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Research Article

NDT Techniques to Investigate Fracture in Continuous Fiber Reinforced Composite Structures-A Review

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Abstract

With wide increase in applications of continuous fiber reinforced composite structures in various fields such as automotive, marine, aero space, civil...etc; the failure of these structures under various modes of fracture has become key area of interest to many researchers. Crack position, crack growth and crack length are some of the vital fracture parameters which need to be identified at an early stage to prevent catastrophic failure especially under cyclic loading. Non Destructive testing techniques are rapidly replacing the conventional testing methods due to their high precision, reliability, repeatability and comparatively low cost of testing in long run. This paper reviews various non destructive testing techniques that have been developed during the recent past.

Keywords: *NDT Technique, crack position, crack length, crack growth, mode of fracture.*

1. Introduction

Failure of composites due to inter laminar, intra laminar fracture and matrix transverse cracking are some of the commonly occurring defects in continuous fiber reinforced composite structures vowing to various reasons such as poor fiber strength, improper curing, poor fiber alignment, sudden changes in temperature, warpage, use of improper bonding agent ..etc. Identification of these defects at micro level in composite structures which are especially used in aerospace and marine applications is very important from the designer’s perspective. It is not always sufficient merely to identify the damage. One of the main challenges lies in the determination of the cause of the damage, its location, its severity and impact on the performance of the structure as a whole. From this perspective, nondestructive testing (NDT) can help to relate the experimental data and results to an analytical model through real time characterization and assessment of severity of the defect. With the advent of high speed data acquisition systems capable of storing huge data and high resolution infra red cameras NDT techniques have been developed during the recent past. Nokes et al. (2001) used portable infrared (IR) inspection technique to detect delamination in composite – concrete bondlines. IR camera FLIR 570 was used to take thermographic images. Halabe et al.(2002) implemented infrared thermography technique to determine the delamination in FRP composite members. Two types of glass fiber reinforced polymer (GFRP) composites i.e. E-glass and S-glass were tested. Miceli et al. (2002) used Infrared thermography in glass reinforced polymer full size bridge deck to find the debonding between integral components. The bridge deck components are made from alternating layers of random mat fibers and unidirectional rovings in an isophthalic polyester resin. Hu et al. (2002) studied the possibility of identifying the air voids between the bond line of FRP and concrete substrate by inducing artificial blisters between the interface of FRP and concrete and used Infrared Thermography to find the voids vaguely at 20 meters distance. Meola et al. (2004) used both pulse and lockin thermography methods to test carbon/epoxy and glass/epoxy specimens. The specimens had embedded foreign materials to simulate defects of different sizes which were positioned at different depths. Kang et al. (2006) used Infrared thermography nondestructive technique to inspect the damage due to impact in honeycomb composite plate. The honeycomb composite material is made of aluminum core and the skins are made of CFRP having a unidirectional laminate at 90^0. Imielinska et al. (2004) used Ultrasonic air coupled C-scan technique to detect the impact damage in thin fiber/epoxy composite plates. Bastianini et al. (2001) used pulsed echo ultrasonic analysis for testing composite materials (CFRP and GFRP) which were embedded to different substrates (concrete, masonry, and polyurethane). Berketis et al. (2004) observed the effectiveness of traditional water coupled and non contact ultrasonic C scan systems on wet damaged Glass Fiber Reinforced Polymer(GFRP) composites for damage identification and evaluation. Doyum et al. (2002) applied Automated Ultrasonic Scanning System to identify and observe

