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REVIEWS

Non-Destructive Evaluation of Defects and Damage in Composite Materials and Structures

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ABSTRACT | The mechanical behaviour of composite materials differs from that of conventional structural materials owing to their heterogeneous and anisotropic nature. Different types of defects and anomalies get induced in these materials during the fabrication process. Further, during their service life, the components made of composite materials develop different types of damage. The performance and life of such components is governed by the combined effect of all these defects and damage. While porosity, voids, inclusions etc., are some defects those can get induced during the fabrication of composites, matrix cracks, interface debonds, delaminations and fiber breakage are major types of service induced damage which are of concern. During the service life of components made of composites, one type of damage can grow and initiate another type of damage. For example, matrix cracks can gradually grow to the interface and initiate debonds. Interface debonds in a particular plane can lead to delaminations. Consequently, the combined effect of different types of distributed damage causes the failure of the component.

A set of non-destructive evaluation (NDE) methods is well established for testing conventional metallic materials. Some of them can also be utilized for composite materials as they are, and in some cases with a little different approach or modification. Ultrasonics, Radiography, Thermography, Fiber Optics, Acoustic Emission Techniques etc., to name a few. Detection, evaluation and characterization of different types of defects and damage encountered in composite materials and structures using different NDE tools is discussed briefly in this paper.

Keywords: *Composite Materials, Defects, Damage, Failure Mechanisms, NDE, DIC, Guided Wave Techniques.*

1 Introduction

Advanced composite materials reinforced with high strength continuous fibers are here to stay. Attractive properties of these materials such as high specific strength and modulus, corrosion and fatigue resistance, tailorability and formability make them suitable for various engineering applications, in particular, for structural components in aerospace and defence applications. Nevertheless, along with the advantages, these materials have also brought new problems and challenges to the structural engineers determined to use them. In fact, most of these problems are due to the basic nature of the materials, viz., anisotropy, heterogeneity and constituency of multiple phases. Theories and criteria which have been existing and have been developed to explain the mechanical behavior and failure of conventional metallic structural materials are essentially based on three main assumptions that, they are homogeneous,

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continuous and isotropic which all fail when we refer to composite materials. Further, the type of defects and damage encountered in structural components made of composite materials are entirely different from those in conventional structural materials. Thus, to understand, to study and to explain the behavior of composite materials we need a different set of theories formulated and tools developed.

The multifarious advantages of the advanced composite materials, some of them mentioned above have perhaps lured the structural engineers to push them into usage for various applications even before understanding the mechanics of the materials well. Thus, these materials have found their way in structural applications in the last two decades and have been successful to certain extent. Further, in aerospace and defence applications where the search is continuously on for high performance materials, composites have offered multiple advantages of saving weight and fuel consumption there by facilitating increased payload.

The fact that these materials are susceptible to different types of defects during fabrication process and damage during service life, some of which could be critical, deserves due attention. In general, every engineering component is subjected to varying loads throughout its service life. Hence, it is not sufficient if we know the basic mechanical properties such as strength and stiffness of the material being used for a structural component but it is also essential to study the overall behavior under different loading conditions. Further, the effect of different types of defects and damage on the performance of a structure, both short term as well as long term, needs to be assessed.

1.1 Defects and damage in composite materials

As mentioned earlier, different types of defects and anomalies get induced in these materials during the fabrication process. Further, during service, the components made of composites develop different types of damages. Flaws of major concern in fiber reinforced polymer composite materials are;

1. Matrix cracks
2. Porosity, voids and inclusions
3. Interface debonds and delaminations
4. Fiber breakage
5. Resin rich and Resin starved areas

Two major types of damage which get induced in composite structural components during its service are, damage due to impact load and damage due to fatigue. These damage may again comprise of two or more different types of flaws listed above. They may occur in a sequence and may coexist to cause progressive cumulative damage.

2 NDE Tools for Composite Materials

No single NDE tool can provide us with all the necessary information with regard to different types defects and damage in composite materials and hence we may have to use a combination of two or more NDE methods. Most commonly used methods are based on Ultrasonics, Radiography, Infra-red thermography, guided wave techniques and fiber optics.

Ultrasonic Testing (UT) involves propagation of high frequency sound in the range of 20 KHz to few MHz in a material. Characteristics of the transmitted or reflected sound are studied to obtain material properties and evaluate defects. Ultrasonic techniques are found to be very effective in detecting and evaluating planar defects such as delaminations in multilayered composites. Attenuation of ultrasonic waves in a medium can also reflect on the interior condition of the material such as existence of porosity, voids, density variations and degradation of the material due to any service conditions.

Radiography basically provides a two dimensional projected image of intensity distribution of transmitted radiation caused by the differential absorption of the energy while travelling through the material. Variation in density, travelled distance, defects results in shadowgraph image of the specimen. X-rays, gamma rays or neutrons beams are used in Radiographic testing of composites. Low-voltage radiography with soft X-rays is particularly useful for polymer composite material inspection. Use of low power and long exposure time enhances sensitivity and contrast. When small differences in attenuation caused by planar defects in composites are not clearly distinguishable, capabilty of the X-ray method can be enhanced using radio opaque additives such as Tetra bromo ethane (TBE) which is a liquid and can be injected into the damage area.

Acoustic Emission Technique (AET) is an online NDE tool with unique features and capabilities. Acoustic emission refers to the stress waves generated by dynamic processes in materials. Emission occurs as a release of a series of short energy packets. The energy thus released travels as spherical waves and can be picked up from the surface of a material using highly sensitive transducers, usually piezo-electric sensors. The wave thus picked up is converted into an electrical signal which on suitable processing and analysis can reveal valuable information about the source causing the energy release. This technique provides us with the dynamic characteristics of active flaws such as its growth, growth rate, criticality and intensity. On the contrary even if a flaw is very large AE cannot directly indicate unless it becomes active.

Infra-red Thermography is another NDE tool where the component under test is subjected to local heating. An infra-red camera is used to map the differential temperature profile on the surface of a component due to thermal absorption or emission by the component. On-line image of the surface temperature profile of the component is obtained on a color monitor. Temperature gradient of less than one tenth of a degree Celsius can be detected. Area with subsurface defects exhibit different thermal profile compared to surrounding region.

Acousto-Ultrasonics is a hybrid technique, a combination of UT and AET. This can give us a measure of degradation of material due to distributed damage.

Acoustic Impulse and Sonic Resonance methods are suitable for detecting gross defects which cause significant change in the stiffness of the material Resonance. A set of probes are used in these methods to transmit acoustic waves at varied frequencies and differences in wave amplitude and phase are measured. Comparisons between a known good bond structure and unknown bonded test component helps in evaluating bond quality or detection and evaluation of debonds.

