A review of microwave testing of glass fibre-reinforced polymer composites

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Abstract

Microwave non-destructive testing has received extensive attention in recent years owing to its advantages of non-contact inspection, no need for a coupling medium or sensors attached on the object surface, a relatively easy measurement setup and no ionising radiation hazards. As an alternative method of traditional X-ray and ultrasonic testing methods, it has been used for evaluation of glass fibre-reinforced polymer composite structures. This paper provides a comprehensive overview of the microwave-based techniques for composites, including material characterisation, cure state monitoring, strain sensing, thickness measurement, near-field and far-field damage detection. Discussions on the research trends are presented.

Keywords	microwave testing; glass fibre; composites; electric permittivity; non-destructive evaluation.
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Covering letter for submission of a paper to *NDT & E International*

3 October 2018

The Editor:

NDT & E International

Iowa State University, Ames, Iowa, USA

Dear Prof. D. E. Chimenti,

We wish to submit a new manuscript entitled “*A review of microwave testing of glass fibre-reinforced polymer composites*” for your consideration.

We confirm that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere.

In this paper, we provide a comprehensive overview of the principles of microwave testing and its applications for glass fibre-reinforced polymer composites, including material characterisation, strain sensing, near-field and far-field damage detection. The microwave non-destructive testing methods have received extensive attention in recent years owing to its advantages of non-contact inspection, no need for a coupling medium or sensors attached on the object surface, an easy measurement setup and no ionising radiation hazards. The review presented here can contribute to guidance for future research work on microwave-related electromagnetic analysis and non-destructive evaluation.

The paper should be of interest to readers in the area of study of microwave non-destructive testing.

Thank you for your consideration of this manuscript.

Sincerely,

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Highlights

- An overview of the microwave-based techniques for glass fibre composites is given.
- Based on the detection principles, the methods are classified into five categories.
- The electromagnetic properties of glass fibre composites are thoroughly discussed.

A review of microwave testing of glass fibre-reinforced polymer composites

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Abstract: Microwave non-destructive testing has received extensive attention in recent years owing to its advantages of non-contact inspection, no need for a coupling medium or sensors attached on the object surface, a relatively easy measurement setup and no ionising radiation hazards. As an alternative method of traditional X-ray and ultrasonic testing methods, it has been used for evaluation of glass fibre-reinforced polymer composite structures. This paper provides a comprehensive overview of the microwave-based techniques for composites, including material characterisation, cure state monitoring, strain sensing, thickness measurement, near-field and far-field damage detection. Discussions on the research trends are presented.

Keywords: microwave testing, glass fibre, composites, electric permittivity, non-destructive evaluation.

1 Introduction

Glass fibre has comparable tensile and compressive strengths to carbon fibre. Although the stiffness is not as high as that of carbon fibre, it is much cheaper and less brittle (higher strain to failure) when used in polymer composites. Due to the lightweight and economical characteristics, glass fibre-reinforced polymer (GFRP) composites have been widely used in aerospace, naval, automotive, construction and wind energy industries [1]. It is noted that air voids could occur during the manufacturing process, and in service GFRP composites are subjected to varied hazards, such as degradation caused by cyclic loads, lightning, hail or ice impact. The typical damage includes fibre/matrix debonding, matrix cracking, delamination (ply separation) and ultimately fibre breakage. Much of these damage modes happen internally and are hardly visible, as GFRP composites are almost opaque for wavelengths in the visible regime. Hence, most optical methods (e.g., visual inspection) are only capable of detecting faults at the surface or flaws expanding to the surface. Considerable efforts have been devoted to utilising non-destructive testing (NDT) for accurate evaluation of the structural integrity. A number of NDT techniques are available for selection, such as conventional strain gauges, ultrasonic testing, guided Lamb waves [2,3], acoustic emission [4], infrared thermography, optical fibre sensing, shearography, eddy current testing (ECT) [5], terahertz imaging [6] and X-ray tomography [7]. However, each NDT method has its own specific advantages, disadvantages and the applications to which it is particularly suited. The NDT research community is therefore continuously searching for new solutions.

An alternative method is the microwave-based. Microwaves are electromagnetic (EM) radiation with frequencies between 300 MHz (wavelength of 1 m) and 300 GHz

(wavelength of 1 mm). They are best known for the use in telecommunications and manufacturing (e.g., food processing and composite curing [8,9]), while they can also be used for material characterisation, estimation of mechanical properties [10], strain sensing [11,12] and damage evaluation [13–15]. Measuring the electromagnetic properties (i.e., permittivity and permeability) can be helpful for assessment of the quality of the material (e.g., moisture content [16], porosity [17] and fibre volume fraction [18]), dimensional metrology (thickness measurement), cure state monitoring, optimal design of the experimental setups and quantitative analysis of the detection results. In damage detection, the amplitude and phase of the received signals can be affected by the variations of the thickness or electromagnetic properties at the damaged region. When employed for glass fibre composites, microwave techniques have proven to be superior to some other NDT methods [19]. There are several attributes when applying microwave testing, such as non-contact inspection, no need for transducers bonded on the surface or coupling agent to couple the microwaves into the test object, no need for complicated signal post-processing, operator friendly, relatively inexpensive, one-sided scanning, good repeatability and non-ionising (unlike X-ray and gamma radiation). Except for heating purposes, the signal power used is generally low, a few milliwatts, hence there is no safety concern or need for protection.

In the past the complicated and expensive microwave equipment hindered the widespread application of the microwave methods, but this situation is changing now due to the increasing availability of low-cost high integrated microwave components [20]. In recognition of the growing interest in microwave testing, in 2011 the Expert committee for microwave and THz testing procedures of the German Society of Non-Destructive Testing (DGZfP) was founded. And in 2014 the Microwave Testing

Committee was established by the American Society for Non-destructive Testing (ASNT). Microwave testing was furthermore recognised as its own NDT method in the 2016 edition of the ASNT standards, and the certifications for Level I and Level II microwave testing inspectors are currently under development [21].

