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A Review of Nondestructive Testing Methods for Aerospace Composite Materials

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Abstract

Composite structures and materials have seen significant advancements in cost-effectiveness, product efficiency, and specific properties, leading to their extensive use in the aerospace industry. Reliable nondestructive testing (NDT) of composites is crucial for reducing maintenance costs and addressing safety concerns. This review provides a comprehensive analysis of various NDT methods, including Ultrasonic Testing, Acoustic Emission, Eddy Current Testing, Shearographic Testing, Infra-Red Thermography, and X-Ray Radiography. Each method's principles, instruments, and applications for defect detection and damage evaluation in composite materials are thoroughly examined. The paper highlights the strengths and limitations of these NDT techniques, emphasizing their roles in ensuring the structural integrity of aerospace composites. Ultrasonic Testing and Infra-Red Thermography are identified as flexible and cost-effective solutions, widely applied in both academic research and industrial sectors. Despite the challenges in providing a complete diagnostic of structural integrity, each NDT method offers unique advantages. Future research in NDT for composites will focus on integrating advanced data processing techniques, such as machine learning and deep learning, and developing smart inspection systems with high precision and rapid data processing capabilities.

Keywords: Non-Destructive Testing; Composite Material; Ultrasound; Shearography; Inspection

1 Introduction

The first aircraft developed by the Wright Brothers was constructed using natural composites such as wood. However, it was not until the invention of carbon fiber in 1964 that composites began to be extensively adopted as primary and secondary structural materials in aircraft [1]. The objective was to develop innovative, lightweight, stiff, and robust materials suitable for aircraft structures. Carbon Fiber Reinforced Polymers (CFRP), which consist of carbon fibers embedded within a polymer matrix, have become increasingly popular due to their exceptional strength-to-weight ratio, corrosion resistance, and the capability to fabricate components with complex geometries. These attributes have led to their widespread use, particularly in the aerospace industry [2]. Nevertheless, periodic testing is essential throughout the operational life of an aircraft to ensure the structural integrity and safety of its composite components. The proliferation of composite materials in aircraft parts such as wing skins, engine covers, and fuselages has introduced unforeseen challenges. For example, T-shaped stringer elements are utilized to reinforce the CFRP shells of aircraft [3]. These stringers require a secondary polymerization process, as they are partially embedded within the aircraft's CFRP shell [4]. Improper polymerization conditions can lead to crack initiation in these stringers. Another significant challenge is the automated fiber placement technique, which involves the robotic layering of pre-impregnated fibers on a composite panel. This method can introduce defects such as gaps, laps, and twists [5].

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Furthermore, hybrid materials combining aluminum alloys and CFRP are now employed in aircraft components like nacelles, wing boxes, and fuselages due to their superior fatigue life, impact resistance, and residual strength properties [6]. The complexity of these components, due to their numerous interfaces, complicated geometries, and diverse elastic properties, makes them difficult to inspect. Additionally, components are often replaced or repaired to extend the lifespan of aging aircraft when damage is minor. A method involving the application of composite patches has been shown to reduce operating costs. Moreover, composites can develop internal defects during manufacturing and throughout their service life. Impacts are a common cause of in-service defects [7, 8]. Even low-energy impacts can result in Barely Visible Impact Damage (BVID), which often leads to a complex network of matrix cracking and delamination internally or on the reverse side without altering the structure's exterior surface [9–11, 6]. Such damage poses a significant risk as it is not visually detectable and can be challenging to identify during routine inspections [12].Other internal defect mechanisms, such as porosity, matrix cracking, delaminations, and inclusions, may also contribute to the failure of composite structures in addition to impact-induced damages [13, 8]. Numerous Non-Destructive Testing (NDT) methods have been developed for diagnostic applications in aerospace composites. This paper reviews advancements in the field, critically evaluating the advantages and disadvantages of each method. In particular, it addresses innovative NDT systems that hold promise for overcoming the challenges associated with damage characterization and detection in composite laminates. These challenges include high aspect ratios, complex geometry, and limited access due to varying elastic properties. The application of smart inspection techniques is proposed to mitigate these difficulties. As outlined in Table 1, various Non-Destructive Testing (NDT) techniques offer specific capabilities and face particular limitations that are critical in their application to aerospace composites.

