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REVIEW ARTICLE

# A review of non-destructive testing for polymeric composites: techniques, challenges, and advances

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**Abstract**

Polymeric composite materials reinforced with carbon fibers are widely used in the aeronautical, automotive, energy, and marine industries due to their excellent mechanical properties and low density. However, these materials are susceptible to defects introduced during manufacturing or service life, requiring reliable non-destructive testing (NDT) methods to ensure quality and structural integrity. Despite the widespread application of NDT , the literature lacks a critical and comparative overview of their limitations, and suitability for composites. This review provides an analysis of the main NDT methods for polymeric composites, including ultrasonic, X-ray, thermography, and microcomputed tomography testing. The study highlights the advantages and challenges of each method, discussing their suitability for different defect types. The findings indicate that combining multiple NDT methods enhances defect detection reliability, addressing the limitations of individual methods. This study provides a reference for researchers and engineers, supporting advancements in material inspection and structural health monitoring.

**Keywords:** *non-destructive testing, microcomputed tomography, thermography, ultrasonic inspection, X-ray.*

**Data Availability:** all data supporting the findings of this study are included in this article and its supplementary materials.

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## 1. Introduction

Advances in technological development in the area of materials have allowed the gradual replacement of aeronautical structures made of aluminum alloys by structures processed in polymer composite materials, with advantages in terms of weight reduction (from 20 to 30%) and the final costs (up to 25%) in parts manufactured in composites[1-5]. Due to the benefits presented, such as excellent mechanical strength (> 700 MPa) and high stiffness (> 50 GPa), combined with low density (~1.5 to 2 g/cm$^3$), the polymer composites are widely accepted in aeronautical, space, wind, automotive, and maritime applications. As a result, parts such as stringers, flaps, ailerons, landing-gear doors, grout cones, and fairings, previously manufactured in aluminum alloys, have been replaced by polymer composites[1,2,4,6-13].

Composite materials are heterogeneous and sometimes anisotropic. Therefore, controlling its manufacturing process minimizes the production of parts and components with defects and damage, which may compromise its service performance. Typical defects that may be found in laminated polymer composites are polymer matrix richness area, due to the unequal reinforcement (fibers) distribution; fibers planar waviness or fibers out of plane creating wrinkling, due to poor interaction between the laminate and the tooling; voids and porosities, attributed to poor percolation of the matrix in the reinforcement; inclusions from contaminated environments; layer misalignment or fiber disorientation, matrix cracks, and laminate warping, due to residual thermal stress, arising from the curing process of the thermosetting matrix. Discontinuities in laminated composite materials act as stress concentration points, which favor the propagation of cracks and delaminations, and reduce the effective strength, stiffness, and part useful life[3,13-15].

Therefore, after manufacturing composite parts, it is necessary to inspect them to guarantee the adequacy of the manufacturing process, compliance with the project requirements, reduction of concerns related to product safety, and minimization of maintenance costs. In this sense, the assessment of components and parts is very important in the processing of composite materials. The use of non-destructive testing stands out because this class of tests does not destroy or damage the item under evaluation. In addition, non-destructive testing can be used to set the best parameters from the manufacturing process and to detect voids during the processing[4,6,13,16].

Laminated composite materials exhibit anisotropic behavior and complex failure mechanisms, which complicate the detection of defects using conventional inspection methods. Despite this, the use of polymeric composites in high-performance industries is increasing continuously. So, ensuring their structural integrity remains a significant challenge. While non-destructive testing (NDT) methods such as ultrasonic, X-ray, and thermography inspections are widely employed, there is a lack of a systematic review comparing their effectiveness, resolution, and applicability for polymeric composites.

This study aims to bridge this gap by providing a critical review of NDT methods and discussing their detection capabilities for defects such as delaminations, voids, fiber misalignment, and matrix cracking. By comparing the advantages and limitations of different methods, this work supports the development of more efficient inspection protocols for polymeric composites, contributing to safer and more reliable applications in the aerospace, automotive, and energy sectors.

## 2. Non-Destructive Tests

NDT methods are tools widely used in the aeronautical and space segments to evaluate components and ensure the quality and reliability of the manufacturing process. Furthermore, it can be used to determine physical properties, measure the thickness of parts, and analyze the extent of corrosion in some types of materials. NDT methods may be used to inspect welds, concrete curing, electric conductivity, medical research, etc. For composite materials, the NDT methods are used to monitor the presence or lack of defects and curing processes and to establish the best parameters for the manufacturing process, ensuring that the manufactured part is approved for use[4,13,16,17].

NDT results are complex and require interpretation. However, if the technique is properly applied, it can detect different discontinuities, such as voids, delaminations, matrix richness area, and porosities. Therefore, the NDT methods are used in manufacturing process control, quality assurance, final inspections, service, and maintenance, minimizing catastrophic failures[4,11,14]. Although the NDT is important, the referred literature does not present a critical discussion of the use of different methods of NDT, with advantages, disadvantages, and restrictions on use.

Faced with this challenge, this revision was motivated to be performed to contribute with a polymeric composite non-destructive area employing a systematic survey combined with a critical discussion under different types of inspection, including advantages and disadvantages, as well as a discussion about the detection sensibility of each technique analyzed.

Various NDT methods are available for the inspection of composite materials, each with distinct detection principles and capabilities. This study focuses on four methods that are widely used, that is, ultrasonic testing (UT), X-ray testing, microcomputed tomography (microCT), and thermography, due to their established applications in polymeric composites. These methods were selected based on their ability to detect internal defects (e.g., voids, delaminations, fiber misalignment) and surface anomalies (e.g., impact damage, matrix richness area). The following sections provide a critical overview of each method, highlighting their principles, advantages, and challenges.

### 2.1 Ultrasonic tests

Ultrasonic testing (UT) is a widely used NDT method for detecting surface and subsurface discontinuities in parts and components. This method uses high-frequency sound waves (0.1 to 25 MHz) to evaluate several materials, requiring direct contact between the ultrasonic transducer and the material to enable wave propagation. Once inside the material, the waves propagate at high speeds, causing molecular vibrations without inducing plastic deformation, as long as they remain below the material's elastic limit[13,15,17,18].

