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Application of Electric Resistance Change Method to Damage Detection of CFRP Bolted Joints

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Abstract. Bolted joints are widely used for composite structures. As is well known, excessive bearing load gives rise to bearing failure at hole boundaries. Detecting bearing failure is important for assuring integrity of composite structures. Conventional nondestructive inspection methods are expensive, cumbersome, time-consuming, and not suitable for health monitoring, and a simple, low-cost inspection method for bearing failure must be developed. Authors have experimentally demonstrated detection bearing failure by an electrical resistance change method. In this study, detectablity of remote damage, which includes bearing failure, using an electric resistance change method is investigated analytically. The results show that fiber breaking and delamination induce permanent increase in the electric resistance of the bolted composite joints, and that the proposed method, which involves measuring electric resistance, is effective for detecting bearing failure.

Introduction

Bolted joints are widely used for composite structures. As is well known, excessive bearing load gives rise to bearing failure at hole boundaries. Bearing failure has been investigated by many researchers [e.g., 1-5], both experimentally and analytically. Bearing failure of bolted composite joints consists of compressive failure, matrix cracks, delamination, kink band formation, and other phenomena. Detecting bearing failure is important for ensuring integrity of composite structures. In general, conventional nondestructive inspection methods, such as C-scan and X-ray inspection, are used to detect bearing failure. The conventional inspection methods are, however, expensive, cumbersome, and time-consuming. In addition, the conventional inspection methods are not suitable for health monitoring, because overlaps, insulators, and washers mask bearing failure areas. Therefore, a simple, low-cost inspection method for bearing failure must be developed.

A lamina of carbon-fiber-reinforced composites has electric conductivity. Besides having conductivity in the fiber direction, such a lamina also has conductivity in the transverse and thickness directions, by virtue of fiber contacts in the lamina [6]. In other words, the lamina has orthogonal anisotropy of electric conductivity. Electric conductivity is much lower in the transverse and thickness directions than in the fiber direction. Damage within composite materials, such as fiber breakage and delamination, changes electric resistance of composite materials. Measuring the change in electric resistance enables detection of the internal damage, and numerous papers have reported the detection of internal damage in composite materials by the electric resistance change method [7-33]. For bolted joints, overlaps, insulators, and washers prevent use of conventional mountable sensors such as strain gauges. One advantage of the electric resistance change method for detecting bearing failure lies in that electrodes can be mounted far away from bolt holes, because of the electric anisotropy. Using embedded sensors such as fiber optic sensors is difficult, because embedding them around the circumference of the bolt holes is impracticable. Another advantage lies in the low cost of a system for the electric resistance change method. Authors have demonstrated experimental detections of bearing failure [30], but the generality is not clear.

In this study, detectablity of *remote* damage in composite plates, which includes bearing failure, using the electric resistance change method is investigated analytically. The results show that fiber breaking and delamination induce permanent increase in the electric resistance, and that the proposed method, which involves measuring electric resistance, is effective for detecting bearing failure.

Remote damage detection by the electrical resistance change method

In order to investigate the detectablity of remote damage, which includes bearing failure, electrical current in CFRP laminated plates and electrical resistance change by damage were analyzed by using finite element analysis.

Plate specimen as shown in Fig.1 was analyzed. The layer thickness is 0.2 mm. The stacking sequences of the specimen are $[45/0/\text{-}45/90]_S$ and $[(\pm 45)_2]_S$. In this study, 8-node solid elements were adopted for analysis. The size of an element in plane was 3mm×3mm and a ply was divided into 10 elements in the thickness direction. Two point electrodes were mounted on the specimen surface. In order to measure the electrical current and resistance change, direct current of 10 [mA] was applied. Electrical conductivity used for FEM analysis is shown in Table 1.

