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Non-Destructive Testing Methods of Composite Materials: A Review

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Abstract: ***A wide range of testing techniques are usually applied in industry to different materials in order to determine their fitness for use. Testing of composite materials present a certain challenge as they are non-homogenous and anisotropic materials. This paper covers several non-destructive testing methodsand the common defects that can occur accidentallyin composite materials either during manufacturing processes or in the course of the normal service life of the component.***

Keywords: visual testing, radiography, shearography, thermography, ultrasonic testing, delamination, debonding

1. Introduction

When manufacturing composite structure, material and structural components are created concurrently. Thus, for composite materials in critical structural applications, it is more important thanevertoindependently assure structural integrity. Complexity of the advanced composite materials manufacturing and composite in service maintenance represents challenges in developing optimized non-destructive tools and tests. Traditional metals based non-destructive methods are inappropriate and often misleading when applied to anisotropic and inhomogeneous composite materials. Composite non- destructive techniques NDT encompasses a range of modified traditional and new tools including ultrasonic, x-ray, acoustic emission, thermal, optical, electrical and a variety of hybrid methods. (1)

It should also be appreciated that for wide acceptance of various NDT, they should be positive in results, economical to procure and easy to apply. (2)However, there are times when a single test method does not provide enough information about the material integrity and thereby combination of different methods is essential. NDT is widely applied in power plants, aerospace, nuclear industry, military and defense, storage tank inspection, pipe and tube inspection and composite defect characterization. (3)

I. Non-Destructive Testing Methods Categories for Composites: Composites are materials composed of more than one base material, with the base materials maintaining their own structures and properties rather than forming a combined alloy. Based on the reviews of the non-destructive testing methods, they can becategorized in different ways according to the applications and situations of the testing.

Contact Methods VS Non – Contact Methods:The basic types ofNDTmethods include contact and non-contact methods and both of them have their specific applications in testing and evaluating the composites. Most NDT require good contactbetween the sensor and tested composite surface to obtain reliable data. Contact methods are traditional ultrasonic testing, eddy current testing, magnetic testing, electromagnetic testing, and penetrant testing. Another approach to speed up the data collection process is to eliminate the need for physical contact between the sensor and tested structure. Non-contact methods are through transmission ultrasonic testing, radiography testing, thermography, shearography, and visual inspection .Optical methods (e.g. thermography, holography or shearography) are mostly non-contact.

1.Visual Testing (VT) - (VI - Visual Inspection):should be the most basic type of NDT that many instances use because it can save both time and money by reducing the amount of other testing, or in some cases reducing the need for other types of testing all together. The most important advantage of the visual inspection is its quick process. The other advantage of visual inspection is the relative affordability of the process. The visual inspection needs no equipment but this method has its intrinsic disadvantage.

2. Radiographic Testing (RT): is the most commonly used testing method.The most common type of damage to composites is a delamination resulting in an air pocket; a delamination can only be seen in RT if its orientation is not perpendicular to the x-ray beam. There are many types of radiography and each has specific applications. Conventional radiography is the most useful when the parts are neither too thick nor too thin. For thin parts, 1 to 5 mm, low voltage radiography is used and γ-rays radiography is good for thick parts. These types of radiography are useful in detecting large voids, inclusions, trans-laminar cracks, non-uniform fiber distribution, and fiber disorientation such as fiber wrinkles or weld lines. Another type of radiography uses γ-rays to penetrate the composite. Gamma rays radiography is good for thick parts because the gamma rays have shorter wavelengths. Penetrant-enhanced is another type of radiography employed specifically to detect small matrix cracks, and delamination in a sample .There are varieties of radiographic testing methods for different applications. These methods are film radiography,computed radiography,computed tomography, and digital radiography. X-ray Computed Tomography (XCT) is a nondestructive technique for visualizing interior features within solid objects, and for obtaining digital information on their 3-D geometries and properties. The great advantage of (XCT) in comparison with the projection radiology is the 3-D visualized image of the structure while in projection radiology the image is only 2-D. Therefore, the (XCT) data is readable quickly and simply.(XCT) will modify the scale of observation from macroscopic to microscopic scale so the results of the(XCT) method are very reliable.(4)

3. Shearography: is a laser optical strain measurement technique that provides useful information about the conditions of the interface between the repair and substrate. This interferometric technique is capable of identifying internal defects in composite materials as delaminations, interfacial disbonds (lack of adhesion) and holes.

