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A review of non-destructive testing methods of composite materials

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Abstract

A review provided about non-destructive testing (NDT) methods for the evaluation of composites. The review considers the capabilities of most common methods in composite NDT applications such as Visual Testing (VT or VI), Ultrasonic Testing (UT), Thermography, Radiographic Testing (RT), Electromagnetic Testing (ET), Acoustic Emission (AE), and Shearography Testing with respect to advantages and disadvantages of these methods. Then, methods categorized based on their intrinsic characteristics and their applications.

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Keywords: NDT; Composite materials; Condition monitoring

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1. Introduction

There are varieties of methods to evaluate materials or components and non-destructive methods are an important category of them with many applications. The field of Non-Destructive Evaluation (NDE) or Non-Destructive Testing (NDT) involves the identification and characterization of damages on the surface and interior of materials without cutting apart or otherwise altering the material (Lockard, 2015). In other words, NDT refers to the evaluation and inspection process of materials or components for characterization or finding defects and flaws in comparison with some standards without altering the original attributes or harming the object being tested. NDT techniques provide a cost effective means of testing of a sample for individual investigation or may be applied on the whole material for checking in a production quality control system (Newswire, 2013).

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A wide variety of NDT methods plays major roles in testing of composite materials (Scott & Scala, 1982). The applications of composite NDT may include manufacturing (Venkataraman, 2001), pipe and tube manufacturing (Hufenbach et al. 2011; Schneider, 1984), storage tanks (Castaings & Hosten, 2008), aerospace (Liew et al. 2011; Yekani Fard et al. 2014) military and defense (Bennett et al. 2013), nuclear industry (Vavilov et al. 2015), and composite defects characterization (Fotsing et al. 2014).

Numerous techniques are used in the composite NDT field, including ultrasonic testing (Peng et al. 2012), thermographic testing (Kroeger, 2014), infrared thermography testing (Vavilov et al. 2015), radiographic testing (Tan et al. 2011), visual testing (VT) or visual inspection (VI) (Bossi & Giurgiutiu, 2015), acoustic emission testing (AE) (Sarasini & Santulli, 2014), acousto-ultrasonic (Su et al., 2014), shearography testing (Hung et al. 2013), optical testing (Liu et al. 2014), electromagnetic testing (Yang et al. 2013), liquid penetrant testing (Kalinichenko et al. 2013), and magnetic particle testing (Lu et al. 2013).

This paper reviews NDT methods for composite evaluation followed by categorizing them and discussion about their advantages and disadvantages and describes non-destructive testing methods of composite material, in order to have a comprehensive review of NDT of composites.

2. Non-Destructive Testing Methods Categories for Composites

Composite materials have become a major component in the construction of aircraft and spacecraft due to their properties of high strength and low weight (Xu & Li, 2012). Composites are materials that 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 NDT methods, they can categorize in different ways according to the applications and situations of the testing. The following sections describe these categories.

2.1. Contact Methods VS Non-Contact Methods

The basic types of NDT methods include contact and non-contact methods and both of them have their specific applications in testing and evaluating the composites. Most NDT techniques require good contact between 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, radiography testing, thermography, shearography, and visual inspection (Newswire, 2013). Optical methods (e.g. thermography, holography or shearography) are mostly non-contact. Table 1 categorized NDT methods to contact methods and non-contact methods.

Table 1: Contact & Non-Contact NDT Methods

Contact Methods	Non-Contact Methods
Traditional ultrasonic testing	Through transmission Ultrasonic
Eddy current testing	Radiography testing
Magnetic testing	Thermography
Electromagnetic	Infrared Testing
Penetrant testing	Holography
Liquid penetrant	Shearography
-	Visual inspection

2.2. Physical Properties & Structural Integrity

There are diverse ways of testing composites. It is important to pay enough attention to factors such as efficiency and safety in analyzing the best method to use. Furthermore, the method chosen should minimize the costs incurred in the operation.

Material defefcts are the major sources of composite failures. These damages as a result of failure in the material composites can manifest as matrix cracking, fiber fracture fibre debonding and fiber pull-out (Mckuur, 2006). Structural integrity is a formalized process which utilize advanced non-destructive testing (NDT) methods in order to detect, localize and determine a size of damage (Andrzej Katunin et al. 2015). Non-destructive tests can categorize based on the factors that they evaluated. Categories of non-destructive tests are mentioned in Table 2.

