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Impact damage detection of a carbon-fibre-reinforced-polymer plate employing self-sensing time-domain reflectometry

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ABSTRACT

A non-destructive inspection method of carbon fibre reinforced polymer (CFRP) is self-sensing technology that uses carbon fibres as sensors. The technology applies electric current to composites and measures the electrical resistance change to detect damage. Although the technique detects damage precisely, it requires many electrodes on the CFRP surface. Time-domain reflectometry (TDR) has previously been proposed to detect damage over a wide area with a small number of electrodes and applied to detect fibre breakage in unidirectional CFRP ply specimens. In the present paper, experiments are conducted for a cross-ply CFRP laminate subjected to impact damage. Three impact loads are applied and the damage is inspected employing self-sensing TDR and a micro-strip line. Results show that the self-sensing TDR can be applied to laminated CFRP structures that have several fibre directions and when damage such as a delamination crack extends under or close to the micro-strip line.

1. Introduction

Carbon fibre reinforced polymer (CFRP) composites are widely used in aerospace components because they have high specific strength and high specific stiffness. A low-velocity impact, such as that generated by a dropped tool, may cause invisible delamination cracking of CFRP structures. Such delamination cracking may reduce compression strength. It is thus important to detect delamination cracking generated by an impact load to improve the reliability of composite structures. One non-destructive inspection method is the use of self-sensing technology that employs carbon fibres as sensors [1–11]. The self-sensing technology applies electric current to composite structures and measures the change in electrical resistance to detect damage. Although the self-sensing technique detects damage precisely, it requires the mounting of many electrodes on the CFRP surface. There is thus a demand for a new method that detects delamination cracking over a wide area with a small number of electrodes.

Several works have used time-domain reflectometry (TDR) to detect damage [12–14]. The authors of the present paper have developed self-sensing TDR for the detection of fibre breakages using a parallel plate [15] and using a micro-strip line (MSL) [16]. The newly developed method adopts a nanosecond-order pulse signal and can detect the pulse signal reflected from a fibre breakage. The method uses carbon fibres as one of the structures of the transmission line. The method has been simulated in finite-difference time-domain analysis [17]. A curved-MSL method has been adopted to detect breakages over a wider area [18]. These previous papers have detected fibre breakage as the type of damage and adopted unidirectional CFRP ply.

The present paper conducts experiments on a cross-ply CFRP laminate to which impact damage is applied. Using a long CFRP cross-ply laminate, the applicability of self-sensing TDR to the detection of impact damage is investigated experimentally; actual damage such as delamination cracking, matrix cracking and fibre breakages is detected. The cross-ply laminate allows investigation of the effect of the fibre direction on self-sensing TDR.

2. Principle of self-sensing TDR

The TDR method uses a pulse signal in a transmission line. The transmission line comprises of two parallel conductive components and insulator that is sandwiched between the two conductive components. In the case of Fig. 1, the micro-strip line (MSL) is the transmission line and the MSL is made from copper foil and CFRP that are electric conductive materials and electric insulator Glass Fibre Reinforced Polymer (GFRP). In the high frequency

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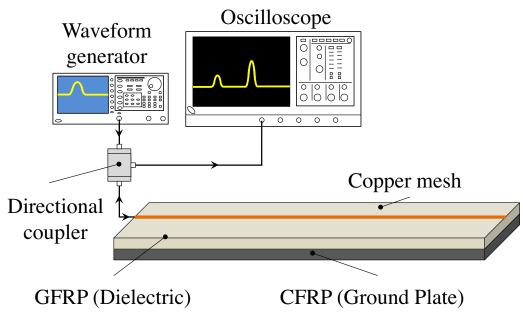

Fig. 1. Schematic representation of self-sensing TDR system.

alternating current such as radio frequency or higher, the electric energy emits from the conductive material to insulator or air. The emitted energy is absorbed in the other conductive material. This process makes a transmission line. Therefore, the transmission line requires two electrically separated conductive components. The sandwiched insulator acts to separate the two conductive components electrically.

The input electro-magnetic wave can propagate in the insulator between the two electric conductive materials: copper foil and CFRP. In the previous paper, we used a parallel plate transmission line. In the case of the parallel-plate transmission line, the air gap between the parallel plates plays a role of insulator, and the CFRP plate and the aluminium plate play a role of conductor.

The pulse signal is input in the transmission line when the impedance of the transmission line is almost equal to that of the normal coaxial cable (50 Ω) which is usually used for measurements. When the characteristic impedance of the transmission line is different from that of the coaxial cable, the pulse signal is reflected at the input terminal of the transmission line.

