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A Review of Common Aerospace Composite Defects Detection Methodologies

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ABSTRACT

There are different aerospace composite defects detection methodologies nowadays. In this paper it is clearly defined the common damage identification techniques namely damage detection, damage assessment techniques and NDT modeling softwares. The main sources of composite defects occurred at aerospace structures are clearly reviewed. Delivering defect free components or structures requires strict attention for aircrafts, launch vehicles, satellites, and other payloads to operate safely. One of the essential safety techniques for spacecraft and their payload is quality control of its components utilizing non-destructive testing technology. Utilizing NDT to test spacecraft components and payloads is essential to ensure their performance with full efficiency for the long term without unexpected maintenance requirements and failure. The main defects are those occurred during production are named as manufacturing defects whereas the other types detected during operation are in-service defects. The common damage identification techniques and detection methods used in composite structures are destructive and non-destructive tests. In this paper we looked more reliable and precise NDI methods for inspecting aerospace composite components.

Keywords: Composite structures; Damage detection; Damage inspection; NDT; Defect

1. Introduction

A composite material sometimes called as a composition material is a material which is produced from two or more constituent materials. They are mostly with dissimilar chemical or physical properties and are merged to create a material with properties unlike the individual elements with better strength but light weight [1]. Composites are, by definition, materials consisting of two or more materials which together produce beneficial properties that cannot be attained with any of the constituents alone. One of the most common examples, fiber-reinforced composite materials consist of high strength and high modulus fibers in a matrix material [2].

Composites can be classified on the basis of the form of their structural components: fibrous composites, which consist of fibers of one material in a matrix material of another; particulate composites, which are composed of macro-size particles of one material in a matrix of another; and laminated composites, which are made of layers of different materials, including composites of the first two types [3]. Composites are also classified by the type of material used for the matrix [4]. Matrix material carries out several functions in a composite structure, some which are binding the fibers together and transferring the load to the fibers, and providing protection to reinforcing fibers against chemical attack, mechanical damage and other environmental effects like moisture, humidity, etc [5]. The basis that makes the composites to have superior structural performance stands on their high specific strength (strength to density ratio) and high specific stiffness (modulus to density ratio) and the anisotropic and heterogeneous character of the material [6]. Composites materials are widely used in aerospace and different fields of Engineering such as commercial mechanical engineering applications namely internal combustion engines, machine components, thermal management and electronic packaging, automobile, train, and aircraft structures [4] [7] [2].

The need for inspection of composed of tanks for the propulsion system, launch vehicle frame, turbine and engine, pressure vessel, wings, fuselage, number of fasteners and other accessories, composite and welds is crucial. In addition, payloads such as satellites also need to be of excellent quality to ensure stable performance where no maintenance provision is available. Utilizing NDT, space industries assess the integrity of these materials and components without causing any damage. Identifying flaws early in the process can saves costs, ensures efficiency, and prevents hazards in this complex process[2] [8] [9]. Generally material testing is classified as destructive and non-destructive tests depending on the purpose and types of structure. Higher cost and defect free composite materials and its manufacturing methods for aerospace equipment must compete with the international market [10].

2. Sources of Composite Defects

Composite are susceptible to damage or defects due to strain, impact, chemical, penetrants, and multi-axial fatigue. Some of the damage modes in composite materials are matrix cracking, fiber-breakage, delamination, transverse cracking, fiber-matrix debonding, matrix degradation and blistering [11]. Some sources of defects are either from production or during operation of the material. It is important to identify and calculate the stress and strain distributions to know the mechanical behaviour of composites. They are largely preferred materials in industries because of their unique mechanical and physical properties [9].

Fig. 1 –Aircraft ultrasonic inspection [11]

Small indentation on the surface can propagate through the laminates forming a complex network of delaminations and matrix cracks. It can reduce the static and fatigue strength and the compression buckling strength depending on the size of the delamination. It can grow under fatigue loading if the crack is large enough [13]. According to the above-discussed defects occurred on the mechanical properties of structures and parts made of composites, the effective methods of their detection and localization is better to be performed at the production inspection (PI) and quality control (QC)stages during operation. This is accomplished through inspection and monitoring during the operation of the composite structure [14].

3. Common Composite Manufacturing Defects

Manufacturing defects occurred in composite structures are delamination, resin starved areas, resin rich areas, blisters, air bubbles, wrinkles, voids and thermal decomposition. Manufacturing damage includes anomalies, such as porosity, micro-cracking and delaminations resulting from processing discrepancies [15] [16].We need to understand the composite important requirements and defects in aerospace structure and their effect on the design of the structure. They indirectly affect Weight reduction, Mechanical properties, High impact resistance and High damage tolerance [17] [18].

Composite defects also include inadvertent edge cuts, surface gouges and scratches, damaged fastener holes, impact damage, and contaminated bond line surface, inclusions, separation film that is inadvertently left between plies during layup [19]. Glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) are some of the commonly used materials in aerospace structures and has inbuilt defects caused during their manufacturing and in-service operations [20]. Detecting defects and undertaking corrective measures is very essential while using composites [21]. Sources of manufacturing defects include: Improper cure or processing, improper machining, Mishandling, Improper drilling, Tool drops, Contamination, Improper sanding, substandard material, inadequate tooling and Misallocation of holes or details [15] [16].

