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Review Article

An Overview of Non-Destructive Testing for Composites Materials

Mete Han Boztepe[1*]
[1]Department of Mechanical Engineering, Sırnak University, Sırnak, Türkiye.
**metehanboztepe@sirnak.edu.tr*

Abstract

Non-Destructive Testing (NDT) methods are essential for assessing the integrity and reliability of composite materials without causing damage. Composite materials are widely used in industries such as aerospace, automotive, and civil engineering. Therefore, the demand for advanced inspection techniques has increased. This study aims to compare the effectiveness of existing Non-Destructive testing (NDT) methods on composite materials and determine the most suitable techniques. Also, this article provides an overview of various NDT methods, including Visual Testing (VT) and Visual Inspection (VI), ultrasonic testing (UT), infrared thermography (IRT), and acoustic emission (AE). The advantages, limitations, and applications of these techniques are discussed. Their role in detecting defects such as delaminations, porosity, and fiber breakage observed in composite structures is highlighted.

Keywords: Composite materials, non-destructive testing, ultrasonic test, infrared thermography, acoustic emission.

Kompozit Malzemeler için Tahribatsız Muayeneye Genel Bakış

Özet

Tahribatsız Muayene (NDT) yöntemleri, hasara neden olmadan kompozit malzemelerin bütünlüğünü ve güvenilirliğini değerlendirmek için gereklidir. Kompozit malzemeler havacılık, otomotiv ve inşaat mühendisliği gibi endüstrilerde yaygın olarak kullanılmaktadır. Bu nedenle, gelişmiş muayene tekniklerine olan talep artmıştır. Bu çalışma, kompozit malzemeler üzerinde mevcut tahribatsız muayene (NDT) yöntemlerinin etkinliğini karşılaştırmayı ve en uygun teknikleri belirlemeyi amaçlamaktadır. Ayrıca bu makale, Görsel Muayene (VT) ve Görsel Muayene (VI), ultrasonik test (UT), kızılötesi termografi (IRT) ve akustik emisyon (AE) dahil olmak üzere çeşitli NDT yöntemlerine genel bir bakış sunmaktadır. Bu tekniklerin avantajları, sınırlamaları ve uygulamaları tartışılmaktadır. Kompozit yapılarda gözlemlenen delaminasyonlar, gözeneklilik ve lif kırılması gibi kusurları tespit etmedeki rolleri vurgulanmaktadır.

Anahtar Kelimeler: Kompozit malzemeler, tahribatsız muayene, ultrasonik test, kızılötesi termografi, akustik emisyon.

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1. INTRODUCTION

Composite materials are made up of two or more different materials, each of which adds superior properties to the final product. Composite materials are basically composed of a matrix and reinforcement. The matrix, a polymer, usually holds the fibers together to enhance the overall mechanical performance of the composite. This allows composites to outperform their components. Thanks to their high strength with low weight, they are used in many fields. Composite materials/structures have product efficiency, cost-effectiveness, and the development of unique specific properties (strength and modulus). It is widely used in aerospace, wind turbines, transportation, automotive, medical equipment and similar fields [1-4]. In the production of composite materials, unwanted materials or random porosity may occur. These unwanted defects adversely affect the structure and mechanical properties. These defects need to be uncovered to check the integrity of the composite. Various techniques can be used to detect such defects [5, 6].

Non-destructive testing (NDT) of composite materials can detect defects without affecting the integrity and mechanical properties of the materials. Various NDT methods have been developed to detect defects such as delaminations, voids, and fiber breakage, which are critical to ensure the reliability of composite structures used in aerospace, automotive, and civil engineering applications [4, 7]. Numerous techniques are used in non-destructive testing (NDT) of composite materials, including ultrasonic testing (UT), thermographic test (TT), infrared thermography test (IRT), radiographic test (RT), visual test (VT) or visual inspection (VI), acoustic emission test (AE), acoustic-ultrasonic (AU), shearography testing (ST), optical testing (OT), electromagnetic testing (ET), liquid penetrant testing (LPT), and magnetic particle testing (MPT) [8].

NDT is used to detect defects in nanocomposites. With this method, defects can be detected without affecting the performance of the inspected objects. The NDT technique can determine the shape, size, direction, and distribution of defects using various physical and chemical phenomena [9].

