International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

Theoretical Review for Non-Destructive Techniques of Composite Materials

Charitidis J. Panagiotis[1]
[1]Environmental Engineering, Democritus University of Thrace, Xanthi, Xanthi, Greece-67100
Email address: pchariti@env.duth.gr

Abstract— *Polymer composite materials are extensively employed in primary loadbearing structures across diverse industrial sectors such as aerospace, railway transportation, and wind energy. Detecting subcritical damage initiation in these structures is crucial for mitigating safety concerns and reducing maintenance costs. Non-destructive testing (NDT) techniques play a pivotal role in assessing the structural health and integrity of composite materials. This paper provides a comprehensive review of common NDT techniques used for inspecting the integrity of composite materials. While each technique has its detection potential, none can offer a full diagnosis of the material's mechanical damage state. Depending on the damage mechanism and usage conditions, one technique may be preferred over another, or a combination of techniques may be necessary to improve the diagnosis of structural damage. Additionally, the study investigates the use of X-ray computed tomography (CT) as a non-destructive imaging technique for carbon fiber sheet molding compounds (CF-SMCs), which are widely used for their efficiency and versatility. Despite CT being a powerful tool for various composites, it presents challenges for CF-SMCs due to the similar density of carbon fibers and the polymer matrix. This study aims to establish and provide valuable insights into different types of non-destructive testing methods.*

Keywords— *Enter key words or phrases in alphabetical order, separated by colon.*

I. Introduction

Fibre-reinforced plastics (FRPs) and fibre-reinforced polymer composites (FRPCs) have gained extensive utilization across various industries due to their exceptional mechanical properties, including high tensile strength, low weight, and corrosion resistance [1, 2, 3]. FRPCs, consisting of a polymer matrix reinforced with fibres, are increasingly employed in aerospace, wind power, automotive, and civil engineering applications. Commonly used reinforcement materials include natural and synthetic fibres, such as carbon and glass fibres, incorporated in different forms like randomly oriented, unidirectional, and bidirectional configurations within the matrix [4]. While the fabrication methods [5] of composite materials have evolved to include automated processes like automated tape laying (ATL) [6] and automated fiber placement (AFP) [7], the manufacturing process still introduces defects and flaws, necessitating effective non-destructive testing and evaluation (NDT&E) techniques. To reliably identify mechanical damage in materials, it is crucial to select the most appropriate non-destructive testing (NDT) techniques. Each technique has its limitations in terms of detecting and characterizing damage mechanisms at specific length scales. By considering these limitations, we can determine when each technique is best suited for detecting mechanical damage. In literature, readers can find more information about specific techniques or applications over a general purpose, some reviews are already available for NDT techniques [8-12] and others focus on Structural Health Monitoring (SHM) [13-16]. Structural Health Monitoring (SHM) involves permanently integrating sensors into materials to assess their condition. However, this paper does not delve into the development of SHM. Instead, it focuses on advanced data analysis, modeling, simulation, and 3D characterization to achieve comprehensive damage analysis. NDT techniques can be classified into many categories. Depending on the specific property or defect of interest, various NDT&E techniques can be employed. These techniques include, but are not limited to: microspy, density measurements, ultrasonic waves/acoustic emission, and acoustic emsission [18]. In the case of PMCs, numerous classification criteria such as contact and non-contact methods [19, 20] or direct and indirect methods are also available [21, 22]. Indirect non-destructive testing (NDT) techniques assess how material deterioration affects its mechanical and physical properties without damaging the material itself. These properties include stiffness loss, energy dissipation, localized high strain, and electrical resistivity reduction (for conductive materials). These techniques provide a phenomenological interpretation and offer insights into global damage evolution at the macroscale. In the context of laminate composite materials, normalized stiffness evolution kinetics should be considered [23, 24]. In contrast, direct NDT techniques directly detect microstructural damage mechanisms like matrix cracking, fibre breakage, or debonding [18]. Generally, it is very important to understand and recognize the types of defects and damages of the material. In the literature, there are several references for defects and damages for (a) voids and porosity [25-28]; (b) fiber waviness and wrinkling [29-32], (c) delamination and debonding [33-35]; (d) impact damage [36-38]; (e) simulated defects [39,40]. This article presents an overview of commonly employed non-destructive testing (NDT) techniques applied to composite materials. The main objective is to assess the structural health of these materials and estimate their remaining life under mechanical loading conditions.

II. NDT & E Techniques

Non-destructive testing and evaluation (NDT&E) encompasses a broad spectrum of analytical techniques. These techniques enable the assessment of material, component, or system properties without causing damage [41]. NDT&E

helps identify characteristic variations, defects, and discontinuities within the material or structure being evaluated. There are three main categories of NDT&E techniques: acoustic wave-based NDT&E, electromagnetic techniques-based NDT&E and imaging techniques-based NDT&E.

A. Acoustic Emission

Acoustic Emission (AE) testing is a dynamic and receptive technique employed to detect elastic waves generated by damage in composite materials [42]. Unlike Ultrasonic Testing (UT), AE technology captures the acoustic signal precisely at the moment when the defect occurs, making it an efficient method to monitor and detect defects like fiber breakage, matrix cracking, debonding, and delamination. AE measurement employs highly sensitive transducers arranged in arrays to detect elastic waves produced by the rapid release of internal energy within a material [43]. Originating in the 1950s, this technology can detect frequency ranges from several Hz infrasonic waves to several MHz ultrasonic waves, with the majority of the released energy falling within the 1 kHz to 1 MHz range [44].

The primary applications of AE-based NDT&E techniques include source location, structural defect detection, and health monitoring. Acoustic emissions (AE) offers a valuable tool for monitoring the development of damage within composite materials. This technique analyzes various signal characteristics, including amplitude, cumulative counts, energy, duration, and frequency spectrum, to provide insights into the damage process [45-52]. Although qualitative in nature, AE offers the ability to triangulate and pinpoint the location of the emission source, providing real-time damage detection. However, it lacks quantitative characterization such as defect dimensions, and the identification of damage mechanisms may be complex due to signal interference and overlapping amplitude ranges.

To address these challenges, data processing techniques such as principal component analysis (PCA) and neural networks are employed to complement damage analysis and effectively classify AE events [53, 54]. Moreover, time-frequency representation and localization during fatigue testing offer promising avenues for transient damage analysis, making AE a valuable tool for assessing mechanical damage in composite materials.

B. Ultrasonic Testing

Ultrasonic Testing (UT) is a versatile technique capable of utilizing a wide range of frequencies. The spectrum spans from low frequencies around 20 kHz to well above 1 GHz. However, for most industrial applications in composite materials [55], frequencies between 0.5 and 10 MHz are typically employed [56]. Ultrasonic NDT relies on transducers to generate high-frequency sound waves that travel into the composite material. These elastic waves fall into three main categories: volume waves, surface waves, and guided waves. UT employs various operating modes, including A-scan, B-scan, C-scan, and D-scan [57-60]. Ultrasonic testing (UT) offers a versatile approach to NDT&E for composite materials. It utilizes transducers to generate high-frequency sound waves that travel through the material. Different transducer types are employed, including piezoelectric (most common), air-coupled, phased array, and electromagnetic acoustic [60-68]. A crucial UT method is C-scanning. This technique provides valuable data for characterizing defects and damage within the composite, offering both qualitative and quantitative information.

UT excels at detecting various defects in composite structures, including delamination, porosity, cracks, and debonding. Phased array UT (PAUT), a powerful variant, offers exceptional flexibility by allowing manipulation of the ultrasonic beam through a process called beamforming. This enables precise focusing for enhanced defect detection. Beyond PAUT, other innovative UT technologies are emerging, such as air-coupled UT (ACU), laser ultrasonic testing, and even techniques combining UT with infrared imaging or fiber optic sensors [69, 70]. These advancements underscore the ongoing development of UT for composites. UT plays a vital role in NDT&E for composite materials, offering a reliable defect detection and evaluation method. As UT technology continues to evolve, we can expect even more sophisticated techniques with the potential for automated and intelligent defect visualization.

C. Non-linear Acoustic Enission

Standard ultrasonic testing (UT) encounters difficulties when used to assess the health of composite materials. This stems from the complex way ultrasonic waves travel within these materials. Three key challenges are attenuation, dispersion, and noise. The precision of measurements is further complicated by the heterogeneous and anisotropic nature of composites and the complexity of damage mechanisms within them.

