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Dielectric properties and noncontact damage detection of plain-woven fabric glass fiber reinforced epoxy matrix composites using millimeter wavelength microwave

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ABSTRACT

Electromagnetic wave reflections from glass fiber reinforced epoxy matrix composites with 0°/90° and ±45° fiber oriented plain-woven glass fabric (PW-GFRP-0/90, PW-GFRP-±45) at incident angles of 30°, 40° and 50° were measured in the frequency range 50–75 GHz using a free-space reflection measurement system. The complex dielectric constants of both composites were calculated using a simple transmission line theory. The complex dielectric constants of PW-GFRP-0/90 and PW-GFRP-±45 are similar and were measured to be $\varepsilon' = 4.61 \pm 0.01$ and $\varepsilon'' = 0.16 \pm 0.002$, respectively.

The damage stored in PW-GFRP-0/90 and PW-GFRP-±45 was also evaluated by dielectric constant changes using the same system at an incident angle of 30°. For both composites, ε' decreased with increasing applied stress and damage parameter. The dielectric constant change is effective for detecting the damage stored in composites and can be used to quantitatively evaluate the damage.

1. Introduction

In telemetry, communication, and radar systems, radar domes (radomes) protect antenna hardware against various environmental hazards such as wind, blowing sand, snow, ice, rain, sunlight, and temperature [1,2]. Glass fiber-reinforced polymer matrix composites (GFRPs) are widely used in radomes because they have superior mechanical properties, such as strength and modulus, environmental resistance, and permeability of electromagnetic waves [1–3]. For designing radomes, there is a demand to increase the electromagnetic wave performance of the antenna. Therefore, it is necessary to not only understand the mechanical properties and environmental resistances but also the electromagnetic wave properties, particularly the dielectric properties of GFRPs [4]. The dielectric properties of GFRPs in the centimeter wave range (8.2–12.4 GHz) were measured using the free-space method of Lee et al. [5–7], and the dielectric properties of GFRPs in the terahertz (THz) frequency range (0.2–1.0 THz) were measured using the THz time domain spectroscopy (THz–TDS) transmission measurements proposed by Naito et al. [8,9].

One of the attractive characteristics of GFRPs is their high ability to sustain and tolerate a large percentage of the damage because the effective damage tolerance in GFRPs is obtained through the potential of cumulative microfracture processes, such as fiber fracture, interface debonding, and matrix cracking [10]. Understanding how much damage is stored in the composite is necessary for the safe use of the structures. Therefore, effective damage detection methods are needed. The detection of local damage has been performed through several experimental techniques (Ultrasonic, X-ray imaging, and Acoustic Emission (AE)) [11–14]. In addition, the application of electromagnetic waves is an effective method for detecting damage in GFRPs [15–17].

In this study, the dielectric properties and in situ noncontact damage evaluation of GFRPs were examined using electromagnetic waves in the frequency range 50–75 GHz. For radomes and other composite structures, it is important to evaluate and monitor the damage by using the measuring apparatus from one side. Thus, the dielectric properties and in situ noncontact damage evaluation of GFRPs were examined by a free-space microwave interference measurement system.

2. Experimental procedure

2.1. Materials and specimens

Commercially available plain-woven fabric glass fiber reinforced epoxy matrix composite (PW-GFRP, fiber: E-glass, IPC standard: 7628 style, matrix: epoxy, ANSI standard: FR-4) were used in the experiments. The as-received PW-GFRP panel was cut into

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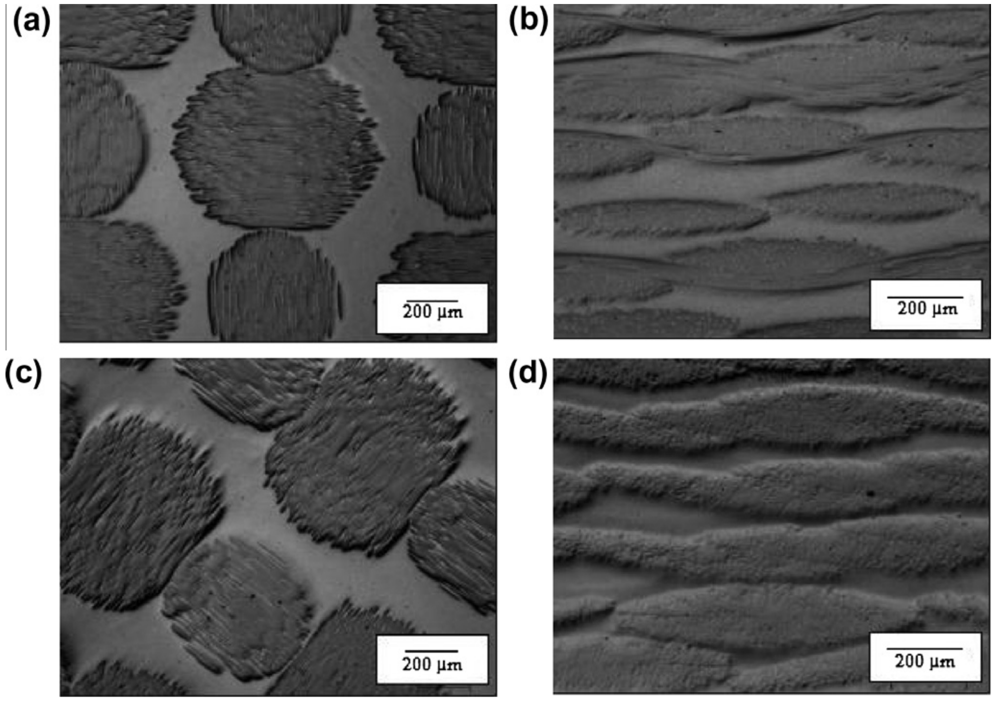