One of the most widely used NDT techniques is ultrasonic testing, which uses high-frequency sound waves to detect internal defects in composite materials. Ciecieląg et al. (2022) showed that ultrasonic testing in combination with repetition analysis effectively detects real defects in polymer composites. Furthermore, non-destructive testing allows the evaluation of the effect of moisture absorption on the mechanical properties of glass fiber-reinforced plastics [10]. Similarly, Acanfora et al. (2022) emphasized the importance of NDT methods for damage detection in composite materials. They stated that NDT methods are preferred due to the high costs of destructive testing [11].

The NDT technique may have limitations in some cases. Composite parts are frequently used in the aviation sector. They have extremely high aspect ratios such as aircraft wings and tails. Therefore, the NDT technique used must be able to examine large surfaces. NDT inspections of composite parts with complex geometries are difficult [12].

Infrared thermography (IRT) is another important NDT method widely applied to composite materials. This technique enables visualization of subsurface defects by capturing thermal radiation emitted from the surface of the composite. Liu et al. (2019) noted that IRT is particularly advantageous due to its fast inspection capabilities and ease of setup, making it suitable for large-area inspections [13]. Bale et al. (2014)used thermography to monitor damage propagation in glass fiber/epoxy composites by analyzing temperature changes on the material surface [14]. To test this method, Świderski & Pracht (2021) inserted artificial defects into a helmet made of aramid composite. The results confirmed the effectiveness of the NDT method used in these tests [15].

In addition to ultrasonic testing and thermography, shearography is another NDT method used for composite materials. This method provides full-field, non-contact measurements and can detect various defects, including delaminations and fiber breakage. This method is particularly used in thick composite structures [16]. Furthermore, the microwave non-destructive evaluation method (MWNDE) is a new technique that works in the electromagnetic spectrum to inspect dielectric structures and is used for composite inspection [17].

This study discusses some of the NDT methods used in composite materials. It categorizes them, discusses their advantages and limitations, and describes the NDT methods of composite materials.

2. CATEGORIZATION OF NDT TECHNIQUES

Composite materials are used in many engineering fields due to their high strength and low weight properties. Based on examinations of NDT methods, they can be categorized in different ways according to the applications and conditions of the test. NDT methods basically include contact and non-contact methods. Both methods have their specific applications in the testing and evaluation of composites. Most NDT techniques require good contact between the sensor and the composite surface under test to obtain reliable data. Contact methods include conventional ultrasonic testing, eddy current testing, magnetic testing, electromagnetic testing, and penetrant testing. Another way to speed up the data collection process is to eliminate the need for physical contact between the sensor and the structure under test. Non-contact methods include thermography, shearography, transmission ultrasonic, radiography testing, and visual inspection. Optical methods (e.g. thermography, holography, or shearography) are mostly non-contact. Table 1 shows contact and non-contact NDT methods [8].

Table 1. NDT methods for contact and non-contact categories

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

There are various methods of NDT technology. Their use depends on the structure, material, cost, and type of damage to be inspected. Each method has advantages and disadvantages. The classification of NDT methods according to defect types is given in Figure 1. For example, X-ray NDT is generally not suitable for detecting delamination defects, but delamination can be detected using ultrasonic or acoustic emission methods [18].

Defects	METHODS						
	X-ray	Ultrasonic	Penetrant	Magnetic Particle	Eddy Current	Thermography	Acoustic Emission
Porosity or Voids	✓	✓	⊙	⊙	⊙	⊙	✓
Delamination	⊙	✓	⊙	X	X	⊙	✓
Debonding	✓	✓	⊙	X	X	⊙	✓
Foreign Bodies	✓	✓	⊙	⊙	⊙	⊙	✓
Cracks	⊙	✓	⊙	✓	✓	⊙	✓
Surface	X	⊙	✓	✓	✓	✓	✓
Internal	✓	✓	X	⊙	⊙	⊙	✓
Limit	Orientation-dependent	Dead zone effect	Only open to surface defects	Ferromagnetic materials only	Conductive materials only	Small thickness	Lack of size and shape
Advantage	Inspection process is simple	Portable and good depth resolution	Suitable for mass-manufactured products	Rapid for complex surfaces	Suitable for hard-to-reach areas	Useful for quick response	Effective for active defects

Applicability→ suitable (✓); weak (*X*); limited (⊙).

