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Review

Nondestructive Evaluation of Fiber-Reinforced Polymer Using Microwave Techniques: A Review

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Abstract: Carbon-fiber-reinforced polymer (CFRP) is widely acknowledged as a leading advanced material structure, offering superior properties compared to traditional materials, and has found diverse applications in several industrial sectors, such as that of automobiles, aircrafts, and power plants. However, the production of CFRP composites is prone to fabrication problems, leading to structural defects arising from cycling and aging processes. Identifying these defects at an early stage is crucial to prevent service issues that could result in catastrophic failures. Hence, routine inspection and maintenance are crucial to prevent system collapse. To achieve this objective, conventional nondestructive testing (NDT) methods are utilized to inspect CFRP components. However, the restricted field penetration within the CFRP makes conventional NDT approaches ineffective. Recently, microwave techniques have been developed to address the challenges associated with CFRP inspection by providing better material penetration and more precise results. This paper offers a review of the primary NDT methods employed to inspect CFRP composites, emphasizing microwave-based NDT techniques and their key features.

Keywords: fibre-reinforced polymer; composite inspection; nondestructive testing; microwave NDT

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1. Introduction

Considering the development in material science, Carbon Fibre-Reinforced Polymer (CFRP) is widely used compared with other structures in numerous manufacturing sectors such as aviation [1], military [2] power plant construction [3], and automotive [4], CFRP offers significant advantages, such as lightweight and stiffness [5], fatigue resistance [6], and compression strength [7] compared to steel and aluminum [8]. However, CFRP is prone to various types of defects during the fabrication process or while in service, including fatigue, matrix cracks, flaws, and delamination defects due to ageing and cyclic processes [9]. Unless immediately detected, the defect presents a critical problem that may lead to a catastrophic failure with many adverse effects, including danger to site workers' safety, environmental harm, and a financial hit in terms of production loss and maintenance costs [10]. Hence, regular inspections are crucial to accurately identify and evaluate CFRP defects and provide timely maintenance solutions before further deterioration occurs.

During maintenance routines, composite structures are usually inspected to detect and evaluate defects using various processes collectively known as nondestructive testing (NDT) techniques. NDT involves assessing changes in material properties, such as delamination,

cracks, and inner flaws, without disrupting the material's stability and suitability for service [11]. Many types of NDT techniques are frequently employed in the industry, such as magnetic particles (MPs) [12], ultrasonic testing (UT) [13], eddy current (EC) [14], lamb waves [15], laser shearography [16], and radiographic testing (RT) [17,18]. Each technique has merits and demerits in foreseeing the inspected material's operation, safety, and performance costs.

Among existing NDT techniques, microwave-based NDT approaches have proven to be effective in inspecting composite materials [19]. In these methods, electromagnetic waves alternating in the microwave frequency range (300 MHz to 300 GHz) can interact with the CFRP's internal structure [20]. These interactions can be monitored by tracking variations in the microwave complex reflection coefficient (Γ), which can reveal defect abnormalities in the CFRP layer [21]. In contrast to traditional methods, microwave NDT does not require controlled environments or couplant materials, making it inexpensive and operator friendly, with significantly lower safety risks. One-sided inspection is another benefit of using microwave NDT due to the inaccessibility of one side of most CFRP-based components [16]. Nevertheless, microwave NDT has some difficulties inspecting CFRP, such as insufficient spatial imaging for large defect sizes and the effects of stand-off distance variations, surface roughness, and porosity irregularities in the estimated depth [22]. Considering the importance of inspecting CFRP materials and the significant potential of microwave NDT approaches, this paper presents a comprehensive review of these techniques and their numerous advantages over conventional methods commonly used for industrial applications.

After presenting the introduction, this paper is organized as follows: Section 2 introduces various conventional NDT methods for inspecting CFRP composites, including magnetic particles, eddy current, radiographic testing, laser shearography, ultrasonic testing, and radiographic testing. The advantages and disadvantages of each method in inspecting CFRP composites are also illustrated and discussed. Next, Section 3 focuses on microwave NDT techniques used for CFRP inspection, such as microwave transmission lines, open-ended microwave waveguides, microwave split-ring resonators, microwave-connected spiral inductors, and chipless radio-frequency-identification (RFID) sensors. Finally, a comprehensive conclusion is provided in Section 4, with recommendations for future endeavors.

2. Conventional NDT Techniques

To mitigate the risk of critical system failure and its consequential effects, it has been identified that NDT techniques must be utilized for ongoing inspections and integrity assessments. A variety of traditional NDT techniques, including magnetic particle inspection, eddy current, ultrasonic, thermography, laser shearography, and radiography, are commonly employed to identify defects in carbon-fiber-reinforced polymer (CFRP). This section examines the advantages and disadvantages of each approach.

2.1. Eddy Currents NDT

The eddy current testing (ECT) method offers useful information to inspect defects in CFRP composites [23]. This technique examines CFRP-coated conductive materials to detect surface and subsurface defects. The probe is excited by an electrical current to induce a current in the conductive material, as illustrated in Figure 1. The coil impedance varies when conductivity distribution is discontinued. The variation of reflected impedance is evaluated by an impedance analyzer, which reveals defects in the CFRP layer.

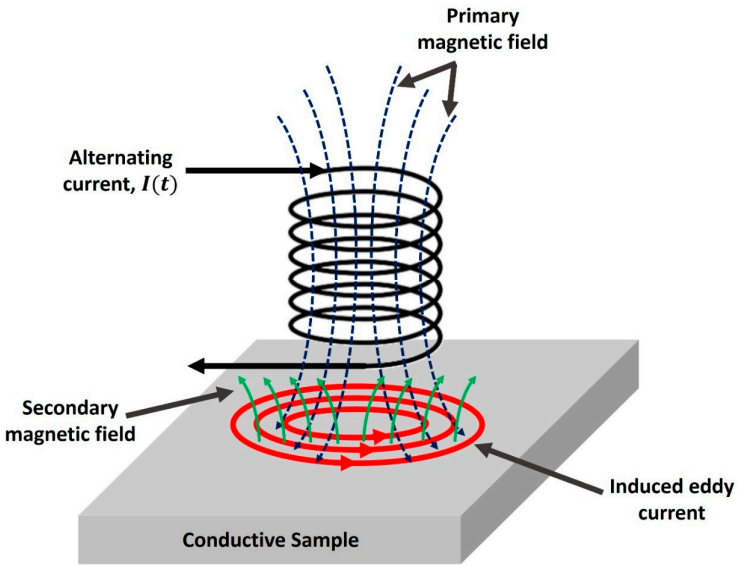


Figure 1. Eddy current working principle for inspecting a conductive sample.

