IJME

Int. J. of Applied Mechanics and Engineering, 2025, vol.30, No.3, pp.97-113
DOI: 10.59441/ijame/202711

AN EXPLORATION OF VIBRATION BASED DAMAGE DETECTION TECHNIQUES FOR COMPOSITE MATERIALS

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Structural damage monitoring is inevitable for the structures to perform during their intended service life adroitly. In the present review, literature related to techniques for diagnosing vibration-intensive damages have been evaluated in order to determine the material characteristics, such as stiffness and damping. Also, extensive review has been presented for damage detection in composite materials. The review encompasses the literature published in last *42* years, i.e., *1982* to *2024*. The literature review is classified into sections as damage detection workflow, composite materials, damage detection techniques, and advanced damage detection techniques. The usage of strain energy, mode-shapes, waveform dimension, wavelet transform and updating finite element models in detection of damage are also discussed. Further, an overview of concepts, techniques, and advancement in vibration-induced damage detection are presented. The limitations of each technique are explained. An insight on advanced techniques and tools from genetic algorithm and artificial neural network regarding their employability to detect the damage is provided. This work portrays the damage detection methodologies.

Key words: composite materials, damage detection, vibration analysis, structural health monitoring, artificial neural network.

1 Introduction

The composite material is a combination of two different materials that exhibits a single or compound unpredicted physical property. As the composites are made of constituents like fiber and matrix, they manifest different mechanical interaction and mode of failure that is dissimilar to metals. Fiber reinforced polymer (FRP) composites show outstanding mechanical characteristics with less weight and ease in shaping. These advantages over metallic alloys make them acceptable in automotive, aeronautical, and naval industries.

On a microscopic scale, composites have two or more chemically different phases segregated by a distinct interface and it is a crucial parameter to identify their characteristics. The matrices are a continuing ingredient utilized in greater quantities for various applications. A metallic, ceramic, or polymeric matrix is normally preferred in composites as shown in Fig.1. An introduction of additional ingredients to generate composites improves the characteristics of matrix.

Composite materials are generally used for structures, spaces, and lightweight applications like watercraft bodies, panels of swimming pools, racing car parts, slowdown of showers of bath, storage tanks, the stone of impersonation, refined sinks marble and countertops. The most remarkable cases perform routinely

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on space shuttle and airplanes. The ever-increasing use of composite materials in critical engineering applications has led to a need for effective methods of damage detection.

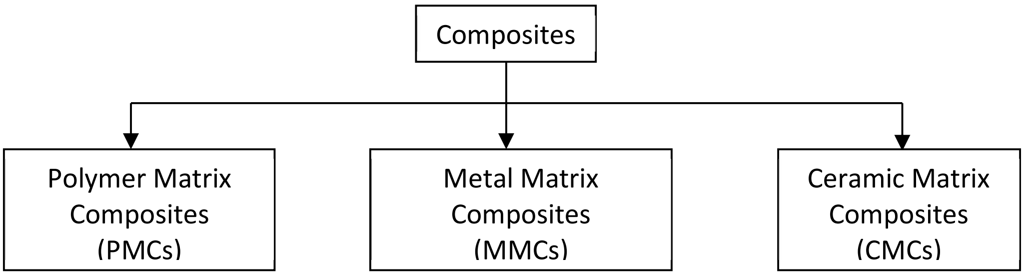

Fig.1. Types of composite materials.

One common type of damage in composite materials is delamination, which is the separation of layers in the material. The root cause of damage may be impact, thermal cycling, or other forms of stress. Delamination leads to decrease in the stiffness of the material and increase in damping. As a result, delamination is typically associated with a decrease in the amplitude of the vibration response and a shift in the resonance frequencies of the material. Particularly, composite materials are prone to structural damage due to delamination, which can occur during production, tooling, processing, or servicing. Another type of damage reported in composite materials is micro-cracking. It is the formation of small cracks in the material, that propagates and lead to the failure. Microcracking is associated with increase in damping and strength of the material. This can lead to a decrease in the amplitude of the vibration response and a shift in the resonance frequencies of the material. Impact damage is another type of damage that can occur in composite materials. This occurs due to high-energy impact or a collision. Impact damage can lead to delamination or microcracking or both. As a result, impact damage is typically associated with a decrease in the amplitude of the vibration response and a shift in the resonance frequencies of the material. Thermal damage is also another type of damage that can occur in composite materials. This is usually caused by exposure to high temperatures. Thermal damage is associated with a decrease in the amplitude of the vibration response and a shift in the resonance frequencies of the material. Finally, fatigue is also one type of damage that can occur in composite materials. Fatigue damage is associated with a decrease in the amplitude of the vibration response and a shift in the resonance frequencies of the material. All types of damages can be detected using mechanical vibrations as one of the tools for analysis.

The matrix cracking, fiber breakage, and voids are commonly reported modes of failure in composites [1]. Also, composite material possesses resistance and tenacity to density relationships which is higher than metals like aluminum and steel. However, they are sensitive to impact loads. Impact loads are characterized as low-energy, medium-energy, and high-energy depending upon the speed of the impact. Normally, carbon fiber reinforced polymers (CFRP) are responsive to impact loading. Crack in the matrix will result in delamination that reduces stiffness of the component and load bearing capacity.

