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RESEARCH ARTICLE

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Damage identification of a large-span concrete cable-stayed bridge based on genetic algorithm

Abstract The global stability of a structure, the stiffness of its main girder and concrete tower, and the variation of the forces of its stay cables are key issues to the safety assessment of an in-service cable-stayed bridge. The efficiency and rationality of local elaborate non-damage-identification could be enhanced by the primary damage identification of cable-stayed bridges on the basis of periodic detection of the cable force and strain monitor in key sections of the main girder. The genetic algorithms of damage identification for cable-stayed bridges were investigated in this paper on the basis of the monitor data of the cable force and strain in a key section of the main girder. A damage detection program for complex civil structure was generated to implement the identification of damage location and extent. The deterioration of the structure was calculated according to the variation of monitor data. It is demonstrated that the results of damage identification from the parametric finite element method are accurate. The method had been verified using a long-span concrete cable-stayed bridge in Ningbo, which has been in use for the past four years.

Keywords damage detection, model updating, genetic algorithms, periodic inspection, large-span cable-stayed bridge

1 Introduction

Parameter identification is the inverse problem in mathematics. Several accurate finite element models have been proposed to solve the problem. A comprehensive survey on the model updating techniques can be found in the works of Mottershead [1] and Natke et al. [2]. A literature review on the finite-element model updating techniques and their applications to damage detection and structural health monitoring can also be found in the work of Doebling, et al. [3]. The representative methods to resolve it are the optimal matrix updating method, the eng-structure assignment method, the eng-sensitivity based method, the neural networks based method, etc. These methods can be classified as non-parametric methods and parametric methods. Non-parametric methods update the model via the direct use of such system matrices, such as stiffness and mass matrices, which are not suitable for large-scale civil structures and the results usually may lose the physical meaning. Parametric methods use a pre-selected set of parameters of the materials, cross sections and structural dimensions, to define the model of the structure in question and the assumed damage mechanisms and their potential location, which are the most promising methods for model updating and damage detection for large-scale bridges.

The effectiveness of some of these techniques has been verified on simple structures such as simply supported beams, cantilever beams, and space truss structures. Recently, the civil engineering community has begun to apply model updating technique. For example, Cantieni investigated the model updating of a concrete arch bridge, while Pavic et al. [4] and Reynolds et al. [5] have been applying the technique to footbridges and concrete floors, and applications to cable-supported bridges have been reported by Brownjohn and Xia [6,7], Zhang [8], and Xu [9]. For a complex structure with large degrees of freedom, such as large-scale bridges, model updating becomes difficult, because it may inevitably involve uncertainties in many parameters, e.g. material and geometrical properties, and boundary conditions. The existing research generally aims at the “little errors model updating” of new construction bridges, and the study on the “large errors model updating” of existing bridges for damage detection is very scarce.

Recently, genetic algorithm (GA) is applied to model updating and damage detection in civil engineering. Unlike the mathematical methods, one of the important characteristics of GA is its effectiveness and robustness in coping with uncertainty, insufficient information, and noise. Furthermore,

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GA uses multiple points to search for the solution rather than a single point in the traditional gradient based optimization method.

Several studies have applied GA successfully in the damage detection and identification in civil engineering. The representative studied have been carried out by Mares and Surace [10], Firswell et al. [11], Hao et al. [12], Chou et al. [13], Rao et al. [14], Ma et al. [15], Yi et al. [16], etc. Otherwise, there is a long way from theoretical deduction to practice in real engineering. The difficulties are as follows:

1) in the parametric analysis of GA in practical structures, we usually carry out the parametric analysis to gain the appropriate parameters of genetic algorithms operators;

2) the module for fitness resolution is not suitable for all sorts of structures. Generally, a specified finite element program code is used to implement the structure analysis, which leads to low efficiency in practical application;

3) several types of measured response must be combined to the analysis for practical health monitoring and damage detection, and sometimes different types of system parameters, such as load patterns and structural parameters, need be identified; whereas, the available methods in existing literatures use simple measured response.

To conquer the difficulties listed above, the genetic algorithm with real encoding number is applied in the structural damage identification analysis, and the damage detection program is developed in this study. The algorithm is used for damage identification of cable-stayed bridges on the basis of the monitor data of the cable force and strain in essential sections of the main girder. The proposed method and program are verified by using an existing long-span concrete cable-stayed bridge in Ningbo, China.

