Visual Abstract

Crack identification in plates-type structures using natural frequencies coupled with success-history based adaptive differential evolution algorithm

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ABSTRACT. In this study, a new method for identifying and characterizing straight cracks in plate-like structures is presented. The method combines the finite element method (FEM) using the software Abaqus and the success history-based adaptive differential evolution algorithm (SHADE).
The objective of the method is to minimize the mean relative error between the measured experimental frequencies of a plate with an unknown crack identity and the numerical frequencies obtained using the Shade-FEM approach. The crack identity is defined by its length, orientation, and centre coordinates.

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To validate the effectiveness of the proposed approach, two strategies are applied. In the first strategy, the inverse problem is solved using the natural frequencies of a plate with a known crack identity obtained through modal simulation in Abaqus. In the second strategy, the experimental frequencies of a cracked plate are used.
The results of the study demonstrate that the proposed approach achieves promising results with just a population size of 25 and 150 iterations. The outcomes show high accuracy, as indicated by a relative error of the objective function below 0.8%. Overall, the study demonstrates the effectiveness of using the Shade-FEM approach for identifying and characterizing straight cracks in plate-like structures, offering potential applications in various engineering and structural integrity fields.

KEYWORDS. Non-destructive testing, Natural frequencies, FEM, Crack identification, SHADE algorithm, Objective function.

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INTRODUCTION

In many industrial fields and structural health monitoring applications, situations where the assessment of the extent of damage sustained by a mechanical part is necessary may be encountered. In order to inspect the part in-situ, non-destructive testing (NDT) techniques must be conducted. NDT techniques allow to evaluate the integrity and quality of a material or structure without causing any damage to it. There are various NDT techniques available that can be used depending on the type of material and the specific requirements of the inspection. Some commonly used NDT techniques include Radiographic Testing (RT), Ultrasonic Testing (UT), Magnetic Particle Testing (MPT), infrared thermography [1-5], acoustic emission, tomography inspection [6] and vibration analysis [7]. These tests make it possible to identify and to characterize eventual defects or cracks. The idea behind these techniques is to excite the part (by ultrasonic wave, vibration, magnetic field...) and to capture the disturbances or reactions by sensors (ultrasonic testing) or by imaging systems (thermography). Nevertheless, these controls always have disadvantages (too expensive, limited sensitivity, material limitations...). These methods also do not give all the needed information about the crack at the same time (orientation, size and location of the damage). Most of the recent progress in identifying cracks by non-destructive techniques was the result of studies conducted in the 1970s on the structures of the oil industry. The lack of knowledge of the location of cracks and the difficulty of accessing certain areas of the structures made the situation somewhat more complicated than other works in recent years, crack identification techniques have become very important in the industry in order to obtain all the parameters of a structural crack. These methods consist of finding optimal or global solutions by minimizing an objective function and considering various constraints [8]. Crack identification consists of applying a multi-variable optimization method, that minimizes a cost function [9]. The solution includes the geometric parameters of the crack. Multi-variable optimization methods have been widely applied in different areas, in order to improve the design as well as for inverse form optimization problems. Inverse problems seek to find the unknown parameters of a system based on measured data about its state. The response of the structure for a given number of model variants of an available reference structure is considered as the problem to be solved [10]. Many studies have focused on identifying cracks using vibration data and metaheuristic algorithms in plates, beams or lattices in two-dimensional space. They are based on the estimation of one or two defect characteristics depending on their location, size, orientation, depth or severity. For the solution of the inverse problem in the domain of crack detection. Nobahari [11] combined a modified genetic algorithm (MGA) with finite element analysis (FEA) to identify multiple damages in a structural system. Gomes [12] discussed the use of optimization algorithms and artificial neural networks (ANN) for structure monitoring in the form of a brief review and focused on damage identification using intelligent signal processing and optimization algorithms based on vibration metrics. Saeed [13] adopted (ANN) and multiple adaptive euro-fuzzy inference systems (ANFIS) in order to predict the size of a crack and its location based on natural frequencies and frequency response functions in curvilinear beams. Jena [14] combined analytical and experimental investigations to evaluate the damage location and severity in a cantilever beam exhibiting a transverse surface crack. The first three natural frequencies were determined using strain energy release rate based analytical methods. Then, an experimental method was adopted to validate the theoretical results. The evaluation of the damage location and severity was formulated as a constrained optimization problem and solved using a differential evolution algorithm. Boukellif in [15]