In recent times, emphasis is given on non-destructive evaluation, structural health monitoring (SHM) and damage detection at early stage. Damage detection methods are of immense significance in domains like mechanical, civil, aeronautical, and offshore engineering due to safety and economic issues. Generally, damage is designated as ‘changes initiated into a system affecting its present and future performance’ [2]. Some of the examples are structural crack, bridge pillar silting, loss in counterweight balancing, and looseness in bolted joints.

Worldwide researchers have employ various damage detection techniques like impedance measurement, infrared thermography, fiber optic sensors, carbonized electrospun polyacrylonitrile (PAN), ultrasonic guided wave, vibration-based, speckle shearography, piezoelectric materials, fiber Bragg grating (FBG) based strain sensor systems, computer vision (CV) etc. [3-13]. Recently, vibration-based damage detection techniques are becoming popular due to cost effectiveness, non-destructiveness, and expedience. This technique utilizes the dynamic characteristics like damping ratio, natural frequencies, and mode shapes for damage detection. The researchers are exploring the possibilities of use of Artificial Neural Network

(ANN) for evaluating vibration signatures in fault detection and gaining the attraction due to its fair accuracy in detection as well as prediction of crack properties [100].

Das and Sahu [14] provides a survey on composites utilized in engineering with special attention to the identification of damage using artificial intelligence (AI) techniques. Similarly, Hassani and Mousavi [15] discusses the techniques for vibro-acoustic modulation with signal processing, machine learning, and deep learning.

The present article focuses on latest techniques in damage detection using vibration analysis specifically for composite materials. This article tries to summarize existing knowledge in the damage detection by providing comprehensive overview of current state of research in the domain. The literature review also endeavors to help the readers to understand trends, elements of key research and find out research gaps providing a systematic pathway for future studies.

Proposed methodology of literature review

A comprehensive literature review is presented here. The articles selected for study spans over past forty years. The basis used for selection of articles was the fundamental principles on which the method was based, novelty of method and accuracy in the prediction of damage as well as damage properties. The literature review is divided in five major sections that comprise of survey of articles from theory to practical orientation as shown in Fig.2. In depth review of literature is necessary to understand theoretical concept as well as practical implications of vibration-dependent damage detection techniques. Therefore, section 2 discusses the damage detection workflow which includes philosophy and process of damage detection. Then, several techniques of damage identification such as natural frequency-based, mode shape-based, curvature-based, and modal-parameter based methods are described in Section 3. Followed by this, articles related to practical-based mechanical vibration detection, their application of optimization, and artificial intelligence are reviewed. Scope for future research is given in Section 5. Finally, conclusion of review is given in last section.

2. Damage detection workflow

The requirement for detecting damage in complex structure has arisen and it can be addressed by monitoring the changes in dynamic behaviour of structure. The modal parameters are related to physical parameters and it can be the basis for the development of damage detection techniques. As the damage alters the modal properties of the structure, they can lay a strong basis for damage detection.

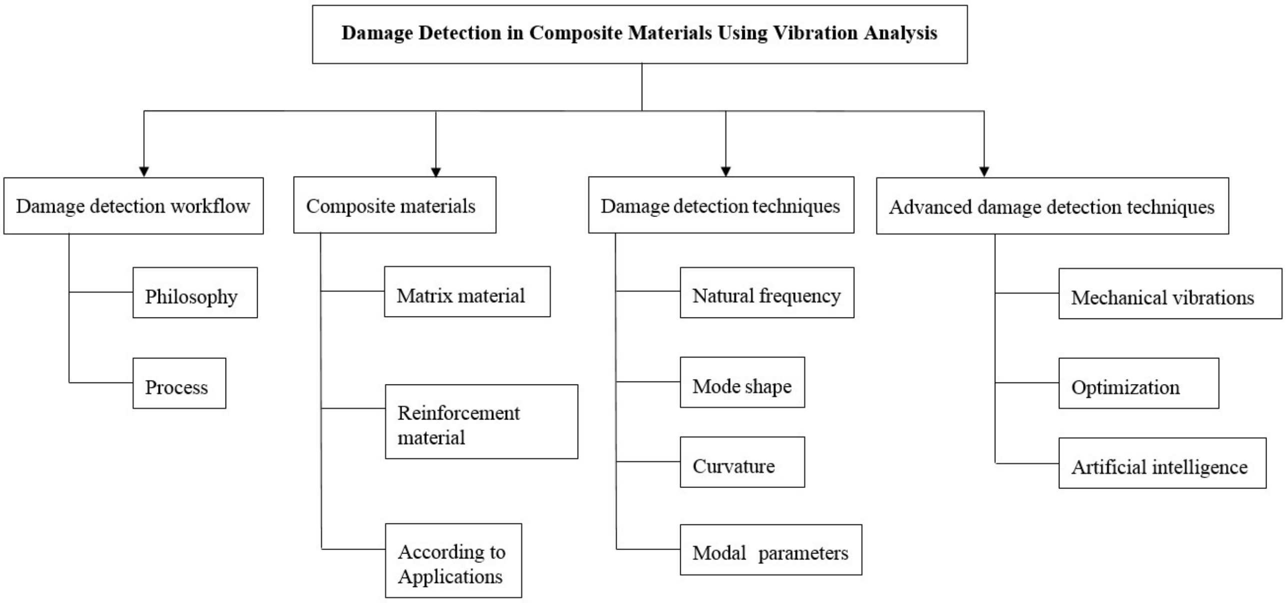

Fig.2. Proposed methodology of literature review.