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defects such as planar voids, core damages, and water/ hydraulic fluid intrusion into the core in honeycomb test specimens. Tsuda et al. (2006) studied the ultrasonic inspection method using small diameter fiber Bragg grating (FBG) sensors to determine impact damage in CFRP plate. The specimen was made of cross ply carbon fiber reinforced plastic plate of dimension 300 mm x 300 mm x 1 mm with fiber volume fraction of 60%.Lestari et al. (2005) used Lamb wave propagation analysis to evaluate the impact damage and delamination in Carbon / epoxy laminated composite plate specimens. Damage location is extracted from the measured time history data of the propagated wave and the wave traveling time. Godinez-Azcuaga et al. (2004) used Acousto-Ultrasonic technique for inspection of FRP wrapped concrete structures for identifying the delamination debonds and other defects by utilizing the processed RF waveforms. Hosur et al. (2004) used Ultrasonic approach on stitched / unstitched woven carbon / epoxy composite laminates subjected to high velocity impact loading. The ballistic impact tests were carried on 7, 17, and 37 layered stitched laminates. Zheng et al. (2000) used acoustic emission signals for detecting damage and defects in E-glass / 920 epoxy composites. A blind deconvolution method has been developed to demodulate the signal and identify the damage. Amoroso et al. (2003) used Acoustic emission capabilities on detection and characterization of the impact damage of FRP composite laminates. Hatta et al. (2005) used the technique Electronic Speckle Pattern Interferometry (ESPI) for detection of damages in carbon – carbon composites (C/Cs). This method is used to identify the small scale delamination. Ambu et al. (2006) used optical methods to detect impact damage in thin laminates using holographic procedure and electronic speckle pattern Interferometry technique. These methods are used to identify delamination due to impact in quasi-isotropic laminates. Ekenel et al. (2004) used Microwave near field nondestructive technique utilizing open ended rectangular waveguides to investigate the influence of cycling loading on delamination in reinforced concrete beams fabricated and strengthened with CFRP laminates. AbouKhousa et al. (2004) used near-field microwave imaging systems for detecting subsurface defects in laminated composite structures. Hughes et al. (2002) used near-field microwave NDT technique for detecting delamination in layered composite structures. Li et al. (2001) developed a microwave system which operates at 10 GHz with one transmitter and one receiver for detection of air voids under Glass Epoxy jackets. Jackson et al. (2001) used ground penetrating radar (GPR) nondestructive evaluation technique for assessing the performance of FRP wrapped concrete columns on a bridge structure. Dutta (2006) used Ground Penetrating Radar technique to evaluate the subsurface debonds (both air filled and water filled) in the FRP wrapped concrete cylinders. Hing (2006) used Ground Penetration Radar nondestructive technique to identify both water and air filled debonds and delamination on low profile FRP bridge decks by using 1.5 GHz ground coupled antenna and 2.0 GHz air-coupled antenna. In this paper the capabilities of NDT techniques such as Infra red, ultrasonic, Acoustic Emission, Micro wave and Ground penetration radar techniques and their applicability towards continuous fiber reinforced composite structures are reviewed.

2. Infra Red Thermography

Infrared Thermography is a non-contact sensing method concerned with the measurement of radiated electromagnetic energy in the infrared zone. An infrared camera is just a spectral radiometer that measures this energy. This technique uses an infrared camera to create fully analyzable images from the thermal radiation given off by a surface. Infrared measurement depends strongly on emissivity (ε) and surface temperature. The theory of measuring infrared radiation is mainly based on the Stefan - Boltzmann law and Planck's law. Infra red thermography uses two schemes a.) Passive thermography and b.) Active thermography. The passive thermographic technique relies on natural heat distributions over the surface of a structure and it is usually employed for non-destructive evaluation of buildings, components and processes.Active infrared thermography uses an external uniform heat source (lamp, laser, etc.) to drive heat through or across the object of interest. The thermal gradients developed at the surface are then observed using an infrared imaging device. Cracks, inclusions, voids, or delaminations that transfer heat at different rates cause these thermal gradients. Active thermography which is highly used to identify cracks and delamination defects in frp materials is once again categorized as 1.) Pulse thermography 2.) Lock-in thermography 3.) Vibro thermography and 4.) Step heating.

2.1. Pulse Thermography

This technique visualizes defects through surface temperature gradients in the transient heating/cooling phase while the object is thermally simulated. It is the disturbance of the thermal equilibrium for a short period of time (typically a few 1/1000 seconds) with an energy impulse. Basically, pulsed thermography consists to briefly heating the specimen and then recording the temperature decay curve. The temperature of the material changes rapidly after the initial thermal pulse because the thermal front propagates, by diffusion, under the surface and also because of radiation and convection losses. The presence of a subsurface defect reduces the diffusion rate so that when observing the surface temperature, a different temperature with respect to surrounding sound area appears over a subsurface defect once the thermal front has reached it. The pulse thermography technique is affected by local variation of the emissivity and non-uniform heating.

2.2. Lock-in Thermography

Lock-in thermography is a dynamic measurement method (thermal wave analysis). It uses sinusoidally modulated excitation signals in order to derive information from the observed phase and magnitude of the wave. The wave is excited sinusoidally with halogen lamps, laser, or hot-air pistols on the surface of the tested component. Wave generation is performed by periodically depositing heat on the specimen surface the resulting oscillating temperature field in the stationary regime is remotely recorded through its thermal infrared emission with the infrared camera. In this technique the exact monitoring of time phase between recorded signal and reference signal is important.

