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Review

The use of intelligent computational tools for damage detection and identification with an emphasis on composites – A review

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ABSTRACT

Today, the Structural Health Monitorin (SHM) methodology is the main way to deal with the detection and identification of damages in a range of engineering sectors, mainly in the military and civil aerospace industry. The need to monitor damages and failures in increasingly complex structures has led to the development of various detection techniques. Identification of damages through intelligent signal processing and optimization algorithms are particularly emphasized. The methods discussed here are mainly elaborated by the evaluation of modal data due to the great potential of their application. Moreover, the optimization of damage identification is approached through methods of optimal positioning of sensors for the acquisition of the data that must be evaluated so that conclusions can be made. This article discusses the use of computational and intelligent techniques for structural monitoring in the form of a review with emphasis on composite materials. Despite the excellent mechanical performance already known about composite materials, they have a weak point. While damages, in a metallic material are easily visible (in some cases), composite materials often have the superficial appearance as if in perfect condition, when, inside, there are serious damages. This paper can be seen as a guideline or a starting point for developing and improving SHM systems. The contents of this paper aim to help engineers and researchers find a starting point in developing a better solution to their specific structural monitoring problems, either by inverse methods, pattern recognition, and intelligent signal processing.

1. Introduction

Structural health monitoring is based on the use of reliable and robust indicators that allow the detection, location, quantification and, if possible, prediction of damages in mechanical structures. The studies related to the detection of damages in engineering structures are of notable interest, since the detection of a structural modification is of fundamental importance to avoid the occurrence of serious social, economic and environmental consequences. In recent years, several studies have been carried out aiming to develop several indicators based on the characteristics of static and dynamic responses of mechanical structures. Damage can be considered a change in the geometric or physical properties of a material. A structure with the presence of damage will have a mechanical behavior (parameter) different than a sound structure. These parameters are directly affected by the variation of the physical properties of the structure, such as its mass and especially its rigidity. In general, structural damage causes a local reduction of the rigidity of the structure and, as a consequence, modifies its characteristics.

Most damage indicators are based on time domain or frequency analysis to extract information through the modal characteristics or evolved indicators constructed from these characteristics. These indicators have proved to be efficient, but there are still areas that need to be improved. Many indicators present sensitivity problems, need a reference state and do not present the probability of detecting false alarms, reducing their reliability.

Nowadays, mainly due to the development of new materials, composite materials have been replacing traditional materials due to their high structural performance. With this, new damage detection strategies must be taken into account and further evolved. For example, while damage to steel armor is easily visible (mostly), composite materials often have the surface appearance as if they were in perfect conditions, when, in its interior, there are serious damages.

Composite materials have been widely used over the years in the aerospace industry and in other engineering applications where structural weight is one of the main justifications for their use. This is due to its excellent advantages such as: high strength and remarkable stiffness in relation to its specific mass, besides its high capacity to withstand

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(a) Inspection of wind turbines. (b) Inspection of aeronautical fuselages. (c) Bridge monitoring.

Fig. 1. An overview of the potential fields of application of structural monitoring techniques (retired from [72]).

fatigue and corrosion [52].

However, such composite structures, in service, may exhibit certain failure mechanisms, such as matrix cracking, fiber rupture and delamination. These failures are caused due to static overload, impact, fatigue, design errors and overheating. Essentially, delamination is considered the greatest "weakness" of laminated composite materials, leading to loss of structural integrity. Delamination can easily spread throughout the laminate of a composite structure and can lead to catastrophic failure when undetected [13].

Programmed visual inspections are usually time-consuming, expensive and require components to be readily accessible, as shown in Fig. 1. Other conventional methods (ultrasonic methods, thermography, X-rays and others) for prior detection of composite damage are often costly and depend heavily on the operator's skill and experience. Structural Health Monitoring (SHM) technologies offer a promising alternative and involve continuous monitoring of a structure using a non-destructive testing approach (NDT) using integrated sensors [43]. In addition, acoustic emission can also be seen as a SHM technique, because it is based on integrated acoustic sensors. But, nevertheless, it depends heavily on the operator's skills and experiences.

SHM inspections that explore vibration metrics are methods based on the principle that degradation due to damage to a structure changes vibration parameters such as natural frequencies, vibration modes and structural damping. Therefore, it is possible to analyze the measured vibration parameters to characterize and identify the presence of damage using inverse modeling techniques and computational intelligence.

According to [38], the SHM methodology aims to provide the tools for the constant or periodic monitoring of critical structural assets in order to determine the need for corrective actions and to prevent catastrophic failures. The SHM methodology therefore has potential application in many areas of engineering, including aerospace, mechanics and civil engineering. The basic idea of an SHM system is to provide a structure of interest, detection and analysis capabilities, and allow monitoring and evaluation to be performed periodically or continuously, autonomously. The SHM method offers potentially greater security, since failures do not evolve to an alarming level. As the potential benefits of this incorporation of SHM are enormous, a great deal of research is underway around the world to develop and improve systems that bring some degree of "self-awareness" to man-made structures [38].

The benefits of a system employing the SHM methodology include (but are not limited to) [38]:

- Allow optimum utilization of the structure, minimized downtime and avoid catastrophic failure;
- Give the designers an improvement in their products;
- Drastically change the work organization of maintenance services. That is, replacement of scheduled and periodic maintenance inspection by maintenance based on performance (or condition), reducing the current maintenance work.

In summary, the development of composite structural monitoring technologies aims to provide safety and cost savings (mainly in regard to maintenance). However, the number of practical applications of these technologies is still limited. This is mainly due to the complexity of possible damage scenarios and the high performance requirements of the identification methods employed. The study developed in this work refers mainly to the relationship between these two aspects, in order to reach a specific level of maturity. Detailed information on the concepts employed for this to occur will be presented in the following sections. The knowledge contained in these sections is necessary to fully understand the theme studied herein. The results obtained in this research clearly indicate the remarkable ability of intelligent computational methods to identify damages. The algorithms in their inverse formulations are capable of predicting delamination parameters.