Table 1: Comparison of Non-Destructive Testing (NDT) Techniques Highlighting Their Capabilities and Limitations in Aerospace Applications

NDT Techniques	Capabilities	Limitations
UT (Ultrasonic Testing)	Capable of identifying surface and subsurface anomalies.	Small anomalies smaller than the grain size may go unnoticed. Largely manual, heavily reliant on the expertise and experience of the operator. Signal misinterpretations can occur.
AE (Acoustic Emission)	Able to detect surface and subsurface flaws and provide details on the progression of the anomaly.	Extrinsic noises can lead to misinterpretations. Stress vibrations may be attenuated by the structure being tested.
ECT (Eddy Current Testing)	Effective in detecting defects in electrically conductive materials, including those that are coated, primarily on or near the surface.	Limited in assessing subsurface abnormalities in ferromagnetic materials. Restricted to the evaluation of elements with electrical conductivity.
ST (Shearography)	Efficient in examining disbands and Barely Visible Impact Damages (BVIS).	The material must be subjected to external stressors such as vacuum, pressure, vibration, or heat.
IRT (Infrared Thermography)	Capable of identifying impact-induced defects such as matrix microcracks, fiber breakage, and delamination.	Limited to near-surface defect imaging; effectiveness depends highly on defect depth and size.
X-Ray	Primarily used to identify cracks developing in a plane perpendicular to the beam direction and to detect mesoscale and macroscale damage in composite laminates.	Conventional X-rays have limited contrast for common radiographic defects in aerospace composites, restricting their effectiveness.

2 Ultrasonic Testing

As shown in Figure 1, ultrasonic testing (UT) is an acoustic inspection technique that utilizes the reflection and transmission of elastic waves within composite materials to identify defects. This method spans a broad frequency range from 20 kHz to 1 GHz, tailored to specific applications. The frequency range most commonly employed in industry for Non-Destructive Testing (NDT) varies between 0.5 and 10 MHz, although frequencies up to 100 MHz are utilized specifically for detecting matrix cracks [14]. UT employs several representation methods, namely A-scan, B-scan, C-scan, and D-scan [14]. The C-scan method is particularly effective for monitoring transmission losses caused by disbands and delaminations under both low-energy and high-energy impacts [15–17]. During ultrasonic inspections, the sound beam aligns with the axis of the reinforcement fibers, efficiently characterizing misalignments. Delaminations and debonding result in discrete reflections and transmission losses from specific material depths.

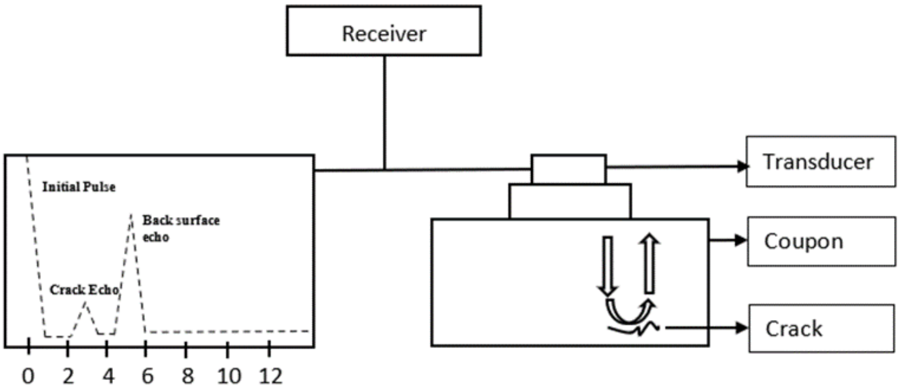

Figure 1: Schematic representation of Ultrasonic Testing [18]

Conversely, porosity leads to the scattering of ultrasonic waves rather than discrete reflections, thus causing transmission losses [8]. Studies have demonstrated that the attenuation of waves propagating perpendicular to CFRP plies can yield crucial information for assessing and interpreting interlaminar quality. Both time domain and frequency domain signal processing techniques are employed to distinguish defect echoes from the multiple reflections occurring within the composite. This aids in localizing defects and enhances the probability of detecting them [18–21]. To address the challenges associated with rough surfaces and non-parallel layers in multi-material joints, a novel signal post-processing method has been developed [22]. A common technique employed in such scenarios is ultrasonic immersion testing, which involves coupling sound waves through a liquid medium to inspect the material. This method is particularly effective where there is a significant mismatch between air and solid materials [23, 24]. Typical frequencies used depend on the composite layer being inspected. Frequencies as low as 0.5 MHz are used for inspecting composites up to 50 mm thick, such as glass/epoxy materials. Swept frequencies ranging from 0.4 to 1.0 MHz have been employed to inspect 25.4 mm thick Glass Fiber Reinforced Polymer (GFRP) composites. Additionally, frequencies between 100 kHz and 400 kHz using air-coupled ultrasound have proven effective for inspecting 48 mm thick glass fiber/polyester resin composites [25]. Despite its extensive applications, ultrasonic testing encounters several limitations. For instance, a shadow effect can obscure larger delaminations near the surface, as these large discontinuities reflect sound and reduce visibility below the delamination [15]. Furthermore, UT faces significant challenges in detecting discontinuities within non-homogeneous materials, such as popular honeycomb composites, due to the mismatch between air and solid materials [15].