2.1 *Ultrasonic methods*

Different methods or techniques of ultrasound can be used for NDE depending upon the application and required information. Though modes of wave propagation in composite materials is a very complex phenomenon owing to the heterogeneous and anisotropic nature of the materials, gross localized defects such as delaminations can be very effectively detected and mapped through ultrasonic imaging.[1–3]

Through-transmission and Pulse-echo are two common methods used in ultrasonic testing. In the first method, a set of two transducers is used, one as transmitter and the other as receiver on either side of the component being tested. The ultrasonic wave emitted by the transmitter travels through the material and after its interaction with the medium, a part of the energy is picked up by the receiver on the opposite side. Studying the amplitude and other characteristics of the received signal would provide us with valuable information about the interior of the component being tested.

Pulse-echo method is more popular and extensively used as an NDE tool. In this method a single transducer is used both as transmitter and receiver. The ultrasound beam emitted by the transducer travels through the medium and whenever encounters an interface a part of the beam gets reflected back and is received by the same transducer. In this method the information on the transit time is also recorded by which it is possible to determine the depth of flaw.

The receiver signal can be presented in different ways known as A, B and C scan displays. A-scan just provides a voltage—time signal which can indicate existence and depth of flaws in the area covered by probe surface. B-scan presents a cross sectional view of the material under test and C-scan is a planar image of the test object at a particular depth.

For ultrasonic imaging, the probe is continuously moved over the required area line by line in zig-zag fashion. The output signal amplitude from the receiver is recorded continuously with respect to its position. This provides us the distribution of amplitude over the scanned area. In the computerized system a multi colored display is used to obtain the image of the scan where different colors represent different range of values of amplitude of the received signal. This method popularly known as C-scan is the most extensively used NDE method for detection, location and mapping of delaminations in multilayered composite materials.

The A and B scans of a healthy composite laminate and a laminate with an impact induced damage in multilayered woven fabric Carbon Fiber Reinforced Polymer (CFRP) composite is shown in Figure 1. The A-scan signal from the healthy laminate shows two voltage peaks in the time signal corresponding to front surface and back surface reflections of the ultrasound waves. B-scan of the same laminate shows a uniform cross section. The A-scan signal from the damaged laminate shows that ultrasound waves are absorbed within first few layers and no back surface reflection can be seen. The cross-sectional view in this B-scan clearly shows multiple delaminations through its depth. The C-scans of the corresponding laminates are presented in Figure 2. The size and shape of the induced delamination can be very clearly seen.

Measurement of attenuation of ultrasonic waves as they pass through the composite laminates can reveal about the material condition such

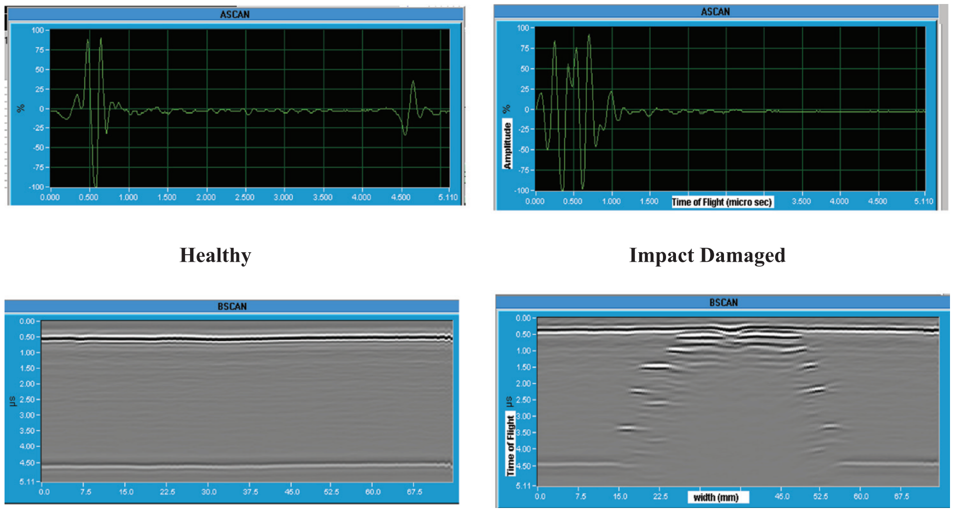
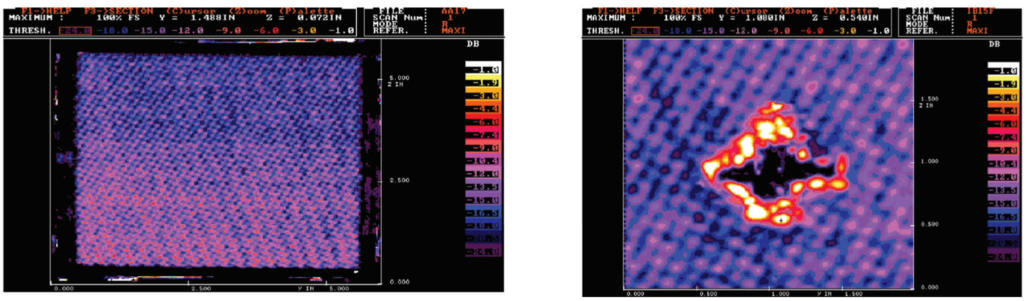


Figure 1: A (top) & B (bottom) scans of healthy and impact damaged composite laminate.



(a) (b)

Figure 2: The C-scans of the healthy (a) and impact damaged (b) laminates.

as existence and extent of porosity and voids.[4] The set of images obtained by ultrasonic scanning of multilayered CFRP specimens with varied porosity contents is as shown in Figure 3.

As can be observed from these images corresponding to different values of porosity there is a definite trend showing decrease in received signal level with increase in porosity. The different colors seen in each of these images represent different ranges of the received signal amplitude values as indicated by the color coded bar displayed to the left of the image. The plot in Figure 4 shows the ultrasonic signal intensity variation with porosity content. The porosity values indicated in the figure were obtained from standard acid digestion tests generally used for determining the porosity content in polymer composite materials.

2.2 *Radiography testing*

Radiography testing is expected to be more effective in detecting volumetric defects than laminar defects. Voids and inclusions of different density compared to surrounding region in any material are reflected in the two dimensional radiographs. The attempt to evaluate varied porosity content in CFRP laminates discussed in the previous section using digital radiography though could show a trend, was not very convincing for a quantitative correlation.[4]

Real time digital X-ray imaging was performed on the sets of CFRP laminates to look for variation in the transmitted radiation with respect to varied porosity. The experimental setup consisted of a portable 100 kV source and portable amorphous silicon based Flat panel X-ray detector. Different test variables and combinations were tried by trial and error method before arriving at a set of parameters, optimum source kV and radiation exposure in milliamp-sec. Sets of images obtained for CFRP laminates were processed to obtain average pixel intensity for each of the laminates with different porosity levels. Figure 5 shows a sample plot of variation in average pixel intensity with porosity in these CFRP laminates.