This work aims to conduct a study on the main methods and methodologies used in the area of SHM for the detection and identification of damages in mechanical structures. The main propose of the article is based on the use of inverse methods for the detection of damages; for this, modal metrics and algorithms are discussed. The in-depth review work carried out in this study serves as a starting point for researchers and engineers in the SHM area who wish to develop or evolve a monitoring system that is capable of achieving an adequate level of confidence.

Although many studies have been reported on the structural health monitoring and damage detection, very few have been focused on the applied computational techniques for damage identification. To the authors' best knowledge, there are no (or very scarce) studies in the literature investigating the review of optimization methods for inverse problems of damage identification in mechanical structures. Details on heuristic optimization methods, as well as the formulation of inverse problems and construction of objective functions that significantly impact the problem, are presented. Here is the main contribution of this pioneering work.

This manuscript is organized as follows: in Section 2, a general bibliographic review is presented, addressing the techniques used in the study, mainly about mechanical vibrations and inverse methods.

Several algorithm types are discussed in Section 2. SHM based vibration (Section 2.1), Optimization algorithms (Section 2.2), artificial neural networks (Section 2.3), and so-called unconventional methods (Section 2.4) are also discussed. The type of structure analyzed is not the focus of this study, but rather the method of analysis. Finally Section 3 draws the conclusions.

2. State of art

Damage is the main cause of structural failure and occurs frequently in mechanical structures. In recent decades, special attention has been given to methods of detecting damage at an early stage to avoid sudden failure of structural components. More specifically, the monitoring of structural integrity based on the vibration of structures has been the focus of attention of many researchers in order to obtain efficient tools of great importance for the civil, aeronautical and mechanical engineering communities. In addition, many research fronts have been focused on the development of reliable damage indicators that allow, in addition to detecting damage, identifying it in terms of location.

One of the first published studies of relevance was developed by [2]. The authors have developed a non-destructive method of assessing structural integrity based on vibration measurements. It was shown that the vibration measurements made in the structure (receptance function) can be used, together with a suitable theoretical model (reference), to indicate the location and magnitude of damage, in a one-dimensional model.

At the same time, [11] realized that a certain state of damage can be generated by a reduction in stiffness or by an increase in structural damping. Changes in stiffness, whether local or distributed, lead to changes in the natural frequencies of the structure in question. Further, since the voltage distribution across a vibrating structure is non-uniform and is different for each of the natural frequencies, any localized damage would affect each mode individually and differently, depending on the particular location of the damage. Thus, the measurement of modal data of a structure in two or more stages of its life offers the possibility of locating damages in the structure. If a set of dynamic responses is measured before the structure is in service, measurements of those responses can be used to determine if the structure still meets certain operational criteria. The present work will describe the use of modal data combined with intelligent evolutionary strategies in an attempt to locate possible critical (damaged) regions. For this, some points of interest on the topic discussed and reviewed in the sequence of this manuscript.

In the following sections, a general approach on vibration methods used as a fundamental methodology in SHM systems will be performed. Next, a more detailed analysis of advanced algorithms used in reverse methods of damage detection will be introduced and discussed in detail. Throughout the article, comparative tables will be displayed summarizing the content of each topic addressed to better understand the reader.

2.1. The use of mechanical vibrations as a damage criterion

The central thought for vibration-based damage detection is that damage causes a modification in the mass, stiffness and damping structural matrix. These modifications will also cause recognizable changes in modal properties (natural frequencies, modal damping, and mode shapes). In this section, some classical and modern methodologies based on vibration signals will be described and discussed. Modal experimental analysis is an efficient tool to detect and identify damages, especially delamination in composite materials.

2.1.1. Natural frequency

The presence of damage or structural deterioration causes changes in the natural frequencies in the structure. The most useful damage-finding methods (based on dynamic tests) are probably the ones that use changes in resonance frequencies (natural frequencies), because they are easy to obtain and are reliable metrics. [59] present what may have been the first article to propose damage detection through vibration measurements. They analyze the change in the dynamic modules, which may be related to the frequency change, indicating structural damage.

The effect of delamination on the natural frequencies of laminated composite beams has been investigated by [95]. The use of vibration at higher frequencies allows the identification of delamination occurrence. Additional setups can be also used in addition with modal frequency data. [60] developed fiber-optic sensors to measure natural frequency in composite structures. The advantage of using fiber-optics is that they can be incorporated in laminated composites structures allowing real-time damage detection. [58] described how a network of embedded optical fibers could be used to detect and monitor damage (in particular, impact damage) within composites.

Also, as stated by [68], transversal cracks in composite structures affect their stiffness as well as the natural frequency values. For a given crack, irrespective of its depth, the frequency drop ratio of any two transverse modes is similar. This permitted separating the effect of damage location from that of its severity and to define a Damage Location Indicator as a function of the square of the normalized mode shape curvatures, according to the authors.

Natural frequencies are good damage metrics, not only for delamination, but also for impact analysis. [96] studied the natural frequency and damping factors before and after impact as well the effect of damage on natural frequency and damping factors. It was shown that natural frequencies increase with the impact velocity.

2.1.2. Modeshape and modal curvature

In addition to the eigenvalues, the eigenvectors (vibration modes) are fundamental and important data in the evaluation of damages in composite materials. In general, natural frequencies are excellent data to detect damage; that is, whether or not there is structural damage. The evaluation of the modes of vibration is more local; that is, these data allow the detection of the location of damage. [27] presented a two-step approach based on modal strain energy (MSE) and response sensitivity analysis to identify local plate damage. The local damage was simulated by a reduction in modulus of elasticity. The important point is that a method to weaken the "neighborhood effect" has been proposed to reduce false alarms in the location of damages, as these are one of the major challenges facing the SHM community today. Numerical examples were then conducted to illustrate the efficiency of the proposed method, and thus, damages could be successfully identified even under the effect of measurement noise. There are some other new developments on the two-step approach or modal strain energy that can be seen in the studies of [45,113,64].

