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REVIEW ARTICLE

Structural Health Monitoring of Composite Materials

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Abstract

Composite materials owing to low density and beneficial properties such as high stiffness, low coefficient of thermal expansion, high mechanical strength, high dimensional stability, good wear resistance, and design flexibility are employed in various fields such as aeronautical, automobile, power generation, civil, and marine engineering etc. Over their course of service, damages can arise in the composite material due to aging, improper service conditions, and erroneous manufacturing and assembly such as inter-laminar voids, porosity, fibre waviness, wrinkles, de-bonding, and delamination. Techniques like structural health monitoring which utilize traditional techniques integrated with sensors to inspect the health of a structure can assist in localization and quantification of several types of damages present in composites based structural models. In this work, several monitoring methods have been reviewed for damage detection including vibration based sensing, embedded sensing, acoustic emissions, lamb wave method, and comparative vacuum monitoring. Several researchers have focused their study on the health monitoring of operational bridges, buildings, and aerospace vehicles for damage detection.

1 Introduction

1.1 Structural Health Monitoring (SHM)

Structural health monitoring (SHM) is a damage detection technique employed for three broad categories namely aerospace, civil, and mechanical engineering structures, to identify deviation from optimal working conditions. This technique has been put to use in monitoring aircraft primary structures [1], bridges [2], buildings [3], rotating machinery [4], pipelines [5], wind turbines [6], railway axles [7], etc. Damage introduced may modify the working condition which, in turn, may lead to a complete breakdown or in severe cases cause catastrophic failures.

Practically, anyone employed in the industry wants to detect damage as soon as possible, so that the maintenance cost is least and there are no life safety issues; for example, monitoring of the operational health of gas turbine engines, gas leak detection in pipes can be hazardous to human life, and the health monitoring of heritage buildings after an earthquake. Health monitoring should be the chief concern when an engineering structure is approaching its initial expected life.

There are four disciplines which include SHM in damage detection are:

1. Continuous monitoring (CoM)
2. Non-destructive evaluation (NDE)
3. Statistical process control (SPC)
4. Damage prognosis (DP)

CoM is usually employed in the monitoring of rotating machinery used for power transmission. NDE is a monitoring tool in pressure vessels and rails, used when we have a prior knowledge of damage location. SPC is a process of monitoring changes using various sensors after there has been a structural damage and DP is used to calculate the remaining useful life of that structure before failure [8].

The Paradigm of SHM

The paradigm of SHM follows a four-phase process [9].

1. Operational Evaluation
2. Data Acquisition, Normalization and Cleansing
3. Feature Selection and Information Condensation
4. Statistical Model Development

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1.1.1 Operational Evaluation

The operational evaluation aims to justify the use of SHM, defines damage for a system and various damage possibilities for that, states conditions under which the system needs to be monitored, and restrictions of acquiring data in the operational environment. It identifies the features that need to be monitored and makes use of the identifying feature of the damage that is to be detected.

1.1.2 Data Acquisition, Normalization and Cleansing

Data acquisition is largely influenced by the monetary resources as it includes selecting the type of sensor used, number of sensors used, excitation method, and storage hardware which is unique for every application.

After data acquisition, there is a need to normalize the data for damage identification. Variability in data can arise due to different environmental and operational conditions. It is required to minimize this variability so that the data acquired can be compared at a similar interval between different operation cycles.

Data cleansing is the process of filtering the undesirable or incompetent set of data and this decision is based on prior knowledge of working with data acquisition.

1.1.3 Feature Selection and Information Condensation

In this phase, we try to identify the features which let us distinguish between a damaged and an undamaged structure. We try to correlate the responses of the damaged structure such as frequency, mode shapes, displacement, velocity, acceleration, etc. with the responses of an undamaged or original structure. In some cases, we introduce defects intentionally which might occur in the life cycle of that structure to study its responses. These defects can also be introduced by computer simulation. The responses obtained will aid us in developing techniques to retain the necessary structural features after damage. The statistical implication of the features should be categorized and used in the condensation process which will be advantageous.

1.1.4 Statistical Model Development

This phase deals with the development of the statistical model to differentiate between a damaged structure and an undamaged structure; although, this has been given least consideration because of its complexity and specificity. Statistical models need to be developed so that we can differentiate between the statuses of the structure and quantify the damage present.

1.2 Composite Materials (CM)

Composite materials can be described as the materials produced from two or more materials that can be differentiated at a macroscopic level to obtain desirable properties that cannot be attained by the parent material individually [10]. The CM contains two phases: a matrix phase and a reinforcement phase. The matrix phase can be polymer, ceramic, or metal and the chief purpose of the matrix is to support the reinforcement that aids in retaining its position [11]. The reinforcement can be particle reinforcement or fibrous reinforcement. The particle reinforcement provides stiffness, increases strength, and toughness of the composite and is favorable due to its wear-resistant properties. The fibre reinforcement provides exceptionally high strength to the weaker matrix material. Owing to the presence of covalent bonds, the non-metallic fibres show a higher strength to density ratio than the metallic fibres [12].

In addition to favorable low density, CM has properties such as high stiffness, low coefficient of thermal expansion, high mechanical strength, high dimensional stability, wear resistance, and design flexibility [13]. Due to these properties, CM are employed in various fields such as aeronautical, automobile, power generation, civil, and marine engineering etc. Alheety et al. [14] developed C_{60}-SESMP-Fe_3O_4 nanocomposite, which proved to be beneficial in the removal of arsenic contaminants from crude oil and water samples as it is toxic for our ecosystem [15]. Abd et al. [16] fabricated graphene oxides with high conductivity by the addition of amines to them. Majeed et al. [17] successfully produced a PoPDA-GO-TiO_2 nano-composite for the storage of hydrogen gas to be used as a clean source of energy [18–20].