4. Common Composite In-service Defects

In-service defects include Environmental degradation, Impact damage, Fatigue, Cracks from local overload, Deboning, Delamination, Fiber fracturing and Erosion. Many honeycomb structures, such as wing spoilers, fairings, flight controls, and landing gear doors, have thin face sheets which have experienced durability problems that could be grouped into three categories: low resistance to impact, liquid ingression, and erosion. SiCp/Al composites have excellent comprehensive properties, such as high wear resistance, high corrosion resistance, high specific stiffness and low thermal expansion coefficient. Therefore, the composites have attracted more and more attention in aerospace industry, automobile industry and electronics industry [22] [16].

i. Fiber breakage

Fiber breakage can be critical because structures are typically designed to be fiber dominant (i.e., fibers carry most of the loads). Fortunately, fiber failure is typically limited to a zone near the point of impact and is constrained by the impact object size and energy [15] [16].

ii. Matrix imperfections

Matrix imperfections usually occur on the matrix-fiber interface or in the matrix parallel to the fibers. These imperfections can slightly reduce some of the material properties but are seldom critical to the structure, unless the matrix degradation is widespread. Accumulation of matrix cracks can cause the degradation of matrix-dominated properties [7] [23].

iii. Delamination and Debonds

Delaminations form on the interface between the layers in the laminate. Delaminations may form from matrix cracks that grow into the interlaminar layer or from low-energy impact. Debonds can also form from production non-adhesion along the bond line between two elements and initiate delamination in adjacent laminate layers. Delamination is the main type of defect that exists within the component which lead to in homogeneity within the composite component [7] [16] [23].

iv. Flawed Fastener Holes

Improper hole drilling, poor fastener installation and missing fasteners may occur in manufacturing. Hole elongation can occur due to repeated load cycling in service [7] [23].

5. Common Defect Identification Techniques

There are different types of defect identification techniques such as destructive and non-destructive tests. Destructive testing is a testing method that analyzes the point at which a component, asset, or material fails. Inspectors subject the material they are testing to different destructive test methods, which will deform or destroy the material completely, in order to gain insights about how the material performs under pressure. Destructive testing methods can identify physical properties of a component, like toughness, hardness, flexibility, and strength. Destructive testing is almost commonly called destructive physical analysis (DPA) or destructive material testing (DMT) [16] [24].

Destructive testing is an important testing method that identifies the limits of components which is used for failure analysis, process validation and materials characterization supported by non-destructive testing techniques. The most common types of destructive testing methods are: Aggressive environment testing, Corrosion tests, Fracture and mechanical testing, Fatigue testing, Hardness testing, Hydrogen testing, Residual stress measurement, Software testing, Tensile (elongation) tests and Torsion testing [16] [24].

For reliable defect detection method, its response on a defective structure must be significantly different to that on a sound structure. In composite structures, defects are most often in the form of either disbonds or delaminations in the plane of the material, or porosity. The reason for favoring ultrasound inspection is that it is very sensitive to these types of defects commonly found in composites [7].

6. Destructive Testing

Destructive testing is used to check the properties of materials to meet the specifications of the engineer‟s part of design of equipment and structures compliance with regulatory body standards. Materials testing may be carried out when materials are initially manufactured. However, the requirements for testing and certification of these materials are more extensive than metallic materials. Due to the anisotropy of the material the materials testing of composite components required increased technical expertise and special testing equipment [25] [26] [27].

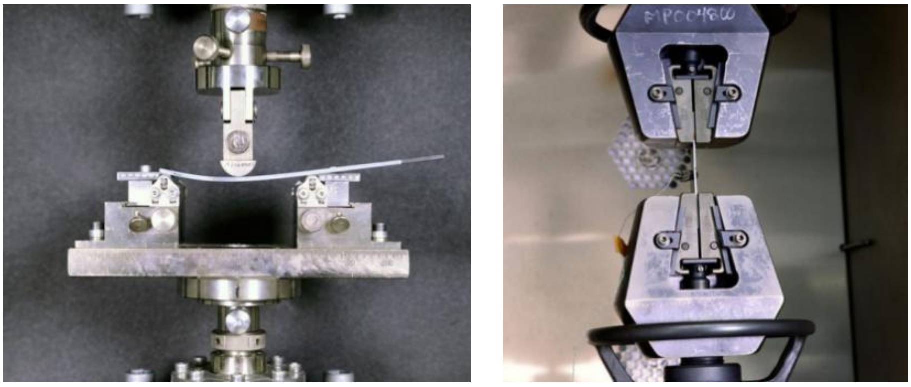


Fig. 2–Destructive testing at Airbus [26]

There are several types of destructive testing methods, which are designed to simulate the environmental factors that materials may actually be exposed to once they are in use. These methods are designed to test the strength of a material under certain types of pressure or strain like aggressive environment testing, corrosion tests, fracture and mechanical testing, fatigue testing, hardness testing, hydrogen testing, residual stress measurement, software testing, tensile (elongation) tests and torsion testing [24] [25] [26] [27]..

7. Aggressive Environment Testing

Aggressive environment testing is used to test fatigue and fracture points of a component when it is exposed to corrosive environments at different pressures and temperatures. Tests mimic the environment where components will be operating. Examples of corrosive environments include those that contain: Salinity, Humidity, Hydrogen sulfide, Carbon dioxide and other natural elements [24] [28] [29].

Environmental testing has always been a necessity in regards to the survivability and reliability of space systems. Among all the space environments, the most treacherous is that of the launch environment. The launch environment is responsible for the most hazardous times of space mission, launch and reentry. Because of high speeds, altitudes, and pressures, molecules in the air behave violently. Vibrations, shock, and acoustics are factors engineers must consider when designing and testing for mission success. Flight hardware and systems are qualified through a series of environmental and operational tests that expose units to environments and scenarios that will be encountered in its lifetime. This testing is a requirement for not only the whole spacecraft system, but also every individual part such as boom structures, electronic components, and space thruster motors [29] [30].