2 Methodologies and implementation

2.1 Real-coded genetic algorithm

Genetic algorithm can be described as search algorithms on the basis of the mechanics of natural selection and natural genetics. They belong to a category of stochastic search methods, with an additional strength that randomized search is conducted in those regions of the design space which offer the most significant potential for gain. The primary reference on the topic is Holland's "adaption in natural and artificial systems". With focus to structural optimization, the paper by Hajela [17] gives a good introduction.

Genetic algorithm is not severely limited by discontinuous design spaces, like techniques derived from mathematical programming principles. On the other side, there is usually a stiff computational requirement associated with the use of GA. Therefore, genetic algorithms represent a good solution approach for design problems where standard techniques are inefficient. The main advantages of GA can be formulated as follows:

1) GA does not require function derivatives;

2) GA proceeds from several points in the design space. It is easier to find global optima;

3) GA works on a coding of the design variables. This allows them to work in design spaces consisting of a mix of continuous, discrete, and integer variables.

Genetic algorithm is based on principles of evolutionary theory, such as natural selection and evolution. Mares and Surace [10] and Friswell et al. [11] briefly introduced binary-coded GA in their respective papers on applying GA in structural damage identification. In this paper, for real number encoding had been used, only a real-coded GA is briefly introduced.

In GA, the term chromosome typically refers to a candidate solution to a defined problem, and fitness is the objective function value of the candidate solution. The component of a chromosome is named the gene. Most GA starts with an initial randomly generated population of n chromosomes, namely, $x_1, x_2, \dots, x_n$. The size of the population is generally related to the problem under consideration. The length of each chromosome is the dimension of the solution space, for example, $\boldsymbol{x}_i = [x_{i1}, x_{i2}, \dots, x_{im}]$, where x_{i1} is the first gene of the chromosome, etc. Then, the calculation of the fitness $f(x)$ of each chromosome x in the population, or called evaluation, is performed. The Darwinian principles of reproduction, survival of the fittest, crossover, and mutation are used to create a new offspring population (generation).

Reproduction is a process in which individual chromosomes are copied into the population according to their fitness. It indicates that chromosomes with a higher fitness have a higher probability to survive in the next generation. However, this may result in some undesirable properties. For example, in the first few generations, it is possible for a few highly fit individuals to dominate the selection process, and this can lead to premature convergence. In the later generations, the population of average fitness may be close to the population of maximum fitness; therefore, all individuals have nearly the same probability to survive, and this leads to a random search behavior. In both cases, scaling of the fitness function, usually linear scaling, must be utilized.

Crossover is to select parent chromosomes randomly and cross over their genes at a randomly chosen point to form two offspring. For example, suppose that two parents (with m genes) are $\boldsymbol{x}_i = [x_{i1}, x_{i2}, \dots, x_{im}]$ and $\boldsymbol{x}_j = [x_{j1}, x_{j2}, \dots, x_{jm}]$. If they are crossed after the kth position (this is named one point crossover), the resulting offspring are

$$\boldsymbol{x}_i' = \left[x_{i1}, x_{i2}, \cdots, x_{ik}, x_{j(k+1)}, \cdots, x_{jm} \right] \tag{1}$$

$$\boldsymbol{x}_j' = \left[x_{j1}, x_{j2}, \cdots, x_{jk}, x_{i(k+1)}, \cdots, x_{im} \right] \tag{2}$$

Normally the crossover is implemented with a probability p_c (crossover probability). If no crossover takes place, the two offspring are exact copies of their respective parents.

The final operation is that of mutation, which simply replaces a gene in a chromosome with one chosen randomly from the solution space. Mutation is needed because the operations of reproduction and crossover occasionally may lose some potentially useful information, and the mutation operator helps protect against this. The frequency of mutation is usually very small; that is, the mutation probability is small. Following reproduction, crossover and mutation, we can now evaluate the new generation and typically iterate the process for many generations.

The simple procedure just described is the basis for most applications of GA. It must be noted that many amendments could be made for different problems in several respects. As for code form, Gray code is one variation of binary encoding especially for function optimization. There is a movement towards integer encoding for combinatorial optimization problems in recent years, and real number encoding for continuous optimization problems is described in this paper.