In this paper the electromagnetic properties (or dielectric properties) of glass fibre polymer composites and definitions of the near-field and far-field inspection approaches that are closely related to the microwave testing are addressed first. Then the methods for material characterisation are introduced. Based on the detection principles, the microwave testing methods for GFRP composites are classified into five categories: near-field detection with an open-ended probe, near-field resonance methods, far-field sensing methods, focusing methods and microwave-based thermography (integration with another NDT method). The basic principles, experimental setup, capabilities and limitations of each technique are reviewed in detail.

2 Concepts involved in microwave testing for glass fibre composites

2.1 Electromagnetic properties of glass fibre composites

The electric permittivity ε and magnetic permeability μ are the two main parameters of EM properties, which describe the interaction between the material and the EM field.

As both glass fibre and epoxy are non-magnetic, permittivity is the parameter of interest in the present work. The permittivity ε can be written as [22]

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 (\varepsilon'_r - j \varepsilon''_r) = \varepsilon_0 \varepsilon'_r (1 - j \tan \delta) \quad (1)$$

where ε_0 is the permittivity of free space (i.e., $8.8542 \times 10^{-12} \text{ F}\cdot\text{m}^{-1}$), and ε_r is the relative permittivity. The real part ε'_r , or dielectric constant, is related to the ability of a material to store the electric field energy, while ε''_r accounts for the dissipation of the

energy within the material in the form of heat. The loss tangent $\tan\delta (= \varepsilon_r'' / \varepsilon_r')$ can also be used to quantify the dielectric loss. ε_r'' is positive due to energy conservation. The complex permittivity is a function of frequency and temperature.

For each component, both glass fibres and epoxy resin are nonconductive, and the dielectric properties of some typical fibres and resins are listed in Table 1 and Table 2. For the glass fibre-epoxy mixture, its effective permittivity change as a function of parameters like frequency, fibre volume fraction, cure state, porosity and fibre orientation. Thus, it is possible to extract useful information about these parameters from the permittivity. Empirical mixing formulae can be adopted for the prediction of the effective dielectric constant, such as Wiener limits, Maxwell Garnett formula and Looyenga formula [29]. In these closed-form solutions, the effective dielectric constant is a function of the dielectric properties of the fibre and resin. The upper and lower bounds of the effective dielectric constant can be provided by Wiener upper limit and Wiener lower limit, respectively [30]. The limits were given based on analysis of laminated structures, which corresponded to fibres orthogonal to or in parallel with the applied electric field. However, most practical cases are between the two limits. More accurate models for description of the anisotropic glass fibre composite structures are needed, as the fibre architecture affects the polarisation in the material. For unidirectional (UD) and multidirectional laminates, Chin et al. [31,32] proposed an equivalent lumped circuit model, where a lamina was built as a parallel lumped resistor–capacitor circuit. This method well predicted the data obtained from free space measurement over X-band (8–12 GHz). In [27], an accurate model for composites with three-dimensional fibre architecture was developed, considering the three-dimensional

effect of the fibre. It was demonstrated that the prediction result agreed with that provided by the transmission line measurements.

2.2 Penetration depth of microwaves

The signal penetration is a practical parameter that should be considered in damage inspection. Due to the lossy medium, the power of the EM signal decays exponentially through the thickness. The penetration depth d_p is defined as the depth where the signal magnitude is reduced to $1/e$ (about 37 %) in the medium. For a plane wave incident on a half space of a medium, the expression for d_p is given by:

$$d_p = \frac{c}{\sqrt{2}\pi f \left\{ \varepsilon'_r \left[\sqrt{1 + \left(\frac{\varepsilon''_r}{\varepsilon'_r} \right)^2} - 1 \right] \right\}^{1/2}} \quad (2)$$

where f is the operating frequency, and c is the speed of light in free space, 299792458 m/s.

It is seen that there is an inverse relationship between the signal frequency and the penetration depth. For a GFRP sample with $\varepsilon'_r=3.49$ and $\tan\delta=0.02$, the penetration depth at 18 GHz is approximately 120 mm [33]. It is suggested that the high penetration depth offered is sufficient for most of practical inspection applications.

2.3 Definition of near-field and far-field approaches

In the cases where the sample is not placed within the probe, in terms of the distance between the microwave probe and the sample under test, microwave testing can be categorised into near-field and far-field approaches. The term “near field” refers to the evanescent field of an open-ended coaxial line or the non-radiative/reactive region of an antenna that exists in the immediate vicinity where mature propagating waves have not yet been formed (Fig. 1). The current distributions on the antenna are affected when an

object is placed in the reactive region, the boundary of which is commonly given by [34]:

$$R < 0.62 \sqrt{\frac{D^3}{\lambda}} \quad (3)$$

where D is the maximum linear dimension of the antenna (or diameter of a conical antenna), and λ is the wavelength in the medium. In the near-field case, the assumption of uniform plane waves is not valid, so Eq. (2) is not suitable for evaluation of the maximum detectable thickness. Here the penetration is associated with the standoff distance (between the inspection surface and the probe/antenna), operating frequency, electromagnetic properties of the materials and boundary conditions.