The laminates with higher porosity are expected to be less denser. This should result in

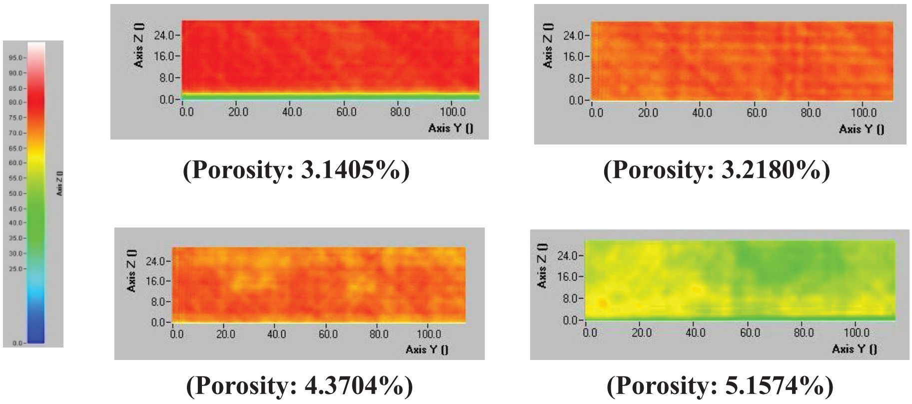


Figure 3: C-Scan images of laminates with different porosity levels.

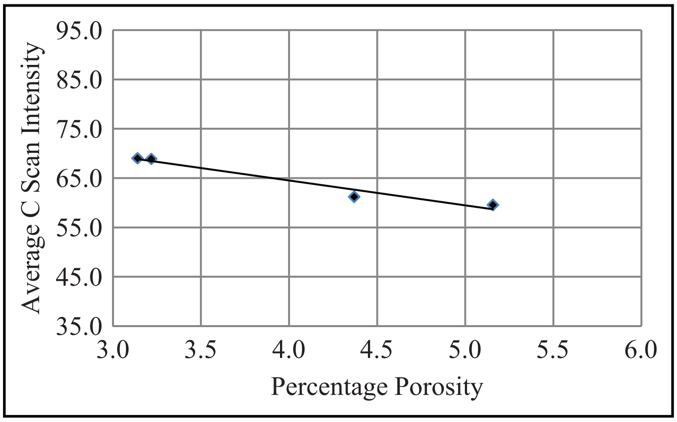


Figure 4: Ultrasonic signal intensity for CFRP samples with different porosity content.

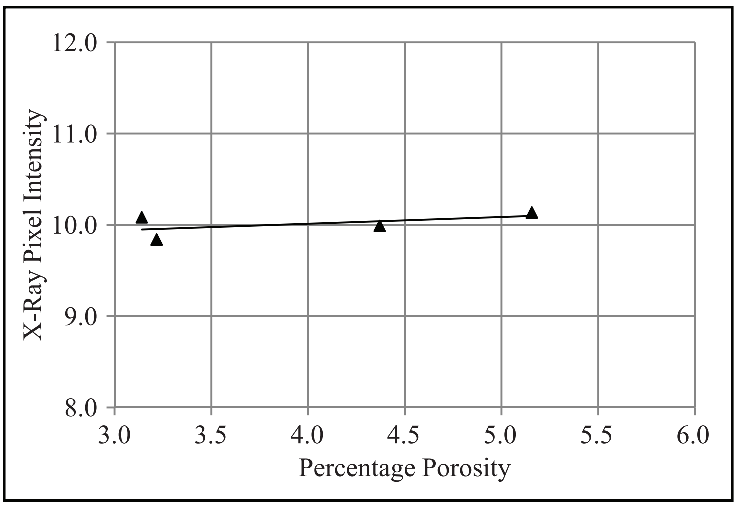


Figure 5: X-ray image intensity variation with porosity in CFRP laminates.

increase in the transmitted X-ray energy with increased porosity. The results obtained though quantitatively not very discriminating, the average intensity values do show a trend with increasing porosity. This technique may not be the best quantitative measure as the laminates themselves are thin structures of lower density materials which may not significantly represent the change in porosity content that can appear as density variation on the obtained image. It could be due to the reason that the CFRP laminates by property are low density material. Also, the laminates tested so far perhaps are not thick enough to map the possible changes due to variation in porosity. The results obtained however are encouraging and thicker laminates with more number of layers may produce better results.

2.3 *Acoustic Emission Technique (AET)*

Several investigators have attempted to study the application of AET for evaluation of composites. Particularly in the 70's a good number of publications have come out with interesting results using AET as an on-line NDE tool for composites. Williams and Lee have presented a thorough review of various investigations on acoustic emission (AE) monitoring of composite materials and structures.[5] While different scientists have repeatedly reported that fiber fracture can be easily detected using AE, some have tried to correlate AE to number of fibers failed.[6,7] AE due to fiber fracture has been observed to be more energetic generating higher amplitude signals compared to interface failure and matrix cracking. A steep rise in the total AE activity has also been consistently observed as failure approached under monotonically increasing load. Use of AE during burst and proof tests of composite components have been reported with interesting results. Some investigators have also attempted to correlate AE activity to change in stiffness or compliance of the composite materials.

Characteristics of AE signals generated due to damage initiation and extension in composite materials can be correlated to failure mechanisms. Amplitude of AE signals generated has been found to be an important parameter that can discriminate the sources causing the emissions in composites. While fiber breakage is known to give out very high amplitude signals, signals due to matrix cracks have been found to be of lower amplitude values just above the ambient noise level. The emissions caused by the interface failure and delamination growth have been reported to have amplitude range that falls in between the fiber failure and matrix cracks.

Under monotonically increasing load composite material has been found to be silent till the load reached about 60% of the failure load. Then on, a constant increase in the AE activity has been observed to 75% of the load followed by an exponential rise then on till the eventual final failure of the component (Fig. 6). Thus, an advanced warning about the impending failure of the component should be possible by a simple measurement of slope of cumulative AE activity with respect to applied load or time.

Fatigue damage progression in composite materials is known to occur in stages. Further, different failure mechanisms are found to be dominantly responsible for these stages. Bhat et al.,[6] have been able to identify these stages by using AET as on line monitoring tool during the fatigue tests on composite specimens (Fig. 7).

Further, it has been shown that it is possible to obtain the signature characteristics of the individual failure mechanisms playing significant roles sequentially in the damage progression. Using pattern recognition approach of multi-parameter analysis a total of three distinct groups of signals representing matrix cracking, interface failure and fiber fracture have been identified. Figure 8 shows a typical result from the study where 1, 2 and 3 represents AE events representing these failure mechanisms respectively.