proposed an approach to detect one or multiple cracks and the calculation of stress intensity factors (SIF) in finite and semi-infinite plane structures applying genetic and adaptive simulated annealing algorithms. Since the Crack detection in 2D structures has been widely addressed in the literature. Khatir [16] presented a technique to estimate the location and the severity of a crack in beam-like structure using PSO and the natural frequency that is determined with FEM. For the same reasons Zenzen [17] extended the method to beam-like too and truss structures using PSO and Bat algorithm based on FRF. Al-Wazni [18] proposed an approach to identify the size and the position of a crack in a clamped beam made of steel with a combination of PSO algorithm and the vibration properties, the dynamic analysis of the finite element model is performed using ANSYS-APDL software. Amoura et al. [19] established a crack identification algorithm for 2-D and axisymmetric structures using a coupled boundary element method and Nelder-Mead function minimization method. In their work, they used a low-discrepancy sequence to produce the initial crack's identity for the simplex launch, which considerably reduced the computing time. In [20] an extension of the method to 3D structures is presented. Benaissa [21] utilized a model reduction method combined with proper orthogonal decomposition method to determine the presence of the crack and its size in a convex and non-convex specimen. The objective was the minimization of the difference between measured and computed displacements. Recently, the application of metaheuristic optimization methods to the problem of damage detection has increased significantly to minimize the numerically simulated and experimentally measured parameters. Jena et al. [22] used the modified PSO with an error of 0.08% for location and 0.11% for depth. And in Ref [22] for a similar purpose, but this time with adaptive fuzzy PSO (A-FSO) and to identify the location and size of cracks in a beam with an error of 0.0130% and 0.025% for location and depth, respectively. In [23] frequencies and shape modes were combined with GA-PSO and then made a comparison between the three algorithms (GA-PSO, GA and PSO) to obtain the location and severity of a crack in a thin plate. Mohan et al. [24] has presented an approach for the detection of cracks on beams or plane trusses based on the dynamic characteristics of the structure combined with PSO or GA.
Ding [25] also did the same work, but they chose other algorithms by comparing I-ABC, DE, PSO and GA algorithm and he favored I-ABC with a normalized cost function value of 0. 0035.Zhang[26] combined the FEM and QPSO to identify mechanical structures damage parameters. The fitness function is a critical element in the final success of the optimization method. Li [27] compared the performance of four cost functions based on natural frequencies using the classical PSO-FEM model. This study is divided into three main sections. In the first section a numerical example is applied using reference frequencies given by FEM after a simulation of a cracked plate (plates are generally elements used to model thin structures, because only one dimension is small compared to the other two) based on the minimization of the objective function using SHADE algorithm and FEM. In the second one an experimental validation is stated to validate the approach.

INVERSE PROBLEM

As discussed in the introduction, determination of the deviations, in the natural frequencies of plates from a given value of crack location and crack types, is a straightforward task. The objective of the inverse approach is to estimate the unknown crack location and its length iteratively, using an optimization algorithm that results in a negligible difference between the actual and the estimated natural frequencies from FEM. The essential task of this approach to crack identification and characterization is to solve the inverse problem with an objective function based on dynamic parameters of the structure. In this case, the domain of variation of the identity vector is such that the crack remains within the limit of the search domain (the structure) while respecting the maximum and minimum value of each decision variable.

NUMERICAL EXAMPLES

Computing natural frequencies by finite element method

The performed simulations using the FEM method are achieved under the Abaqus 6.14 software, which is a powerful simulation software used in many fields of mechanical engineering. In this section, the investigated plate has a thickness of 1 mm, with 480mm in length and 280mm in width and the four edges of the plate are clamped. The crack has a length of
120 mm and is in the centre of the plate. The Young's Modulus and Poisson's ratio of the material are$E$=200GPa and ν=0.33 respectively. The plate is meshed with quadrilateral elements with the size of the element fixed to 4.0 mm. The Fig. 1 shows the values of natural frequencies in modes 4 and 7 present the opening of the crack in each mode. In this study 10 modes are considered.

