

Review Article

Recent developments in damage detection of CFRP composites using non-destructive techniques – a review

Abstract

Defects/damages in carbon composites may be created unintentionally during the manufacturing process or during the component's normal service life. In composite structural elements, damage occurs in a variety of forms, levels, and locations which affects the life of a composite structural component under a given load. Damage to structures such as airframes, helicopter rotors, rockets, space-launch vehicles, aerospace flight vehicles, automotive structures, marine, and sporting equipment is of great concern because of their strategic significance in terms of structural performance, service efficiency, homeland security, and human safety. Even a small amount of delamination could have a large effect on weight-saving advanced structures and lead to a major failure. Therefore, using non-destructive techniques to detect damage is important to keep structures healthy and safe. In this paper, an attempt is made to present alphabetically the review of literature on earliest to modern NDT methods published by various authors and how it continues to expand and become a viable technique for damage estimation.

Keywords: *Damage, CFRP, NDT, Structures, Sensors*

I. Introduction

The damage appears in different types, levels, and locations in composite structural components. The different types, levels, and locations of damage have different effects on the fatigue life of a composite structural component under a given fatigue load. It may be relatively easy to predict the fatigue life of a composite structural component with different damage levels based on a series of laboratory fatigue tests on identical specimens if the damage level is the only controlling factor. However, because of the various effects of the types, levels, and locations of damage, it is not reliable to predict the fatigue life of a particular structural component based on laboratory tests in a simplified approach [1]. Thus, the monitoring of the location and extent of damage (including all types of damage) of the structural component is obligatory. The need for monitoring is heightened by the aging of the flight vehicles, especially the 2001 accident of a passenger jet due to a composite joint failure of the vertical tail wing section. The propensity for damage and the type of damage depend on the structural material. Self-sensing refers to the structural material sensing itself. Real-time self-sensing of damage in carbon fibre polymer–matrix composites by electrical resistance measurement is reviewed [2]. The structures made of carbon fibre polymer–matrix composites are prone to lightning damage, due to the low electrical conductivity of the composites compared with that of metals. The epoxy used in polymer–matrix

structural composites tends to degrade in the presence of moisture. In the presence of moisture and heat (i.e. hygrothermal condition), the degradation tends to be even more severe. Furthermore, due to the difference in thermal expansion coefficient between the fibre and the polymer matrix, the fibre–matrix interface can degrade when the temperature is too high or too low, thereby leading to composite degradation. The thermal damage is worsened when the temperature excursion occurs repeatedly. On the other hand, structures made of metals such as aluminium suffer from corrosion, creep, and plastic deformation. Plastic deformation (yielding) causes the dimensions of a component to change irreversibly. In general, both metallic and composite structures are liable to suffer from damage. The reliability of composites is complicated by the fact that flaws such as fibre waviness and delamination (local separation of the laminae, which refer to the fibre layers or plies) can occur in a composite component even before its initial structural use and that the type and spatial distribution of the flaws in a composite component can vary from piece to piece of the same component, even though the process of manufacturing is identical for the various pieces. The inherent flaws, though small in size, can be the sites for the initiation and growth of more dangerous flaws during the use of the composite component. The growth can occur slowly, as in the case of fatigue. The variability in quality tends to be smaller for metallic components than composite components. As a result, the prediction of the service life of a composite component based on prior use records of similar components is relatively unreliable. This situation makes the need for structural health monitoring or damage detection greater for composites than metallic structures.

II. Developments in detection of damages in composites

(i) Assessment of Damage Detection in Composite Structures Using 3D Vibrometry: Structural health monitoring (SHM) aims to continually monitor a structure throughout its entire life and can allow aircraft owners to identify impact damage as it occurs. This means that it can be repaired prior to growth, saving weight with the repair and the time that aircraft is grounded. Two areas of SHM being researched are Acoustic Emission (AE) monitoring and Acousto-Ultrasonics (AU) both based on an understanding of the propagation of ultrasonic waves. In this work, authors [3] have used 3D Scanning laser vibrometry to monitor the propagation of AU waves with the aim of gaining a better understanding their interaction with delamination in carbon fibre reinforced polymers. Three frequencies were excited with a PZT transducer and the received signal analyzed by a cross correlation method. The results from this and the vibrometer scans revealed 100 kHz as the most effective propagating frequency of the three. A high resolution scan was then conducted at this frequency where it could be seen from figure – 1 that only the out of plane component of the wave interacted with the damage, in particular the A0 mode. A 3D Fast Fourier Transform was then plotted, which identified the most effective frequency as 160 kHz.