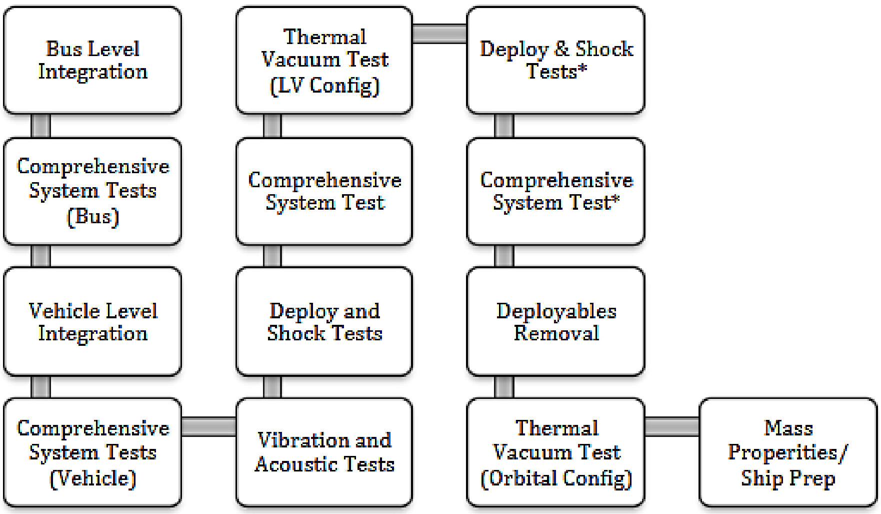


Fig. 3 –Launch environment tests [30]

8. Non-destructive Inspection (NDI) of Composites

Nondestructive testing (NDT), as it is commonly understood, refers to any means of determining the strength and integrity of an object without destroying the object. Similar terms like nondestructive inspection (NDI), nondestructive evaluation (NDE), and nondestructive examination (NDE), are used interchangeably. NDT describes a category of examination, not a specific testing method. The basic purpose of nondestructive testing is to assess the qualities of an object without destroying it. The underlying reason for doing that is risk management. While nondestructive testing does not eliminate risk, it can significantly reduce or mitigate it. NDT allows objects and equipment actually in service to be tested. Nondestructive testing is worthwhile when the risk of an object failing outweighs the cost of testing it [7] [9].

Among the currently applied NDT techniques that found wide application in numerous studies, one can mention, among others, ultrasonic testing (UT), radiographic testing (RT) and X-ray computed tomography (XCT), and infrared thermography (IRT), as the most popular ones in the detection and identification of internal defects and damage due to their sensitivity to these types of flaws [31].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. Categorized NDT methods to contact methods and non-contact methods are shown in the table below [10] [33] [34].

a. Visual Testing (VT)

A basic and useful part of the inspection of composite structures is a visual inspection. The inspector looks for visible signs of damage to the structure like burns, debonds, and delaminations. The oldest type of non-destructive testing is visual testing. It uses low-power equipment including flashlights, magnifying glasses, mirrors, borescopes and fiberscopes for monitoring imperfections. Fast, inexpensive, and direct, visual testing can be an initial tool to identify asset and infrastructure issues from cracks to corrosion [7] [9] [10].

Fig. 4 -Visual inspection for composite [10]

b. Audible Sonic Testing (Tap Testing)

Sometimes referred to as audio, sonic, or coin tap, this technique makes use of frequencies in the audible range (10 Hz to 20 Hz). This is another basic method of inspection. Tapping with hammer-like device along the part's surface and a bright, sharp, metallic (ringing) sound indicates good structure. A dull "thud-like" sound (dull) would indicate a flaw such as delamination or debond. It is more effective on thinner structures and loses its effectiveness on very thick laminates. Another disadvantage is that it won't go through the core. It can also sometimes give false readings [34].

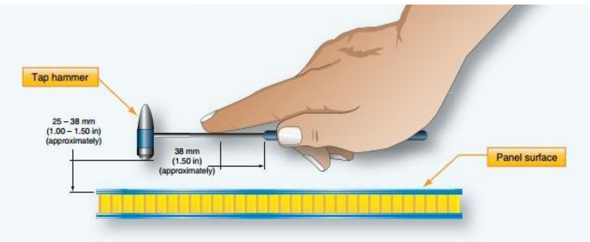


Fig. 5 – Tap test with tap hammer [10]

In aviation tap test is very similar to the manual tap test except that a solenoid is used instead of a hammer. The solenoid produces multiple impacts in a single area. The tip of the impactor has a transducer that records the force versus time signal of the impactor. The impact duration (period) is not sensitive to the magnitude of the impact force; however, this duration changes as the stiffness of the structure is altered [35].

Fig. 6–Aviation Tap Testing at Maintenance Depot [36]

c. Eddy current testing (ECT)

Eddy current testing uses magnetic fields to form images of conductive materials. Changes in material properties create discontinuities in the field. These changes provide indications of corrosion, cracks, voids, honeycombing, delamination, and thickness loss. Eddy current technology finds regular use in industry due to its portability, speed, and accuracy. Handheld eddy current equipment allows for inspections in situ, reducing the amount of downtime required to perform inspections [7] [9]. A recent innovation in eddy current testing is eddy current array (ECA) technology, ideal for surface and near-surface mapping across a range of industries including aerospace, rail, manufacturing, oil and gas. ECA is an extremely fast, cost-effective and easy to use technique that provides highly accurate results. If the current meets a defect, a reaction is produced in the receiver coil [7] [36].

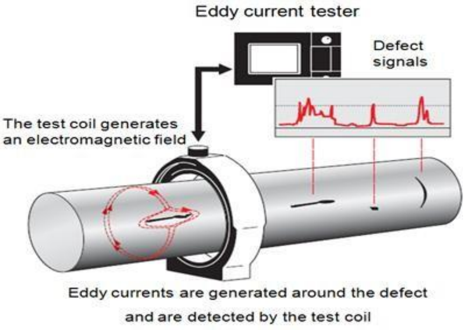


Fig. 7 –Eddy current testing [36]

d. Ultrasonic Testing (UT)

Ultrasonic inspection is another type of non-destructive testing that may be considered for the inspection of composite structures. The ultrasonic 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, orientation, and other characteristics inspected [34]. There are three basic types, A-Scan, C-Scan, and ANDSCAN [10]. It has proven itself to be one of the most effective methods of modern NDT. This method works by inducing high-frequency sound waves into solid objects, typically metal or composites.

