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Non-contact detection of impact damage in CFRP composites using millimeter-wave reflection and considering carbon fiber direction

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ABSTRACT

Carbon fiber reinforced polymers (CFRPs) are widely used for various structural materials because of their high stiffness and strength. Detecting damages in CFRP composites is important for structural safety. This study was conducted to detect impact damage in CFRP specimens using the millimeter-wave of 65–67 GHz. The impact damage was artificially produced by impact energies of 3.63 J, 8.89 J and 13.21 J, respectively. Since the CFRP composites are electrically anisotropic materials, reflection coefficients are affected by the angle between the electrical field vector direction of the electromagnetic wave and the carbon fiber direction in the CFRP surface. When this angle was 0°, reflection coefficients on the surface with and without damage were easily distinguished. Accordingly, imaging the CFRP specimens including the impact damage was conducted using changes of the reflection coefficient. In addition, in order to obtain better image, the edge detection image processing technique was applied to the original image, and a more natural image was obtained. The magnitude of impact energy producing damage could also be distinguished through the image.

1. Introduction

Fiber reinforced polymers (FRPs) have been widely used as alternatives to metallic components due to their low cost, light weight and easily-manufactured characteristics [1]. According to the fibers they contain, FRPs are divided into aramid FRPs, glass FRP, carbon FRP (CFRP) and so on. Among them, CFRPs are popular materials for automotive, civil engineering, aerospace components and so on because of their high stiffness and strength. CFRPs are also used for the strengthening and rehabilitation of existing structures. However, since the CFRP can be damaged by impact loading, the detection of impact damage is important to maintain the safety of the structures. Various nondestructive evaluation (NDE) techniques such as ultrasonic wave [2–4] and transient thermography [5] have been applied to detect the impact damage of CFRP. Particularly, because of CFRP's strong electrical anisotropic characteristic, electrical methods such as electrical resistance [6–9] and eddy current [10,11] have been used to detect the impact damage of CFRPs.

However, most NDE techniques for the damage detection of CFRP are contact or almost contact techniques. If the damage in CFRP composites can be detected by a full non-contact NDE technique, the detection process and system structure will be simplified. Although the transient thermography method is a non-contact technique, its accomplishment largely depends on the choice of heat sources, isolation of ambient light and the image processing technique. The electromagnetic wave technique may be one of promising methods for the non-contact detection of impact damage of CFRP. Many researchers have used the electromagnetic wave as a NDE technique for various purposes, such as crack detection in pipes and metal surfaces, the internal inspection of cement-based materials, and the evaluation of pipe wall thinning [12–16]. Similarly, terahertz (THz) radiation has been used to obtain the scanned images of CFRP specimens through reflection, using transmitting and receiving antennas [17] and time-domain spectroscopy (TDS) [18]. Although the THz techniques can be effective non-contact NDE methods, their systems are still very complicated and expensive to commercialize.

In this study, the detection of impact damage in CFRPs was conducted using the millimeter-wave of 65–67 GHz. Several studies have indicated that the conductivity of CFRP is influenced by the direction of the carbon fiber, which is caused by characteristics of the CFRP, such as its electrical conductive and anisotropy [17–20]. Therefore, the effect of the carbon fiber direction on the damage detection of CFRP specimens was investigated, and based on this effect, images of impact damage on the CFRP specimens were obtained. In addition, the image was improved by applying an edge detection image processing technique.

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2. Theory

2.1. Effects of the carbon fiber direction in CFRP on an electromagnetic wave

The changes of electrical conductivity of the CFRP according to its fiber direction have been reported [12–14] and their changes can be expressed as in Ref. [21]

$$\sigma(\theta) = \sigma_l \cos^2\theta + \sigma_t \sin^2\theta \tag{1}$$

where θ is the angle between the electrical current direction and fiber direction, and $\sigma(\theta)$ is the overall electrical conductivity at θ. σ_l and σ_t are longitudinal and transverse conductivity. When an electromagnetic wave is transmitted to a CFRP specimen, θ becomes the angle between the electrical field (E-field) vector and the carbon fiber directions. Because CFRP is an anisotropic multilayer material, longitudinal conductivity (σ_l) is much higher than the transverse conductivity (σ_t) on a layer. The longitudinal conductivity is determined by Eq. (2) [21].

$$\sigma_l \approx \sigma_f \nu_f \tag{2}$$

where σ_f and ν_f are the fiber conductivity and the fiber volume fraction, respectively. From Eqs. (1) and (2), the following two facts can be established. Firstly, when the fiber direction is parallel to the E-field direction, the electrical conductivity will be the highest and hence the reflection of an electromagnetic wave will effectively be changed, according to conditions of the CFRP surface. On the other hand, when the fiber direction is perpendicular to the E-field direction, the reflection of the electromagnetic wave will be decreased due to the low conductivity. Then, it will be hard to measure the changes of the reflection caused by the damage in spite of there being impact damage in the CFRP specimen. Secondly, if the volume of each carbon fiber is not uniform, the electrical conductivity will vary according to the carbon fibers. Then, if the CFRP is scanned across the different fibers, the reflection of the electromagnetic wave may fluctuate without the presence of any damage. As a result, these two characteristics of the electromagnetic wave on the carbon fiber may be the key elements for the detection of damages in the CFRP specimen.

