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ORIGINAL PAPER

# A numerical–experimental study for structural damage detection in CFRP plates using remote vibration measurements

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**Abstract** The performance and behavior of composite structures can be significantly affected by degradation and damage. Degradation can be caused by exposure to environmental conditions and damage can be caused by handling conditions, such as impact and loading. Such damages are not always visible on the surface and could potentially lead to catastrophic structural failures. This paper addresses the specific challenge of using numerical simulations to assess damage detection techniques applied to composite laminated plates. This study aims to solve the direct and inverse problem of damage detection by combining numerical and experimental data. Finite element analysis was carried out to analyze the direct problem of mechanical response. Heuristic optimization techniques were used to solve the direct and inverse problem by combining data from a model with that of the experiment to identify structural damage. This study also sought to update the finite element model by minimizing the objective function. The structure studied was constituted of a composite plate. Two damage models were used: (i) circular hole and (ii) delamination (local stiffness reduction). The results of the optimization algorithms show good efficacy in the detection of structural damage, identifying the damaged location on the structure and also quantifying the size of the damage in real composite structures. A method has been proposed to identify the damage in CFRP plates using remote vibration measurements. Furthermore, the numerical simulation and experimental tests have been used to verify the method.

**Keywords** Damage identification · Genetic algorithm · Composite plate · Natural · Frequency · Laser vibrometer

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## 1 Introduction

Although composite structures are designed to sustain structural damage, reliable structural health monitoring (SHM) systems demand the improvement of structural design and maintenance performance while maintaining safety. Impact damage detection techniques for SHM ring are widely established; however, the associated costs are high because often the damaged area cannot be localized, and hence inspection of the whole component is required. Much research has been conducted to assess the success of non-destructive damage detection techniques, especially on new composite materials used in the aerospace industry [20].

The effect of defect or damage to the structural integrity of composite components is essential for understanding the criticality of the defect. The defects may be grouped into specific categories according to when they arise during the life of composite structure, their relative size, location or origin in the structure of the material. Some examples of damage in composites are shown in Fig. 1. The service components have defects that occur through mechanical action or contact with hostile environments, such as the impact site overload, local heating, chemical attacks,

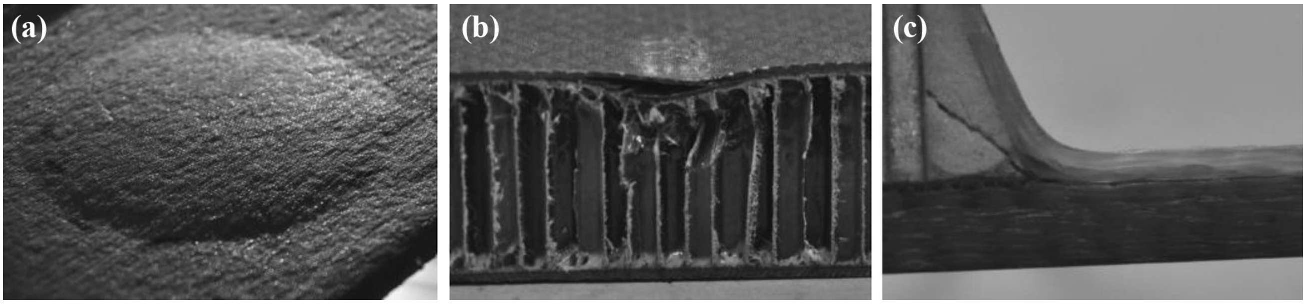


**Fig. 1** Some characteristic damage in composite materials: surface bubble (**a**), crush on a sandwich panel (**b**) and delamination (**c**) [12]

ultraviolet radiation, acoustic vibration, fatigue or inadequate action repair. The size of a defect has a significant influence on its criticality and may be present in isolation from structural features such as slots and bolted joints, or even a random accumulation resulting from the interaction between other defects [32].

The monitoring of structural integrity or SHM aims to provide, throughout the life of a structure, a diagnosis of the "state" of their constituents, the different parts and the complete set of these parts constituting the structure as a whole. Structural monitoring is a new and improved way to make a non-destructive evaluation, involving the integration of sensors, possibly intelligent materials, computational power transmission and data processing capacity within the structures. This makes it possible to reconsider the design of the structure and integral management itself as a part of larger systems [1].

One way to overcome this problem of monitoring the structural integrity is the use of inverse methods to detect damage. The structural damage detection method based on inverse method combines an initial model of the structure and measured data to improve the model or test a hypothesis [10]. An approach frequently used, according to [10], is the use of a model based on finite element analysis. Experimental data are normally given in the form of accelerations and forces often in the form of a modal database, although frequency response function (FRF) is also used.

Computational intelligence methods have been applied to the problem of structural damage detection and identification. Advanced computational methods such as neural network and genetic algorithm (GA) are highly adaptive methods originated from the laws of natural biology. Unlike the traditional mathematical methods, one of the important characteristics of computational intelligence methods is their effectiveness and robustness in coping with uncertainty, insufficient information, and noise. Optimization techniques are implemented as the main components in damage detection using the system identification method. In system identification, optimization techniques are used to match the finite element model responses to the damaged structure responses. When the optimization procedure arrives at the solution, the values of the parameters indicate the state of the structure, i.e., if, where and how it is damaged [16].

There have been some damage identification methods based on the optimization algorithms which were used to identify the location and extent of damage [8, 21, 27, 34]. The main idea of these methods is to transform the damage identification problem into an optimization problem in which the objective function is usually defined by minimizing the difference between measured and analytical model characteristics of the structure and the design variables are the damage ratios of elements in the structure. Several meta-heuristic optimization algorithms such as genetic algorithm GA particle swarm optimization (PSO), ant colony optimization (ACO) have been applied successfully for structural damage localization [9, 27, 34, 38]. One important advantage of this approach is that the complete set of model characteristics (e.g., modes or displacements) is not needed because the objective function involves only the difference between the main components of these vectors. Another advantage of this approach is that they can determine both the location and the extent of structural damage [34].

Structural damage can be defined as the modification of the stiffness or mass of an element. One of the main ways to assess the presence of local damage is to be based on the variation of structural dynamic parameters. This method assumes that the damage results in alterations in the properties of the structure, i.e., may cause a variation in the mass matrix, damping and/or stiffness of a given system, which in turn will result in changes in the dynamic response of the same [19].

According to [28], another advantage of using vibration in detecting damage occurs because of the ease of analytical developments, or even models of finite elements of structures studied, thus allowing the measurement points (sensors) properly chosen so that there is not only a quick and efficient detection of changes in frequency, but also the identification of the location and severity of damage.

It is true that there are a considerable number of publications using changes in frequencies. However, few articles address the detection problem using optimization algorithms coupled with the finite element method considering model updating. One of the key points of this article refers to the identification of damages using GA-FEM, where a numerical–experimental model adjustment is addressed by inverse method. Experimental results were very satisfactory with numerical models studied. The frequency response is a good overall criterion for damage detection; however, when a set of frequencies is used it may be an indicator of the possible location of damage. Still, the use of natural frequencies is a sub-component of evaluation in this article, the key point being the complete methodology for damage identification.

Based on the brief review and the reasons stated above, it was proven that damage detection is still a serious problem in composite structures, which requires more attention. The methods of identification of damage in structures are gaining importance in the recent past due to safety and economic aspects. In this study, a numerical model, which allows the detection and identification of structural damage, is investigated using finite element analysis and genetic algorithm in laminated composite plate. This model allows the identification of local damage, with no need of previous knowledge of its location. Additionally, the model is applied to a laminated rectangular plate with free edges as boundary conditions. The optimization process using heuristic methods such as GA is used in the inverse method procedure because heuristics methods, such as GA, are methods of zero-order, especially suitable for non-linear and multi-modal problems [18], since the damage detection problem has a functional that is not convex with multiple local minima [31]. Good results were found using this proposed methodology.