In ref. [24], an ECT technique was proposed to inspect defects in CFRP by enhancing the sensitivity of the sensor to detect delamination. The method is based on an investigation of the optimal distance between a pickup coil and a driver coil. The technique clearly shows delamination with a length and width of 10 mm at a 200 mm distance between the coils. However, intensive pre-knowledge about the optimal distance selection between the coils is required for accurate defect detection. This requirement is not practical for many real applications. In [25], the authors proposed a low-frequency transmitter–receiver (T-R) probe for delamination detection in CFRP. In the T-R probe, a small size coil of 3.2 mm is operated in a frequency range of 1–250 Hz. In terms of delamination detection sensitivity, the proposed probe can visualize the location and size of delamination down to 0.25 mm in CFRP based on C-scan images. The inspection sensitivity improves without intensive pre-knowledge. Blurred images result from the probe's sensitivity due to lift-off variations, which affect the delamination evaluation's precision. To handle the consequences of lift-off variations, a high-frequency T-R probe for the ECT probe was proposed to evaluate defects in the CFRP structure. The probe has a unique 8-shaped structure transmitter and circular receiver coils. The coils are located at an equal distance of 4.5 mm from the two parts of the transmitter coils, which operate at a frequency range of 10–25 MHz. The proposed probe is sensitive enough to detect CFRP waviness and characterize fiber orientation. Nevertheless, the high-frequency ECT technique is more susceptible to different interference factors, which creates several difficulties in the construction and implementation of the system. In [26], a pulsed eddy current thermography was designed for impact damage detection by offering a quick and effective technique. The CFRP composites' microstructure variation may alter the medium's electrical conductivity tensor. Therefore, the temperature of the medium will increase due to the Joule effect. A variation in the induced current flows was revealed by an infrared (IR) camera. In [27], it was shown that a low-frequency spectrum offered by pulse excitation provides a larger infiltration depth than other ECT approaches. Tian et al. [28,29] utilized pulsed eddy currents to inspect surface cracks and low-energy impact damage in CFRP composites. The ECT technique is restricted to conductive material, surface, and subsurface inspection in CFRP composites.

2.2. Ultrasonic NDT

Compared to eddy currents, the ultrasonic testing technique is not limited to inspecting conductive materials [30]. Ultrasonic testing (UT) improves defect detection in CFRP, as illustrated in Figure 2. UT utilizes an ultrasonic transducer to transmit sound waves into the CFRP sample. Ultrasonic signals' A-scan, B-scan, and C-scan were employed to scan

the sample. This technique is important in inspecting CFRP materials because defects, such as delamination, voids, and porosity, are sensitive to ultrasonic signals [31]. However, UT is a contact method, which means that the ultrasonic transducer should be in contact with the inspected sample for sufficient energy injection.

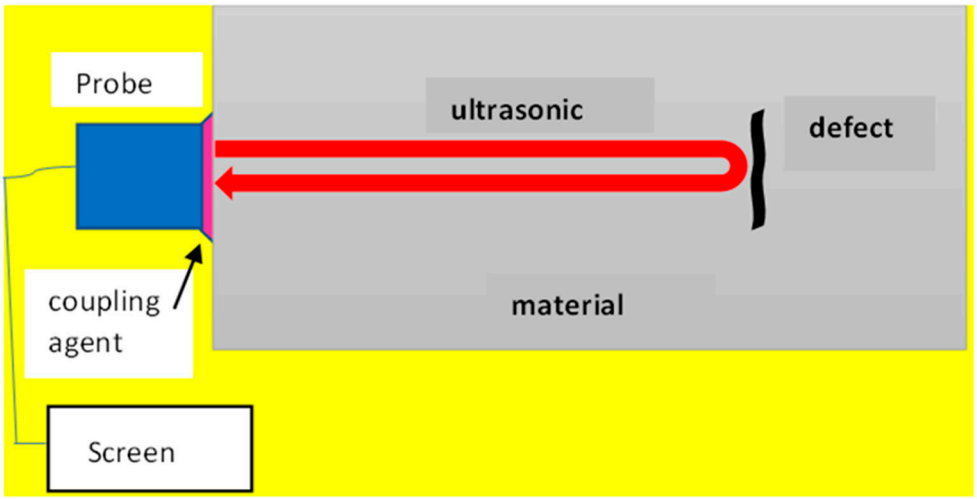


Figure 2. The basic setup of ultrasonic testing technique.

In ref. [32], an ultrasonic testing approach that employs sound waves to detect defects in CFRP was proposed. This system provides high sensitivity to detect minor flaws and can evaluate their orientation, size, shape, and nature. In [33], an air-coupled ultrasonic testing technique inspected composites with delamination defects. This method measures the distance between the ultrasonic detector and the examined object. The acquired ultrasonic waves were subjected to principal component analysis (PCA) algorithms to extract assertive characteristics. The features obtained are then divided into two groups as follows: defect and non-defect. Despite delamination flaws significantly impairing ultrasonic responses, splitting the data into two groups—defect and defect-free—yields a defect detection accuracy rate of 87.5%. However, the classification accuracy declines to 50% when the classification attempts to gauge the degree of the defect, such as minor, extensive, and defect-free [34].