3 Acoustic Emission

Acoustic Emission (AE) is an inspection method that utilizes the sound waves generated by a material under stress to detect flaws. These sound waves, known as stress waves, interact with any discontinuities within the material, altering their amplitude and speed. Inspectors detect these changes to locate flaws. The working principle of AE is illustrated in Figure 2 [26]. Figure 2 depicts pictographically the principle of AE. In composite materials, events such as fiber breakage, matrix cracking, and fiber misalignment lead to the sudden release of stress waves [27–29]. AE techniques utilize a series of piezoelectric interdigital transducers or sensors to capture these stress waves. These sensors convert the stress waves into electrical signals, which can then be analyzed by inspectors. AE is distinct because the stress waves are emitted by the material itself, not from an external source. This technique not only records displacement data but also monitors the dynamic processes within a composite material, tracking the evolution of specific defects and providing valuable information during fatigue testing [30].

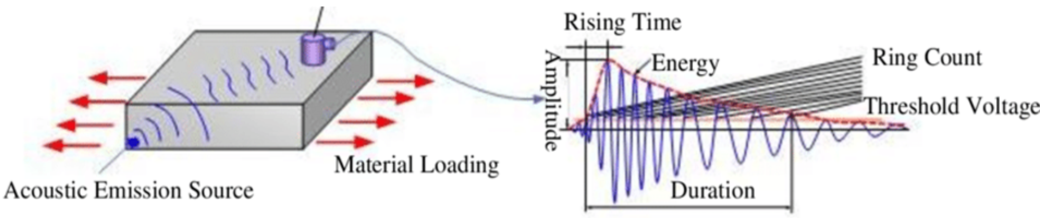

Figure 2: Principle of Acoustic Emission Testing [31]

Features extracted from the AE waveform, typically in the time range specified in studies [27, 31, 32], along with AE spectra [33], are crucial for Non-Destructive Testing of composite structures. These features can facilitate a classification system that assesses the current condition of the component. However, AE testing presents several challenges. Each AE event produces a unique stress wave that cannot be halted or replicated. For example, the slow growth of a crack might generate a weak signal, whereas a rapid expansion of a similar crack could produce a more pronounced, albeit temporary, signal [34]. The data collected during AE testing can vary, with amplitude signals being the most common.

The range of ultrasound frequencies used in AE spans from 20 kHz to 1 MHz. Processing and analyzing this data requires specific expertise and is time-consuming. Overlaps in the amplitude distributions can also complicate the correlation with specific damage mechanisms. To address these challenges, researchers have explored multiple parameters to enhance damage analysis, such as the duration or frequency of amplitude signals [35, 36], cumulated event count [37, 38], and energy [39]. Additionally, microscopy is often used to confirm damage modes and ensure accurate analysis. Several ASTM standards govern the use of AE in testing composite materials: ASTM E1067 for examining glass fiber-reinforced plastic tanks/vessels under a maximum internal pressure of 1.73 MPa; ASTM E1118 for composite pipes under pressures up to 35 MPa; ASTM E2191 for filament wound composite pressure vessels tested up to 68.9 MPa; ASTM E2076 for composite fan blades; and ASTM E2661 for materials containing continuous high modulus fibers greater than 20 MPa, such as plate-like and flat composite structures in aerospace applications [40].