2.3 Vibro Thermography

Vibrothermography (VT) is an active infrared thermographic technique where, under the effect of externally induced mechanical vibrations, direct conversion from mechanical to thermal energy occurs and heat is released due to friction precisely at locations of defects such as cracks and delaminations. By changing (increasing or decreasing) the mechanical excitation frequency, local thermal gradients appear or disappear at specific resonance frequencies. Figure 1 shows the infra red image of a carbon fiber composite laminate with a delamination defect shown in the encircled portion.

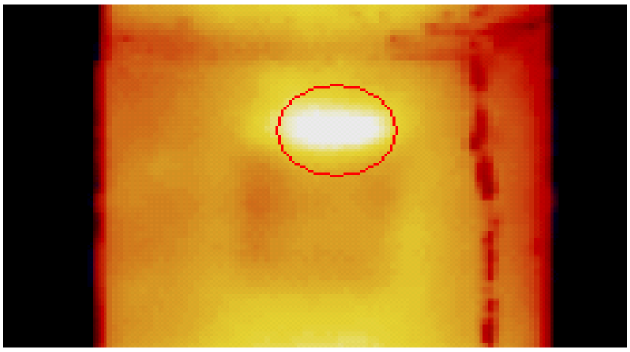

Figure1: IR Image of CFRP with delamination

3. Ultra Sonic Testing

Ultrasound is acoustic (sound) energy in the form of waves having a frequency above the human hearing range. Ultrasound inspection methods are powerful tools for nondestructive testing and are widely used in the industry because high resolutions are possible depending on the chosen frequency (100 kHz to 40 MHz). The transducer is a very important part of the ultrasonic instrumentation system. The transducer incorporates a piezoelectric element, which converts electrical pulses into mechanical vibrations in the sending mode and mechanical vibrations (stress waves) into electrical signals (receive mode) for analysis when receiving. The component mainly used is piezoelectric transducer that converts electrical energy into sound. Ultrasonic data can be collected and displayed in a number of different formats. The three most common formats are known in the NDT world as A-scan, B-scan and C-scan presentations. Each presentation mode provides a different way of looking at and evaluating the region of material being inspected. Modern computerized ultrasonic scanning systems can display data in all three presentation forms simultaneously. Pulse-echo ultrasonic measurements can determine the location of a discontinuity in a part or structure by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through a thickness of material, reflect from the back or the surface of a discontinuity, and be returned to the transducer. Figure 2 shows the Ultra sonic scan image of an FRP laminate damaged due to impact force.

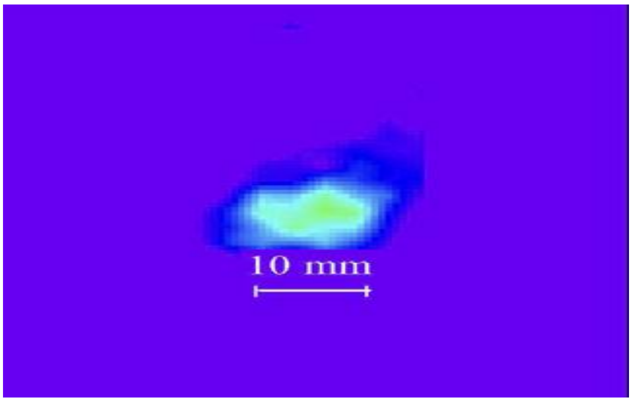

Figure 2: UV Scan Image of damaged FRP

4. Acoustic Emission Technique

Acoustic Emission (AE) uses elastic waves that are produced by moving dislocations, cracks, fiber breaks, bonds etc for defect detection and analysis of solids. Sensors are used to record the stress waves when a structure is subjected to external stimulus i.e., change in pressure, load or temperature in the form of stress waves. In composite materials, matrix cracking and fiber breakage and debonding contribute to acoustic emissions. For other materials like polymers, wood and concrete, AE's have also been measured and recorded. It has been using in many industrial applications such as assessing structural integrity, detecting flaws, testing for leaks or monitoring weld quality and also used extensively as a research tool. AE signals are typically described by parameters such as amplitude, duration, counts, events, rise time and energy. The relationship between these parameters and damage type is of interest because different damage emits different levels of energy. However, the discrepancies in these relationships may occur among different composite specimens and structures due to the attenuation of the stress waves as they propagate through different composite materials. Boundary conditions, size and many other factors may also result in the inconsistent AE amplitude measurements. Compared to other nondestructive techniques, Acoustic Emission has two major differences. The first difference is regarding to the origin of the signal. Instead of supplying energy to the object under examination, AET simply listens for the energy released by the object. The second difference is that AET deals with dynamic processes, or changes, in a material i.e., only active features such as crack growth are highlighted.