When the sound waves travel through a homogeneous material with minimal or no discontinuities, energy loss is minimal, allowing the waves to propagate smoothly until they reflect off an external surface. However, when discontinuities (for example, cracks, voids, or delaminations) are present, they interrupt the wave path, causing partial reflection or scattering. The pattern of these reflections enables the identification and localization of defects[17,18].

The intensity of wave reflection depends primarily on the physical state of the materials at the interface and, to a lesser extent, on their intrinsic physical properties. For example, at the interface between metal and gas, sound waves are almost completely reflected. In contrast, at interfaces between metal and liquid or metal and solid, only a portion of the energy is reflected. So, the amount of reflected energy depends on the acoustic impedance mismatch between the two materials[13,15,17,18].

This method is particularly effective in detecting cracks, delaminations, voids, porosities, and debonding, as well as inclusions and other heterogeneities that alter wave propagation. Such defects cause variations in the wave reflection and attenuation, which can be detected and analyzed. Inclusions and other heterogeneities may also be detected because they cause partial reflection or scattering of sound waves or even produce some other effects detectable by sound waves[13,15,17,18].

Ultrasonic inspection equipment typically detects discontinuities by monitoring one or more of the following parameters[17]:

- Time of flight: The time taken by the sound wave to propagate through the material and return to the transducer;
- Attenuation: The reduction in wave amplitude due to absorption and scattering in the calibration standard, and
- Spectral response: The variation in frequency components between transmitted and received signals.

Ultrasonic inspection is extensively used for quality control and structural inspection in various industries, including aerospace, automotive, marine, and energy sectors. Common applications include inspecting electronic components, metallic structures, composite materials, pipelines, pressure vessels, bridges, and aircraft fuselages. In maintenance operations, ultrasonic testing plays a crucial role in detecting potential failures before they become critical, preventing structural failures, and ensuring safety[17,18].

### 2.1.1 Ultrasonic testing techniques

There are several ultrasonic testing techniques, including pulse-echo, phased array, immersion, and transmission, which are described below:

- Pulse-echo: A single transducer emits and receives sound waves, and the reflection pattern is displayed as an amplitude *versus* time graph.

- Phased array ultrasonic testing (PAUT): Utilizes multiple elements in a single transducer to generate cross-sectional images, allowing better defect characterization.

- Transmission technique: Uses two separate transducers, one for emitting and the other for receiving sound waves, to detect defects based on signal transmission variations.

- Immersion testing: A single transducer emits and receives sound waves. The test piece is submerged in a liquid medium (e.g., water) to enhance wave coupling and eliminate surface irregularities.

Figures 1 and 2 present the images for a single and two separate transducers, respectively. Figure 3 shows images obtained from pulse-echo, phased array, and transmission techniques for the same carbon fiber (CF)/poly(ether imide) (PEI) laminate.

### 2.1.2 Applications in composite materials

Several studies have validated ultrasonic testing for polymeric composite materials. The ultrasonic inspection was performed by Costa et al.[19,20] to determine the absorption coefficient of carbon fiber (CF)/epoxy and CF/bismaleimide laminates, correlating them with porosity levels. The specimens were inspected by transmission ultrasonic technique using an ultrasonic failure detector Reflectoscope S80 with a 0.750″, frequency of 5 MHz, transmitter type Automation X19625, receiver type Automation X19267, and water as coupling. An Automation US640 system transported the transducers. The study confirmed that higher porosity leads to higher ultrasonic absorption, demonstrating the technique's reliability in assessing laminate quality.

Melo and Menezzi employed ultrasonic testing to evaluate the physical and mechanical properties of laminated veneer lumber (LVL) composites[21]. By measuring the sound wave velocity, the authors determined the dynamic elastic modulus, with a good correlation with data obtained in mechanical testing. This result proves that ultrasonic testing can replace destructive testing in some cases.

Smagulova and Jasiuniene[22] investigated ultrasonic phased array testing for dissimilar material joints composed of steel and glass-fiber-reinforced polymer (GFRP). For this, the authors used polyethylene tape as artificial discontinuities. The results showed that inspection from the steel side was more effective due to lower attenuation compared to the GFRP side, and the 3.5 MHz transducer provided the best defect detection capability, overcoming acoustic impedance mismatches.