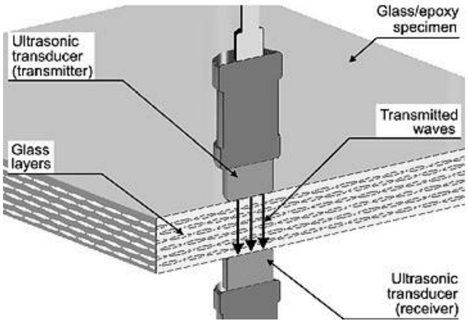


Fig. 8 –Ultrasonic inspection [10]

Ultrasonic testing relies on transducers to convert electrical energy into ultrasonic waves. While older methods used a single transducer at a time, modern phased array ultrasonic testing (PAUT) equipment uses several transducers operating in tandem [9] [37].

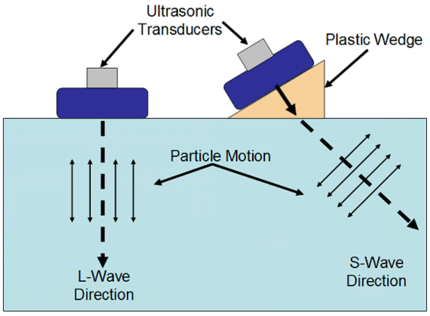


Fig. 9 – Schematic Ultrasonic Testing [38]

e. Long-range Ultrasonic Testing (LRUT)

Long Range Ultrasonic Testing (LRUT) is an advanced non-destructive examination technique that was developed for testing large volumes of material from a single test point. For this reason, LRUT is one of the fastest inspection tools for carrying out pipeline surveys for corrosion and other damage mechanisms [39]. Ultrasonic transducers or coils are built into a ring, which travels along the pipe. The transducers emit waves, which provide an image of the pipe wall‟s interior [40].

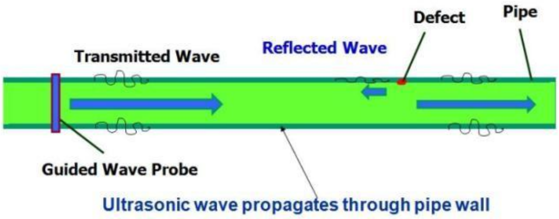


Fig. 10– LRUT testing methodology

LRUT is traditionally used to detect corrosion, erosion and other defects in pipe work. An array of transducers is clamped around the pipe and ultrasound is transmitted simultaneously along the pipe in both directions. The return signal is received by the same transducers, and the data are analyzed using the system‟s calibrated software [41].

f. Pulse Echo Ultrasonic Inspection

Single-side ultrasonic inspection may be accomplished using pulse echo techniques. In this method, a single search unit is working as a transmitting and a receiving transducer that is excited by high voltage pulses [42]. A waveform is generated in the test part and is picked up by the transducer element. Any change in amplitude of the received signal, or time required for the echo to return to the transducer, indicates the presence of a defect [43] [44].

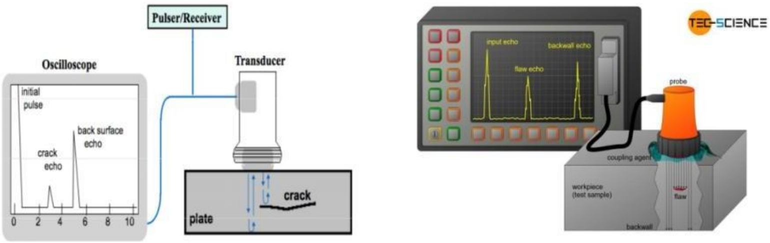


Fig. 11 – Pulse echo test equipment [43]

g. Ultrasonic Bond Tester Inspection

Low-frequency and high-frequency bond testers are used for ultrasonic inspections of composite structures. The high-frequency bondtester is used to detect delaminations and voids. It cannot detect a skin-to-honeycomb core disbond or porosity [45]. It can detect defects as small as 0.5-inch in diameter. This inspection method does not detect which side of the part is damaged, and cannot detect defects smaller than 1. 0-inch. This instrument has long been used on most existing aircraft, but new methods were developed recently as shown below [46].

Fig. 12 – Bond tester

h. Magnetic Flux Leakage (MFL) Testing

Magnetic flux leakage is an effective field testing technique primarily used to inspect large pipes, tubes, and tank floors. A powerful magnet is used to saturate the material with a magnetic field. A sensor detects fluctuations in the magnetic field caused by differences in material properties, such as corrosion, pitting, thickness loss, or cracks [47]. Tank floors must be scanned using field generators arranged in series. This technology is good for ferrous materials and a capable means of detecting flaws in large infrastructure [48].

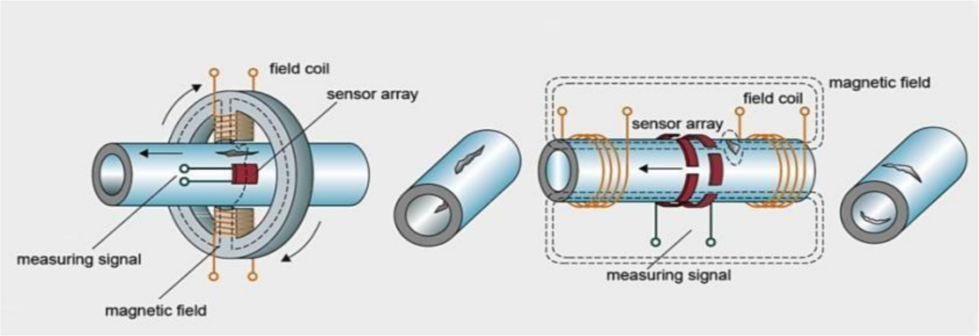


Fig. 13 – Magnetic flux testing principle in different crack orientations [49]

i. Laser Testing Methods (LM)

A Laser Testing Methods (LM) is one of NDT (Non-Destructive Testing) techniques that use lasers to perform the inspections including three distinct methods: Holography, Shearography and Profilometry performing the inspection and detect defects and flaws [50].