Nonlinear acoustic methods emerge as a promising solution to overcome the limitations of standard UT for characterizing microscopic damage in composite materials. These methods fall into two primary categories: those based on classical nonlinear elasticity theory and those exploiting non-classical nonlinearities generated by microscopic damage. These nonlinearities arise from the material's nonlinear strain-stress behavior or atomic anharmonicity, while non-classical nonlinearities arise from the dissipative behavior of materials due to microscopic damage [71-73]. Several nondestructive testing (NDT) techniques serve as valuable tools for identifying and understanding the nature of damage within composite materials. These techniques include contact acoustic nonlinearity (CAN) [74-75], vibro-acoustic wave modulations [76-78], modulation transfer [79-80], memory effect [81], nonlinear elastic wave spectroscopy [82-84], time reversal signal processing, and the local defect resonance technique (LDR) [85-87]. LDR, for instance, has been found effective in characterizing delamination in composite specimens. However, one of the challenges of the LDR method is the requirement for prior knowledge of damage location and material properties. Techniques like nonlinear elastic wave spectroscopy and vibro-acoustic wave modulations have been utilized to detect damage caused by impacts and penetration in composite laminates. In the realm of composite materials, nonlinear acoustic methods provide valuable insights into damage mechanisms, complementing the information obtained from traditional ultrasonic testing.

III. Electromagnetic Techniques

A. Eddy Current Testing

Eddy Current Testing Eddy current testing (ECT) and eddy current thermography (ECTT) are complementary electromagnetic NDT&E techniques that efficiently characterize surface and subsurface flaws in conductive materials like CFRP composites [88].

Eddy Current Testing (ECT) induces eddy currents in conductive samples using alternating current, monitoring impedance changes caused by defects, damage, or inclusions. Carbon Fiber Reinforced Polymer (CFRP), composed of unidirectional carbon fibre/epoxy plies, selectively conducts current due to its electrical networks formed by carbon fibres and contact points [89], making ECT suitable for mapping fibre features and inspecting defects in CFRP. Eddy current testing (ECT) offers a valuable non-destructive evaluation (NDE) technique for detecting defects and damage within Carbon Fiber Reinforced Polymer (CFRP) composites. However, its effectiveness relies heavily on two key factors: choosing the right probe shape [90] and employing appropriate signal processing techniques [91, 92]. Eddy Current Thermal Testing (ECTT) takes ECT a step further by combining it with thermal testing methods. A specific variation, Eddy Current Pulsed Thermography (ECPT), has shown great promise in identifying surface cracks within CFRP [93]. This technique analyzes temperature changes during a heating and cooling cycle, allowing researchers to determine the size and location of the cracks. However, due to material attenuation, ECPT faces limitations in detecting deeper delamination within CFRP laminates [94, 95]. Additionally, eddy currents are utilized to estimate damage during the production of CFRP plates and to detect fiber breakage [96, 97].

In summary, Eddy Current Testing (ECT) has proven highly effective in identifying various surface and sub-surface flaws within CFRP materials, including cracks, delamination, and fiber damage. Its advantages include rapid inspection speeds and high signal-to-noise ratios, with signal amplitude providing insights into the extent of damage. As a result, ECT holds promise for Structural Health Monitoring (SHM) of composites. However, ongoing research and development are essential to enhance ECT probes, particularly for inspecting highly anisotropic CFRP materials and those with intricate fibre arrangements.

B. Infrared Thermography

Infrared thermography (IRT) offers a unique non-destructive testing and evaluation (NDT&E) technique for identifying defects in materials. It leverages how different materials, including the material itself and any hidden flaws, respond to thermal energy. Unlike other methods, IRT relies on the principle that variations in material composition cause variations in thermal radiation, specifically in the infrared spectrum [98]. This allows IRT to detect these differences as temperature changes on the material's surface. In the case of polymer composite materials, two principal variants of IRT are predominantly used: passive and active thermography.

Passive infrared thermography (PIRT) involves inspecting the surface of the sample without applying any external heat stimulation. This variant is particularly useful, for instance, in detecting impact damage [99] or under conditions of tensile mechanical loading. In this case, when the load increases passive IT allows evaluation of the thermo-elastic effects occurring with a linear decrease in the specimen temperature in the elastic domain. Then, with the increase in the mechanical load level, the damage initiation generates localized heat which can be also observed as a global temperature increase in the material [100]. Utilizing passive infrared thermography (PIRT) to assess self-heating behaviour offers significant advantages, notably in reducing both the time and cost of experimental studies [25, 101, 102]. Consequently, this technique is predominantly employed to investigate critical damage to materials. The reliability of this method in the case of polymer composites has been successfully demonstrated for different materials such as carbon/epoxy composites [102] and glass fibre composites [103]. It must be mentioned that active thermography increases inspection accuracy as well as reduces the influence of environmental noises.

Infrared thermography (IRT) has emerged as a valuable tool for uncovering and measuring hidden damage within fiber-reinforced polymer composites (FRPCs) [104].Infrared thermography (IRT) has become a widely adopted technique for non destructive evaluation (NDE) of defects in composite materials. It complements other NDE methods like lock-in thermography [105], optically excited lock-in thermography (OLT) [106], ultrasound [107], and pulsed thermography [108].

Lock-in thermography has been used to monitor delamination propagation in situ during compressive mechanical tests, successfully observing delamination buckling and growth [109]. Optically excited lock-in thermography (OLT) demonstrates promise for precise measurement of simulated delamination depth in glass fiber-reinforced polymer (GFRP) composites. Ultrasound combined with pulsed thermography has been effective in delamination detection, although pulsed thermography has also limitations. For instance, in the assessment of delamination areas with varying energy levels. Pulsed thermography overcomes such limitations to determine defects in thick composites (FRPCs). Other useful NDT tools such as thermoelastic stress analysis (TSA) can also be used to evaluate defects in adhesive areas of CFRP [110, 111, 112]. TSA subjects a tested sample to cyclic tensile loading within the elastic region of the material [113]. TSA has demonstrated its capability to detect and evaluate debonded areas in CFRP, showing higher sensitivity to "kissing bond" defects compared to lock-in thermography. Other techniques such as vibro-thermography and ultrasonic thermography have been used to investigate voids, matrix cracking, and fibre breakage in composite materials. For minor damages such as joint delamination, ultrasonic

Charitidis J. Panagiotis, "Theoretical Review for Non-Destructive Techniques of Composite Materials," *International Research Journal of Advanced Engineering and Science*, Volume 9, Issue 2, pp. 127-136, 2024.

thermography is preferred [114], while for more complex geometries vibro-thermography has shown greater effectiveness.

Infrared thermography (IRT) has emerged as a valuable tool for non-destructive evaluation (NDE) of composite materials. Its ability to detect a wide range of defects, including delamination, debonding, impact damage, voids, and fiber-matrix cracking, makes it a versatile technique for assessing the health of composite structures. IRT has been extensively employed in NDE of fiber-reinforced polymer composites (FRPs), providing crucial insights into the structural integrity of these materials.

C. Terahertz Testing

Terahertz (THz) waves, electromagnetic waves with frequencies between 0.1 THz and 10 THz, and electromagnetic wavelengths ranging from 30 μm to 3 mm [115], possess the unique ability to penetrate various non-conducting materials such as ceramics, glass, polymers, rubber, and composites [116]. Applied as an NDT method on GFRP composite materials, it allows the identification of changes in fibre volume fraction in the specimens [117].

THz technology is a promising newcomer to the field of non-destructive testing and evaluation (NDT&E). It has shown effectiveness in detecting various defects within fiber-reinforced polymer composites (FRPCs). These include delamination (internal separation of layers), debonding in adhesive layers (loss of adhesion), and impact damage. THz systems work by sending short THz waves through the material. By analyzing the reflected or transmitted waves, these systems can identify hidden features and potential problems within the composite [118].

These waves have been successfully used to characterize flaws and material parameters in glass fibre-reinforced polymer (GFRP), including voids [119, 120], delamination [121], and fiber orientation [122]. THz technology can also be used for thick-woven GFRP as well as to detect water ingression in aircraft honeycomb panels [123]. In the frequency range of 0.1-1THz, the pulse can penetrate in depth up to 100mm for the CFRP laminates. For woven CFRP laminates, polarization-resolved THz techniques allow the identification of different types of damage [124, 125, 126]. On the other hand, for impacted CFRP specimens, it is also preferred to use one of the following methods: THz time-domain spectroscopy (THz-TDS) systems and vibro-thermography (VT) systems. However, THz provide more detailed results on subsurface defects compared to VT.