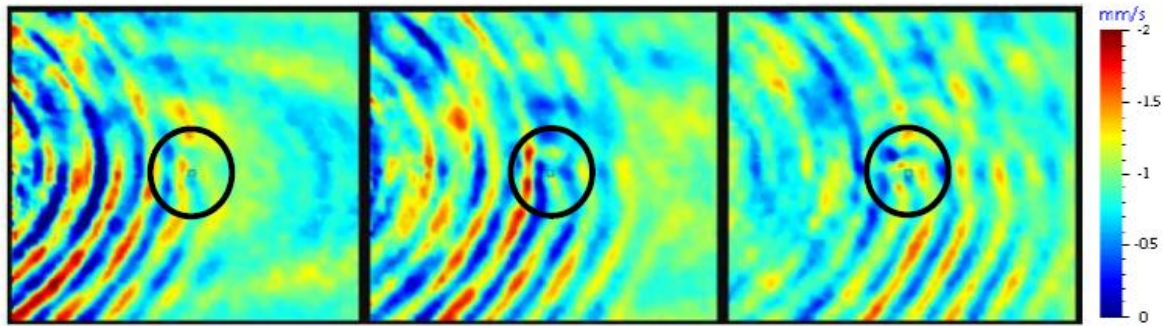


Figure 1. Interaction of the A0 mode with the damage from the high resolution scan at 100 kHz with area of damage circled

(ii) Acoustic emission and infrared thermography: Acoustic emission (AE) and infrared thermography (IT) are simultaneously combined to identify damage evolution in carbon fibre reinforced composites. Samples are subjected to tensile static loads while acoustic emission sensors and an infrared camera record the acoustic signals and the temperature variations respectively. Unsupervised pattern recognition procedure is applied to identify damage mechanisms from acoustic signals. Thermodynamic arguments are introduced to estimate global heat source fields from thermal measurements and anisotropic heat conduction behavior is taken into account by means of homogenization technique [4]. A spatial and time analysis of acoustic events and heat sources is developed and some correlation range in the AE and IT events amplitude are identified.

(iii) Bootstrap Method for Detecting Damage in CFRP: In this, a new method is developed to increase the probability of detecting delamination in carbon fiber reinforced plastic (CFRP) by narrowing the confidence interval of the changes in natural frequency. The changes in the natural frequency in delaminated CFRP are tiny compared with measurement errors. Authors [5] have used the bootstrap method, a statistical technique that increases the estimation accuracy from small samples, for detecting damage in CFRP. The natural frequency was measured using a macro fiber composite sensor to investigate the efficiency of the method. The results show that the confidence intervals of the natural frequency are improved by using the bootstrap method.

(iv) Capacitive Imaging of Impact Damage in Composite Material: This work [6] presents capacitive non-destructive imaging of impact damage in woven fibre CFRP using a coplanar capacitive sensor. Novelty of the approach consists in that spectral characteristics of the capacitive sensor response to CFRP properties are firstly used to establish excitation frequencies for optimum imaging of delamination. For the tested samples optimum excitation frequencies were found to be above 200MHz. Clear capacitive images of delaminations were obtained on each sample shown in fig 2. Ultrasonic (UT) C-Scans of delaminations due to impacts were acquired using phased array technique to confirm presence and extent of the delaminations. Capacitive imaging technique can be used as complementary to UT for imaging shallow defects in composite materials at depths where UT has insufficient time domain resolution.

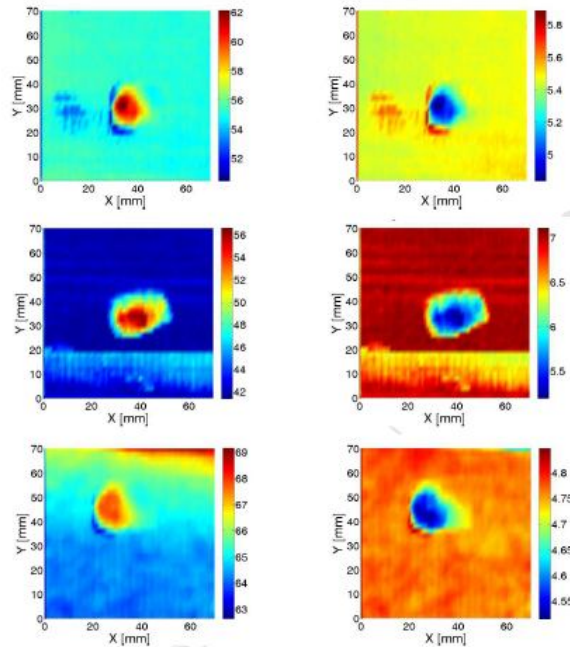


Figure 2. Capacitive images of delamination due to impact in the CFRP samples acquired at 300.04MHz, al capacitance