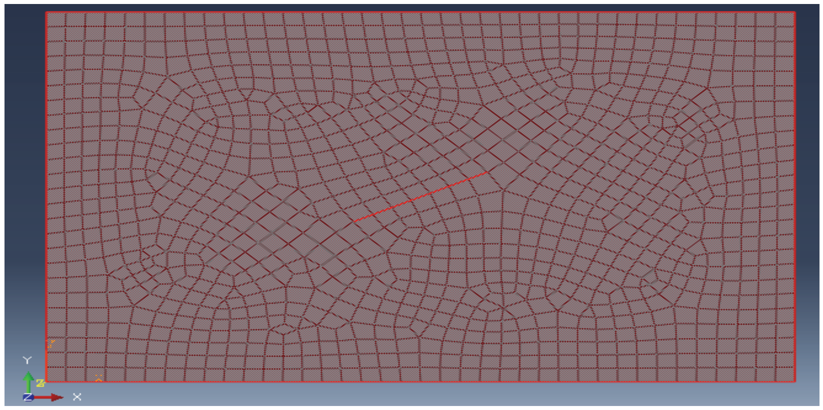
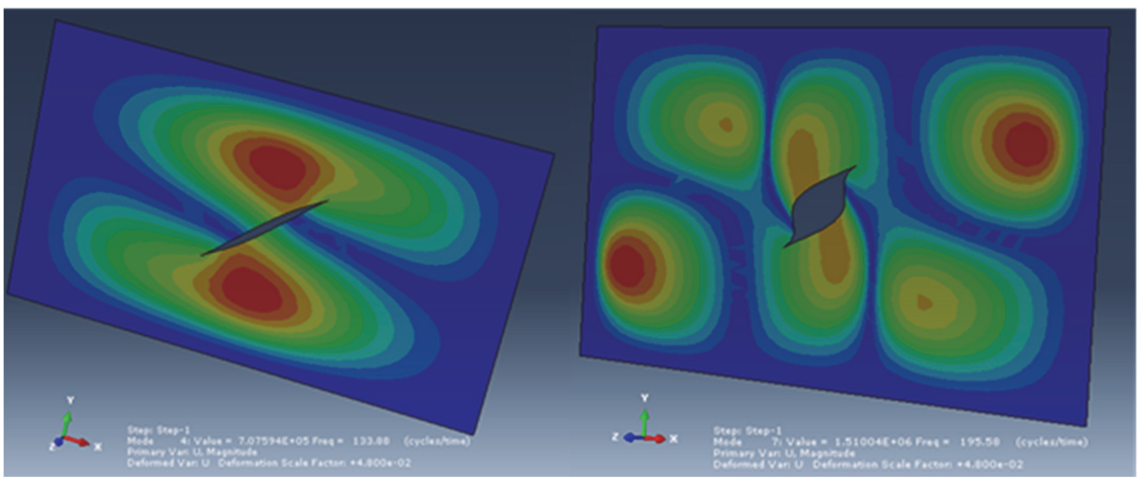


Figure 1: Mesh of the cracked plate

The optimization algorithm coupled with the finite element method - The objective function

The presence of a defect in a structure modifies its stiffness and as consequence the modal frequencies are also modified. Taking advantage of this change, the variation of natural frequencies could be used for the identification and reverse characterization of defects. The damage identification process involves two essential stages.



(a) (b)

Figure 2: Natural mode results (a) 4th mode and (b) 7th mode.

In the first stage, the direct problem is formulated, and the response parameters associated with the unknown damaged area are selected. The second stage is devoted to the use of an optimisation algorithm by introducing the crack parameters, which correspond to every possible solution into the considered area of search, in order to obtain the corresponding frequencies. Therefore, the value of the fitness function is computed as the normalized error between these frequencies and the ones produced by the actual crack parameters. The evaluation of the objective function uses the following equation:

$$F(X_i)=\sqrt{\sum_{i=1}^{n}\left(\frac{f_i^{ex}-f_i^{c}}{f_i^{ex}}\right)^2} \quad (1)$$

where $\mathbf{X_i}$ is the vector of decision variables, f_i^{ex} are the experimental natural frequencies given by the actual crack parameters, f_i^{c} are the natural frequencies given by a guessed crack parameters end n is the number of natural frequencies used in the optimization process.

The optimization algorithm coupled with the finite element method - Decision variables

Decision variables are the elements of the identity vector describing the crack geometry parameters, selected to minimize the objective function. For an inclined straight crack, the parameters to be optimized are the coordinates of the segment centre, its length and its orientation angle in a two-dimensional search space (Fig. 3).