2.2 Damage identification based on GA

The flowchart for structural damage identification using GA is shown in the Fig. 1. The measurements for fitness evaluation include modal responses, such as modal frequencies, modal shapes, modal curvatures, etc., and static responses, such as static strain, displacement, load, etc., in actual application.

2.3 Damage detection

The GA toolbox of Matlab was used to develop the genetic algorithms here, the m-files in Matlab were translated into the format of C++, and were compiled in visual C++, integrating the developing environment through Mideva, which was developed by Mathtools Corporation. The program can run independently without the Matlab engine. The modules of the present damage identification program are illustrated as Fig. 2.

The present damage detection program is implemented by doing mixed-language programming in Visual C++6.0, integrating Matlab language and standard ANSYS parametric design language. The fitness value of GA individuals is evaluated by the finite element software ANSYS, which makes the program apply to all sorts of large-scale civil structures.

The program with a friendly interface makes the user resolve the problems of structural model updating and damage

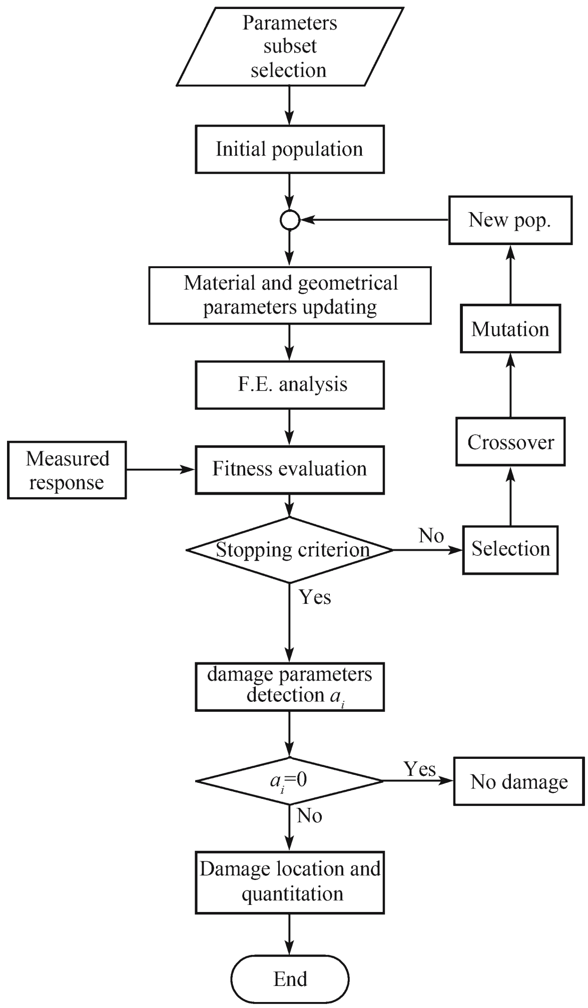

Fig. 1 Flowchart for identification of structural damage using GA

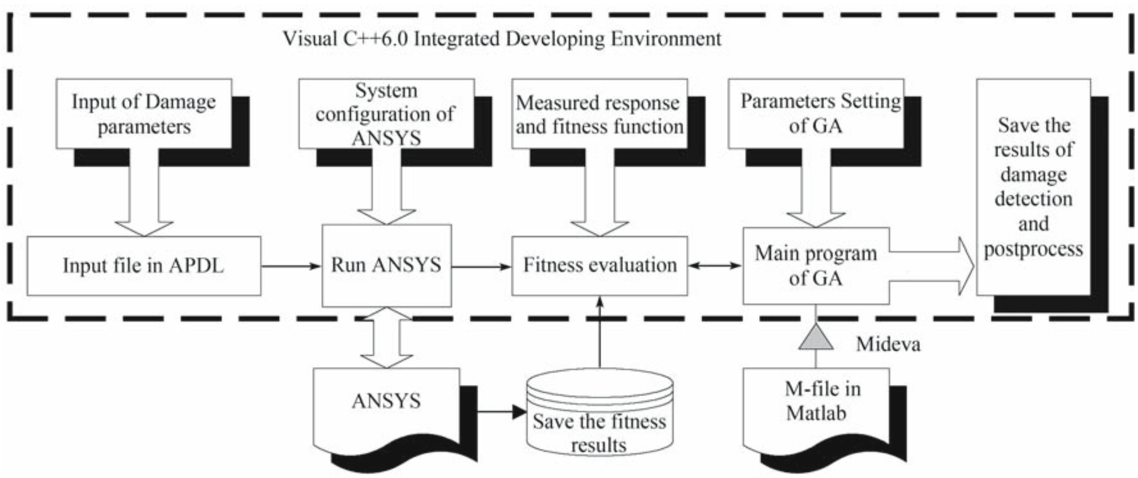

Fig. 2 Framework of the damage identification program

detection without understanding the detailed algorithms. The users can select effective operator and key parameters of GA according to the engineering skill and parameter study through the friendly user interface of the program. Operators and coding methods can be set by users on the basis of the practical structures.

3 Simulation

3.1 Description of Zhaobaoshan large-span cable-stayed bridge

Zhangbaosh (ZBS) Bridge is located on the entrance of Yong River at the Eastern Sea of Ningbo, crossing mountain Zhaobao in district Zhenhai and mountain Jinji in district Beilun. The ZBS Bridge is a single-tower and double-cable plane pre-stressed concrete cable-stayed bridge with a cooperative system, and its main span is 258 meters in length. The main tower is 148.4 meters in height. There are 25 pairs of double cable arrangements upstream and downstream, and there are six traffic lanes. The representative deck cross section is a single chamber and a double open concrete box girder 29.5 m wide and 2.5 m high. A severe engineering accident of a girder being destroyed happened in 1996 during construction of ZBS cable-stayed bridge. The destroyed segments of the girder were rehabilitated after being removed, and the reserved segments of the girder were strengthened. The ZBS Bridge opened to traffic on June 8, 2001. The general view of ZBS cable-stayed bridge is illustrated in Fig. 3.