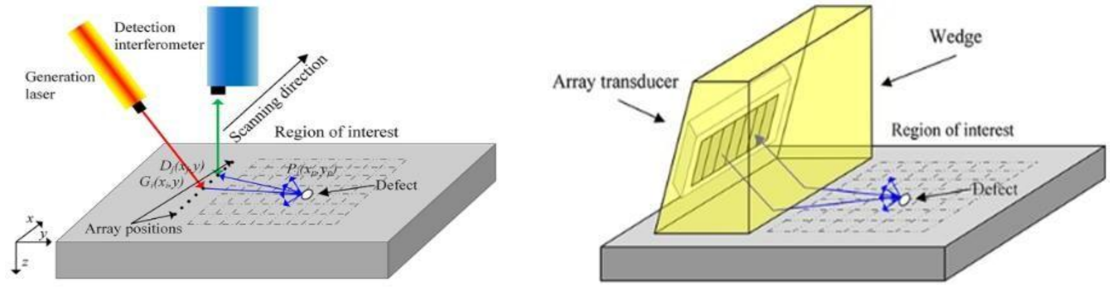


Fig. 14– Schematic diagram of laser induced ultrasonic for FMC data acquisition [51]

With a large increase in the use of composite materials and sandwich structures, the need for high speed, large area inspection for fracture critical, sub-surface defects such as disbonds, delaminations, sheard core or non-visible damage in aircraft, missiles and marine composites lead to broad acceptance of laser based NDT methods [52].

j. Magnetic Particle Testing

Magnetic particle testing uses the motion of indicator particles to evidence internal discontinuities in ferromagnetic materials. The part being testing must be coated in dyed magnetic particles, either in dry powder or liquid suspension form. A magnet induces an electromagnetic field into the material being tested. The field causes the magnetic particles to move towards any discontinuities transverse to the direction of the magnetic field, providing a visual indication of flaws. Abroad discipline and a variety of methods can be used to induce magnetic fields. Magnetic particle testing requires significant setup and cleanup, and cannot easily be used in the field [53] [54].

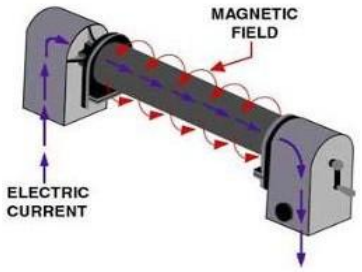


Fig. 15 – Magnetic particle testing

k. Vibrations Analysis Testing

Vibrations analysis excels at testing the integrity of rotating parts, including turbines, gears, shafts, and bearings. Three types of vibrations analysis are commonly used namely accelerometers, velocity sensors, and eddy current displacement sensors [55] [56]. Some authors in this field subsequently used a tool of vibration in their studies to investigate the structures behaviour and the effectiveness of vibration as a tool of non-destructive control and the FFT analyzer collects the vibration data and shows it in the FFT plots in different display according to the defect [57] [58].

Fig. 16 – Researchers' setup for vibration test of carbon fiber beam [59]

l. Liquid Penetrant Testing

Liquid penetrant testing provides visual indication of cracks or other defects that connect to the surface of materials. Liquid penetrant is primarily useful for non-porous materials. This fluid flows into openings in the material‟s surface. Anywhere liquid resurfaces reveals a defect and liquid penetrant requires significant equipment, setup, and cleanup to handle the liquid itself. While this technique can be used effectively, it is often slower and more cumbersome than other NDT methods [60] [61] [62] [63].

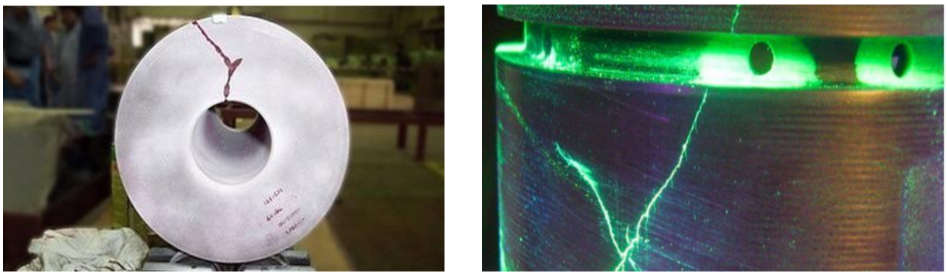


Fig. 17 - Detected defects [64]

m. Leak testing (LT)

Leak testing is a category of nondestructive testing, referring to several methods for determining the presence of leaks in sealed vessels. There are four common methods for detecting gas leaks, though some are similar. Pressure change testing either pressurizes or creates a vacuum in a sealed vessel. Loss of pressure or vacuum indicates a leak. A leak can be defined as an unintended crack, hole or porosity in an enveloping wall or joint, which must contain or exclude different fluids and gases allowing the escape of closed medium [65] [66][67].

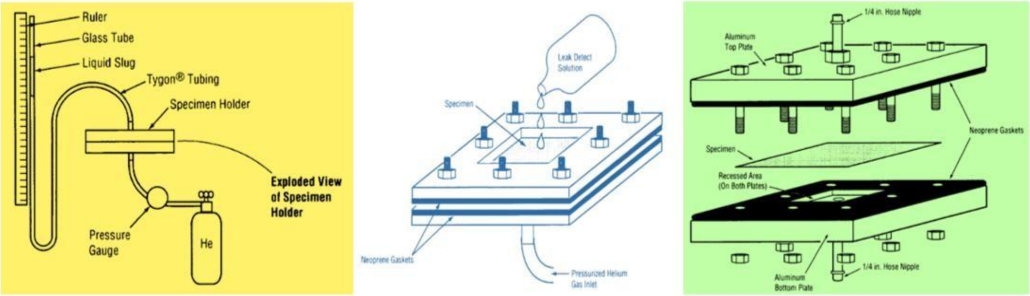


Fig. 18- Leak detection apparatus for plate

These damages can result in gas and liquid leak. In order to prevent leakage different researchers propose different leak prevention methods depending on product function, operating conditions, applied processing technology and other factors [68] [69]. Bubble testing also relies on a pressure indicator. Preliminary studies addressing the gas tightness or leak test of epoxy-based carbon composites are carried out using different methods [70] [71].

n. Phased Array Inspection

Phased array inspection is one of the latest ultrasonic instruments to detect flaws in composite structures. It operates under the same principle of operation as pulse echo, but it uses 64 sensors at the same time, which speeds up the process [72] [73] [74].Its main advantages of phased array are excellent repeatability, increased inspection speed, accurate results, ability to inspect complex geometries, ability to inspect large areas, permanent auditable results and no safety hazards[74] [75].