Table 2: Category of NDT Methods Based on the Detecting Factors

Category	Applications
The estimation of the physical and mechanical properties, and the material defects detection, in composite	Measurement of: dynamic mechanical analysis (DMA) (Šturm et al. 2015) fiber amount of portion (El-Sabbagh et al. 2013) mechanical strength and stiffness (Ray, 2006) elastic constants (Rojek et al. 2005) material content (El-Sabbagh et al. 2013) damage failing initiation and subsequent damage evolution (Talreja, 2008) delamination (Ghadermazi e tal. 2015) construction connected with laminate (Scarselli et al. 2015) condition of resin cure (Aggelis & Paipetis, 2012) condition regarding to fiber/ matrix interface (Kersemans et al., 2014)
To determine the integrity of structural components which are manufactured from composite	Detection of: cracks and debonding (Giurgiutiu, 2016) mechanical rubbing (Gostautas et al. 2005) fibre pull out (Short et al. 2002) fibre breakage (Narita et al. 2014)

The mechanical properties of a material determine its manufacturability, performance, and longevity. This means that knowledge of the mechanical properties is essential for physical and mechanical characterization of a composite material (Šturm et al. 2015). Mayer & Council (1993) showed that the mechanical performance of GFRP composites depends on the fibers' strength and modulus, the strength of the matrix and the chemical stability. Ray (2006) has demonstrated that the higher the temperature of the environment and the longer is the exposure time, the larger will be the decrease in the strength and modulus of the GFRP. Rojek et al. (2005) found that the best methods for elastic-properties determinations are the ultrasound methods. El-Sabbagh et al. (2013) studied the feasibility of using an ultrasonic longitudinal sound wave in the definition of the fiber content and the distribution in natural fiber. Talreja (2008) investigated about the mechanical characterization and damage behavior of composite materials. Delamination type defects are detected experimentally on Glass/epoxy composites by employing step heating thermography by Ghadermazi et al. (2015).

2.3. Inspection Type versus NDT Method

According to the literature review, there are many types of inspections to evaluate composites and there are many proposed methods by researchers for each of which. For damage identification in aircraft composite structures, aircraft composites assessment, and health monitoring of aerospace composite structures the suggested methods in the literature is ultrasonic testing (Andrzej Katunin et al. 2015; Staszewski et al. 2009), thermographic testing (Andrzej Katunin et al. 2015; Maierhofer et al. 2014), vibration methods (Andrzej Katunin et al. 2015; Loutas et al. 2012; Rizos et al. 2008), infrared thermography (Meola & Carlomagno, 2014), shearography (Růžek et al. 2006), and XCT (Bull et al. 2013).

Ultrasonic testing is the most applied method in health monitoring of a composite wing-box structure (Grondel et al. 2004), damage identification in aircraft composite structures (Andrzej Katunin et al. 2015; Polimeno & Meo, 2009), aircraft composites assessment (Růžek et al. 2006), health monitoring of aerospace composite structures (Loutas et al., 2012), and structural health monitoring (SHM) (Staszewski et al. 2009). Table 3 presents the inspection type and the methods that have used for each one. This table provides a quick suggestion for the readers to make a decision when needs to evaluate a specific type of composite.