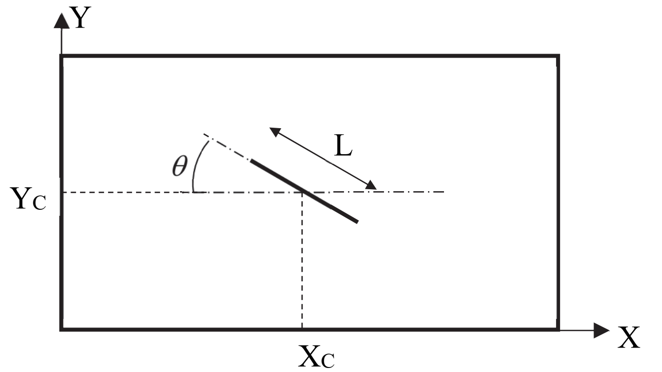


Figure 3: Plate geometry and identity crack parameters.

Each decision variable has its own range of acceptable values to limit the search field of the optimization algorithm. Tab. 1 gives the upper and lower bounds for each decision variable in the case of an inclined straight crack.

Decision variables	Min	Max
L (mm)	1	170
θ (°)	0	180
X_C . (mm)	0	150
Y_C . (mm)	0	90

Table 1: Variables' constraints for the inclined straight crack.

The optimization algorithm coupled with the finite element method - SHADE Algorithm

Differential evolutionary algorithm is based mainly on the strategy of mutation and crossover, the first is to generate an individual mutant from existing solutions:

$$v_{i,G} = x_{i,G} + F_i\left(x_{pbest,G} - x_{i,G}\right) + F_i\left(x_{r_1,G} - x_{r_2,G}\right). \quad (2)$$

with $x_{pbest,G}$ drawn randomly from rand (min, 0.2) of top of the population, $x_{r1,G}, x_{r2,G}$ two different individuals drawn randomly and F a parameter of the individual, with:

$$x_{r1,G} \neq x_{r2,G} \neq x_{i,G} \quad (3)$$

Tecond is the binomial css performed between the mutant solution $v_{i,G}$ and the parent $x_{i,G}$:

$$u_{j,i,G} = \begin{cases} v_{j,i,G} & \text{if rand}\left[0,1\right] \leq CR_i orj = j_{rand} \\ x_{j,i,G} & \text{otherwise} \end{cases} \quad (4)$$

After the generation of the whole population u_G , a selection process took place to keep the best solutions:

$$x_{i,G+1} = \begin{cases} u_{i,G} & \text{if } f\left(u_{i,G}\right) \leq f\left(x_{i,G}\right) \\ x_{i,G} & \text{otherwise} \end{cases} \tag{5}$$

In the SHADE algorithm [28]the F and CR parameters are determined from the historical sets that contain only the best values of these two parameters (i.e., that depend on individual success according to reference [7]).

EXPERIMENTAL EXAMPLE

Experimental setup

In order to verify the accuracy of the proposed approach for identifying cracks in a plate, an experimental setup was carried out using a plate made of steel (Fig. 4). The dimensions and material properties of the plate are given in Tab. 2. The hammer test is chosen for the extraction of the experimental natural frequencies. PCB Piezo electronics™ accelerometer, model 608A11, is fixed on the plate using a cyanoacrylate glue at a location close to the plate centre. The sensor converts the mechanical vibration produced by the hammer shock into electrical signal and transmit it to a Spectra quest™ data acquisition system.

(a)

(b)

Figure 4: Experimental setup (a) and cracked plate (b).

To extract the experimental natural frequencies, a spectrum analysis is performed on the output time waveform. The input, the force of a hammer blow at a specific location, must have a bandwidth wide enough to include all the required modes.

In this experimental part a rectangular steel plate is used. An inclined central crack is created using a precision laser cutter. The considered crack has a length of 120 mm and is oriented with an angle of 35°. The plate has the four edges clamped.