(v) Damage detection of 3-D braided composite materials using carbon nanotube Thread:

In this study, a carbon nanotube thread strain sensor was fabricated into a three-dimensional (3D) braided composite preform for the strain sensing of SHM. Authors [7] present the results of an investigation on a carbon nanotube thread network in 3D composites for damage detection, in which the variation of the electrical resistance of the carbon nanotube thread embedded into 3D composites was recorded. Based on the variation of the electrical resistance, the location and size of damages were estimated by the response surface method, providing an effective solution for the estimation of the location and size of damages in 3D composites depicted in fig 3.

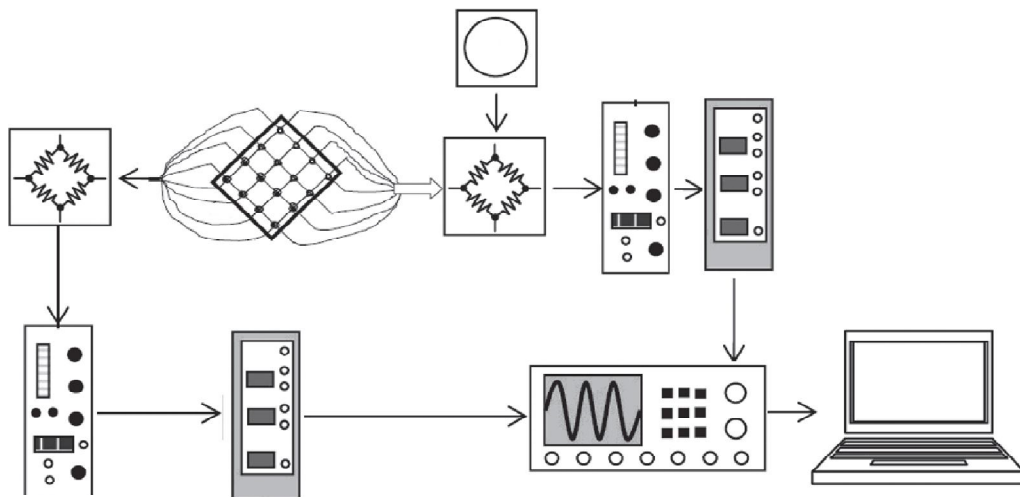


Figure 3: Schematic illustration of the experimental setup for dynamic measurements.

vi) DIC method: Use of full-field digital image correlation (DIC) for detecting damage in UD CFRP components was reported by [8]. Stereo-DIC data was used to analyze changes in vibration modes due to artificial defects. Finally, the effect of the defects was assessed and the suitability of the DIC method was evaluated.

vii) Distributed BOCDA Optical Fiber Sensor: The Brillouin optical correlation domain analysis (BOCDA) technology is one of the distributed optical sensing technologies utilizing the Brillouin scattering phenomena. This paper [9] reports the developmental status of the BOCDA monitoring ability for composite damages such as debonding at adhesive joints and micro-damages at bolted joints.