The far field is the region of operation for most antennae, where the radiation does not change with distance and absorption of the radiation in the far-field region does not feed back to the transmitting antenna. The far-field (Fraunhofer) distance must satisfy three conditions:

$$R > \frac{2D^2}{\lambda} \quad R \gg D, \lambda \quad (4)$$

For an antenna, it should be mentioned that there is a radiative near field (Fresnel region) between the reactive near field and the far field. In this region the reactive fields do not dominate. However, unlike the far-field region, the shape of the pattern varies appreciably with distance. Depending on the values of R and the wavelength, this field may or may not exist. Hence, the radiative near-field region is not in the scope of this paper. To perform a far-field inspection, as shown in Fig. 2, either monostatic configuration (a transmitter and receiver sharing one antenna with a circulator), Fig.2(a), or bistatic configuration (a pair of transmitting and receiving antennae), Fig.2(b), can be used. Each kind has inherent advantages and disadvantages. In the

monostatic system here, the circulator is a passive non-reciprocal three-port microwave device, which routes microwave signals from the transmitter to the antenna and from the antenna to the receiver and prevents signals from passing directly from the transmitter to receiver. Compared with the bistatic counterpart, the dimensions of the monostatic system are more compact, while the lower isolation can result in a significant leakage [36]. Additional measures must be undertaken to reduce or suppress the undesirable leakage. The bistatic configuration has a high isolation between transmitting and receiving channels. During in-service inspections, commonly only one side of the object under test can be accessed, so the reflection mode is more advantageous.

3 Microwave characterisation of GFRP composites

There are mainly two types of permittivity measurement methods: resonant methods and non-resonant methods. Resonant methods can provide permittivity values with high accuracy and sensitivity at the resonance frequencies, while non-resonant methods can characterise materials over a frequency range. In terms of sample preparation, the measurement methods can be categorised as intrusive or non-destructive/non-invasive. Intrusive methods include the resonant method and transmission line method, where cutting and machining of test samples is required. Sample preparation work is labour intensive and cutting sections from the examined component may not be permissible. Open-ended probe method and free space measurement are the two main non-destructive approaches. The permittivity of GFRP can be calculated from one S-parameter (either the transmission coefficient S_{21} or reflection coefficient S_{11}), which can be measured with the use of a vector network analyser (VNA).

3.1 Transmission line method

Here the sample under test is placed in a measurement cell of a transmission line, which is a short section of a coaxial line or a waveguide as shown in Fig. 3. There are standard test methods that can be referred to: ASTM D7449M-14 [37] (for coaxial line) and ASTM D5568-08 [38] (for waveguide). The Nicolson-Ross method [39] or Tischer model [40] can be employed for the permittivity calculation. The sample need to be cut and perfectly fit within the cell, otherwise the air gaps between the sample and the metallic walls can affect the measurement accuracy [41]. With the gap filled with a low-melting-point alloy (e.g., silver conductive epoxy), the unwanted effect could be reduced. It is not required to fill the whole measurement cell along the transmission line, i.e., $t_1 \geq 0$ and $t_2 \geq 0$. The transmission line technique is useful for broadband frequency measurement of high loss and medium loss materials.

3.2 Open-ended probe method

The specimen can be placed in the near-field region (Fig. 4) or in contact with an open-ended transmission line (e.g., coaxial line [42,43]) or waveguide (e.g., circular waveguide [44] or rectangular waveguide). In the contact measurement, the probe should be pressed against the surface of the sample to reduce the negative effect caused by possible air gaps. As a one-port measurement, the reflection coefficient is used to reveal the information of the permittivity of the material.

1) coaxial probe. The electromagnetic fringe field of an open-ended coaxial probe closely surround the tip of the probe [45]. Compared with the waveguides, the coaxial lines can be operated over a relatively wider frequency range. The apertures of the probes for NDT purposes are relatively small, resulting in higher spatial resolutions. In addition, rigid, semi-rigid, semi-flex and flexible coaxial lines are commercially

available, so hard-to-reach regions of a structure for other NDT methods can be inspected.

There are some off-the-shelf coaxial probes, like Agilent ‘Performance’ dielectric probe with operating frequencies from 200 MHz to 50 GHz. This kind of dielectric probe is well-suited for liquids or semi-solids, as the probe can be immersed in the materials.

However, the material under test is assumed “infinite” in size, and the probe is not recommended for accurate estimation of low-loss materials ($\tan\delta < 0.5$) with $\epsilon'_r > 5$ [46].

2) waveguide. The field region around the waveguide is larger than that around the coaxial probe, as the waveguide performs like an antenna. Hence, a higher standoff distance (within the near-field range) is allowed. The rectangular waveguide is commonly operated in the dominant mode, where the electric field inside the waveguide is linearly polarised. Therefore, the open-ended rectangular waveguide is more capable for measurements of anisotropic materials.

Permittivity calculation requires rigorous mathematical formulation of the electromagnetic field outside the probe, while the exact solution of Maxwell’s equations is not available. Approximate 2D models of an open-ended probe radiating into the material have been reported [47–50]. However, these models could not be widely applied due to the assumptions made, for example, the problem is considered with an infinite dielectric half-space, the analysis is limited to layered structures, the probe has an infinite waveguide flange and only the dominant mode is studied. Kempin et al. [51] pointed out that using an open-ended waveguide with a standard finite-sized flange could cause errors in evaluating the complex dielectric properties of a composite structure. A novel design of flange with all four edges rounded was proposed to reduce this undesired effect and produce similar electric field distribution at the flange aperture

to those created by an infinite flange. By recalculating the permittivity of the five layers (three GFRP layers separated by two identical low-density low-permittivity paper honeycomb layers) of a stratified composite structure from the measured data, the improvement in the accuracy of permittivity estimation was demonstrated.

Instead of using approximate mathematical models, the finite element method can be employed to provide better description of the experimental arrangements and the electromagnetic field. In [52], as illustrated in Fig.5, a model with the real experimental setup was built, and electromagnetic simulation software and optimisation methods (i.e., quasi-Newton method and particle swarm optimisation (PSO)) were adopted to calculate the permittivity. The permittivity value initially used in the computation was optimised until a converged solution was found, where the simulated reflection coefficients S_{11} approximated the data acquired. From the measurement of a woven glass fibre-reinforced ceramic filled thermoset material, it was indicated that the proposed method can provide more accurate permittivity results.