Acoustic emission signals cover a wide range of energy levels and frequencies, but are usually considered to be of only two basic types, they are burst type and continuous emission type. The burst type is a qualitative description of emission signals corresponding to individual emission events and continuous emission is a qualitative term for an apparently sustained signal level from rapidly occurring emission events. Figure 3 shows the two types of signal patterns emitted in this process.

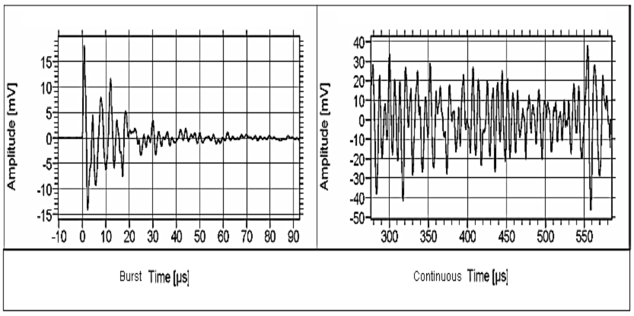

Figure 3: Burst & Continuous signal patterns

5. Micro Wave Technique

Microwave NDE is defined as the inspection and characterization of materials and structures using high frequency electromagnetic energy. The frequency range is from few hundred megahertz (MHz) to a few hundred gigahertz (GHz) and the corresponding wavelengths ranges from 100cm to 1mm. In this technique, the test sample is tested by measuring the various properties of the electromagnetic waves scattered by or transmitted through the test article. The microwave inspection system consists of several components and devices such as oscillators, network analyzers, antennas, directional couplers...etc, that are assembled to provide proper and useful output signals. Custom designed equipments can be small, modular frequency specific and relatively inexpensive. Various types of microwave sensors are used depending on the type of the material to be tested. All the microwave sensors are mostly either transmission type or resonating type or image type sensors. Figure 4 shows the Micro wave Image of the fractured test specimen at a frequency of 24 HZ and at a standoff distance of 7mm.

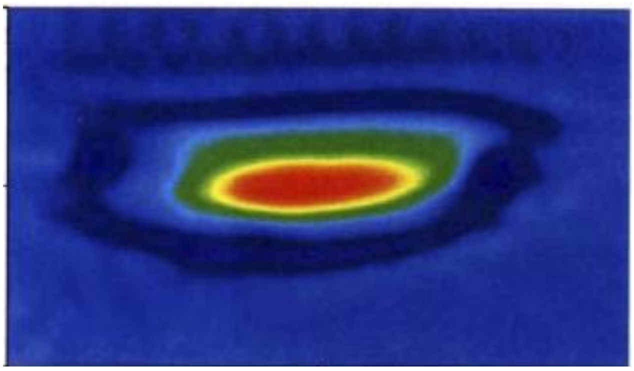

Figure 4: Micro wave image of a cracked specimen

6. Ground Penetration Radar Technique

Ground-penetrating radar (GPR) is a geophysical method that uses radar pulses to image the subsurface. This non-destructive method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and detects the reflected signals from subsurface structures. GPR uses transmitting and receiving antennae. The transmitting antenna radiates short pulses of the high-frequency (usually polarized) radio waves into the ground. When the wave hits a object or a boundary with different dielectric constants, the receiving antenna records variations in the reflected return signal. Ground Penetrating Radar (GPR) operates by transmitting electromagnetic energy into the probed material and receiving the reflected pulses. The transmitted EM pulses are reflected as they encounter discontinuities. The discontinuity could be a boundary or interface between materials with different dielectrics or it could be a subsurface object such as debonds or delamination. The antenna receives the pulses with varying amplitudes and arrival times. The amplitudes of the received echoes and the corresponding arrival times can then be used to determine the nature and location of the discontinuity. The main components of GPR are data acquisition system, sensors and antenna. The image shown in Figure5 gives the brief details of the data acquisition system used in this technique.

Figure 5: Data acquisition setup used in GPR Technique

Conclusions

As mentioned earlier, with the advent of efficient, reliable and fast, data storage and retrieval facilities coupled with high resolution image capturing cameras, NDT techniques are finding many applications compared to conventional testing methods. However it can be concluded that the applicability of a particular technique is governed by various parameters such as material of the specimen, supporting devices, frequency and wave length of the penetrating light, economics, damage parameters of interest such as crack length, crack position...etc. For example, the efficient working of active thermographic technique is highly influenced by external heat source. Improper heating or sudden change in heat flux may result in erratic image patterns which could be misinterpreted to be specimen defects or damage. Similarly, the ultrasonic technique is dependant on the operator efficiency as the signal generated from the flaw or defect inside the specimen could be corrupted due to external noises such as those emitted from structural foundations and other noises due to vibrations.

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