Fig. 1. Typical optical micrographs of in-plane and through-the-thickness sections of PW-GFRP. (a) In-plane section micrograph of PW-GFRP-0/90. (b) Through-the-thickness section micrograph of PW-GFRP-0/90. (c) In-plane direction micrograph of PW-GFRP-±45. (d) Through-the-thickness section micrograph of PW-GFRP-±45.

rectangular straight-sided specimens measuring 170 mm × 25 mm. Two types of specimens were prepared: (i) in one, the fiber axes were oriented in line with the length of the specimen (fiber orientation 0°/90° specimen, PW-GFRP-0/90) and (ii) in the other, the fiber axes were oriented ±45° to the length of the specimen (fiber orientation +45°/−45° specimen, PW-GFRP-±45). Fig. 1 shows the typical optical micrographs of in-plane and through-the-thickness sections of PW-GFRP-0/90 and PW-GFRP-±45. The fiber volume fraction, V_f is ~50 vol.% the thickness, d, is ~1.0 mm. The number of woven fabric plies, N, in the through-the-thickness section of PW-GFRP is six ($N = 6$). Thinner PW-GFRP (0.3 mm) tabs were affixed to the specimen to minimize the damage from the grips used to secure the specimen in the specimen fixture (testing machine). To eliminate the effect of stress concentrations caused by surface roughness from the edges, the edges of the specimens were slightly polished to remove deep scratches. The in-plane surfaces of PW-GFRP are unpolished, i.e., as-fabricated composite surfaces are used.

2.2. Measurement of electromagnetic wave reflection

Reflection measurement of electromagnetic waves in the gigahertz frequency region was carried out using a free-space microwave interference system [18]. Fig. 2 shows a schematic representation of the experimental setup used in measurements of dielectric properties and damage detection. This system consists of a signal generator (Agilent, E8257D), wave source module (Agilent, 83557A), harmonic mixer (Agilent, 11970 V), two horn antennas (Keycom, CC35R) with spot-focusing dielectric Teflon® lenses, and a spectrum analyzer (Agilent, 8562A). Electromagnetic waves were generated by the signal generator, emitted by the transmitter antenna, and focused on the specimen surface. The frequency range 50–75 GHz was used, which corresponds to a wavelength range 6–4 mm, respectively. The diameter of the electromagnetic wave at the specimen surface was ~3λ, which gives a spot size of 12 mm at 75 GHz at the specimen surface. Electromagnetic waves reflected from the specimen were collected by the receiving lens and the receiver antenna and transferred to the spectrum analyzer. Detected signals were transferred to a computer via a General Purpose Interface Bus (GPIB) connection and stored at sampling steps of 0.1 GHz. The antennas and lenses were positioned on an aluminum stage with a semicircular rail to allow the incident and detection angles to be changed with the specimen fixture (testing machine) positioned at the center. In this study, the incident (the definition is given in Fig. 2) and detection angles were similar. The angles at which the dielectric property measurement was carried out were 30°, 40°, and 50°, for the damage detection measurement, an angle of 30° was used. Before the measurement was carried out at each incident angle, the antenna positions were adjusted to obtain maximum reflectance using an aluminum alloy plate.

For comparison, the dielectric properties of PW-GFRP-0/90 in the frequency range 18–30 GHz were measured using a free-space method. The measurement system, procedure, and accuracy of this technique are reported elsewhere [19]. The scattering parameters (S-parameters) method was applied and the complex dielectric constants were obtained using the Nicolson–Ross method [20].

2.3. Tensile test

Uniaxial tensile tests of GFRPs were conducted using a hydrostatic testing machine (Shimadzu, Servopulser EHF-F1) with a load cell of 10 kN. A specimen was affixed to a tensile jig that was pulled downward at a constant crosshead speed of 2.0 mm/min until the specified load was reached. Before testing, the thickness of GFRPs was measured using a micrometer. Once the specified stress (load) was achieved, the crosshead was stopped and held for 2 min. While the crosshead was held stationary, the thickness of GFRPs and the electromagnetic wave reflectance were measured. Then, the stress was removed. The unloading speed was similar as loading speed. This loading and unloading procedure was repeated on the specimen until specimen failure with the applied stresses from 50 to