The open-ended setup is similar to that of the short-circuited line method [53], where the sample is inserted inside the probe and backed by a conductor, as shown in Fig. 6. The short-circuited line method can be viewed as a combination of the transmission line method and the open-ended probe method, but it is a destructive approach and the measurement accuracy is not as good as the transmission line method.

3.3 Free space measurement

In the free space method, as shown in Fig. 7, the sample in the form of flat sheet is kept positioned at the reference plane between two identical antennae. A reflection or transmission mode illustrated in Fig. 2 can be employed. Special attention must be paid to the sample geometry and location. The microwave wave front is approximated as a

plane wave. In the test a high-gain antenna or dielectric lens should be used to meet this requirement. For high-gain (directional) antennae, the sample is placed in the far-field region. For dielectric lenses, the sample is located at the focal point of the lens, and the dimensions need only be on the order of the focal spot size [21]. The lenses can help minimise the diffraction effects due to the edges of the sample that may exist in the former setup [54].

3.4 Resonant method

The sample is placed in a resonant cavity (e.g., re-entrant cavities, cylindrical and rectangular cavities) or on an open resonator (e.g., planar microwave resonator, complementary split-ring resonator (CSRR)) [55–57]. The dielectric properties of the sample can be derived from the changes in the resonance frequency and quality factor (or Q factor) of the cavity. The resonance approach is inherently narrowband, and it requires careful sample preparation (spheres or cylinders required) and calibration [58]. More details about this technique can be found in Ref. [59–62].

3.5 Advantages and limitations

Each electric permittivity measurement technique has its own advantages and shortcomings. A number of parameters should be taken into account when choosing an appropriate method for GFRP composites:

- 1) Measuring the permittivity. The electric field in a coaxial line/circular waveguide is not linearly polarised as the rectangular waveguide. Hence, these two methods could not be effective to reveal the anisotropic nature of the fibre-reinforced polymer composites.
- 2) Frequency of interest. For NDT purposes, the permittivity data over a frequency range are more desirable, so the resonant methods are not preferred.

- 3) Measurement accuracy. For the transmission line method, uncertainties of ϵ_r' are better than $\pm 1 \%$, and the resolution of $\tan\delta$ is typically ± 0.01 [63]. For the open-ended probe, the typical uncertainties of ϵ_r' are $\pm 3 \%$. In the free space techniques, the uncertainties for ϵ_r' are in the range of $\pm (1-10) \%$ and those for $\tan\delta$ are from $\pm 5 \%$ to over 20% [64]. It is seen that destructive methods are more favourable if machining of the sample is acceptable, as high measurement accuracy can be provided.
- 4) Contact or non-contact measurement. Non-contact method is not affected by sample surface imperfections and no lubricant is required, hence preferable technique.

4 Microwave non-destructive evaluation methods for GFRP composites

4.1 Near-field detection with an open-ended probe

The open-ended methods for permittivity measurement can also be applied for non-destructive detection. In addition, a horn antenna can be used, while the lateral resolution offered could be less attractive for its larger aperture when compared with the open-ended probes operated over the same frequency range.

The equivalent lumped circuit for this detection method is illustrated in Fig. 8. The capacitance C_g is linked to the standoff distance, while the inductance L_s , capacitance C_s and resistance R_s are associated with the material properties and sample dimensions. Surface unevenness can affect C_g , while damage in the material will lead to changes in L_s , C_s and R_s , and subsequently the signal received. Hence, the defect/damage can be identified by evaluating the reflection coefficient S_{11} .

In most of the research work, the signal responses were examined at a predefined frequency. However, it is noted that the responses of the defect/damage at varied frequencies are different. The inspection frequency suitable for one case with a good signal contrast cannot be applied to another case. Hence, selection of the frequency for an optimal signal contrast is mainly made case by case.

(a) open-ended rectangular waveguide

An open-ended rectangular waveguide is the mostly used probe. Waves can only be transmitted with frequencies above a certain cut-off frequency, which depends on the cross-sectional dimensions. The higher the operating frequency range, the smaller the aperture size. In addition, the spatial resolution of a scan image is highly dependent on the aperture size, not the wavelength [65]. Therefore, there is a compromise between the signal penetration and the spatial resolution.

1) cure state monitoring

Qaddoumi et al. [66] scanned a 25.6 mm thick conductor-backed fiberglass sample with 18.6 % resin content. In the two-dimensional microwave image at 24 GHz and a standoff distance of 4 mm, a substantial difference in the signal responses between the four inclusion regions (with no resin, uncured resin, 9.4 % resin and 13.8 % resin) was shown. The effect of the standoff distance was also investigated. It was found that it was difficult to distinguish among the inclusions at lower standoff distances (1-3 mm) for the present case. Calibration was needed in order to obtain an estimate of the resin content.

2) Detection of fabrication defects and in-service damage

Umeda et al. [67] detected air voids and conductive foreign materials in a resin sample. The amplitude and phase of the signal received were presented in a polar coordinate system. The type of the defect can be determined by the direction in which the point was with respect to the reference point of the case with no defect, clockwise for air voids and anticlockwise for conductive materials. The size of the air voids or conductive foreign materials can be estimated by observing the distance between the present point and the referent point.

Qaddoumi et al. [68] presented a theoretical study on detection of disbonds at varied depths in a glass fibre composite sandwich panel. The phase of the reflection coefficient at the waveguide aperture was used as an indicator of damage presence. It was suggested that a combination of frequency and standoff distance could be used for unambiguous depth determination. At K band (18.0-26.5 GHz) and a standoff distance of 1 mm, all six disbonds were located correctly at three frequencies, i.e., 25.3 GHz, 25.5 GHz and 25.7 GHz.

Greenawald et al. [69] detected impact damage and flat bottom holes in 42.5 mm thick GFRP sandwich composites using three microwave bands: K band, Ka band (26.5-40 GHz) and V band (50-75 GHz). The impact damage was best revealed at 25 GHz with a standoff distance of 0.5 mm, and strongest indications of the presence of the holes were produced at 30 GHz with a standoff distance of 4.0 mm. Optimisation of the inspection parameters was necessary for each specific flaw type and depth.