Under this approach, [46,47] showed the detection of surface cracks in a laminate using the modal strain energy method. First, the properties of the material were unknown and were obtained using an inverse method through finite element analysis and experimental modal analysis. Modal displacements were used to calculate the modal deformation energies and a damage index was defined by the authors employing the fractional modal deformation energy of the laminate before and after the damage. Consequently, the damage indices obtained from global and local measurements were able to locate the surface crack in the laminate. In this proposed method, only a few modes of vibration were required, and the authors concluded that the method has a relatively low cost and flexibility in measurement, allowing a non-destructive evaluation and feasibility of real-time detection in laminated structures.

It is also noted that [123] presented a new method of detecting damage to plates based on the curvature of the frequency shift surface (FSS). Unlike other vibration properties commonly used as vibration modes that may present low accuracy in practice, the proposed method was used as a way to overcome this problem. In addition, it has been found that local damage will only cause local change in FSS, which can be considered an abnormality, since the curvature of the FSS of an intact plaque is smooth, according to the assumption that intact plaque structures are often homogeneous. Compared with traditional methods, the method proposed by the authors has been shown to be more sensitive and accurate in identifying damage.

Techniques based on vibrations and modal data, although they have existed for some decades, are still widely used to the present day. [62] presented a time domain method based on Poincaré maps of the motion of a beam subjected to harmonic loading. The proposed damage index is based on the Poincaré maps of the forced response of the healthy and damaged structures. Numerical and experimental results confirmed that the Poincaré map-based method can be successfully used to detect and locate damage. [116] presented a Chebyshev pseudo spectral modal curvature formulation for damage detection in beam-like composite structures. The proposed method was developed to overcome the wrap-around problem of the Fourier spectral modal curvature and the authors stated that the damage detection performance is better than the Fourier. Similar results can also be seen in the research of [118,117,112]. Recently [120] dealt with the problem of vibration health monitoring based on Poincare map method, which has been numerically and experimentally verified as an effective tool in damage assessment. The authors concluded that the performance of the Poincare maps method depends on the selection of excitation, also stated by [119].

A nondestructive identification method for composite beams damage was explored by [41]. The authors based their work on the curvature mode difference (CMD) as damage index. By combining experimental modal analysis with finite element simulation, the authors were capable of detecting and identifying damage sites. In a like manner, [128] studied curvature mode shapes for damage identification in laminated composite plates. Numerical simulations demonstrate that the Continuous Wavelet Transform (CWT) is more sensitive to damage identification. Indeed, finite element simulation can be considered as very powerful tool in SHM systems. Some related works using FEA and SHM damage detection problems can be seen in [4,15,62,53].

2.1.3. No-baseline methods

Many methods used by the SHM community need to know the *a priori* condition or structural response of an intact or healthy structure and then, with continuous monitoring, be able to detect damage from changes in a known signal. This strategy works very well and has been used to this day. On the other hand, new methods that do not need a baseline (no-baseline methods) have been emerging.

Ref. [93] presented a Vibration-Based Structural Health Monitoring (VSHM) technique which is developed and applied for delamination assessment in composite laminate structures. The work suggests that the mutual information is a measure for nonlinear signal cross correlation. The mutual information between two signals measured on a vibrating structure is suggested as a damage metric and its application for the purposes of damage assessment is discussed and compared to the application of the traditional linear signal cross-correlation. The authors modeled the damage as a local stiffness reduction (delamination modeling) and stated that the developed damage metric is efficient for the purposes of delamination diagnosis in a composite laminate beam. The same results for laminated plates can be seen in the work of [29]. Going further, in the same context, [30] introduced a methodology for structural vibration analysis and vibration-based monitoring which utilizes a special type of Principal Components Analysis (PCA), known as Singular Spectrum Analysis (SSA). The method was applied in a composite laminate beam based on the decomposition of the frequency domain structural variation response using new variables, the Principal Components (PCs). Experimental results demonstrated that different damage scenarios can be clustered and clearly distinguishable.

Due to the above, other unconventional methods making use of structural dynamics are proposed by some researchers [10,75,94,121,1,122,88,17]. It is clear that there is a need in the development of effective structural monitoring techniques so that the safety and integrity of the composite structures can be improved. [79] evaluated dynamic-based damage detection techniques for laminated composite plates using intelligent piezoelectric materials and modern instrumentation such as the Scanning Laser Vibrometer (SLV). The study, aimed at the detection of delamination, made use of the measurements of the curvature of the modes of vibration, measured indirectly and directly. The implementation of the algorithm by the authors was successful in the detection of laminated plate delamination, demonstrating that the dynamic-based damage detection approach using curvature is a viable technique for the monitoring of composite structures.

Equally important, [97] presented studies on free vibration analysis of some aircraft composite structures with a tapered shape which were analyzed using a 1-D Carrera Unified Formulation (CUF) model, considering different types of damage. The authors' results demonstrated that their approach provided an accurate solution for the free vibration analyses of complex structures and is able to predict the consequences of a global or local failure of a structural composites components.

2.1.4. Hybrid methods

As discussed in the previous paragraphs, natural frequencies are excellent overall damage detection metrics while vibration modes are excellent local metrics for identification. Methods that implement both data can be considered more robust and in some cases, more efficient.

In the face of this reality, in recent years, several research fronts have been joining efforts to design better damage rates based on modes of vibration, since these are more effective in locating structural damage. Citing a similar case, [56] pointed to a methodology to locate and non-destructively estimate the size of damage in structures, for which only some natural frequencies or some modes of vibration are available. First, the authors devised a method of natural frequency-based damage detection. An algorithm was then developed to locate damages by alterations in natural frequencies, being able to estimate crack size from frequency disturbances. Next, a method of damage detection based on vibration modes is described. Both methods are evaluated for several numerically simulated damage scenarios, for which two natural and mode shapes are generated from finite element models. The results of the analyses indicated that the two methods correctly located the damage, but the methodology based on the modes presented greater precision in the identification of cracks.