The shearography is a special case of digital speckle pattern interferometry technique, in which the interfering wavefronts coming from the sample (both speckled) are reference and object at the same time. Since it is a common-path interferometric technique, shearography has the advantages of allowing short coherence-length illumination and being less sensitive to environmental disturbances, such as low vibration levels, than other holographic techniques.

The shearography system was built as a portable unit and it is able for scanning large structures, such pipes to tank wall and ship hulls. Shearography images show changes in surface slope in response to a surface modification generated by an applied load. This technique is sensitive to subsurface disbonds, delaminations, core damage, and core splice joint separations, as well as surface damage.

The changes in the applied load required to reveal subsurface anomalies frequently induce significant deformation for this optical technique. Shearography mainly detects the derivative of the displacement and usually tends to show only the local deformation on the target surface that is due to the presence of a surface or subsurface flaw.

As shown infigure 1, a traditional shearography setup requires some basic elements: an illumination module, an interferometer and software that drives the image acquisition procedure. In addition, an excitation module is required to apply the load required to reveal the subsurface anomalies. This excitation may be performed by different methods. Usually it uses a thermal or pressure variation to apply the load. A variation about 4°C or 1 bar is usually sufficient. The surface under investigation is illuminated by an expanded laser beam, which generates speckle patterns on the surface . Within the sensor head, a modified Michelson interferometer is designed to form the laterally sheared image of the surface.

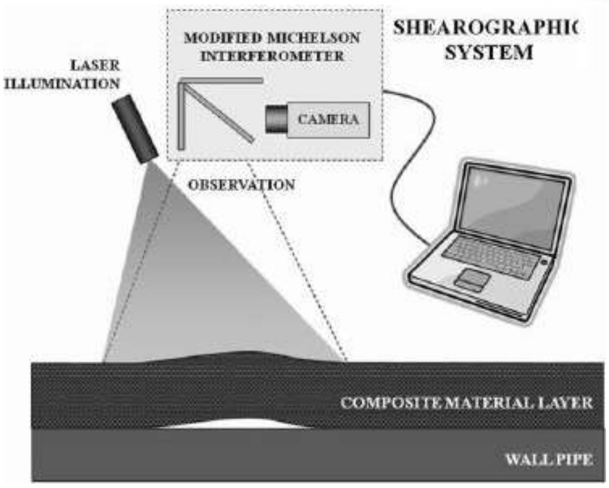

Figure 1: Shearographic inspection Set-up.

4. Thermography:is a non-contact NDT technique for inspection of materials in wide application areas, including corrosion detection inmetals, and delamination, porosity and moisture detection in composite materials. Composites often are highly anisotropic in nature. This anisotropy coupled withlow thermal diffusivity in thickness direction, severely restricts detection of deeper defects in composite materials.(6)

Automation Technology has developed a series of test-equipment based on the principle of active thermography. These systems do not only perform measurements within a few seconds, but they can also cover a relatively large area per inspection (for example, up to 1m²). Active thermography is therefore an effective NDT-method to meet the required performance of inspection work on composite materialswithin a reasonable economic framework.

The principle of active thermography is based on the analysis of thermal flow that originates from the thermal excitation of an object. The propagation of thermal energy within the inspected material has a direct influence on the object’s surface temperature over time. This temperature development is recorded with the help of an infrared camera and analyzed by special software. Through mathematical analysis the software calculates a result-image that enables the identification of the internal structure of the material, as well as possible defects in it.