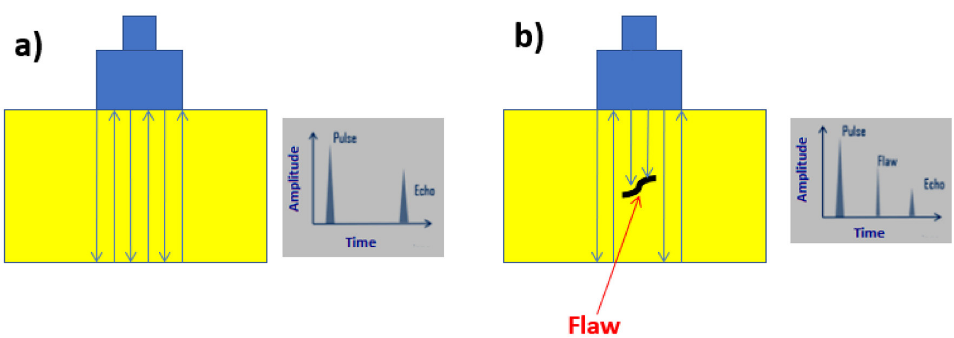


**Figure 1.** Ultrasonic testing with a single transducer. (a) region without flaw; b) region with flaw.

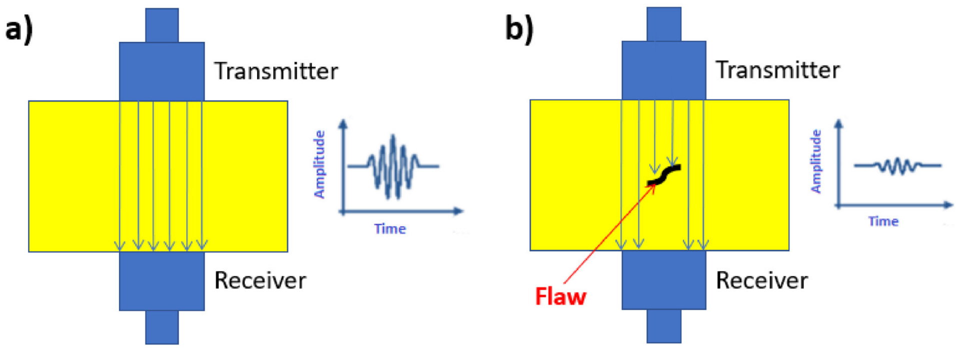


**Figure 2.** Ultrasonic testing with two separate transducers. (a) region without flaw; (b) region with flaw.

Rus et al. investigated multiple ultrasonic techniques for the inspection of CF/epoxy laminates manufactured by the resin transfer molding process, inducing impact damages (15 J), according to ISO 18352[23]. The study compared different ultrasonic techniques: air-coupled ultrasonic (ACU), transmission with piezoelectric transducers (cPP), laser-induced ultrasonic, immersion testing, phased array ultrasonic testing (PAUT), and, finally, thermoacoustic emission (TAE). This study showed that. ACU is suitable for automated plate inspections, cPP provides high contrast and is cost-effective for large impact damage detection, laser-induced ultrasonic and immersion testing are recommended for high-sensitivity applications requiring superior spatial resolution, PAUT is ideal for single-sided inspection of thick composite parts but is challenging to automate, and TAE is capable of producing short pulses, offering the potential for single-sided ACU inspection with improved depth resolution.

Gonçalves et al. evaluated CF/epoxy laminates using three ultrasonic techniques: critically refracted longitudinal wave (LCR), B-scan phased array system, and total focusing method (TFM) signal-to-noise ratio (SNR) analysis[24]. Their findings allowed them to conclude that the LCR was ineffective in identifying defect locations; B-Scan images accurately detected delaminations but struggled with fiber waviness detection, and SNR-TFM imaging successfully detected both delaminations and fiber misalignment.

Montagna et al.[4,25] manufactured CF/poly(phenylene sulfide) (PPS) laminates using semipreg scraps from the aerospace sector through hot compression molding processing and evaluated them by ultrasonic testing, using the phased array (PAUT, with a voltage of 40 V, at 5 MHz of frequency and the images showed the presence of some voids, internal discontinuities, and some processing defects that may be due to the overlapping of CF/PPS semipreg scraps, as shown in Figure 4.

Morgado et al.[26] used ultrasonic analyses to support the establishment of the processing cycle of CF/PPS laminates through hot compression molding. Based on the ultrasonic images, the authors established a reliable and repetitive processing cycle for this composite material.

Gomes et al.[2] used ultrasonic testing to evaluate GF/poly(aril ether ketone) (PAEK) laminates with carbon nanotube buckypapers (BPs). Based on the ultrasonic images, the authors concluded that the consolidation of the reference's laminate (without BPs) was not entirely uniform (Figure 5a). In the laminates with BPs (Figure 5b-e), the ultrasonic inspection indicates polymer accumulation in certain regions (red areas), BP location (reddish areas), as well as potential fractures and ruptures at the end of the BP films (bluish and greenish areas), probably caused by excessive pressure applied during consolidation step.

The studies from the literature show that ultrasonic testing is a versatile and widely used NDT method for detecting discontinuities in polymeric composites. This method is effective for identifying cracks, voids, and delaminations, but its accuracy depends on the material properties, discontinuity characteristics, and chosen ultrasonic method. Recent advancements in phased array and air-coupled techniques have enhanced resolution and automation potential, making UT a key tool for composite inspection in aerospace, automotive, and structural engineering applications.

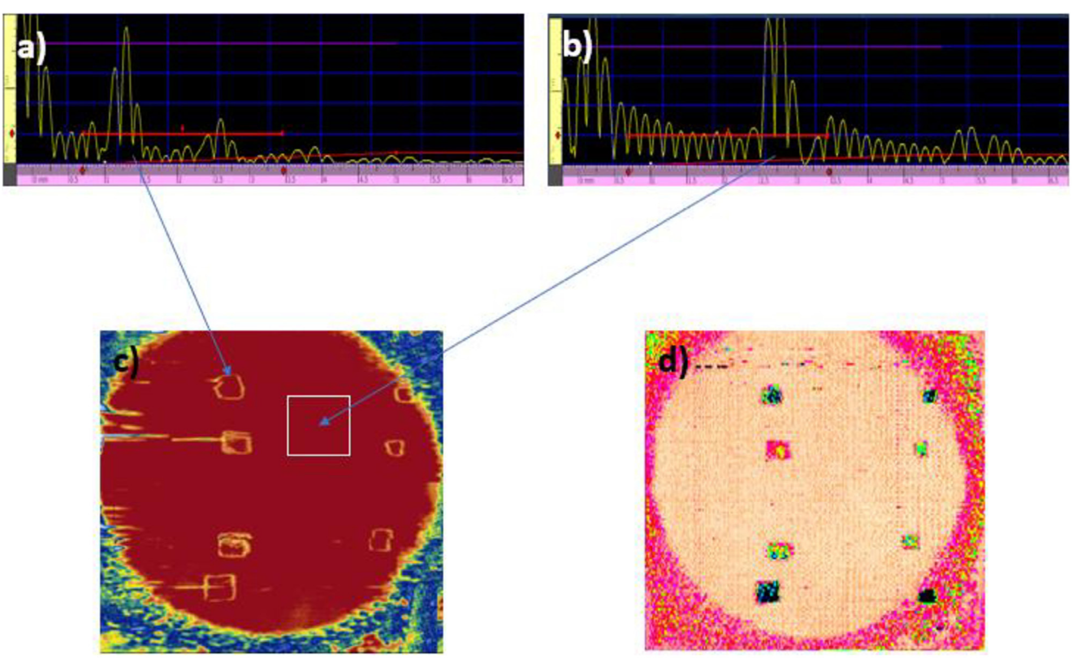


**Figure 3.** CF/PEI laminate with a polyimide release film intentionally added. (a) Image obtained of a discontinuity area using the pulse-echo technique; (b) Image obtained of an area without discontinuities using the pulse-echo technique; (c) Image obtained using the phased array technique. In the same area, it is possible to see regions with and without discontinuities; (d) Image obtained using the transmission technique. In the same area, see regions with and without discontinuities.