A hybrid technique proposed by [61] was able to identify delamination in composite plates. The damage was identified using a technique that the measured curvature differences before and after impact damage and also natural frequencies. Based on the hybrid technique presented, it was possible to identify internal damage on a laminated composite plate. Equally important, [32,33] applied an inverse optimization problem in order to detect and identify circular holes and delamination in CFRP plates. The cost function in the optimization procedure was a built in function of natural frequencies and mode shapes. The authors realized that when greater importance (weight) is given to the portion of the mode of vibration, better results are obtained. In fact, as discussed in this review, modes of vibration are better at identifying damages while natural frequencies are more robust and are excellent detection metrics (whether or not there is damage).

Ref. [23] proposed a procedure based on comparison of modal strain energy for different structural conditions from a damage index (DI). The DI was constructed based on modal data from natural frequencies and mode shapes, respectively. It was noticed that both the experimental and numerical results showed good agreement in identifying damages in flexural structural elements. In the same way, [73] measured changes in the first three natural frequencies and corresponding amplitudes of the measured acceleration frequency response function were used as a damage detection scheme in beams. Since the frequencies and amplitudes depend on the crack depth and location, these values can be uniquely determined by an inverse problem, thus identifying the damage location. Related research can be found in the literature about damage detection in composite materials using hybrid methods [79,81,26,126,6].

2.1.5. Frequency response function

In addition, safety and economic aspects are the main motivations for increasing research on the monitoring of structural integrity. Since the damage changes the dynamic characteristics of a structure, its modal properties (natural frequencies, damping and modes of vibration), several techniques based on experimental modal analysis have been developed in recent years. Not only are natural frequencies used as damage metrics, but also the use of frequency response functions (FRF) are widely explored by several researchers. As an example, the FRF curvature method was proposed by [84], based only on measured data without the need for any modal identification. In the authors' work, the method was described theoretically and compared to two, more referenced methods in the literature. The results showed that the FRF curvature method obtained good results in the detection, localization and quantification of damages, although this last item still needs more attention. Its main advantage is its simplicity. From FRF measurements, [58] evaluated the damage effects on changes in the peaks of FRFs. The authors stated that, based on correct FRF analysis, FRF can accurately determine damage levels from the natural frequency and damping levels.

Many current methods for identifying structural damage, such as Genetic Algorithm (GA) and intelligent methods such as artificial neural networks (ANNs) are often implemented on the basis of some Measured data and a large number of simulation data of structural vibration responses. Therefore, [108] emphasized that the establishment of a precise and efficient dynamic model for a structure is an important precondition. The authors presented an improved modeling method based on modifying the stiffness matrix of the element at the position of structural damage using a modifying coefficient. The influence of the position of structural damage and boundary conditions on the coefficient of modification for structural damage was verified, and for this the authors made use of FRF and natural frequencies. The stiffness matrix can be used in two different contexts. On the one hand, it is used in Finite Element Modelling (FEM) describing a part of the equation system that has to be solved. On the other hand, it describes material parameters in Hooke's law of elasticity where the relation between mechanical stress and strain is given (also known as stiffness tensor).

A brief recapitulation of the Section 2.1 is shown in Table 1 exposing the years of research in the area through the work of several researchers, making use of different vibration metrics. In view of the work and arguments presented by the previous paragraphs and the additional ones present in the Table, it is clear that the use of modal data as a metric in damage detection studies is of paramount importance, permeating important scientific challenges from the 80s to the present day.

Table 1
Review of damage detection by means of dynamic metrics of vibrations mechanics in composite structures (table arranged in chronological order).

Author	Structure	Studied damage	Metric
[3]	Concrete bridge	Stiffness Reduction	Natural frequency
[84]	Concrete bridge	–	FRF
[21]	Laminated Plate	Stiffness Reduction	Modeshape
[56]	Concrete Beam	Cracks	Natural frequency and modeshapes
[108]	Composite Pressure Vessel	Cracks	FRF
[9]	Concrete Plate	Young Modulus Reduction	Modeshape
[79]	Laminted Plate	Delamination	Modeshape
[46]	Laminated Plate	Cracks	Modeshape
[123]	Laminated Plate	Stiffness Reduction	Modeshape
[77]	Laminated Plate	Impact	Modeshapes
[106]	Composite Plate	Delamination	Curvature Modeshape
[76]	Composite T-beam	Crack	Natural frequencies and Modeshapes
[31]	Laminated Plate	Stiffness Reduction	Natural frequency
[32]	Laminated Plate	Circular holes	Natural frequency and accelerations
[111]	Laminated Plate	Delamination	Curvature of the modal flexibility
[115]	Composite Plate	Stiffness Reduction	Fourier Spectral Method
[114]	Composite Beam	Crack	Scale-wavenumber filtering
[62]	Composite Beam	Delamination	Modal displacements and Curvature
[116]	Composite Beam	Crack Model	Modal Curvature
[118]	Composite Beam	Crack Model	Modal Curvature
[110]	Composite Plate	Delamination	Modeshapes
[41]	Composite Beam	Delamination	Modal Curvature
[91]	Composite Beam	Crack	Natural frequencies
[16]	Laminated Plate	Crack	Modeshapes
[55]	Composite Beam	Delamination	Modeshapes
[87]	Composite Plate	Delamination	Vibration Amplitude
[97]	Aircraft Composite Structures	Several Damage Types	Modeshapes
[128]	Laminated Plate	Cutout	Modeshapes
[54]	Composite Plate	Delamination	Vibration Time Response
[69]	Composite Beams	Delamination	Natural Frequencies and Modeshapes
[124]	Laminated Plate	Delamination	Natural Frequencies
[37]	Laminated Plate	Delamination	Natural Frequencies

2.2. Application of optimization methods and inverse methods

Finding the best solution for a particular problem is an important area of research and application in many fields of engineering. A variety of different optimization problems can be identified in the monitoring of structural integrity, where a number of different possible mathematical tools are offered to find a better solution [104].

Genetic algorithms (GAs) have been of considerable interest since they provide a robust solution to complex problems. Because of the way in which the genetic algorithm exploits the region of interest, it avoids getting stuck in a local minimum point, i.e., a non-optimal solution of the problem in question.