Though the plot shows event duration (ED) and Ring down counts (RDC) as parameters along X and Y axes, the clustering in three groups has been arrived at by multi-parameter analysis of the AE signals taking into consideration four signal

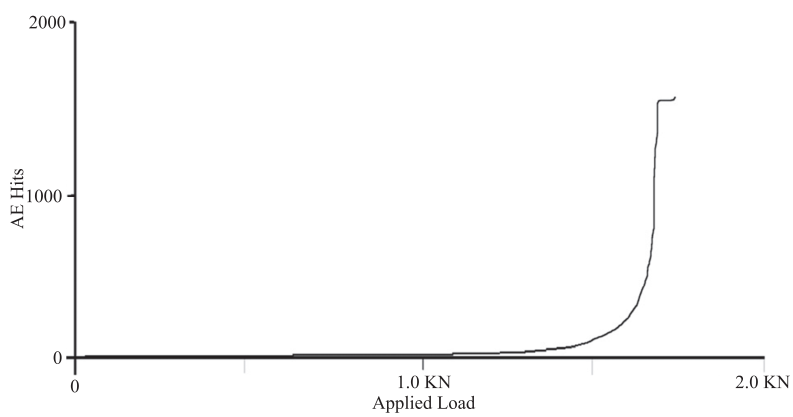


Figure 6: AE activity hits vs. applied load during tensile test.

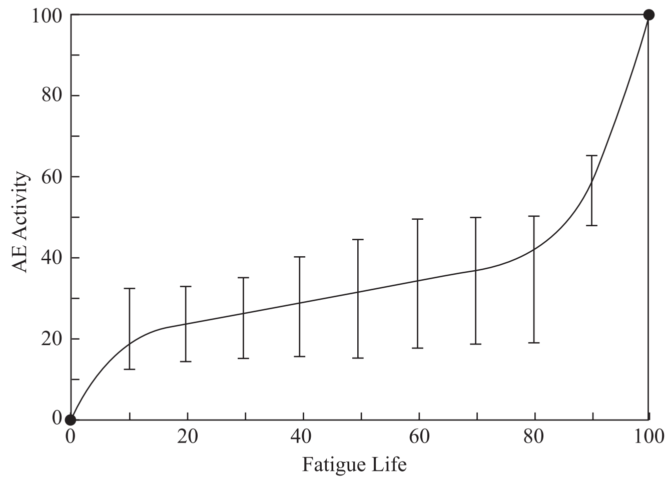


Figure 7: AE activity in three stages of % fatigue life of composites.

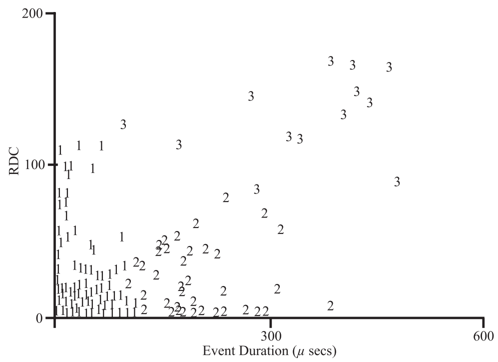


Figure 8: Category of AE signals representing three failure mechanisms in composites.

parameters namely, Peak Amplitude, RDC, ED & energy parameters.

Understanding of the complex mechanical behaviour of composites involving different failure mechanisms requires a very special tool and AET with appropriate signal analysis approach can be of great help. It should be noted though that interpretation of AE test data is an involved process which calls for great skill, technical experience and multi disciplinary knowledge.

2.4 *Infrared thermography*

All objects around us emit electromagnetic radiations. At ambient temperatures and above, these are predominantly infrared radiations (IR). Infrared Radiations are invisible to the eye. But with the aid of a suitable detector, IR can be converted into a visible thermal image. Variations in the temperature of the surface of the object can be visualised in the thermal image of an object.[8]

Thermography makes use of the infrared spectral band of the electromagnetic spectrum (in the wavelength range of 10–100 micrometers) and the properties of infrared radiations are similar to those of other electromagnetic radiations such as visible light.

They can propagate in vacuum as well as in certain liquids, solids and gases. They can be optically focussed and directed by lenses or mirrors or dispersed by prisms and can also be transmitted through certain materials, which are opaque to light.

The relationship between the radiation intensity, wavelength and temperature of a radiating black body is given by Planck's law

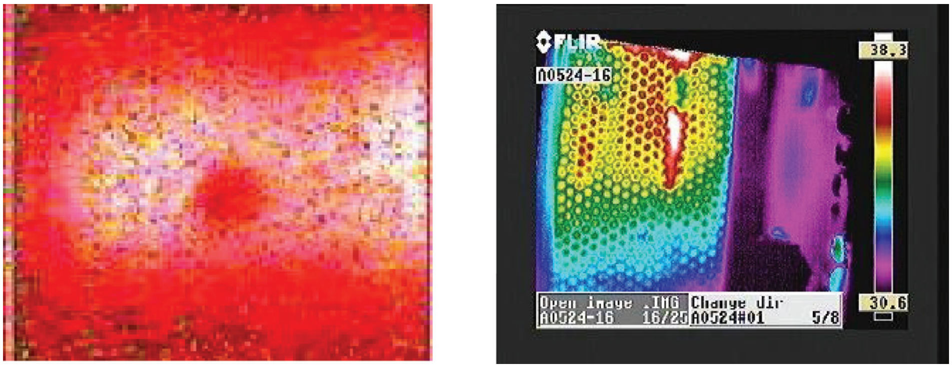
$$W(\lambda) = \frac{2\pi hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)}$$

where W(λ) is the black body spectral radiant emittance at wavelength λ(m), T is the absolute temperature of the blackbody (K), 'c' is the velocity of light (3×10^8 m/sec), 'h' is the Planck's constant (6.6×10^{-34} Joule-sec), 'k' is the Boltzmann constant (1.4×10^{-23} Joule/K).

Infrared Thermography can be utilised as an effective NDE tool over a wide range of engineering and other applications. In principle, any deviation from the normal conditions of a component or a process that causes a change in the surface temperature profile can be a potential application of thermography. Though the NDE through IR thermography has been qualitative in nature in most of the applications, the features of the technique such as the speed, safety and ease of display has made the non contact method quite popular, particularly for subsurafce defects.

Planar defects in composite materials and structures to a particular depth can be effectively detected and mapped using this NDE tool.[9]

Figure 9 shows a thermal image of a multilayered CFRP laminate (a) carrying a delamination



(a) (b)

Figure 9: Thermograph of (a) an impact damaged CFRP panel and (b) sandwich composite component.

in between layers. The other thermal image (b) shows the interior of a sandwich composite component, a piece of a rotor blade. The image clearly indicates damaged honeycomb core sections and debonded region between the core and the outer skin. With appropriate calibration procedure information with regard to size of the flaw and its depth can also be obtained.

2.5 *Fiber optic sensors for NDE of composites*

The rapid improvement of the Fiber Optic Sensor technology for strain, vibration, ultrasonic and acoustic emission measurements in recent times makes it feasible alternative to the traditional strain gauges and conventional Piezoelectric sensors used for Non Destructive Evaluation (NDE) and Structural Health Monitoring (SHM). Optical fiber-based sensors offer advantages over conventional strain gauges, and PZT devices in terms of size, ease of embedment, immunity from electromagnetic interference (EMI) and potential for multiplexing a number of sensors.