4 Eddy Current Testing (ECT)

Eddy current testing (ECT) is an electromagnetic testing method that utilizes electromagnetic induction to inspect surface and sub-surface flaws in composite materials. Recent studies have demonstrated that eddy currents can be employed to review conductive composite materials such as Carbon Fiber Reinforced Plastics (CFRP) and metal matrix composites. ECT is classified into two types: pulsed ECT and remote ECT. Pulsed ECT is utilized to detect flaws in conductive materials. It has been shown to be effective for inspecting conductive composite materials like metal-matrix composites and CFRP [6]. Eddy currents are particularly well-suited for detecting low-energy impact damage, thermal damage, fiber damage with or without matrix cracking, and other types of damage affecting the fibers in the sample material. In CFRPs, ECT measurements specifically respond to carbon fibers [41–43]. The principle of ECT is based on the fluctuation of the magnetic field caused by eddy currents. Figure 3 [44] illustrates a typical ECT set-up, which consists of two circuits: a primary and a secondary circuit. In this set-up, the primary circuit is connected to an AC supply, establishing a primary fluctuating magnetic field that induces eddy currents in the experimental object. These eddy currents generate a secondary magnetic field that interferes with the primary magnetic field, thereby impacting the current flowing through the coil. Changes in the eddy currents alter the current configuration caused by the secondary magnetic field, consequently modifying the primary current. This variation results in a change in the impedance reading, indicating a discontinuity.

ECT employs both high and low frequencies, each generating different fields. The High-Frequency Eddy Current Technique (HFECT) was developed to visualize fiber orientation, fiber fraction changes, resin-rich regions, delamination, and impact damage in CFRP composites [45]. HFECT is better suited for less conductive materials. When high frequencies, such as 50 MHz or above, are used, only near-surface defects can be described due to limited penetration depth to the top few plies below the sample surface [41]. Conversely, low-frequency ECT is more commonly used for sandwich structures, allowing for a higher evaluation of the sample material's integrity at lower frequencies. The development of a high-precision low-frequency ECT up to 250 kHz enabled the identification and visualization of several defects, including fiber orientation, misaligned fiber bundles, cracks, delamination, and impact damage in scanned images [46].

Despite its capabilities, ECT has limitations in non-destructive testing for detecting surface and sub-surface defects in CFRPs due to its limited penetration depth. Interpreting measured signals can be challenging, as distinguishing interlaminar fractures from delamination can be difficult. This method is applicable only to composites made of conductive fibers, such as carbon fiber, and is often modified to work with less conductive structures [15]. The lift-off effect, caused by variations in the distance between the probe and the test sample, as well as the need to consider the surface status, refers to changes in the mutual inductance between the excitation coil and the test sample [47].

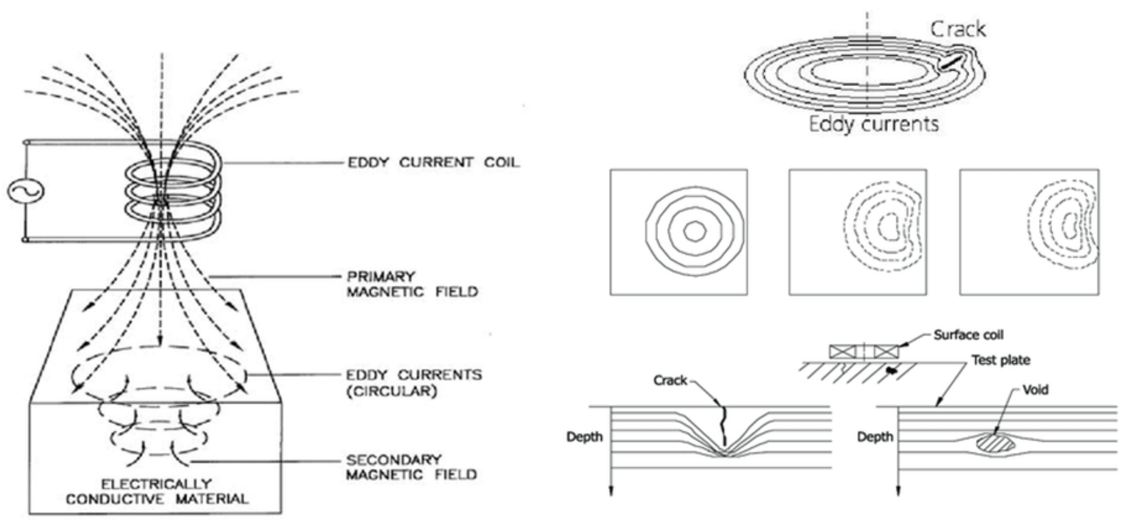

Figure 3: Schematic diagrams of Eddy Current Testing (ECT) set-ups showing primary and secondary magnetic fields, eddy currents, and typical crack detection scenarios [44].

5 Shearographic Testing (ST)

Shearography is a laser-based optical technique [48]. To introduce image shearing in digital shearography, a shearing device must be placed in front of the camera. This setup allows light reflected from two distinct object points to interfere at a single point in the image plane [49]. Various shearing instruments, including an optical wedge or biprism, a Mach-Zehnder interferometer [50], and an updated Michelson interferometer, have been used in digital shearography evaluations. The modified Michelson interferometer is the most popular shearing device due to its simple structure and ease of adjusting the shearing amount and orientation.

