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Nondestructive evaluation of hidden multi-delamination in a glass-fiber-reinforced plastic composite using terahertz spectroscopy

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ABSTRACT

In this study, a terahertz time-domain spectroscopy (THz-TDS) imaging system was devised to detect hidden multi-delamination in a glass-fiber-reinforced plastic (GFRP) composite laminates. Shapes, thicknesses and locations in the *z*-direction of each delamination among the overlapped multi-delamination were analyzed considering the interaction between the pulsed THz wave and the GFRP composite. THz wave power and phase were discussed by the analytical calculations and the experimental results with the evaluation of hidden multi-delamination. Then, the THz image results were compared with those of the ultrasound wave inspection method. Finally, hidden multi-delamination in the GFRP composite laminate was successfully detected and imaged using the THz-TDS imaging system, showing that this system can be widely utilized to evaluate the reliability of composite structures as a nondestructive evaluation method.

1. Introduction

A fiber reinforced composites are being widely used for the structural applications such as aerospace, vehicles, architecture and light industrial products due to their superior performance and high specific strength, stiffness, corrosion resistance and fatigue related properties [1]. However, the defects such as delamination, voids, moisture absorption, and fiber fractures caused by mechanical and environmental stresses have a negative effect on the mechanical properties of composite structures. Especially, the importance of delamination has been progressively pointed up. Delamination appeared as a debonding of adjoining plies in laminated composites can lead the composite structures to rupture or reduce their stiffness and strength (Fig. 1) [2,3]. Therefore, it is much important to inspect the hidden delamination in composite components [1].

In order to detect hidden delamination, non-destructive evaluations (NDEs) such as X-ray, liquid penetrant, magnetic particles, and ultrasound waves have been widely investigated and developed [4–9]. These NDE technologies can provide information about internal delamination without damage of the materials; however, there are some disadvantages to these methods [10]. For example, the X-ray can damage the composite materials and cause harm to the human body due to its high radiation energy. The liquid penetrant inspection method is sensitive to environmental conditions, especially temperature change, and is only able to detect surface cracks [11]. The magnetic particle method is also limited to the detection of surface cracks, and it is harmful to composite structures and materials. Additionally, the requirement of a liquid couplant and the presence of edge effects are two drawbacks of the ultrasound wave inspection method [12–14]. The thickness of the delamination also cannot be measured accurately (only the location can be determined), because the ultrasound waves are unable to penetrate the air in the delamination layer.

Terahertz (THz) inspection methods have been recently developed to solve these problems [15]. Due to their low photon energy, THz wave are not harmful to biological tissue, and can provide high spatial resolution due to their wavelength [15]. Furthermore, the THz inspection method does not require a liquid couplant, an advantage for the non-contact and real-time inspection of composite defects [16–19].

In this study, a THz time-domain spectroscopy (THz-TDS) imaging system was used to evaluate the hidden multi-delamination in glass-fiber-reinforced plastic (GFRP) composite laminates. The

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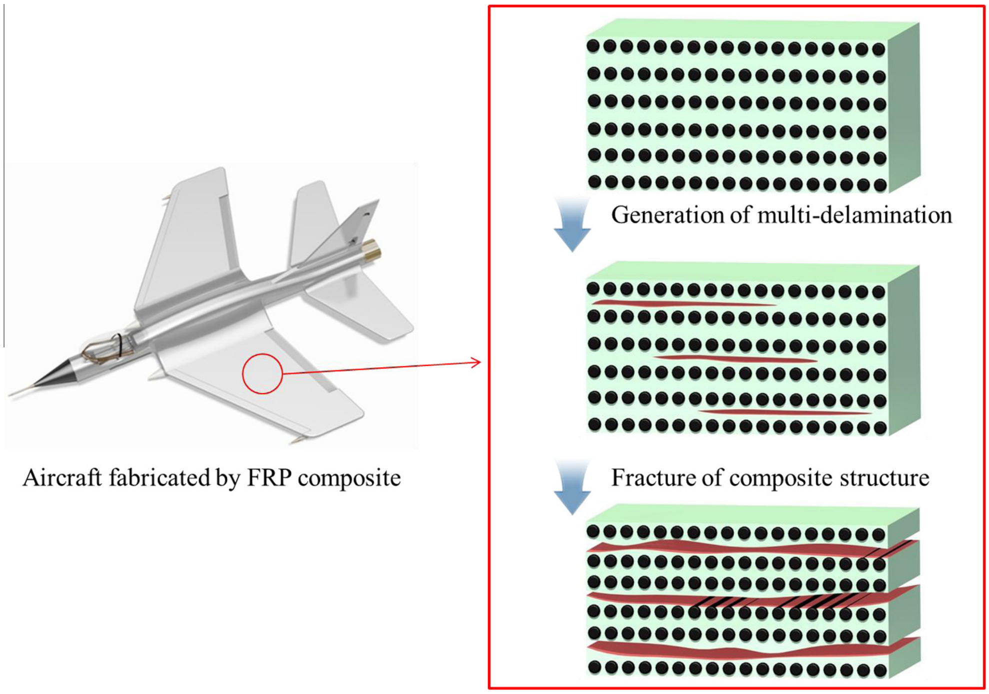