In ref. [35], One proposed method for detecting defects in CFRP involves using a high-resolution air-coupled ultrasonic laser in combination with a piezoelectric sensor. This approach shows promise for accurately identifying and characterizing defects within the material. The piezoelectric sensor inspects the material's ultrasonic waves. The experiment outcomes showed that a low-frequency transducer is superior to a higher-frequency transducer. However, a transducer with a higher frequency attenuates the ultrasonic waves more severely. In [36], multi-mode ultrasonic visualization was used to explore porosity defects in CFRP. Multi-mode visualization, including an A-scan, B-scan, C-scan, and tomography scan, employed a focused ultrasonic transducer to detect CFRP porosity defects ranging from 0.15% to 2.33%. The ultrasonic transducer focal diameter was 1.0 mm, producing an exceptional spatial resolution for varying depths of porosity defects in CFRP at a frequency of 5 MHz. However, due to anisotropy, ultrasonic wave propagation in CFRP laminates causes dispersion and attenuation to be high for porosity-contained CFRP. This results in a reduction in beam focal diameter and weakened penetration ability. In [37] a laser ultrasonic testing (LUT) technique, which combines a laser system's flexibility and ultrasonics' sensitivity, was used to inspect defects in the CFRP composite. LUT is excited by a pulsed laser and causes thermal expansion on the sample's surface, producing ultrasonic waves in the region. LUT does not require a couplant because it is a non-contact technique, unlike conventional UT, which requires gel or water. The LUT technique can produce higher spatial resolution.

2.3. Thermography NDT

Traditionally, infrared thermography (IRT) NDT is based on utilizing an infrared camera to record infrared radiation (IR) emitted by the sample under evaluation, which reflects the temperature distribution in the examined sample [38]. Passive IRT depends on temperature differences between the two mediums. Active IRT, on the other hand, depends on external excitation, such as a laser source, to excite the sample. The basic principle of IRT is illustrated in Figure 3.

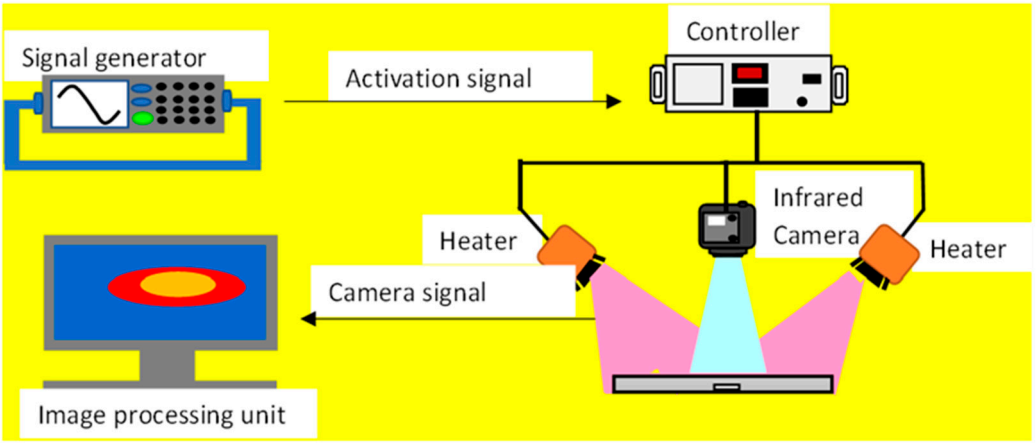


Figure 3. The basic principle of infrared thermography for defect detection.

The defective region produces a different temperature distribution from its surroundings, which generates the defect's shape. In [39], laser thermography techniques were employed to examine delamination defects in CFRP. A semiconductor laser was used for thermal simulation in this method to excite the surface of the specimen. A thermal camera was employed to record the exciting thermal heat and evaluate the depth and size of the defects. The resulting thermograms revealed a deep crack in the CFRP sample. However, raising the laser beam density to improve the chance of defect detection on deep surfaces exposes the sample to the danger of permanent damage. In [40], the authors estimated defects in CFRP material composites using vibro-thermography (VT) and terahertz (THz) imaging. For THz imaging, a high-resolution detector is used for a simple peak-time shift to detect defects on the surface and subsurface of CFRP. Mechanical vibrations transfer sound energy deeper into the CFRP sample. An infrared (IR) camera records the flaws when heat energy is conducted through the surface. Two additional postprocessing techniques, namely principal component analysis and the Fourier transform [41] are used to process the IR camera's data further. The frequency domain amplitude and phase images were evaluated using the Fourier transform technique [42]. Both methods improved defect detection in CFRP, significantly reducing noise. However, due to heat dispersion in three dimensions, the limitation of vibro-thermography (VT) raw images have blurry edges. The electrical conductivity of CFRP makes it challenging for THz imaging to penetrate deeper layers of the material. In [43], the authors proposed new fiber thermography with a laser homogenizing technique to evaluate delamination defects in CFRP. Laser illumination was excited on the sample to evaluate the temperature field change. The raw thermal images of the laser-irradiated specimen were classified into two groups. Defect detection in the thermal image becomes challenging due to laser noise. The noise was removed by using the principal component analysis (PCA) algorithm, and two main features were revealed. The PCA algorithm improves image processing of laser thermography's ability to detect delamination defects in CFRP. Nevertheless, defect detection in thermal images is challenging due to laser noise. The radiography technique is proposed to overcome the drawbacks of the thermography technique to detect delamination defects in CFRP composites.

2.4. Radiography NDT

The X-ray inspection method is a radiography evaluation used to differentiate the noise of permeating radiation in materials [44]. Figure 4 illustrates a simple radiography setup. The X-ray approach employs a short radio wave of electromagnetic radiation to capture defect regions on the sample under test (SUT) [45]. X-ray microcomputed tomography (XCT) is utilized to characterize damage in CFRP laminates, and the defect's inner geometry component is presented in 3D format by the technique [46]. However, the XCT approach could not find defects below the physical resolution of the inspected sample [47].

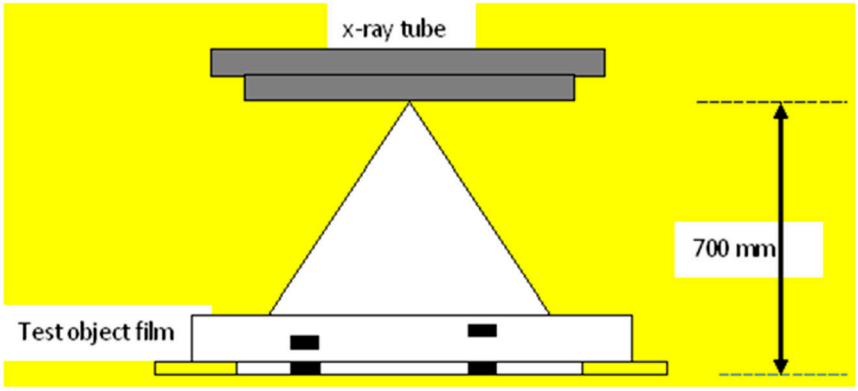


Figure 4. A basic setup of radiography.