The conventional shearographic configuration in Figure 4 [49] produces interference at point P and determines the shearing amount using a modified Michelson interferometer. By slightly moving mirror 1, the shearing effect can be achieved. Point P on the sensor plane can then receive light waves from locations P1 and P2 on the object's surface. A speckle pattern, also known as a speckle interferogram, is produced when these light pulses collide, and the resulting pattern is recorded by a CCD camera and stored in the computer. Further improvements can be achieved using a loading system and quantitative evaluation methods.

There are four shearographic methods that utilize a loading system to inspect composite materials: Pressure Shearography, Heat Pulse Shearography, Vibration (Acoustic) Shearography, and Vacuum Shearography. Shearography is widely adopted in aeronautics for evaluating composite parts. When used in the aerospace sector, Shearography offers several advantages, such as high speed and real-time monitoring of large composite panels [51, 52]. Due to these benefits, Shearography is currently used for Non-Destructive Testing (NDT) on various aircraft, including the NASA space shuttle, the F-22, the F-35 JSF, the Airbus, the Cessna Citation X, and the Airbus [53].

Shearography is primarily employed to detect debonding or the initiation of delamination, as stress concentrations around a particular defect intensify the failure risk of composites [54–59]. However, Shearography has significant disadvantages, such as the difficulty in characterizing fiber breakage, matrix cracking, or matrix/fiber debonding (i.e., microscopic to mesoscopic damage mechanisms). Additionally, its sensitivity to environmental disturbances makes it challenging to apply in industrial operations [60].

To help identify specific defects, Shearography is sometimes combined with other non-destructive evaluation methods [61]. Utilizing double pulse laser illumination (spatial stage modulation) and stroboscopic laser (temporal stage modulation) can also enhance damage localization in Shearography [62]. Both excitation techniques are employed to detect delaminations; however, the latter method yields better results due to noise reduction in the maps of the temporal phase modulation. Research indicates that fuzzy neural analysis can significantly improve the ability to identify delamination in composite materials [63].

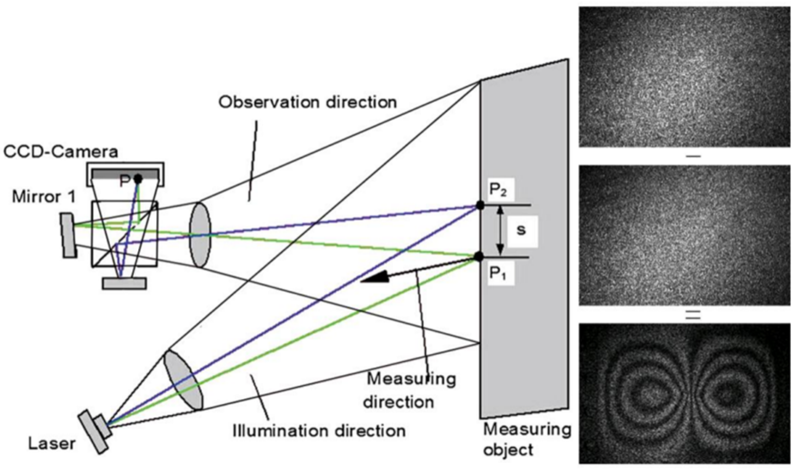

Figure 4: Schematic diagrams of Shearographic Testing (ST) set-ups showing image shearing using a modified Michelson interferometer [49].

6 Infra-Red Thermography (IRT)

Infra-Red Thermography (IRT) is a technique that uses thermal distributions to map and measure infrared energy emissions from an object. Infrared energy, which is electromagnetic radiation with longer wavelengths than visible light, is emitted by every object with a temperature above absolute zero [64]. Over the past few decades, IRT has rapidly advanced with improvements in infrared cameras, data acquisition, and processing methodologies. It offers capabilities such as non-contact, non-invasive, real-time measurement, high resolution, and the ability to cover large areas [65].

In IRT testing, a thermal gradient is produced due to varying emissivity coefficients when thermal energy diffuses through an object and encounters material defects such as porosity, matrix cracking, delaminations, and inclusions. This thermal gradient can be used to assess the damage [66]. A surface temperature map of the structure under examination is obtained by analyzing the thermal output of the material in the infrared electromagnetic band of the employed detector (infrared camera), as shown in Figure 5 [67]. Consequently, it is feasible to identify flaws in composites, especially if their thermal properties differ significantly from those of the base material.