Figure 1. The classification of NDT methods according to the defect

2.1 Visual Testing (VT) and Visual Inspection (VI)

Visual Testing (VT) and Visual Inspection (VI) are the most basic NDT methods used in many situations. This is because it can save both time and money by reducing the amount of other tests. One of the important advantages of visual inspection is that it is fast. Visual inspection does not require equipment, but this method has its disadvantages [8]. Inspection by visual method is highly dependent on the experience of the expert and the light conditions. Therefore, a more efficient and effective NDT method is highly demanded [19].

VT is an NDT method performed with professional equipment in accordance with certain standards. The VI technique is used for situations where simple visual inspection is sufficient and does not require detailed testing procedures. If critical defects in composite components need to be detected, VT is used. However, VI may be sufficient for general surface controls.

Visual Inspection (VI) is mainly used to detect superficial defects such as surface cracks and delaminations. However, it is not an effective method for detecting internal defects that may not be visible on the surface. For example, low-speed impacts can cause internal damage that is not easily detected by conventional visual methods [20]. Despite these limitations, more than 80% of inspections on large transport aircraft are performed using this method [21]

Visual inspection is one of the simple techniques often used in pipelines. The method is low-cost and fast. It sometimes provides enough information for decision-making. It is informative enough to eliminate the need for other advanced NDT methods. It is suitable for visual inspection, on-site inspection, in-service, and accessible pipelines. It is often used to diagnose visually obvious macro-scale defects such as leaks, surface cracks, and misaligned joints. Visual inspection is a contact-based technique that requires access to the pipeline itself and is only suitable for external defects such as cracks and porosity. During the process, site preparation is performed (such as pitting, target surface cleaning, etc.). A liquid paint (or paint spray) is then applied to the target pipe surface. The specialist can detect defects on the pipe surface with the naked eye or using an endoscope [22].

Various NDT techniques have been developed to overcome the disadvantages of VI. Infrared Thermography (IRT) and Electronic Speckle Pattern Interferometry (ESPI) are other methods used to detect defects in composite materials [23]. These techniques can identify subsurface defects that VI may miss. In addition, ultrasonic testing is used to detect impact damage in composite laminates and to measure the location and size of defects [24, 25].

Advanced techniques such as 3D scanning and digital image correlation (DIC) are being investigated to enhance visual inspection. These techniques allow real-time monitoring of composite structures, facilitating the detection of defects during manufacturing [26, 27]. Recent advances in artificial intelligence (AI) and machine learning have been applied to visual inspection techniques. AI-based algorithms can automate parts of visual inspection, increasing efficiency and accuracy while reducing the time and cost of manual inspections [28].

2.2 Ultrasonic Testing (UT)

Another most preferred method is ultrasonic testing. This is a form of inspection that uses the propagation of ultrasound waves inside materials, Figure 2. The analysis of reflections due to abnormalities in the internal structure allows the measurement of properties such as thickness or the depth of any defect. Although advanced ultrasonic tools provide 3D C-scan and cross-sectional B-scan to obtain sufficient information about a structure, quantifying and locating defects can be challenging and multiple tests may be necessary [18].

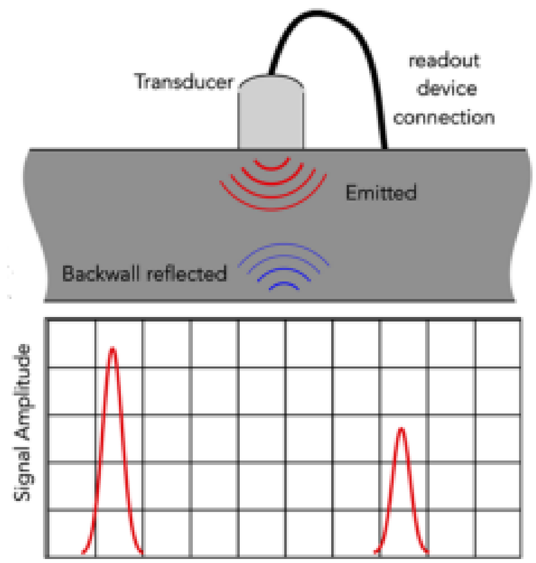

Figure 2. Schematic representation of the ultrasonic test method

Ultrasonic Testing (UT) is an important NDT method used especially in the aerospace industry. The basic principle of UT is to detect internal defects such as delaminations and disbonds that could compromise structural integrity. For this, it transmits high-frequency sound waves into the material [29, 30]. The accuracy and reliability of UT in sandwich composite materials are higher than other NDT methods such as X-ray or penetrant testing [31, 32].