Without electronic focusing (DDF) (Conventional method: focus is 25 mm)

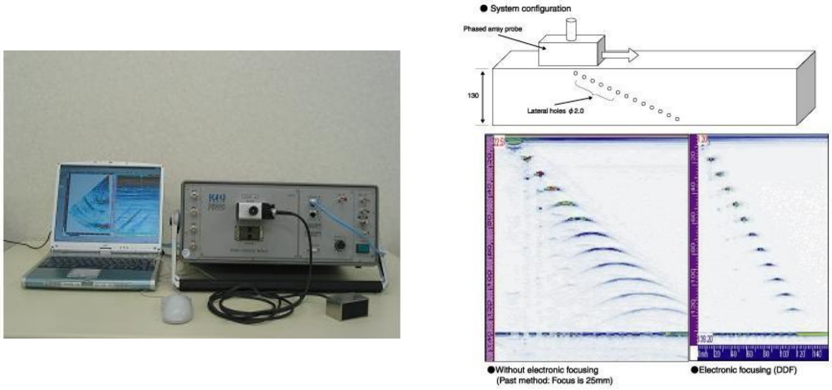


Fig. 19 - Phased array UT inspection technology [76] [77]

o. Radiographic Testing

Radiographic Testing (RT) often referred to as X-ray is the most commonly used testing method for composites. This inspection method is accomplished by passing X-rays through the part or assembly being tested while recording the absorption of the rays onto a film sensitive to X-rays. The exposed film, when developed, allows the inspector to analyze variations in the opacity of the exposure recorded onto the film [78]. In X-ray radiography, short wavelength electromagnetic radiations are used to penetrate various materials and generate a shadowgraph image of the test object [79] [80].

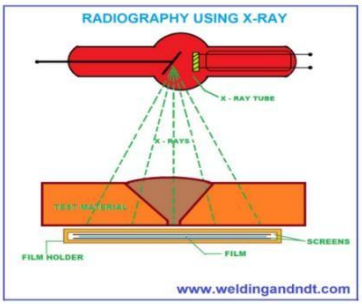


Fig. 20- Radiography testing using x-rays

Internal anomalies, such as delaminations in the corners, crushed core, blown core, water in core cells, voids in foam adhesive joints, and relative position of internal details, can readily be seen via radiography [81]. The most common type of damage to composites is delamination resulting in an air pocket. 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 [34] [78].

p. Thermography Testing

Thermography can be used to inspect composite structures. In its most basic form, heat is applied to a part and then the part is viewed through an infrared camera as it cools. This can give indications of a flaw to a trained eye [34]. In Infra-Red Thermography (IRT), When thermal energy propagate inside the object by diffusion and reaches a material defect a thermal gradient is generated due to different emissivity coefficients that can be used to evaluate the damage. IRT is generally classified into „„„passive” and „„„active” thermography [80] [82].

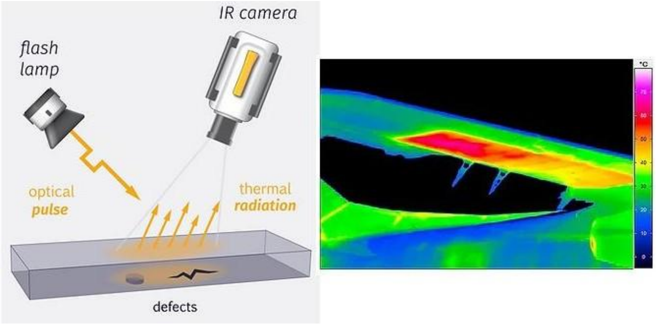


Fig. 21- Thermography testing

In Active IRT, however, the structure is externally exposed to thermal energy to induce a temperature difference between the regions of interest using different heat sources. Active thermography has been frequently applied for NDT of aerospace components [20] [83].

Fig. 22- IRT of aircraft fuselage and its 3D view of thermal data [80]

q. X-ray inspection

X-ray inspections of composites are performed like those on metal structures. Images are based on material density. There are three x-ray imaging system computed tomography (CT), fluoroscopy and radiography. X-ray also used to detect voids presented in bonded joints. X-rays passes as penetrating radiation through an object, and recording the emerging radiation on a film, a two dimensional picture of the differences in thickness or density of the object can be obtained. Hence, flaws in the object can be detected. A lamination can, therefore, be difficult to detect by radiography. Cracks parallel to the beam, porosity, slag inclusions and root defects show very well. The industrial radiography uses two sources of penetrating radiation [84] [85] [86] [87] [88].

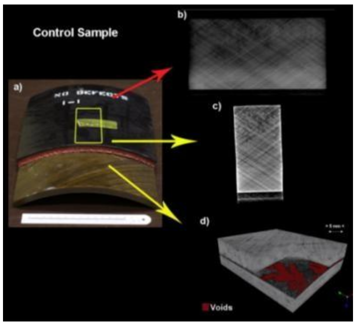


Fig. 23- X-ray imaging inspection of fiberglass reinforced by epoxy composites [89]

Digital X-ray system has revolutionized inspection of X-rays. Details in thin and thick regions of the inspection item become visible while the item is in motion and without constant adjustment of the X-ray parameters. We can detect voids, gas pores, porosity, microporsity, areas of localized porosity and cracks [90] [91].

r. Acoustic Emission Testing

Acoustic Emission (AE) is an effective method of imperfection analysis. This mechanical vibration is generated by material defects such as matrix micro-cracking, fiber-matrix debonding, localized delamination, or fiberpullout and breakage. 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 piezoelectrics [34].