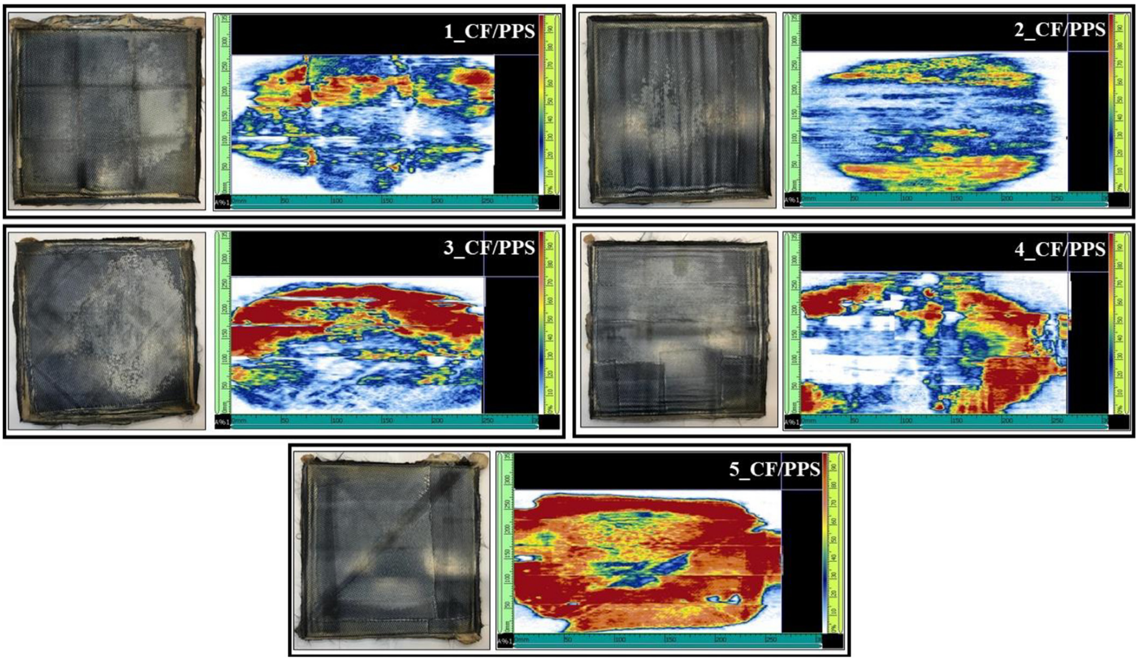


**Figure 4.** Ultrasonic images of CF/PPS laminates obtained with different scrap arrangements: Blue/white areas correspond to the presence (e.g., voids). Red/orange/yellow regions correspond to good consolidation, suggesting the absence of voids[25].

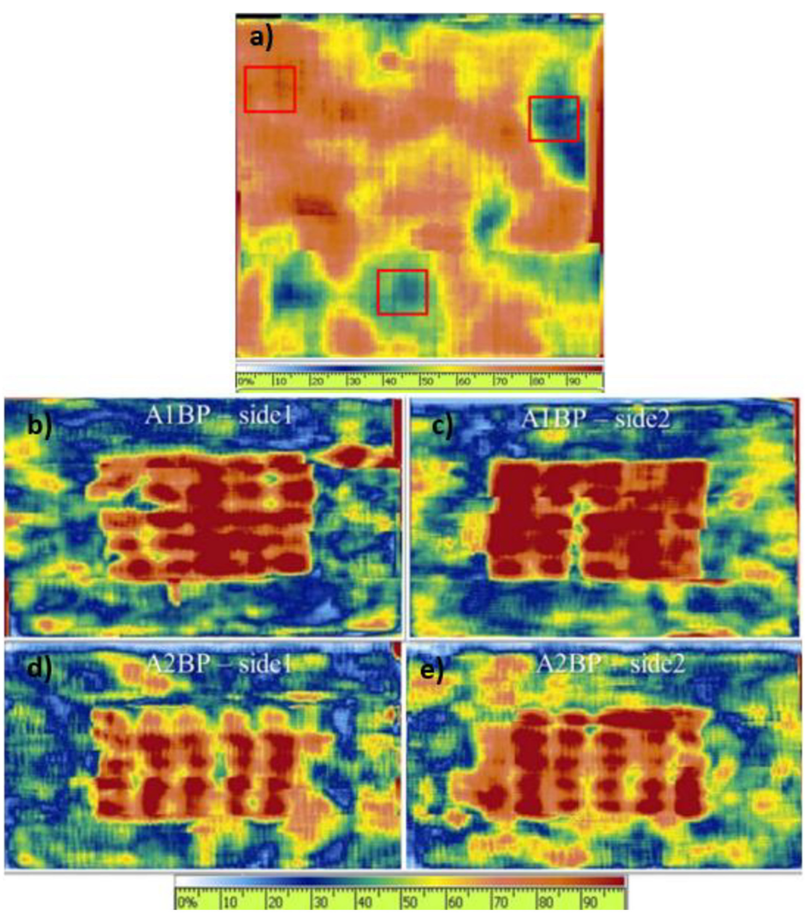


**Figure 5.** GF/PAEK laminates. (a) Sample 1 without BPs; (b-c) sides 1 and 2 from sample 2; (d-e) sides 1 and 2 from sample 3[2].

### 2.2 X-ray test

X-ray testing is an NDT method that utilizes electromagnetic radiation to inspect materials for internal defects. When a material has non-uniform characteristics, such as variations in thickness, density, or chemical composition, it absorbs penetrating radiation at different rates. This difference in absorption allows the identification of failures or discontinuities within the structure[27,28].

The intensity of electromagnetic radiation passing through a material decreases exponentially with increasing material thickness, according to Equation 1[28-30]:

$$I = I_0\left(E\right).e^{\left(-\mu\left(E\right)x\right)} \quad (1)$$

where:

E is the energy of the incident radiation;

$I_0$ is the intensity of the radiation source;

I is the intensity of the radiation after passing through the material;

x is the material thickness;

μ is the total absorption coefficient of the material.

The total absorption coefficient is defined as the sum of the absorption coefficients of the material. Differences in density, thickness, and composition directly affect the intensity of the absorbed radiation and, consequently, the transmitted radiation. Therefore, discontinuities appear in radiographic images due to variations in radiation absorption between the defect and the surrounding material[28,29].

The greater the density difference between a defect and the surrounding material, the higher the contrast in the radiographic image. This means that X-ray testing sensitivity is directly proportional to object density and inversely proportional to the defect size[29].