In the past, damage detection on the basis of modal response has been studied by many researchers, and the response includes the mode frequencies and mode shapes. From the mode shapes, the following indexes are deduced: mode curvatures, mode strain, modal assurance criterion (MAC), co-ordinate modal assurance criterion (COMAC), etc. In real large-span bridges, however, the damage detection methods on the basis of modal response have many difficulties, that is, the mode frequencies vary in confined range. Especially, the former ten mode frequencies are less than 1.5–2 Hz, which makes it is very difficult to distinguish the signal due to structural deterioration from noise in the measured response. On the other hand, the measured degrees of freedom are much less than the real degrees of freedom, and the mode expanding or model reduction need be carried out.

In recent years, the static response of structures under dead load is introduced to damage identification by many researchers due to the advantages of higher precision and higher stability in measurement. Many researchers use the static response to detection the damage of simple structures.

In this study, static responses, such as the cable force, displacement and strain in the key sections of the main girder of ZBS Bridge, which had been tested in periodic inspections, were employed for detecting the structural damage. The damage detection program for complex civil structures developed above can be used to implement the identification of damage location and damage extent. Then, local elaborate non-damage-identification can be used to identify the detailed deterioration on the bridge.

3.2 Periodic inspection of ZBS Bridge

For identifying the damage emerging in the girder of ZBS Bridge, a project of three-year periodic inspection and health monitoring during operation period is carried out by the author's research group.

The stresses of girder, cable forces, displacements, cracks in concrete of the girder, and external cables in pre-stressed concrete girder are acquired by the researchers, and the variance of the strain and the displacement in key sections of the main girder, and the variance of cable force between the inspections were applied to construct the fitness function of genetic algorithms with the damage detection program above. The displacements of the main girder and main tower are measured by a total station instrument. The cable forces are tested by using the method of ambient vibration technique.