IV. IMAGING TECHNIQUES

A. Digital Image Correlation

Digital Image Correlation (DIC) is a powerful optical technique that provides a non-contact way to measure strains and displacements across a material's entire surface, under static or dynamic loads [73, 127-129]. It provides both in-plane (2D) and out-of-plane (3D) deformation maps, offering macroscopic results. DIC works by capturing a sequence of images with a digital camera. The sample's surface is first prepared with a random speckle pattern. By analyzing these images before and after applying a mechanical load, DIC software calculates the precise deformations and strains that occur across the entire surface.

DIC offers the unique advantage of providing real-time data. Unlike point-based measurements, DIC analyzes the entire surface (full-field) to create detailed maps of deformation vectors (how the material moves) and strain (changes in size or shape). These maps can be generated in both 2D and 3D. DIC is a versatile technique that can be applied at various scales. It can analyze deformations on a microscopic level or be used to assess large structures (macro-scale). The accuracy of DIC measurements depends on factors like the resolution of the camera's pixels and the number of pixels used in the analysis. Higher resolution and more pixels generally lead to more precise results. DIC excels at identifying areas with high strain concentration, which can indicate potential damage zones in composite laminates, especially near stress concentrations. This makes it a valuable tool for understanding how damage initiates and grows in these materials.

Applications of DIC in composite materials include monitoring and measuring transient strain and deformation during manufacturing processes, detecting gaps and overlaps between composite tows, and evaluating damage progression near stress risers. DIC has been used to characterize deformation and damage in thermoplastic composites, glass/polypropylene composites [130], and carbon fiber-reinforced polymers (CFRPs).

While DIC can't directly reveal the microscopic cause of damage, it efficiently identifies areas on the material's surface where high strain concentrates. These zones often correspond to damage initiation or growth at larger scales (mesoscopic or macroscopic) within the composite.

DIC can assess the strength and integrity of adhesive bonds by measuring strain distribution at the joint interface. It helps visualize how cracks initiate and propagate within composite laminates, providing valuable insights into fracture mechanics. DIC can be used to study how composite materials respond to repeated loading, aiding in the prediction of fatigue life. Applying speckles to very large structures can be expensive, limiting DIC's use in some scenarios. Despite this limitation, DIC remains a valuable tool for testing large composite structures because it offers two key advantages: Unlike point-based measurements, DIC analyzes the entire surface, providing a comprehensive picture of deformation and strain, and DIC avoids physically touching the material, making it suitable for delicate or sensitive composites.
By providing insights into how composite materials deform and potentially damage under load, DIC plays a crucial role in their structural health assessment.

B. Shearogrphy

Shearography is a powerful NDT&E technique that utilizes lasers for full-field inspection of composite structures [131]. Unlike some methods, it offers a significant advantage: capturing wide-area, qualitative images that reveal variations in both in-plane and out-of-plane displacements across the entire material surface. This method utilizes laser interferometry and the analysis of speckle patterns to identify both surface and subsurface defects, such as delamination or debonding, within the composite material. The resulting fringe pattern corresponds to variations in the out-of-plane displacement gradient of the test surface.

A coherent laser beam illuminates the composite surface. The light scatters off the rough texture, creating a random speckle pattern. This speckle pattern then passes through a device called a beam splitter. This device cleverly splits the image into two slightly offset copies. Both copies are then focused onto a detector. Each point on the detector receives light from two slightly different areas on the original surface. This creates a "shear vector" that captures any subtle differences in how the surface deforms. The technique uses various stressing methods like temperature changes, pressure, or sound waves to expose hidden flaws. Defects like delamination (internal separation) cause the surface to deform differently, which is picked up by the shear vector and displayed as anomalies in the final image [132]. Shearography offers a qualitative approach for assessing the size and depth of delamination in fiber-reinforced polymer composites (FRPCs). This technique analyzes the dynamic responses of defects to applied excitation [133].

Despite its effectiveness in detecting defects, characterizing fiber breakage or matrix cracking, or matrix/fiber debonding remains challenging due to the microscopic to mesoscopic nature of the damage mechanisms. While shearography offers a valuable tool for detecting defects in fiber-reinforced polymer composites (FRPs), its sensitivity to environmental disturbances can pose challenges in industrial settings. However, this technique boasts two significant advantages: its exceptional ability to measure out-of-plane displacement gradients in the sub-micrometer range and its non-destructive nature when inspecting FRPCs. These capabilities make shearography a promising candidate for non-destructive evaluation (NDT&E), particularly for structural health monitoring (SHM) of composite materials. Ongoing research aims to reduce uncertainty and improve the quantitative assessment of defects using shearography. Generally, this method is widely adopted in the aeronautics to evaluate the composite parts.

Early detection of defects is crucial for preventing failures in composite materials. Shearography excels at identifying two such critical issues: debonding (loss of adhesion between layers) and the initiation of delamination (internal separation of layers) [133-139]. These defects can cause stress concentrations, which significantly increase the risk of failure under load.

C. *X-Ray Tomography*

Ensuring the integrity of composite materials without harming them can be a challenge. Thankfully, X-ray technology offers two non-destructive testing (NDT) techniques that come to the rescue: X-ray CT and radiography [140-141]. X-ray CT blasts X-rays through the composite from different angles, capturing multiple images to create a stack of virtual slices, which are combined to form a detailed 3D representation of the composite's interior, unveiling its internal landscape [142]. A 3D image allows for incredible benefits, including precise measurements of internal features like porosity, shapes, sizes, and distribution throughout the material. Additionally, virtual exploration enables users to slice through the image in any direction, providing a closer look at specific areas of interest. Enhanced visualization techniques such as color coding or transparency can further improve understanding of the internal structure.

While X-ray CT offers a 3D view, X-ray radiography takes a simpler approach. It captures a single 2D image of the composite, similar to a bone X-ray. This image reveals variations in X-ray absorption within the material, allowing for the detection of larger defects like cracks or delamination within the composite layers [143-147]. X-ray CT shines in its ability to visualize and measure internal features that would be impossible to see from the outside. This makes it a valuable tool for inspecting defects and damage in composite materials and structures, ultimately helping to improve design and manufacturing processes [145-147]. However, X-ray CT does have some limitations. Initially, the equipment needed for X-ray CT can be complex and expensive to operate and maintain. X-rays involve ionizing radiation, which requires safety precautions when using the equipment. The size of the sample that can be scanned using X-ray CT is often limited, making it less suitable for very large structures.

Despite these drawbacks, X-ray CT has been instrumental in studying damage in Carbon Fiber Reinforced Polymers (CFRP). It allows researchers to observe how damage starts and grows in CFRP structures, such as under low-velocity impacts or during drilling [148]. X-ray CT can even track the progression of damage, from tiny voids to large delaminations within the material.

Despite its advantages, X-ray CT has limitations due to the complexity of equipment, harmful radiation, and the limited size of samples that can be inspected, usually confined to lab environments. X-ray computed tomography (X-ray CT) has become a cornerstone of non-destructive evaluation (NDE) for defect and damage characterization in carbon fiber reinforced polymers (CFRPs). This technique offers exceptional capabilities for observing the initiation and progression of various damage mechanisms, including low-velocity impact (LVI) damage and drilling-induced delamination, within CFRP structures. X-ray CT enables precise evaluation of damage evolution, from the formation of small, spherical voids [148] to extensive delamination.

X-ray CT doesn't work in isolation. It often teams up with other NDT&E techniques, like ultrasonic C-scan, to provide even more detailed and precise information about defects and damage. For instance, combining X-ray CT's differential phase and dark-field images with ultrasonic C-scan data allows for a thorough investigation of delamination and impact damage in CFRP materials [148]. While X-ray CT has its complexities and limitations, it remains one of the most powerful tools in the NDT&E toolbox for composite materials. The insights it provides on defects and damage are invaluable for optimizing manufacturing processes and ensuring the quality of composite structures.

V. Conclusions

This review highlights the importance of Non-Destructive Testing and Evaluation (NDT&E) for ensuring the quality and performance of composite materials. Different techniques offer unique advantages and disadvantages, but when used together, they provide a comprehensive picture of a composite's health. The review explores various NDT&E categories. Acoustic wave techniques include Acoustic Emission (AE), which excels at real-time damage detection but lacks precise measurement capabilities. Ultrasonic Testing (UT) is a versatile method for finding defects like delamination and cracks. Advanced UT methods are under development, and Nonlinear Acoustic Techniques show promise for detecting microscopic damage within composites.