## 2 Problem formulation

### 2.1 Direct problem: finite element model

According to [30], for a multi-degree-of-freedom undamped linear dynamic system, the equation of motion is:

$$M\ddot{y}(t) + Ky(t) = Y(t) \tag{1}$$

where $M$ is the system mass matrix and $K$ is the system stiffness matrix with initial conditions $\ddot{y}(t) = y(t) = 0$. Both mass and stiffness matrices are of the order $(n \times n)$. $y(t)$ and $Y(t)$ are the physical displacement and applied load vectors of order $(n \times 1)$, respectively, where $n$ is the number of degrees of freedom. The associated $j$th eigenvalue equation is:

$$K\phi_j - \lambda_j M\phi_j = 0 \quad \text{for } j = 1, \ldots, m_u. \tag{2}$$

where $\phi_j$ is eigenvector (mode shape), $\lambda_j$ the eigenvalue (natural frequency) of the structure, and $m_u$ the total number of mode shapes obtained for the undamaged structure. In the finite element model of the structure, the global stiffness matrix can be represented as an assemblage of element stiffness matrices, i.e.,

$$K = \sum_{i=1}^{m} k_i \tag{3}$$

where $k_i$ represents the stiffness matrix of the ith element, m is the total number of elements and represents the assembly of elemental stiffness matrices based on nodal connectivity and the associated degrees of freedom.

In this study, the modal results calculated for different structural conditions (i.e., undamaged and damaged states) are used in the corresponding damage identification algorithms to locate simulated damages. The following assumptions and steps, addressed by [2], are used to calculate damage indices/performance: (i) the excitation force is assumed to be a stationary ergodic random process; (ii) the effects of internal damage are more apparent in local stiffness reduction; (iii) the influence of damping on global accuracy in the proposed global damage identification method is considered non-critical while low-frequency vibration modes are used.

For well-separated lower modal frequencies, changes in damping properties due to damage are assumed to be consistent across modes. Because of this, damping is neglected in the numerical modeling of the problem.

According to [35], structural damage can be characterized as changes in physical or geometric properties of a structure at levels that alter the original terms of design, but also allow that it perform the function for which it was designed. For this study, the following models of damage are studied: circular holes (changes in geometry) and localized stiffness reduction (physical properties).

The direct problem was modeled as a square plate side equal to 30 cm. The structure is symmetrically laminated composite material consisting of 12 layers of different orientations, i.e., $[0/90]_{3S}$. Once the composite laminate has been defined, it is necessary to determine the configuration of elements within the finite element method to have a close structure of an actual laminate. In general, the following assumptions are made with respect to modeling of composite materials: (i) there is a perfect union between the layers of the laminate, which means that the blades cannot slide one over the other; (ii) displacement field has the least curvature continuity throughout the thickness of laminates. In this work we used an element having the following characteristics: (i) element type: shell and (ii) eight nodes with six degrees of freedom in each one: translation and rotation on the axes *x*, *y* and *z*.

With regard to the mesh used in the analysis, it was decided to partition the structure into 20 side elements. In the cases of circular holes, 400 elements (20 × 20) were defined and 121 elements (11 × 11) for the localized stiffness reduction of the structure were studied.

### 2.2 Inverse problem: genetic algorithm optimization

In engineering, the real problems are mostly complex, non-linear, difficult to represent and non-differentiable, requiring advanced numerical methods for their solution. Deterministic methods, based on the derived calculation or approximations of these gradients, produce good results when the functions are continuous, convex and unimodal. However, in most cases, they are inefficient when applied to problems which present discontinuity [37]. According to the author, the main difficulties in deterministic methods are:

- The convergence to an optimal solution depends on the choice of the initial solution.
- Many algorithms tend to get "stuck" in a sub-optimal solution (local minimum).
- An efficient algorithm for solving an optimization problem cannot be effective in solving other.
- They are efficient in dealing with problems where the search space is discrete.

Heuristic methods can reduce some of the difficulties presented above, justifying the fact that more and more research is being developed using these methods, to compare their results with the classical methods in solving optimization problems. Heuristic methods, also known as natural methods, are characterized by finding the best solution using probability rules. Such methods use only the information of the optimization function, requiring information on their derivatives or possible discontinuities [18].

The GA is a global searching process based on Darwin's principle of natural selection and evolution. A sequential GA proceeds in an iterative manner using three main operations: selection, genetic operations, and replacement. The GA starts with an initial population; the individuals of this population are subjected to the three operators. The result is a population with a higher fitness than the initial one as in natural selection. This process is iterated until a convergence criterion is achieved. A correct selection of the GA operators and parameters is crucial as they affect the solution and the algorithm run time [16].

According to [18], many practical optimization problems are characterized by discrete variables and discrete search space and are not convex. If non-linear standard programming techniques are used for this type of problem, the solution will be ineffective, expensive, and in most cases there is an optimal solution that is strongly connected with the starting point of the search. Genetic algorithms are suitable for solving such problems, and in most cases they can find the best overall solution with a high probability.

Genetic algorithms differ from traditional algorithm optimization in some aspects: based on an encoding of the set of potential solutions, rather than the optimization of the parameters themselves, the results are presented as a population of solutions and not as a single solution. They require no prior knowledge of the derivative of the objective function and use probabilistic transitions and not deterministic rules [18].

For numerical simulations and experimental test, there was a study on the definition of the optimizer parameters, in this case genetic algorithms, so that they could provide satisfactory results. The configuration of GAs was selected after the performance of various detection methods, until a set of more satisfactory values was obtained. Table 1 shows the configuration used for the GAs in this work.

### 2.3 Numerical adjustment

Numerical and experimental methods are sensitive to errors because the numerical model is always based on a number of assumptions. If the actual structure does not meet one or more of these assumptions, the structural model is, of course, convenient. Since the development of mixed numerical–experimental techniques for identifying materials is intended to obtain a practical method that yields rapid and reliable results, much research has been made to minimize these model errors [3].

In this work, the numerical–experimental method proposed for the identification of elastic constants from the vibration tests consists of the following stages. In the first stage, experimental tests are performed to obtain the natural frequencies of the laminated board. In the second phase, the finite element method is used to model the response of the structure under previously known conditions and finally in the third stage, the numerical data obtained by the solution in finite elements are used to construct the inverse method update models, where the

**Table 1** GA operators

| Genetic operator | Value |
|---|---|
| Population size | 300 |
| Crossover | 60% |
| Mutation | 2% |
| Elitism | 2 |
| Generations (stop criteria) | 100 |

identification of the elastic properties is carried out, because, according to [13], vibration tests combined with a numerical method is a potential alternative strategy to determine the elastic constant of a material because of its non-destructive character, where only a single vibration test is capable to determine the elastic constant of a specific material.

For this, the objective function must be minimized (Eq. 1) based on the vibration modes 8, 9 and 10, performing the calculation of the numerical and experimental difference, namely a function error. The optimization was performed using the same genetic algorithm developed in this work, maintaining all the parameters of the genetic operators fixed.