#### 2.2.1 X-ray detection mechanisms

When X-rays interact with a material, they can be absorbed, transmitted, or scattered. The absorbed fraction is detected by an image receptor, known as a detector, which can be either conventional or digital. Conventional radiography uses radiographic film, and the image development process is chemical and latent. On the other hand, digital radiography (flat panel detector) converts absorbed radiation into an electrical signal, generating a digital image displayed in real time on a computer screen[27].

Similar to ultrasonic testing, X-ray investigation has a wide range of applications. Ferreira et al.[27] applied X-ray digital testing to evaluate laminated pipe joints in composite materials reinforced with CFs. The study successfully visualized the junction of ducts and the laminated layers. Additionally, the author introduced acetate tapes into the tubes to simulate delaminations and assess the detection sensitivity of the technique. While all tapes were detected, discrepancies were found between the actual defect sizes and those measured via X-ray imaging. Figure 6(a-f) shows a pipe joint X-ray digital image.

#### 2.2.2 Challenges of X-ray inspection for polymeric composites

X-ray inspection is commonly applied to metallic materials, but its use in polymeric composites is limited when the difference in atomic weight of the materials, that is, among the phases of the composite material, is less pronounced. In other words, the X-ray interaction mechanisms are different for different materials[31,32]. So, the success of the use of this method includes two key challenges that is,

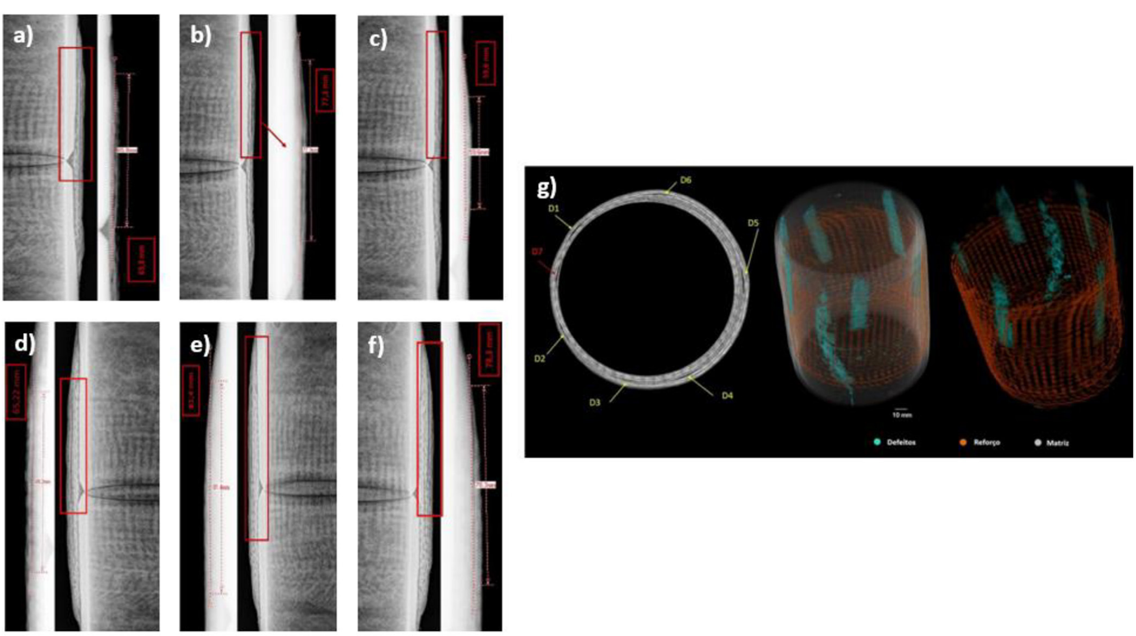


**Figure 6.** Pipe joint made in CF-reinforced composite material containing acetate strips (in red rectangle) inspected by: (a-f) X-ray digital technique (2D image) and (g) microCT (3D image). Figure 6(a-f) shows the X-ray inspection detected the presence of the acetate strips (red delimited regions)[27].

density and X-ray absorption. Knowing that metals have a higher density than polymeric composites, they absorb X-rays more efficiently, resulting in high-resolution images that reveal clearer cracks, porosities, and inclusions. On the other hand, polymeric composites, having lower density, absorb less radiation, producing low-contrast images, making defect detection more difficult.

X-ray imaging of metals provides high contrast between a defect and the surrounding material due to their higher atomic number and density. However, the contrast may be insufficient in polymeric composites, impairing the detection of small defects or internal variations, especially when the polymer matrix and fiber reinforcement (e.g., CF) have similar densities. Industrial applications of X-ray inspection of metallic materials are widely used, requiring high precision in defect detection, such as in aerospace and automotive manufacturing. Metals are often used in high-strength applications, where internal defects could lead to catastrophic failures, making radiographic testing essential.

Alternatives more effective for interface inspection and internal defect characterization of polymeric composites are UT and microcomputed tomography (microCT) inspections, considering that the X-rays cannot provide sufficient contrast and spatial resolution for some composite structures.

#### 2.2.3 Advancements in X-ray testing for composites

The use of X-ray techniques for polymeric composites monitoring has shown limited application due to the low density contrast and limited defect detectability. However, advancements in this area have allowed the X-ray application with good results. In this case, it can be cited that digital radiography, phase-contrast imaging, and microfocus X-ray methods improved the detection of discontinuities in polymeric composites.

##### 2.2.3.1 Phase-contrast X-ray Imaging

Vavrik et al.[33] developed a phase contrast X-ray technique to detect closed delaminations in CF reinforced plastic (CFRP) composite. According to the authors, closed delaminations mean layers of delamination in contact, and the X-ray radiography projection cannot contribute to image formation by attenuation. In this study, the authors used a microfocus X-ray tube technique with a photon-counting energy-sensitive hybrid semiconductor pixel detector and a relatively large sample-to-detector distance. According to the authors, the best approach for detecting closed delaminations is to attenuate the image by performing two measurements using two different energy thresholds (5 and 16 keV) with the same experimental setup. This methodology is good because the absorption depends on the energy as $1/E^4$ and the refraction as $1/E^2$. In this way, the absorption contrast is strongly energy sensitive. With this approach, the authors identified and visualized closed delaminations successfully.

For detecting open delaminations, meaning a physical gap between delaminated layers, high-resolution computed tomography techniques may be used. However, there is an experimental challenge once the volume of the open delamination is relatively small and the local density varies by several hundred percent. Therefore, the contrast and spatial resolution are very high. For this analysis, the authors used a high-resolution setup based on a micro-focus X-ray tube and an appropriate beam-hardening calibration. Thus, open delaminations were successfully identified and visualized.