As discussed before, composite materials and structures are susceptible to complex failure mechanisms. It would be useful to have life time health monitoring of laminated composite structures since damage in these multilayered materials is usually invisible from the surface, yet can be catastrophic. In addition, sections that must be monitored are often located in areas of the layered structures that are inaccessible to users, thus preventing the use of conventional Non-Destructive Evaluation (NDE) techniques. For continuous and in-situ monitoring of realistic structures, the use of surface bonded resistive foil strain gages, and PZT sensors offers a potential method. However, they are affected by Electro Magnetic Interference (EMI) in addition to signals obtained due to existing damage. Fiber Optic Sensors (FOS) have the

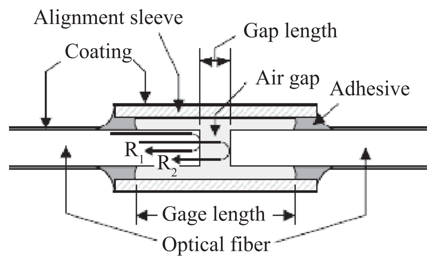


Figure 10: Extrinsic Fabry-Perot Interferometric sensor.

potential to measure static strain, temperature, and acoustic wave (dynamic strain) propagation. They can be easily integrated into composite structures making them smart, so as to access inside material and structural locations where other sensing methods can not easily probe. Fiber brag grating (FBG) and Extrinsic Fabry-Perot Interferometric (EFPI) sensors are two commonly used fiber optic sensors for NDE. These have been tried for Strain measurement as well structural condition monitoring.[10–12] Basic principles of working of these sensors and some experimental investigations carried out using them are briefly presented in the following.

2.5.1 Extrinsic Fabry-Perot Interferometric (EFPI) sensors: EFPI sensors measure strain along the sensor axis. Axial strain produces change in output light intensity. The sensor consists of a single mode input/output fiber and another fiber whose inside end is used as a reflecting mirror. The two fibers are inside of an axially aligned capillary glass tube as shown in Figure 10. They are separated by an air gap of 30–50 µm. the two partially reflecting fiber ends inside the tube are approximately parallel to each other and perpendicular to the fiber axis; together with the air gap they form a Fabry-Perot cavity produce optical power output variation as the sensor is strained. The number of sinusoidal cycles, usually referred to a fringes; is given by

$$\varepsilon = \frac{m\lambda}{2L_0} \quad (1)$$

where, ε is strain along sensor axis, *m* is number of fringes, λ is wavelength of light, and L_0 is gage length of the sensor.

The change in the length of Fabry-Perot cavity causes changes in phase difference between the reference reflection and sensing reflection. This change in phase difference modulates the intensity of the light monitored at the output arm of coupler. Since the reflectivity of glass/air interfaces in the EFPI is very low, the sensor is infact a low-finesse Fabry-Perot interferometer and can be treated as two-beam interferometer. The phase change Φ of the interference signal is given by.

$$\phi = \frac{4\pi d}{\lambda} \quad (2)$$

The number of interference fringes is determined by the EFPI cavity length (d). the cavity length can be determined from the separation of wave lengths across one or more complete fringes

$$d = \frac{m\lambda_1\lambda_2}{2(\lambda_2 - \lambda_1)} \quad (3)$$

where the difference between wavelengths λ_1 and λ_2 is 2 *m*π and where *m* is an integer. The relation between the change of cavity length and strain can be described by:

$$\varepsilon = \frac{\Delta d}{L_0} \quad (4)$$

2.5.2 Experiments with EFPI sensors for NDE of composite laminates: Experiments carried out with Fiber Optic Sensors bonded on GFRP laminates with intentionally introduced holes of different sizes as defects demonstrate that this has the potential to be a health monitoring tool.

Dynamic response measurement of a cantilever beam made of glass fiber reinforced polymer composite with surface bonded EFPI sensor was performed subjecting it to impulse force. Figure 11 shows the experimental set up.

A GFRP beam of 250 mm long and 20 mm wide with 2 mm thick structure with surface bonded EFPI sensor was clamped to a table for the dynamic response measurements. And the sensor out is connected to Fiber Scan 2000 (EFPI interrogation system) for recording the sensor dynamic strain response and the analog output of Fiber Scan2000 was given to NI data acquisition system through a band pass filter to filter out the high frequency noise. The response was measured using a code developed in Lab-View. An impulse hammer with a charge amplifier was used to give an impulse force to the beam.

Figure 12 shows the dynamic response of the GFRP specimen with different sized induced damages middle of the cantilever beam, the amplitude of the response decreases as size of the damage increases. The FFT of the response was shown in Figure 13. It can be observed that the EFPI sensor output indicates change in the condition of the GFRP specimen corresponding to the different size of induced defects.

Degradation of a composite structure due to accumulation of damage during service resulting in loss of stiffness can be similarly evaluated with this approach.

Figure 11: Experimental set up for dynamic response measurement of a cantilever beam made of glass fiber reinforced polymer composite with surface bonded EFPI sensor.

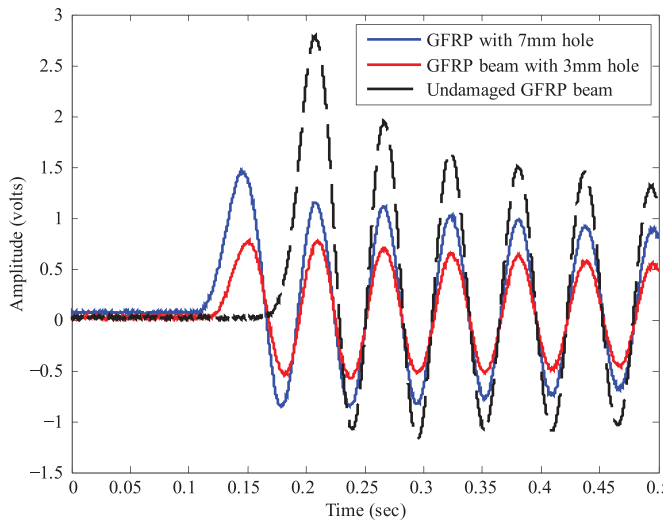


Figure 12: Dynamic response cantilever beam made of glass fiber reinforced polymer composite carrying different sized defect using surface bonded EFPI sensor.

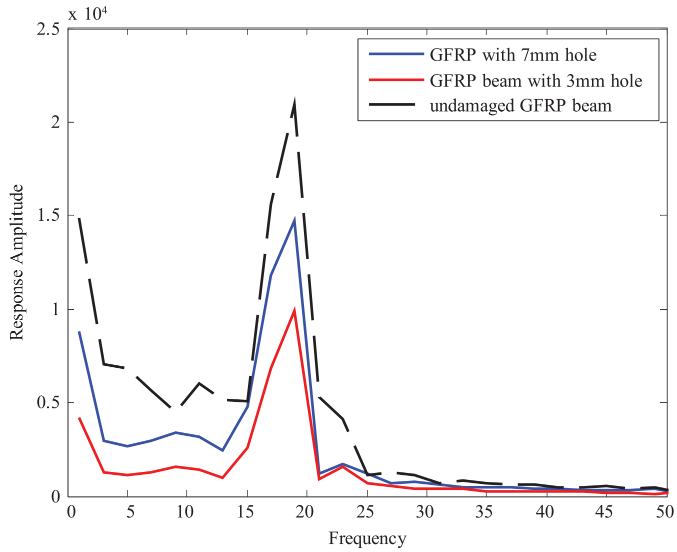


Figure 13: Frequency Response (FFT) of the GFRP specimens with different sized defect.