Only modes 8–10 were used as the evaluated response due to experimental inconveniences. The fundamental mode (first non-zero mode), that is, the 7th mode (not taking into account rigid body behavior) was not perfectly acquired by the experimental system and the first three that were considered reliable (8–10).

$$J = \sum_{i=8}^{10} \left(\omega_i^{\text{real}} - \omega_i^{\text{calculated}}\right)^2_{\text{undamaged}} \tag{4}$$

The numerical–experimental approach proposed is used to identify the elastic properties of the laminated board. It is assumed that the dimensions of the square plate of 30 square centimeters, constant density $\rho = 1408.8$ kg/m$^3$ (data obtained through experimental laboratory testing), and layup $[0/90]_{3S}$. The parameters to be identified are comprised of four elastic constants: Two elastic moduli $E_1$ and $E_2$, shearing module $\text{tt}_{12}$ and Poisson coefficient $\nu_{12}$. Longitudinal direction is indicated by 1 and the two transverse directions are indicated by 2 and 3. Typically, the poor accuracy of the identification of Poisson's ratios and to simplify the three-dimensional identification problem to a two-dimensional one, assumptions about the additional parity of elastic constants are introduced (Eq. 2) [24].

$$\begin{cases} E_3 = E_2 \\ \nu_{13} = \nu_{23} = \nu_{12} \\ G_{13} = G_{12} \\ G_{23} = \dfrac{E_2}{2(1+\nu_{23})} \end{cases} \tag{5}$$

It is necessary to further constrain the optimization problem by adding a constraint equation (Eq. 6) for designating a positive definite matrix of elasticity [3]. According to [23], an accuracy in the estimation properties in the order of 10% of experimental data is sufficiently acceptable for modeling composite materials for the initial design purposes, since it is generally not possible to design in strict tolerances in most cases. Thus, the upper and lower limits of the design variables were defined with a 10% band, i.e., $0.9\alpha_0 < \alpha = \{E_1, E_2, \nu_{12}, G_{12}\} < 1.1\alpha_0$.

$$\begin{cases} g_1(x): \dfrac{E_2}{E_1} > 0 \\ g_2(x): \dfrac{G_{12}}{E_1} > 0 \\ g_3(x): \dfrac{G_{23}}{E_1} > 0 \\ g_4(x): \sqrt{\dfrac{E_2}{E_1}} - |\nu_{12}| > 0 \end{cases} \tag{6}$$

## 2.4 Damage I: circular hole

The circular hole damage type is parameterized by their Cartesian $x$- and $y$-positions on the plate and the radius $r$ thereof. It is important to note that this damage model is robust and can be interpreted as a hole by itself or by corrosion, erosion, tooth, etc., where there has been localized loss of material and stiffness. Other interpretations can be given to this model, but the goal of the adopted model is to intervene on structural physical characteristics (mass or stiffness) of the composite in question

$$\text{Minimize} \quad J = \sqrt{\frac{1}{n}\sum_{i=1}^{n} c_i \left(1 - \frac{\omega_i^{\text{damaged}}}{\omega(X)_i^{\text{calculated}}}\right)^2} \tag{7}$$

where $n$ is the number of natural frequencies obtained, $c_i$ the scalar weighting factor to higher natural frequencies, $\omega^{\text{damaged}}$ the natural frequencies corresponding to the actual damaged structure and $\omega^{\text{calculated}}$ the natural frequencies of the structure modeled by finite element comprising by one or more damaged areas, according to a parameterized vector design of variables.

This first objective function is based on the root mean square error (RMSE) of the first natural $n$ frequencies of the plate. The minimization of this objective function suggests that the natural frequencies of the actual damaged plate will be equal to the frequencies obtained by the optimization process, that is, its minimum value will be zero ($J_1 = 0$). However, to improve the damage detection process, it is essential to work with an adequate objective function, aiming at a shorter computational time and better identification.

According to [14], parameter selection is a key issue in optimization processes. Confidence in different test values for measuring parameters and initial estimates can be expressed by means of weights in the objective function. Suitable weighting factors (weights) can improve optimization results significantly. However, this requires a good deal of knowledge about the assumptions used in the finite element modeling of the system, as well as the possible sources of error in the analysis.

According to the authors, damage detection methods that take into account higher order natural frequencies are more reliable. Therefore, in the objective function $J_1$, we take a weight vector $C$ composed of scalars ci of increasing order, $C = \{1, 2, 3, 4, 5, 6\}$, to give greater importance to higher order frequencies.

It is known that structural damage can be characterized as changes in the physical or geometric properties of a structure at levels that not only alter its initial design conditions, but also allow it to perform the function for which it was designed [36]. In addition, the models of holes as models of damages were chosen due to their importance in the aerospace industry in question [11, 15, 17, 33, 39].

### 2.5 Damage II: localized stiffness reduction

It is known that the occurrence of damage in a structure modifies some of its mass, stiffness or damping properties, changing the vibrational response of the structure. So the damaged model used in this study will be based on local stiffness reduction which results in changes in dynamic parameters such as natural frequencies, mode shapes and damping ratios. The background of this model, for the discretized undamaged structure, according to [6], the eigenvalue equation can be written as

$$Kq_i = \lambda_i M q_i \quad \text{for} \quad i = 1, \ldots, n. \tag{8}$$

where $K$ and $M$ are the stiffness and mass matrices, respectively, $\lambda_i$ is the $i$th eigenvalue, $q_i$ is the $i$th eigenvector and $n$ is the computed or experimentally available number of mode shapes of the undamaged structure. If the structure undergoes some kind of damage, which reduces its stiffness, Eq. (1) is rewritten as

$$K^* q_j^* = \lambda_j^* M q_j^* \quad \text{for} \quad j = 1, \ldots, m. \tag{9}$$

where $K^*$ is the stiffness matrix, $\lambda_j^*$ the $j$th eigenvalue, $q_j^*$ the $j$th eigenvector and $m$ is the computed or experimentally available number of mode shapes of the damaged structure. The mass matrix of the damaged structure is assumed equal to the mass matrix of the undamaged structure. Matrices $K$ and $M$ are assumed symmetric positive definite and, therefore, the eigenvalues $\lambda_i$ are positive and the eigenvectors $q_i$ can be taken as $K$-orthogonal. Similar conditions apply to $K^*$, $\lambda_j^*$ and $q_j^*$.

Considering the mass normalization of the mode shapes, the orthogonality conditions are defined by

$$q_i^{*T} K^* q_j^* = \delta_{ij} \lambda_i^* \text{ with } \begin{cases} \delta_{ij} = 0 & \text{for } i \neq j \\ \delta_{ij} = 1 & \text{for } i = j \end{cases}. \tag{10}$$

Since the damage stiffness matrix is given by $K^* = K - \delta K$ and on element $e$ the corresponding perturbed matrix is $\delta \mathrm{K}_e = \delta b_e \mathrm{K}_e$, where $\delta b_e$ ε [0, 1[ is the damage parameter, expression (3) yields

$$\sum_{e=1}^{N} q_{ie}^{*T} K_e q_{je}^* \delta b_e = q_i^{*T} K q_j^* - \delta_{ij} \lambda_{ij}^*. \tag{11}$$

Then, to simplify those notations, we consider $\alpha = \delta b_e$ as the multiplier parameter in the element. So, the total stiffness reduction can be introduced as $\beta$

$$\beta = 1 - \alpha. \tag{12}$$

Structural damage often causes a loss of stiffness in one or more elements of a structure, but not a loss in the mass. In the theoretical development that follows, the structure is modeled in a finite element analysis (FEM), and damage is assumed to affect only the stiffness matrix of the system (Fig. 2). Small changes in the stiffness of the system produce small changes in the modal frequencies and mode shapes. When damage occurs in the structure, it can be represented as a small perturbation in the original system [30].

The main goal of the optimization procedure is to adjust the fractional order α and the damaged element number $N_{\text{elem}}$ to obtain the best properties of the damage identification algorithm. Hence, the optimization problem can be written as follows:

$$\text{Minimize} \quad J = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( 1 - \frac{\omega_i^{\text{damaged}}}{\omega_i(\overrightarrow{X})^{\text{calculated}}} \right)^2} \tag{13}$$

Subject to:

$$\begin{cases} 1 < N_{\text{elem}} < N_{\max} \\ 0 < \alpha < 1 \end{cases} \tag{14}$$

where $\omega_i^{\text{damaged}}$ is the target frequency shift obtained either from measurements (in the case of experimental validation) or from FE test cases (numerical validation) and $\omega_i^{\text{calculated}}$ is the frequency shift obtained from the surrogate model.