2.1. Philosophy of damage detection

The purpose of damage detection is to identify and locate the damage at early stage and increase the lifetime. The damage has to be detected before it develops and creates a severe issue otherwise it may lead to catastrophic failure. A classification of damage can be done on the basis of the damage-existence, location, type, extension and prognosis. It is observed that prior knowledge of the structural behavior is required to identify damage type and extension. Prognosis is the term that relates to fracture mechanics and fatigue.

The philosophy of damage detection emphasizes the need of multidisciplinary approach and encourages academics and practitioners to seek out to people who work in domains that are not directly related to their own in order to improve the state of the art. The correlation can be established amongst domains like engineering, computer science, materials science, which is another essential tenet of the philosophy behind damage detection. As new techniques and approaches are established, it is necessary to put them through their paces in terms of testing, refining, and adapting them to various kinds of settings. This rationale can safeguard the structures that we depend on.

2.2. The process of monitoring

Monitoring is a vital aspect of the process flow that enables about occurrence of damage. It entails the persistent gathering of data from sensors and other measuring devices. Monitoring helps in early detection of damage that may avert catastrophic failure and cut down the time and money needed for repairs.

The first step in the process of monitoring is to identify suitable sensors and measuring tools. Depending on the nature of damage to be identified, the selection of sensors have to be done on the basis of principle of operation, strain, temperature, vibration, or sound emissions. The sensors are mounted on the framework of the system, and the information they collect is sent to a monitoring system where it may be saved and analyzed. This process also includes feature extraction and statistical correlation to evaluate health of the system [16]. Following are major steps in the monitoring process:

1. Evaluation of operation.
2. Acquisition and cleansing of data.
3. Extraction of feature.
4. Development of model for differentiation of features.

In following section, literature pertaining to different types of composite materials and their damages are reviewed.

3. Composite materials

Classification of the different types of composite materials and the types of damages are as follows:

3.1 Classification by matrix material

This involves categorizing composites based on the type of matrix material used, such as polymer matrix composites, metal matrix composites, or ceramic matrix composites. Each type of matrix material may have unique types of damage that are more likely to occur, such as delamination in polymer matrix composites. Amongst the majority of failure, delamination is majorly reported failure type in composite materials. From the available literature, enough scope is available for intralaminar damage impact and its effect on the interfacial release energy and progression of delamination. Most of the delamination mechanisms involve the edge effect caused by change in temperature or humidity. Other commonly observed technical issues in manufacturing of composites are curing time, residual stresses and working stresses create delamination in polymer composites [98]. In ceramic matrix composites, longitudinal and transverse matrix cracks, fiber-matrix bending can create delamination. Distinct ply interfaces can initiate and propagate delamination ceramic matrix composites [99]. In order to investigate the function of intralaminar damages in the process of delamination propagation, researchers makes use of the SMart-Time XB delamination simulation tool as well as a Hashin criteria based user-material subroutine [17].

Because of their excellent resilience to damage and flexibility in design, thin-ply composites are becoming an increasingly popular material choice. Researchers suggested that a damage mechanics model be developed to replicate the impact of ply thickness on the progression of damage [18].

3.2. Classification by reinforcement material

Another possible classification is based on the type of reinforcement material used in the composite, such as carbon fibres, glass fibres, or aramid fibres. Different types of reinforcement materials can have varying susceptibility to certain types of damage like fibre breakage or debonding.

Green composites are becoming popular due to their cheap cost, renewability, and biodegradability. Coir pith has exceptional characteristics, however working with it may be difficult because of its adherence to the polymer matrix phase at the interface. The shape as well as the chemistry of fibres may be changed by application of a chemical treatment to natural fibres. According to the findings reported, processed coir pith is better at soaking up water than its raw, untreated counterpart. In preparation of composites, interfacial adhesion is the issue with water absorption capacity. It can be resolved by altering the morphology of natural fibers through chemical treatment [97].

The incorporation of hydroxyapatite (HAp) and carbon nanotubes (CNT) into functionalized-HAp/CNT reinforced UHMWPE composites for acetabular cup liners led to an improvement in the materials' mechanical characteristics. In order to achieve better adhesion with the polymer, the surface of the reinforcements was silane-treated. Spectroscopy provided evidence of an increase in dispersion and interfacial adhesion of functionalized HAp and CNT. The UHMWPE matrix exhibited improved strength on many length scales, as proven by atomic level alteration. The bulk mechanical characteristics are significantly improved as a direct consequence of the crystallinity increased by *28%* [19].