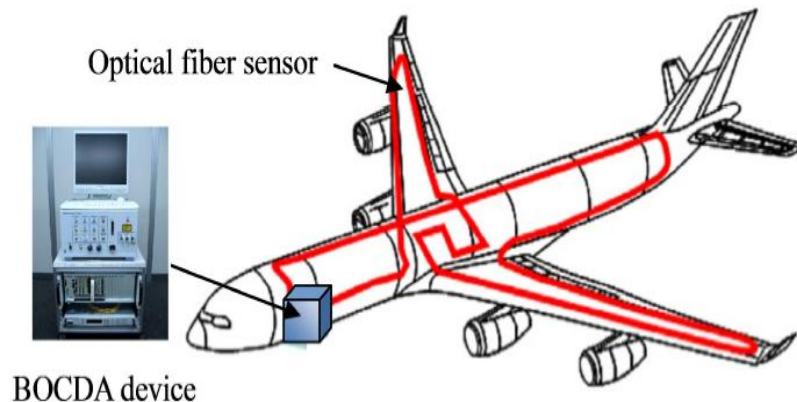


Figure 4. Application concept of BOCDA-SHM Technology

Carbon fiber reinforced plastics (CFRP) are widely used in aircraft structures such as Boeing 787 and Airbus A380 because of their light weight and high strength. In primary structures, bolted joints are still applied. The main failure mode at bolted joints is bearing failure. Bearing failures may cause catastrophic failures because CFRP are brittle materials and have the low degree of yielding and stress concentrations that occurred near bolted joints are not relieved by plastic deformation. Therefore, bolted joints are important inspection parts. If it becomes able to inspect damages at bolted joints without removing fittings, inspection period will be shorter than that now. Adhesive joints have been applied mainly in secondary structures because difficulties of manufacturing quality control cause sudden failures at these joints. If it becomes able to detect these failures initiation and propagation, adhesive joints of CFRP components will be applied to aircraft structures more widely. Therefore, in order to improve the monitoring ability for these damages in composite structures utilizing the BOCDA, debonding detection tests and bearing damage detection tests were conducted shown in Fig-4. Debonding at stiffened or repaired panels was detected by BOCDA distributed strain measurement. Bearing damages at bolted joints were detected by Brillouin gain spectrums (BGS) shapes changes, BGS is one of the BOCDA measurement results, with an embedded optical fiber sensor.

(viii) Damage Detection based on the Natural Frequency shifting: Damage detection of any structure becomes the main concern in a failure analysis. Early failure detection is very important

as it can prevent any catastrophic failure by replacing or repairing the damage part at early stage. One of the non-destructive methods of damage detection is using frequency based vibration analysis. Identification and comparison of a set of natural frequencies before and after damage is the main concern of this research [10]. A CFRP rectangular plate clamped at all edges represented an initial undamaged structure. Based on Kachanov's definition, damage existence in a structure is introduced in the presence of some circular voids. The voids are generated randomly at different level of damage value. To obtain the Natural Frequencies, a Finite Element Model (FEM) of a clamped plate with the updated value of Young's Modulus is analyzed. From the FEM analysis result, it is found that the Natural Frequencies are shifted as the void existence increase. Using curve fitting, the model of Natural Frequency shifting as a function of damage evolution has been generated. It is found that the shifting of the Natural Frequency is greater at higher frequency value as indicated by the higher absolute gradient.

(ix) Eddy current pulsed thermography: This is well established for nondestructive testing of electrical conductive materials, featuring the advantages of contactless, intuitive detecting and efficient heating. The concept of divergence characterization of the damage rate of carbon fibre-reinforced plastic (CFRP)-steel structures can be extended to ECPT thermal pattern characterization. It was found in this study [11] that the use of ECPT technology on CFRP-steel structures generated a sizeable amount of valuable information for comprehensive material diagnostics. The relationship between divergence and transient thermal patterns can be identified and analysed by deploying mathematical models to analyse the information about fibre texture-like orientations, gaps and undulations in these multilayered materials. The developed algorithm enabled the removal of information about fibre texture and the extraction of damage features. The model of the CFRP-glue-steel structures with damage was established using COMSOL Multiphysics® software, and quantitative non-destructive damage evaluation from the ECPT image areas was derived. The results of this proposed method illustrate that damaged areas are highly affected by available information about fibre texture. This proposed work can be applied for detection of impact induced damage and quantitative evaluation of CFRP structures.

(x) Electrical Resistance Mapping: New sensing method of damage detection of carbon fiber/polypropylene composites via 2 dimensional electrical resistance mapping was reported out by [12]. Carbon fibers are used as sensing elements in CFRP due to their electrical conductivity. The basic theory, in such studies, was that the movement of carbon fiber could be detected by Electrical Resistance (ER) measurement. This work evaluated the potential use of carbon fiber/polypropylenepolyamide (CF/PP-PA) composites in thermoplastic automobile applications. Two dimensional electrical resistance (2D ER) mapping was used to sense and predict damages. The extent of random dispersion of carbon fibers (CF) in PP-PA matrix was evaluated using 2D ER mapping contour charts. ER data collected at nine different positions was used to evaluate dispersion and micro-damages. The uniformity of dispersion of CF in fractured surfaces was observed for comparison. Pyrolyzed specimens were used to measure CF amount in each part and compared with 2D ER mapping. The differences in ER for tensile and compressive stresses were compared to explore their usage for real time monitoring and sensing of damages. The observation of the fractured surfaces exhibited an acceptable consistency with 2D ER results.