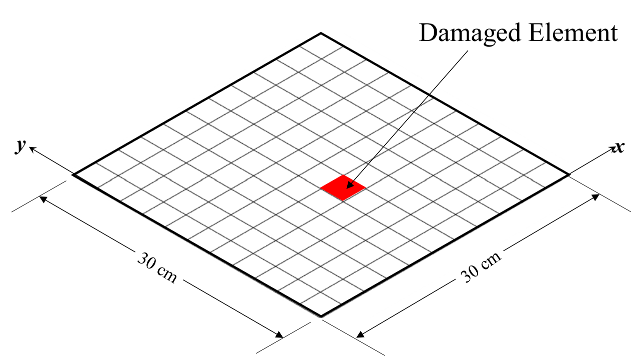


**Fig. 2** Meshed composite plate with a damaged element (damage case 2)

### 2.6 Experimental procedure

The method developed in this part of the work takes into account the optimization of $J_1$ objective function composed of the first three natural frequencies. Therefore, it is necessary to obtain the first ten natural frequencies of the analyzed structure, since the first six frequencies in this case will be zero due to boundary conditions for the plate to be free–free, i.e., no displacement restrictions on axes $x$, $y$ and $z$, as little rotations in relation to the same axis, totaling six degrees of freedom adding to the fact that the seventh mode of vibration was not captured in the experiments, namely we used the correspondents frequencies for modes of paragraph 8–10.

According to [25], there is a useful excitation frequency range limited by a cut-off frequency, which means that the structure has not received sufficient energy to excite the modes beyond this frequency. If the selected impact hammer (input) is not able to excite all frequencies, both coherence as the FRF obtained in the measurement are damaged, or some vibration modes are not properly excited, its acquisition is not possible.

Composite structures have excellent performance, although this significantly deteriorates the presence of damage. Unfortunately damage due to impact events, for example, is difficult to visually detect, and, therefore, needs methods for non-destructive testing of these structures. According to [10], although these materials present other failure modes such as cracks in the matrix, the fiber breakage or delamination damage these mechanisms produce changes in the vibrational response similar to a metal structure when there is a damage.

For the reasons explained in the previous chapters of this work, a significant importance in the application of the methodology evaluated in detecting damage in a real structure. Furthermore, a laminated composite carbon fiber/epoxy plate was manufactured at NTC/UNIFEI. The carbon fiber is of the type AS4, unidirectional, GA45 and 5052 epoxy resin (Huntsman). The plate was produced by the VARTM process—transfer molding vacuum-assisted resin symmetrically to 12 layers depending on the orientation of 0° and 90°, i.e., [0/90]3s. Each layer of the laminate in turn has 0.1824 mm, with the final structure being 2.1886 mm thick. The orientation of the fibers of this compound is structured symmetrically about the median plane of the laminate, which means that each layer above the median plane has a layer identical to the similar distance below the average plane. The laminate was made using a 30 $cm^2$ edge and subsequently damage was added to the medium, this being a circular hole of 8 mm radius in the central position of the plate ($x = 0.15$ cm and $y = 0.15$ cm), as shown in Fig. 3.

The mechanical properties of the laminate, used in the design of the numerical model, are the result of a study on the estimation of material properties for model adjustment purposes. The numerical results in the following paragraphs will show the process performed for this purpose.

For operational and experimental limitations, the laminated plate was simulated with free boundary conditions. The assay was then performed with the aid of a laser vibrometer (Brand: Ometron, Model: VQ-500-D) to avoid contact sensors such as accelerometers and used a portable system for acquisition of data. Figure 4 shows the experimental scheme used in this work. The detection method developed in this work, briefly, will take place in two steps.

The first step of damage detection combines data from a finite element modeled structure without damage and with a potentially damaged structure. This first step will employ some damage criterion. For example, the DLAC (Damage Location Assurance Criterion) could be an interesting criterion for detecting whether or not there is the presence of any damage. DLAC compares the frequency obtained experimentally with a finite element model to locate and quantify damage. This criterion calculates the correlation between the change in frequency, $\Delta\omega$, expected from the finite element model and the actual changes, $\delta\omega$, estimated from experimental procedures as shown in the equation below [29]:

$$DLAC = \frac{\left|\{\Delta\omega\}^{\mathrm{T}}\{\delta\omega\}\right|}{(\{\Delta\omega\}\{\Delta\omega\})\left(\{\delta\omega\}^{\mathrm{T}}\{\delta\omega\}\right)} \quad (15)$$

The DLAC assumes the value of 1 for an exact pattern match between the sets of natural frequencies and 0 for patterns that are uncorrelated. This method only requires the measurement of a few frequency changes between the undamaged and damaged states of the structure. In the application, a DLAC value of 0.9 (90%) would be considered good correlation between the model and the actual structure, values above 0.90 are considered similar and values below 0.9 represent dynamic data that are significantly different [7].

The second step is the damage identification process. This identification routine optimization algorithm is introduced to make the search for damage to the geometry of the structure, with interaction between the finite element software where the model structure is adapted to receive the design variables and optimization software that will hold a series of calculations order to generate input data for the finite element software. The flowchart in Fig. 5 displays the steps to be performed during the search for damage. The method for detecting damage in this study meets three of the four criteria proposed by [26], the

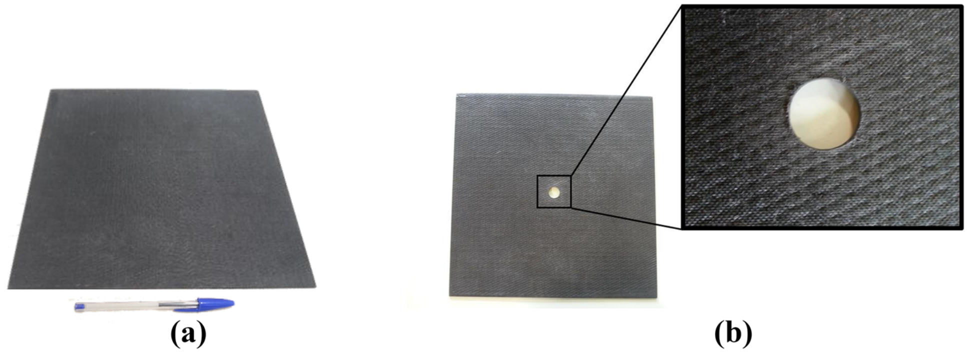


**Fig. 3** Experimental case: undamaged composite laminated plate (**a**) and a damaged plate with a circular hole (**b**)

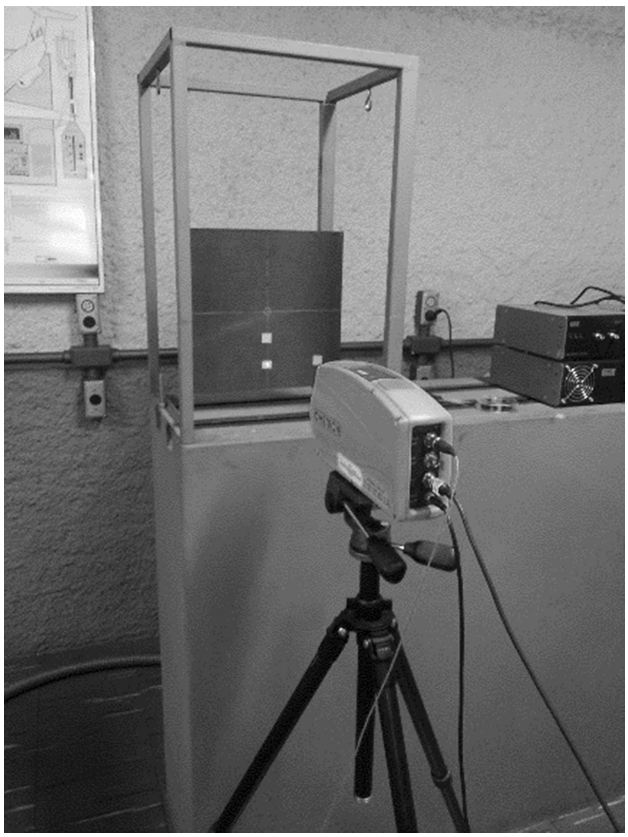

**Fig. 4** Experimental setup of damage detection using contactless vibration measurement

detection, localization and quantification of damage (damage models studied).