Until now active thermography systems were primarily for laboratory use. They were considered too complex for mobile applications or for their integration into production lines. However, with the development of new systems, such as the compact inspection head C-CheckIR Sensor, the thermographic NDT technique has gained entrance into these fields too.

The measuring head consists of an optical excitation source with integrated control electronics and an uncooled infrared camera that has been specially developed for NDT applications. Therefore, its lightweight and compact design enables its easy integration into robotic arms or other supporting tools. A standard Ethernet cable connects the sensor head to the control computer (or laptop) where the analysis software processes the thermal images recorded by the infrared camera.

This newly developed inspection head also forms the core component of the new thermographic NDT solution that has been designed for mobile use. For this purpose, the inspection head is mounted on a light support frame with three legs equipped with vacuum-driven suction cups. These suction cups enable the easy fixation of the measuring head to the surface of the object being inspected, which allows NDT inspections even on vertical surfaces.(7)

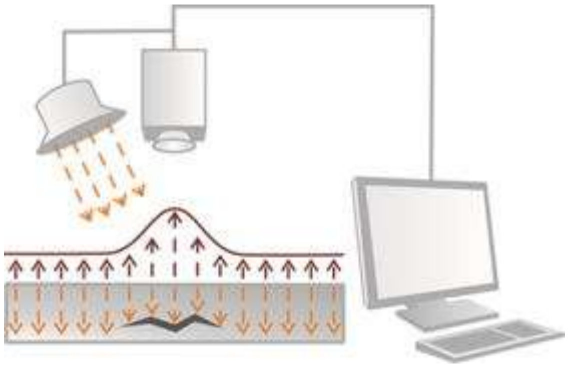

Figure 2: The active thermography principle.

5. Ultrasonic Testing: ultrasonic waves are sound waves with frequencies ranges from 500 kHz to 10MHz. These are more directional than audible sound waves and travel freely in liquid & solid, depending on density and elastic properties of the medium. Ultrasonic waves are widely used for NDT applications. Sound waves can propagate in two modes namely, longitudinal or shear. Longitudinal wave is most common for NDT applications. It is faster and can travel both in solid and liquid media whereas, shear wave forms when material particles oscillate normally to the direction of wave propagation. These waves require acoustically solid media to travel and hence, do not proceed effectively in liquid and gases. This property limits its application in Ultrasonic NDT testing. A piezo electric material is used to generate sound waves by applyingvoltage difference between any two of its surfaces. The change indimension of the piezo electric material generates a pulse of mechanical vibration that consists of ultrasonic waves.

For ultrasonic testing to work reasonably well, it is necessary that the discontinuity/flaw must be larger than one-half of the wavelength. Moreover, the quality of results depends on equipment's sensitivity and resolution. Sensitivity is an ability of a UT system to detect smallest flaws. Resolution is its ability to detect two closely spaced flaws within the material and near to the surface. Both sensitivity and resolution increase with the frequency of the sound wave used for inspection. The optimal frequency of a UT system to detect flaws in material also depends upon material structure, type of flaw, size of flaw and its location. The higher the frequency of wave, larger will be the vibrational scattering of energy in the material due to frequent collisions between wave particles and material. This effect results in the reduction of penetrating power of wave i.e. maximum thickness of material, where flaws could be detected. The intensity of sound wave echo also depends on mismatch in acoustic impedance between flaw and surroundings. Hence, an echo from a void will be stronger than from an inclusion in material due to large difference in the impedance. The large mismatch in acoustic impedance within the material allows thicksection inspection due to stronger echoes. A large bandwidth results in less damping of frequency range around a central frequency and provides UT system more resolution due to high final frequency, but obviously, less penetrating power. On the other hand, a smaller spectrum of highly damped frequencies will result in a system with poor resolution, but higher penetration.(8)

Two Conventional Ultrasonic Testing Modes:

A. Pulse-echo Mode

Pulse-echo, also named as reflection method, is based on the ultrasonic energy reflection from the median interfaces. One transducer is used as both transmitter and receiver. When ultrasonic waves encounter the interface of impact damage, the reflected energy in the form of pulse-echo amplitude can be distinct from a normal situation when there is no damage. In case of difficult interpretation of superimpose backwall signals in thinner laminates, higher transducer frequency should be selected in order to obtain sufficient resolution of discovering through-thickness occurrences. However, ultrasonic pulse-echo signals travels two times through the sample thickness thus this type of scans is not feasible for relatively thicker samples because more energy is attenuated during propagation.

