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Matrix crack detection of CFRP using electrical resistance change with integrated surface probes

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Abstract

For the cryogenic tanks of next generation reusable launching vehicles, the laminated composite tank is one of the key technologies. For composite fuel tanks made from laminated carbon fibre reinforced polymers (CFRP), matrix cracking is a significant problem that may cause fuel leakage. In the present paper, an electrical resistance change method with integrated probes on a single side of the surface of a CFRP composite structure is adopted to detect the matrix cracking of the laminated composites. For a fuel tank structure made of a CFRP laminate, we cannot mount electrical probes on the end of structure or on the inside of the tank structure. We have to mount all probes only on the outside surface. The present method used finite element analyses (FEA) to search for the best placement of probes for matrix crack detection using a rectangular plate. To simulate the tank structure, all probes are placed on a single surface of the CFRP plate specimen. The present study adopted a four-probe method for measuring the electrical resistance change. The FEA revealed that the electrical resistance increases linearly with increase in the number of matrix cracks inside of the probes. By means of thin CFRP cross-ply laminate, the method was experimentally confirmed to be useful for detecting matrix crack density between the probes. Residual electrical resistance at the completely unloaded condition increased with increase in matrix crack density. Measurements of the residual electrical resistance enabled us to detect the matrix crack density without loading.

Keywords: A. Carbon fibres; A. Polymer-matrix composites; B. Matrix cracking; C. Finite element analysis; B. Electrical properties; B. Electrical resistance

1. Introduction

Carbon fibre reinforced polymer (CFRP) laminated structures are very effective for weight saving in aerospace structural components. The cryogenic tank of next generation reusable launching vehicles adopts laminated composite tanks [1]. For a fuel tank comprising a laminated CFRP, matrix cracking of the CFRP laminates causes fuel leakage, and detection of matrix cracking, therefore, is a demanded target.

Change of electrical resistance of the CFRP structure has been applied to the detection of damage to the CFRP structure like fibre breakages, fibre–matrix debonding, matrix cracks and delamination [2–11]. Applied strain and fibre breakages of the CFRP structures are monitored using the electrical resistance changes: electric current is applied to the end of the rectangular specimens [2,4,6]. The research group of Chung [3,5] uses circumferential lead wires with silver paste as probes for the unidirectional CFRP laminated specimen to apply the electric current.

The authors' research group has proposed a delamination monitoring method [12–16] and a strain monitoring method with reliable probes [17,18] for the CFRP laminates. For this research, multiple probes for applying electric current and to measure electric voltage change are integrated on the single specimen surface using co-cured copper foil or silver paste. Since the integrated surface probes method requires installing electrodes on only a single side of the target CFRP structures, the method does not cause troublesome wire placement on inside surfaces of the

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composite tank structures. This enables us to install the electrical resistance change measurements on a CFRP composite tank without design changes to the target composite fuel tank.

The previous method for monitoring the delamination location and size employs a two-probe method with narrow spacing probes on a single side surface. These probes produce electric current in the thickness direction, and this enables delamination monitoring without electrical resistance change due to matrix cracking [19]. To detect matrix cracking, modification to the spacing of probes and the applicability of the integrated surface probe must be investigated. In the present study, therefore, a cross-ply CFRP laminate was adopted as a target specimen, and FEM analyses were performed to confirm the applicability of the electrical resistance change method with the integral surface probes. Experimental investigations were also conducted to confirm the applicability of the method at room temperature using tensile tests of cross-ply CFRP laminates.

2. Principle of the electrical resistance change method

In CFRP laminates, carbon fibres have high electrical conductivity; the epoxy matrix is its insulator. The actual carbon fibres in a unidirectional ply are not straight. The curved carbon fibres contact one another, comprising a carbon–fibre network within a ply. The contact-network brings non-zero electric conductivity even in the transverse direction. In the same way, the fibre-network produces non-zero electrical conductivity in the thickness direction in a ply. Electric conductivity in the transverse direction is much lower than that in the fibre direction. Abry et al. [7] and the authors' group [14] found experimentally that the fraction of electrical conductivity in the transverse direction (σ_{90}) to the fibre direction (σ_0) is very small, and that the fraction of the electrical conductivity in the thickness direction (σ_t) to the fibre direction is smaller than that of the transverse direction. The results indicate that CFRP laminates have significantly strong orthotropic electrical conductivity.

Although the fibre-network structure in the thickness direction is almost identical to the structure of the transverse direction in a ply, through-the-thickness conductivity σ_t of a laminate is smaller than the transverse conductivity of a single-ply (σ_{90}) for normal laminates. That is because a thin electrically insulating resin-rich layer exists there. For actual CFRP composites, however, prepreg plies are curved like the fibres in a ply. The ply curvature induces fibre contact through the plies and causes non-zero electrical conductivity in the thickness direction, even for thick laminated CFRP laminates. Contact among plies causes non-zero electrical conductivity in the thickness direction. Thus, the σ_{90} is usually larger than the σ_t. When a crack grows in the matrix of the CFRP laminate, the crack breaks the fibre-contact-network in a ply. Breakage of the contact network causes increased electrical resistance of CFRP composites.

Fig. 1 shows a schematic representation of the delamination-monitoring system proposed by the authors [12–16]. Multiple probes of equally narrow spacing are integrated on a single surface of the specimen as shown in Fig. 1. All these probes are placed on a single side of the specimen. Usually, it is impossible to place electrodes and lead wires outside aircraft structures. Location of electrodes on a single side surface is a model of placing electrodes inside a thin shell aircraft structure. The authors have performed several finite element analyses (FEA) and concluded that the electric current should be applied in the fibre direction of the surface ply to monitor delamination cracks [14]. The electrical resistance change of each segment between the electrodes is measured with a conventional electrical resistance bridge circuit. The electrical resistance changes among all segments are measured for various delamination sizes and locations. Using the measured values, the relationship between the electrical resistance changes and

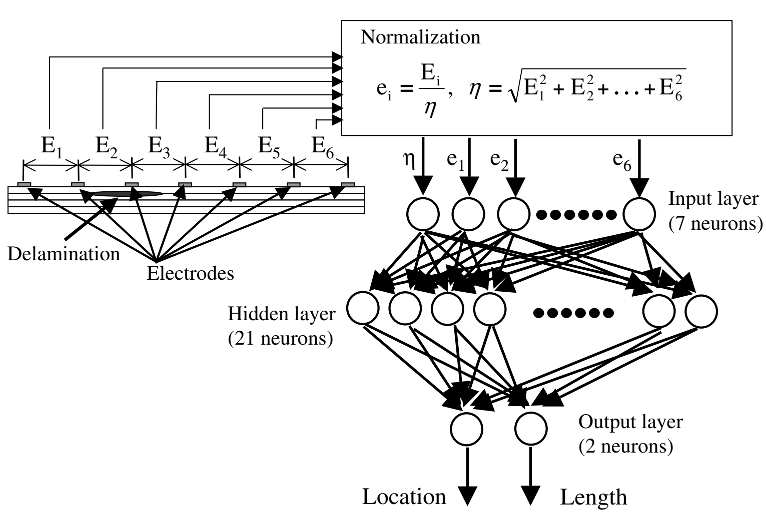

Fig. 1. Schematic representation of delamination identification method using electrical resistance change method with an artificial neural network.