From the same point of view, the vast majority of structural evaluation techniques have been using numerical modeling techniques, such as the finite element method. Following this path, monitoring of structural health through the use of finite element model fitting techniques (FE updating) generally addresses the minimization of one or more complex, non-linear, nonconvex, and multi-objective functions. Local minimums use data from a real (possibly damaged) structure and data from the optimization model. Depending on the criteria adopted in the proposed methodology, the inverse method has the ability to detect and identify structural damages. Therefore, stochastic optimization algorithms with promising performance in solving global optimization problems have received considerable attention for the purpose of updating finite element models in recent years.

In view of the above, the monitoring of structural health through the use of techniques for updating finite element models using efficient optimization techniques has received considerable attention for the purpose of detecting damages in recent years.

It is known that the modal deformation energy (MSE) is a sensitive physical property that can be used as an index of damage in structural monitoring. In the work of [12], a harm-detection approach using MSE-based hybrid multi-objective optimization algorithms has been proposed to detect damage in several three-dimensional steel structures. The authors have pointed out that minor damage has little effect on the difference in the modal properties of the structure, and therefore such damage with multiple locations in a structure is difficult to detect using traditional methods of damage detection based on modal properties. The proposed hybrid multi-objective genetic algorithm was able to detect the exact location of small damage induced in the structure, even from the use of incomplete modal data.

In the same way, Swarm algorithms are well applied in engineering. In reference, [40] reported on the finite element method and Particle Swarm Optimization method (PSO) for modeling and identification of delamination in composite materials. Damage was modelled as a local stiffness reduction. As mentioned in the previous section, this modelling strategy represents well the delamination behavior. Only natural frequencies were used in order to identify local delamination and in general, showed consistent results.

An energy-based deformation method and a differential evolution algorithm (DE) was proposed by [99]. The algorithm was used to locate and quantify damage on a laminated board. Firstly, the modal strain energy method was used to identify a set of potential damaged elements. Then, the differential evolution algorithm was used to minimize an objective function based on the error of the vibration modes. Numerical examples treated by the authors were able to detect damages even under noise conditions. Identically, [100] performed similar results, based on a two-step approach, based on the modal strain energy method and an improved differential evolution algorithm for damage detection in laminated composite structure.

It is known from the literature that the most used heuristic algorithms are GA, PSO and Ant Colony Optimization (ACO). However, as nature is an amazing source of inspiration, day by day, new nature-inspired algorithms are developed. In this context, [83] presented a fast approach for crack identification in composites structures using vibration analysis and the Cuckoo Search (CS) algorithm. The objective function was based on numerical and experimental natural frequencies of the test specimen. In the same prospect, [42] proposed a hybrid algorithm combining an adaptive real-parameter genetic algorithm with Simulated Annealing (SA) to detect damage in spherical laminate shells. An objective function built in terms of natural frequency and mode shapes was applied in the inverse problem. Results indicated that the proposed technique is very efficient in finding the exact damage locations and extents of both damage examples.

Equally, [80] developed a damage diagnostic algorithm based on frequency response functions and the principal components (PC) for the health monitoring of laminated composite structures. The inverse problem was solved by using a PSO algorithm and an objective function built in terms of singular values (SV) of modal data. Their proposed SHM scheme was robustly capable of identifying the location and the extent of delamination. Another approach based on an improved particle swarm optimization (PSO) algorithm was proposed by [102] for structural damage (delamination) detection in composites beams. The cost function proposed by the authors is composed by natural frequencies in mode shapes, simultaneously. Numerical results demonstrated that the method was efficient and effective for structural damage identification when measurement noise is considered.

A general review is presented in Table 2 exposing the parameters used by several researchers in order to solve the problem of detection of damages by inverse methods of optimization.

Table 2
Systematic review of the parameters used in optimization inverse problem damage detection in composites structures (chronological order).

Author	Algorithm	Objective function
[42]	GA - SA	$J=\sum_{i=1}^{k}\left[(\overline{\omega}_i-\omega_i)^2+100\times\sum_{j=1}^{m}\left(\frac{\overline{\phi}_{ij}-\phi_{ij}}{\overline{\phi}_{ij}}\right)\right]$
[101]	GA and PSO	$RMSE=\sqrt{\sum_{i=1}^{ndv}(X_i-X_{id})^2}$
[12]	GA	$J=\sum_{i=1}^{ms}\sum_{i=1}^{el}\lvert\Phi_i^{dT}K_j\Phi_i^d-\Phi_i^{sT}K_j\Phi_i^s\rvert$
[80]	PSO	$J=\sum_{i=1}^{n_{mf}}\lvert SV_i^m-SV_i^e(\beta)\rvert$
[37]	GA	$J=\sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(1-\frac{\omega_i^d}{\omega_i(\overrightarrow{X})^c}\right)^2}$
[40]	PSO	$J=\sum_{i=1}^{n}(\omega_{measured}^2-\omega_{numeric}^2)$
[99]	DE	$J=\sum_{i=1}^{nm}\frac{\lVert\Phi_i^d-\Phi_i^d(x)\rVert}{\lVert\Phi_i^d\rVert}$
[100]	DE	$J=\sum_{i=1}^{nm}\frac{\lVert\Phi_i^d-\Phi_i^d(x)\rVert}{\lVert\Phi_i^d\rVert}$
[83]	CS	$J=\frac{(\lVert u(f_o)-u(f)\rVert)^2}{\lVert u(f_o)\rVert^2}$
[102]	PSO	$f=\sum_{j=1}^{NF}w_{\omega j}\Delta\omega^2+\sum_{j=1}^{NM}w_{\phi j}(1-MAC_j)$
[37]	GA	$J=\sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(1-\frac{\omega_i^{real}}{\omega_i(\overrightarrow{X})^{model}}\right)^2}+\sum_{i=1}^{n}(\ddot{x}^{real}-\ddot{x}^{model})^2$
[124]	GA	$J=\sqrt{(\Delta\omega_{t1}-\Delta\omega_{p1})^2+\ldots+(\Delta\omega_{tn}-\Delta\omega_{pn})^2}$

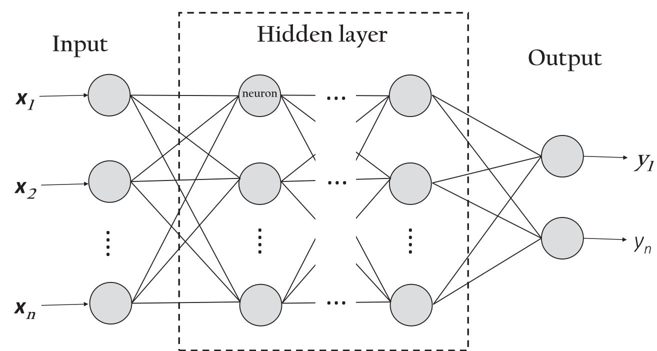

Fig. 2. An example of Multilayer Artificial Neural Network.