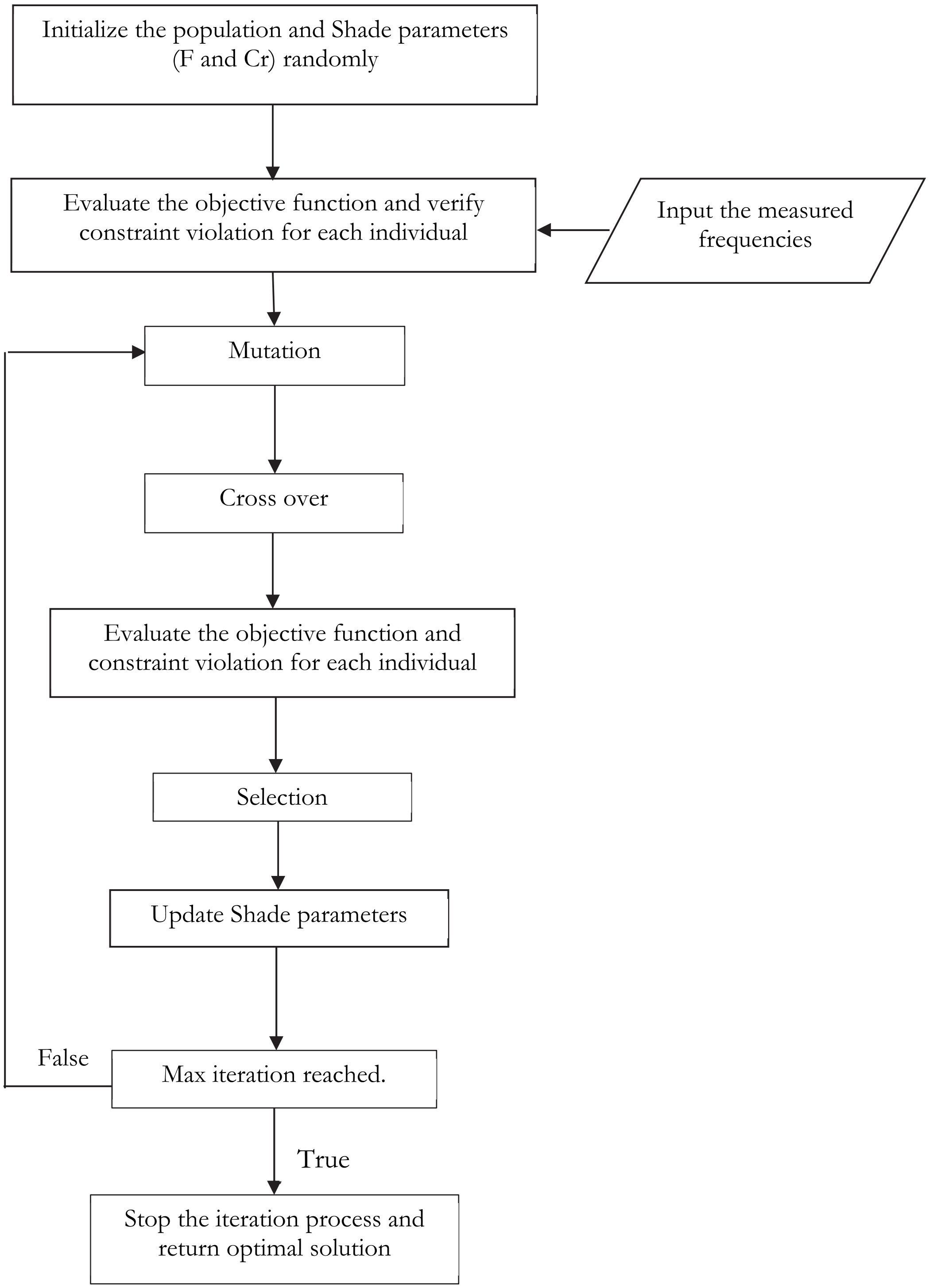


Figure 5: Flowchart of the crack identification approach.

Elastic modulus	Density	Poisson's ratio	Length	Width	Thickness
210 GPa	7.8 g/cm^3	0.3	480mm	280mm	0.7mm

Table 2: Material properties and geometry of the cracked plate.

Modes	Uncracked plate frequencies (Hz)	Cracked plate frequencies (Hz)	Differences (%)
1	60.39	55.93	-7.39
2	85.62	79.50	-7.15
3	110.25	115.12	4.42
4	140.75	133.12	-5.42
5	170.87	165.00	-3.44
6	182.63	176.25	-3.49
7	200.37	198.75	-0.81
8	250.59	244.87	-2.28
9	274.62	265.12	-3.46
10	282.94	273.00	-3.51

Table 3: Experimental natural frequencies of a clamped cracked and crack-free plate.