1.2.1 Difficulties in Working with Composite Materials

By virtue of its structure, the properties of CM are anisotropic. The mechanism of failure is very complex for CM. Damage evolution of CM remains a very challenging work making the optimization of the design of the CM very difficult, which, in turn, makes it likely to be over-designed by the designer [21].

In addition to this, the lack of reinforcement in out of plane direction makes it vulnerable to impact damage. A matrix crack and delamination will occur in case of low to medium impact energy and total penetration occurs in case of high impact energy. At the opposite end of the impact, fibre breaking will occur [22]. Damages can also occur in CM due to aging, improper service conditions, and erroneous manufacturing and assembly.

Apart from the fact that damages in CM can propose a safety issue because of a tradeoff between the weight and strength of the material [23], the manufacturing of CM may be potentially hazardous to humans. The pre-impregnate process used in the manufacturing of CM is found to be advantageous over the traditional method but utilizes corrosive amines which can often act as skin, eye, and respiratory irritants [24]. Machining and recycling of the CM continuously liberate small airborne fibres which cause lung tissue damage when inhaled [25].

1.2.2 Need of SHM for Composite Materials

Most of the damages that occur in CM are not visible as they occur below the surface. So, traditional non-destructive techniques such as x-rays, thermography, and ultrasonic imaging are used to detect the damages. These techniques can only be used when the region to be evaluated is accessible. Moreover, they are labour and cost-intensive processes [26]. Often, there is a need to disassemble the structure for performing the required inspection [27]. Foreign object inclusions, inter-laminar voids, fibre waviness and wrinkles, debonding, and delamination are the damages that occur in composite materials. The porosity in CM is found to be beneficial in biomedical orthopaedic implants [28] and electronic applications [29, 30], but it can significantly reduce the strength and stiffness of the structural composite materials [31, 32].

Due to the above-discussed drawbacks, the use of SHM has become a necessity while working with composite materials. Many techniques of SHM are being widely used in research as well as industrial environments for detecting the performance of such materials. These techniques are discussed in detail in the next section.

2 Major SHM Techniques for Composite Materials

Some of the major SHM techniques for composite materials are summarized in Fig. 1.

2.1 Vibration Sensors Based Techniques

2.1.1 Wired Setup

Kessler et al. [33] introduced damage in a composite specimen under different conditions and compared the natural frequencies of the damaged specimen and an undamaged control specimen using a scanning laser vibrometer system. The dynamic responses for all the specimens were studied and the effect of damages in the frequency response was established. The frequency reduction can be easily explained by structural dynamics. When a specimen is damaged due to one reason or the other there is a reduction in local stiffness ratio which affects the overall natural frequency. In the case of delamination, the region behaves as two separate laminates which reduces the overall stiffness [34]. The localization of the damage can also be performed by correlating the changes in vibration modes to loss of stiffness [35].

Ratcliffe et al. [36] compared the experimental results obtained from structural irregularity and damage evaluation routine (SIDER) algorithm and an array of micro electro mechanical systems (MEMS) accelerometer for damage detection in composites. It was established that though the setup time was less in the SIDER algorithm but data acquisition required ample amount of time and skilled labour [37] whereas in the array of MEMS accelerometer the setup time was more but data acquisition was rapid and remote diagnostic and solitary testing can be performed. The experimental results for both the setups were similar, which proved that low-cost accelerometer can be employed instead of the high-performance transducer.

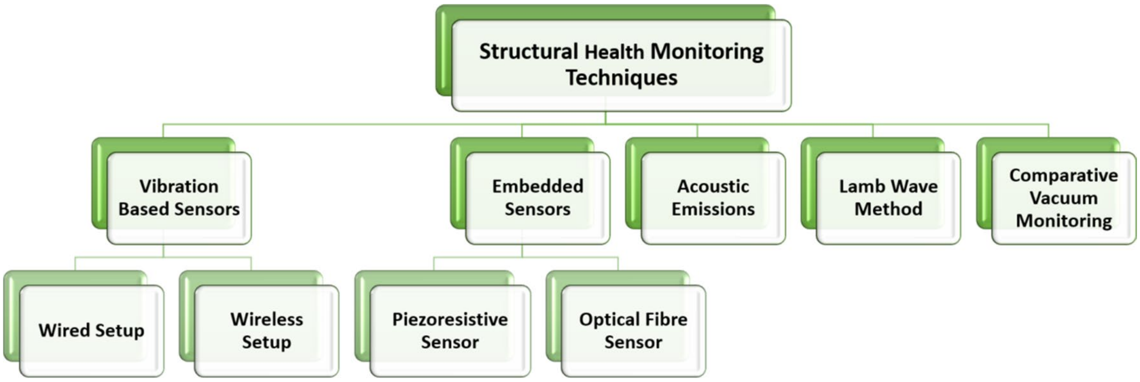

Fig. 1 Structural health monitoring techniques for composite materials

Mariani et al. [38] opted for a three-axis MEMS accelerometer for monitoring the cracks and delamination in composite material. The main purpose of using accelerometer was cost-reduction and avoiding interaction between the SHM system and mechanical integrity of the composite [39, 40]. Only one accelerometer was employed and that also was optimally placed to avoid spreading of the outcomes. The specimen was subjected to cyclic loading a relationship between crack growth and change in compliance was developed. The analytical results were in agreement with the experimental testing.

Masango et al. [41] studied the structural health of a flexible composite sample using polyvinylidene fluoride (PVDF) sensors. PVDF is a slender and flexible polymer, having high sensitivity which makes it suitable for strain sensing [42, 43]. The three-point bending test was performed on the workpiece. The sensor needs to be firmly attached to the workpiece to proper output readings [44]. A comparative study between the defected samples and a flawless sample was undertaken and the sensor validated its competency in detecting damage by output voltage variation. Lead zirconate titanate (PZT) sensors are also employed due to its high sensitivity but owing to its brittle nature, they cannot be utilized in strain sensing of flexible structure [45].