Green et al. [70] successfully detected the impact damage in a 10 mm thick composite sample at 35 GHz, which is shown in Fig. 9. The area of damage observed visually from the impacted surface (front face) was small compared with that observed on the back

side. An image generated from microwave inspection over the front face reproduced the size and shape of the overall damage.

Abou-Khousa et al. [71] used Ka-band and V-band waveguides to detect damage in honeycomb composite panels with a thin GFRP laminated skin. In the 2D map of the phase, the embedded flaws were identified and their relative spatial locations and sizes were determined. Some flaws were shown in the V-band images, but not in the Ka-band images. The results given were comparable to those by X-ray imaging (with the exception of flaw depth evaluation).

Hosoi et al. [72] used K-band microwaves to detect slits, fluorine and aluminium films inserted in E-glass fibre composite laminates. The measurement results were found more stable at lower frequencies (18 GHz), while for small defects the measurement sensitivity was better at higher frequencies (26 GHz). It was indicated that microwaves could detect an aluminium film in a at least 30 mm thick laminate.

Li et al. [33,73] detected delamination in T-joints of wind turbine blades with an K band waveguide adapter. The waveguide assembly was mounted on an X-Y-Z scanning stage and connected to an HP 8720D VNA by a semi-rigid coaxial cable. A personal computer (PC) was connected to the analyser for data acquisition. From the images produced at 19 GHz and a standoff distance of 5 mm, as shown in Fig. 10 (d-e), it was found that the magnitude was more sensitive to thickness changes (locations of the web and thickness variation), whereas the phase was more useful for delamination detection. In addition, electromagnetic simulation was performed to identify the optimal inspection frequency and standoff distance. It was revealed that the decreased standoff distance could significantly improve the detection sensitivity, and the location of the delamination region could be recognised from the sensitivity curve. When the sample

was scanned at 19 GHz with a standoff distance of 5 mm, delamination down to 0.2 mm in width can be detected.

3) Strain sensing

In an electromagnetic field glass fibre composites behave like uniaxial pseudo-crystals, where the principal axes of anisotropy coincide with the direction of the reinforcement. When mechanical loads are applied, the fibres are mutually displaced, which could lead to changes in the complex permittivity of the composite. Kovalev et al. [74] studied the effect of the mechanical strains and found that there was a linear relationship between the deformation and the dielectric constant. It was also possible to obtain the strain distribution by measuring the dielectric constant with the electric field in different directions with respect to fibre orientation.

(b) open-ended circular waveguide

Rahman et al. [75,76] detected artificial defects in the fiberglass skin laminate of a sandwich honeycomb structure using a Teflon-filled circular waveguide and an air-filled K-band rectangular waveguide. The inner diameter of the circular waveguide was 6.25 mm, while the inner dimensions of the rectangular waveguide were 10.7 mm $\times$ 4.3 mm. The circular and rectangular waveguides were operated in the dominant modes, TE_{11} and TE_{10} modes, respectively, where only one propagating mode exists in the frequency band of operation. The standoff distance of the probe was set to 1 mm, and the thickness of the sandwich structure was 13 mm. Both probes were scanned over the surface where the defects were not visible. At 24 GHz the defects were seen in the raster scan images produced by both methods, and the ability of the system to penetrate through the structure was demonstrated.

(c) open-ended coaxial line

Wang et al. [77] used a coaxial adapter to detect, identify and evaluate the liquid ingress in honeycomb sandwich structures with GFRP skins. This kind of lightweight sandwich structures are susceptible to moisture ingress. The setup of the liquid ingress detection is shown in Fig. 11. In the test, water, ethyl alcohol and oil were intentionally injected into different regions of the honeycomb cores. The top skin was removed for the easy implementation of the fluid injection. The top surface of the core layer was placed in the vicinity of the end of the probe at a distance (0.5 mm) much smaller than the wavelength. Over 32-40 GHz significant differences in the reflection coefficients corresponding to water, ethyl alcohol and lubricant oil were revealed, and the three liquid types were easily distinguished due to their different polarisation characteristics. A linear relationship between the magnitude of the reflection coefficient and the height of the intruding liquids in the near field of the probe was found. A peak method was proposed to quantify the position and size of the ingress region from a line scan.

4.2 Near-field resonance methods

(a) Near-field scanning microwave microscopy (NSMM)

As shown in Fig. 12, a near-field microwave microscope is generally composed of a resonant cavity and a sharp tip. The sample is placed close to the probing tip, from which evanescent microwaves are emitted. The probe scans across the surface of the object at a fixed standoff distance. The unevenness or material discontinuity of the surface can result in local changes of the parameter values of the air gap and the sample, subsequently the resonance frequency and Q factor of the whole resonant circuit. Thus, a surface contour plot of the resonance frequency can be produced. High resolution can be achieved when using this technique [78]. The sharper the tip is, the higher the spatial

resolution that would be obtained. However, this is more suited to surface profiling due to the limited penetration of the low-intensity evanescent waves.

(b) Planar resonators

Microwave planar resonators can be employed for damage detection as well. The electromagnetic field around the resonator can be perturbed due to the presence of defects/damage. Albishi et al. [79] designed a complementary split-ring resonator (CSRR) sensor to detect cracks in a fibreglass material. Two cracks with widths of 150 μm and 200 μm and depths of 1.5 mm were scanned. A maximum frequency shift of more than 312 MHz was observed with respect to the reference case. Mukherjee et al. [80] developed a SRR sensor for imaging of sub-wavelength defects in a GFRP laminate. In the test, three defects, i.e., surface flat bottom holes with a diameter of 0.7 mm ($\lambda/45$), were easily found. Some coupling occurred between two closely-positioned (a distance of 0.7 mm) defects and a simple threshold could be applied to enhance the image contrast.