Composite materials, including carbon fiber-reinforced plastics (CFRPs) and glass fiber-reinforced plastics (GFRPs), are susceptible to various defects throughout their production and service life. These defects can significantly affect the mechanical properties and overall performance of the materials [10, 33]. Therefore, these materials need to be continuously monitored and evaluated. It plays an important role, especially in sectors where safety is at the forefront of applications such as the aerospace and automotive industries [34]. Advances in ultrasonic techniques improve detection capabilities by increasing resolution and imaging quality. This facilitates the identification of defects that might otherwise go unnoticed [35].

The Ultrasonic Testing (UT) method consists of a transmitter and receiver circuit, a transducer tool, and imaging devices. By looking at the information carried by the signal, flaw size, orientation, and crack location can be determined. The advantages of ultrasonic testing include flaw detection capabilities, scanning speed, and good resolution. This makes it suitable for use in the field. The disadvantages are the skill required to scan the part accurately and the difficulty of setup. There are two different ultrasonic NDT methods used in different applications; the pulse echo and transmission approach. Both methods use high-frequency sound waves in the range of 1-50 MHz to detect defects within the material. In this method, testing is performed in three modes: transmission, reflection, and backscattering. Each of these uses a range of transducers, coupling agents, and frequencies [8].

Recent studies have shown that ultrasonic testing is applied in combination with thermography to provide a more comprehensive and reliable evaluation of composite materials. Thermography is another NDT technique. For example, the use of ultrasonic techniques with infrared thermography enables the effective detection of subsurface defects by visualizing the thermal responses associated with material anomalies [15]. Furthermore, the development of sophisticated signal processing techniques for ultrasonic data analysis has further enhanced the capabilities of UT in composite materials. These developments enable better interpretation of ultrasonic signals, allowing for more precise detection and localization of defects [35].

2.3 Infrared Thermography Testing (IRT)

The first studies on IRT were done on metal test specimens. It was not a suitable method for testing composite materials. However, nowadays it can detect many defects in composite materials including impact damage, delamination, rupture, etc. [5]. Thermography testing is a thermal imaging method. The thermal conductivity of a material can vary depending on the depth and size of the defect in it. Thermography inspection is often effective in the handling of thin parts. This is because it produces fewer heat fluctuations if the defects present are far below the surface of a part. Usually, deeper and smaller defects cannot be detected. A defect in the material, such as delamination or impact damage, causes a change in the thermal radiation of the area [8]. Infrared thermography (IRT) is one of the NDT methods and was developed to reveal defects in materials. This method is used to detect delaminations, cracks, and other subsurface defects that can compromise structural integrity. It uses thermal radiation emitted from the surface of materials to do this. The advantages of IRT include rapid inspection and the ability to examine large areas without direct contact with the material being tested [13].

Infrared Thermography uses a heat source and causes short thermal stress on the material. Thermal waves propagate on the surface of the sample. When these waves hit a different surface, the propagation is distorted and a thermal gradient is created. In this way, different emissivity coefficients are created and these are captured by an IR sensor. An InfraRed camera used in the setup allows the emissivity coefficient to be converted to temperature. Thermal two-dimensional mapping is created and inhomogeneous regions are detected [5]. When thermal energy diffuses through a material and reaches a crack, delamination, or pore, a thermal gradient is generated due to the different emissivity coefficients that can be used to interpret the damage. An infrared camera detects the heat emitted from the material, and this information is used to create a map showing the temperature differences on the surface of the structure, Figure 3. Infrared thermography can be used to find defects in composite materials, especially those with different thermal properties. NASA has been using this method to inspect spacecraft for years. Researchers are also using it to quickly inspect parts, engines, and turbines of aircraft and spacecraft. Research is still ongoing on thermography techniques that use automated scanning with robots to inspect large composite structures [12].