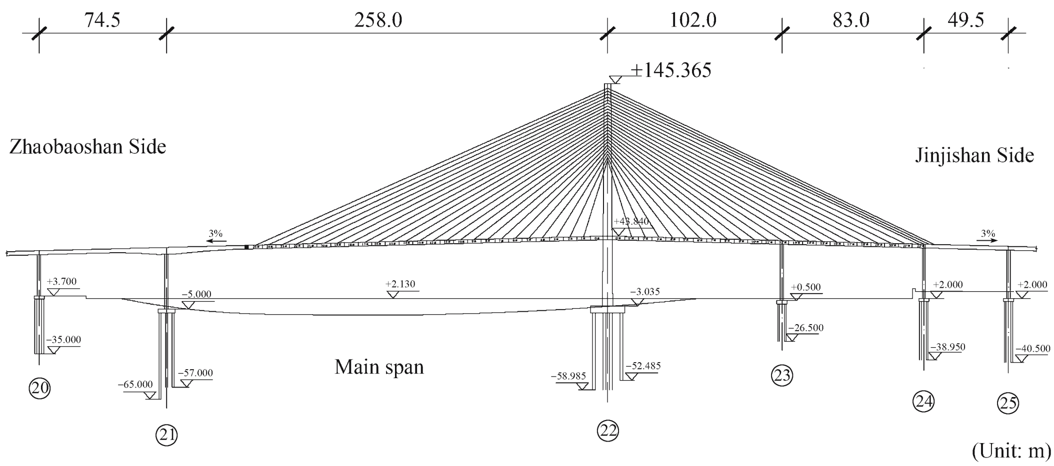

Fig. 3 General view of Zhaobaoshan cable-stayed bridge

For gaining the variance information of the main girder of structure in good time, and offering the data to identify the damage in the structure, vibrational chord strain gauges for concrete are used to acquire the strain data of a key section of the main girder. A suit of wireless real-time monitoring system is fixed on the ZBS Bridge, and the global position system (GPS) communication network is used to transmit the signal to a personal computer terminal in the office.

3.3 Static reverse analysis optimization model

The cable force measured at the beginning of opening to traffic and the cable force measured during inspection are substituted in the parametric finite element model to get the referred and deteriorated states of bridge.

The following static reverse analysis optimization model with GA is used to resolve the optimization problem.

Objective function

$$\text{minimize} \quad j(x)=\sum_{i=1}^{N}\left|\frac{\Delta\sigma_i^m-\Delta\sigma_i^a(x)}{\Delta\sigma_i^m}\right| \tag{3}$$

$$\text{subject to} \quad \left|\Delta y_j^a-\Delta y_j^m\right|\leqslant\xi \tag{4}$$

$$\left|\Delta z_k^a-\Delta z_k^m\right|\leqslant\xi \tag{5}$$

where, $\Delta\sigma_i^m$, $\Delta\sigma_i^a$ are the ith measured and predicted variance of stresses. Δy_j^m, Δy_j^a are ith measured and predicted variance of displacement of the main girder, Δz_k^m, Δz_k^a are ith measured and predicted variance of displacements of main tower. N is the sum of measured signals. ξ is a preset constant to control the precision, 1.0e-5.

Penalizing strategy is adopted to handle the constraints of genetic algorithms, and the fitness function with penalty function has the following form

$$\text{Eval}(x)=j(x)+p(x)\quad\begin{cases}p(x)=0 & x\text{ is feasible}\\ p(x)<0 & x\text{ is infeasible}\end{cases} \tag{6}$$

where, x is chromosome, $j(x)$ is objective function, Eval(x) is fitness function, $p(x)$ is penalty function.

3.4 Details of simulation

Conventional planar linear elastic beam elements with three degrees of freedom each node are used to model the girder and main tower of ZBS Bridge after the equivalent properties of the model have been determined. The cables are modeled as 3D spar elements, having an equivalent modulus of elasticity to consider the non-linear behavior of cables caused by cable tension and sag. The equivalent modulus of elasticity is determined by using the parameters of dead load cable stress, cable mass, cable length and true modulus of elasticity.

The proposed model is illustrated as the Fig. 4, with the sum of 215 nodes and 410 elements.

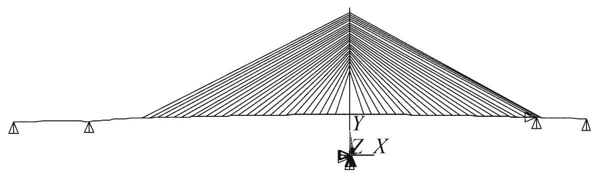

Fig. 4 Finite element (FE) model of ZBS Bridge

A sensitivity analysis on the basis of the finite element model constructed above was carried out for attaining the inspection cross sections of the main girder, and the results are illustrated in Fig. 5. In this study, seven cross sections of all sensitive sections were chosen to monitor the strain variance during the operation period.