Ultimately 2D ER mapping was useful in evaluating and predicting damages in Carbon Fiber/Poly Propylene composites under various loading conditions.

(xi) Elliptical Method of damage detection: In this work, the elliptical plane modal identification method is proposed to be used as a damage identification method itself. Authors [13] observed that when the receptance is plotted in the elliptical plane, the area of the ellipse formed close to the resonant frequencies (which depends on the modal constants) is used to detect damage, namely, composite carbon fibre reinforced polymer (CFRP) rectangular plates. Although a mathematical correlation has not been established yet, results show that the method is sensitive to the presence of damage in the test plates, as the area of the ellipse changes with damage. It was shown that the area of the ellipse, which is related to the modal constants (local modal properties), is sensitive to damage in a consistent manner. Hence, this paper offers new possibilities for other researchers who are concerned with damage diagnosis in lightly damped structures since the elliptical plane modal identification method provides promising results for damage identification in CFRP rectangular plates.

(xii) Fiber Bragg Grating Sensors: This work [14] starts with the analysis of relationship between the changes of the strain distribution and damage expansion of CFRP laminated plates and proposes the damage recognition method of CFRP laminated plates based on strain information shown in fig - 5. Then, the CFRP laminate damage monitoring system based on Fiber Bragg Grating (FBG) sensor is established, and the CFRP laminate damage identification experiment based on FBG sensor is made to verify the accuracy of the CFRP laminate damage identification method. The results show that the maximum error between the load when the damage appears on the FBG sensor and that when the damage of CFRP laminated plates expands based on the simulated analysis does not exceed 16%. The accuracy of the damage recognition method of CFRP laminated plates is verified and the damage recognition of CFRP laminated plates and their expansion process is achieved.

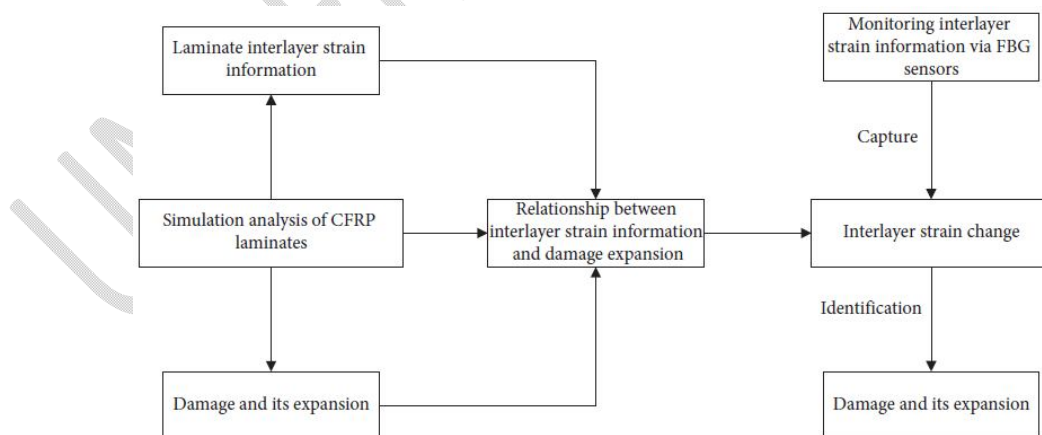


Figure 5. Damage recognition principle of CFRP laminated plates based on FBG Sensor

(xiii) Free-space microwave non-destructive techniques: Investigation of a free-space microwave method for non-destructive testing of unidirectional CFRPs has been carried out [15]

by means of a pair of standard gain horn antennas, covering a frequency range from 26.5 GHz to 40 GHz. With the simulations, experimental results related to the presence/severity of the analyzed defects are linked to the variations of the measured scattering parameters S_{ij} . The approach is based on the comparison between the electromagnetic signal reflected and transmitted through a healthy sheet material under test, when a radio frequency (RF) wave is incident on it, and the one reflected and transmitted by a damaged sheet. The eventual presence of the defect is revealed by measuring the mismatch between the two transmitted waveforms. The performance of this radio wave technique is investigated in relation to surface defects and also in relation to those types of defects that are less detectable with this method, such as delaminations, cavities and inclusions. The simulations make use of the finite integration technique (FIT) and the finite element method (FEM).