2.3. The use of artificial neural networks for predicting structural damage

Artificial Neural Networks (ANNs) follow the idea of the functioning mechanism of biological neurons in the human brain. Just as biological neurons deal with electrochemical signals, RNAs deal with input and output of numerical values. Considering that organic neural networks learn from the environment in which they are inserted, ANNs learn from a set of given data samples in order to predict the unknown results of future data sets [35,36].

There are several types of artificial neural network architectures, each possessing particular characteristics. ANNs are usually classified according to their construction and their training algorithms. Multiple layer networks are composed of an input layer, hidden layer(s) and an output layer (Fig. 2). The nodes present in the hidden layers are called hidden neurons. When you add one or more hidden layers, the network is enabled to extract higher-order statistics. It is said that the neural network is fully connected in the sense that each node in each layer is connected to each other node in the adjacent front layer.

Although existing mathematical models for complex structures may be sufficiently accurate for analysis and design purposes, these models are not, in and of themselves, capable of diagnosing which members can cause the changes observed in a dynamic structural response, for example. A robust damage assessment methodology should be able to recognize patterns in the observed response of the structure resulting from individual limb damage, including the ability to determine the extent of limb damage. This capability is within the scope of ANN pattern recognition capabilities [105]. According to [63], the use of neural networks in damage detection procedures has been motivated by the possibility of different types of damage occurring in several different locations in the same structure, making damage detection a highly complex process.

Experimental and theoretical studies were conducted for many authors in order to investigate the effect of delamination on modal frequencies of composite beams. [71], used backpropagation neural network models to predict delamination size in composite beams. The results obtained showed that ANN was able to predict the correct location of delamination in composite beams.

Citing some of the key work in the field, [13] worked on the prediction of delamination in fiber-reinforced laminates using only natural frequencies as input parameters in the neural network. Hundreds of finite element models were run to generate a natural frequency database of up to 10 modes for various combinations of size, shape, and location of delamination embedded in a board, and then this data was used to train a backpropagation Network Neural to an acceptable level of accuracy. It has been observed that the network can effectively learn about the size, shape and location of the embedded delamination present in the laminate and can predict reasonably well when tested with an unknown data set.

ANNs have received increasing attention in their use in detecting structural damage, relying primarily on modal vibration parameters. However, some uncertainties may still exist and produce false positives/negatives from this network. [48] presented an approach for SHM using ANN. The approach relies on the use of changes in natural frequencies between undamaged and damaged structures to identify the delamination interface, location and its size. According to the authors, the ANN is a superior and accurate modeling technique as it represents the nonlinearities (due to the inserted damage) of the problem in a much better way.

It is known that delamination is a serious damage that can occur in laminated composites due to the weak interlaminar fracture toughness of the matrix [125]. Vibration-based damage detection methods use structural modification caused by loss of rigidity/stiffness in dynamic response, such as natural frequencies and/or mode shapes to detect, localize or evaluate the damage site. One of the main challenges of making use of natural frequency variations or natural frequency shifts for damage detection, according to [125], is that while the presence of damage can be identified by a variation of a set of frequencies, determining its location is not an easy tasks and requires complex data analysis and uncertainty models [74,14,7,57]. In an attempt to solve the problem of damage identification, some research has used the inverse problems in solving a set of simultaneous nonlinear equations [125,51,22,70].

In a different aim, [92], has conducted an investigation into the development of a robust SHM via a weighted ANN, which can be immune against potential manufacturing errors in a composite airfoil NACA structure. The ANN proved to be powerful tools for pattern recognition in the SHM for NACA airfoils, being able to predict the evaluated damages.

A non-parametric, vibration-based, fast and highly accurate algorithm for the detection of structural damage based on one-dimensional adaptive convolutional neural networks was proposed by [1]. The main objective was to identify and locate any structural damage in real time by processing the raw vibration signals acquired by a network of accelerometers. The proposed approach was able to directly classify the accelerometer signal without requiring any extraction, pre or post-processing features. Consequently, this leads to a speed-efficient system, allowing real-time application. Large-scale experiments were conducted on a real structure and showed excellent performance and verified the computational efficiency of the proposed real-time damage detection method.

It is clear, through the references raised, that modal data are excellent data for the construction of a neural network. [34] addressed the detection of laminating plate delamination using natural frequencies and reduced vibration modes. The author modeled the network with 6 inputs for both cases independently and two outputs (location of damage and severity). The author concluded that the term "severity of damage" inserted a certain level of confusion for the network. With the removal of this term, the network was able to predict the localization of delamination with good performance.

According to [85], ANN schemes are used in many engineering fields to solve problems where a huge collection of data is available to train the network scheme. In their research, modal data such as natural frequencies and mode shapes are used to identify the location of damage and the damage level in a laminated composite beam with localized matrix cracks. It is found by the authors that the combination of a modular radial basis neural networks with natural frequencies can be used as robust damage detection for localized matrix cracks in composite beams.

Table 3
Systematic review of the parameters used to search for structural damage through artificial neural networks (table arranged in chronological order).