IRT-based Non-Destructive Testing (NDT) has been widely used in both Boeing and Airbus for structural health monitoring to ensure the functionality of their composite products. NASA has utilized IRT for many years to examine manned flight vehicles during orbit inspection [68]. Numerous researchers have also explored the use of IRT to quickly examine large aerospace components, including jet engines, spacecraft parts and their subsystems, and aircraft primary and secondary structures [69–72]. Current field research is investigating the development of robotized line scan thermography methods to inspect large composite structures [71, 73].

IRT is typically classified into two types: "passive" and "active" thermography [74]. In passive thermography (PT), thermal radiation is directly emitted from the test body's surfaces under ambient conditions and then observed. In active thermography (AT), a heating or cooling flow is generated and propagated into the test object to reveal internal structures. Thermal responses in accordance with the Stefan-Boltzmann law are then detected and documented. Recent advancements in signal processing techniques and equipment have made the AT method more practical and efficient than the traditional PT strategy [75, 76].

Active IRT is generally divided into optically stimulated thermography [77], ultrasonic stimulated thermography [77–79], eddy current stimulated thermography [80], and metal-based thermography, depending on the external heat source used [81]. The most frequently used setup in the IRT of aerospace structures is optically stimulated thermography. Pulsed or transient thermography is a popular optical technique for aerospace applications. Research has shown that local material non-uniformities, which cause small variations in thermal energy, can prevent thermography from accurately measuring the entire extent of the delaminated zone [82]. Additionally, it has been documented that the temperature contrast on composite laminates diminishes as the orientation angles between adjacent layers become more varied [83]. As a result, cross-ply or multi-angle ply laminates are more challenging to examine for flaws than unidirectional laminates, particularly when thick laminates made from CFRP are reinforced with high thermal conductivity fibers [84].

While higher aspect ratios are anticipated in aerospace applications, the aspect ratio of the defects at the detection limit is between two and three [85]. Therefore, IRT is restricted to near-surface damage identification with low aspect ratios in both impact-induced and machining-induced defects. The technique is not particularly sensitive to in-depth damage and microcracks with sizes varying from ten microns to a few millimeters [70, 86].

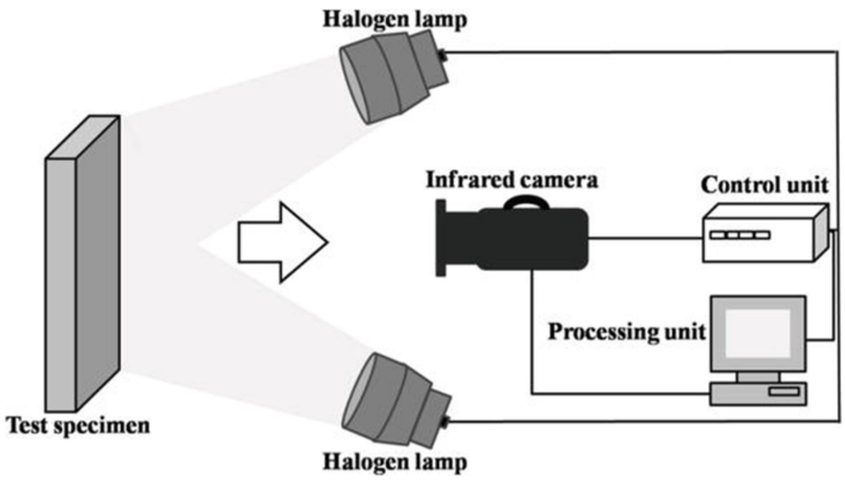

Figure 5: Schematic diagrams of Infra-Red Thermography (IRT) showing thermal distributions and defect detection [67].

7 X-Ray Radiography

X-ray radiography is based on the characteristics of radiation, which are waves or electrons emitted from a source that travel through a medium. The Beer-Lambert rule explains how X-rays of a particular energy interact with matter. In X-ray radiography, short wavelength electromagnetic radiations (high-energy X-ray photons) penetrate different materials to produce a shadowgraph image of the test object. The attenuation of X-ray radiation as it travels through the object toward an X-ray detector is affected by the test object's density, path length, and level of X-ray absorption. Conventional radiography is widely used to identify non-planar defects in aerospace composites, such as solid inclusions, fiber misalignment, and matrix cracking, provided the orientation of these defects is not perpendicular to the X-ray beam [61, 87].