Carrino et al. [46] actively monitored the health of a glass fibre composite pipe using surface-mounted PZT sensor. A nonlinear Lamb wave method was employed to identify a "breathing" defect on the pipe. The position of PZTs is typically defined by preventing the direct wave packet from overlapping with reflections due to boundaries. A metallic coin was adhered to the surface to create a breathing damage which generated nonlinearity. This nonlinearity produced higher harmonics which aided in locating its source without defining a baseline for the structure. Nonlinear are also a favourable contender for detecting micro-damages [47, 48].

Fan et al. [49] performed a comparative study of vibration-based health monitoring of a composite structure. The vibration methods that were scrutinized were natural frequency-based method, mode shape-based method, curvature mode shape-based methods and methods using both mode shape and frequencies. It was postulated that natural frequency-based methods could only localize and quantify small damage in simple structures. The mode shape-based and curvature-based methods only could roughly localize the damage but it required optimization algorithms to accurately localize the damage. Yan et al. [50] also summarized and evaluated various vibration damage detection techniques for health monitoring. The same results as above were concluded that the conventional structural vibration theory should be combined with signal processing, artificial intelligence, mode identification etc. to enhance the accuracy of damage localization in complex structures.

2.1.2 Wireless Setup

Wireless strain sensors have also become popular in the last two decades. Inspired by the human skin Tata et al. [51] developed a patch antenna for strain measurement which also worked as a data transmitter. Jia et al. [52] developed a prototype for wireless strain senor which displayed great linearity and sensitivity. The sensor was principally a series connection between the planar spiral inductor and an interdigital capacitor. Melik et al. [53] also developed and fabricated an radio frequency MEMS strain sensor with high Q-factor. A MEMS differential capacitive strain sensor having a high-performance strain sensing microsystem was fostered by Suster et al. [54]. Han et al. [55] also succeeded in developing a wireless stress/strain measurement device for health monitoring of concrete structures. Other wireless passive strain sensors have also been developed that fully capable of taking accurate dynamic measurements in real-time [56–59]. Such sensors are fully proficient in structural health monitoring and non-destructive evaluation of composite materials and structure.

Gasco et al. [60] tested the accuracy of wireless identification and sensing platform (WISP) in strain sensing and compared the results to traditional wired strain gauges. Carbon fibre compared was tested under uniaxial loading. The Quasi-static indentation test was also performed to examine WISP's ability to evaluate complex strain state. In both the case the strain values accurately measured by the WISP. The sensor was bonded to the surface of the composite using a double-sided tap which electrically insulated it. Carbon fibre is conductive in nature which interferes with the transmitting capacity of the sensor. The use of double-sided tape did not interfere with the strain sensing capacity of the sensor [61, 62].

Manzano et al. [63] tried to fabricate a wireless, robust self-sensing composite to the identify the exact location of the impact on the workpiece. They embedded piezoelectric sensors in the composite with a micro-controller and power source. They were only able to identify the vicinity of the impact rather than the exact location. Only the impact locations that were towards the centre were recognized appropriately. The output signal provided by the sensor was a vibration in one direction only, so the pairing of the sensors was the main challenge faced which was approached by [64].

Lee et al. [65] initially, injected electrodes into a cement composite incorporating 1.0 vol % multi-walled carbon nanotubes (MWCNT) as conductive filler, to fabricate a cement-based sensor. A wireless signal transmission module was also developed which can be mounted and dismounted from the sensor to transmit and collect data. The sensor was used for self-monitoring of a concrete structure at railway stations. The output signal from the pair was very similar to a wired transmission sensor and had a range of 200 m in open space and 100 m in a genuine railway operational environment. Wireless sensors are favourable as they can be employed at an inaccessible location which can be difficult for a wired sensor [66]. The health of the concrete structure has been studied earlier too using a wireless sensor [67–70].

2.2 Embedded (Piezo/Optical) Sensors Based Technique

2.2.1 Piezoresistive Sensor

Tang et al. [39] compared the results of embedded piezoelectric wafers and surface mounted piezoelectric wafers. The workpieces were tested in axial tensile fatigue, and pitch-catch waveforms were recorded through their life. In the former group, it was found that most of the failure occurred at the leads of the piezoelectric wafers, specifically for a diameter greater than 15 mm [71] and they also acted as stress raisers. It was also postulated that additional difficulties will develop if the thickness of the wafer was of the order of one to five times the average ply thickness of the composite material. In the latter group, it was found that failure occurred reasonably away from the piezoelectric wafers.

Alexopoulos et al. [72] embedded conductive carbon nanotube (CNT) fibre to the non-conductive glass fibre reinforced plastic (GFRP) material for sensing and damage monitoring. Identical mechanical properties were obtained for GFRP with and without CNT fibres. A correlation between the mechanical stress on the specimen and electrical resistance of the CNT fibre was established. These parameters can be represented on a parabolic or an exponential growth curve. CNT fibres were advantages when compared to their competitors i.e. carbon fibres [73] and modified (doped) conductive matrix because of their high modulus value and brittle nature.

Ding et al. [74] developed smart structural components by embedded electrostatic self-assembled CNT/nano carbon black (NCB) composite fillers into concrete columns. The fractional change in resistivity of the sensor was measured for cyclic and monotonic loading and it exhibited a stable and repeatable self-sensing property. The embedding does not influence the load-bearing capacity of the column and can be used in monitoring the stress/strain state of the same. The smart sensor can be embedded to fabricate smart products such as bricks, beams and pier for low-cost monitoring.

Luo et al. [75] fabricated piezoresistive fibre sensors by coating single-walled carbon nanotube SWCNT on non-conducting fibres such as glass fibre, polyaramid, nylon and polyethylene terephthalate fibres. They were embedded in the polymeric composite structure. The sensors were able to provide the in situ resin curing information during the manufacturing process and detecting micro-cracks by mapping the stress and strain states during cyclic loading. This information is extremely valuable in quality assurance of composite material. In this study 1D fibre sensors were embedded as they are economical, simple and environmentally nonthreatening [76–79] and their sensing characteristics can be modified through manipulating the SWCNT structures in the dispersion [80].