2.5.3 Fiber bragg grating sensors: A fiber-optic Bragg grating (FBG) is a permanent, periodic perturbation of the refractive index which is laterally exposed in the core of an optical fiber, extending over a limited length of the fiber. The grating is characterized by its period, amplitude and length, usually 1–20 mm. Such a periodic structure acts as a filter for light traveling along the fiber line. It has the property of reflecting light in a predetermined range of wavelength centered around a peak wavelength value. This value, the Bragg wavelength λ_B, is given as follows:

$$\lambda_B = 2\bar{n}_{eff}\Lambda \quad (5)$$

where Λ is the grating period and $\bar{n}_{eff}$ is the mean effective refractive index in the grating region. External forces such as strain, pressure or a temperature change lead to changes in the grating period and in the effective refractive index. Consequently, the wavelength of the light reflected from the grating varies. The relative shift of the Bragg wavelength for an applied strain along the fiber axes ε_z and a temperature change where C_ε and C_T are material constants usually determined from calibration experiments. Typical values for the relative shift of the Bragg wavelength are ~10 pm K − 1 for the temperature sensitivity and ~1.2 pm/μ strain for the strain sensitivity in the 1500 nm wavelength region. The use of Bragg gratings as strain or temperature sensors demands a high resolution interrogation system with a high absolute accuracy. Such a system can be based on a tunable laser and a high precision wavelength measurement and attachment unit as described in.

ΔT is, in a first approximation, given as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = C_\varepsilon \varepsilon_z + C_T \Delta T \tag{6}$$

2.5.4 Experiments with FBG sensors bonded to composite laminates for SHM: Experimental Investigations using Fiber Bragg Grating Strain sensor was conducted to determine its sensitivity and efficiency compared to the conventional strain gauge. A Mini Air Vehicle (MAV) composite wing was bonded with a electrical resistance strain gauge and a FBG sensor. Schematic of the experimental set-up is as shown in Figure 14. Broad band light source with in-built 3dB coupler was used to input the light in to FBG sensor and the reflected output spectrum was monitored using Proximion WISTOM (C-Band 1524–1570 nm) Optical Layer Monitor (OLM).

Then the gradual load applied from 1 kg to 4 kg on the tip of MAV wing and reflected spectrum from FBG and strain indicator reading was recorded. Figure 15 shows the strain measurement as recorded by conventioan strain gauge and by FBG sensor. Figure 16 shows the reflected spectrum from FBG at 2 kg and 4 kg load, it is observed that the spectrum shifted towards left which means FBG subjected to the compressive strain. This shift in wavelength will be converted into strain using the coefficient factor (~1.2 pm/μ strain for the strain sensitivity in the 1500 nm wavelength region).

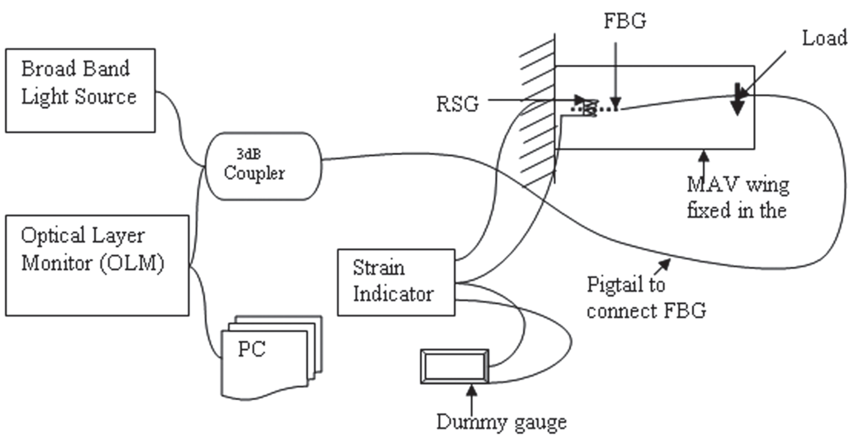


Figure 14: Experimental set up with FBG sensor for strain measurement on a composite beam.

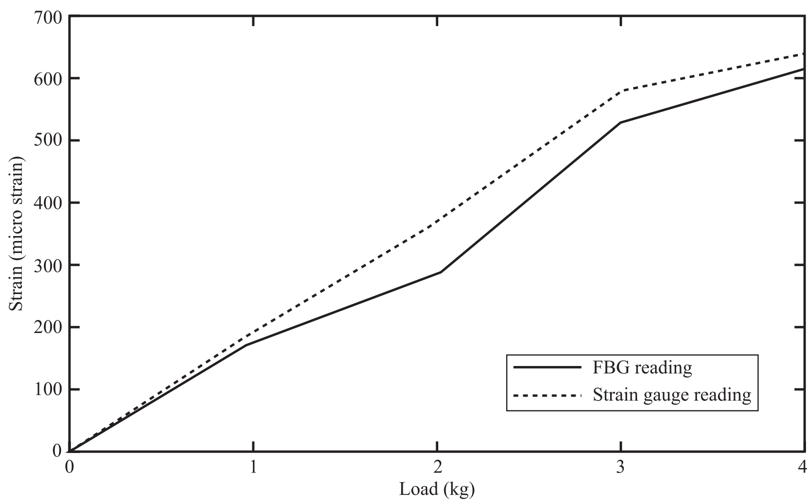


Figure 15: Comparison of FBG strain reading with conventional strain gauge.

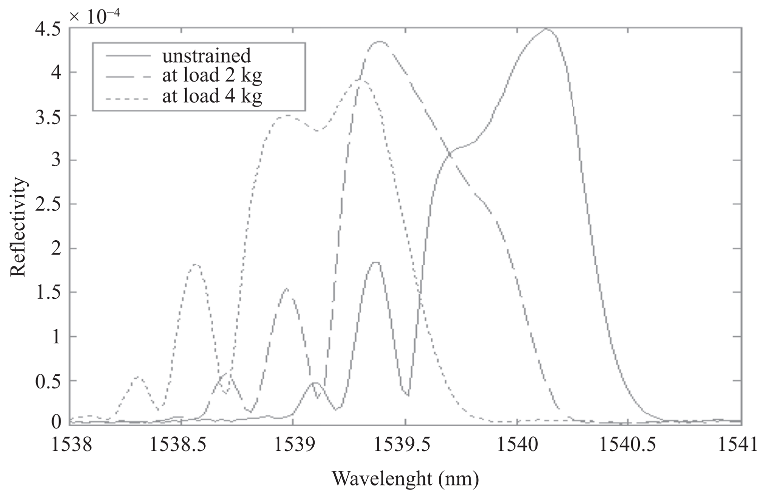


Figure 16: Reflected Spectrum of FBG output at different loads.