Table 3: Inspection Type and NDT Methods

Inspection Type	NDT Method
Damage identification in aircraft composite structures (Andrzej Katunin et al. 2015; Polimeno & Meo, 2009) Aircraft composites assessment (Růžek et al. 2006) Health monitoring of aerospace composite structures (Loutas et al. 2012)	Ultrasonic Testing (Andrzej Katunin et al. 2015) Thermographic Testing (Maierhofer et al. 2014; Usamentiaga et al. 2013) Vibration Methods (Loutas et al. 2012; Rizos et al. 2008) Infrared Thermography (Meola & Carlomagno, 2014) Shearography (Růžek et al. 2006) XCT (Bull et al. 2013)
Health monitoring of a composite wing-box structure (Grondel et al. 2004)	Ultrasonic Testing (Grondel et al. 2004; Andrzej Katunin et al. 2015)
Structural Health Monitoring (SHM) (Staszewski et al. 2009)	Ultrasonic Testing (Andrzej Katunin et al. 2015; Staszewski et al. 2009)
Damage in GFRP (Meola & Carlomagno, 2010; Rique et al. 2015)	Thermographic Testing (Maierhofer et al. 2014; Usamentiaga et al. 2013) Radiography (Ataş & Soutis, 2013; Rique et al. 2015)
Auto-detection of impact damage in carbon fiber composites (Usamentiaga et al. 2013) Characterizing damage in CFRP structures (Ataş & Soutis, 2013; Maierhofer et al. 2014)	Thermographic Testing (Maierhofer et al. 2014; Usamentiaga et al. 2013) Radiography (Ataş & Soutis, 2013; Rique et al. 2015)
Impact damage in glass/epoxy with manufacturing defects (Meola & Carlomagno, 2014)	Infrared Thermography (Meola & Carlomagno, 2014)
damage assessment in sandwich structures (Meo et al. 2005) parameters influencing the damping of a structure (Adams et al. 1978) the structures behavior (Cawley; & Adams, 1979) dynamic characteristics for damage detection of structures (Cawley & Adams, 1978) skin damage statistical detection and restoration assessment (Rizos et al. 2008)	Vibration Methods (Loutas et al. 2012; Rizos et al. 2008; Trendafilova et al. 2008)
Multiple Cracks Detection (Zhang et al. 2010)	Neutron Radiography (Zhang et al. 2010)

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.

Ultrasonic Testing (UT) evaluation system consists of a transmitter and receiver circuit, transducer tool, and display devices. Based on the information carried by the signal, crack location, flaw size, its orientation and other characteristics could be achieved (Lu, 2010). Advantages of ultrasonic testing include speed of scan, good resolution and flaw detecting capabilities, and ability of use in the field. Disadvantages include difficulty of set up, needed skill to scan a part accurately, and the need of test sample to insure accurate testing. This type of testing is excellent for use in an assembly line where the same part design must test repeatedly. There are two approaches of ultrasonic NDT generally used in different applications; pulse echo and through transmission approaches. Both of these approaches use high frequency sound waves on the order of 1-50 MHz to detect internal flaws in a material (Garney, 2006). Ultrasonic testing conducted in three modes, transmission, reflection, and back scattering. Each of which uses a range of transducers, coupling agents, and frequencies (Stonawski et al. 2008).

Pulse echo ultrasonic method can readily locate defects in homogeneous materials. In this method, the operator more concerns about the transit time of the wave and the energy loss due to attenuation and wave scattering on flaws. It helps to locate inconsistency in a material whether it is homogeneous or heterogeneous (Warnemuende, 2006). For large defect detection, location, and imaging purposes, and quality control, ultrasonic pulse velocity measurements are quite suitable (Oguma et al. 2012). The through transmission ultrasonic method is different from conventional ultrasonic methods. This method keeps the transducer and receiver off the surface and at a fixed distance away from the sample. This is particularly advantageous when complex geometries do not allow for the contact of a traditional transducer and receiver to the surface of the part.

The most commonly used indicators of properties are wave propagation velocity and amplitude (or energy) loss. Some of the testing methods described herein only address one property, while others, more versatile, may measure two or three (Ducharne et al. 2015). Most applications consider only the pulse velocity and relate it to different parameters. Considering energy loss can discover a few additional characteristics of a material (Karabutov & Podymova, 2014a). A number of authors have studied the method of pulse attenuation analysis (El-Sabbagh et al. 2013; Genovés et al. 2015). Scattering, absorption and geometric are three parameters that affect the attenuation. Small discontinuities like grain boundaries are the source of scattering.

Thermography testing also called thermal imaging. The thermal conductivity of a material may change by the presence of defects, thermography inspection used for thin parts because when defects moved deeper under the surface of a part, they tend to produce less heat fluctuation than defects seen closer to the surface of the part. As a generally rule, defects that have a diameter smaller than their depth in the part, cannot be picked up by this type of inspection. A flaw, such as a delamination or impact damage causes a change in the thermal radiation of the area (Meyendorf et al., 2013). There are many advantages and disadvantages to this type of inspection. One advantage is it can inspect a large surface of a part. The second advantage is that unlike many other types of inspection it does not have to couple. This allow for the inspection of parts where only one side of the part is accessible to inspection. Disadvantages of this type of inspection include the need for sensitive and expensive instrumentation, the need for highly skilled inspectors to run the instruments, and the lack of clarity of defects if they fall too deeply under the surface of the part. Infrared Thermography Testing (IRT) is based on the recording of the thermal radiation emitted by a surface of a specimen by means of an infrared camera (Mulaveesalaa & Tuli, 2008).