Nag-Chowdhury et al. [81] fabricated nano-composite quantum resistive sensor (QRS) by deposition of MWCNT on E-glass fibres which was embedded in epoxy resin matrix for monitoring. The two parameters which were considered were the thickness of QRS and adhesion of the same to fibre and epoxy resin [82]. The mechanical integrity of GFRP was not compensated by inclusion of QRS [83]. QRS were able to monitor structural change provided that they were located at relevant locations. Crack creation and propagation can be detected by the change in resistance of QRS and no such change occurred in low strain conditions.

Thostenson et al. [84] employed CNT sensor in detecting damage and bolt loosening in mechanically fastened composite joints. While designing the workpiece, emphasis on the loading condition and the physical contact of the elements was given. Experimental results revealed that the stresses acting in the vicinity of the bolt hole initiated transverse tensile failure in the polymer matrix, resulting in longitudinal cracks due to low shear strength longitudinal to the fibre orientation [85, 86]. The sensor successfully detected the onset and progression of the cracks.

Ladani et al. [87] investigated the fatigue failure of adhesive bonded composite joints using carbon nano fibres (CNF). It was found that the conductivity of CNFs increased by five orders in magnitude by inclusion in epoxy adhesive which enabled the use of electrical response to monitor disbond length. The resistance change was monitored using a four-probe test. A correlation between the change in resistance and disbond length and size were formed. For determining the crack length CNT fibres are also employed in epoxy adhesive under tensile fatigue loading [88–90]. But CNF are better alternative as they are cheaper and widely available [91].

Hasan et al. [92] developed conductive coated polyether ether ketone (PEEK) by plasma treating it and coating the same with Silver (Ag) nanoparticles. It was found that as the weight percentage (wt. %) of Ag increased on the surface of PEEK the electrical resistance decreased. The principle of bonding Ag particle on filaments was discussed in detail in [93]. For the given setup, an optimal value of 4.39 wt. % of Ag was found. The Ag coated PEEK monofilament was integrated into glass fibre (GF) / polypropylene (PP) thermoplastic composites. A gradual increase of change in fractional resistance for the steady increase in stress up to 325 MPa before fracture of the composite shows the potential of Ag coated PEEK monofilament to be used as strain sensor in high temperature and pressure applications.

Lu et al. [94] embedded graphene platelets (GnPs) in epoxy for monitoring damage owning to its high sensitivity. It was discovered that only after the percolation threshold of 0.76 vol. %, the electrical resistance of GnPs increased due to overlapping and/or tunnelling [95, 96]. The relationship between strain and resistance was linear which confirmed that it can be used as strain sensor.

Steinke et al. [97] monitored the damage of aramid composites under dynamic loading conditions. The workpiece i.e. Aramid fibre reinforced polymer composite was modified by embedding piezoresistive laser-induced graphene (LIG) interface for impact sensing. It was found that by monitoring the electrical impedance during the impact using the four-point probe resistance monitoring method, a correlation was found between projectile velocity and change in electrical impedance and a prediction can be made of the extent of damage and failure. The relation between change in resistance and delamination was also established. The LIG interface embedded aramid composite also showed improved toughness which demonstrates the multifunctionality of LIG-treated aramid composites.

2.2.2 Optical Fibre Sensor

Takeda [98] stipulated the advantage of using the optical fibre sensor (OFS) in health monitoring in composite material as early as 2000. The sensor of diameter 52 µm was embedded in carbon fibre reinforced polymer (CFRP). It was also established that when the sensor was embedded in parallel to the fibres in the lamina it did not demote the material strength [99]. The strain on the composite was measured as a function of wavelength peak shift in reflected light.

Jones et al. [100] studied the ability of OFS in health monitoring of ageing aircraft in 2002. Crack growth and delamination in bonded repairs were studied using the sensor. The sensor was tested for known strain and the experimental results were encouraging. Preference to embedded sensors was given as surface sensor cause residual thermal and loading induced strain gradients which reduced the quality and intensity of the output signal.

Leng et al. [101] monitored the cure processing of CFRP composite laminates with and without damage. The monitoring was carried out by embedded Fabry–Perot interferometer (EFPI) and fibre Bragg grating (FBG) sensors in the laminate. It was established that both can be employed to monitor and detect the damage in composites. Both the EFPI [102] and FBG [103] sensors have a thermal expansion coefficient similar to quartz material and found to be temperature insensitive. Three-point bending test was performed on the specimens. The experimental result presented that flexural strain in CFRP composite with damage was more than the CFRP composites without damage for the same load in 0 and 90^{o} direction.

Holmes et al. [104] manufactured a planar optical sensor using flame hydrolysis deposition and reduced its substrate to < 50 µm via physical machining. The planar sensor using an embedded planar optic sensor was validated on laminated fibre reinforced composite material for measuring the through-thickness and in-plane strains. It is first of its kind, scalable demonstration of through-thickness strain monitoring of advanced composites. These planar optical sensors have a negligible influence on the structural integrity ones the surface was roughened and edges tapered. Its results were verified and consistent against strain calculations from classical laminate theory and strain values measured from foil strain gauges and digital image correlation. Zhang et al. [105] theoretically proposed the use of polarisation maintaining (PM) optical fibre for determining the through- thickness strain of a composite material.

Qiu et al. [106] reviewed various OFS for SHM of composite materials. It was established that FBG sensors owing to their small size, lightweight and flexible layout was more advantageous than other OFS. Other OFS considered were Raman optical time-domain reflectometry (ROTDR), Raman optical frequency domain reflectometry (ROFDR), Brillouin optical time-domain reflectometry (BOTDR), Brillouin optical-fibre frequency domain reflectometry (BOFDR) and monitoring of structures by optical fibres (SOFO). The need for the development of OFS was also emphasised to make them more economical and prediction of the growing need for OFS mainly FBG was made in every sector of the market [107–109].