In ref. [48], the edge-illumination X-ray phase-contrast imaging (the EI-XPCI) method was employed to compare the impact damage in the CFRP sample. This method was used to make performance analyses with traditional techniques. The conventional radiography contrast agent can see cracks in CFRP. However, this method requires a direct path between the point of impact and the damaged region to permit the contrast agent to reach a specific segment. The limitation of the technique can be subdued by applying the EI-XPCI approach, which depends on the existence of an interface in the specimen generated by impact damage. Nevertheless, prior knowledge of traditional contrast of radiography agents is required. Similarly, in [49] a different method called dark-field X-ray imaging was proposed to detect microcracks in CFRP samples. This technique uses qualitative and quantitative approaches to characterize microcracks in CFRP samples. The outcomes were compared with other techniques. The combined techniques can detect defects in CFRP. However, low-resolution traditional XCT could not detect errors in a problematic region. However, due to image-imposed noise, dark-field contrast (DFC) imaging cannot identify flaws perpendicular to grating. Thus, the laser shearography technique has a better performance than previously discussed techniques.

2.5. Laser Shearography NDT

The laser shearography (LS) technique uses an optical source based on laser speckle pattern interferometry. LS is used to inspect defects in CFRP composites utilizing coherent and monochromatic laser light to illuminate the sample. The reflection of light from rough surfaces reveals defective regions. Figure 5 illustrates the basic working principle of this technique. Digital shearography (DS) is used to inspect delamination defects in CFRP composites, where thermal loading is utilized to illuminate the sample under test. The DS technique reveals CFRP defects when two distortion states are compared for the inspected sample. This technique has the benefits of full-field and non-contact measurement, as well as its ability to detect defects in CFRP composites [50]. Mohamad et al. applied the DS technique for subsurface defect detection in polymer material by employing various loading methods. Thermal loading easily reveals cracks due to its non-contact nature. Moreover, tiny crack detection requires more loading methods to be applied [51]. Additionally, Mikhail et al. utilized the shearography technique to inspect the honeycomb CFRP panel. This

method is used to detect barely visible impact damage (BVID) on the sample. A thermal loading approach was applied to the sample, and laser light was employed as a coherent illumination source. The test results revealed that the energy impact of 1 joule does not generate damage using shearography testing; however, impact damage with energy from 2 to 5 joules results in the distortion of BVID in CFRP composites [52].

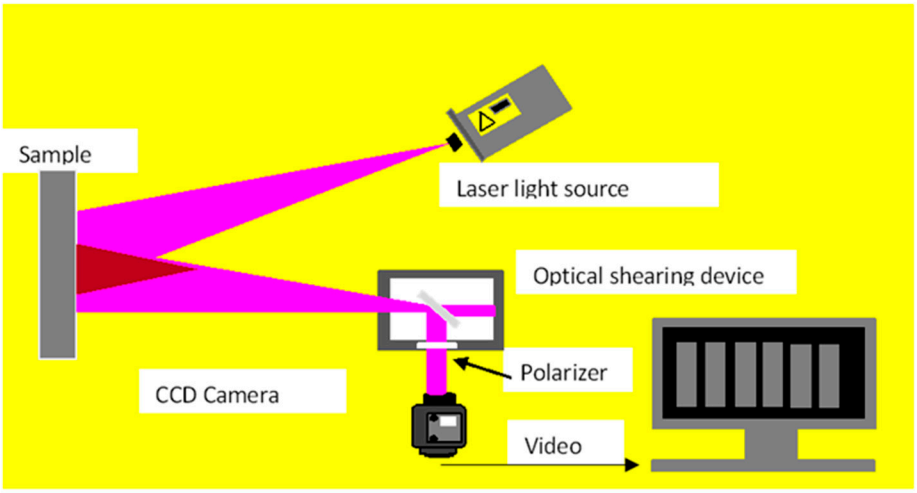


Figure 5. The basic setup of Laser Shearography.

In ref. [53], on the other hand, employing shearography to inspect defects in CFRP composites using spatially modulated thermal excitation was proposed. This technique investigates global and local heating of thermal modulation to improve defect detection in CFRP. A laser beam illuminates the sample's surface, producing a speckled pattern. A thermal infrared camera is used to assess the sample's transient temperature and detect defects in the composite. The result demonstrates that defects in the sample increase with local rather than global heating. However, the defect detection efficacy for local heating can differ significantly depending on the heating positions. Nevertheless, local heating's ability to concentrate heat greatly impacts fiber deformation close to the surface.

Additionally, to assess the method's validity, a modeling and empirical study involving boundary conditions, defect size, depth, and heating are needed. Moreover, research has been carried out to examine defect imaging in CFRP composites employing the acoustic shearography technique. This technique prepares a CFRP sample with multiple defects by executing an open-hole compression (OHC) test with various maximum loads. Coherent light is used as an exciter to illuminate the surface specimen and create an interferometry route using shearography optics. In composite materials, surface and subsurface defects are detected using the shearography sensor. By synchronizing the ultrasonic wave frequency with a stroboscopic laser, image defects sufficiently improve in quality. However, when evaluating the data, it should be noted that frequency responses of the piezoelectric transducer are not flat at frequency ranges [54]. Furthermore, digital image correlation is applied to realize a better result of defect inspection assessment in CFRP.