##### 2.2.3.2 Digital X-ray for bonded joints

Rique et al.[34] applied a digital X-ray technique to evaluate bonded joints in GF-reinforced epoxy pipes, using three types of samples: one without defects (control samples), samples with insufficient adhesive, and samples with poor adhesion. The results showed that the control samples showed voids in high-contrast regions; samples with low adhesive content had minimal voids, likely due to reduced thickness, allowing greater radiation transmission, and the ones with poor adhesion exhibited small voids. However, the gap between the adhesive layer and pipe wall was not visible clearly, indicating the limited effectiveness of X-ray for this type of defect.

##### 2.2.3.3 Microfocus X-ray for composite blades

Anoshkin et al. analyzed CF/epoxy straightener blades using microfocus X-ray technology[35]. A radiation source with a focal spot size of <100 μm was used to detect interlayer delaminations, pores, and wrinkles. According to the authors, the studied polymeric composites have close density values (reinforcing element and polymeric matrix), resulting in low-contrast images, reducing the probability of detection and identification of discontinuities by traditional radiography techniques. Thus, the microfocus X-ray technique can obtain informative X-ray images with a lower radiation load compared to the traditional X-ray technique. In the study, Anoshkin and collaborators used a microfocus X-ray machine with an anode voltage of less than 130 kV, an anode current of less than 200 μA, and a focal spot size ranging from 20 to 100 μm[35]. The authors concluded that the microfocus X-ray technique allows the inspection of the bending of layers from blades, which means inaccessible areas for other non-destructive testing methods. The inspection time does not exceed 1 minute, and the total analysis time is around 5 - 7 minutes.

Thus, while X-ray testing is a valuable NDT for metallic materials, its application to polymeric composites remains challenging due to the low density contrast and limited defect detectability. However, advancements in digital radiography, phase-contrast imaging, and microfocus X-ray have improved defect visualization in polymeric composites. In many cases, combining X-ray with other NDT methods, such as ultrasonic or microcomputed tomography (microCT), increases reliability, ensuring better defect characterization in critical applications.

### *2.3 Microcomputed tomography test*

Traditional X-ray radiographic equipment allows the evaluation of materials on a two-dimensional (2D) scale. However, 2D imaging does not provide depth information, making it difficult to determine precisely the position and extent of internal discontinuities. In contrast, microCT generates high-resolution three-dimensional (3D) X-ray images, allowing a detailed evaluation of microstructure and morphology[27,36].

The microCT reconstructs X-ray transmission data from multiple 2D projections to create cross-sectional images of the sample, eliminating interference from overlying and underlying structures[17,27,36].

The quality of the images obtained via microCT depends on the material density, atomic number, and X-ray beam energy. This technique offers high sensitivity, even in cases where density differences between structures are minimal (< 1%)[17,37,38]. Figure 7 illustrates examples of 2D and 3D X-ray imaging.

The microCT systems are classified based on the shape of the incident X-ray beam[39] as Fan Beam Computed Tomography (FBCT) and Cone Beam Computed Tomography (CBCT). Figure 8 presents examples of CBCT and FBCT imaging techniques.

#### 2.3.1 Applications of MicroCT in composite materials

Rique et al.[34] employed microCT to analyze voids in bonded joints made from GF-reinforced epoxy resin. The study demonstrated that voids compromise adhesion, potentially leading to mechanical failure. The authors aimed to develop inspection methodologies to identify and quantify defects in bonded regions. MicroCT allowed the measurement of void volume, size, shape, and distribution, as well as the anisotropic characteristics of the microstructure of the bonded joints. The results confirmed that microCT effectively detected adhesion failures and impurities within the adhesive layer.

Ferreira et al.[27] evaluated laminated pipe joints made of carbon fiber-reinforced composites, comparing X-ray radiography and microCT. The study found that certain discontinuities were undetectable via conventional X-ray imaging but identified through microCT. The improved defect detection using the microCT method was attributed to its smaller focal spot size, which enhances spatial resolution, providing superior imaging of internal structures. So, microCT has been shown to be a powerful NDT tool for 3D imaging of polymeric composites, offering high resolution and precise defect characterization. Unlike traditional 2D radiography, microCT enables the detection of voids, delaminations, and adhesion failures with improved depth resolution. Due to its ability to reconstruct detailed internal structures, microCT is increasingly applied in composite materials research, failure analysis, and quality control. Figure 6g presents the difference between X-ray radiography (2D) and microCT (3D) for the same sample of polymeric composite, that is, a pipe joint made in CF-reinforced composite material containing acetate strips.

### 2.4 Thermography test

Thermography testing is an NDT method that enables the inspection of large areas in relatively short periods. This technique is widely used to assess impact damage and to detect delaminations in composite materials[40-42]. It is particularly advantageous for inspecting complex geometries and bonded joints between similar or dissimilar materials. Additionally, thermographic testing can be performed from a single side of the structure, making it a fast and practical inspection method[17,40,41].

#### 2.4.1 Principles of thermography

Any object with a temperature above absolute zero (0 K) emits thermal radiation, most of which falls within the infrared spectrum. Thermographic cameras are designed

