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Polarization-resolved terahertz imaging of intra- and inter-laminar damages in hybrid fiber-reinforced composite laminate subject to low-velocity impact

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ABSTRACT

Terahertz imaging is applied to characterize a hybrid fiber-reinforced composite laminate subject to low-velocity impact in this study. The hybrid fiber-reinforced composite laminate comprises unidirectional glass/epoxy and carbon/epoxy plies with a cross-ply stack pattern. Both impact-induced intra- and inter-laminar damages are successfully detected, and the damage evolution throughout the thickness is also evaluated. The interaction between the terahertz polarization and carbon-fiber orientation is investigated in detail. Inter-laminar damage at the interface and the intra-laminar damage close to the same interface can be differentiated via polarization-resolved imaging. With a parameter fitting method based on multiple regression analysis, delamination is characterized quantitatively. Terahertz C- and B-scan images clearly exhibit the propagation of the damage from the top to the bottom surface in three dimensions.

1. Introduction

Fiber-reinforced composites, such as carbon and glass fiber-reinforced composites, are increasingly being utilized in the industrial world to provide an alternative to conventional structural materials due to their high specific stiffness and strength, low weight and corrosion resistance. Hybrid fiber-reinforced composites, which combine two or more types of fibers in the same composites in order to benefit from the merits of each constituent fiber type, have also been used in many applications which need to meet both the requirements of cost and performance. Usually, one type of fiber in hybrid composites is high-modulus and/or high-cost, such as carbon or boron and the other type is low-modulus and/or low-cost, such as glass or Kevlar. The high-modulus fiber provides the stiffness and load bearing capability, whereas the low-modulus fiber makes the composite more damage tolerant and reduces the cost [1]. Therefore, hybrid composites can provide the balance of strength and stiffness, reduce the weight and/or cost while also improving fatigue resistance, fracture toughness, and impact resistance.

Fiber-reinforced composite laminates are vulnerable to impact. The resulting impact-induced damage in laminates involves a combination of intra-laminar damage (such as matrix cracking or fiber/matrix debonding and fiber distortion/fracture) and inter-laminar damage, which leads to the separation of adjacent plies (delamination) [2]. High-velocity impact, with speed up to 2500 m/s, results in perforations and the breakage of fibers. On the other hand, low-velocity impact damage, with energy in range of 5–25 J or with speed between 5 m/s and 15 m/s, sometimes invisible on the surface, involves a combination of matrix cracking and delamination within the laminate [3]. Delaminations are considered the most important failure mechanism, because they can severely degrade the strength and the integrity of the structure, and may propagate undetected during service, leading to a significant decrease in stability and durability. For these reasons, there is an urgent need for advanced nondestructive evaluation (NDE) techniques for impact damage in fiber-reinforced composite laminates over component lifecycle—during service and maintenance.

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Various NDE techniques have been developed for impact damage detection in composite structures over the last few decades, such as shearography [4], ultrasonic testing [5,6], eddy current [7], thermography [8] and X-ray computed tomography [9]. However, not all these methods can provide information in depth to observe the morphology and evolution of the impact damage throughout the entire thickness of the laminate [3]. Ultrasonic C-scans in pulse-echo mode can be utilized for imaging the evolution of impact damage in carbon fiber-reinforced composite laminate [10]; however, the attenuation of ultrasonic waves in glass fiber-reinforced composite laminate is prohibitively high so that the operating frequency cannot in practice typically exceed 5 MHz, limiting the spatial resolution [11]. Ultrasonic C-scans also frequently suffer from the problem of liquid coupling. The spatial resolution of X-ray computed tomography is high and can provide three-dimensional imaging; however, it is difficult to implement for large composite laminates and, as X-rays are ionizing radiation, it carries significant health risks.

Terahertz (THz) imaging, as a new promising NDE technique, can provide a noninvasive, noncontact, and nonionizing method to characterize nonmetallic materials. The THz portion of the electromagnetic spectrum extends from approximately 100 GHz to 10 THz, and lies between the microwaves and infrared; the wavelength range in this region is 3 mm down to 3 μm. THz waves can penetrate numerous nonmetallic materials which may be opaque in the range of visible and infrared light [12]. Moreover, as nonionizing radiation, THz waves present minimal known health risks [13]. Due to these remarkable properties, THz waves have already been used to characterize various types of defects, such as impact damage, voids, delamination, and intrusions in glass fiber-reinforced composites [11,14–17]. Moreover, THz waves can also be applied to measure the optical material parameters [18] and the fiber orientation [19] for glass fiber-reinforced composites. However, the conductivity of carbon fibers hinders the applications of THz waves to carbon fiber-reinforced composites to some extent, and THz waves have to date only been demonstrated to detect the impact-induced matrix cracking on the surface [20].