Conventional radiography uses penetrating X-rays to examine the internal structure of composite materials. A 2D image, known as an X-radiograph, is created by projecting the attenuated beam onto an X-ray-sensitive film or a digital scanner. The X-radiograph displays the attenuation of X-rays due to variations in electron density along the beam path. Radiography can detect translaminar cracks and delamination, as well as meso- and macroscale damage to composite laminates [88]. However, it primarily enables the detection of cracks developing in a plane perpendicular to the path of the beam [89]. Figure 6 illustrates the principles of gamma radiography [90].

For thin components (less than 5 mm in thickness), low-voltage radiography is used, while thicker parts are better suited for gamma-ray radiography. When defects overlap and are superimposed onto a planar surface, they cannot be separated, and depth quantification is not feasible without multiple radiographs. Applying a dye penetrant before inspection can enhance the ability to identify microscale damage mechanisms, such as matrix cracking, if the cracks are linked to the material's surface. Guild et al. [91] used penetrant-enhanced radiography to track the initiation and propagation of matrix cracking in pre-notched carbon/epoxy laminates subjected to tensile fatigue loading. Additionally, Atas et al. [92] identified and monitored the development of subcritical damage processes in CFRP joints.

More sophisticated methods, such as X-ray Computed Tomography (XCT or CT) and X-ray Computed Laminography (XCL or CL), have been developed from traditional X-radiography to visualize interior features within components and obtain digital data on their three-dimensional geometries. These techniques shift the scale of Non-Destructive Testing (NDT) from macroscopic to microscopic, showing promise for resolving the current challenges in monitoring highly sensitive aerospace materials.

X-ray tomography (µCT) differs from traditional radiography methods in that it relies on the computerized reconstruction of a series of radiographs taken by rotating the sample at controlled angular steps. The resulting data is coded in greyscale and corresponds to 3D maps of elementary basic elements (referred to as voxels). The differences in the linear attenuation coefficients of the material's constituents (such as matrix, fiber, and porosity), where elements with high atomic numbers are the most absorbent and elements with low atomic numbers or low density, such as air cavities, are the least absorbent, are reflected in the grey level contrasts within the 3D images produced by standard laboratory µCT equipment. Consequently, if the difference between the linear absorption coefficients is large enough, it is possible to distinguish between the various components of the composite and locate the damage.

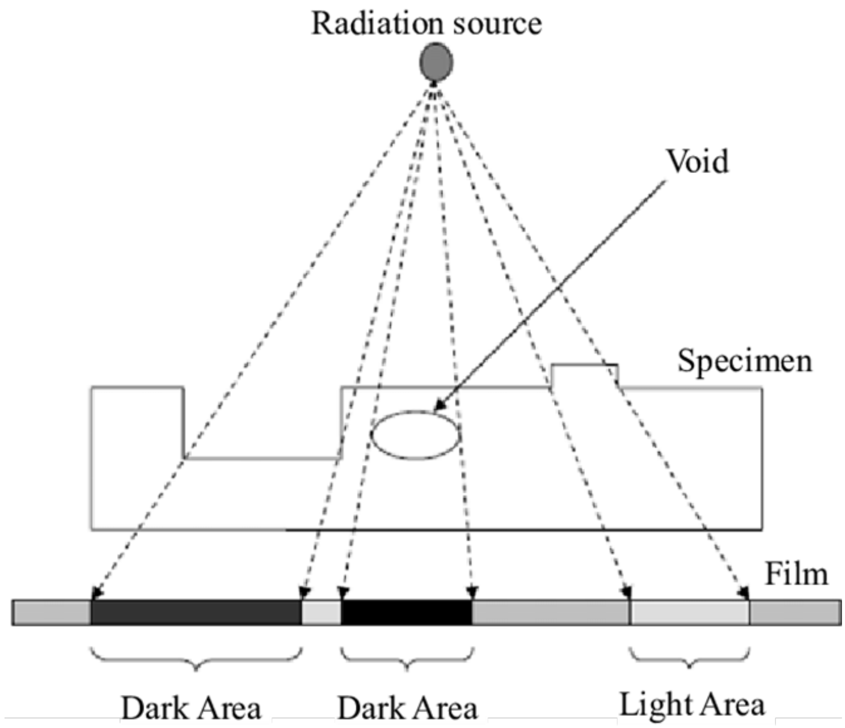

Figure 6: Schematic diagrams illustrating the principles of gamma radiography [90].