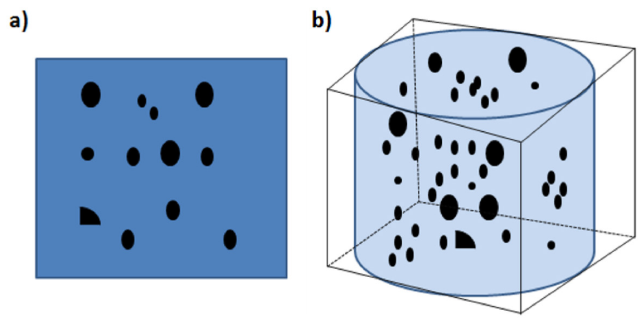


**Figure 7.** Comparison of: (a) 2D X-ray imaging and (b) 3D microCT imaging.

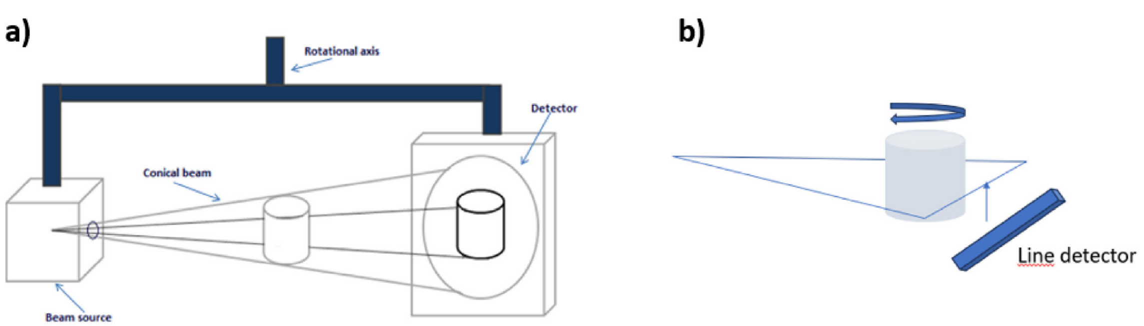


**Figure 8.** MicroCT systems: (a) CBCT and (b) FBCT tomography techniques.

to detect infrared radiation emitted by the inspected object and convert it into a visible thermal image[43].

According to the radiation law, when an object is exposed to thermal radiation, it exhibits three key radiative properties: a) absorbance, when a fraction of the incident radiation is absorbed by the material, b) reflectance, when a fraction of radiation is reflected by the surface of material and c) transmittance, when a fraction of radiation passes through the material. For opaque materials, the transmittance is zero, meaning that the sum of absorption and reflection is equal to one[43].

The thermographic inspection method can be classified into two main categories that is, passive thermography and active thermography[41,43,44]. In the first technique, the test object naturally emits infrared radiation, without external heat application, and it is commonly used in predictive maintenance and structural health monitoring. The latter involves an external energy source (e.g., flash lamps or lasers) that heats the material, and the thermal diffusion is analyzed. This technique is used in non-destructive evaluation to detect subsurface defects[41,42,44,45]. Figure 9 schematically shows the difference between active and passive thermography.

In active thermography, localized heat diffusion is affected by internal defects, causing temperature variations on the surface of the material. Defective regions exhibit different thermal behavior compared to defect-free areas, enabling the quantification of internal damage[17,41,44-46].

### 2.4.2 Emissivity and Kirchhoff's law

Emissivity is the characteristic of a material to emit thermal radiation at a given temperature. Kirchhoff's Law states that the absorption capacity of a material is equal to its emission capacity at the same wavelength. The amount of radiation emitted by an object is directly proportional to its emissivity and temperature. Low-emissivity materials (e.g., polished metal surfaces) emit less radiation, making thermographic testing more challenging[43].

Several factors influence emissivity, including a) surface condition, knowing that polished surfaces reflect more infrared radiation, reducing emissivity; b) material composition (different materials have distinct emissivity values), and viewing angle, which affects the image clarity and must be considered in result interpretation[41].

### 2.4.3 Applications of thermography in composite materials

Several studies have demonstrated the effectiveness of thermographic techniques in detecting defects in fiber-reinforced polymer (FRP) composites. Santiago (2019) employed principal component thermography and pulsed phase thermography to inspect carbon fiber-reinforced polymer (CFRP) composites[47]. Based on the signal-to-noise ratios, the study concluded that the principal component thermography provided higher defect visualization accuracy.

Pscheidt used thermography to detect discontinuities in epoxy-based CFRP laminates[48]. The author manufactured samples with induced defects (30 mm and 50 mm in size) and heated them by immersion in water at 30, 40, and 50 °C until thermal equilibrium was reached. After removal from the water, thermal images were captured. The results showed that defects were detectable at all temperatures, but 40 °C provided the highest thermal contrast, making defects more visually distinguishable.

Luo et al.[49] explored stepped heating and lock-in thermography to inspect CFRP composites used in railway components. The study confirmed that the technique was effective in detecting defects up to 10 mm in depth in complex composite structures. Tromaras and Kappatos[50] and Zhang et al.[51] demonstrated that thermographic techniques are highly effective for subsurface defect detection in CFRP and GFRP composites[50,51]. Luo et al.[49] also applied thermography to hybrid CFRP/PET/CFRP sandwich composites and confirmed its ability to identify defects in surface and subsurface layers, even in low-emissivity materials.

Thermographic inspection is a powerful NDT technique for evaluating polymeric composites, particularly in detecting delaminations, impact damage, and subsurface defects. While passive thermography is useful for monitoring temperature variations over time, active thermography enhances defect detection through controlled heat diffusion