(xiv) Multimodal Damage Detection in Self-Sensing Fiber Reinforced Composites: Internal delamination damage is detected in fiber reinforced polymer composite materials containing active functionality. Damage-triggered magnetization of the delaminated zone is accomplished using a vascular system to deliver fluids that precipitate magnetic particles upon mixing indicated in Fig – 6. Multiple modes of detection are used to sense the presence of this magnetic material. Visual detection is accomplished by the high contrast between damaged and undamaged areas provided by the biomimetic “bruise” formed by the magnetic particles. Magnetic scanning is also used to detect the particles, even if obscured by paint or by opaque reinforcement, such as carbon fiber. Additionally, thermal detection is accomplished by inductively heating the magnetic particles and sensing the temperature differential with an infrared camera. The effectiveness of each detection mode is discussed [16] and compared to industry standard C-scan to assess accuracy. Using the damage area measured with C-scan as the benchmark, visual detection measures the damage area with 76% accuracy, and magnetic detection measures the damage area with 91% accuracy. Thermal detection accuracy is time-dependent as expected. All detection modes consistently detect the presence of damage. The multifunctionality of this material can tailor damage detection techniques for the application and provide a parallel system to augment and potentially enhance self-healing.

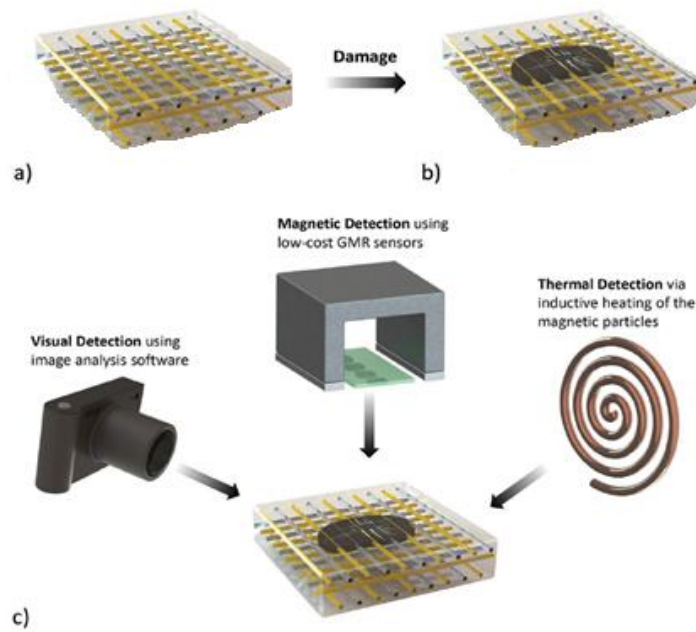
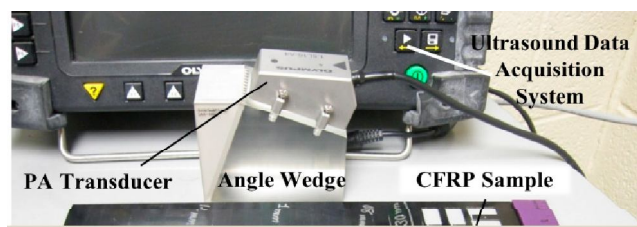


Figure 6. a) Schematic of the active vascular material system used to deliver the liquid constitutive parts of the magnetic particles. b) Mixing of the liquids causing precipitation of magnetic material in the damaged region. c) Schematic of three modes of damage detection: visual, magnetic, and thermal. Each mode is possible because of the high contrast between damaged and undamaged areas provided by the magnetic particles.

(xv) Phased Array Nondestructive Ultrasonic Inspection of Composite Materials: Carbon- and glass fiber-reinforced polymer (CFRP and GFRP) composite materials have been used in many industries such as aerospace and automobile because of their outstanding strength-to-weight ratio and corrosion resistance. The quality of these materials is important for safe operation. Nondestructive testing (NDT) techniques are an effective way to inspect these composites. While ultrasonic NDT has previously been used for inspection of composites, conventional ultrasonic NDT, using single element transducers, has limitations such as high attenuation and low signal-to-noise ratio (SNR). Using phased array ultrasonic testing (PAUT) techniques shown in fig -7, signals can be generated at desired distances and angles. These capabilities provide promising results for composites where the anisotropic structure makes signal evaluation challenging. Defect detection in composites based on bulk and guided waves are studied [17]. The capability of the PAUT and its sensitivity to flaws were evaluated by comparing the signal characteristics to the conventional method. The results show that flaw sizes as small as 0.8mm with penetration depth up to 25mm can be detected using PAUT, and the result signals have better characteristics than the conventional ultrasonic technique. In addition, it has been shown that guided wave generated by PAUT also has outstanding capability of flaw detection in composite materials.