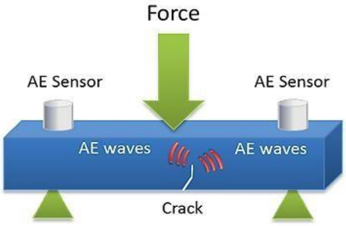


Fig. 24 - Acoustic emission test

A traditional NDI method for composite components is acoustic testing (also known as tap-testing), during which a testing hammer lightly taps the component surface to induce an acoustic response from the structure [92].

s. Acousto-Ultrasonic Testing

Acousto-Ultrasonic is a combination method of acoustic and ultrasonic testing that is used specifically to determine the severity of internal imperfections and inhomogeneity in a composite. In non-destructive testing, the acoustic/ultrasonic class of testing has great potential based on optimal economy, flexibility, and sensitivity. It is a 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 [93].

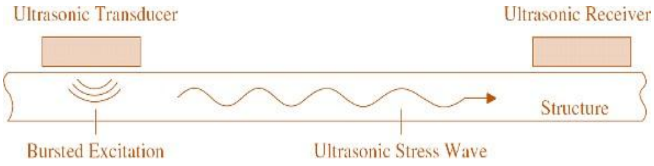


Fig. 25- Schematics of Acousto-ultrasonic technique

The development of an Acousto-Ultrasonic Inspection system which utilizes oblique incidence low frequency waves. The name Acousto-Ultrasonics (AU) is derived from a combination of Acoustic-emission monitoring and Ultrasonic characterization. Acousto-Ultrasonics is useful for the inspection of components that have repeatable shapes [94] [95].

Shearography Testing

Shearography testing is a laser optical method commonly known as Laser Shearography (LS). 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. The shearography is less susceptible to noise than many other types of non-destructive testing. Shearography when applied in the aerospace industry offers several potential advantages including high speed and real time monitoring of large composite panels and it allows less skilled users to be able to inspect and determine the usability of a part without extensive training [34][96][97]. 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 [34].

Loading is needed to induce some deformation or alter the deformation of the surface of the sample. Loading systems that are frequently used in shearography include vacuum shearography, thermal pulse shearography, pressure shearography and vibration (acoustic) shearography [80] [98] [99]. Vacuum shearography has proven to be highly effective for imaging fibre debonding in CFRP laminates [100]. Effective in aluminium and aluminium honeycomb panels as well as in a composite element panel of the tail unit of a helicopter [101] [102]. It is also effective in delaminations, core damage and core splice-joint separations [103].

Fig. 26- Shearography (LTI) Image in aviation [104]

In situations where the test object is in motion or vibrating, or the applied strain is continually varying, a pulsed laser can be used to effectively freeze the motion of the object. The pulsed shearography system built by researcher is shown below. Images collected by the four camera lenses are transported to the shearing interferometer by fibre-optic imaging bundles and are spatially multiplexed onto the four quadrants of a CCD camera [105].

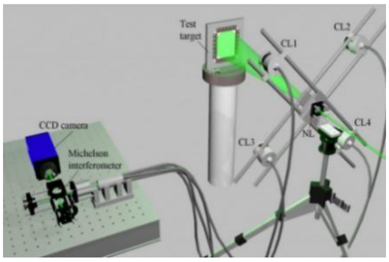


Fig. 27-The multiple-observation-direction, pulsed laser shearography system incorporating fibre-optic imaging bundles.

CL = camera lens, NL = negative lens.

t. Moisture Detector

A moisture meter can be used to detect water in sandwich honeycomb structures and it measures the RF power loss caused by the presence of water. The moisture meter is often used to detect moisture in nose radomes [106]. There are researches in a wide variety of moisture induced behaviour is becoming popular like coefficients of thermal expansion (CTE) and coefficient moisture expansion (CME). They are common design parameters for polymeric matrix based fiber reinforced composites [107].

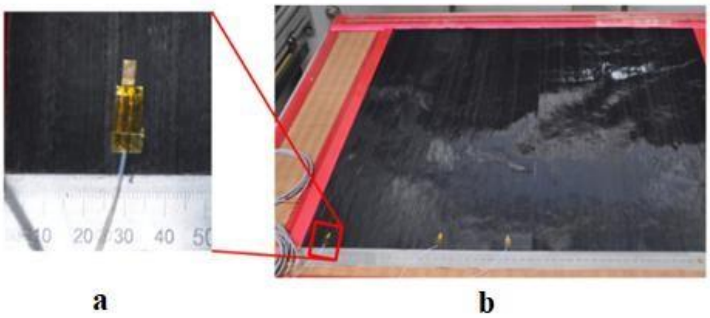


Fig. 28- (a) Moisture sensor (b) Carbon fiber prepreg plate with sensors during fabrication

CFRPs are exposed to different levels of moisture, which can diffuse in the composite and it absorb nearly no water compared to the matrix material which influence the moisture diffusion [108] [109]. There are different apparatus employed for moisture detection purposes [109].

Fig. 29- Cure monitor type M50 universal moisture detector

u. Self Heating based Vibrothermography (SHVT)

The self-heating based vibrothermography (SHVT) is a new non-destructive testing method dedicated for testing of polymer matrix composite structures, where the excitation is performed by externally applied mechanical vibrations in a low frequency range. Vibrothermography is a type of IR thermography methods in which ultrasound excitations are used to produce thermal gradient in the material as shown in the figure below [110] [111] [112] [113].

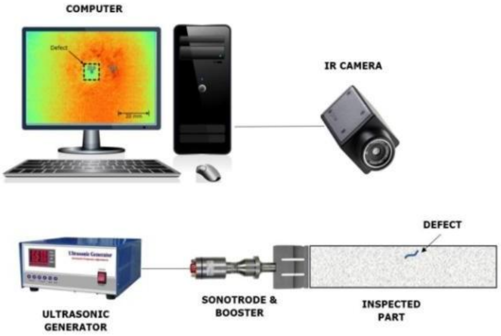


Fig. 30- Vibrothermography with ultrasonic thermal excitation

v. X-ray computed tomography (XCT)

X-ray computed tomography (XCT) or sometimes called as computed tomography (CT) is a technique which allows reconstructing the 3D internal structure of objects non-destructively without any prior preparation, by acquiring radiographic projections from many different viewing angles from 0 to 180 degrees. Each of the recordings is fed into a computer [114].