Rito et al. [110] studied the patch repair of GFRP under four-point flexural loading in fatigue using chirped FBG (CFBG) sensors. The fatigue disbanding initiated at the edges and progressed towards the centre. For the undamaged specimen, the edges of the patch were noticeable within the reflected spectra. During loading, the disbonds were either in adhesive/patch interface or at the adhesive/parent interface. In both cases, the progression of damage was visible in the reflected spectra. Similar results were also found in theoretical Finite element modelling of the specimen. It was postulated that two sensors should be incorporated within the bond-line so that both susceptible edges of the repair can be examined. Previous studies also suggested that damage identification in the CFBG sensor is much easier than in FBG sensors [111–113].

Kister et al. [114] integrated Braggs grating sensor into an all-composite bridge to test its structural integrity. The interfacial bonding strength of the adhesives was tested using the pull-out test to evaluate the effect of dry and wet conditions on the fibre bonding. For bonding cyanoacrylate and epoxy adhesives were used. The durability of the sensor protection systems was assessed by carrying out three-point bending tests on composite samples. 100% sensor survival rate was achieved after three year of bridge construction and the protection strategies for the sensor were found to be successful. Details for integrating Bragg grating sensor technology in bridge construction can be obtained in [115]. Later it was also ascertained that knowledge regarding the position, weight, speed and configuration can be extracted by continuous monitoring of the bridge [116].

Hegde et al. [117] investigated and compare two types of the multifibre assembly consisting of high-birefringent (HiBi) sensing fibre and a single-mode PM fibre. PM-HiBi and PM-HiBi-PM were the two fibre assemblies for which experimental and theoretical studies were carried out for health monitoring under static and dynamic loading. The polarization behaviour of both the assembly was analysed theoretically using the Stokes matrix method for the monochromatic case. The experimental results proposed that the PM–HiBi–PM fibre configuration presented better response than PM-HiBi fibre and hence can be used in other smart structures for non-destructive testing. The PM–HiBi–PM fibre sensor showed a pronounced frequency shift indicating a better sensitivity in picking up the structural defects than the PM-HiBi configuration. Different factors such as pre-stress conditions, input azimuth, fibre coating, and fibre splicing also affect the dynamic performance of polarimetric fibre optic sensor (PFOS) [118].

Rufai et al. [119] embedded distributed optical sensor (DOF) in GFRP for cure monitoring. A single length of a fibre can be used as a multiple in DOF sensors, making them appropriate for strain measurement in large structures [120–122]. A portion of the DOF was micro-braided using fibreglass and the rest was left bare. A quasi-static four-point bending test was performed on the specimen and the strain in the length of DOF was documented. The result for both the portions were compared and it was postulated that, micro-braiding was much more advantages than the other because of better strain measurement sensitivity. Micro-braiding aids in protecting, handling and improving the mechanical properties of the fibre [123].

Nguyen et al. [124] investigated the advantage of using whispering gallery modes (WGMs) optical sensor for health monitoring of composites. In WGM sensors, a dielectric microparticle is side coupled to an optical fibre. One end is coupled to tunable laser and other to a photodetector to monitor the transmission spectrum. A minute modification in the shape, size or refractive index of the micro-particle causes a shift in the WGM of the optical sensor. By combing the analytical and FEM model this shift can be interpreted to calculate the strain on the specimen. A force as small as 10^{-5} N can also be detected [125]. WGM sensor can also be employed to detect temperature [126], pressure [127], acceleration [128] and force [129].

Hegedus et al. [130] embedded a fibre bundle of the reinforcing E-glass fabric of the polymer composite structure for structural health monitoring without any special surface preparation. A general-purpose resin system was selected as a matrix for the composite. The load was applied to the specimen. Arbitrarily chosen fibre bundle was illuminated and microscopic inspections of the ends were performed. In the case of fibre breakage and fibre-matrix debonding, the power of the emitted light decreased to zero. The breakage can be recognized by emitted light visible at that point. Similar studies have been performed using cheaper E-glass fibre bundles and different matrix resin for structural health monitoring for composites [131, 132]. It is advantages to use E-glass Fibre as its light-transmitting capacity is not limited to a few metres but they have to be specifically made.

2.3 Acoustic Emissions

Groot et al. [133] studied the frequency response of acoustic emission signal under different loading conditions of CFRP to failure. Upon investigation, it was postulated that a matrix failure and fibre failure produced a frequency of 100 kHz and 300 kHz respectively, whereas the intermittent frequency response was for debonding and pull-out failures. Real-time analysis for each category of failure was performed, which is more efficient as compared to the analysis performed after the failure [134–136].

Morscher [137] studied the modal acoustic emission to monitor damage in the ceramic composite. The investigation established that as the specimen was damaged with increasing strain, the elastic modulus decreased which in turn decreased the speed of sound through the specimen and the frequency response of acoustic emission located the damage precisely. The modal analysis of acoustic emission from CRFP laminates was similarly advantageous as compared to the classical acoustic emission analysis for damage detection, localization and orientation [138].

Das et al. [139] employed piezoelectric sensors and actuators for delamination detection in composite material. The main aim of the study was to optimally place the sensor to locate the delamination in the material. The placement of the sensor was based on the intensity of the sensor output signal and the concept of certainty region. Optimization of the placement of sensor for locating damage is tackled using methodologies such as formulating a mixed integer programming problem [140], state-space model and a back propagation strategy of neural networks [141], power-efficient approach [142], and combinatorial approach for modal shape identification [143, 144].

Fu et al. [145] performed a comparative study between the results of surface-mounted and fibre optic acoustic emission sensor (FOAES) for structural health monitoring of CRPF. The three-point bending test was performed in both cases. The elastic wave energy released by the damaged specimen was detected by the FOAES to detect damage time and quantification of the damage. In this analysis, the FOAES was fabricated, consisting of silica capillary tube and fused-tapered fibre and then calibrated for the specimen. The major techniques of FOAES studied till now have the drawback of being expensive and complicated [146–150].