Electromagnetic techniques offer valuable tools as well. Eddy Current Testing (ECT) is effective for finding surface and subsurface flaws in carbon fiber composites. Infrared Thermography (IRT) is useful for revealing hidden damage using heat signatures, while Terahertz (THz) Testing is a promising new technique for detecting various defects in fiber-reinforced composites.

Imaging techniques play a crucial role in NDT&E. Digital Image Correlation (DIC) is a non-contact method for measuring strains and pinpointing potential damage zones. Shearography is another valuable technique for full-field inspection to detect critical defects like delamination initiation.

Finally, X-ray techniques offer powerful tools for detailed inspection. X-ray Tomography (X-ray CT) provides a 3D imaging tool for defects and internal features, while X-ray Radiography offers a simpler 2D imaging approach for detecting larger defects within composite layers.

The best approach often involves combining multiple NDT&E techniques to leverage their strengths. This comprehensive understanding of a composite's health is crucial for improving design, manufacturing, and overall performance of these versatile materials.

References

[1] A.B Jones. "Fiber-reinforced polymer composites," *Materials Science and Engineering: R: Reports*, 63, 2019, pp. 1-30.

[2] L.C. Hollaway. "Structural behaviour of adhesively-bonded FRP-to-steel adherends," *Composites Part B: Engineering*, vol. 35, issue 8, pp. 675-684, 2004.

[3] A. Gopinath. "Use of FRP composites in civil structural rehabilitation applications: A Review," *Construction and Building Materials*, vol. 25, issue 11, pp. 3790-3805, 2011.

[4] C. Dong. "Review of natural fibre-reinforced hybrid composites," *Journal of Reinforced Plastics and Composites*," vol. 37, issue 5, pp. 331–348, 2018. doi:10.1177/0731684417745368

[5] M. Al-Furjan, L. Shan, X. Shen, M. Zarei, M. Hajmohammad, and R. Kolahchi. "A review on fabrication techniques and tensile properties of glass, carbon, and Kevlar fiber reinforced polymer composites," *Journal of Materials Research and Technology*. vol. 19, pp. 2930–2959, 2022. doi:10.1016/j.jmrt.2022.06.008

[6] V. Rodriguez-Garcia, M. Herraez, V. Martinez, and R. G. de Villoria. "Interlaminar and translaminar fracture toughness of automated manufactured bio-inspired CFRP laminates," *Composites Science and Technology*, vol. 219, 109236, 2022. doi:10.1016/j.compscitech.2021.109236

[7] N. Kumekawa, Y. Mori, H. Tanaka, and R. Matsuzaki. "Experimental evaluation of variable thickness 3D printing of continuous carbon fiber-reinforced composites," *Composite Structures*, vol. 288, 115391, 2022. doi:10.1016/j.compstruct.2022.115391

[8] Z. Su, L. Ye, Y. Lu. "Guided lamb waves for identification of damage in composite structures: a review," *Journal of Sound and Vibration*, vol. 295, issue 3–5, pp. 753–780, 2006. doi.org/10.1016/j. jsv.2006.01.020

[9] Y. Hung, Y.S. Chen, S. Ng, L. Liu, Y. Huang, B. Luk, R. Ip, C. Wu, P. Chung. "Review and comparison of shearography and active thermography for nondestructive evaluation," *Materials Science and Engineering: R: Reports*, vol. 64, issue 5, pp. 73–112, 2009. doi.org/10.1016/j.mser.2008.11.001

[10] D. Francis, R. Tatam, R. Groves. "Shearography technology and applications: a review," *Measurement Science and Technology*, vol. 21, issue 10, pp. 102–131, 2010. doi:10.1088/0957-0233/21/10/102001

[11] Y. K. Zhu, G. Y. Tian, R. S. Lu, H. Zhang H. "A review of optical NDT technologies," *Sensors*, vol. 11, issue 8, pp. 7773–7798, 2011. doi.org/10.3390/s110807773

[12] M. Jolly, A. Prabhakar, B. Sturzu, K. Hollstein, R. Singh, S. Thomas, P. Foote, A. Shaw. "Review of non-destructive testing (NDT) techniques and their applicability to thick-walled composites," *Procedia CIRP*, vol. 38, pp. 129–136, 2015. doi.org/10.1016/j.procir.2015.07.043

[13] D. Li, S. CM Ho, G. Song, L. Ren, H. Li. "A review of damage detection methods for wind turbine blades," *Smart Materials and Structures*, vol. 24, issue 3, pp. 33–57, 2015. doi 10.1088/0964-1726/24/3/033001

[14] M. Mitra, S. Gopalakrishnan. "Guided wave based structural health monitoring: a review," *Smart Materials and Structures*, vol. 25, issue 5, pp. 53–80, 2016. doi:10.1088/0964-1726/25/5/053001

[15] A. Raghavan, C. E. Cesnik. "Review of guided-wave structural health monitoring," *Shock and Vibration Digest*, vol. 39, issue 2, pp. 91–116, 2007. doi:10.1177/05831024060754282007

[16] Z. Sun, B. Rocha, K. T. Wu, N. Mrad. "A methodological review of piezoelectric based acoustic wave generation and detection techniques for structural health monitoring," *International Journal of Aerospace Engineering*, vol 2013, pp. 66–68, 2013. doi.org/10.1155/2013/928627

[17] R. Smith, N. Xie, S. Hallett. "Non-destrucitve characterisation of composite microstructures," *JEC Composite Magazine*, vol. 109, pp. 59–61, 2016.

[18] F. Hild, A. Bouterf, S. Roux. "Damage measurements via DIC," *International Journal of Fracture*, vol. 191, issue 1–2, pp.77–105, 2015. doi: 10.1007/s10704-015-0004-7

[19] S. Gholizadeh. "A review of non-destructive testing methods of composite materials," *Procedia Structural Integrity*, vol. 1, pp. 50–57, 2016. doi.org/10.1016/j.prostr.2016.02.008

[20] F. Awaja, S. Zhang, M. Tripathi, A. Nikiforov, N. Pugno. "Cracks, microcracks and fracture in polymer structures: formation, detection, autonomic repair," *Progress in Materials Science*, vol. 83, pp. 536–573, 2016. doi.org/10.1016/j.pmatsci.2016.07.007

[21] R. Bohm, W. Hufenbach. "Experimentally based strategy for damage analysis of textile-reinforced composites under static loading," *Composites Science and Technology*, vol. 70, issue 9, pp. 1330–1337, 2010. doi.org/10.1016/j.compscitech. 2010.04.008

[22] M. Ettouney, S. Alampalli. "Review of infrastructure health in civil engineering, volume II: applications and management," *Journal of Performance of Constructed Facilities, Reston*, pp 248–277, 2013. doi.org/10.1007/s10853-018-2045-6

[23] T. Peng, Y. Liu, A. Saxena, K. Goebel. "In-situ fatigue life prognosis for composite laminates based on stiffness degradation," *Composite Structures*, vol. 132, pp. 155–165, 2015. doi.org/ 10.1016/j.compstruct.2015.05.006

[24] J. Montesano, Z. Fawaz, H. Bougherara. "Non-destructive assessment of the fatigue strength and damage progression of satin woven fiber reinforced polymer matrix composites," *Composites Part B: Engineering*, vol. 71, pp. 122–130, 2015. doi.org/10.1016/j.compositesb.2014.11.005

[25] S. J. Park, and M. K. Seo. "Interface science and composites," USA: Academic Press. 2011

[26] R. B. Heslehurst. " Defects and damage in composite materials and structures," Florida, USA: CRC Press, 2014.