4.3 Far-field sensing methods

A pair of antennae are commonly employed for far-field sensing, where the transmission coefficient S_{21} is analysed in the frequency domain and/or time domain [81]. Moll et al. [82] developed a radar-based sensing system for wind turbine blades with a realistic demonstrator system in the laboratory environment. Two pairs of frequency-modulated continuous-wave (FMCW) bistatic radars, horn antennae operated in the frequency band from 24.05 to 24.25 GHz and 33.4 to 36.0 GHz were employed. The radar sensors were placed at a distance of about 1 m in front of a wind turbine demonstrator, which consisted of a rotary stage that can rotate the GFRP sample at a maximum frequency of 1 Hz. Two types of damage in the 800 mm $\times$ 300 mm $\times$ 10 mm

GFRP plate were tested: a cut of 30, 60 and 90 mm in length and a water pack at the backside of the plate. The 24-GHz system was only able to discriminate the difference between the undamaged structure and the water pack, while the 35-GHz radar system successfully identified the structure with cuts and the water pack. In Fig. 13 (b), it is seen that the damage indicator (DI) increases with increasing damage size, which suggests damage quantification potentials of the 35 GHz detection system. In this work, some real environmental conditions, such as variations in temperature or wind speed, were not considered.

Viegas et al. [83] used active W-band (75-110 GHz) radiometry to detect defects (two blind holes of 2 and 4 mm diameters and 3 mm depth) in GFRP composites. In the test, an amplified photonic source generating random millimetre-wave noise illuminated the sample. A quasi-optical test bench comprised of polytetrafluoroethylene (PTFE) lenses was used for focusing the free space signal, and the receiver was a high-sensitivity W-band Schottky diode-based radiometer. The 4-mm diameter defect was clearly observed in the transmission signal intensity profile. As the spontaneous thermal radiation of the GFRP sample was lower compared with the transmitted photonic noise, only the changes in the transmission noise due to the air-dielectric interface were detected by the radiometer.

4.4 Focusing methods

Focusing techniques can be employed to improve the spatial resolution. For example, a dielectric lens can be used to focus the microwave energy from a high-gain horn antenna to a point. Both high-resolution images and high-signal levels can be obtained when the region of interest is close to the focal point [84], which indicates that this

approach is limited to detection of damage close the surface of the specimen. The main disadvantage is that most lenses are narrowband since the lens is inherently resonant. As well as the real focusing, the synthetic focusing techniques can be adopted, such as synthetic aperture radar (SAR), microwave holography and digital beam forming. In this kind of methods, mathematical means are employed to synthetically focus the microwave signals to any point in the volume. The synthetic focusing methods can be applied in both near and far fields.

For SAR, a radar antenna is typically mounted on a moving platform, and the phase history of the scattered wavefront recorded varies with the vehicle position over a modest bandwidth obtained through pulsing or chirping the radar frequency [85]. For digital beam forming, radar phased-arrays are operated by creating a beam which can be electronically steered to point in different directions. However, the circuitry for phase shifting is complicated, and the system is currently not cost-effective. In microwave holography, the single-frequency two-dimensional (2D) holography is combined with wideband 2D SAR to produce a three-dimensional (3D) representation of an object [86]. In addition, one can slice the 3D image at various depths (depending on the available signal bandwidth), creating image slices similar to those produced by X-ray computed tomography [87–89]. Inverse synthetic aperture radar (ISAR), analogous to SAR, is not discussed here, for in this method the radar is stationary and the targets are in motion [90]. This setup is not practical in many engineering applications.

(a) Real focusing

Meier et al. [91] used a focused W-band FMCW radar to detect manufacturing defects (e.g., local regions where there are dry fibres with no resin around) in a GFRP sample. As illustrated in Fig. 14, two offset parabolic mirrors were located to focus the signal on

the sample (device under test (DUT) shown in Fig.14), and the transmitting and receiving elements were rectangular 15 dBi gain waveguide horn antennae separated by 1 mm and placed in the focal plane of an offset parabolic mirror. The polarisation of the radar signal was orthogonal to the orientation of the glass fibres. During the measurement the height of the sample was held constant with the focal point of the radar signal in the centre of the 35 mm thick sample. The Gaussian beam width at the focus point was approximately 15 mm, and the depth resolution was 3.1 mm inside the sample. In the radar intensity image for 2 mm deep below surface, the dry fibre fabric was shown due to the difference in the dielectric properties of the glass fibres and the rest of the GFRP component and an increased surface roughness at the dry fibre region.

(b) Synthetic aperture radar

Nezadal et al. [92,93] employed a W-band SAR system to identify flat bottom holes in GFRP samples. These holes had different diameters (5, 10, 15 and 20 mm) and depths (from 0.5 to 14.5 mm), and the overall thickness of the composite plate was 15.0 mm. The magnitude data enabled the detection of holes with residual wall thicknesses up to 7.5 mm. The average of all the magnitudes measured over the frequency range was used in order to reduce unwanted interference patterns and some artefacts generated at a single frequency. By using the phase and time-domain information it was possible to detect all the hidden defects. The test setup had a lateral resolution of approximately 3.0 mm and a range resolution of approximately 4.3 mm in free space. The lateral resolution enabled the detection of defects with diameters of down to 5 mm.

(c) Microwave holography

So far, most of the microwave holography studies were focused on surveillance and concealed weapon detection on personnel [94,95]. However, few papers have been

found on detection of damage in glass fibre composites. Case et al. [88] first applied Sheen's algorithm to detect embedded defects in a 25.4 mm thick honeycomb composite panel. The top skin was a thin glass fibre composite laminate. Planar disbonds, crushed dielectric core and delaminations (ply separation) were produced at various depths within the thickness. A Q-band (33-50 GHz) open-ended waveguide probe held approximately 22 mm above the panel. The spatial resolution of the holographic images was high (in the few millimetre range), while the range resolution was around 8.8 mm. The flaws under the skin at a depth of 2 mm also appeared in the image for the section at a depth of 10 mm. This image distortion along the thickness direction is due to the inadequacy of some assumptions in Sheen's algorithm used, where the amplitude decay with range is not considered, the transmitting and receiving antennae are assumed to be coincident at the midpoint between the two antennae, the speed of the wave travelling through the sample is not delayed, and no refraction exists at the air-sample interface. Future work could be done on the modification of the imaging algorithm.