Aggelis et al. [151] studied the acoustic and ultrasonic behaviour of cross-ply laminates for damage monitoring. The damage can be identified by studying output signals of acoustic emission and ultrasonic waves. When damage is introduced in the specimen, the average energy of the acoustic emission decreases [152]. For shear fracture, there is a higher rise time and lower amplitude than tensile fracture [153]. The damage also alters the mechanical properties of the specimen which influence the pulse velocity and transmission efficiency of the ultrasonic waves [154].

Masmoudi et al. [155] prepared two groups of the specimen without and with an embedded piezoelectric sensor. The inclusion of the sensor in the composite laminate does not affect the mechanical behaviour of the same [156]. The acoustic emission technique was employed for in-situ monitoring of both the groups under three-point bending test. There was a very low degradation of the properties in the embedded category but these sensors have higher sensitivity than surface-mounted sensors. The analysis of the acoustic emission signal aided in recognizing the damage mechanism in the laminate [157, 158].

Martins et al. [159] monitored the health of GFRP reinforced by tufting using piezoresistive effect and acoustic emission technique. Tufting is said to improve the fracture toughness [160, 161] in composite laminates and damage resistance from impacts [162–164]. Both the approaches were found to be valuable in identifying delamination and tuft fracture. The delamination resulted in structure unloading and loss of resin contact which decreased the electric resistance, whereas in the case of tuft fracture the electric resistance increased due to an increase in the longitudinal strain [165–168]. The change in electrical resistance was in correction to the energy of the acoustic emission signal.

Denghong et al. [169] studied the health of ceramic composites using acoustic emission techniques. Ceramic composites are employed in high-temperature applications but are highly susceptible to random vibrations [170]. The material damage in random vibration environment has not been explored fully using acoustic emission technology [171]. This technology was found to be feasible in evaluating damage and load on the specimen. Similar to other composites, the type of damage in ceramic composites can also be identified by studying the acoustic emission signal [172, 173]. But, the same type of damage produced different characteristics of the signal at a different location in the structure.

2.4 Lamb Wave Method

The lamb waves are generated from a transmitter and they travel through the solid up to the receiver, in case of an abnormality or damage, they get diffracted or reflected by the boundaries of the discontinuity, thus detecting the damage in a structure [174]. Prasad et al. [175] constructed tomograms by generating and sensing Lamb Wave for an anisotropic composite for damage detection. The PZT sensors were surface mounted and excited. It was established that the modified cross-hole configuration was more suitable in detecting damage than the conventional cross-hole configuration [176].

Rosalie et al. [177] embedded PZT sensors in Aluminium fiber reinforced polymer composite for damage detection. Lamb waves were employed in constructing tomograms for health monitoring of the workpiece. The setup was successful in in-situ structural health monitoring of flat plates. This technique also has the potential for large scale application as well [178, 179].

Giurgiutiu et al. [180] embedded piezoelectric wafer active sensors (PWAS) in a composite that acted as a transmitter and receiver of Lamb waves for monitoring. The PWAS can detect cracks, delamination and corrosion damage in thin-walled structures [181, 182]. The experimental setup was efficient in detecting a hole of diameter 0.8 mm in unidirectional and 2.7 mm in quasi-directional composite laminates. The lamb waves can also detect damage in thick plates [183] and large structures [184].

Giurgiutiu et al. [185] also detected damage in large composite plates. The minimum damage diameter detected was 2.77 mm. It was established that placement of the PWAS transducer is one of the key factors influencing the damage detection abilities. In composites, the anisotropic wave propagation characteristics complicates the tuning effect between PWAS transducer and composite plates [186] which is similar to the tuning effect between the PWAS transducer and metallic plates [187].

Munian et al. [188] proficiently predicted the delamination length and thickness position by employing the lamb wave method for delamination detection in a composite. It was postulated that as the depth of the delamination increased the power of the reflected signal decreased and the detection abilities increased when the frequency of the incident wave is closer to the resonance frequency of the sub-laminate [189, 190]. Detecting damages in beams can also performed using lamb wave method [191, 192].

Gorgine et al. [193] investigated the feasibility of the lamb wave method in the health monitoring of composites in real-world conditions. The temperature was found to affect the dielectric permittivity and the piezoelectric coefficient of the actuator and sensor. The presence of moisture in composite decreased its flexural strength and velocity of the wave. The amplitude normalization was sufficient to compensate for the presence of external vibrations in the structure. Applied load and bond defects similarly influenced the propagated wave characteristics.

2.5 Comparative Vacuum Monitoring (CVM)

Roach et al. [194] studied the CVM sensor under fatigue testing for crack detection. The sensor was discovered to be reliable without giving any false-alarms and detecting cracks effectively. In the CVM sensors, a very small volume of gas or air is retained at a low vacuum. The fluid in the sensor is very sensitive to the ingress of air. When there is a crack on the component to which the sensor has adhered, it causes a leakage which aids in damage detection well before the critical length of the crack is achieved; the crack size is directly proportional to the rate flow due to leakage [195, 196].

As the CVM system is a vacuum-based, pneumatic sensor and adheres itself to the component, they are generally employed for in-situ inspection in inaccessible and hazardous locations. Such as fuel tanks in an aircraft for damage detection. Moreover, they are an economical and reliable damage sensing setup. The CVM sensor can detect cracks as small as 0.250 mm [197]. Delamination can also be monitored in composites using CVM [198]. Barton et al. [199] extensively reviewed the CVM for health monitoring of composite structure in aircraft structures.

Wheatley et al. [200] employed CVM as means of NDE for crack detection in an aircraft. The sensor was adhered to the component using a stiff adhesive and the system was vacuum based. The inspection time in CVM is exponentially reduced and can adjust itself to complex shapes.

Stehmeier et al. [198] embedded the CVM sensor in between the component having a lap joint to detect crack and corrosion damage. 5 CVM sensors were embedded in the lap joint and it was subjected to fatigue testing. This technology successfully detected cracks of 1.9 mm.