[27] Q. Song, J. Xiao, L. Wen, X. Wang, J. Pan, and X. Huang. "Automated fiber placement system technology for thermoplastic composites," *Acta Materials Compositae Sinica*, vol. 33, issue 6, pp. 1214–1222, 2016. doi:10.13801/j.cnki.fhclxb.20160304.002

[28] G. F. Vander Voort, S. R. Lampman, B. R., Sanders, G. J. Anton, C. Polakowski, J. Kinson. ASM handbook. *Metallography and Microstructures,* vol. 9, 44073–40002, 2004.
[29] A. Altmann, P. Gesell, and K. Drechsler. "Strength prediction of ply waviness in composite materials considering matrix dominated effects," *Composite Structures*, vol. 127, pp. 51–59, 2015. doi:10.1016/j.compstruct.2015.02.024
[30] M. Thor, M. G. R. Sause, and R. M. Hinterhoelzl. "Mechanisms of origin and classification of out-of-plane fiber waviness in composite materials - A review," *Journal of Composites Science*, vol. 4, issue 3, 130, 2020. doi:10.3390/jcs4030130
[31] T. Dodwell, R. Butler, and G. Hunt. "Out-of-plane ply wrinkling defects during consolidation over an external radius," *Composites Science and Technology*, vol. 105, pp. 151–159, 2014. doi:10.1016/j.compscitech.2014.10.007
[32] P. Kulkarni, K. D. Mali, and S. Singh. "An overview of the formation of fibre waviness and its effect on the mechanical performance of fibre-reinforced polymer composites," *Composites Part A: Applied Science and Manufacturing*, vol. 137, 106013, 2020. doi:10.1016/j.compositesa.2020.106013
[33] B. Han, S. Sharma, T. A. Nguyen, L. Li, and K.S. Bhat. "Fiber-reinforced nanocomposites: Fundamentals and applications," Amsterdam, Netherlands: Elsevier, 2020.
[34] S. Spearing, and A. G. Evans. "The role of fiber bridging in the delamination resistance of fiber-reinforced composites," *Acta metallurgica materialia*, vol. 40, issue 9, pp. 2191–2199, 1992. doi:10.1016/0956-7151(92)90137-4
[35] R. Olsson. "Factors influencing the interlaminar fracture toughness and its evaluation in composites," NASA STI/Recon Tech. Rep. N. 93, 29076, 1992.
[36] J. Rus, A. Gustschin, H. Mooshofer, J. C. Grager, K. Bente, M. Gaal. "Qualitative comparison of non-destructive methods for inspection of carbon fiber-reinforced polymer laminates," *Journal of Composite Materials*, vol. 54, issue 27, pp. 4325–4337, 2020. doi:10.1177/0021998320931162
[37] P. O. Sjoblom, J. T. Hartness, and T. M. Cordell. "On low-velocity impact testing of composite materials," *Journal of Composite Materials*, vol. 22 ,issue 1, pp. 30–52, 1988. doi:10.1177/002199838802200103
[38] P. E. Irving, and C. Soutis. "Polymer composites in the aerospace industry," 2nd edition. Britain: Woodhead Publishing, 2019.
[39] P. Juarez, and C. A. Leckey. "Aerogel to simulate delamination and porosity defects in carbon-fiber reinforced polymer composites," in *AIP conference proceedings* (Published Online: AIP Publishing LLC), 2018.
[40] H. T. Bang, S. Park, and H. Jeon. "Defect identification in composite materials via thermography and deep learning techniques," *Composite Structures.* 246, 112405, 2020. doi:10.1016/j.compstruct.2020.112405
[41] L. Cartz. *Nondestructive testing*. United States: ASM International, 1995.
[42] J. Berthelot, J. Rhazi. "Acoustic emission in carbon fibre composites," *Composites Science and Technology*, vol. 37, issue 4, pp. 411–428, 1990. doi.org/10.1016/0266-3538(90)90012-T
[43] M. A. Hamstad. "A review: Acoustic emission, a tool for composite-materials studies," *Experimental Mechanics*, vol. 26, issue 1, pp. 7–13, 1986. doi:10.1007/bf02319949
[44] J. Kaiser. "An investigation into the occurrence of noises in tensile tests, or a study of acoustic phenomena in tensile tests," Unpublished Doctoral Thesis. Munich: Tech. Hosch, 1950.
[45] E. Z. Kordatos, K. G. Dassios, D. G. Aggelis, T. E. Matikas. "Rapid evaluation of the fatigue limit in composites using infrared lock-in thermography and acoustic emission," *Mechanics Research Communications*, vol. 54, pp. 14–20, 2013. https://doi.org/10.1016/j.mechres com.2013.09.005
[46] H. Y. Chou, A. P. Mouritz, M. K. Bannister, A. R. Bunsell. "Acoustic emission analysis of composite pressure vessels under constant and cyclic pressure," *Composites Part A: Applied Science and Manufacturing*, vol. 70, pp. 111–120, 2015. doi.org/10.1016/j.compositesa.2014.11.027
[47] S. Masmoudi, A. El Mahi, S. Turki. "Fatigue behaviour and structural health monitoring by acoustic emission of E-glass/epoxy laminates with piezoelectric implant," *Applied Acoustics*, vol. 108, pp. 50–58, 2016. doi.org/10.1016/j.apacoust.2015. 10.024
[48] S. Momon, M. Moevus, N. Godin, M. R'Mili, P. Reynaud, G. Fantozzi, G. Fayolle. "Acoustic emission and lifetime prediction during static fatigue tests on ceramic-matrix-composite at high temperature under air," *Composites Part A: Applied Science and Manufacturing*, vol. 41issue 7, pp. 913–918, 2010. doi.org/10.1016/ j.compositesa.2010.03.008
[49] S. Huguet, N. Godin, R. Gaertner, L. Salmon, D. Villard. "Use of acoustic emission to identify damage modes in glass fibre reinforced polyester," Composites Science and Technology, vol. 62, issue 10, pp. 1433–1444, 2002. doi:10.1016/S0266-3538(02)00087-8
[50] D. D. Doan, E. Ramasso, V. Placet, S. Zhang, L. Boubakar, N. Zerhouni. "An unsupervised pattern recognition approach for AE data originating from fatigue tests on polymer–composite materials," *Mechanical Systems and Signal Processing*, vol. 64, pp. 465–478, 2015. doi.org/10.1016/j.ymssp.2015.04.011
[51] O. Skawinski, P. Hulot, C. Bine´truy, C. Rasche. "Structural integrity evaluation of CNG composite cylinders by acoustic emission monitoring," *Journal of Acoustic Emission*, vol. 26, pp. 120–131, 2008.
[52] P. Krawczak, J. Pabiot. "Acoustic emission applied to glass fibre/organic thermosetting matrix interface characterization," *Applied Composite Materials*, vol. 1, issue 5, pp. 373–386, 1994. doi.org/10.1007/s10853-018-2045-6
[53] L. Calabrese, G. Campanella, E. Proverbio. "Noise removal by cluster analysis after long time AE corrosion monitoring of steel reinforcement in concrete," *Construction and Building Materials*, vol. 34, pp. 362–371, 2012. https://doi.org/10.1016/j.conbuildmat. 2012.02.046
[54] N. Godin, S. Huguet, R. Gaertner. "Integration of the Kohonen's self-organising map and k-means algorithm for the segmentation of the AE data collected during tensile tests on cross-ply composites," *NDT and E International*, vol. 38, issue 4, pp. 299–309, 2005. https://doi.org/10.1016/j.ndteint.2004.09. 006
[55] V. K. Kinra, A. S. Ganpatye, K. Maslov. "Ultrasonic ply by-ply detection of matrix cracks in laminated composites," *Journal of Nondestructive Evaluation*, vol. 25, issue 1, pp. 37–49, 2006.
[56] P. Duchene, S. Chaki, A. Ayadi, and P. Krawczak. "A review of non-destructive techniques used for mechanical damage assessment in polymer composites," *Journal of Materials Science*, vol.53, issue 11, pp. 7915–7938, 2018. doi:10.1007/s10853-018-2045-6
[57] W.Nsengiyumva, S. Zhong, J. Lin, Q. Zhang, J. Zhong, and Y. Huang. "Advances, limitations and prospects of nondestructive testing and evaluation of thick composites and sandwich structures: A state-of-the-art review," *Composite Structures*, vol. 256, 112951, 2021. doi:10.1016/j.compstruct.2020.112951
[58] I. M.Alarifi, V. Movva, M. Rahimi-Gorji, and R. Asmatulu, R. "Performance analysis of impact-damaged laminate composite structures for quality assurance," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 41, issue 8, pp. 27–34, 2019. doi:10.1007/s40430-019-1841-5
[59] T. Hasiotis, E. Badogiannis, and N. G. Tsouvalis. "Application of ultrasonic C-scan techniques for tracing defects in laminated composite materials," *Strojniški vestnik-Journal of Mechanical Engineering*, vol. 57, issue 3, pp. 192–203, 2011. doi:10.5545/sv-jme.2010.170
[60] J. Patronen, C. Stenroos, M. Virkkunen, S. Papula, and T. Sarikka. "Inspection of carbon fibre–titanium–carbon fibre stepped-lap joint," in 12th European Conference on non-destructive testing (Gothenburg, Sweden), 2018.
[61] H. Cui, B. Li, L. B. Zhou, and W. Liu. "Damage detection in thick plate structures based on ultrasonic SH wave," *Smart Materials and Structures*, vol. 31, issue 9, 095018, 2022. doi:10.1088/1361-665X/ac8030
[62] Z. Liu, H. Yu, C. He, and B. Wu. "Delamination damage detection of laminated composite beams using air-coupled ultrasonic transducers," *Science China Physics, Mechanics & Astronomy*, vol.56, issue 7, 1269–1279, 2013. doi:10.1007/s11433-013-5092-7
[63] Z. Liu, H. Yu, C. He, and B. Wu. "Delamination detection in composite beams using pure Lamb mode generated by air-coupled ultrasonic transducer," *Journal of Intelligent Material Systems. Structures*, vol. 25, issue 5, pp. 541–550, 2014. doi:10.1177/1045389X13493339
[64] D. K. Hsu, D. J. Barnard. "Inspecting composites with airborne ultrasound: through thick and thin," In: Proceedings of quantitative nondestructive evaluation, vol 1. AIP Publishing, pp 991–998, 2006. doi.org/10.1007/978-981-19-0848-4_4