The experimental results showed that a continuously varying strain due to the deflection of the composite wing under monotonically increasing load could be recorded using FBG sensor and these strain values were matching with that of conventional strain gauge readings.

2.6 *Guided wave techniques for NDE and SHM of composite structures*

The ability of Lamb waves to interrogate large and complex structure quickly and the generation (and reception) of Lamb waves using embedded or surface bonded PZT wafers makes them suitable for Structural Health Monitoring (SHM) applications.[13,14] Wang *et al.*[15] employed an active Lamb wave diagnostic system to determine the location, size and orientation of the impact damage in carbon fiber reinforced composites. Paget *et al.*[16] embedded PZT discs on composite laminates and used wavelet transform to study the interaction of Lamb waves with damages like sawcut, delamination and impact damage. Su *et al.*[17] presented a comprehensive review on the generation and reception of Lamb waves in composites using various physical principles, mode selection for interrogation with damage, signal processing and wave based damage identification algorithms in plate structures.

In Lamb wave based methods, the existence of damage in a structure is generally traced by comparing the wave response of the structure at its present state with a base-line response. The presence of new peaks (scattered waves) compared to the baseline signal is correlated to the presence of damage in the structure. But the limitation is the sensitivity of baseline signals to environmental conditions like change in temperature, moisture affect the damage identification and lead to false predictions. Another major problem of employing Lamb waves for SHM is being multimodal and dispersive in nature which makes it more difficult to analyze and interpret the experimental signals. The effect of damage on the Lamb waves are small comparable to the effects due to geometry of the finite structure which causes dispersion and scattering of waves. To solve the dispersion problem, advanced signal processing techniques based on time-frequency analysis have been employed to extract the useful information from the Lamb waves.[18] But signal processing techniques post process the wave response and remove the dispersion effects. Therefore a new approach is required to make Lamb wave based damage detection method baseline free and also to reduce the dispersion effects of Lamb waves before applying signal processing techniques and one such method is the time reversal method.

Lamb waves are plain strain waves that propagate in a free plate guided by the lower and upper surface of the plate. For a given plate thickness and frequency, there are many propagation modes which are grouped into symmetrical and anti-symmetrical fundamental modes. This characteristic distinguishes Lamb waves from bulk waves. The dispersion relation obtained for the symmetric and anti-symmetric modes are referred as the Rayleigh-Lamb dispersion equations. Detailed theoretical and experimental work on Rayleigh and Lamb waves was conducted by Viktorov.[19] A comprehensive discussion on the Lamb wave propagation problem in anisotropic plates is given by Nayfeh[20] and Rose.[21]

2.6.1 T-pull carbon-epoxy composite specimen: Experiments were performed on T-pull carbon-epoxy specimen (Fig. 17) and the change

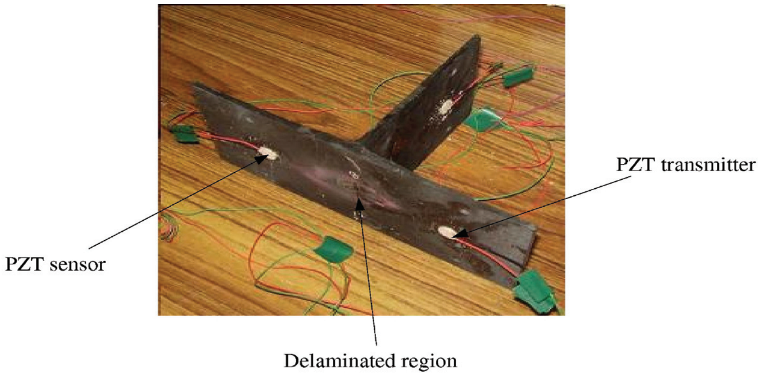
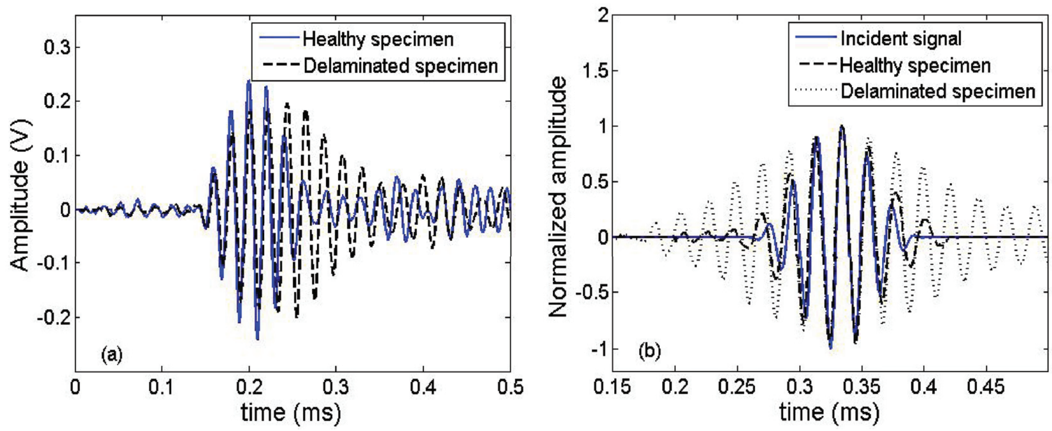


Figure 17: T-pull composite specimen with surface bonded PZT sensors.



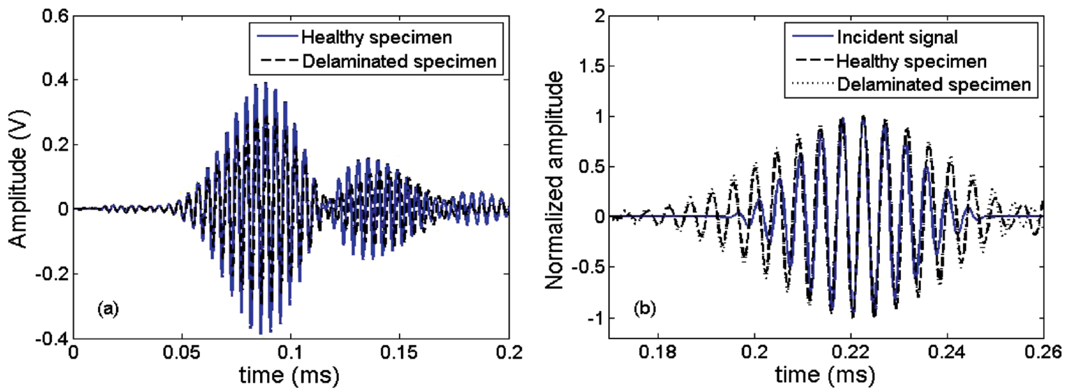
(a) (b)

Figure 18: (a) Forward propagating A_0 mode picked up by sensor. (b) Time reversed A_0 mode picked up by sensor.

in shape of the time reversed Lamb wave in the presence of delamination was studied. The T-pull specimen was subjected to tensile loading in an universal testing machine. As a result of loading, delamination was induced in the specimen. To begin with, the interaction of the time reversed A_0 mode with delamination was studied. A seven cycle hanning window tone burst signal centered at 50 KHz was used to excite the PZT sensor. Time reversal experiments were performed on healthy and damaged specimens. The forward propagating A_0 mode is shown in Fig. 18a for both healthy and delaminated specimens. Fig. 18b clearly shows that for healthy specimen the time reversed signal closely resembles the original tone burst signal, but for delaminated specimen the shape of the time reversed signal is distorted. This result clearly indicates that the delamination breaks the time reversibility condition and decrease in the similarity coefficient shows the effectiveness of time reversed A_0 mode for damage detection.