2.6. Digital Image Correlation (DIC) NDT

The digital image correlation (DIC) method is a non-contact approach used to evaluate defects in CFRP. The method employs a sensing mechanism to examine samples under test (SUT). The DIC approach is advantageous in regulating CFRP distortion, strain, and stress replacement [3]. This method has been utilized in several studies, such as that by Yuansong et al. [55], who applied the DIC technique to inspect damage in CFRP laminates. The DIC approach is employed to monitor surface strain in CFRP laminates. Promising results were observed when the DIC method was used to monitor damage in CFRP. The DIC method has the advantage of permitting full-field replacement to be obtained in a speedy manner, as well as strain of the inspected structures [56]. Nevertheless, pre-knowledge for

further analysis using machine learning is required. Furthermore, Ryan et al. [57] employed the DIC technique to evaluate fiber orientation in CFRP. The technique uses quasistatic mechanical loading and local thermal loading to inspect the sample. The results revealed partial fiber orientation by applying quasistatic mechanical loading with good resolution. Similarly, local thermal loading offers better excitation to evaluate fiber orientation in CFRP. However, quasistatic mechanical loading is limited by boundary conditions to regulate fiber orientation properly. On the other hand, Mahoor et al. [58] applied multi-scale DIC to detect and evaluate matrix cracks in CFRP. The application of this method involved analyzing images of the distorting composite material to visually represent the length scales and ultimately determine the extent of deformation. The method obtains images in situ, utilizing optical cameras and an electron microscope. Matrix cracks and evaluations were automatically detected through strain mapping at the sample's multi-scale. The application of this technique provides an informative approach to investigating cracks in CFRP.

The NDT techniques that are often employed in industrial applications are compared in Table 1.

Table 1. Merits and demerits of conventional NDT techniques.

Ref.	Method	Application	Benefits	Limitations
[59]	DIC	Cracks/strain	Full-field and non-contact methods. Yields the estimation of a large area of structures accurately from a distance.	DIC equipment setup is not feasible. More power is required to illuminate huge structures.
[60]	ECT	Delamination defects in CFRP	Delivers better sensitivity for defect detection visualization of delamination defects in CFRP.	background noise is higher and becomes susceptible to lift-off conditions. Cross-talk and lots of energy receiver signal due to high-frequency signal.
[61]	UT	Porosity defects	Spatial resolution for porosity differing depths are excellent. Delivers comprehensive information that is essential for porosity characterization in a composite.	Weaker penetrability due to energy dispersed because of inhomogeneity of CFRP. The inability of the C-scan to separate and resolve porosity.
[62]	IRT	Delamination	Detects defects on the surface and subsurface in CFRP. Image filtering, Contrast enhancement and Edge detection	THz waves cannot penetrate deep layers due to 3D thermal diffusions influence on vibro-thermography pictures, damage borders are blurred.
[63]	RT	Impact damage	Evaluates impact damage to a large extent of the CFRP composite.	There must be a direct path from the point of impact to the damaged features.
[52]	LS	BVID	Removes speckle noise in the maps of BVID. Local heating offers good defect detection efficacy.	Increasing the resolution of processing time slows the technique.

The review suggests that eddy current testing is the most sensitive and effective technique for detecting delamination defects in CFRP composites. Ultrasonic testing is suitable for inspecting porosity defects, but its effectiveness is limited by the non-inhomogeneity of CFRPs and energy dispersion. Infrared thermography is effective for detecting surface and subsurface delamination defects, but it is limited by blurred boundaries due to thermal diffusion. Radiography is suitable for evaluating impact damage in CFRP composites, but it lacks a direct route from the place of impact to the damaged features. Laser shearography and digital image correlation techniques are also effective for detecting defects, but both have their limitations.

To overcome the limitations of traditional NDT methods, microwave NDT techniques have emerged as promising alternatives. Microwave NDT offers several benefits, including its non-contact nature, interaction with interior structures, and no signal processing demands. However, it is crucial to note that each technique has its limitations and requirements for effective operation, and their effectiveness depends on the specific application and the type of defect being detected.

3. Microwave NDT

The microwave NDT technique overcomes several issues that conventional NDT techniques cannot address to measure defects, such as delamination, cracks, voids, and porosity, in CFRP composites. The microwave NDT technique is sufficient to assess composite materials because the electromagnetic spectrum in the microwave frequency range can offer greater examination resolution for composite materials. Microwave signals can penetrate internal composites, such as dielectric insulation, and can be used to determine their internal structure. Despite the traditional, superior microwave performance, stand-off distance variation, poor spatial image quality, data complexity, and optimal frequency selection, which downgrade measurement geometric defects, lead to blurred defect shapes in microwave NDT methods. The following subsections explore a few microwave NDT techniques used for defect detection in CFRP, along with their benefits and drawbacks.

3.1. Microwave Transmission Line

A microwave transmission line can be used to detect impact damage in the CFRP plate, using self-sensing time-domain reflectometry (TDR) as illustrated in Figure 6. This method transfers an electric current through the sample and evaluates the electrical resistance change to detect damage. The TDR technique has been used to detect damage over a range of areas. Many electrodes are utilized, and the damage is examined using TDR and a microstrip line. The outcomes show that the self-sensing TDR approach is useful in evaluating laminated CFRP structures. Employing self-sensing TDR, damage such as cracks and delamination close to the microstrip line are identified based on the reflected signal [64]. However, self-sensing TDR cannot detect damage away from the microstrip line. Microwave NDT employing a microwave transmission line (MTL) sensor has also been demonstrated in [65]. The microwave transmission line method was employed to evaluate defects in CFRP. A change in the material's permittivity detected defects in the CFRP composite. In [66], a copper transmission line was used to detect flaws in the CFRP plate's weight position. The proposed method uses CFRP to serve as an insulating layer between the surface of the copper tape and the CFRP sample. A coaxial cable connects the copper tape and CFRP conductors at the transmission line end.

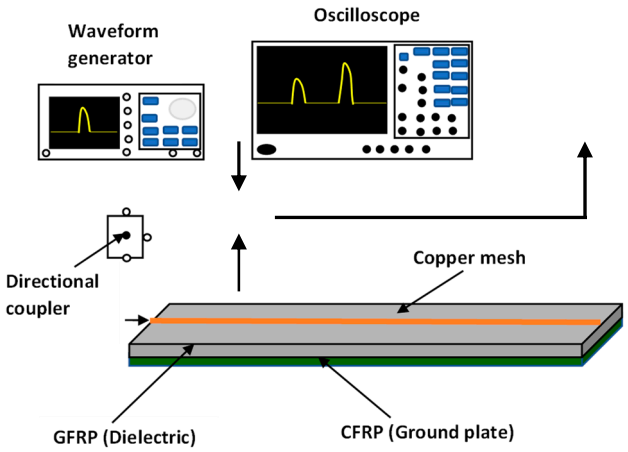


Figure 6. Time -domain reflectometry (TDR) based on the microwave transmission line (MTL).