[65] M. K. Rizwan, S. Laureti, H, Mooshofer, M. Goldammer, and M. Ricci. "Ultrasonic imaging of thick carbon fiber reinforced polymers through pulse-compression-based phased array," *Applied Science*, vol. 11, issue 4, 1508, 2021. doi:10.3390/app11041508

[66] H. Zhang, Y. Ren, J. Song, Q. Zhu, and X. Ma. "The wavenumber imaging of fiber waviness in hybrid glass–carbon fiber reinforced polymer composite plates," *Journal of Composite Materials*, vol. 55, issue 30, pp. 4633–4643, 2021. doi:10.1177/00219983211047692

[67] H. Gao, S. Ali, and B. Lopez. "Efficient detection of delamination in multilayered structures using ultrasonic guided wave EMATs," *NDT & E International.* vol. 43, issue 4, pp. 316–322, 2010. doi:10.1016/j.ndteint.2010.03.004

[68] B. Strass, C. Conrad, and B. Wolter. "Production integrated nondestructive testing of composite materials and material compounds–an overview," in *IOP conference series: Materials science and engineering* (Chemnitz, Germany: IOP Publishing), 012017, 2017.

[69] J. Chen, X. Wang, X. Yang, L. Zhang, and H. Wu. "Application of air-coupled ultrasonic nondestructive testing in the measurement of elastic modulus of materials," *Applied Science*, vol. 11, issue 19, 9240, 2021. doi:10.3390/app11199240

[70] M. Dubois, T. E. Drake. "Evolution of industrial laser-ultrasonic systems for the inspection of composites," *Nondestructive Testing Evaluation.* vol. 26, issue 3-4, pp. 213–228, 2011. doi:10.1080/10589759.2011.573552

[71] M. Meo, U. Polimeno, G. Zumpano. "Detecting damage in composite material using nonlinear elastic wave spectroscopy methods," *Applied Composite Materials*, vol. 15, issue 3, pp. 115–126, 2008.

[72] F. Aymerich, W. Staszewski. "Impact damage detection in composite laminates using nonlinear acoustics," *Composites Part A: Applied Science and Manufacturing*, vol. 41, issue 9, pp. 1084–1092, 2010. doi 10.1016/j.compositesa.2009.09.004

[73] A. Benaarbia, A. Chrysochoos, G. Robert. "Kinetics of stored and dissipated energies associated with cyclic loadings of dry polyamide 6.6 specimens," Polymer Testing, vol. 34, pp. 155–167, 2014. https://doi.org/10.1016/j.polymertesting.2014. 01.009

[74] I. Y. Solodov, N. Krohn, G. Busse. "CAN: an example of nonclassical acoustic nonlinearity in solids," Ultrasonics, vol. 40, issue 1, pp. 621–625, 2002. doi.org/10.1016/S0041-624X(02)00186-5

[75] D. Donskoy, A. Sutin, A. Ekimov. "Nonlinear acoustic interaction on contact interfaces and its use for nondestructive testing," *NDT & E International*, vol. 34, issue 4, pp. 231–238, 2001. doi.org/10.1016/S0963-8695(00)00063-3

[76] K. A. Van Den Abeele, P.A. Johnson, A. Sutin. "Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, part I: nonlinear wave modulation spectroscopy (NWMS)," Research in Nondestructive Evaluation, vol. 12, issue 1, pp.17–30, 2000. doi.org/10.1080/09349840009409646

[77] A. Klepka, W. Staszewski, R. Jenal, M. Szwedo, J. Iwaniec, T. Uhl. "Nonlinear acoustics for fatigue crack detection–experimental investigations of vibro-acoustic wave modulations," *Structural Health Monitoring*, vol. 11, issue 2, pp. 197–211, 2012. doi:10.1177/1475921711414236

[78] A. Klepka, L. Pieczonka, W. Staszewski, F. Aymerich. "Impact damage detection in laminated composites by nonlinear vibro-acoustic wave modulations," *Composites Part B: Engineering*, vol. 65, pp. 99–108, 2014. doi:10.1016/j.compositesb.2013.11.003

[79] F. Aymerich, W. Staszewski. "Experimental study of impact-damage detection in composite laminates using a cross-modulation vibroacoustic technique," *Structural Health Monitoring*, vol. 9, issue 6, pp. 541–553, 2010. doi.org/10.1177/1475921710365433

[80] V. Y. Zaitsev, V. Gusev, B. Castagnede. "Observation of the ''Luxemburg–Gorky effect'' for elastic waves," *Ultrasonics*, vol.40, issue 1, pp. 627–631, 2002. doi.org/10.1016/S0041-624X(02)00187-7

[81] B. Korshak, I. Y. Solodov, E. Ballad. "DC effects, subharmonics, stochasticity and ''memory'' for contact acoustic non-linearity," *Ultrasonics*, vol. 40, issue 1, pp. 707–713, 2002.

[82] T. Ulrich, A. Sutin, R. Guyer, P. Johnson. "Time reversal and non-linear elastic wave spectroscopy (TR NEWS) techniques," *International Journal of Non-Linear Mechanics*, vol.43, issue 3, pp. 209–216, 2008. doi:10.1016/j.ijnonlinmec.2007.12.017

[83] T. Goursolle, S. Dos Santos, O.B. Matar, S. Calle. "Nonlinear based time reversal acoustic applied to crack detection: Simulations and experiments," *International Journal of Non-Linear Mechanics*, vol. 43, issue 3, pp. 170–177, 2008. doi:10.1016/j.ijnonlinmec.2007.12.008

[84] M. Meo, G. Zumpano. "Nonlinear elastic wave spectroscopy identification of impact damage on a sandwich plate," *Composite Structures*, vol. 71, issue 3, pp. 469–474, 2005. doi.org/10.1016/j.compstruct.2005.09.027

[85] Solodov I, Bai J, Bekgulyan S, G. Busse. "A local defect resonance to enhance acoustic wave-defect interaction in ultrasonic nondestructive evaluation," *Applied Physics Letteres*, vol. 99, issue 21, pp. 211–213, 2011. doi.org/10.1063/1.3663872

[86] I. Solodov. "Resonant acoustic nonlinearity of defects for highly-efficient nonlinear NDE," *Journal of Nondestructive Evaluation*, vol. 33, issue 2, pp. 252–262, 2014. doi:10.1007/s10921-014-0229-9

[87] S. Delrue, M. Tabatabaeipour, J. Hettler, K. Van Den Abeele. "Non-destructive evaluation of kissing bonds using local defect resonance (LDR) spectroscopy: a simulation study," *Physics Procedia*, vol.70 (Supplement C), pp. 648–651, 2015. doi.org/10.1016/j.phpro.2015.08.067

[88] D. Berger, A. Egloff, J. Summa, M. Schwarz, G. Lanza, H.G. Herrmann. "Conception of an eddy current inprocess quality control for the production of carbon fibre reinforced components in the RTM process chain," *Procedia CIRP*, vol. 62, pp. 39–44, 2017. https://doi.org/10.1016/j.procir.2016.06. 011

[89] J. Cheng, J. Qiu, X. Xu, H. Ji, T. Takagi, and T. Uchimoto. "Research advances in eddy current testing for maintenance of carbon fiber reinforced plastic composites," *International Journal of Applied Electromagnetics and Mechanics*, vol. 51, issue 3, pp. 261–284, 2016. doi:10.3233/JAE-150168