3.3. Classification by application

Polymer composites are an essential kind of material that are put to use in high performance applications owing to their low weight in relation to their strength and improved efficiency in terms of fuel consumption. The aeronautics industry is reducing the weight of major and secondary structures by using polymer composite materials. This article provides an overview of thermoplastic and thermosetting polymers used in the aerospace industry, including their characteristics and uses. Author explains that the fuel efficiency has been improved by reducing the weight of Airbus A350 (2007) and Boeing B787 (2013)[20].

Because of their low cost, quick availability, flexibility in design, and ability to be processed in a variety of ways, carbon-based composites have an exciting future in the field of military technology. They comprise of a variety of carbonaceous elements including coke, char, black carbon, activated carbon, carbon fibre, and other nanomaterials derived from carbon. Distinct applications of composite materials are discussed like electromagnetic interference (EMI) shielding for defence industry [21]. Increased fuel economy and decreased carbon dioxide emissions are being driven by the desire for lighter vehicles and aeroplanes. Both automobile and aircraft components are now manufactured using composite materials extensively. Applications of composite materials include carbon fibre-reinforced plastics and glass fibre-reinforced plastics Some of the applications of the laminated composites in the automobile includes spare parts, body stiffener, engine frame, engine hood and door panels [22].

4. Damage detection techniques

Damage detection techniques are classified in four major categories of natural frequency, mode shape, curvature mode-shape, and modal parameters dependents [23]. Table 1 lists various vibration based health monitoring techniques with their merits and shortcomings.

Table 1. Vibration-dependent health monitoring technologies.

Technique	Researchers	Merits	Shortcomings
Mode shapes	Sazonov and Klinkhachorn [24], Cao and Qiao [25], Maeck and Wahab [26], Xu and Zhu [27]	High level of precision, Finding faults in concrete and composite buildings, Identification of damage without knowledge of its intact condition	Susceptible to the presence of signal noise. Uncertainties brought on by variable environmental changes and inconsistent boundary conditions.
Modal strain energy	Shi and Law [28], Dewangan and Parey [29], Nick and Aziminejad [30], Alavinezhad and Hassanabad [31]	Multiple damage localization, outstanding noise reduction, and useful real-world applications	Unfavourable results were obtained when the sampling frame was oversampled and under sampled. Various damage types are identified and measured.
Wavelet transform	Douka and Loutridis [32], Rucka and Wilde [33], Saadatmorad and Jafari-Talookolaei [34], Vamsi, Hemanth [35], Jahangir and Hasani [36], Zhou and Lei [37]	Damage detection in buildings using beams and plates, fewer computational steps Detecting damage in concrete and composite buildings	It's crucial to do a thorough dynamic examination of the intact structure. It is necessary for the structure's material properties to be accurate.
Finite element model	Zhu and Li [38], Nozari and Behmanesh [39], Mishra and Vanli [40]	Applications that are useful in the real world, excellent noise reduction	Direct techniques cannot be used in an industrial setting.
Optimization and machine learning	Tiachacht *et al.* [41], Al Thobiani *et al.* [42]	Useful in online damage detection	The need for large amounts of high-quality data to train models effectively. In some cases, it may be difficult to collect the necessary data, and in other cases, the data may be too noisy or incomplete to provide accurate results.

4.1. Natural frequency-based methods

These methods are convenient to use as natural frequencies can be gauged from limited points on the component, which are unaffected by the noise. There are two types of approaches the forward problem solving technique and the inverse problem solving technique. The reported limitations of these methods are that they are based on approximations of higher order frequencies and found imprecise for first mode with crack situated at the boundary [43]. The natural frequency-based methods are model-based. Therefore, they provide precise prediction only in case of slender beam-type structure with small cracks. Also, only first few modes are used for the damage detection. Furthermore, difference in frequency caused by damage is small compared to change in frequency by environmental conditions [23].

Damage detection in composite materials is often accomplished via the use of technologies that are based on natural frequencies. This method entails the natural frequencies of a composite structure both before and after damage has occurred. Later, the changes in the frequencies are compared with the changes that have occurred to determine the location and level of damage.

4.2. Mode shape-based methods

Another sort of vibration-based approach that is often employed for damage identification in composite materials is based on the mode shapes. When a structure vibrates at its normal frequency, it creates deformation patterns known as mode forms. Mode shapes are the names given to these patterns. These mode forms are one-of-a-kind for each structure, and they may be used to recognize changes in the structure that can suggest degradation.

Finite element model or experimental tests are used to establish association with location or severity of damage and modal shape. Hu and Wang [44] identified damage for continuous FRP composite for symmetrical laminate plate and a surface crack. They utilized change in mode shapes, mode shape slopes, and strain energies for computing the damage index for specifying location of damage to accurately predict dynamic response.

4.3 Curvature mode shape-based methods

Damage detection in composite materials is well suited to a particular subcategory of mode shape-based techniques known as curvature mode shape-based methods. The deformation patterns that take place in a structure as a result of being exposed to bending stresses are referred as curvature mode forms. These curvature mode forms may be used to detect changes in composite materials such as delamination, fiber breaking, and matrix cracking. Curvature mode shape-based techniques have the ability to identify damage in composite materials that cannot be identified by other vibration-based methods. As a result, they are an invaluable tool for damage detection in composite materials.