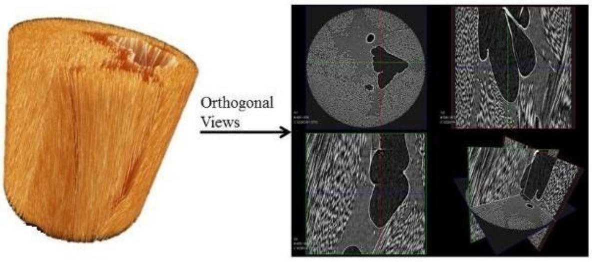


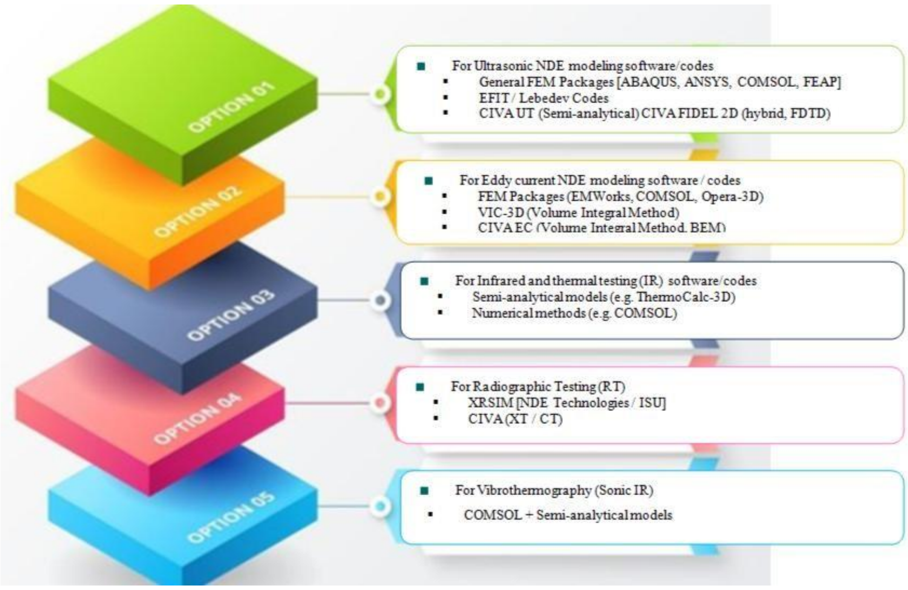
Fig. 31-3D X-Ray Computed Tomography of an As-Manufactured Composite Sample Showing Defects [115]

CT provides an excellent imaging technique to characterise the size and volumetric details to a high accuracy and in three dimensions which is particularly useful for NDT of aerospace composites where inspecting the structural integrity of the components (i.e. hidden and complex geometries) is critical [116][117].

9. Discussion

New composite materials development initiate manufacturers keep looking for new ways to inspect them for defects. Aerospace crack detection is more complex with limited accessibility has a lot of tasks to identify faults in local areas where fastener are in place and presence of multiple signals. Currently some of the new instruments are capable of using the “Cloud”. Cloud technology allows the inspector to upload inspection information to a secure site and others from different locations to access inspection results and to evaluate results or even help engineer a repair. There growing tools which assist in modeling NDT with a part under test for probable defect to facilitate effective testing.

Modeling has been a part of NDT since its earliest applications. It is defined as any tool that assists in the understanding NDT method and its application to a test piece. It has been used for several of the common NDT methods. The modeling methodologies are grouped into three general categories such as simple geometric, mathematic computations and visualization [120] [121]. In order to solve NDT models, we need NDT modeling using simulation tools and upgrade know-how on this software. The benefits of modeling are to perform simulated parametric studies like Design of Experiment (DOE) to reduce experimentation and improve performance. In addition to this used to evaluate the probability of detection (POD) using model-assisted POD (MAPOD) approach. All NDT models have errors but they are useful for inspection and to upgrade with developed skill. Some software required for different NDT methods are listed below [122];



- For Ultrasonic NDE modeling software/codes
    - General FEM Packages [ABAQUS, ANSYS, COMSOL, FEAP]
    - EFIT / Lebedev Codes
    - CIVA UT (Semi-analytical) CIVA FIDEL 2D (hybrid, FDTD)
- For Eddy current NDE modeling software / codes
    - FEM Packages (EMWorks, COMSOL, Opera-3D)
    - VIC-3D (Volume Integral Method)
    - CIVA EC (Volume Integral Method, BEM)
- For Infrared and thermal testing (IR) software/codes
    - Semi-analytical models (e.g. ThermoCalc-3D)
    - Numerical methods (e.g. COMSOL)
- For Radiographic Testing (RT)
    - XRSIM [NDE Technologies / ISU]
    - CIVA (XT / CT)
- For Vibrothermography (Sonic IR)
    - COMSOL + Semi-analytical models

Fig. 32- Summarized software required for different NDT methods (Discussion Result)

10. CONCLUSIONS

In reality it is not possible to totally avoid any types of composite defects. Defect identification, detection, inspection and taking remedies are some of the techniques required to avoid malfunctions of components or structures. In addition to this some defects also occur as a result of changes in material properties in time due to environmental factors. The defects may occur during manufacturing process, variations and deviations in pressure, temperature and material shelf life. The new composite material development results in a new defect techniques and the testing equipment used becomes more sophisticated. All-in-all, we prospect the future NDT technology will be on cloud technology, NDT modelling, testing softwares and codlings like POD (MAPOD), FEM packages, semi-analytical models, volume integral methods (VIM) with their modified versions to effectively facilitate NDT testing. The cloud technology allows the inspector to upload inspection information and others from different locations to access inspection results and this should be stored in accessible database to help Engineers facilitate repair results. The upgrading of DOE for different parameters and test objects used for different NDT techniques is more preferred technically.

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