Kousourakis et al. [201] embedded CVM sensors in CFRP laminates to investigate its effects on the interlaminar properties. It was established that the fracture toughness of the composite increases with the gallery diameter of the sensor up to a critical value because of blunting effect of the crack tip around the edges of the galleries [202]. But the composite tends to have an unstable delamination characteristic. The shear strength was also found to be decreased due to reduction in the area because of galleries [203, 204].

2.6 Other SHM Techniques

Afshari et al. [205] predicted the remaining reliability of the composite material after each impact using probability density evolution method (PDEM). Reliability was described as "the ability of a system to complete the required functions in the given conditions, during a specified period" [206, 207]. PDEM model was first proposed by Li and Chen in 2004 [208]. Analytical as well as the experimental evaluation was performed for the Twintex laminate and they predicted identical trends similar to the population level response. Analytical results are advantageous as they are economical [209] whereas the experimental results accurately predicted the reliability [210].

Grassia et al. [211] developed a neural network to perform as the fingerprint of the reference structure. The algorithm required the strain reading at different locations of the sensor without any prior knowledge of load, mechanical property and geometry. The neural network was developed by establishing a correlation between the strain developed at a location and strain quantified in its locality. The strain was calculated by using a large number of strain gauges under biaxial loading of the specimen. The damage was detected by comparing the result of the strain value presented by the strain gauge and value predicted by the neural network.

James et al. [212] studied the impact velocity for generating barely visible impact damage (BVID) of 1-inch damage diameter on CFRP coupons of 2–6 mm thickness. Impact testing machine was employed to study the structural health of composite. It was found that for thin coupons (2–4 mm) hemispherical indentations were found after impact same as the tip of the indenter. But, for the case of thick coupon (5–6 mm) flatter indentations were found irrespective of the hemispherical indenter. This occurrence of this phenomenon was attributed to the increase in the flexural stiffness of the thick coupons. This confirmed that controlled damage was unproblematic to be obtained in thin coupons as compared to thick coupons [213].

Verijenko et al. [214] embedded metastable ferrous alloy in composite laminates for structural health monitoring. The metastable ferrous alloy had an austenitic structure at room temperature, but upon application of strain, it transformed to a thermodynamically stable martensitic structure, which resulted in the change in magnetic susceptibility [215, 216]. This change in magnetic susceptibility can be correlated with the strain experienced by the material. The inclusion does not effect on the material strength and no delamination occurred between the inserts and laminate. Several workpieces were loaded to failure and consistent results were presented which made the technology successful.

Qin et al. [217] embedded glass-coated ferromagnetic microwave in the composite for damage detection. The microwaves were found to have a negligible effect on the strength of the composite material. In the case of wire breakage, there was a significant change in the effective permittivity upon the application of a magnetic field which can be utilized in damage detection. The smaller spacing of the ferromagnetic wires was discovered to be desirable for fine-tuning but there was an increase in the plasma frequency [218].

Patil et al. [219] combined vibration-based method and modal analysis for localization and quantification of impact damage in composite materials. Ultrasonic C-scanning was utilized for damage detection. BVID was detected by comparing the frequency response function of the undamaged and damaged workpiece as the low velocity impact was the most reoccurring damage in in-service composites [220].

3 Summary of Major SHM Techniques for Composite Materials

Summary of the major SHM techniques particularly applicable to composite materials is provided in Table 1.

3.1 Applications of SHM Techniques

Engineering structures are susceptible to a wide range of factors such as environmental and induced by humans, which can shorten their life by introducing some sort of damage in them [221]. As discussed above, the different techniques monitor the structural health of composite materials, which are employed in a broad spectrum of applications. The structural health monitoring of civil structures is of utmost importance as their life cycle is shortened by damages produced; identifying the damage and determining the remaining life of the structure is crucial [222, 223]. Several researchers have focused their study on the health monitoring of operational bridges [150, 224–229].

Ko et al. [2] discussed the advantages of sensor and signal processing in evaluating the structural integrity, reliability and durability of large scale bridges. Nair et al. [230] reviewed the employment the acoustic emission technology in structural monitoring of bridges which presented the techniques promising future. Gatti [231] studied the vibrational response of static and dynamic loading of a concrete bridge built in the late 1960s for health monitoring of the operational bridge. Alampalli [232] employed the SHM technique to study the in-service performance of FRP material in bridge applications. Kister et al. [114, 116] embedded FOS in the bridge during construction for damage detection and it was found to be fully operational when it was tested after three years.

After bridges, the building is the second most monitored civil structures [233–239]. Gonzalez et al. [240] developed a neural network by employing modal parameter to identify seismic damage on a five-storey building. Bandara et al. [241] also developed an artificial neural network from the vibration response of different floors in the building. The neural network was successful in identifying the damaged floor from a ten-storey building. Mishra [242] proposed the advantages of machine learning in damage detection in a heritage building. It was established that it would minimize maintenance repairs and ensure the longevity of heritage sites. Gopinath et al. [243] reported the results of the long term and short term monitoring on damage detection in a heritage building. He was successful in damage localization and quantification.

The structural monitoring of large structures is not economical as the sensor systems are found to be expensive for accurate results. Pachon et al. [244] evaluated algorithms for optimal placement of the sensor in a heritage building. The SEMRO method displayed the most promising results, requiring only eight sensors with a maximum error of 1%. He also worked on reducing the number of the sensor in the monitoring of a bridge structure [245]. The bridge structure required only four sensors with a maximum error of less than 2%. Upon damage detection, in the case of timber beams, it is repaired or retrofitted with a composite material. Rescalvo et al. [246] employed an acoustic emission technique in recognizing delamination between wooden beams and CRPF material. This technique aided in locating the wood-resin breaking zones.