2.2. Reflection coefficient on impact damage of CFRP

When a horn antenna is placed over the CFRP specimen perpendicularly, the reflection coefficient (Γ) can be expressed by Eq. (3), where the real part (n) and the imaginary part (k) are given by Eqs. (4) and (5) [22].

$$\Gamma = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \tag{3}$$

$$n^2 = \frac{1}{2}\left[\sqrt{\mu^2\varepsilon^2 + (4\mu^2\sigma^2/\omega^2)} + \mu\varepsilon\right] \tag{4}$$

$$k^2 = \frac{1}{2}\left[\sqrt{\mu^2\varepsilon^2 + (4\mu^2\sigma^2/\omega^2)} - \mu\varepsilon\right] \tag{5}$$

where μ and ε are the permeability and permittivity of the specimen. σ and ω are the conductivity of the specimen and the frequency of the electromagnetic wave. When the CFRP specimen is damaged by impact, the thickness of damaged part will be thinner and the carbon fiber array in that part will be distorted. Then, the permeability, permittivity and conductivity of the CFRP specimen will have been changed by the impact damage, and the reflection coefficient of the electromagnetic wave is changed at the impact damage. These reflection coefficients include information in the CFRP surface area as large as the antenna aperture. Because the size of the impact damage is usually much smaller than the area of the antenna aperture, the detectable size of the impact damage is dependent on the wavelength of the electromagnetic wave. Furthermore, the changes of the electrical conductivity (σ) according to the carbon fiber direction will additionally affect the changes of the reflection coefficient based on Eqs. (3), (4) and (5). As a result, fixing the angle between the E-field vector and the carbon fiber directions is very important for detecting the impact damage of CFRP specimens.

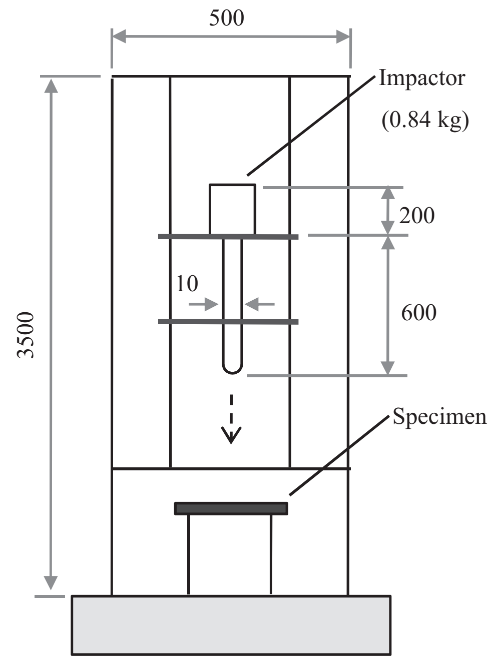

Fig. 1. Schematic diagram of impacting instrument. (unit: mm, not to scale).

3. CFRP specimen preparation

The CFRP specimens were prepared from one directional prepreg sheets, of which carbon fibers are CU125NS and do not include scrim. The specimens' sizes were 200 mm of width, 200 mm of length and 2.5 mm of thickness. The type of specimen was $[0^\circ{}_2/90^\circ{}_4/0^\circ{}_2]_s$ so that the fiber direction of the surface was laid along the direction of length. The damage was produced by a falling impactor with weight, diameter and curvature of 0.84 kg, 10 mm and 14 mm, respectively. The impacting instrument is shown in Fig. 1. The amplitude of impact was adjusted by changing the distance between the impactor and the specimen. In other words, when the impactor hit the center of the specimen, the velocity of impactor was adjusted based on this distance, and the impact energy was determined by the weight and the velocity. The velocity of the impactor was determined by measuring the time taken to pass two known positions just prior to the moment of hitting. More detailed information about the impact experiment is referenced in [23]. Three experimentally measured impact velocities were 2.939 m/s, 4.600 m/s and 5.069 m/s, and the calculated impact energies were 3.63 J, 8.89 J and 13.21 J, respectively. As a result of the impact experiments, the sizes of the impact damages were approximately 3–5 mm in diameter and these were dimly visible on each CFRP specimen.

4. Experiments

The experimental set-up to measure the reflection coefficient of millimeter-wave signal from the composite specimen is shown