structures by Frequency. Acta Mech. Solid Sin., 21(01): 79-84. (in Chinese)

[13] Wu D.H. Research on Bridge Structural Health Monitoring System Based on Genetic Algorithms and Neural Networks. Doctoral thesis, Journal of Southwest Jiaotong University, 2003. (in Chinese)

[14] Abolbashari, M.H., Nazari, F., Rad, J.S. (2014) A multi-crack effects analysis and crack identification in functionally graded beams using particle swarm optimization algorithm and artificial neural network. Struct. Eng. Mech., 51(2): 299-313.

[15] Li, K., Ma, Z., Fu, P., et al. (2018) Quantitative evaluation of surface crack depth with a scanning laser source based on particle swarm optimization-neural network. NDT E Int., 98: 208-214.

[16] Karaboga, D., Basturk, B. (2007) A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. J. Global Optim., 39(3): 459-471.

[17] K.J, J.F., Celal, O., Wang, D., et al. (2021) Sizing and layout optimization of truss structures with artificial bee colony algorithm. Structures, 30: 546-559.

[18] Ding, Z., Lu, Z., Huang, M., et al. (2016) Improved artificial bee colony algorithm for crack identification in beam using natural frequencies only. Inverse Probl. Sci. En., 25(2): 218-238.

[19] Zhao Z.H. Analysis of fatigue short crack evolution law based on genetic algorithm-BP neural network method. Master’s thesis, Journal of Dalian University of Technology, 2011. (in Chinese)

[20] Wang, Z., Fei, Y., Ye, P., et al. (2020) Crack characterization in ferromagnetic steels by pulsed eddy current technique based on GA-BP neural network model. J. Magn. Mater., 500: 166412: 1-9.

[21] Zhang, X.W., Gao, R.X., Yan, R.Q., et al. (2016) Multivariable wavelet finite element-based vibration model for quantitative crack identification by using particle swarm optimization. J. Sound Vib., 375: 200-216.

[22] Hattori, G., Saez, A. (2013) Crack identification in magnetoelctroelastic materials using neural networks, self-organizing algorithms and boundary element method. Comput. Struct., 125: 187-199.

[23] Rabinovich, D., Dan, G., Vigdergauz, S. (2010) Crack identification by 'arrival time' using XFEM and a genetic algorithm. Int. J. Numer. Meth. Eng., 77(3): 337-359.

[24] Wang, J.P., Du, C.B., Jiang, S.Y. (2017) Analysis of structural defect inversion based on extended finite element and genetic algorithm. J. Eng. Mech., 39(06): 591-596. (in Chinese)

[25] Khatir, S., Wahab, M.A. (2019) A computational approach for crack identification in plate structures using XFEM, XIGA, PSO and Jaya algorithm. Theor. Appl. Fract. Mech., 103: 102240: 1-12.

[26] Jiang, S.Y., Du, C.B. (2015) Back analysis model of internal defects (inclusions) based on extended finite element method. J. Theor. App. Mech-Pol., 47(06): 1037-1045. (in Chinese)

[27] Sun, H., Waisman, H., Betti, R. (2013) Nondestructive identification of multiple flaws using XFEM and a topologically adapting artificial bee colony algorithm. Int. J. Numer. Meth. Eng., 95(10): 871-900.