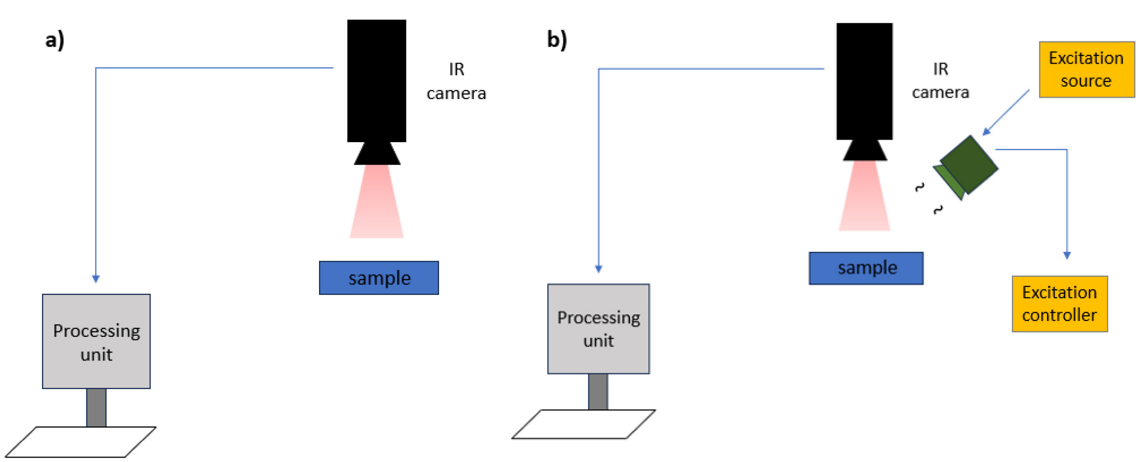


**Figure 9.** Schemes showing (a) passive thermography and (b) active thermography.

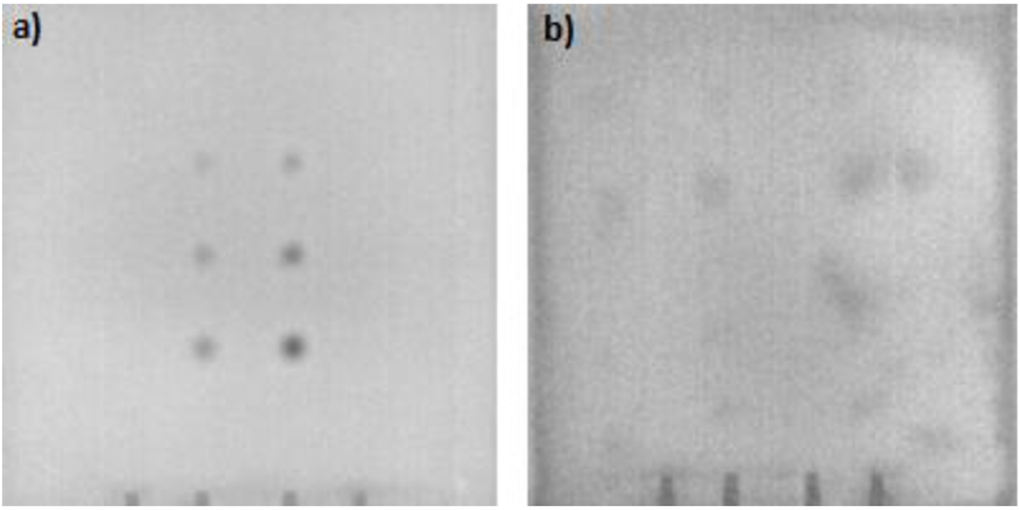


**Figure 10.** Active thermography of CF/PEI laminates with: (a) six recesses machined and (b) GF fabric scraps between layers.

**Table 1.** Comparison of the main non-destructive testing (NDT) methods applied to polymeric composites, highlighting their principles, detectable defects, advantages, limitations, and typical applications.

| NDT Method | Working Principle | Detectable Defects | Advantages | Limitations | Typical Applications |
|---|---|---|---|---|---|
| Ultrasonic Testing (UT) | High-frequency sound wave propagation | Delaminations, cracks, voids, internal discontinuities | High sensitivity, portable, relatively low cost | Requires a coupling medium, complex interpretation, limited to irregular geometries | Aerospace, automotive, energy |
| X-ray Testing (XR) | Radiation attenuation by density and thickness | Voids, delaminations, inclusions | Fast 2D imaging, well-established for metals | Low contrast in composites, limited resolution for small defects | Joint inspection, tubes, flat structures |
| Microcomputed Tomography (microCT) | 3D reconstruction from multiple X-ray projections | Voids, delaminations, adhesion failures, microcracks | High resolution, 3D visualization, defect quantification | Expensive equipment, time-consuming, and a limited sample size | Research, failure analysis, process validation |
| Thermography (Active/Passive) | Detection of infrared radiation emitted by the sample | Delaminations, impact damage, interfacial debonding | Fast, contactless, suitable for complex geometries | Affected by surface emissivity, limited depth resolution | Predictive maintenance, structural monitoring |

analysis. This technique is especially effective for complex geometries and hybrid composite structures, making it a valuable tool for aerospace, automotive, and railway applications. Figure 10 presents images of CF/poly(ether imide) (PEI) laminates evaluated by active thermography. This NDT technique allowed determining the presence of the discontinuities in the CF/PEI laminates, but the resolution is limited.

A comparative overview of the main non-destructive testing methods applied to polymeric composites is summarized in Table 1, providing a concise visualization of their operational principles, capabilities, and limitations.

## 3. Conclusions

This review provided a comprehensive and critical overview of non-destructive testing (NDT) techniques applied to polymeric composites, highlighting their capabilities and limitations in detecting manufacturing and service-induced defects. Among the methods discussed, ultrasonic testing (UT) demonstrated high sensitivity to internal discontinuities, while X-ray techniques and microCT offered superior spatial resolution for internal defect characterization. Thermography, in turn, proved effective for identifying surface and subsurface anomalies, especially in complex geometries, particularly in detecting delaminations and impact damage.

The comparative analysis reveals that no single NDT technique is universally sufficient to detect all types of defects in polymeric composites. Therefore, hybrid approaches, combining two or more NDT techniques, are encouraged to enhance accuracy and reliability in critical applications.

Based on the state-of-art in the NDT area, it is suggested for future researches to focus on a) the integration of complementary NDT methods for more complete damage assessment; b) the development of AI-based image processing tools to automate defect detection and improve analysis speed, and c) the standardization of inspection protocols to ensure consistency and reproducibility across different industries.

By providing a structured comparison and practical insights, this study contributes to advancing NDT practices in polymeric composites and supporting safer and more efficient applications in aerospace, automotive, and energy sectors.

## 4. Author's Contribution

- **Conceptualization** – Ingrid Regina dos Santos Lacerda.
- **Data curation** – Ingrid Regina dos Santos Lacerda.
- **Formal analysis** – Ingrid Regina dos Santos Lacerda; Michelle Leali Costa; Mirabel Cerqueira Rezende.
- **Funding acquisition** – Mirabel Cerqueira Rezende.
- **Investigation** – Ingrid Regina dos Santos Lacerda.
- **Methodology** – Ingrid Regina dos Santos Lacerda; Michelle Leali Costa; Mirabel Cerqueira Rezende.
- **Project administration** – Ingrid Regina dos Santos Lacerda; Michelle Leali Costa; Mirabel Cerqueira Rezende
- **Resources** – Mirabel Cerqueira Rezende.
- **Software** – NA.
- **Supervision** – Michelle Leali Costa; Mirabel Cerqueira Rezende.
- **Validation** – Ingrid Regina dos Santos Lacerda; Michelle Leali Costa; Mirabel Cerqueira Rezende.
- **Visualization** – Ingrid Regina dos Santos Lacerda; Michelle Leali Costa; Mirabel Cerqueira Rezende.
- **Writing – original draft** – Ingrid Regina dos Santos Lacerda.
- **Writing – review & editing** – Ingrid Regina dos Santos Lacerda; Michelle Leali Costa; Mirabel Cerqueira Rezende.

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