Recently, Govindasamy and Kamalakannan [45] investigated damage in the form of crack in laminated plate using modal curvature. They utilized node-releasing technique of FEA for crack modelling of varying depths and lengths. They found precise damage detection using all three algorithms.

4.4. Other methods based on modal parameters

Damage detection in composite materials often makes use of methods based on modal parameters. Modal parameter-based approaches also have the advantage to detect damage in composite materials at an early stage. Modal flexibility-based methods have been suggested by number of researchers for damage detection [46, 47]. Several methods formulate damage detection as optimization problem and utilize number of modal parameters as objective functions [48-50]. It can be concluded from the results that the natural frequency decreases as degree of degradation of rigidity. Also, a specific vibration mode may detect position of the crack [51].

It concludes that, in a controlled laboratory environment, the frequency variation dependent damage detection processes can be used to spot and compute damage in plain structures with minor damage. Typically, a curvature mode shape-based algorithm can successfully pinpoint the damage, whether it uses a direct variation in curvature or applies signal processing methods to curvature. Advanced damage detection techniques are reviewed in the next section.

5. Advanced damage detection techniques

In this section, articles employing vibration as a tool for damage detection and utilization of optimization principle and AI techniques in damage detection are presented.

5.1. Mechanical vibrations as damage detection

This section presents literature pertaining to investigations on using mechanical vibration for detection of damage. Specific damping capacity (SDC) measurement is a practical potential technique for damage identification. Using quasi-static loading or fatigue, beams have been examined both before and after the introduction of damage [52]. According to the findings, measuring SDC proves to be a promising technique for identifying damage in woven fabric composites.

A laminated composite plate's local and minor delamination damage detection is investigated by scientists [53]. The approach is based on the structural vibration sub-signal's energy distribution. With the technique, a delamination area of just *0.13%* of the composite plate's total area was examined. Delamination causes a mode-dependent variation in energy dissipation in plate vibration. The damage-induced modifications to natural frequencies and mode shapes for comparatively little delamination are too minute to be recognized. However, even more subtle delamination can be found by analyzing the energy spectrum of wavelet packet decomposition [54].

It is studied whether the random decrement technique may be used to detect damage in composite beam-type constructions. To determine the system's reaction to a random input, theoretical models of composite beams with varied degrees of delamination are built [55]. An actuator attached to the center of a FRP composite panel provided controlled vibration, which is then bolted to a steel frame [56]. To track changes in bolt load, dynamic strain sensors are positioned at the panel's four corners. Changes in strike load have a significant impact on damage indices based on changes in transmittance function.

A broadband operational curvature-based method is used by Ratcliffe and Heider [57] for structural irregularity and damage evaluation routine (SIDER). They observed that only a few areas were aroused after installing an array of reaction transducers on the structure. Instead of employing hundreds of conventional accelerometers, their research depicts use of a variety of inexpensive micro-electromechanical systems (MEMS) accelerometers.

With the use of the cross-correlation function of the structure's recorded vibration responses, a novel idea known as an inner product vector (IPV) is presented by Yang and Wang [58]. The sudden shift in IPV between damaged and unbroken buildings identifies the damage location. Results from numerical simulations demonstrate the efficacy and validity of the suggested strategy. A plain-woven laminate is created using the carbon cloth F3T-282/epoxy (DICY) by Hu and Wang [59]. Then, they created three equivalent models, namely, cross-ply, orthotropic, and representative cell. Tensile tests are performed to compare the mechanical properties.

The detection of faults in multi-cracked thin Euler-Bernoulli beams are presented in the study by researchers [60]. The technique is based on a rotational spring model of a crack. The results of the analysis of a cantilever beam with two cracks demonstrate the effects of multiple cracks. Herman and Orifici [61] presents a study on defect in T-stiffened panels using vibration modal analysis numerically and experimentally. The outcome of this study depicts that the vibration mode altered by defective panels and change in mode shape curvature of damage caused to stiffened panel.

A novel non-destructive damage detection methodology is introduced by researchers for identifying delamination in composites [62]. The method exploits the vibration signature of the structure, obtained through piezoelectric sensors. They find that the method was successful in distinguishing delamination locations. The researchers report an idea for improving the electromagnetic interference (EMI) method's capacity for damage detection by using piezoceramic (PZT) material [63]. The use of the lower frequency band for damage identification is one of the suggested technique's key advantages. Also, the proposed method gets rid of the trial-and-error method's time-consuming issue.

La Saponara and Brandli [64] studies uniaxial test data of woven epoxy/glass parts. They quantified contours of a wavelet transform from ultrasonics. They observed that contour perimeters track strain accumulation and residual strain in the testing accurately. Perez and Gil [65] presents methodology to study feasibility of using vibration-dependent techniques to identify damage in composite laminates due to low-velocity impact. Anderson and Aram [66] developed a novel system to study dynamic performance of vibration structures with the help of frequency-main features. They also demonstrate utility of method in frequency excitation evaluation of composite plate in undamaged and damaged condition.