Modes	Experimental frequencies (Hz)	Numerical frequencies (Hz)	Differences (%)
1	55.93	53.20	-4.88
2	79.50	79.43	-0.09
3	115.12	116.73	1.40
4	133.12	137.44	3.25
5	165.00	166.26	0.76
6	176.25	175.04	-0.69
7	198.75	201.44	1.35
8	244.87	244.73	-0.06
9	265.12	264.24	-0.33
10	273.00	275.13	0.78

Table 4: Numerical and experimental natural frequencies of a cracked plate having a crack length of 120mm inclined by 35°.

First, an estimate of the natural frequencies of the cracked and the crack-free plate is obtained by means of a hammer test. The plate is impacted by the hammer, and an estimate of the natural frequencies is obtained from the peaks on the frequency spectrum (Tab. 3). An average of several readings is taken for each natural frequency. Tab. 4 relates the numerical values of the natural frequencies of the cracked plate, given by a finite element analysis with Abaqus software, and the experimental frequencies.

Estimation and results

Numerical case

In order to assess the accuracy of the identification algorithm, we took a plane steel sheet containing a linear inclined crack. After computing the ten first natural frequencies with a direct modal simulation by FEM we used the inverse identification by SHADE algorithm to evaluate the identity parameters of the crack given by Tab. 5. The approach was initiated by taking several random initial identities of the crack.

Parameters	Value
Length (mm)	120.0
Orientation (°)	35.0
X_C (mm)	240.0
Y_C (mm)	140.0

Table 5: Crack parameters.

The results, given on the chart of Fig. 6, show that for the damaged plate, the centre location, length and orientation were determined with a high precision after only 50 iterations with a population size of 25 and the convergence is monotonic after the algorithm has accomplished half the total number of iterations. Fig. 7 shows that the maximum error obtained on the normalized objective function is less than 0.25%.

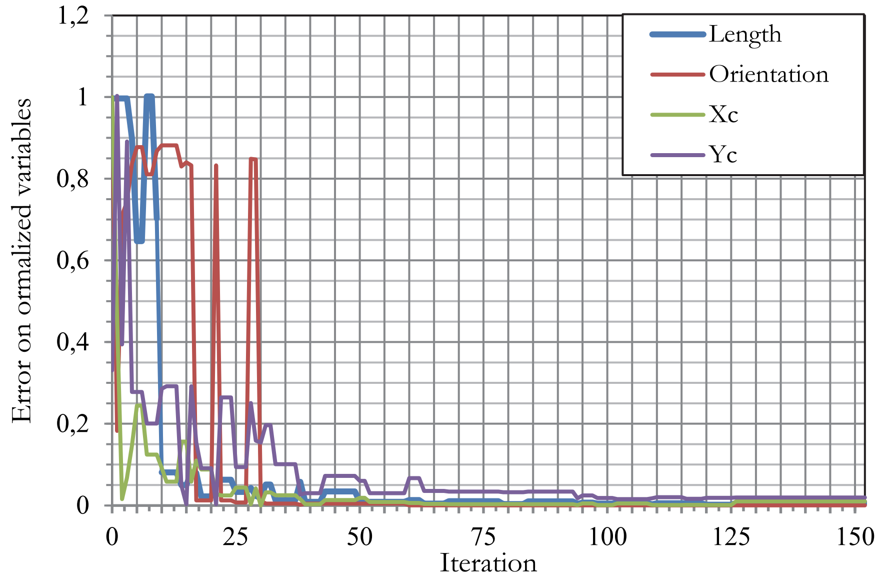


Figure 5: Numerical convergence of crack variables using SHADE algorithm.

Experimental case

In this section, a method for solving the crack identification problem by SHADE algorithm is discussed. The aim of this formulation is to identify the identity parameters of the crack, named centre coordinates, crack length and crack orientation, by evaluating the objective function based on the natural frequencies of the plate. Prior to the optimization process, it is necessary to carry out a theoretical simulation in order to estimate the natural frequencies of the plate for different crack configurations. For the numerical simulation we took a steel plate with the four borders clamped, which is used to find the changes in natural frequencies depending on the crack parameters. Geometrical and mechanical properties of the plate are the same for both the numerical and the experimental study.