In addition, Modal analysis can be quite sensitive when the size of the damage is no less than 10% of the surface area being monitored by a sensor (e.g., delamination in composite materials). It has thus to be kept in mind that monitoring of a small delamination will require a dense network of sensors (e.g., a delamination of 5 mm in diameter requires a sensor network with sensors approx. every 50 mm to detect the damage) [4].

Complementing the method investigated in this work, the addition of Gaussian white noise in the optimization process was considered to verify the robustness of the built method to simulate ambient noise coming from a measurement error from sensors or from external environmental.

## 3 Numerical results

### 3.1 Model adjustment

The results of the search process for the optimal properties for the model adjustment are shown in Table 2. Note that in these cases the averages were not taken, but the best set of values that generated the lowest fitness, i.e., a smaller error between the numerical and experimental model. This process is necessary due to the fact that experimental errors are always present, either due to problems in non-perfect boundary conditions, sensor noise and non-homogeneous material. Therefore, the results of Search 4, as highlighted in Table 2, were used as properties in the numerical model to correlate the models.

Next to the optimization process, the properties that best related the models were used; we obtained the results for numerical frequency (Table 3) with a very small error. Figure 6 exhibits the behavior of frequencies in the experimental and numerical characters before and after the optimization process properties (set response).

### 3.2 Damage detection

Figure 7 shows the results obtained for three simulations performed simultaneously for the detection of a central hole. The optimization technique used is a heuristic method. It is interesting to get an average of some simulations, because the method is based on a system of random searches (probabilistic). The results of numerical simulations show that the algorithm developed obtained good accuracy in identifying the presence of a relatively small circular hole in the structure in question. This specific case (Fig. 8) consider a hole at the center of the

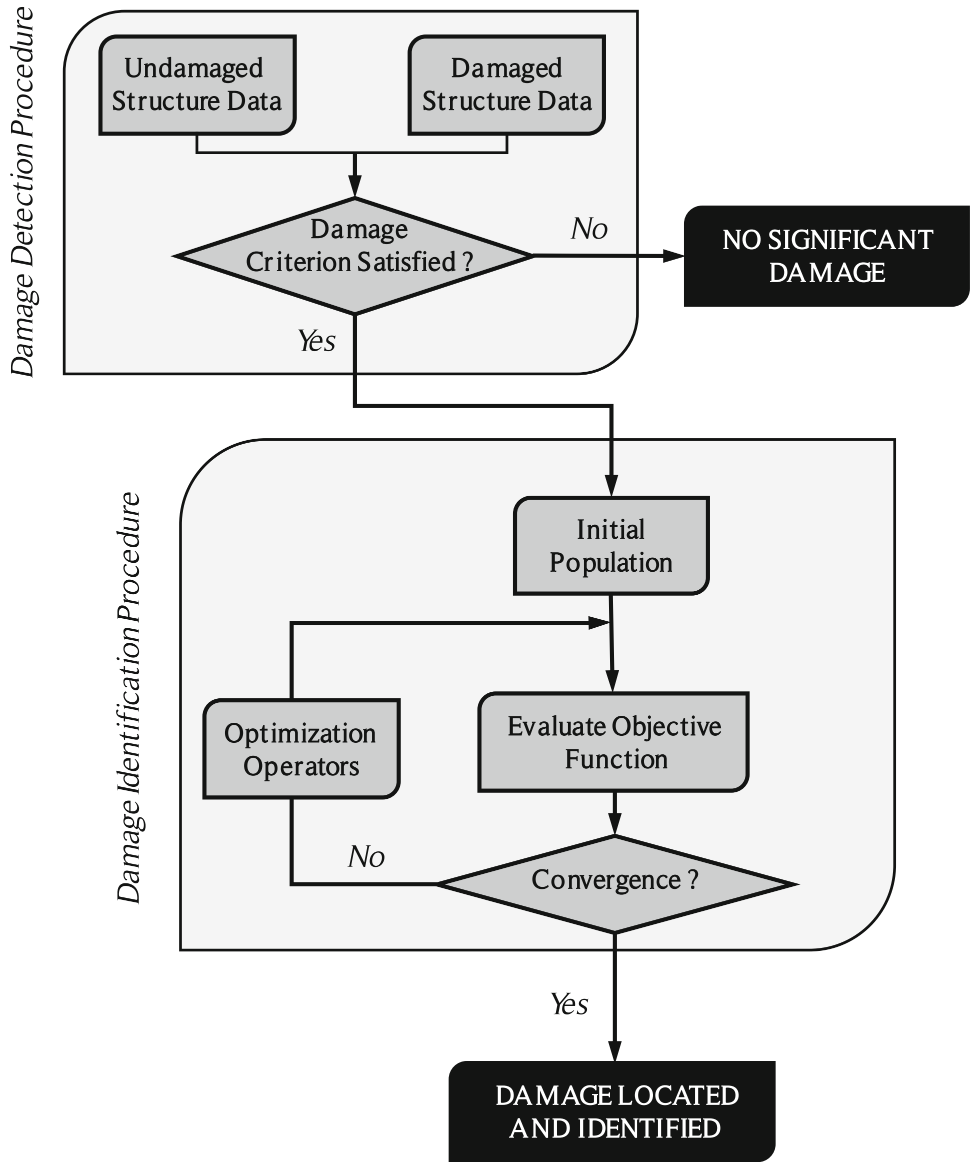


**Fig. 5** Flowchart for damage detection and identification procedure using genetic algorithm

**Table 2** Optimization results for model adjustment showing the best values for the search 4

| Search | $E_1$ (GPa) | $E_2$ (GPa) | $\nu_{12}$ | $G_{12}$ (GPa) | Fitness |
|---|---|---|---|---|---|
| References | 88.80 | 6.30 | 0.29 | 7.56 | – |
| 1 | 83.52 | 5.69 | 0.31 | 8.31 | 0.16 |
| 2 | 82.8 | 5.27 | 0.31 | 8.36 | 0.03 |
| 3 | 82.47 | 5.67 | 0.31 | 8.31 | 0.15 |
| 4 (best) | 83.01 | 5.13 | 0.32 | 8.36 | 0.01 |

**Table 3** Model adjustment results showing excellent efficiency with errors smaller than 0%

| Mode | Undamaged (Hz) | Initial (Hz) | Adjusted (Hz) | Error (%) |
|---|---|---|---|---|
| 8th | 123.50 | 129.31 | 123.85 | 0.2826 |
| 9th | 155.00 | 161.43 | 154.81 | 0.1227 |
| 10th | 176.00 | 176.74 | 175.98 | 0.0114 |

plate. However, it is important to take into account damages (circular holes in this case) in other positions, that is, in a position outside the axis of symmetry of the plate. As can be seen from Fig. 8 the proposed method was able to identify such damages.

Data obtained by any measurement are usually contaminated by noise, typically from different sources. Noise may be associated with environmental factors, human errors, accuracy of measuring devices, systematic errors and other specific ways, affecting in a direct way the measured data. For these reasons, noise was added in three different levels to evaluate the robustness of the proposed