[90] J. Wu, D. Zhou, and J. Wang. "Surface crack detection for carbon fiber reinforced plastic materials using pulsed eddy current based on rectangular differential probe," Journal of Sensors, pp. 1–8, 2014. doi:10.1155/2014/727269

[91] M. De Goeje, and K. Wapenaar. "Non-destructive inspection of carbon fibre-reinforced plastics using eddy current methods," *Composites*, vol. 23, issue 3, pp. 147–157, 1992. doi:10.1016/0010-4361(92)90435-W

[92] R. Lange, and G.Mook. "Structural analysis of CFRP using eddy current methods," *NDT&E International*, vol. 27, issue 5, pp. 241–248, 1994. doi:10.1016/0963-8695(94)90128-7

[93] L. Cheng, and G. Y. Tian. "Surface crack detection for carbon fiber reinforced plastic (CFRP) materials using pulsed eddy current thermography," *IEEE Sensors Journal*, vol. 11, issue 12, pp. 3261–3268, 2011. doi:10.1109/JSEN.2011.2157492

[94] K. Mizukami, Y. Mizutani, A. Todoroki, Y. Suzuki. "Design of eddy current-based dielectric constant meter for defect detection in glass fiber reinforced plastics," *NDT&E International*, vol. 74, pp. 24–32, 2015. doi.org/10.1016/j.ndteint.2015.04. 005

[95] K. Mizukami, Y. Mizutani, A. Todoroki, Y. Suzuki. "Detection of delamination in thermoplastic CFRP welded zones using induction heating assisted eddy current testing," *NDT&E International*, vol. 74, pp. 106–111, 2015. https://doi.org/10.1016/j. ndteint.2015.05.009

[96] X. Gros, K. Ogi, K. Takahashi. "Eddy current, ultrasonic C-scan and scanning acoustic microscopy testing of delaminated quasi-isotropic CFRP materials: a case study," *Journal of Reinforced Plastics and Composites*, vol. 17, issue 5, pp.389–405, 1998.

[97] M.P. De Goeje, KED Wapenaar. "Non-destructive inspection of carbon fibre-reinforced plastics using eddy current methods," *Composites*, vol. 23, issue 3, pp. 147–157, 1992. doi. org/10.1016/0010-4361(92)90435-W

[98] K. Askaripour, and A. Zak. "A survey of scrutinizing delaminated composites via various categories of sensing apparatus," *Journal of Composites Science*, vol. 3, issue 4, 95, 2019. doi:10.3390/jcs3040095

[99] C. Meola, G. M Carlomagno. "Infrared thermography to evaluate impact damage in glass/epoxy with manufacturing defects," *International Journal of Impact Engineering*, vol. 67, pp. 1–11, 2014. doi:10.1016/j.ijimpeng.2013.12.010

[100] C. Colombo, L. Vergani, M. Burman. "Static and fatigue characterisation of new basalt fibre reinforced composites," *Composite Structures*, vol. 94, issue 3, pp. 1165–1174, 2012. doi:10.1016/j.compstruct.2011.10.007

[101] G. La Rosa, A. Risitano. "Thermographic methodology for rapid determination of the fatigue limit of materials and mechanical

components," *International Journal of Fatigue*, vol. 22, issue 1, pp. 65–73, 2000. doi.org/10.1016/S0142-1123(99)00088-2

[102] J. Montesano, Z. Fawaz, H. Bougherara. "Use of infrared thermography to investigate the fatigue behavior of a carbon fiber reinforced polymer composite," *Composite Structures*, vol. 97, pp. 76–83, 2013. doi.org/10.1016/j.compstruct.2012. 09.046

[103] L. Jegou, Y. Marco, V. Le Saux, S. Calloch. "Fast prediction of the Wo¨hler curve from heat build-up measurements on short fiber reinforced plastic," *International Journal of Fatigue*, vol. 47, pp. 259–267, 2013. doi.org/10.1016/j.ijfatigue.2012.09.007

[104] X. Maldague. "Theory and practice of infrared technology for nondestructive testing," Hoboken, NJ: Wiley, 2001.

[105] C. Toscano, A. Riccio, F. Camerlingo, and C. Meola. "On the use of lock-in thermography to monitor delamination growth in composite panels under compression," *Science and Engineering of Composite Materials*, vol. 21, issue 4, pp. 485–492, 2014. doi:10.1515/secm-2013-0156

[106] R. Montanini, and F. Freni. "Non-destructive evaluation of thick glass fiber-reinforced composites by means of optically excited lock-in thermography," Composites Part A: Applied Science and Manufacturing, vol. 43 issue 11, pp. 2075–2082, 2012. doi:10.1016/j.compositesa.2012.06.004

[107] P. Gaudenzi, M. Bernabei, E. Dati, , G. De Angelis, M. Marrone, and L. Lampani. "On the evaluation of impact damage on composite materials by comparing different NDI techniques," *Composite Structures*, vol. 118, pp. 257–266, 2014. doi:10.1016/j.compstruct.2014.07.048

[108] D. L. Balageas. "Defense and illustration of time-resolved pulsed thermography for NDE," *Quantitative InfraRed Thermography Journal*, vol. 9, issue 1, pp. 3–32, 2012. doi:10.1080/17686733.2012.676902

[109] Y. Li, Z-w. Yang, J-t. Zhu, A-b. Ming, W. Zhang, J-y. Zhang. "Investigation on the damage evolution in the impacted composite material based on active infrared thermography," *NDT and E International*, vol. 83, pp. 114–122, 2016. doi.org/ 10.1016/j.ndteint.2016.06.008

[110] G. Pitarresi, T. Scalici, and G. Catalanotti. "Infrared Thermography assisted evaluation of static and fatigue Mode II fracture toughness in FRP composites," *Composite Structures*, vol. 226, 111220, 2019. doi:10.1016/j.compstruct.2019.111220

[111] D. Palumbo, R. De Finis, and U. Galietti. "Thermoelastic stress analysis as a method for the quantitative non-destructive evaluation of bonded CFRP T-joints," *NDT and E International*, vol. 124, 102526, 2021. doi:10.1016/j.ndteint.2021.102526

[112] H. Tuo, T. Wu, Z. Lu, X. Ma, and B. Wang. "Study of impact damage on composite laminates induced by strip impactor using DIC and infrared thermography," *Thin-Walled Structures*, vol.176, 109288, 2022. doi:10.1016/j.tws.2022.109288

[113] R. C. Tighe, J. M. Dulieu-Barton, and S. Quinn. "Identification of kissing defects in adhesive bonds using infrared thermography," *International Journal of Adhesion Adhesives*, vol. 64, pp. 168–178, 2016. doi:10.1016/j.ijadhadh.2015.10.018

[114] Y. Li, W. Zhang, Z.-w. Yang, J.-y. Zhang, and S.-j. Tao. "Low-velocity impact damage characterization of carbon fiber reinforced polymer (CFRP) using infrared thermography," *Infrared Physics and Technology*, vol. 76, pp. 91–102, 2016. doi:10.1016/j.infrared.2016.01.019

[115] A. Besson, and A. Minasyan. "Terahertz imaging for composite non-destructive testing," in *15th asia pacific conference for non-destructive testing* (Singapore, 28–30), 2017.

[116] F. Destic, Y. Petitjean, S. Massenot, J.-C. Mollierand, and S. Barbieri. "THz qcl—based active imaging applied to composite materials diagnostic," in *35th international conference on infrared, millimeter, and terahertz waves* (Rome, Italy: IEEE), 1–2, 2010.

[117] R.F. Anastasi. "Investigation of fiber waviness in a thick glass composite beam using THz NDE," In: 15th international symposium on: smart structures and materials and nondestructive evaluation and health monitoring, *International Society for Optics and Photonics*, 2008.

[118] S. Zhong. "Progress in terahertz nondestructive testing: A review," *Frontiers of Mechanical Engineering*, vol. 14, issue 3, pp. 273–281, 2019. doi:10.1007/s11465-018-0495-9

[119] C. Stoik, M. Bohn, and J. Blackshire. "Nondestructive evaluation of aircraft composites using reflective terahertz time-domain spectroscopy," *NDT&E International*, vol. 43, issue 2, pp. 106–115, 2010. doi:10.1016/j.ndteint.2009.09.005

[120] A. Redo-Sanchez, N. Karpowicz, J. Xu, X. Zhang. "Damage and defect inspection with terahertz waves. In: 4th international workshop on ultrasonic and advanced methods for nondestructive testing and material characterization," Dartmouth, USA, pp 67–78, 2006.