Author	Network type	Neural structure	Input
[71]	backpropagation	42–10-1	ω_n
[107]	backpropagation	32–16-4	Vibration Response
[8]	backpropagation	unknown	AE signals
[89]	backpropagation	50–22-1	Vibration Amplitude
[107]	backpropagation	32–16-4	FRF
[13]	backpropagation	10–9-3	ω_n
[125]	backpropagation	7–20-20–3	ω_n
[48]	backpropagation	Variable	ω_n
[92]	backpropagation	17–24-20–8-2	Strain
[85]	Radial Basis	3–1-1	ω_n
[34]	backpropagation	6–10-1	ω_n and Φ
[98]	backpropagation	25-x-25	Strain
[124]	backpropagation	5-x-5	ω_n

Further work on neural network damage detection is presented in Table 3, where different network structures are applied in an attempt to solve the damage detection challenge.

2.4. Unconventional and advanced methods for damage detection and identification

Conventional (classical method widely used in the literature) methods for detecting structural damage are probably the modal test, in which changes in modal parameters are used as detection parameters. Non-traditional methods refer to more specific techniques based on signal processing techniques such as wavelet analysis, Hilbert Huang trans-form (HHT), principal component analysis (PCA), fuzzy logic, lamb waves, and others.

Ref. [28] developed a fuzzy logic system for helicopter rotor blade monitoring. Structural damage was modeled as a loss of stiffness in the damaged site that may result from delamination. A finite element model of the rotor blade was used to calculate the change in blade frequencies (both rotating and non-rotating) due to damage. Measurement deviations due to damage are then "fuzzified", and mapped using a fuzzy logic system. The author's system was able to correctly classify the "no-harm" condition in up to 30% noise levels, thus reducing the possibility of false alarms, which is a key problem in this subject. The fuzzy logic system that was proposed would be an information processing tool aimed at assisting in the location of an approximate damage area.

When it comes to vibration signals, the Hilbert-Huang transform (HHT) has been employed in several works. The transform comprises an empirical decomposition in different modes and then the application of the transform in each mode separately. Because of its ability to analyze non-linear and non-stationary time-series data, the HHT method has many potential applications, including providing instantaneous amplitude and frequency of a signal, unlike an FFT (Fast Fourier Transform).

Likewise, [127] focused on the development of a guided wave monitoring system for aircraft wing inspection. To interpret the signals collected by piezoelectric sensors, an algorithm based on correlation analysis called *RAPID* was developed for the detection and localization of defects, as well as monitoring the evolution of damages. The authors obtained good results for the mapping of the simulated defects in the wing panel and pointed out that the actual defects in an aircraft wing may be different from the machined defects, and the sensor responses are likely to be different, which leads one to believe that an even greater maturity in the subject.

Along with the new techniques, [24] has presented a two-dimensional continuous wavelet-based damage detection algorithm for plate-like structures. The proposed algorithm is a damage detection technique based only on the response of the damaged structure, requiring only its vibration mode. The algorithm was applied to plates with different types of damage, illustrating its effectiveness and viability, and it can be used as a viable and effective technique to identify damages in shell structures.

Since the presence of a crack or a delamination causes a discontinuity in the first derivatives of the modal forms, a numerical method for detecting discontinuities by a technique called polynomial annihilation was presented by [90]. The method, already proposed for beam-like structures, has been extended to allow the detection and localization of damages in plate-like structures. Encouraging results indicated that the development of the technique for non-destructive testing of plate-like structures is highly valuable.

On the other hand, non-destructive testing techniques applied to high responsibility materials as well as composite materials should be evaluated in several categories: efficacy in detection, localization and identification of damages in the early stages, application complexity and cost of inspection. In the study of [51] the authors experimentally tested three composite structures, one of them being extracted from the vertical stabilizer of a military aircraft, having impact damage and poorly visible delamination. The tests were performed using various techniques, including detection by piezoelectric sensors (guided waves), ultrasound, thermography and vibration inspection, in order to analyze the applicability of these methods in the environmental conditions of inspection of the elements of the aircraft. The analysis made it possible to conclude upon the efficacy of the applied methods and their specific applications in non-destructive tests of compound elements.

For a deeper understanding of the initiation, growth, and evolution of different types of damages, [103] used the acoustic emission technique (AE) together with post-processing techniques such as Empirical Mode Decomposition (EMD), Intrinsic Mode Functions (IMF) and transformed HHT. Statistical results show that the peak frequency of the AE signal can distinguish several failure modes effectively. The HHT transform of the AE signals was able to clearly illustrate the frequency distribution of the components of the IMF at time scales at different stages of harm and was also able to calculate the precise instantaneous frequency for recognition of failure modes to help understand the Damage process.

It is known that composite materials are very useful in the structural aspect, particularly in weight-sensitive applications. Test models of the same structure made from composite materials may exhibit a very different dynamic behavior due to the great uncertainties associated with the properties of the composite material. In addition, composite structures may suffer from pre-existing imperfections such as delamination, voids or cracks due to fabrication. [14] proposed a modelling of uncertainties in composite structures through a robust fuzzy logic system and used it for delamination detection. The logic was designed using variations in natural frequencies due to randomness in the properties of the material. The probabilistic analysis was then performed using the Monte Carlo simulation in a finite element model. The authors concluded that the system presented excellent robustness in detecting delamination at very high levels of randomness in the input data.

Table 4 provides a brief review of the literature on the main unconventional methods used in the problem of detection and identification of structural damage.

The aim of this study was to review some of the studies in the literature, in order to substantiate the relevance of the work herein, which aims to study the identification of damages in composite materials from modal parameters to form optimally distributed sensor signals. It is clear that the need to seek and design efficient structural monitoring is a scientific challenge to be overcome. Vibration metrics as damage criteria are strongly employed as parameters to be diagnosed. Evolutionary computational techniques and computational intelligence are powerful tools used to aid the diagnosis of structural responses. In addition, obtaining answers in a small number of sensors without significant loss of quantity and quality of structural information is a dilemma to be solved that requires a significant amount of work. In addition, it is observed that related research on the subject is recent and of high industrial and scientific interest all over the globe. Therefore, in this study, computational intelligence techniques will be used, giving continuity to the contributions already existing by several researchers in the area.