(xvi) Relief and LSSVM Method: The damage identification method of carbon fiber reinforced polymer structure is of great significance for the timely detection of structural invisible damage and the avoidance of catastrophic consequences. The damage identification method of composite materials based on ReliefF and LSSVM (Least Squares Support Vector Machine) was reported by [18]. Firstly, the damage signals of composite structure were obtained by using non damage active excitation method. Then, Fourier transform is used to extract the damage feature and reduce the feature dimension of ReliefF. On the basis of this, the damage identification model based on LSSVM was established by taking the damage feature as input and the damage mode as output. The experimental results showed that for the 20 test, the correct recognition time was 19 times, which showed higher damage identification accuracy. This work provides a feasible method for damage identification of composite structures. ReliefF is a feature weight algorithm, which gives different weights according to the correlation of each feature and class removes the feature selection. It is a feature selection algorithm with excellent performance.

(xvii) Self-Sensing Curved Micro-Strip Line Method: A self-sensing Time Domain Reflectometry (TDR) method for Damage Detection of CFRP laminates has been proposed in the present study by [19]. Carbon fibers are used as sensors using a transmission line. Authors have published research articles of the self-sensing TDR method. The self-sensing TDR method reduces number of required electrodes for damage detections although the sensitivity of detection is sacrificed. A micro-strip line (MSL) method is adopted to obtain impedance matching with a coaxial cable and successfully detected damage in a CFRP laminate in the previous study. In the present study, a long curved MSL is experimentally investigated as impedance- matched transmission line for detection of damage of a CFRP laminate in wider area illustrated in fig - 8. Fibre breakage is simulated as a hole made by drilling. As a CFRP laminate has strongly orthotropic electric conductance and the electric properties of a CFRP laminate at the high frequency are not clarified, the effect of the orthotropic conductance at the curved transmission line is experimentally investigated.

As a result, the effect of orthotropic conductance at the curved strip line is shown to be negligible, and fiber breakage that locates closed to the copper strip line can be detected by the self-sensing curved MSL method.

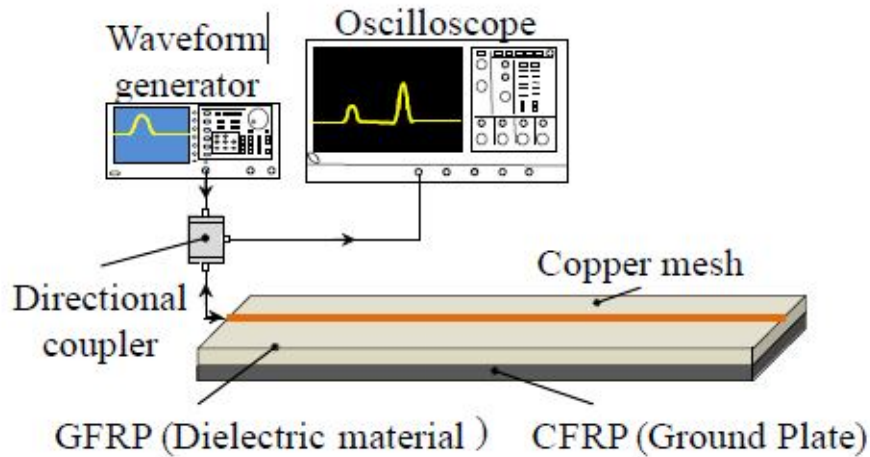


Figure 8. Schematic representation of self-sensing TDR method for damage detection of a CFRP laminate.

(xviii) Supramolecular approach: Self-diagnosis of early stage damage in a carbon fiber epoxy composite material, via the incorporation of a CB8 based ternary complex as an additive using supramolecular approach was reported [20]. The complex comprising a fluorescent probe and a quencher encapsulated by the CB8 is introduced into the epoxy resin of the composite as a supramolecular crosslinking agent, whose stress-induced dissociation results in the turn on of fluorescence of the probe. In this way, detection of irreversible mechanical strain and fatigue at an early stage is attainable, enabling the assessment of micro damage in the material shown in figure -9.