In Fig. 8, the convergence of the position, length and orientation of the crack is shown. We can notice that regarding the experimental errors, the normalized values for the crack length and crack position have an error range of 20% while the normalized value of the orientation converges to a local minimum. Fig. 9 shows the monotonic convergence of the error on the objective function after 50 iterations.

It is apparent from the above figures that SHADE algorithm has a good convergence in finding the optimal crack location and length regarding experimental errors on the measured natural frequencies. Fig. 6 shows the performance of SHADE algorithm in detecting crack length and position in comparison with the actual ones. Concerning the crack orientation, the inverse problems are often characterized by non-uniqueness, where multiple crack configurations can produce similar or identical responses in the measurements. As a result, it becomes difficult to pinpoint the exact orientation of the crack from the available data. It is noted that the variation of natural frequencies has no significant effect on this parameter. This fact has already been reported by Natarajan [29]. And Tab. 7 shows that the numerical study exhibits the best precision, which is likely to have changes regarding experimental errors, (human errors, instrumentation errors, failure to accurately simulate support conditions, etc).

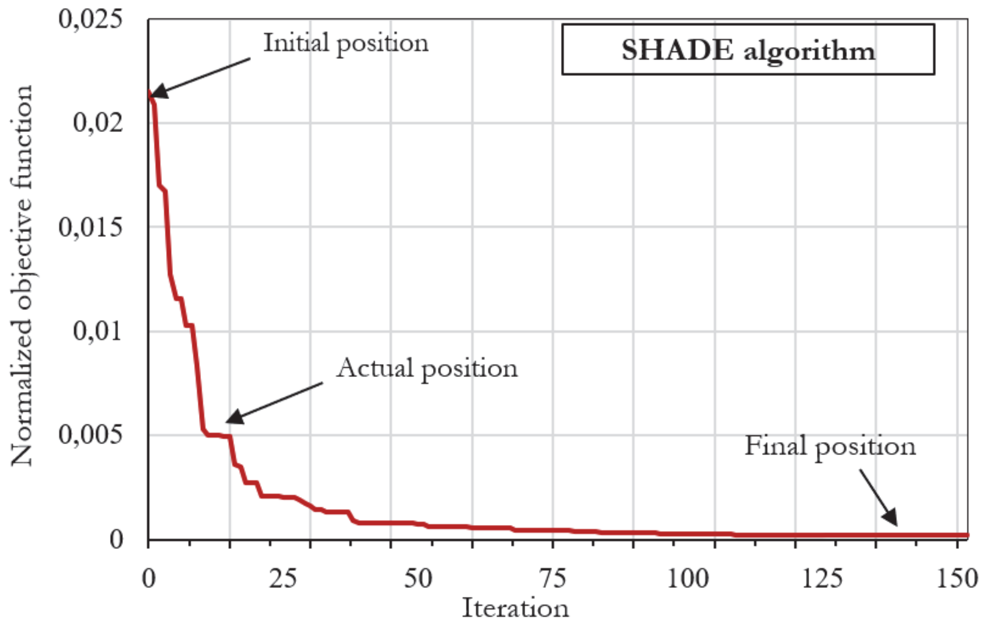


Figure 6: Numerical iteration process of the objective function.

Variables	Actual	SHADE	Error (%)
Length (mm)	120.0	102.9	-14.3
Orientation (°)	35.0	87.9	151.1
X_C (mm)	240.0	259.0	7.9
Y_C (mm)	140.0	167.2	19.4

Table 6: Optimal solution for each variable for 2D structure.