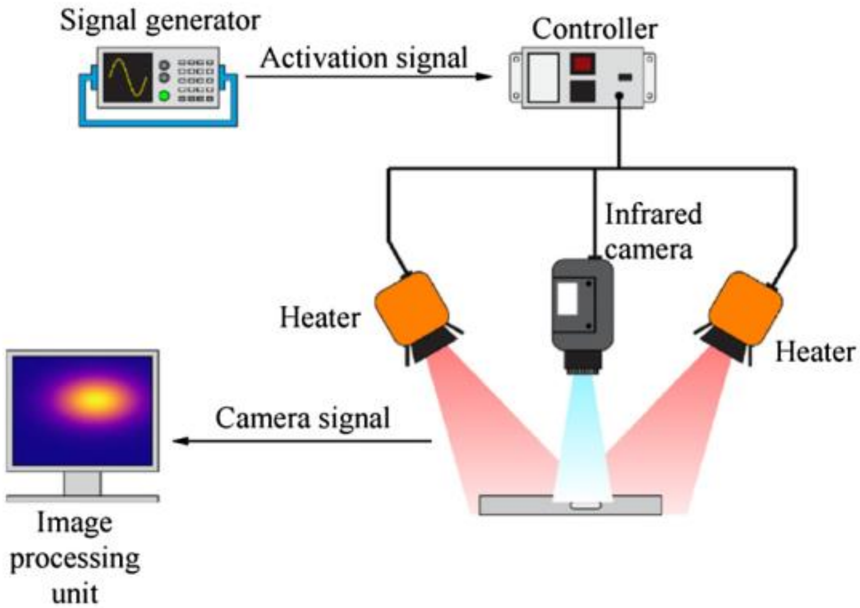

Figure 3. Schematic illustration of IRT

Infrared thermal imaging examination techniques are classified as active or passive. If an external energy source is used for imaging, it is called active IRT. If no external energy source or stimulus is used, it is called passive IRT [36]. Active infrared thermography, which uses an external heat source to excite the material, is effective at identifying various types of defects in composite materials. For instance, studies have shown that active IRT can successfully detect flat bottom holes (FBHs) and delaminations in carbon fiber-reinforced polymers (CFRP) [9, 37]. The effectiveness of the technique is further enhanced by advanced post-processing techniques that improve defect visualization and characterization [37]. The passive IRT technique can perform in situ analysis using the natural thermal emissions of the material. For example, this technique can be used to examine wind turbine blades without an external heating source [9].

The IRT technique is also used to detect complex defects and monitor the structural integrity of composite materials under various loading conditions. For example, studies have shown that IRT can detect fatigue damage and crack propagation in ceramic matrix composites. It can also provide insight into the remaining life of materials subjected to cyclic loads [38, 39]. This predictive capability is vital for industries such as aerospace, where the integrity of composite components is critical for safety and performance [39].

Moreover, the integration of IRT with other NDT methods such as acoustic emission (AE) has been investigated to improve detection capabilities. This new technique allows for a more comprehensive assessment of damage mechanisms in composite materials [39]. The versatility of IRT is used to monitor structural integrity and detect defects in critical components, so it is used in a variety of fields including civil engineering, aerospace, and automotive industries [40, 41].

2.4 Acoustic Emission (AE)

Acoustic Emission (AE) technology is an NDT method used to detect the integrity and damage mechanisms of composite materials. This technique is particularly used to detect internal damages that occur during mechanical loading, such as matrix cracking, fiber breakage, and delamination [42-44]. The AE method detects transient elastic waves generated by the rapid release of energy from localized sources within the material, allowing for continuous monitoring of damage progression [45].

One of the major challenges in applying AE to composite materials is their anisotropic nature, which makes the interpretation of AE signals difficult. To address this, Modal Acoustic Emission (MAE) was developed, which treats AE signals as mechanical waves propagating in the composite in various modes. This allows for more comprehensive insights into damage mechanisms. This approach improves the qualitative and quantitative analysis of AE data, making it particularly useful for thin composite structures under tensile stress [46]. Acoustic emission (AE) tests are not exactly repeatable due to the nature of the signal source. Each AE event is a different stress wave. For example, a slow crack growth will produce a weak AE signal, while a fast crack growth of the same size will produce a transient signal [12]. In the Acoustic Emission (AE) method, mechanical vibration is generated by material defects such as fiber-matrix separation, local delamination, or matrix microcracking in the material. The resulting stress waves propagate through the material and are detected by the sensitive piezoelectric [8].