Radiographic Testing (RT) is the most commonly used testing method (Lockard, 2015). 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 misorientation such as fiber wrinkles or weld lines (Garney, 2006). 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 delaminations in a sample (Ataş & Soutis, 2013). There are varieties of radiographic testing methods for different applications. These methods are film radiography (Burkle & Lemle, 1993), computed radiography (Tan et al. 2011), computed tomography (Katunin et al. 2015), and digital radiography (Aidi et al. 2015). 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 (Bayraktar et al. 2008).

Electromagnetic Testing (ET) methods use magnetism and electricity to detect and evaluate fractures, faults, corrosion or other conditions of materials. ET induces electric currents, magnetic fields, or both inside a test object and observes the electromagnetic response. Electromagnetic (EM) methods include Eddy Current Testing (EC) (Koyama et al. 2013), Remote Field Testing (RFT), Magnetic Flux Leakage (MFL) and Alternating Current Field Measurement (ACFM). In each of these techniques, the underlying physics is fundamentally different as the fields described by different classes of partial differential equations (PDEs).

Acoustic Emission (AE) is an effective method of imperfection analysis. This mechanical vibration generated by material defects such as matrix micro cracking, fiber-matrix debonding, localized delamination, or fiber pullout and breakage (Arumugam et al. 2011; S. Gholizadeh et al. 2015). The stress waves that result from these types of defects spread out concentrically from their origin and are detected by an array of highly sensitive peizoelectrics.

Acoustic emission technique is different from most other NDE techniques in two aspects. The first difference is the origin of the signal. Instead of supplying energy to the object, this method listens to the “sound” generated by energy released in the object. The second difference is the method that AE deals with dynamic processes in a material. The ability to discern between developing and stagnant defects is significant. Other advantages of AE method include high sensitivity, fast and global inspection using multiple sensors, permanent sensor mounting for process control, and no need to disassemble and clean a specimen (Lu, 2010). The second advantage of the AE is that it is very useful in detecting many different types caused by fatigue loading. Fatigue damage types which acoustic emission testing can detect include fatigue cracks, fiber fractures, matrix micro-cracks, fiber-matrix debonding, and delamination. The drawback to this type of testing is the great skill that is required to correlate acoustic emission data to specific types of damage mechanisms.

Acousto-Ultrasonic is a combination method of acoustic and ultrasonic testing that used specifically to determine the severity of internal imperfections and inhomogeneity in a composite. In nondestructive testing, the acoustic/ultrasonic class of testing has great potential based on optimal economy, flexibility and sensitivity. However, no available method is sensitive or reliable enough to effectively detect. It is useful method because it allows non-critical flaws to see and assess. The second advantage is that it is a good indicator of accumulated damage in a structure due to fatigue loading or impact damage. The disadvantage of this type of inspection is the setup and pre-calculations that is mandatory before any testing. The second disadvantage is that this type of testing is not useful to detect individual large flaws such as delamination or voids (Schroeder et al. 2002).

Shearography Testing is a laser optical method. The failure of composites usually happens by stress concentrations and the criticality of defects will easily deduct by the degree of strain concentrations around a particular defect, this is an advantage of shearography (Hung et al. 2013). A second advantage of shearography is that it is less susceptible to noise than many other types of nondestructive testing. This is good because it allow less skilled users to be able to inspect and determine the usability of a part without extensive training. A major disadvantage of shearography is that characterization of defect types other than delamination is extremely difficult. Therefore it is sometimes paired with other types of non-destructive evaluation techniques that can help to identify certain defects.

3. Conclusion

This paper reviewed NDT methods for composite evaluation by categorizing their advantages and disadvantages as well as describing NDT methods of composite materials in order to have a comprehensive review of NDT of composites. Due to the fact that composite tools are mostly used in critical-safety applications for example in aircraft primary constructions, the non-destructive testing of composite materials has become more crucial and demanding. Factors such as efficiency and safety should be used in analyzing the best method to be used. Furthermore, the method chosen should minimize the costs incurred in the operation. It is based on methods that depend on the use of physical values to determine the characteristics of materials. In addition, non-destructive tests use physical principles to identify and evaluate faults or destructive defects.

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