The pulse signal input in the transmission line propagates in the transmission line. When the transmission line has different characteristic impedance, which comes from carbon fibre damage or change of distance between the two conductive materials because of such as debonding of the insulator or dent, the input signal is reflected at the place. The pulse signal reflected from the transmission line is measured and the result is plotted with the abscissa representing time and the ordinate representing the voltage.

The TDR method requires a wave generator, an oscilloscope, and a target transmission line, as shown in Fig. 1. Fig. 1 shows a MSL type transmission line made on the CFRP plate. The wave generator produces a pulse wave signal, which is sent to a directional coupler. The signal propagates only in the MSL type target transmission line because of the directional coupler. Part of the signal is reflected at the input end of the MSL type transmission line because of the slight difference in the characteristic impedance. The other part propagates in the MSL type transmission line. The signal input to the MSL type transmission line is divided into reflection and transmission components at the damaged point. The reflected signal returns and is measured using an oscilloscope. The time difference between the input signal and reflected signal indicates the distance to the damaged point after multiplication by the speed. Using the TDR method, the damage and its location can be measured. The distance L from the input end to the damage is calculated as [19]

$$L = \frac{V_p \Delta T}{2}, \tag{1}$$

where V_p is the transmission velocity and ΔT denotes the time difference between the input signal and reflected signal. The transmission velocity V_p, which is affected by the transmission line, is approximately 0.6–0.9 times the velocity of light. To measure the V_p, the time difference ΔT of the reflected signal between the input terminal and the end terminal is measured, and the transmission line length is set to L in the Eq. (1). Solving Eq. (1) with respect to V_p gives the transmission velocity.

When the cable is simply replaced by a CFRP plate, the characteristic impedance of the CFRP plate differs greatly from that of the coaxial cable that is used to connect the wave generator and oscilloscope. This arrangement provides perfect reflection at the input end of the CFRP plate. Therefore, the pulse signal does not propagate in the CFRP plate. An impedance matching process is indispensable when applying the TDR method to the CFRP plate. A previous study revealed impedance matching using a parallel aluminium plate [16], and another study adopted an MSL [17]. The impedance matching allows the detection of the reflected impulse signal of the CFRP plate.

3. Experimental method and analytical method

3.1. Experiments

A CFRP plate was fabricated with a stacking sequence of $[0/90]_s$ from IM600/133 prepreg (TohoTenax Co. Ltd., Tokyo, Japan). To cure the long specimen, four sheets of an SRH640 silicon rubber heater (152 mm × 1016 mm, Sakaguchi E.H VOC Corp., Tokyo, Japan) were used. The specimen was sandwiched between aluminium plates of the same size to give compression stress during curing process. Glass fibre heat-insulating materials were used to keep the specimen at 180 °C for 2 h. The specimen was a CFRP plate with length of 1980 mm, width of 120 mm, and thickness of 0.6 mm, as shown in Fig. 2. During curing, 32 vices were used to apply pressure of approximately 0.55 MPa to the specimen. After curing, copper plating was employed to produce a copper electrode on the specimen edge for the application of an electric pulse signal [20]. A BNC cable was soldered to the copper plating electrode as shown in Fig. 3.

Three dropped-weight impact loads were applied to the specimen. The first was applied on the strip line at a point 600 mm from the specimen edge. The impact energy was 14.1 J (mass of 3.19 kg falling from a height of 0.45 m). The impactor head was a hemisphere with diameter of 14 mm made of stainless steel. As the specimen was thin, a GFRP plate with thickness of 2 mm was attached to the backside of the CFRP plate to prevent penetration of the impactor. The impact load was applied to the CFRP surface, and after the impact load, the MSL was mounted to prevent fracture of the transmission line of the MSL. Naturally, when the MSL was damaged as a transmission line, the damaged point reflected the pulse signal. In the present study, to investigate the ability of detecting impact damage of the CFRP plate using

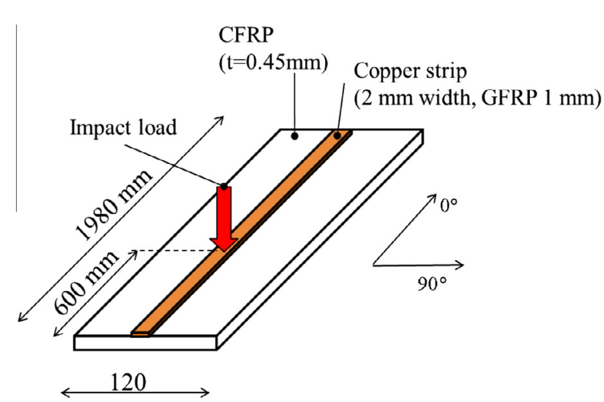

Fig. 2. Specimen configuration and impact load location of the first test.