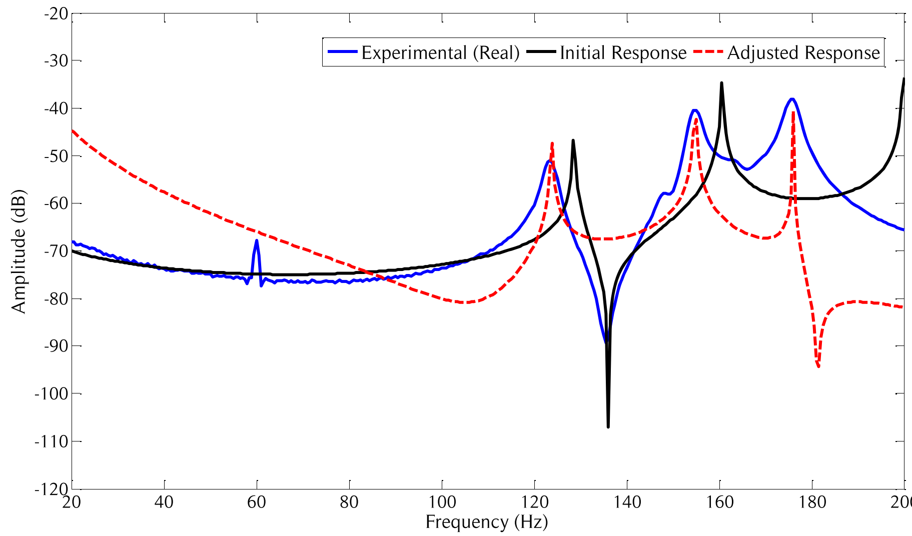


**Fig. 6** Initial, experimental and optimized FRF response of the laminated plate (color figure online)

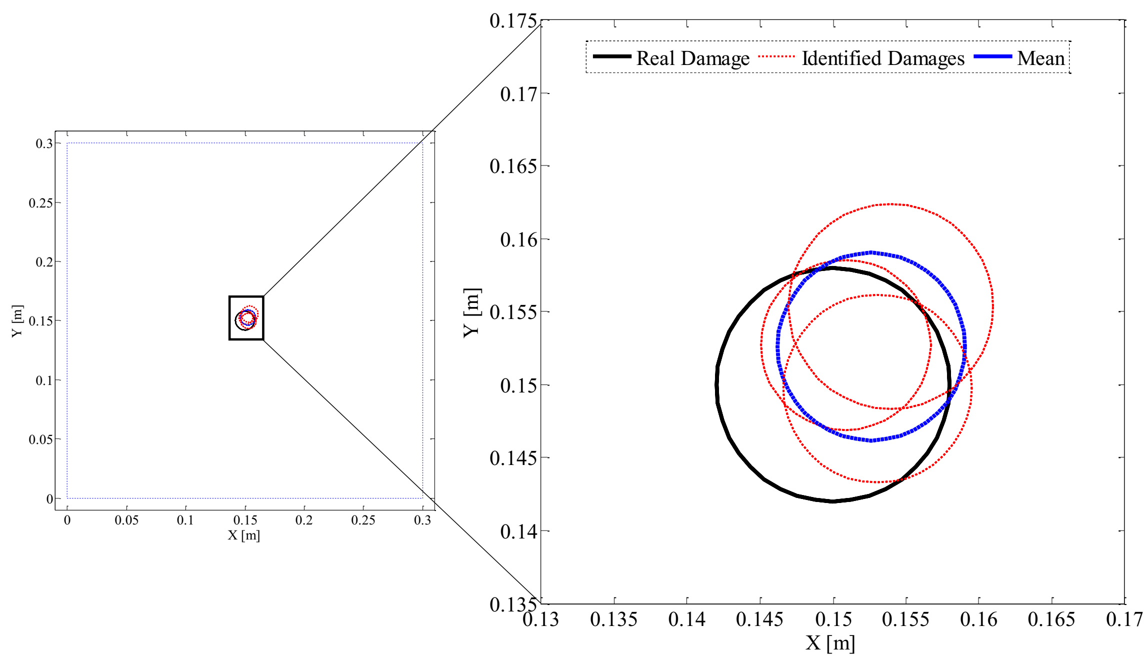


**Fig. 7** Numerical results for damage detection being precisely detected after 100 generations (color figure online)

optimization algorithm. The noise was added as a Gaussian white noise, i.e., zero mean and deviation according to the noise level (Fig. 9).

According to [5], noisy simulated data can be defined as $\omega_{noisy} = \omega \times (1 + u\alpha)$, where ω is the calculated measurement, u is a random number in the interval $[-1, 1]$, and α is a noise level parameter (1–10%). The addition of noise further reduces the probability of correct damage classification.

Initially, a noise level below 1% of the output signal sequence was added, and was then increased to values of 5 and 10% (Fig. 9). The excellent performance obtained by the proposed method (also in presence of high noise—up to 10%) can be explained by the fact that objective function is purely based on natural frequencies. This function is robust to variations for this specific case of damage identification.

It is observed in both Table 4 and Fig. 10 that there is a small change in the natural frequency of the carbon fiber plate. The same figure also shows the vibration modes corresponding to each natural frequency for the structure without damage. In fact, as stated in this paper, the change of the natural frequencies of a structure is a good indication of damage on a global character. In addition, the presence of the circular hole does not significantly alter the dynamic behavior of the structure, with a maximum variation of 2 Hz for 9th mode.

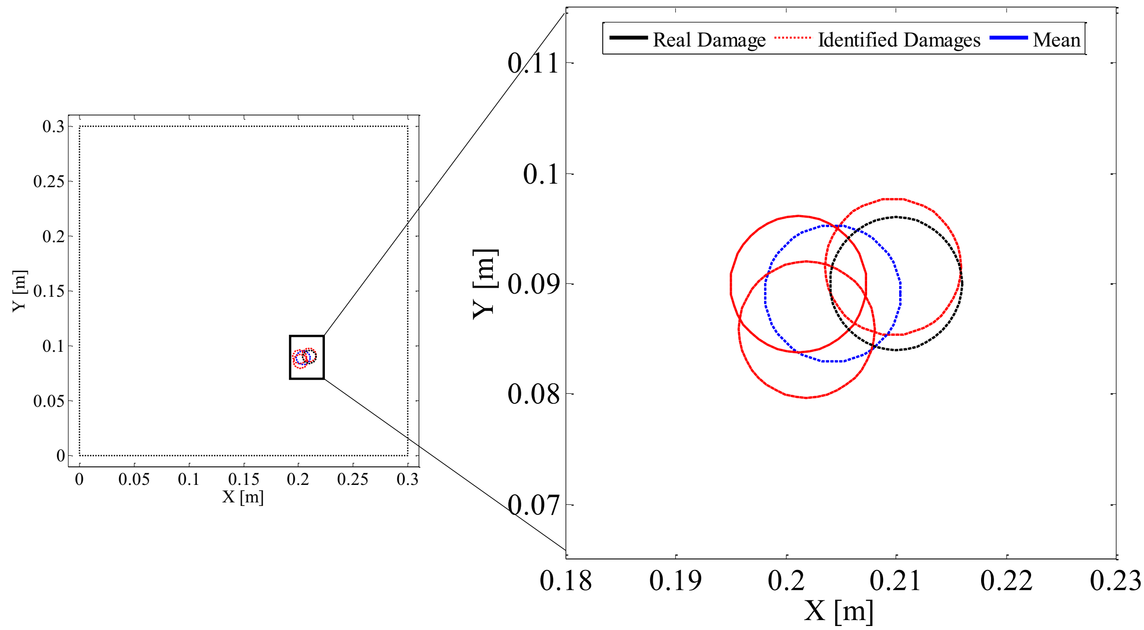


**Fig. 8** Numerical results for damage detection detected after 100 generations in a different position (color figure online)