Vo-Duy and Ho-Huu [67] proposes an approach based on modal strain energy method and advanced differential algorithm of evolution for detection of damage in laminated composite materials and plate structures. The developed approach is found effective from numerical results. Pieczonka and Ambroziński [68] introduces a damage detection technique based on guided ultrasonic waves and 3D laser Doppler vibrometry. They validated the proposed technique on elements of fuel tank of reusable launch vehicles required for space exploration.

Geweth and Khosroshahi [69] employ laser vibrometer to study experimental modal analysis of FRP components. Later, they discussed advantages and limitations of the proposed method. Porcu and Pieczonka [70] apply scaling subtraction method (SSM) for inspection of two laminated composite plates with different sizes, position of impact and arrangement of sensors. They also studied sensitivity of the proposed system for various combinations of sensor and receiver, frequencies of excitation and levels of amplitude. De Fenza and Petrone [71] implemented SHM system for purpose of identification of damages on wings of an aircraft. They also developed radar graphs for gauging direction of Lamb waves and studied the sensitivity of Lamb waves. De Menezes and Souza [72] presented a novel numerical-experimental methodology to study effect of change in design factors on dynamic response of laminated composite materials. They employ python programming language for implementation of FEA codes. The proposed method quantifies damage indices using experimental frequency response functions (FRFs). Pacheco-Chérrez and Cárdenas [73] identify the features of the damage reliably from the damage signal. Thus, automatic damage detection using arrays of sensors is possible for beams made of composite materials. Hassani and Mousavi [74] have a motive to propose a novel damage identification method based on variational mode decomposition (VMD) algorithm, which remains unaffected un-affected by noise and eigenvalues. Afterwards, they compared performance of the method with existing two methods and found its reliability over other methods. Loi and Uras [75] propose vibro-acoustic modulation (VAM) technique to a composite laminate beam to generate flexural excitation that introduce probe waves and vary structural response. They conclude that selection of probe frequency and pump excitation significantly affects sensitivity of the system.

The summary of different studies that investigate the use of mechanical vibration to detect damage in composite materials is presented in the next section. Researchers have used techniques such as specific damping capacity (SDC) measurement and structural vibration sub-signal's energy distribution to identify damage in woven fabric composites and laminated composite plates. They also developed non-linear vibration analysis approaches to evaluate the dynamic response of composite laminates with embedded and/or surface-bonded piezoelectric sensors and finite/discrete delamination. Scientists have investigated whether the random decrement technique may be used to detect damage in composite beam-type constructions. Additionally, the study regarding verifies the use of macro-fiber composites (MFC) as both a sensor and an actuator to determine the modal parameters of an inflatable structure to reduce vibrations. Furthermore, researchers have examined the use of sensors integrated in composite materials to provide real-time information about the host integrity. Lastly, the passage highlights the use of different detectors to evaluate the performance of vibration-based damage detection techniques.

5.2. Optimization techniques for damage detection

A set of accelerometers and computational methods are the main components used to evaluate the structural integrity of composite materials. By increasing the precision and effectiveness of the computational tools, the time needed to determine the degree of the damage can be reduced. Computational techniques facilitate the classification, prediction, and time optimization required for damage detection. The genetic algorithm (GA), principal component analysis (PCA), and particle swarm optimization (PSO) are some of the common computational tools in optimization that may be employed in damage detection process.

Delamination causes a mode-dependent variation in energy dissipation in the case of plate vibrations. The reduction in natural frequencies and mode shapes for relatively minor delamination or damage are too minute and difficult to be detected. However, even more subtle delamination can be found by analyzing the energy spectrum of wavelet packet decomposition [76].

Wang and Liang [77] propose a novel damage detection method for determining damage in wind turbine blades. The proposed method detects the size and location of damages with the help of dynamic analysis and mode shape difference curvature. They find that the proposed method is best tool for monitoring wind turbine conditions. Pan and Zhang [78] suggest a novel concept of noise response rate (NRR) to determine sensitivity of each node of shift in frequency due to noise. The outcome converges to selection of modes of vibration with low NRR with improved accuracy in damage prediction. Raut and Kolekar [79] present a discussion on various methods of optimization for damage detection in composite structures. Gillich and

Furdui [80] aim to invent a method based on multi-modal analysis that evaluates damage in beams due to axial forces caused by change in temperature. The outcome converges to predictive models that describes vibration behavior of beam-like structure.

Zhang and Zhan [81] intend to add random noise of 10 levels of uniform and normally distributed to the numerical frequencies. The frequency shifts are input to graphical technique and it gives the outcome of surrogate-assisted optimization and ANN for prediction of damage location. They find that trend in error prediction become consistent with increase in quantity of samples. The higher reliability of this process using ANN is found reported even for increased noise level. Kahya and Şimşek [82] utilizes limited amount of vibration data, i.e., frequency and mode shapes with harmony search algorithm (HSA) to quantify damage in laminated composite beam. Han and Kumon [83] studies a damage detection in carbon fiber specimens using digital image correlation (DIC) and acoustic emission (AE). They propose to establish correlation between occurrence of AE event and the timing of failure of the specimen. Zacharakis and Giagopoulos [84] aims to develop a novel vibration-based damage detection method using PSO metaheuristic algorithm and FEA. The performance of the proposed method is gauged using a small-scale structure and experimental CFRP composite structure and found promising. Loi and Aymerich [85] proposes the exploration of effect of sensing transducer position in respect of mode shape of pump excitation, which influences sensitivity of vibro-acoustic modulation (VAM) technique. This technique detects damage in the composite laminates effectively. They find that position of sensors significantly influences the performance of the technique.