Further, time reversal experiments were repeated for S_0 mode on healthy and delaminated specimens. For S_0 mode the similarity coefficient increases with the tone burst cycles and a 13 cycle hanning window signal centered at 230 KHz was used for actuation. The experimental results are shown in Figure 19. The results shows that the time reversed S_0 mode has under gone less change in shape due to delamination when compared to A_0 mode. Thus both the A_0 and S_0 Lamb wave modes under narrow band excitation were combined with time reversal for damage detection in T-pull composite specimen.

In the case of T-pull specimen, both the A_0 and S_0 mode under narrow band excitation were combined with time reversal for delamination detection. The results showed that for healthy specimen the time reversed signal resembles the original input signal and for damaged specimen, the presence of nonlinearity due to delamination distorts the shape of the time reversed signal. Thus the



(a) (b)

Figure 19: (a) Forward propagating S0 mode picked up by sensor. (b) Time reversed S0 mode picked up by sensor.

above results establish Lamb wave time reversal method as a baseline free technique for damage detection in composite structure.

3 Conclusion

Advanced composite materials which have been increasingly used in high performance engineering applications such as aerospace, energy sectors, automobile etc., are prone to complex type of failure mechanisms involving different types of defects and damage. Integrity evaluation of structural components made of this category of materials need to make use of a band of different types of NDE tools to cater to detection, location and characterization of these defects and damage. Each of these NDE tools have set of advantages and limitations when it comes to application to composite materials and structures. Since most of these NDE methods are secondary methods, generation of reference standards and calibration procedures for interpretation and quantification of experimental results is also a tough challenge. Large number of variables and parameters associated with these composite materials and structures only further complicates the matter. Never the less, the attractive high specific properties of the advanced composite materials over weigh all these limitations and encourages more and more research activity in related NDE field as well. Advanced signal processing and image processing tools also have been immensely contributing towards gaining confidence in using these NDE tools for such applications.

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References

1. W. Hillger, "Ultrasonic Testing of Composites—from Laboratory Research to Field Inspections", 15th world conference on Nondestructive Testing, Rome (Italy) 15–21 October 2000.
2. Abrate, Serge, "Impact on Laminated Composite Materials" ASME Applied Mechanics Review, Vol. 44, No. 4, April 1991, pp. 155–190.
3. Bhat, M.R. and Murthy, C.R.L., 'Evaluation of Impact Induced Damage in Woven Fabric CFRP Laminates', Jnl. of Aerospace Sciences and Technologies, 2003, Vol. 55, No. 2, pp. 144–152.
4. Bhat, M.R., Binoy, M.P., Surya, N.M., Murthy, C.R.L., Engelbart, R.W. 'Non-destructive evaluation of porosity and its effect on mechanical properties of carbon fiber reinforced polymer composite materials'. Review of Progress in Quantitative Nondestructive Evaluation. AIP Conference Proceedings, Vol. 1430, pp. 1080–1087. American Institute of Physics, New York (2012).
5. Williams, J.H. and Lee, S.S. 'Acoustic Emission Monitoring of Fiber Composite Materials and Structures' Jl. of Composite Materials 12 October 1978, pp. 348–370.
6. Bhat, M.R., 'Acoustic Emission Technique for Evaluation of Advanced Composite Materials', Jnl. of Non Destructive Evaluation. Vol 20, No. 2, pp. 39–43, 2000.
7. Jess R. Richter, 'Acoustic Emission Testing: A Composite Manufacturers Experience', Materials Evaluation, Vol. 57, No. 5, May 1999.
8. ASM Materials Handbook, Vol. 17—Nondestructive Evaluation and Quality Control.
9. N.K. Ravikiran, A. Venkataramanaiah, M.R. Bhat and C.R.L. Murthy, 'Detection and Evaluation of Impact damage in CFRP Laminates Using Ultrasound C-Scan and IR

Thermography', Proceedings of National Seminar NDE-06, Hyderabad, December, 2006 (Paper no. TP – 75).

10. Baskar Rao Mattapally, M.R. Bhat And Murthy C.R.L., 'Health Monitoring of Composite Structures Based on Acoustic Wave Sensing Using Fiber Optic Sensors' Proceedings of International Conference on Advanced NDE-ANDE , Korea—Nov 2007.
11. E. Udd, "An overview of fiber-optic sensors", American Institute of Physics, Vol. 66, pp. 4015–4030, 1995.
12. C. Boller, "Ways and options for aircraft structural health management", Smart materials and Structures, Vol. 10, pp. 432–440, 2001.
13. V. Guirguitiu, *Structural Health Monitoring: with Piezoelectric Wafer Active Sensors*, Academic press, USA, 2007.
14. V. Giurgiutiu, Embedded NDE with piezoelectric wafer active sensors in aerospace applications, *Journal of Materials- Special issue on NDE,* Jan 2003.
15. C.S. Wang, F. Wu, F.K. Chang, Structural health monitoring from fiber-reinforced composites to steel-reinforced concrete, *Smart materials and Structures* 10, pp. 548–552, 2001.
16. C.A. Paget, Sebastien Grondel, Klas Levin, Christophe Delabarre, Damage assessment in composites by Lamb waves and wavelet coefficients, *Smart materials and Structures* 12, pp. 393–402, 2003.
17. Z. Su, L. Ye, Y. Lu, Guided Lamb waves for identification of damage in composite strucutures: A Review, *Journal of Sound and Vibration* 295, pp. 753–780, 2006.
18. R. Gangadharan, D.R. Mahapatra, S. Gopalakrishnan, C.R.L. Murthy, M.R. Bhat, On the sensitivity of elastic waves due to structural damages: Time-frequency based indexing methid, *Journal of Sound and Vibration* 320, pp. 915–941, 2009.
19. I.A. Viktorov, *Rayleigh and Lamb Waves—Physical Theory and Applications*, Plenum press, Newyork, USA, 1967.
20. A.H. Nayfeh, *Wave Propagation in Layered Anisotropic Media: With Application in Composites*, Elsevier press, Amsterdam, Netherlands, 1999.
21. J.L. Rose, *Ultrasonic Waves in Solid Media*, Cambridge university press, Cambridge, UK, 1999.

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