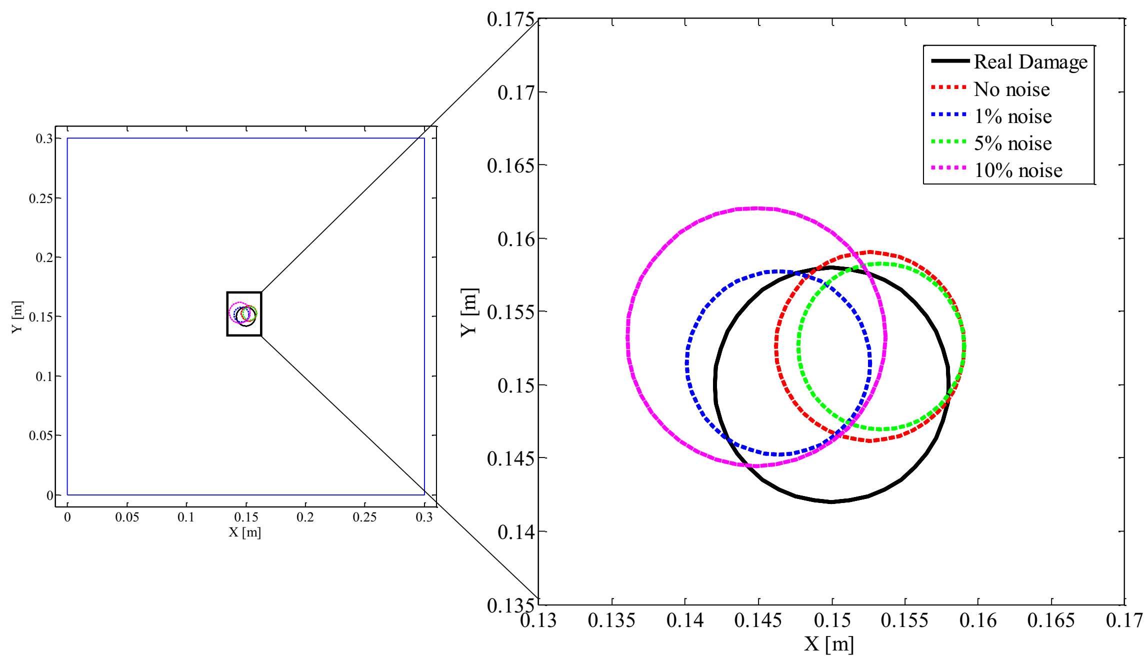


**Fig. 9** Numerical results of damage detection considering white Gaussian noise at the output response (color figure online)

**Table 4** First three non-zero values of natural frequencies for the undamaged and damaged plate

| Mode | $\omega_n$ undamaged (Hz) | $\omega_n$ damaged (Hz) |
|---|---|---|
| 8th | 123.5 | 122.5 |
| 9th | 155.0 | 153.0 |
| 10th | 176.0 | 175.0 |

Figures 11 and 12 show the result of the search performed by the optimization algorithm for structural damage imposed on the laminate. It is observed that the method was not able to detect with great accuracy the presence of the hole (Table 5). This mainly happens because the inserted structural damage is not sufficiently great as to cause a significant change in modal properties, in this case the natural frequencies of the laminate. However, the

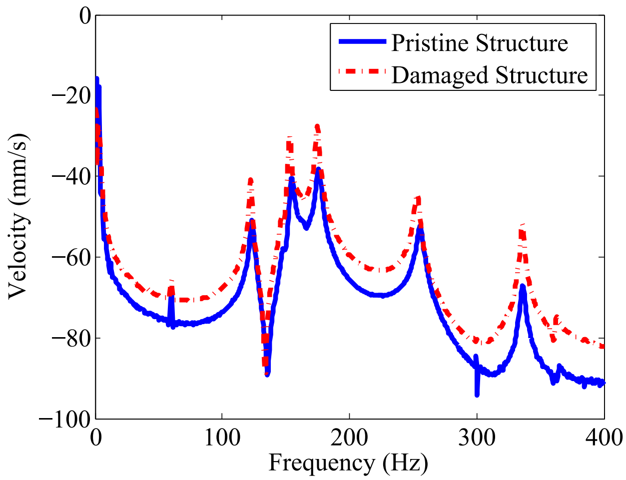


**Fig. 10** Experimental FRF for the damaged and undamaged composite plate showing a small variation in frequencies

damage is detected at a region that is not so distant from the actual bore which leads for example, in the case of inspection of large structures (fuselage of aircraft, for example), a starting point (region with possible damage) facilitates the identification of the damage.

Following the idea that the plate has a total area of 900 $cm^2$, a rectangular imaginary area (red dashed line in figure) may be formed in an area covering both real and average damage that leads to obtaining an area possibly 8.66 $cm^2$ damaged, or the method promotes a reduction in an area unknown to be monitored to an area already known with possible damage, and less than the initial, promoting a reduction of about 99% of the region searched in the maintenance process, repair, identification, etc. It was also observed that the method effectively met along the axis of the damage location *x*, with an error of only 0.86%.

Subsequently, there was the opposite problem now of treating the damage as a structural change in the physical properties (stiffness). From the natural frequencies collected from the FRF-damaged plate with a circular hole, it was possible to make the search method for identifying the damaged element (loss of strength). It can be seen in Table 6 that the element 61 is expected to be damaged (center of the plate). However, the local loss of stiffness is unknown ($\alpha$), but is believed to be of very low order due to the circular hole inserted. Despite not having precisely identified the damaged element in this process, the identified damage is very close to the actual damage (Fig. 13).

According to [4, 22] that there is no need to locate damage to within a few millimeters. The cost and efforts involved in predicting damage to a high-level accuracy can be prohibitive. In addition, because of measurement, model and signal processing inaccuracies, systems that claim to predict damage with great accuracy are likely to give false alarms. Hence, a better idea is to roughly locate damage in the structure and then use standard NDT methods such as acoustic emission and ultrasound for closer analysis of damaged area. Modal analysis methods are useful in roughly locating the damage.

It is noteworthy that the damage considered as local change in stiffness behaved closer to the real case. The insertion of damages in the laminated plate induced a slight variation of the natural frequencies in the experimental tests. The same phenomenon was observed through