Acoustic emission (AE) can be used to evaluate the burst pressure of composite pressure vessels. Wang et al. (2021) investigated the relationship between the damage behavior (matrix cracking, fiber/matrix separation, fiber breakage) of hydrogen storage pressure vessels using AE signals during hydrostatic burst tests with multi-stage loading. The burst test using acoustic and optical sensors can be used to obtain the actual burst pressure and damage behavior of composite vessels [47, 48]. The AE method is a reliable and real-time technique for early detection of transient stress waves in materials. Although this technique is quite sensitive to small changes in dynamic defects, it may not be as sensitive to static defects. AE is more suitable for electrical defects rather than mechanical defects. It may also have deviations in the size and orientation of the defects within the material [18].

The application of AE technology is also used in various types of composites, including carbon fiber reinforced polymers (CFRP) and glass fiber composites. Studies have shown that AE can effectively detect damage under different loading conditions, including low-velocity impacts and quasi-static tension tests [43, 44, 49]. For example, Mahdian et al. (2016) highlighted that the AE technique can detect multiple failure modes in laminated composites subjected to impact [44]. Similarly, the study by Fotouhi et al. (2015) highlighted the effectiveness of AE in detecting delamination growth in sandwich composites, demonstrating its superiority over conventional NDT methods [50].

The integration of advanced signal processing techniques, such as Fast Fourier Transform (FFT) and wavelet analysis, has further enhanced the capability of AE in identifying and characterizing damage mechanisms [51]. These methods allow for more detailed analysis of acoustic signals and facilitate the identification of specific failure modes, thereby increasing the reliability of the testing technique [52].

3. CONCLUSIONS

Composite materials are widely used in aerospace, automotive, and civil engineering industries. Therefore, NDT methods are an important testing technique in ensuring the reliability and structural integrity of composite materials. NDT testing techniques are performed without damaging the material. In this study, the most commonly used Visual Testing (VT) and Visual Inspection (VI), ultrasonic inspection (UT), infrared thermography (IRT), and acoustic emission (AE) methods are included.

Visual Inspection (VT) and Visual Inspection (VI): Visual Inspection (VT/VI) is a basic and cost-effective technique for detecting surface defects such as cracks and imperfections. However, the disadvantage of the method is that it cannot detect subsurface or internal defects, making it inadequate for comprehensive material evaluation.

Ultrasonic Testing (UT): To overcome the limitations of the visual inspection (VT/VI) technique, Ultrasonic Testing (UT) is used. This method is one of the most widely used techniques to detect internal defects such as delaminations and fiber breakage. The high sensitivity of UT makes it an important method for assessing the structural integrity of composite materials. However, the efficiency of this method depends on the acoustic properties of the material. Also, complex geometries are another limitation of this method.

Infrared Thermography (IRT): It is a non-contact inspection technique that is particularly suitable for detecting surface and near-surface defects. IRT detects inconsistencies in material structures by analyzing thermal gradients. However, its ability to penetrate deeply is limited, and external factors such as ambient temperature can affect its accuracy.

Acoustic Emission (AE): Acoustic Emission (AE) is a dynamic technique that allows real-time monitoring of damage progression. It is particularly useful for assessing the response of a material under load, making it suitable for detecting active damage mechanisms. However, AE requires advanced signal processing, interpretation, and experience, which can make its application difficult.

Each NDT technique has its advantages and limitations. The method chosen should be determined by the material properties and inspection requirements. Combining multiple NDT techniques with advances in artificial intelligence (AI) and automated inspection systems can increase defect detection accuracy and efficiency. Future research can enhance the capabilities of NDT technologies through the development of hybrid techniques, improved data analysis methods, and real-time monitoring solutions.

Consequently, NDT methods for composite materials are important for defect detection and the detection of structural changes. Various NDT techniques, such as ultrasonic testing, infrared thermography, acoustic emission, and visual inspection, are frequently used to test the integrity and reliability of composite structures.

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