In this case, through-transmission method can be considered because it only requires one pass through the sample. (9)

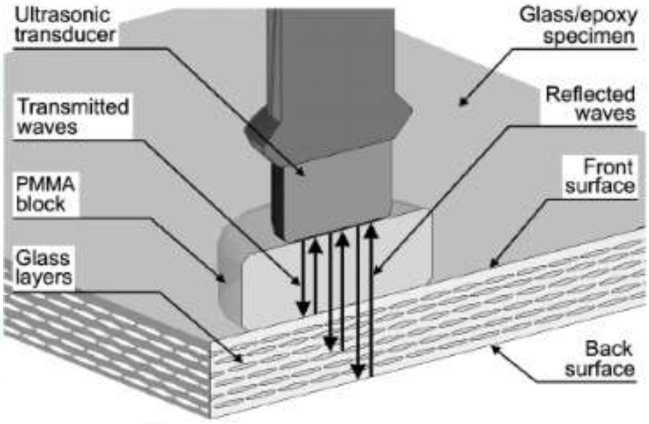

Figure 3: Scheme of the ultrasonic testing (pulse – echo technique). ..(10)

B. Through-transmission Mode

Through-transmission is the most conventional ultrasonic testing mode, in which two transducers are used- one transmitter placed on one side of the sample, one receiver on the reverse side of the sample. When defects exist on the penetrating path, the signal would be attenuated thus revealing their presence. The ultrasound waves only travel one time through the sample thickness, hence the attenuation of the waves is less for through-transmission mode than pulse-echo and pitch-catch mode, which requires the waves travel twice the sample thickness. This enables through-transmission mode more capable for inspection on relatively thicker composite laminates. Gross flaws within thick composite laminates can be obtained by conventional through-transmission C-scan.(9)

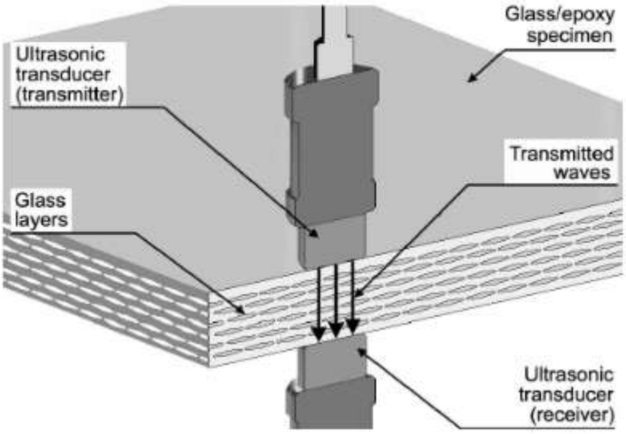

Figure 4: Scheme of the ultrasonic testing (through – transmission technique) (10)

6. Pulsed eddy current:is a form of electromagnetic NDT,it is a method based on Faraday's Law of Magnetic Induction. This principle states that when an electrical conductor is in the presence of a moving magnetic field, it will generate a current. Conversely, when a current is run through a conductor, it will generate a magnetic field. Pulsed eddy current uses a transmitter to produce alternating currents that induce looping currents, or eddy currents, in nearby conductive materials in this case the substrate.

This method detects defects that interfere with the flow of the eddy current. As the current flows around the defect, the current weakens and decreases the amount of current flowing through the coil of the transmitter. While a handheld pulsed eddy current transmitter can be oriented to find cracks and other defects in the substrate, this method is primarily used to measure the thickness of the substrate walls and detect wall loss. The data presented of the tested area by pulsed eddy current can be shown as a colored grid (though this may vary between inspection companies). Areas with greater wall loss will show up as a color corresponding to the severity of loss.