1) Damage index. Damage index is defined as the attenuation of the girder stiffness a_i, and has the form of $E_i=(1-a_i)\cdot E_{i,0}$, where $E_{i,0}$, $E_i$are the elastic modulus of the elemental material before and after being damaged, respectively. In this case, the damage parameters are given as $a_{38}=0.5$; $a_{71}=0.6$; $a_{72}=0.8$.

2) Parameters of GA operators. The program developed by the authors was used to get the most appropriate parameters of genetic algorithms for this case. The real number coding method has been applied in this case. The population size of 50, the tournament selection with the size of 2, multiple points

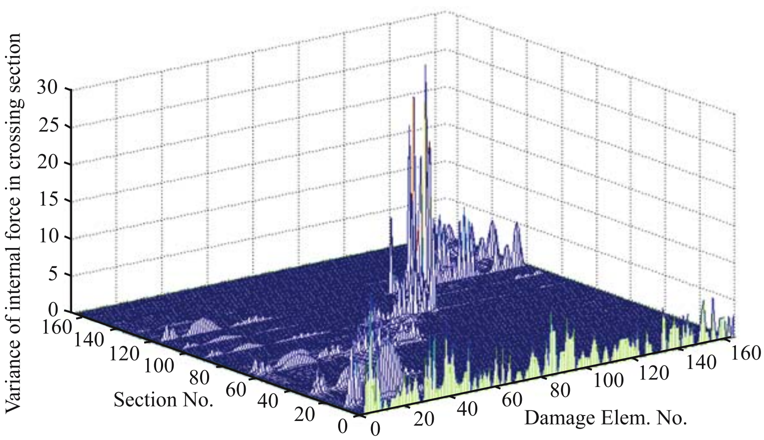

Fig. 5 Sensitivity of variation of internal force during constant loading to damage location

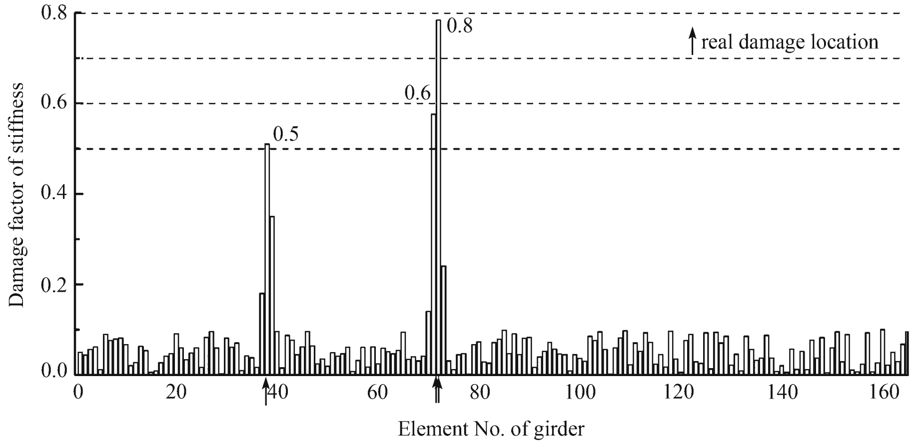

Fig. 6 Identified stiffness reduction factor after 150 generation

crossover with the probability of 0.85, and multiple points non-uniform mutation with the probability of 0.3 have been used in the numerical simulation.

3.5 Results of the damage identification

One hundred and fifty iterative steps were run to gain the results shown in Fig. 6. From the results, we can see that the damage location and extent can be detected effectively. Furthermore, the damaged nearby elements can be identified only having little damage, which suit for the concept of continuous damage in practical beam-type structures.

4 Conclusions

The damage detection strategy on the basis of the model updating is the most suitable for large-scale bridges. Due to their globally optimal solution strategy and their effectiveness and robustness, considering uncertainty, insufficient information, and noise, the genetic algorithm is proposed in the field of damage detection of large civil structures. The damage identification program, introduced in section 2, impulses the application of GA in practical engineering. Damages in the large-span pre-stressed concrete (PC) cable-stayed bridges are successfully detected by using the present damage identification algorithm. Also, the results are in great agreement with periodic inspections. Whereas, the simplified planar finite element model is suggested to carry out the primary damage detection, because it saves the running time of a CPU.

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