An and Youn [86] presents a novel framework of optimum quantity of sensors and their placement under model uncertainty for vibration-dependent damage identification in structures of composite materials. The validated optimized sensors are tested using an optimization-based delamination detection process.

Structural integrity of composite materials can be evaluated using accelerometers and computational methods. Damage can be detected through these methods, but it is found cumbersome and time consuming. However, the precision and effectiveness of computational tools can be increased to reduce the time needed to determine the extent of damage. Common computational tools that are used for optimization include genetic algorithms, principal component analysis, and particle swarm optimization. Damage in wind turbine blades can be detected using a novel method proposed by Wang and Liang, which uses dynamic analysis and mode shape difference curvature to determine the size and location of damages. Various optimization techniques such as GA and PSO are used to evaluate the position and severity of damage in composite structures. The position of sensors significantly influences the performance of the vibro-acoustic modulation technique for detecting damage in composite laminates. The analytical hierarchy process can be a promising alternative to study and rank non-destructive testing techniques, with specimen size as the significant factor. A new framework for optimizing sensors and their placement for vibration-dependent damage identification in structures of composite materials is also being presented.

5.3 Artificial intelligence techniques for prediction of damage

AI techniques have gained importance for prediction of damage in composite materials. AI approaches have the advantage that they do not require prior knowledge of material qualities based on stress-strain relationships. The biggest limitation of other approaches is that the strain correlations characterize the structure and its mechanical behavior while they are valid for the whole range of operating load.

Estimating the fatigue life of high-speed composite crafts often involves use of progressive fatigue damage modelling. In order to put it into practice, a MATLAB code is written, and an energy-based unified fatigue life model is used. This helps to cut down on the number of tests that are necessary [87]. Researchers claims to invent a unique method for monitoring the structural health of beams that is based on the combination of statistical properties of vibration mode shapes and discrete wavelet transforms. The use of regression statistics between intact and damaged modes and the extraction of a quasi-Pearson-based mode shape index is done. Both parameters contribute to an improved accuracy of damage identification [88].

This research presents a unique swarm intelligence system known as the marine predator algorithm (MPA), which may be used in an efficient manner for damage identification. In order to enhance the capacity for learning possessed by feedforward neural networks, it makes use of an optimum foraging strategy and marine memory. The optimal combination of connection weights and biases is generated by the MPAFNN and is then re-entered into the networks for the purpose of prediction. The findings demonstrate that the suggested method can successfully identify damage for a variety of buildings, for both types of cases with a single damage and with many damages [89].

K-means Optimizer (KO) is an entirely novel metaheuristic optimization method that was developed for solving a variety of optimization issues. It applies two movement methods to a structural damage identification (SDI) issue of a complicated three-dimensional concrete structure, where it creates a balance between exploitation and exploration using the proposed movement techniques. According to the Wilcoxon rank-sum and Friedman ranking test findings, the results suggest that KO has the greatest performance for the benchmark functions under consideration [90].

Queiroz and Santos [91] present an analysis for defects of composite plates of resin utilized in wind turbines by tap test. Then, collected data from accelerometers and microphone is further investigated using neural networks. Despite involving direct human access to the structure, vibration-based model-dependent methods paired with modal analysis provide global and local information on the health condition of the structure.

Dabetwar and Ekwaro-Osire [92] conclude that the combination of data fusion and deep neural network (DNN) provide better results due to availability of more information on modes of damage relevant to composite materials. Woo [93] suggest to conduct vibration experiments on composite cylindrical structure of plastic and silicon to obtain vibration data in areas of low-frequency. The data obtained is fed to CNN algorithm through image processing. The proposed technique is competent to clearly differentiate between damaged and intact element with fair accuracy.

Reis and Iwasaki [94] put forward a process to recognize and classify damage in glass fiber reinforced polymer (GFRP) composite beams using vibration data and ANN. They reduced dimensions of the raw data using dislocated series method and improved efficiency of the process by properly tuning hyper parameters. Saadatmorad and Jafari-Talookolaei [95] converges to a model for damage detection using multilayer perceptron (MLP) and FEA. They used activation function as hyperbolic tangent sigmoid. The outcome of analysis depicts that the proposed model can predict damage scenario with precision of *0.9*. Maurya and Sadarang [96] use ANN to decide about delamination in CFRP composites. The proposed ANN model predicts the length of delamination from one end. Barshikar *et. al.* [100] use different ANN algorithms for the fault classification present in rotating machinery.