Performed with a single transmitter, the pulsed eddy current method requires only the portion of pipe that is being tested to be accessible. While pulsed eddy current is not used for defect detection within the composite itself, this method is commonly used in addition to other NDTs.(11)

2. Faults and Defects

There are many reasons why damage occurs and it can be certain that once there is damage that this will perpetuate further.The damage of a composite and its components can roughly be attributed to one or more different stages in their life: during the manufacturing of fibers , during the construction of the composite and during the in-service life of the composite . A matrix crack typically occurs where there has been a high stress concentration or can be associated with thermal shrinkage during manufacture especially with the more brittle high-temperature adhesives. Deboning occurs when an adhesive stops adhering to an adherent or substratematerial. Deboning occurs if the physical, chemical or mechanical forces that hold the bond together are broken. Delamination is a failure in a laminated, often a composite, which leads to separation of the layers of reinforcement or plies. Delamination failure can be of several types, such as fracture within the adhesive or resin, fracture within the reinforcement or deboning of the resin from the reinforcement.(Figure 5) shows matrix cracks, broken fibers , deboning and delamination and other defects.

A void or blister is a pore that remains unoccupied in a composite material. A void is typically the result of an imperfection from the processing of the material and is generally deemed undesirable. Because a void is a non-uniformity in a composite material, it can affect the mechanical properties and lifespan. Blisters are generated in the outermost layers. Porosity can be caused by volatile entrapment during the curing of the resin. Wrinkles are common when adding new layers; it is significant to eliminate them as they can weaken the composite . The inclusion of foreign bodies in the composites (see Figure 5) can include backing film, grease, dirt, hair to finger prints, which can lead to areas rich or deprived of resin.(12)

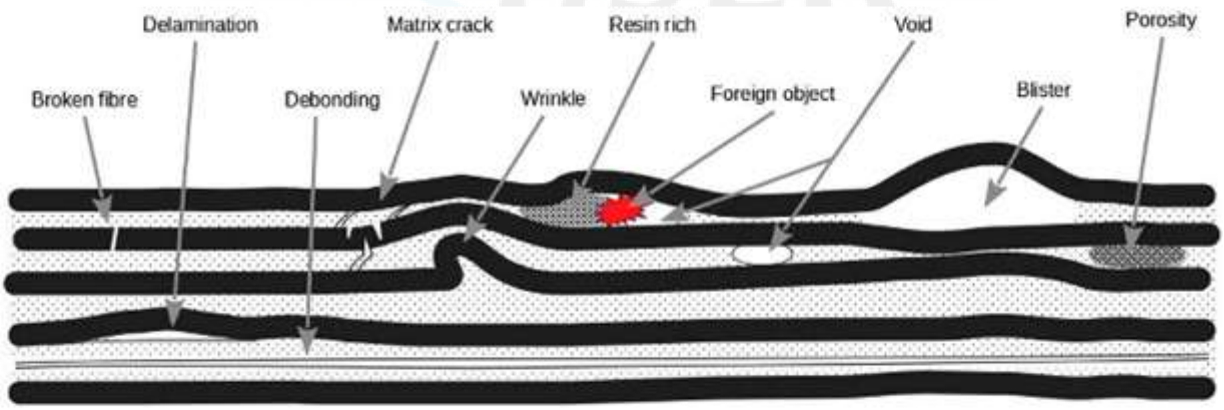

Figure 5: Faults and defects in composite materials

3. Summary

Non-destructive testing procedures are regularly accessible and there have been notable advances in this field of technology over the recent years.The detection of internal defects in composite materials with non-destructive techniques is an important requirement both for routinequality checks during the production operations and in-service inspection maintenance operations.

Visual inspection allows only the analysis of surface characteristics of materials and then if internal faults occur inside the composite structure, a deeper analysis is needed.

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