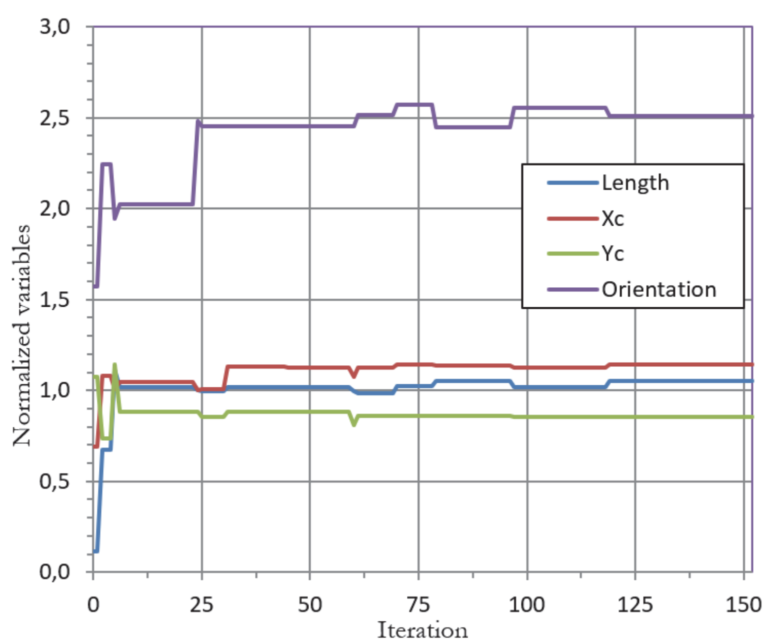


Figure 7: Experimental iteration process of crack variables.

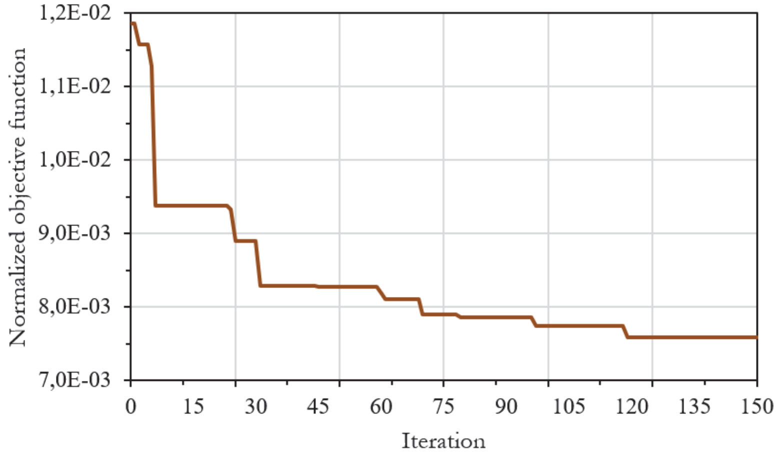


Figure 8: Experimental fitness using Shade algorithm.

Function	Best (10^{-4})	Worst (10^{-4})	Mean (10^{-4})	Standard deviation (10^{-4})
Numerical	1.9	4.8	2.9	1.7
Experimental	75.8	81.0	77.0	2.1

Table 7: Comparison of optimal solution for each variable for numerical and experimental study.

CONCLUDING REMARKS

The paper investigates a new procedure for the identification of cracks in plates structures that allow detecting simultaneously the location and the length of the damage. The method exploits the changes in the natural frequencies of the structure caused by the presence of the flaw. These changes in frequencies result in several scenarios depending on the crack parameters.

The proposed method uses the first ten natural frequencies with a minimisation algorithm to achieve a sharp identification. The results of this work indicate that the approach can be successfully used for the identification and characterization of cracks in plate-like structures avoiding local minima, except for the orientation of the crack which is insensitive to natural frequencies changes. SHADE algorithm, used to minimize the objective function, has proved to significantly reduce the computation time (less than 50 iterations to achieve good convergences) and do not need constraints on the random initial identities used to start the minimization process.

The proposed approach has been numerically validated in the case of a steel plate with an inclined straight crack identified by its length, orientation and coordinates of the centre. To evaluate the efficiency of the minimization algorithm, the natural frequencies obtained by a modal analysis are used in an inverse search problem to get the identity of the crack and the results have showed good convergences on both objective function and crack's parameters. In a second experimental proof, a hammer test is used to measure the natural frequencies of a cracked steel plate with the same dimensions as in the first example. The frequencies of the plate, with some experimental errors, are used to set the fitness function to be minimized by SHADE algorithm. The results obtained by this experience demonstrate that a certain level of accuracy for the measured data is essential for accurate damage detection. Furthermore, the method developed here cannot be used effectively if the measurement errors exceed 10%, and the accuracy on the crack identity parameters with this level of experimental errors could reach 20%. Once the value of the crack orientation angle is changed, it can be observed that there are some minor changes in the frequencies, but they are quite negligible.

Investigating the impact of crack orientation on the fundamental frequencies, it was noticed that it induces only marginal variations in the frequencies. Consequently, even small changes in the orientation do not affect the values to which the minimization algorithm converges.

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