4.5 Microwave-based thermography

The microwave techniques can be combined with other NDT methods for more detailed and better detection performance. For example, microwaves can be used as a heat source (like microwave curing [9]) for thermography. Compared with the existing thermal excitation methods, such as thermal lamps, laser, ultrasonic and pulsed eddy current (PEC), microwaves can provide more uniform, volumetric and selective heating [96–98]. When a microwave signal is applied, the composites will be heated due to the dielectric loss dominated by the polymer matrix [99]. If the penetration depth of the microwave signal is much smaller than the sample thickness, only the material within

the penetration depth is heated and the rest of the material is heated by thermal conduction. Therefore, the penetration ability of the microwave-based thermography is better than that of conventional microwave NDT techniques.

Damage and defects could be revealed in the thermogram with an infrared (IR) camera. Owing to good performance by commercial infrared cameras, high sensitivity and high spatial resolution (much better than the microwave wavelength) can be offered. In addition, rapid inspection is achievable, as a large area can be inspected within a short time.

When using this specific technique, special attention should be paid to the electromagnetic shielding. According to the guideline issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [100], the reference level for occupational exposure to electromagnetic fields is 50 W/m^2 over 2-300 GHz, which is equivalent to an electric field strength of approximately 137 V/m in free space. This health and safety requirement should be strictly satisfied in the implementation. In [101], a low power signal (115.2 mW, approximately maximum output of a mobile phone signal) was used with no need for shielding, while the heating time was longer (a few minutes compared with 1-10 s in the high power case).

A schematic diagram of the microwave thermography approach is illustrated in Fig. 15. A horn antenna is used to direct the waves into the region of interest. A microwave source can be a magnetron, travelling wave tube or signal generator. An IR camera is located on the same side as the excitation source (reflection configuration). The antenna is placed at a distance from the sample that a sufficient field of view for the thermal camera can be provided. This distance affects the microwave illumination pattern (which in turn determines the effective inspection area) and strength at the surface. A

personal computer is used for setting the measuring instruments, data acquisition and signal post-processing.

In [102], a microwave pulsed thermography system was developed for detection of a hole with a radius of 4.5 mm in a GFRP sample. A 2.45GHz magnetron with maximum power 1kW was used for microwave excitation. A maximum temperature increase of 0.6 °C around the hole was observed after 2s heating.

4.6 Discussion on thickness measurement

An open-ended rectangular waveguide [103–106], a resonant cavity [107] and a planar CSRR [108] can be used for near-field non-contact thickness measurement of thin samples (a few millimetres). For the first method, same as the permittivity calculation, approximate but complicate mathematical models were commonly adopted. In [52], the simulation-assisted open-ended waveguide approach was extended to thickness measurement, and the computation was quicker as only one parameter was involved in this case. For the last two methods, appropriate calibration is needed to establish the relationship between the resonance frequency and the sample thickness.

For thick-section composites, either the monostatic or bistatic antenna configuration illustrated in Fig. 2 can be adopted. With known dielectric properties of the material and the time difference obtained between the reflection from the surface and the first reflection from the bottom side, the sample thickness can be determined [109]. UWB antenna can be employed to obtain better time resolution.

5 Concluding remarks

The basic principles and types of the microwave testing methods for glass fibre-reinforced polymer composites have been presented here. Various applications have been demonstrated: cure state monitoring, thickness measurement, detection of liquid

ingress, cracks, holes, manufacturing induced defects, absence of adhesive, dry fibre spots (resin starved regions), delamination and impact damage. The advantages and limitations of the five categories of methods have been discussed for the readers' benefit. Though great progress has been made on the development of the microwave detection methods, the potential of microwaves for wider applications is yet to be fully exploited. More work could focus on the following aspects:

- (1) Theoretical models: it is demonstrated that some pioneering work on modelling the open-ended waveguide radiating into stratified dielectrics has been done by Zoughi's group at Missouri University of Science and Technology [45]. However, the model developed is limited for specific applications, and more work should be conducted on thorough investigation of the wave propagation in polymer composites. A multi-physics approach is needed when simulating the microwave-based thermography.
- (2) Damage classification: as seen above there is a lack of research on differentiating the type of damage, though various types of defects/damage are observed during fabrication or in service (e.g., impact damage). Artificial intelligence (AI) can be introduced for automatic classification. For instance, an artificial neural network (ANN) can be used with input nodes that are matched to the input data format, output nodes in the form of damage probability and intermediate hidden layer nodes. The connection parameters between the nodes can be optimised by training, using a set of tests with and without specific type of defects or in-service induced damage modes.
- (3) Microwave planar resonators: several parameters involved in the design of this type of sensors can be adjusted to improve the near-field sensor performance,

such as type of the feed line (e.g., stripline, microstrip line or coplanar waveguide), type of the resonator (e.g., CSRR or split ring resonator (SRR)), shape of the resonator (e.g., rectangular, polygonal or circular), dimensions of the resonator, damage indicator (e.g., resonance frequency shift or change of the magnitude [110]).