In this study, THz imaging is firstly applied to a hybrid fiber-reinforced composite laminate, comprised of unidirectional glass/epoxy and carbon/epoxy laminae with a cross-ply stack pattern. The evolution of intra-laminar and inter-laminar damage throughout the thickness of the laminate (1.65 mm) subject to low-velocity impact is evaluated. Inter-laminar damage at the interface and the intra-laminar damage close to the same interface can be differentiated by taking advantage of the sensitivity of the carbon-fiber orientation to the THz polarization. THz C- and B-scan images are obtained to exhibit the propagation of the damage from the top to the bottom surface in three dimensions.

2. Theoretical background

The conductivity of carbon fibers limits the penetration ability of THz waves into the material. For unidirectional carbon fiber-reinforced composites, the conductivity is anisotropic and depends on the THz polarization and fiber orientation, which can be expressed as [21].

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

where θ is the angle between the THz polarization and fiber orientation and σ_l and σ_t are the longitudinal and transverse conductivities, respectively. Along the fiber direction, the electric current flows through the carbon fibers, so the longitudinal conductivity depends on the conductivity of carbon fibers σ_f and on the fiber volume fraction ν_f,

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

For the transverse conductivity, because the resin material is nonconductive, the flow of electric current only occurs due to random contact between adjacent carbon fibers, which depends on the manufacturing process and the quality of the composites [21]. Therefore, the longitudinal conductivity is much higher than the transverse conductivity. Based on the literature [22], longitudinal conductivity ranges from 1×10^4 S/m to 6×10^4 S/m, and the transverse conductivity varies from 2 S/m to 600 S/m.

By analyzing the electric conductivity, one finds that (1) when the THz polarization is parallel to the orientation of carbon fibers, the electric conductivity is maximum and the THz reflectivity also reaches the maximum; (2) when the THz polarization is perpendicular to the carbon fibers, conductivity and reflectivity achieve their minimum. The ideal amplitude reflection coefficient $R_{\_ideal}$ can be expressed as

$$R_{\_ideal} \approx 1 - \sqrt{\frac{2\omega\varepsilon_0}{\sigma}} \tag{3}$$

where ω is the THz frequency, and ε_0 is the permittivity of free space. The reflection coefficient approximately equals to 1 when THz polarization is parallel to the carbon-fiber orientation.

Monitoring the reflection coefficient across the surface of carbon fiber composites with THz imaging can be utilized as a method to characterize the impact damage on the surface. When carbon fiber-reinforced composites suffer from impact damage, carbon fiber distortion and fracture will occur in the damage area, which will lead to spatial variation of the reflection coefficient as well as the polarization anisotropy. The reflection coefficient in regions with and without impact damage can be more easily distinguished with polarization parallel to the carbon-fiber orientation [23].

3. Sample

The tested sample is a cross-ply hybrid fiber-reinforced composite laminate, shown in Fig. 1. The dimension of the laminate is 120 mm (length: x direction) × 120 mm (width: y direction) × 1.65 mm (thickness: z direction). The laminate is formed from prepregs of unidirectional E-glass fibers with epoxy resin, and prepregs of unidirectional carbon fibers with epoxy resin. For the prepreg of glass/epoxy, the fiber volume fraction is 60 vol.% and the resin content is 33 wt.%, the orientation of the glass fibers is along the direction of length (x direction); for the prepreg of carbon/epoxy, the fiber volume fraction is 60 vol.% and the resin content is about 42 wt.%, the orientation of the carbon fibers is along the direction of width (y direction). The stacking sequence of the laminate is $[0^{\circ}_2{}^{G}/90^{\circ}_3{}^{C}]_s$, corresponding to the thicknesses $[0.400 \text{ mm}/0.425 \text{ mm}]_s$. The electric conductivity of the carbon fiber is 5.88×10^4 S/m in our case. Damage was generated by controlled free-fall impact: an impactor of 50 g struck the center of the top surface of the laminate at a speed of 9.5 m/s, schematically shown in Fig. 2.

This damaged sample was firstly scanned with ultrasonic waves to get initial knowledge of the damage pattern and also to provide a point of comparison for the THz imaging results. A customer-designed ultrasonic scanner fabricated by Inspection Technology Europe BV was used for the ultrasonic C-scan experiment. The transducers chosen for this investigation are focused immersion transducers with a manufacturer-provided central frequency of 5 MHz, since this frequency provides a balance between the attenuation and resolution. Ultrasonic C-scans were performed on the sample with water coupling under both transmission (pitch-