The transmission line impedance and surface damage changes as the distance between the copper tape and CFRP surface changes. The CFRP flaw close to the transmission is detected using the TDR approach. The TDR method can detect defects accurately; however, it may produce false defects if the predicted transmission velocity is close to the speed of light, making precise measurements necessary.

3.2. Microwave Split-Ring Resonator

Split-ring resonators (SRRs) are made up of two concentric metallic rings embedded into dielectric substrates with slits etched into opposite sides. SRRs exhibit an electrical impact in response to an alternating electromagnetic field. The resonators are utilized to generate media with a left-hand and negative refractive index. The structure operates as an effective medium with negative effective permeability in a confined band above SRR resonance [67,68]. A time-varying magnetic field activates an array of electrically small SRRs. A planar transmission line and SRRs are coupled to create a transmission line for metamaterials. Due to their benefits, SRRs are used at microwave frequency to design resonant sensors for the inspection of a CFRP composite. As reported in [69], a microwave split-ring resonator (SRR) sensor was studied to inspect edge coupling in a CFRP composite. The designed sensor behaves as a sub-wavelength resonant tank when excited by a time-varying magnetic field. The sensor utilizes the reflective SRR to permit the interrogation of different sizes of multiple unit cells. The sensor could detect submillimeter defects in the CFRP composite, which offers high-resolution abilities. The simulation results confirm the sensor's ability to detect defects in the CFRP composite. The advantages of the sensor are high-resolution imaging, huge penetration, and greater area coverage. However, the structures cannot show signal propagation in a narrow band close to their resonant frequency. In [70], an innovative microwave-complementary split-ring resonator (CSRR) sensor was utilized to examine impact damage in CFRP composite. Variations in the resonator's resonance frequency allowed the sensor to identify faults in the CFRP composite. The variation in resonance frequency exposes defects in CFRP. Impact damage causes a dent to form in the sensors near the field, and the damage also causes resonance frequency to change shape. The sensor has benefits, such as high sensitivity, low cost, and an easy-to-design structure. However, the Q-factor is low and requires improvement. In [71], a modified SRR sensor for near-field microwave imaging was proposed to examine image damage in CFRP composites using the sensor. The sensing ring's edge is enlarged to optimize the sensor for imaging. The robust execution of parametric sweeps of the main sensor design parameters enhanced the sensor's Q-factor. The microwave imaging of the SRR sensor of the modified design reveals its ability to detect sub-wavelength defects in CFRP. The fundamental benefit of the SRR sensor is that it can integrate numerous unit cells on the same structure because it is inductively excited by the magnetic field [72]. The potential of a single detector to detect small cracks in CFRP composites is exceptionally high [73]. In ref. [74], several defects were evaluated, and electromagnetic characteristics were quantified using a microwave sensor. The coatings thickness in the CFRP plate composite was assessed using a novel microwave cavity resonator sensor. The sensor's cavity radius and height (h) were 4.75 mm and 40 mm, respectively. CST MW studio was used in a finite-difference time-domain (FDTD) simulation to assess the electromagnetic attributes at a resonant frequency. The relationship between changes in thickness and resonant frequency shifts was found to be linear. Using two reference examples of resonant frequencies, estimated coatings thickness was supplied directly with low errors (0.04%), demonstrating the benefit of a direct sensor implementation. In [75], a hybrid approach employing a single spiral-coil sensor, consisting of a capacitor and inductor, was proposed to evaluate defects in the CFRP composite. This technique uses a hybrid planar coil sensor to detect flaws in the CFRP sample. Line scanning was conducted on the sample under test. At lower frequency excitation, no defect was detected, indicating that the conductor is insensitive to non-conducting materials. Additionally, at higher frequency excitation, a conducting surface detects defects. However, the sensor's sensitivity requires improvement to detect defects effectively in the CFRP composite. The SRR sensor's dependency on the transmitted signal to excite the sensor and the low sensitivity of the sensor to detect defects accurately are some of the limitations that require another technique to overcome the limitations. This led to the introduction of an open-ended rectangular waveguide.

3.3. Open-Ended Rectangular Waveguides (OERWs)

The open-ended rectangular waveguide (OERW) is a fundamental radiating structure that requires a lot of effort to analyze the structure's reflection coefficient or admittance precisely. More OERWs with higher-order modes are considered to enhance the precision of results. In practical application, open-ended waveguide material characterization uses OERW probes. This technique has the unique benefit of a composition that can manage materials with several layers [76]. As a result of its advantageous features, this method is deemed suitable for characterizing numerous defects in CFRP composites, which is why it is being introduced in this particular section. In [77], the authors examine cracks in CFRP composites using an open-ended microwave waveguide imaging sensor. To inspect the CFRP defect, an electrical current is applied to the material under test. The electrical current is transferred to the material, which induces a current in the test object. The magnitude and phase of electromagnetic wave reflection reveal defect information. The reflection coefficient received from the vector network analyzer (VNA) helps to evaluates the extent and size of the defects in CFRP. The depth and size of the defects increase with the amount of modification. Furthermore, in [78], the authors proposed an ideal frequency and stand-off distance to ensure the measurement is sensitive to the presence of the disbond. A little disbonding in the range of 20 mm by 5 mm may be seen at a frequency of 24 GHz. Despite this, the microwaves' high-frequency results are limited to waveguide size. Additionally, because the former is waveguide-dependent, it has been identified that there is a compromise between penetration and spatial resolution [79]. Another technique is needed to improve the penetration and spatial resolution of the defects in CFRP composites. In [80], Ruslee et al. applied an open-ended waveguide probe to inspect CFRP image damage and fiber texture. The scanning process C-scan was employed on the sample to detect impact damage. Due to CFRP's inhomogeneous and layer attributes, texture and depth data were evaluated. The reflection coefficient of the spectrum was obtained and examined. The responses at precise frequency points of the reflection coefficient revealed diverging depth information regarding impact damage. Therefore, the chipless radio-frequency-identification sensor is introduced in the next subsection.