- (4) Real-time imaging: In [111], a real-time microwave camera was reported. By using real-time synthetic focusing algorithm and modulated scattering technique (MST), the microwave camera was able to generate high-resolution images of test specimens in real time. Its applicability for damage detection is to be explored.
- (5) Use of the RFID technique: the active radio frequency identification (RFID) technology with the capability of damage inspection has started to attract some attention [112]. With a RFID tag attached on the surface of the object under test, the local damage information can be wirelessly interrogated with a RFID reader. Hence, the microwave RFID-based detection concept can be introduced, and further Internet of Things (IoT) can be integrated for remote inspection and long-term structural health monitoring [113].
- (6) Automated inspection: there is a high demand for automated inspection by the industry, while many of the applications addressed are still at the laboratory level rather than real service environment. For example, a X-Y or X-Y-Z positioner is often used when scanning a flat specimen, while it does not readily conform to other complex structural configurations (curved surfaces). Future research need be carried out to facilitate industrial adoption.

Carrigan et al. [114] designed a robotic pipe crawling apparatus to position the open-ended microwave waveguide probe for detection of defects in a high-density polyethylene (HDPE) pipe. The robotic system consisted of two sets of wheels sprung against the inner wall of the pipe. The rear set was motorised to position the pipe crawler, while the front set was fitted with rotary encoders to measure the linear distance travelled. The microwave probe was held by a rotating clamp head on the front of the robot. A crack with a width of 1 mm and a depth of 1 mm in a 9.8 mm thick pipe was identified in the 2D scan image produced. The scanning speed of the system was not mentioned, while this is also an important feature that should not be ignored, especially when long pipe systems are examined. In [115], a EddyCus[®] instrument for eddy current testing was presented, and a maximum speed of 300 mm/s at a sampling rate of 3000 samples per second was reported.

- (7) Potential applications in additive manufacturing (AM): additive manufacturing is an emerging technique where successive layers of material are formed under computer control to create a three-dimensional object. It significantly revolutionises the design of products with complex geometries and concept of spare parts management. However, at present the complex parts are posing difficulties for inspection, and a standard verification procedure for quality control is not established [116]. For this reason, the 3D printing has not been widely used in industry. It is required that any defect should be identified and corrected before finishing parts. For example, porosity of each layer should be checked when fabricating continuous glass fibre reinforced polymer composites [117,118]. Microwave testing can be applied for in-process monitoring of

additive manufacturing. In addition, a customised microwave sensor can be made possible by AM to fit complex (e.g., curved) surfaces.

Hajisaeid et al. [119] first developed an all 3D-printed free space measurement system including focusing lenses, antenna holders, lens holders and sample holder. With respect to redesigning and reprinting flexibility, it was concluded that 3D printing proved the most practical and feasible choice for rapid prototyping; further research effort is required by academia and industry.

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Tables

Table 1 Dielectric properties of some typical glass fibres
at 10 GHz at room temperature [23]

	D Glass	E Glass	ECR Glass	R Glass	S-2 Glass
ϵ'_r	4.0	6.1	7.0	-	5.2
$\tan\delta (= \epsilon''_r / \epsilon'_r)$	0.0026	0.0038	0.0031	0.0051	0.0068

Table 2 Dielectric properties of some typical epoxy resins at room temperature

	828/T403 (1.0-2.5 GHz) [24]	Araldite F (4.28 GHz) [25]	Epikote Resin 828 (8-12 GHz) [26]	LY 564/XB 3486 (8-12 GHz) [27]	E44 [28]
ϵ'_r	3.456	3.14	3.1	2.74	2.95
$\tan\delta$	0.0012	0.035	0.032	-	0.034

Figure captions

Fig. 1. Near- and far-field regions of an antenna (adapted from [35]).

Fig. 2. Two typical antenna configurations for far-field microwave inspection. (a) monostatic configuration. (b) bistatic configuration.

Fig. 3. Illustration of the transmission line method for permittivity measurement. (a) experimental setup. (b) test sample placed within the test cell. (c) coaxial line cell. (d) rectangular waveguide cell.

Fig. 4. Illustration of the open-ended probe method for permittivity measurement.

Fig. 5. Schematic diagram of the simulation-assisted approach for non-contact permittivity measurement with an open-ended waveguide [52].

Fig. 6. Illustration of the short-circuited line method where the sample is in the probe but short-circuited by a good conductor.

Fig. 7. Illustration of the free space method for electric permittivity measurement. (a) setup with two high-gain horn antennae only. (b) setup with dielectric lenses for focusing.

Fig. 8. Equivalent circuit model for near-field inspection with an open-ended probe.

Fig. 9. Microwave detection of impact damage in a 10 mm thick GFRP sample. (a) front surface. (b) back surface. (c) image of the overall damage produced at 35 GHz from scanning over the front (impacted) surface [70].

Fig. 10. Microwave inspection of delamination in a GFRP T-joint [33]. (a) locations of T-joints in a wind turbine blade. (b) photograph of the T-joint specimen. (c) experimental setup. (d) scan image of the magnitude. (e) scan image of the phase.

Fig. 11. Experimental setup of the near-field microwave system for detection of liquid ingress in honeycomb sandwich structures [77].

Fig. 12. A general near-field microwave microscope ($\lambda/4$ coaxial resonator) for surface profiling. (a) schematic diagram. (b) lumped circuit model.

Fig. 13. Far-field damage inspection using FMCW bistatic radars. (a) photograph of the cut (60 mm) in the GFRP plate (b) damage detection at 35 GHz.

Fig. 14. Block diagram of the focused radar measurement system including radar front end, offset parabolic mirrors and 3D movable stage [91].

Fig. 15. Schematic diagram of the experimental setup for microwave-based thermography.

Sample

Reflection mode

Transmission mode

Conductor

Sample

Probe

Horn
antenna

Sample

Lens

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[illegible][illegible]

Movement control on
a X-Y-Z scanning stage

$f_0 = 7.85 \text{ GHz}$
 $\text{BW} = 2 \text{ GHz}$
 $P_{\text{out}} = 7 \text{ dBm}$

$f_0 = 94.2 \text{ GHz}$
 $\text{BW} = 24 \text{ GHz}$
 $P_{\text{out}} = -4 \text{ dBm}$