8 Discussion

The advancements in nondestructive testing (NDT) techniques have significantly enhanced the ability to monitor and evaluate composite materials. This review provides a comprehensive analysis of various NDT methods, highlighting their unique strengths, limitations, and applications. The novelty of this review lies in the comparative analysis and integration of advanced data processing techniques, such as machine learning and deep learning, with traditional NDT methods. One of the most significant advancements in NDT is the incorporation of machine learning (ML) and deep learning (DL) algorithms. These technologies can process large datasets, identify patterns, and predict outcomes with high accuracy. Integrating ML and DL with NDT methods enhances defect detection, characterization, and evaluation. For instance, algorithms can be trained to recognize specific defect signatures in ultrasonic testing (UT) or interpret complex thermal patterns in infrared thermography (IRT). This capability reduces human error and increases the reliability of NDT evaluations. The integration of multiple NDT techniques addresses the limitations of individual methods, providing a more comprehensive assessment of composite materials. For example, combining X-ray radiography with ultrasonic testing allows for detailed internal and surface defect analysis. The synergy of different NDT techniques enables the detection of a broader range of defects, from surface cracks to deep-seated flaws, thus ensuring more robust structural health monitoring. The development of smart materials with embedded sensors is another novel aspect discussed in this review. These materials can continuously monitor their own condition and provide real-time data on stress, strain, and other critical parameters. Embedded sensors enhance the capabilities of traditional NDT methods by offering continuous and in-situ monitoring, leading to more accurate and timely assessments of material health. Technological advancements have also led to the creation of portable and handheld NDT devices. These innovations allow for in-field inspections, providing real-time data that can be crucial for immediate decision-making. Portable devices, coupled with advanced data processing techniques, can perform complex analyses on-site, reducing the need for laboratory-based testing and speeding up the inspection process. Despite these advancements, several challenges remain. The complexity of interpreting data from integrated NDT techniques, the need for high-resolution imaging, and the development of cost-effective solutions are ongoing research areas. Future directions include the further integration of AI and machine learning, the development of more sophisticated sensors, and the creation of standardized protocols for multi-NDT applications. These advancements will enhance the accuracy, efficiency, and applicability of NDT methods in various industries.

9 Conclusion

Nondestructive testing (NDT) techniques are essential resources for testing and assessment at various points in a composite product's lifecycle. While every technique has potential, only a few can fully diagnose potential flaws and the evolution of damage in a composite system. The strengths and weaknesses of the reviewed NDT methods are shown in Table 1. Selecting the appropriate NDT method can be challenging, yet it is crucial for preserving the structural integrity of composite materials and structures. The applications and capabilities of each reviewed NDT technique for identifying and evaluating defects and damage evolution in composite materials/structures are summarized.

As the volume and structural complexity of composite parts increase, the use of multi-NDT techniques is becoming more common for maintaining structural integrity, and research in this area is expanding significantly. The initial development and application of various NDT techniques were driven by demands in the aerospace industries, which have rapidly expanded to other fields. The main techniques used in the composite industries are X-ray radiography, acoustic emission, ultrasonic testing, infrared thermography, shearography, eddy current testing, and thermography. NDT techniques based on ultrasound, IRT, and AE are adaptable and cost-effective solutions that have been used extensively in many industrial fields and academic research.

GHz waves can penetrate opaque materials and detect internal defects and damage. Innovation and technological advances in small and portable NDT devices will continue to play a significant role in future NDT equipment, offering in-service inspections to aid the decision-making process. Although X-rays are highly effective NDT instruments with high resolution, the method is more expensive than other non-destructive testing approaches due to its reliance on ionizing radiation. The accessibility and cost of radiation facilities are further hampered by their limited locations and availability.

When used in non-destructive testing for identifying surface and subsurface defects in CFRPs, ECT has several drawbacks. For instance, it can be challenging to differentiate between interlaminar fractures and delamination from measured signals. This technique is limited to composite materials composed of conductive fibers. Considering the complex nature of flaws and damage identification in composites, the future development of NDT techniques will increasingly depend on smart inspection systems with high precision and effectiveness in data processing. Machine learning and deep learning show tremendous potential for the NDT evaluation of composite materials. Artificial intelligence–based systems allow quick decision-making without human interference. Numerous automated diagnostics for various NDT techniques have been developed, using algorithms for the automatic identification and recognition of flaws or damage, or by coding artificial neural networks.

NDT techniques have made significant progress, but much more work is required to provide quick and inexpensive systems for both data processing and equipment to support their practical application in industry.

Declaration of Competing Interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

Md. Shaishab Ahmed Shetu: Conceptualization, Investigation, Data curation, Writing - original draft, review and editing.

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