3.4. Chipless Radio-Frequency-Identification (RFID) Sensor

In ref. [81], a chipless RFID sensor also investigated the characterization and detection of cracks in CFRP composites. The chipless RFID tag used the ultra-wideband (UWB) radio frequency and radiating dipole antenna for crack detection in CFRP. The crack sensor can evaluate and detect two crack variables, such as crack alignment and width, when the resonant frequency of the circular microstrip patch antenna (CMPR) alters. The chipless RFID sensor has several merits, such as its capacity to operate in areas of severe temperatures and its ease, affordability, and printability. However, the chipless RFID sensor tag only picks up a crack when placed behind the resonator. Furthermore, the ID tag can also be challenging to read in other circumstances. The limitation of the discussion can be overcome by employing an ultra-high-frequency RFID sensor.

On the other hand, the authors of [82] proposed a passive ultra-high-frequency RFID sensor for crack detection and structural health monitoring (SHM). The tag sensor investigates crack characterization and detection [83]. Applying the phase change feature from dipole RFID tags, it was observed that a submillimeter crack might be discovered at 1.5 m. The sensors have several benefits, including affordability and ease of integration with wireless sensor networks (WSNs). However, resolution, size enhancement, and antenna sensing sensitivity are drawbacks that need to be overcome. For wireless crack detection in CFRP, the use of sensing multifunctional composite has been proposed. The sensor transfers an electrical signal to the sample; the damaged CFRP structure causes a change in its electrical properties. When a crack is present in the sample, it affects the CFRP's current path and narrows the structure. An evaluation of the crack in the test sample is obtained by a shift in resonance frequency induced by the length variation [84]. Furthermore, a chipless RFID sensor based on time-domain reflectometry (TDR) is designed to investi-

gate crack and localization defects in the CFRP composite. Two components comprise the sensor, namely an ultra-wideband antenna and a short transmission line. TDR-based crack detection and localization implementation in CFRP composites use a transient UWB pulse with a length of a few nanoseconds [85]. A modified TDR-based sensing system utilizing a chipless RFID technique is developed. The modified technique uses super-wide band (SWB)-based interrogation. The sensing system can precisely differentiate and detect a crack in CFRP composite, even close to the sensing antenna. The sensor provides an improved resolution, which offers precise crack detection in CFRP using TDR [86]. The sensor has several drawbacks, including the incapability of chipless RFID sensor tags to detect cracks when positioned behind the resonator, low resolution and size enhancement, and antenna sensing sensitivity. Furthermore, the ID tag may encounter challenges when reading in certain circumstances. The coupled spiral inductor can be a good alternative to address the limitations of the above sensor. The sensor offers better resolution and higher sensitivity to detect defects.

3.5. Microwave-Coupled Spiral Inductors

The coupled spiral inductor is used to inspect defects in CFRP composites. The coupled spiral inductor is employed to inspect defects in CFRP, such as delamination, matrix crack, buried holes, and disbonds as illustrated in Figure 7 [87]. In [88], the authors studied a spatial image of defects in CFRP using the coupled spiral inductor sensor. The sensor was connected to the vector network analyzer to obtain the magnitudes of transmission coefficient (S_{21}) required to generate a 2D image.

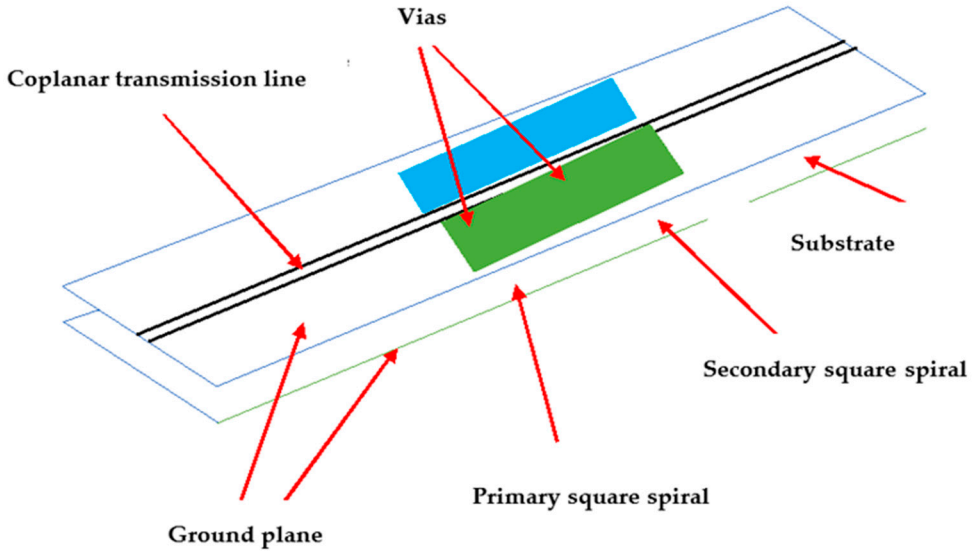


Figure 7. Simple coupled spiral inductor sensor.

Nevertheless, because of the diffraction, the coupled spiral inductor technique is inadequate for geometrical evaluations of defects at the edge, which extends to the non-defect zone. In [89] the authors proposed a new electromagnetic coupled spiral inductor (CSI) to investigate defects in CFRP. The sensor uses the electromagnetic signal to evaluate the defects in CFRP. The sensor scans the sample at distinct excitation frequencies to examine the defects. The results of the scanning revealed the presence of defects in CFRP. The sensor was able to detect resin microfractures and delamination in CFRP. The benefits of the sensor are low power consumption and user-friendliness, as well as being less expensive.