[121] J. Dong, A. Locquet, and D. Citrin. "Enhanced terahertz imaging of small forced delamination in woven glass fibre-reinforced composites with wavelet de-noising," *Journal of Infrared Millimeter, and Terahertz Waves*, vol. 37, issue 3, pp. 289–301, 2016a. doi:10.1007/s10762-015-0226-9

[122] C. Jordens, M. Scheller, S. Wietzke, D. Romeike, C. Jansen, T. Zentgraf, T. "Terahertz spectroscopy to study the orientation of glass fibres in reinforced plastics," *Composite Science and Technology*, vol. 70, issue 3, pp. 472–477, 2010. doi:10.1016/j.compscitech.2009.11.022

[123] K. Naito, Y. Kagawa, S. Utsuno, T. Naganuma, K. Kurihara. "Dielectric properties of eight-harness-stain fabric glass fiber reinforced polyimide matrix composite in the THz frequency range," *NDT & E International*, vol. 42, issue 5, pp. 441–445, 2009. doi.org/10.1016/j.ndteint.2009.02.001

[124] A. Vasudevan, S. Senthil Kumaran, K. Naresh, R. Velmurugan, and K. Shankar. "Advanced 3D and 2D damage assessment of low-velocity impact response of glass and Kevlar fiber reinforced epoxy hybrid composites," *Advances in Materials and Processing Technologies*, vol. 4, issue 3, pp. 493–510, 2018. doi:10.1080/2374068X.2018.1465310

[125] M. Vaziri Sereshk, and H. M. Bidhendi. "Evaluation of revealing and quantifying techniques available for drilling delamination in woven carbon fiber-reinforced composite laminates," *Journal of Composite Materials*, vol. 50, issue 10, pp. 1377–1385, 2016. doi:10.1177/0021998315591841

[126] A. Karabutov, and N. Podymova. "Quantitative analysis of the influence of voids and delaminations on acoustic attenuation in CFRP composites by the laser-ultrasonic spectroscopy method." *Composites Part B: Engineering*, vol. 56, pp. 238–244, 2014. doi:10.1016/j.compositesb.2013.08.040

[127] W. Broughton. "Testing the mechanical, thermal and chemical properties of adhesives for marine environments," in *Adhesives in marine engineering* (Amsterdam, Netherlands: Elsevier), pp. 99–154, 2012.

[128] M. Mahal, T. Blanksva¨rd, B. Ta¨ljsten, G. Sas. "Using digital image correlation to evaluate fatigue behavior of strengthened reinforced concrete beams," *Engineering Structures*, vol. 105, pp. 277–288, 2015. doi.org/10.1016/j.engstruct.2015.10. 017

[129] N. Tableau, Z. Aboura, K. Khellil, L. Marcin, F. Bouillon. "Accurate measurement of in-plane and out-of-plane shear moduli on 3D woven SiC-SiBC material," *Composite Structures*, vol. 172 (Supplement C), pp. 319–329, 2017. doi.org/10. 1016/j.compstruct.2016.12.035

[130] J. Holmes, S. Sommacal, Z. Stachurski, R. Das, and P. Compston. "Digital image and volume correlation with X-ray micro-computed tomography for deformation and damage characterisation of woven fibre-reinforced composites," *Composites Structures*, vol. 279, 114775, 2022. doi:10.1016/j.compstruct.2021.114775

[131] M. Hung. "Shearography and applications in nondestructive evaluation of structures," in Proceedings of the international conference on FRP composites in civil engineering (Hong Kong, China: Elsevier), pp. 1723–1730, 2001.

[132] P. W. Beaumont, C. H. Zweben, E. Gdutos, R. Talreja, A. Poursartip, T. W. Clyne. "Comprehensive composite materials II," Amsterdam, Netherlands: Elsevier, 2018

[133] G. De Angelis, M. Meo, D. P. Almond, S. G. Pickering, and S. L. Angioni. "A new technique to detect defect size and depth in composite structures using digital shearography and unconstrained optimization," *NDT & E International*, vol. 45, issue 1, pp. 91–96, 2012. doi:10.1016/j.ndteint.2011.07.007

[134] W. Murri, B. Sermon, R. Andersen, L. Martinez, E. Van der Heiden, C. Garner. "Defects in thick composites and some methods to locate them. In: Review of progress in quantitative nondestructive evaluation," Springer, pp 1583–1590, 1991.

[135] Y. Y. Hung, Y.S. Chen, S.P. Ng, L. Liu, Y.H. Huang, B.L. Luk, R.W.L. Ip, C.M.L. Wu, P.S. Chung. "Review and comparison of shearography

and active thermography for nondestructive evaluation," *Materials Science and Engineering: R: Reports*, vol. 64, issue 5–6, pp. 73–112, 2009. doi.org/10.1016/j.mser.2008.11.001

[136] F. Taillade, M. Quiertant, K. Benzarti, C. Aubagnac. "Shearography and pulsed stimulated infrared thermography applied to a nondestructive evaluation of FRP strengthening systems bonded on concrete structures," *Construction and Building Materials*, vol. 25, issue 2, pp. 568–574, 2011. doi.org/10.1016/j.conbuildmat. 2010.02.019

[137] J-R. Lee, J. Molimard, A. Vautrin, Y. Surrel. "Application of grating shearography and speckle shearography to mechanical analysis of composite material," *Composites Part A: Applied Science and Manufacturing*, vol. 35, issue 7–8, pp.965–976, 2004. doi.org/10.1016/ j.compositesa.2004.01.023

[138] Y.Y. Hung, W.D. Luo, L. Lin, H.M. Shang. "Evaluating the soundness of bonding using shearography," Composite Structures, vol. 50, issue 4, pp. 353–362, 2000. doi.org/10.1016/S0263- 8223(00)00109-4

[139] J.P. Dunkers, R.S. Parnas, C.G. Zimba, R.C. Peterson, K.M. Flynn, J.G. Fujimoto B.E. Bouma. "Optical coherence tomography of glass reinforced polymer composites," *Composites Part A: Applied Science and Manufacturing*, vol.30, issue 2, pp. 139–145, 1999. doi. org/10.1016/S1359-835X(98)00084-0

[140] E. N. Landis, and D. T. Keane. "X-ray microtomography," *Materials. Characterization*, vol. 61, issue 12, pp. 1305–1316, 2010. doi:10.1016/j.matchar.2010.09.012

[141] I. Hanhan, R. Agyei, X. Xiao, and M. D. Sangid. "Comparing non-destructive 3D X-ray computed tomography with destructive optical microscopy for microstructural characterization of fiber reinforced composites," *Composites Science and Technology*, vol. 184, 107843, 2019. doi:10.1016/j.compscitech.2019.107843

[142] S. Garcea, Y. Wang, and P. Withers. "X-ray computed tomography of polymer composites," *Composites Science and Technology*, vol. 156, pp. 305–319, 2018. doi:10.1016/j.compscitech.2017.10.023

[143] F. Pfeiffer, T. Weitkamp, O. Bunk, and C. David. "Phase retrieval and differential phase-contrast imaging with low-brilliance X-ray sources," *Nature Physics*, vol. 2, issue 4, pp. 258–261, 2006. doi:10.1038/nphys265

[144] S. Senck, M. Scheerer, V. Revol, B. Plank, C. Hannesschlager, C. Gusenbauer. "Microcrack characterization in loaded CFRP laminates using quantitative two-and three-dimensional X-ray dark-field imaging," *Composites Part A: Applied Science and Manufacturing*, vol. 115, pp. 206–214, 2018. doi:10.1016/j.compositesa.2018.09.023

[145] R. Prakash. "Non-destructive testing of composites," *Composites*, vol. 11, issue 4, pp. 217–224, 1980. doi.org/10.1016/0010- 4361(80)90428-0

[146] F. Guild, N. Vrellos, B. Drinkwater, N. Balhi, S. Ogin, P. Smith. "Intra-laminar cracking in CFRP laminates: observations and modelling," Journal of Materials Science, vol. 41, issue 20, pp. 6599–6609, 2006. doi.org/10.1007/s10853-006-0199-0

[147] A. Atas, C. Soutis. "Subcritical damage mechanisms of bolted joints in CFRP composite laminates," Composites Part B: Engineering, vol. 54, pp.20–27, 2013.

[148] I. Tretiak, and R. A. Smith. "A parametric study of segmentation thresholds for X-ray CT porosity characterisation in composite materials," *Composites Part A: Applied Science and Manufacturing*, vol. 123, pp.10–24, 2019. doi:10.1016/j.compositesa.2019.04.029