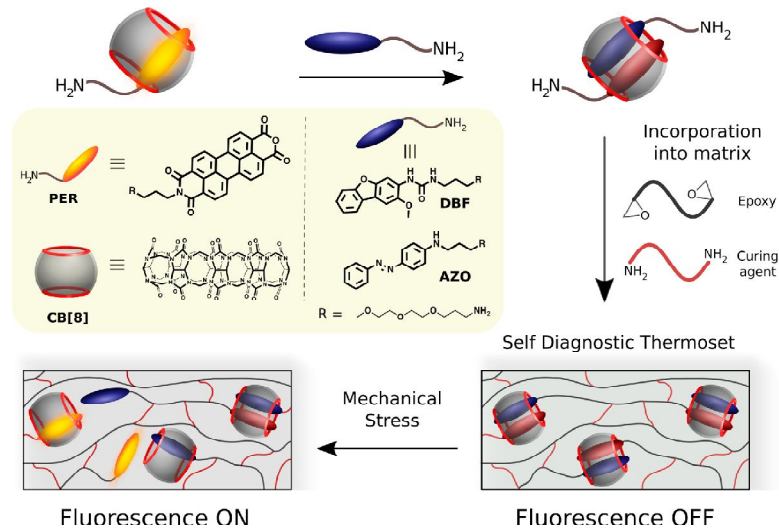


Figure 9. Schematic representation of the working principle and components of the damage reporting carbon fiber-epoxy resin composites

(xix) Ultrasound and electromagnetic method of detecting damage in CFRP composites: In this paper authors [21] presents the behavior of carbon fiber woven-PPS composites at low velocity impacts. The transversal electrical conductivity is modified due to the plastic deformation following the impacts, and thus electromagnetic procedures (fig 10a) can be used

for assessment of CFRP using a high resolution sensor with metamaterials lens and comparing the results with those obtained from ultrasound testing with phased array sensor. The area of the delamination is overestimated when the method of phased array ultrasound (fig 10b) is used and substantially underestimated by the electromagnetic testing. They found a good agreement between the simulations with finite element method and experimental measurements.



Figure 10.a - Electromagnetic testing



Figure 10.b - Ultrasound Testing

(xx) **X-ray combined with Ultrasound for damage detection in CFRP:** Combining x-ray with ultrasound testing (UT) for multimodal inspection depicted in fig – 11 was developed by Radalytica [22] which is helpful in detecting impact damage of composites. Because delamination is not detectable by x-ray but it's very well detected by ultrasound. For impact damage, high-resolution x-ray imaging provides a lot of details if there are cracks, but one cannot see any surrounding delamination. With ultrasound, however, one can visualize the delamination but not all of the details of the impact. So, combining these two technologies to provide a much better overview of damage detection in composites is trending today.

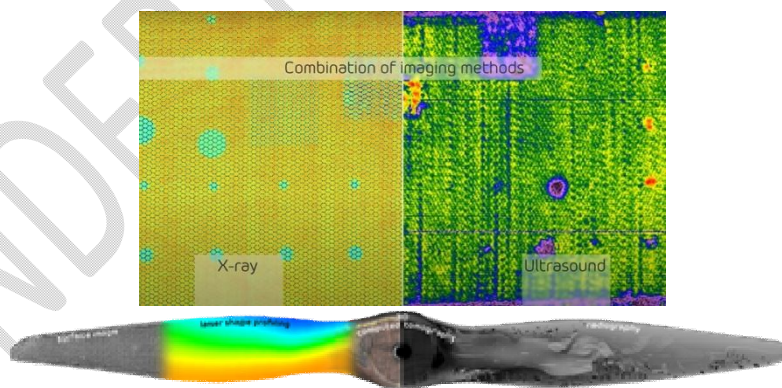


Figure 11. Multimodal inspection – x ray and ultrasound

III. Conclusions:

This paper reviewed different modern NDT methods for evaluation of damage detection in CFRP composites by categorizing their benefits and drawbacks, in order to provide a comprehensive review of composite NDT. The ability to detect early damage is of great significance in load bearing composite materials used for high performance applications.

Because carbon composites are primarily used in critical-safety applications, such as aircraft primary construction, automotive, marine, transportation etc., hence non-destructive testing of carbon fiber composite materials has become more critical and demanding. Efficiency and safety should be considered when determining the best method to use. Besides, the method chosen should reduce the operation's costs. It is based on methods that rely on the use of physical values to determine material properties. Furthermore, non-destructive tests employ physical principles to detect and evaluate flaws or destructive defects.

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