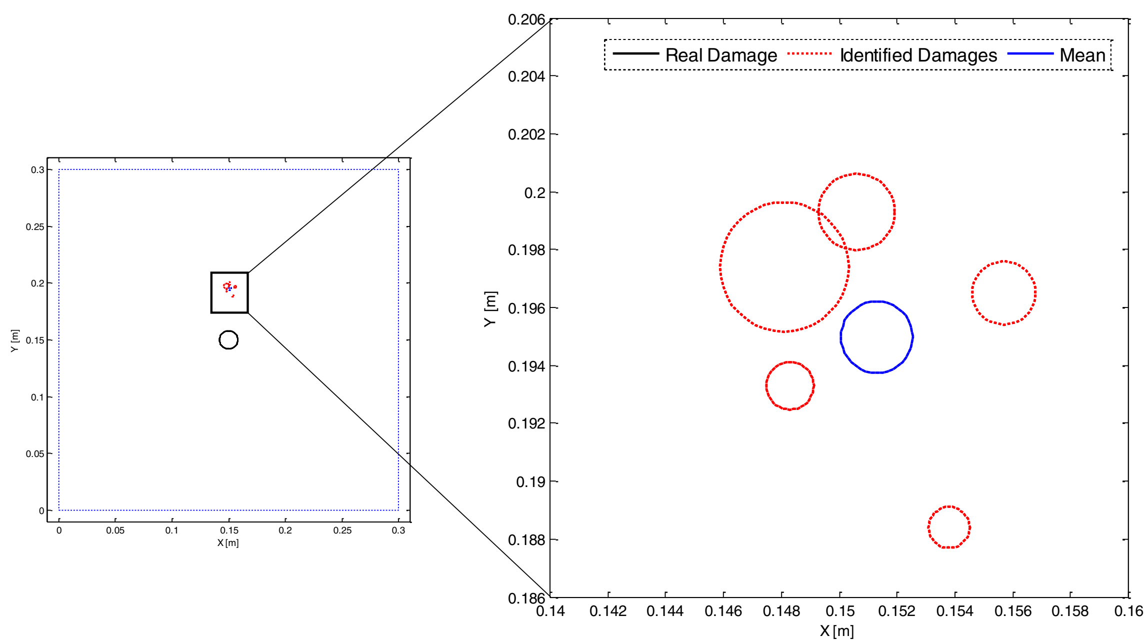


**Fig. 11** Results of the damage search process considering the experimental laminated carbon/epoxy plate

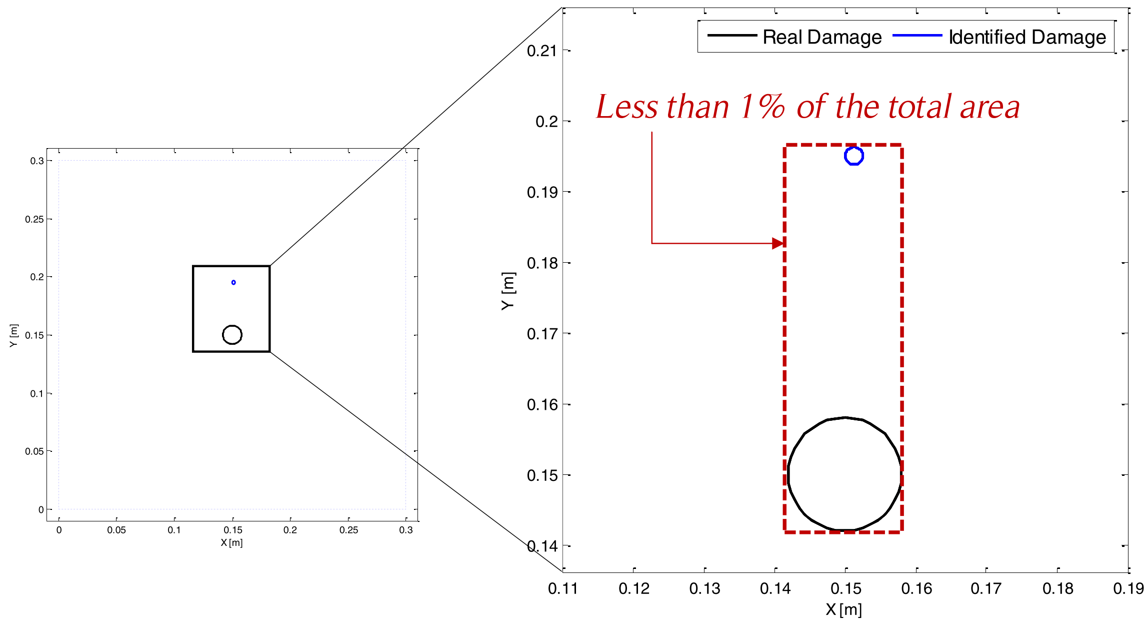


**Fig. 12** Minimum area covering the obtained and induced damage, producing a global reduction of area inspection (color figure online)

**Table 5** Results for the damage detection algorithm search considering circular holes as a damage

| | $X_1$ (m) | $Y_1$ (m) | $R_1$ (mm) | $J$ |
|---|---|---|---|---|
| Objective | 0.1500 | 0.1500 | 8.0000 | – |
| Search 1 | 0.1483 | 0.1933 | 0.8220 | $\sim 0$ |
| Search 2 | 0.1538 | 0.1884 | 0.7092 | $\sim 0$ |
| Search 3 | 0.1481 | 0.1974 | 2.2314 | $\sim 0$ |
| Search 4 | 0.1506 | 0.1993 | 1.3229 | $\sim 0$ |
| Search 5 | 0.1557 | 0.1965 | 1.0931 | $\sim 0$ |
| Mean | 0.1513 | 0.1949 | 1.2357 | – |
| SD | 0.0033 | 0.0042 | 0.6057 | – |
| Error (%) | 0.8667 | 29.9867 | 84.5535 | – |

**Table 6** Results for the damage detection algorithm search considering local stiffness reduction as damage

| | $N_{elem}$ | $\alpha$ ($\times 10^{-4}$) | $J$ |
|---|---|---|---|
| Objective | 61 | Unknown | 0 |
| Search 1 | 84 | 9.0380 | $\sim 0$ |
| Search 2 | 84 | 12.9761 | $\sim 0$ |
| Search 3 | 84 | 12.0023 | $\sim 0$ |
| Search 4 | 84 | 12.7378 | $\sim 0$ |
| Search 5 | 84 | 7.4103 | $\sim 0$ |
| Mean | 84 | 10.8329 | – |
| SD | 0 | 2.4761 | – |

numerical modeling. Therefore, the proposed methodology can be used to simulate the phenomenon in a similar way.

As previously mentioned, the article mainly addresses the rapid methodology of integrating optimization methods with numerical modeling methods (finite element) in addition to the modal response benefits. However, normal disadvantages occur. One is because no damage can be detected on a very small scale. In this study, the use of this methodology in larger structures (fuselage of aircraft, ships, submarines, etc.) is considered and the damage is aimed at detecting up to 1 square inch (a barely visible impact damage).

## 4 Conclusions

The study was focused on the detection and identification of structural damage based on dynamic parameters of vibration of a square plate of composite material, including finite element numerical modeling and programming for the inverse problem detection using a genetic algorithm. Numerically the problem of vibration of a laminated composite material was validated by a finite element tool allowing choice of the correct parameters for modeling the inverse problem. Eventually the damage modeled as circular holes, the radius of the hole proved to be the most difficult variable to be identified with precision. The radius value is in this case the extent of structural damage present in the medium (structure).

The presented damage detection method showed to be efficient. The numerical damage is successfully detected and false damage detection is avoided, despite the presence of experimental noise or modeling errors. In both application cases, the damage detected has a good correspondence with the experimental damage. Even though, in the

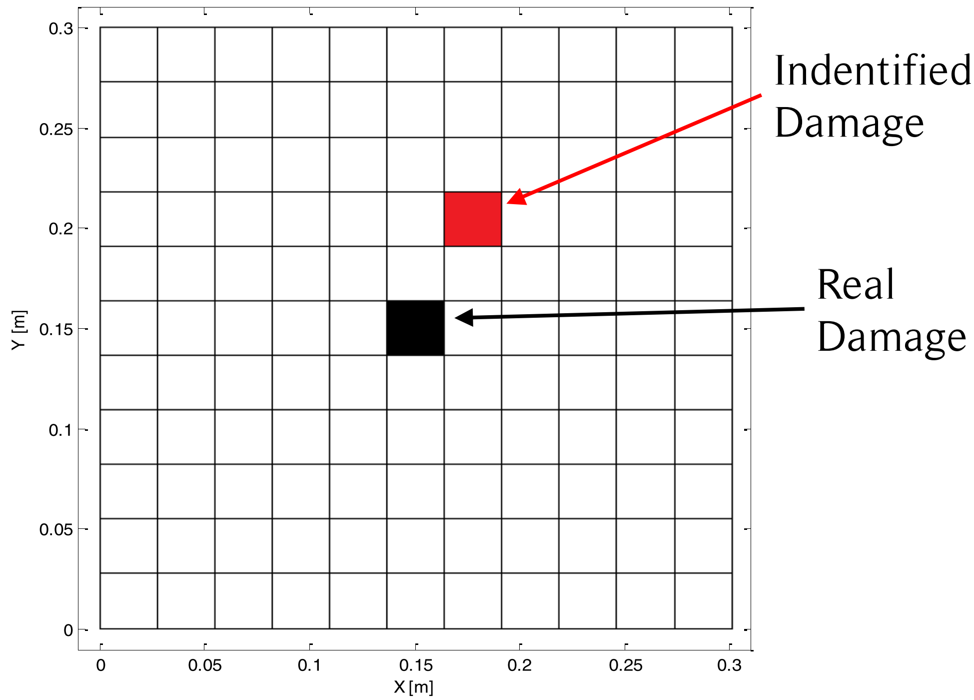


**Fig. 13** Experimental results for the damage detection showing a calculated damaged element number near of a real damaged element

case of the real composite structure, the experimental setup was not the optimum, the damage detected was still consistent with the experimental damage.

The application of this method in a real structure confirmed that the use of natural frequencies is more qualitative than quantitative for the identification of damages. Experimental tests showed that there is rather the variation of certain frequencies in the presence of structural damage, but the degree of severity was not large enough to cause wide variation ranges of the set of modal parameters. Then, it was observed that natural frequencies are good parameters to obtain a global criterion for damage detection.

The frequency response is a good global criterion for damage detection; however, when a set of frequencies is used it may be an indicator of the possible location of damage. Still, the use of natural frequencies is a subcomponent of evaluation in this study.

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