The development of a structural integrity monitoring strategy involves relevant research challenges, as demonstrated in the previous section. Fig. 3 illustrates schematically the multidisciplinary framework associated with this challenge, including four main components: structure, damage identification method, damage scenario and sensing technology. The characteristics of these components are closely interlinked and, together, define the performance of the proposed strategy. Ideally, a good strategy combines a high level of detection with a low number of false positives. The success of a damage identification strategy depends, however, on the structure and damage scenario that is considered. The selection of the most appropriate approach is therefore far from trivial and direct [72].

This work is dedicated to the identification of structural damages in mechanical structures. As already pointed out, SHM technology is a field that requires a deep understanding of materials, sensors, and the ability to perform sophisticated numerical and analytical modeling and signal processing. Each of these topics is a matter in its own right, and developing a study that incorporates all of the above is really a difficult task [38]. Modeling is an important component in SHM technology. Simulated data are used to support the development of new algorithms for damage detection, or for a better understanding of the effects of structure response damage. One of the specific objectives of this research is therefore to present some computational tools that can be used for the detection/identification of structural damage.

Approaches in structural vibrations are emphasized in this study because the presence of damage results in the modification of the structural matrices (stiffness, damping and mass). That implies a modification of the structural dynamic response (vibration). The use of dynamic methods is justified in the first place because they do not require the structure to be easily accessible and because low frequency methods provide relatively easy to interpret data.

The ability to identify damaged components in aerospace, mechanical and civil systems is becoming increasingly important [20,25,18]. Although considerable efforts have been devoted to the diagnostic and prognostic community to develop effective methods of diagnosing and identifying damages over the past decades, the identification of structural damage is still considered a practical challenge for the assurance of safety of engineering structures [39].

3. Final remarks

In summary, the objective and focus of this study is based on the solution of the inverse problem and the recognition of patterns of damage identification (and quantification of its severity) in composite material (but not restricting only) of computational intelligence using structural modal parameters in an attempt to identify the possible location of structural damage and its magnitude, that is, its severity.

Unfortunately, the more than a hundred studies referred to in this article represent only a very small fraction of the published work available in the research field. Throughout the literature, there is an immense range of techniques for detecting and identifying damages. Each technique in particular has its advantages and disadvantages and in general there is no overall technique that effectively satisfies more than one specific problem.

The great challenge in the SHM community is, after identifying the specific damage detection problem, to adjust the parameters of the employed method so that it presents the greatest efficiency in the

Table 4
Systematic review of the parameters used in the search for structural damages through non-conventional techniques applied in composites structures.

Author	Structure type	Studied damage	Applied technique
[28]	Helicopter rotor blade	Stiffness reduction	Fuzzy logic
[127]	Aircraft wing	Holes simulating corrosion	Guided waves
[82]	Beams and plate	Cracks and local thickness reduction	ANN + wavelet
[49]	Plates	Cracks and local thickness reduction	B-spline wavelet transform
[19]	Plates	Impact	Deflectometry
[78]	Plates	Impact	Vibrothermografy
[90]	Beam and plate	Cracks and delamination	Polynomial annihilation
[50]	Plates	Cracks and local stiffness reduction	Wavelet transform
[65]	Plates	Local thickness reduction	CMV
[86]	Plates	Impact	Electromechanical impedance
[51]	Aeronaultic structures	Delamination by impact	Guided waves
[80]	Beam and composite plates	Composite matrix cracks and delamination	PCA
[103]	Beams	Small holes	AE, EMD e HHT
[66]	Beams	Cracks	Acoustic Emission
[14]	Plates	Delamination	Fuzzy logic
[5]	Plates	Local thickness reduction	Wavelet transform
[67]	Plates	Local thickness reduction	CMV e Wavelet transform
[44]	Wind turbine blade	Stiffness reduction	PCA
[110]	Plate	Delamination	Wavelet transform
[109]	Beam	Delamination	Wavelet transform

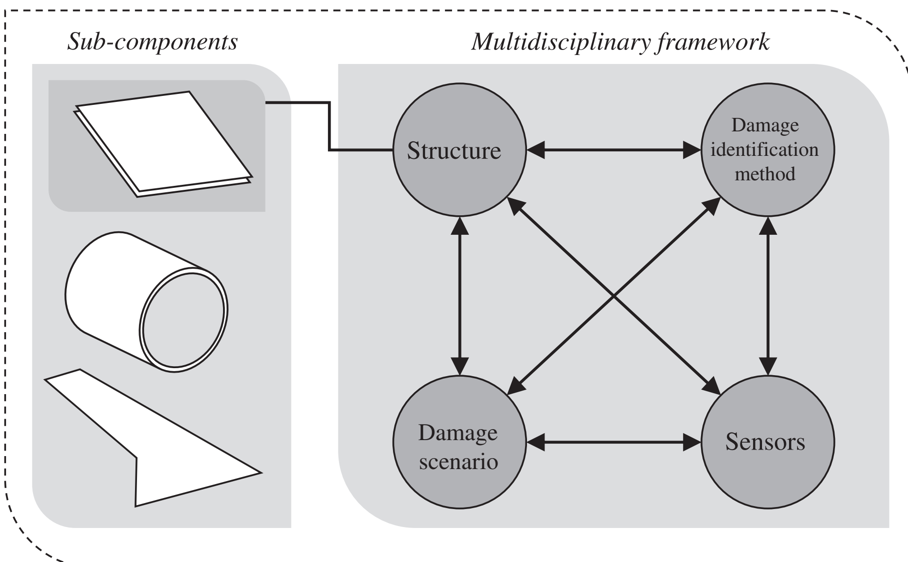

Fig. 3. The multidisciplinary framework for the design of a structural health monitoring system (adapted from [72]).

detection and identification of damages. Furthermore, it contributes to the uncertainties, avoiding the identification of false positives.

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Conflict of interest

The authors declare that they have no conflict of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, athttp://dx.doi.org/10.1016/j.compstruct.2018.05.002.

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