In ref. [90], a printed circuit board (PCB)-based planar spiral coil was proposed to improve defect detection in CFRP. This method scans the CFRP sample using an excitation frequency of 65 MHz to detect defects. The results revealed that the technique is more effective in detecting impact damage in CFRP laminate. The technique is direct, versatile, and affordable for detecting defects in CFRP. However, the approach produces data scans

with limited resolution and a low signal-to-noise ratio. In [91], a PCB-based T-R probe technique was introduced to evaluate fiber orientation and detect defects in CFRP. The signal shifts in the sample utilize an excitation current to drive a transmitter coil of variable frequency, while a pickup system is coupled to a receiver coil. The technique uses drive frequency and lift-off length to detect defects in CFRP at varying values. At 30 MHz, the drive frequency is used to scan the CFRP's orthogonal woven laminate, and crack defects are detected. The lift-off length of various values is introduced to inspect CFRP flaws. The results indicate a reduction in the lift-off length image of the defects. Additionally, it becomes difficult to detect defects in CFRP when the lift-off length rises. Lower-driving-frequency scan images cannot be seen, while a higher frequency improves the signal-to-noise ratio and produces better images. However, greater frequency influences skin depth, reducing penetration depth and leaving the system vulnerable to electromagnetic interference. In [92], a brand-new electromagnetic method based on power loss was presented to inspect CFRP. This method uses a brand-new probe that analyzes CFRP laminate defects at a low frequency of 750 kHz. This approach examines the distribution of heat at the point on the surface of CFRP laminates by heating the sample at both ends of the defect with a microprobe. The information shows high-precision defects and can be detected in CFRP laminates using a probe operating at a 750 kHz frequency. However, the novel method's detection accuracy is improved by higher excitation frequency. The high frequency is also likely to result in a shallow skin depth because it exposes the system to electromagnetic interference and causes background noise, reducing the novel technique's efficiency.

Table 2 presents a summary of various microwave NDT techniques. The microwave transmission line sensor has demonstrated promising advancements in detecting near-surface flaws and estimating material properties. However, its effectiveness is hampered in non-conducting materials due to low permittivity, rendering defect detection unpredictable. Similarly, the SRR sensor can detect near-surface microcracks with high reliability, but its performance depends on the ability of the transmitted signal to excite the SRR sensor through the tested material, making it less sensitive in materials with low permittivity. CSI inspection provides appropriate detection of various defects, but the estimation of defect detection is highly complex. The dispersive nature of the edges of the defect causes the defect-free zone to widen, leading to an erroneous spatial image. Additionally, determining the precise defect size is challenging due to significant contact between faults and defect-free zones. Microwave OERW sensors also offer a reliable signal interaction with layers of various structures.

Table 2. Merits and demerits of microwave NDT techniques.

Ref.	Technique	Advantages	Disadvantages
[93]	OERW	One-sided evaluation. Non-contact testing method.	Restricted penetration due to high-frequency resolution.
[94]	MTL	Sensitive to detecting defects of near-surface. One-site examination.	Restricted to deep defects. Not suitable for surfaces of irregular shape.
[69]	SRR	High sensitivity to near-surface detection of microcracks	It is suitable for conductive material only. For excitation, the internal magnetic circuit is dependent.
[69]	CSI	Buried holes, cracks, and delamination defects are detectable	Spatial image has inferior quality and blurred defect shape unsuitable for geometrical measurements of defects.
[95]	Chipless RFID	Ability to detect and characterize the defect. Ability to work in an extreme temperature environment.	Only detects cracks positioned behind the resonator sensor. The ID tag is troublesome to read in certain conditions.

Nevertheless, the success of OERW imaging is hindered by the choice of stand-off distance and frequency points, necessitating prior knowledge of these parameters to achieve high-quality imaging and reliable inspection. Furthermore, delamination defects in CFRP

composites can be evaluated using open-ended waveguide imaging. However, the waveguide size is reduced due to the high frequency of the microwave spectrum, and the spatial resolution and penetration depth are dependent on waveguide size, leading to degraded precision.

RFID sensors offer advantages such as affordability, printability, ease of use, and temperature resistance, and they can be used to analyze and detect cracks in CFRP composites. However, the defects in the sensor tag only manifest as cracks when placed behind the resonator sensor, and precise identification of conditions using the ID tag is challenging.

Signal processing and artificial intelligence can be integrated with conventional microwave NDT techniques to address issues of low sensitivity to defect detection and unreliable defect estimations. The spatial penetration and sensitivity of traditional microwave NDT methods can be improved by employing hybrid models of signal processing and artificial intelligence. However, data analysis becomes complex due to variations in stand-off distance and the selection of optimal frequency spots, making it difficult to determine the size, depth, and location of defects.

4. Conclusions

The present review paper focuses on the utilization of traditional nondestructive testing (NDT) techniques for detecting and assessing defects in carbon-fiber-reinforced polymer (CFRP) composite structures. Traditional NDT techniques are crucial in factory settings during production or in-service inspections to ensure the high output of top-quality products and the prompt identification of hazardous defects, thereby preventing system failure. However, traditional NDT methods face limitations in terms of their field penetration capabilities, which reduce their effectiveness in investigating CFRP composite materials. Eddy currents, radiography, ultrasonic testing, thermography, magnetic particles, and shearography are examples of traditional NDT techniques. To overcome these limitations, microwave NDT methods have been proposed as alternative approaches. This review paper covers a range of microwave NDT sensors, including microwave-coupled spiral inductors, MTL sensors, microwave SRR sensors, microwave antenna open-ended rectangular waveguide, open-ended waveguide imaging, and chipless RFID sensors. The microwave NDT sensors possess several benefits, such as one-sided inspection capability, low power consumption, affordability, and ease of use. This paper provides a comprehensive comparison of microwave NDT methods with NDT techniques commonly used in industrial applications. To address the challenges associated with microwave NDT techniques, the following recommendations have been proposed:

1. Hybrid microwave NDT methods that utilize artificial intelligence and signal preprocessing could enhance poor spatial imaging.
2. Selecting appropriate microwave NDT methods based on frequency and stand-off distance could improve sensor sensitivity to detect defects in CFRP composite.
3. The use of paired spiral inductors sensors with lower frequencies for penetrating conductive materials could improve the detection of delamination defects in CFRP, and sensitivity could be increased by incorporating ferromagnetic materials, such as ferrite coil and ferrite yoke in the sensor design.

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