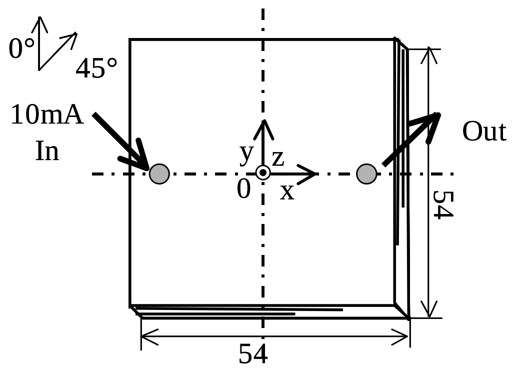


Fig.1 Analytical model of CFRP plate for the electrical resistance change method

Table 1 Electrical conductivities of CFRP laminates used for analysis

σ_0 [$\Omega^{-1}m^{-1}$]	σ_{90} / σ_0	σ_t / σ_0
5500	3.7×10^{-2}	3.7×10^{-3}

Current path in CFRP laminated plate

For isotropic materials, electrical current is likely to flow the shortest path between electrodes. On the contrary, the electrical current can detour and the current path depends on the stacking sequence in the case of CFRP laminated plates. Fig. 2 shows the result of the vector diagram of electrical current density in angle layers of a $[45/0/\text{-}45/90]_S$ laminate.

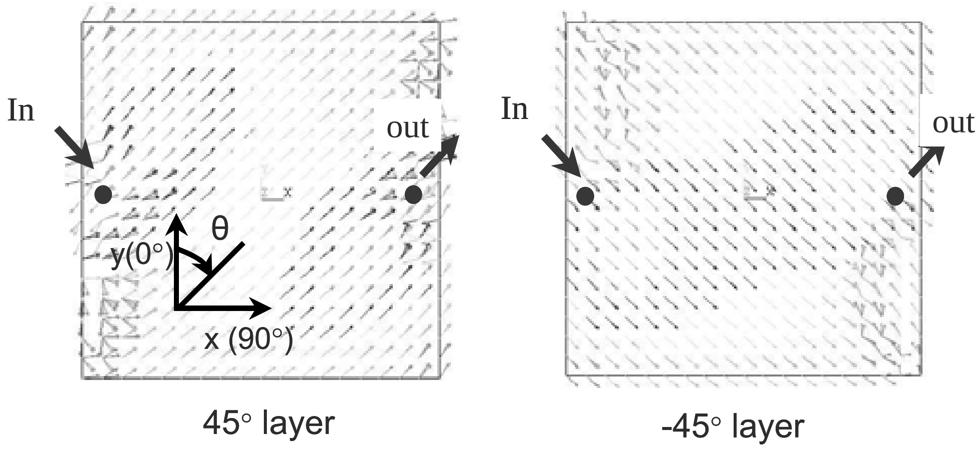


Fig.2 Vector diagram of electrical current density in 45˚ and –45˚ layer of $[45/0/-45/90]_S$ laminate

These figures show that the most part of the electrical current detours along with the fiber direction, and this enables us to detect remote damage by using the electrical resistance change method.

Electrical current ratio through an internal cross section

In order to investigate the detectability of damage, the magnitude of electrical current that flows through an internal cross section was analyzed. If an electrical current path is cut by damage, the electrical current that flowed in the current path must detour. It is supposed that the larger the magnitude of the electrical current becomes, the stronger influence on electrical resistance becomes. Thus, the electrical current that flows an internal cross section is an indicator of damage detectablity if damage cuts the current path through the internal cross section.

As fracture modes, delamination, fiber breaking and matrix cracking were assumed. Fig. 3 shows the positions of electrodes and internal cross sections to calculate electrical current ratios for three fracture modes. The meshed area in Fig.3 corresponds to delamination, and is between 45˚ and 0˚ layer. The diagonal internal cross-sections correspond to fiber breaking and matrix cracking, and is in 45˚ layer.