Composite materials are extensively used in aerospace vehicles owing to their favourable properties. Therefore, plenty of research is correspondingly conducted on the health monitoring of such vehicles [247–251]. Alvarez et al. [252] embedded FBG sensor in the composite material of the front spar of an aircraft wing for strain sensing. The system was found to be robust and accurately transmit data about the damage. Ochoa et al. [1] studied the propagation of ultrasonic guided waves for health monitoring of aircraft primary structure. Wang et al. [253] developed a lightweight network of piezoelectric sensors with shared signal transmission to the monitoring of aircraft skin. Bergmayr et al. [254] detected damage in an aircraft spoiler using strain measurements. The strain sensors were effective in damage localization and monitor debonding propagation.

Structural health monitoring has also shown promising results in damage detection, localization and quantification in a wide range of applications ranging from pipelines, railway axles, wind turbine tower, rotating elements etc.

4 Research Gaps

1. Real-time damage identification and updating of composites based structural models using smart wireless sensors needs further exploration.
2. Application of combined SHM, damage identification, finite element model updating in prediction behavior of composites based building model under the effect of an earthquake needs to be explored further.

Table 1 Structural health monitoring of composite materials

Structural Health Monitoring of Composite materials						
Vibration based sensors		Embedded sensors		Acoustic emissions	Lamb wave method	Comparative vacuum monitoring
Wired setup	Wireless setup	Piezoresistive sensor	Optical fibre sensor			
Damage can be localized by correlating the changes in vibration modes to loss of stiffness		It does not influence the mechanical integrity of the composite	The planar optical sensors have a negligible influence on the structural integrity ones the surface is roughened and are edges tapered	The frequency response of acoustic emission can located the damage accurately	In case of an abnormality or damage, lamb waves get diffracted or reflected by the boundaries of the discontinuity, thus detecting the damage in a structure	In the CVM sensors, a very small volume of gas or air is retained at a low vacuum. The fluid in the sensor is very sensitive to the ingress of air. When there is a crack on the component to which the sensor has adhered to causes a leakage which aids in damage detection well before the critical length of the crack is achieved and the crack size is directly proportional to rate flow due to leakage
Setup time is considerable but data acquisition is rapid and remote diagnostic and solitary testing can be performed		A correlation between the mechanical stress on the specimen and electrical resistance of the CNT fibre can be established	FBG sensors owing to their small size, lightweight and flexible layout is more advantageous than other OFS	The analysis of the acoustic emission signal can help in recognizing the damage mechanism in a laminate	The lamb waves can detect cracks, delamination and corrosion damage in thin-walled structures, thick plates and large structures	The sensor is economical and reliable without giving any false-alarms and detecting cracks effectively
It does not influence the mechanical integrity of the composite		The sensor successfully detected the onset and progression of the cracks	Damage can be detected by studying the shift in the wavelength or time delay of the incident light	The type of damage in ceramic composites can also be identified by studying the acoustic emission signal of the same. Ceramic composites are employed in high-temperature applications and are highly susceptible to random vibrations	The temperature was found to affect the dielectric permittivity and the piezoelectric coefficient of the actuator and sensor	They are generally employed for in-situ inspection in inaccessible and hazardous locations

Table 1 (continued)

Structural Health Monitoring of Composite materials				
Vibration based sensors	Embedded sensors	Acoustic emissions	Lamb wave method	Comparative vacuum monitoring
The natural frequency-based methods could only localize and quantify small damage in simple structures	CNT fibres were advantages when compared to their competitors i.e. carbon fibres and modified (doped) conductive matrix because of their high modulus value and brittle nature, but CNF are better alternative as they are cheaper and widely available		The presence of moisture in composite decreased its flexural strength and velocity of the wave. And the amplitude normalization was sufficient to compensate for the presence of external vibrations in the structure	The inspection time in CVM is exponentially reduced and can adjust itself to complex shapes
The mode shape-based and curvature-based methods only could roughly localize the damage but it required optimization algorithms to accurately localize the damage	The smart sensor can be embedded to fabricate smart products such as bricks, beams and pier for low-cost monitoring			
Surface mounted sensor can act as stress raisers	Preference to embedded sensors is given as surface sensor cause residual thermal and loading induced strain gradients which reduced the quality and intensity of the output signal			

3. There is a need to generalize the various health monitoring techniques and optimize the embedded sensing process in the non-destructive evaluation for complex geometric shapes of composite materials.
4. It would also be obligatory to devise robust structural health monitoring techniques which are efficient under severe working conditions without affecting the performance of the composites based system under consideration.

5 Conclusion

An abundant and adequate quantity of literature has been published on structural health monitoring recognizing its applications and importance in various fields. This review paper focuses mainly on the advanced health monitoring techniques for damage detection in composite materials specifically vibration-based sensors, embedded sensors, acoustic emissions, lamb wave method, and comparative vacuum monitoring. By virtue of the desirable properties of composite materials, they are employable in various fields, but due to their anisotropic structure, the mechanism of failure is complex and damages like inter-laminar voids, porosity, fibre waviness and wrinkles, de-bonding and delamination may occur during their working. Structural health monitoring techniques are employed to identify the damage before complete failure and advanced techniques can identify very minute cracks also. A limited amount of study has been published on real-time damage identification cum updating using smart wireless sensors, optimized embedded sensing process and robust cum efficient structural health monitoring techniques under severe and variable working conditions. The SHM techniques discussed in this paper namely vibration-based sensing, embedded sensing, acoustic emissions, lamb wave method, and comparative vacuum monitoring technique are individual in their sense and are very application specific. The employability of these techniques depends upon several factors which include, but are not limited to sensitivity, accuracy, resolution, frequency range, mode of data transfer, processing hardware and its speed, sampling rate, sensor location and number, safety requirements, environmental conditions and economical aspects. Due to such complex situation, it is practically not possible to label any one single SHM technique as the best. However, after a thorough reading of this review paper, one can compare the pros and cons of different SHM techniques in order to find the most suitable SHM technique under given set of operational requirements.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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