6. Limitations and challenges

The curvature mode shape-based damage detection method is suitable only for damage detection and localization. This method is highly sensitive to signal noise. However, future research might also include damage quantification. The uncertainties of instruments and environmental effects like noise, structure prone vibrations, surrounding of conduct of experiment alters the outcomes of experiment. This method can be investigated further for various damage scenarios in real life applications. Additional research must be done to improve the modal strain energy method's algorithms for damage estimation and prognosis. It is also possible to design an innovative and effective strain sensor assembly.

Future research on damage detection in composite materials using vibration analysis may emphasize on improving the accuracy of vibration analysis methods for detecting early signs of damage, such as delamination and cracks, in composite materials. This could involve developing robust algorithms for extracting features from vibration signals and using machine learning techniques to identify and differentiate between normal and abnormal signals. Additionally, a gap is sensed for research to investigate the potential of integrating another non-destructive testing (NDT) methods, such as ultrasonic testing and eddy current testing, to enhance the accuracy of vibration analysis. Another area of research that can be explored is to improve the efficiency of vibration analysis that monitors the health of composite materials in real-time and in harsh operating environments. Finally, research is needed to develop more cost-effective and accurate damage detection techniques for composite materials.

7. Conclusion

The review of published literature in the domain of damage detection ranging from the year 1982 to 2024 is presented. It is classified into three sections like damage detection workflow, damage detection techniques and advanced damage detection techniques. Monitoring the health of the structure is crucial since it poses a risk and helps to take the appropriate corrective measures to avoid the propagation of the damage leading to catastrophic failure. These methods are examined for their principle, limitations and remedies for damage detection. The uncertainties reported in most of the techniques are non-linearity, modelling errors, incorrect physical parameters, boundary conditions, fluctuating environmental conditions, and error due to noise in the vibration signal. These are the sources of fictitious structural dynamic responses that alter the detection process. To make these methods reliable and capable of detecting defects in higher-order frequencies, an exploration of research is needed. For different damage scenarios, it is also possible to optimize the parameter selection procedure for a certain structure and environment.

Figure 3 shows percentage contribution of literature related to damage detection techniques. It is observed that maximum number of articles have explored mechanical vibrations as damage detection tool. Also, AI techniques would be the emerging area for damage detection.

Due to a number of criteria, including cost-effectiveness and the simplicity of measurement and processing, vibration dependent SHM and damage identification has emerged as a promising alternative and projects enough scope.

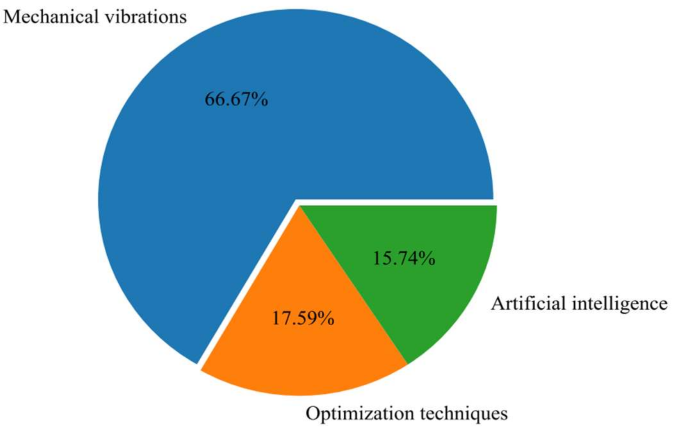

Fig.3. Percentage contribution of literature related to damage detection methods.

The prognosis stage of damage identification has received the least attention. Researchers have also conducted side-by-side analysis of various damage detecting methods. No consensus has been found reported about best suitable data format and identification method. An emerging branch of multidisciplinary research covering Structure-related knowledge, sensor technology, data measurement and processing, and computer methods has been gaining the importance in the field of structural health monitoring. In order to provide a new and optimal technique, correlation between these scientific disciplines is required to establish.

In conclusion, vibration analysis is an effective technique for damage detection in composite materials. It is capable of detecting various types of damage like delamination, cracking and impact. It would gain importance if the damage is detected at an early stage to prevent further deterioration. The technique is inexpensive, non-destructive, and relatively easy to employ. Additionally, it can be used to detect damage in inaccessible areas like inner thick laminates of composite material. With the development of advanced vibration techniques like Digital Image Correlation and Lamb Wave Analysis, the accuracy and sensitivity of vibration analysis can be improved for damage detection in composite materials.

Some of the recent advancements are mentioned that presents the fusion of the data and deep neural network to feed to CNN algorithm. It differentiates precisely between damage and intact entity. Artificial Neural Network (ANN) is also used to predict the length of delamination in CFRP composites.

It is possible to employ artificial intelligence (AI) approaches to forecast damage in composite materials without having previous knowledge of the material properties by using stress-strain equations as the basis for the prediction. The slime mould algorithm (SMA), the K-means optimizer (KO), and the marine predator algorithm (MPA) are the examples of innovative optimisation algorithms to assess structural damage and monitor structural health. In addition, methods like vibration analysis, thermography, and neural networks are found competent to identify damage and precisely estimate its position, severity, and elastic modulus. In general, the data suggest that these approaches are suitable in identifying damage and monitoring the health of structural components. In all, they can converge and envisage as potentially useful solutions for online damage detection.

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Received: September 27, 2024
Revised: March 7, 2025