Fig. 1. A schematic diagram of the multi-delamination in composite structures.

shapes of each delamination were detected and imaged using the reflection mode of the THz-TDS imaging system. The thicknesses and locations in the *z*-direction of each delamination are analyzed using Fresnel equations and compared to the experimental results. Finally, the THz-TDS image results are compared to the results of the ultrasound wave inspection method.

2. Experimental details

2.1. Terahertz spectroscopy imaging system

In this study, the commercial THz-TDS imaging system (FiCO™, Zomega Terahertz Corp., USA) was used for the detection of hidden multi-delamination of GFRP laminates. The main components of this system are a femtosecond laser module, THz-TDS module, emitter module, detector module and XY imaging stage (Fig. 2a). The THz-TDS module is composed of a pair of photoconductive antenna (PCA) (emitting PCA and detecting PCA) and optical facilities such as beams, lenses, splitters, and reflectors. The THz-TDS module is configured in reflection mode, with a 25° incidence angle. As shown in Fig. 2b, an ultra-short THz pulse is generated from the emitting PCA. The THz pulse is then reflected at the GFRP specimen. The detecting PCA receives the reflected THz pulse and transmits it to a data processing system for THz waveform analysis and image processing. The THz-TDS imaging system has a frequency range from 0.1 THz to 3.0 THz with a frequency resolution of 11 GHz and a time resolution of 20 fs. The signal-to-noise ratio (SNR) and dynamic range are guaranteed to be 60 dB and >70 dB (peak), respectively. The speed and resolution of the imaging stage can be controlled from 5 mm/s to 50 mm/s and from 50 μm to 1 mm, respectively. The repeatability of our installation is determined by taking two consecutive data sets and normalizing their frequency spectra. This normalization gives about 99% data repeatability after 100 scans averaging for each data set in less than 1 s. Additionally, to prevent water vapor absorption, dry air at 1% relative humidity was supplied to our sealed installation.

2.2. Ultrasound wave inspection system

For the result comparison with THz inspection, the scanning acoustic microscopy (SAM) was used. The SAM facility (HS-1000, Sonix, USA) is composed of various components including an ultrasound pulser-receiver, an analog-to-digital converter, and a scanner for *X*-, *Y*- and *Z*-axis motions. Also, this facility has a tomographic acoustic micro imaging (TAMI) scan system which can collect a series of images in a single scan. The TAMI system has a frequency range of 5–230 MHz (ultrasound). In this study, 15 MHz was chosen to inspect the GFRP specimen in reflection mode.

2.3. Specimen preparation

In this work, the GFRP specimen with hidden multi-delamination was prepared. Glass fiber prepreg (UGN 150, GF contents: 66 wt%, SK Chemical, South Korea) was used and the GFRP specimen was laminated by hand-layup with unidirectional direction. As shown in Fig. 3, the hidden multi-delamination was generated via three layers of 100 μm in thickness of Teflon films with various shapes: rectangles, circles, and triangles. Each Teflon film (top: rectangle, middle: circle, bottom: triangle) was inserted between the stacked layers of glass fiber prepregs. The total laminated 12 prepreg layers have 1.5 mm thickness. After the laminating process, the GFRP specimen was cured for 5 h at 125 °C. After the curing process, the Teflon films were removed from the GFRP specimen to prepare multi-delamination, as shown in Fig. 3. Note that the top rectangular delamination covered the entire regions of the middle-circular and bottom-circular delamination below.

3. Results and discussion

3.1. THz inspection for top rectangular delamination case

Fig. 4 shows the THz inspection results of the GFRP specimen for only the first delamination. The photograph of the GFRP specimen

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