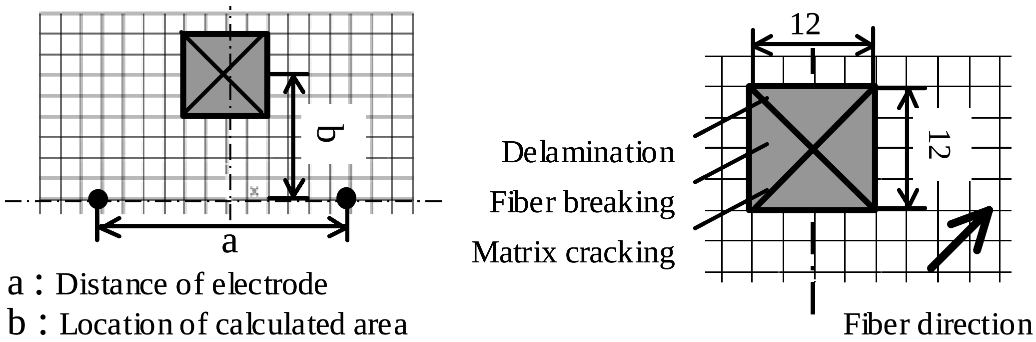
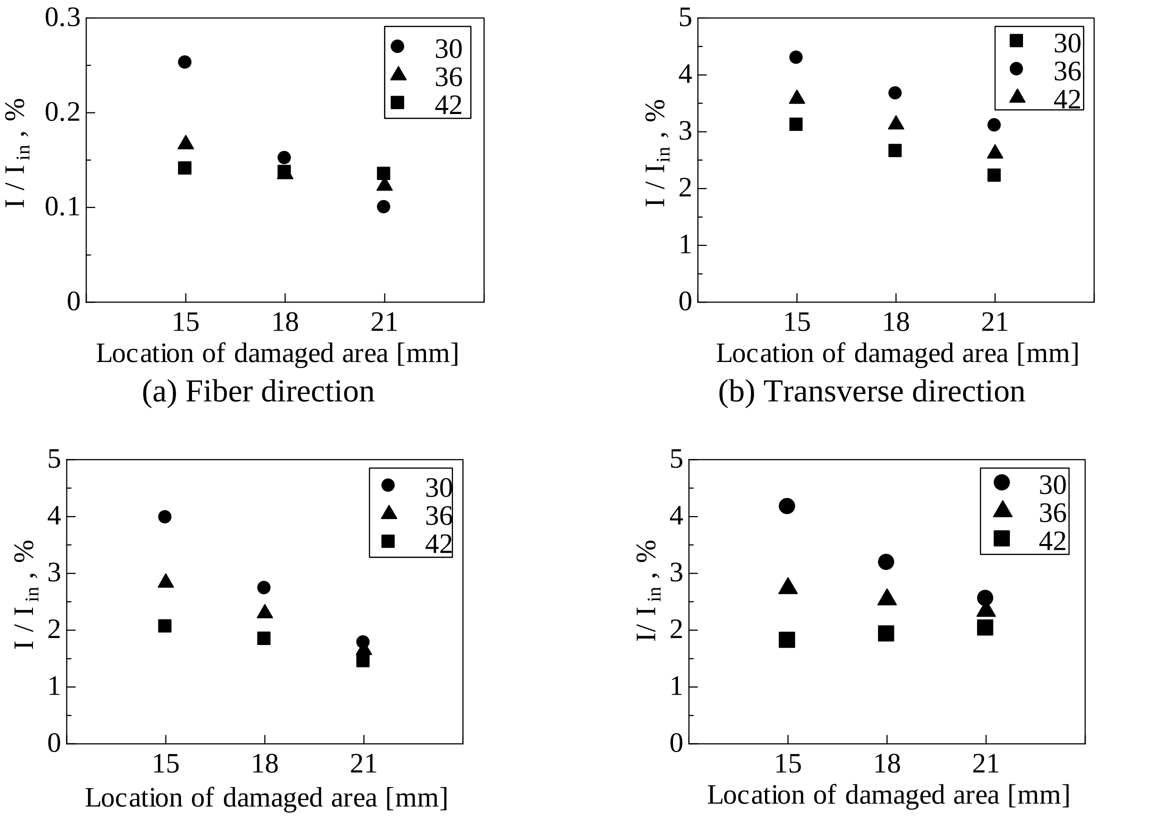


Fig.3 Internal cross-sections to calculate electrical current ratio

The electrical current ratios through three internal cross-sections are shown in Fig.4 (a)-(c) for $[45/0/-45/90]_S$. The vertical axis is the electrical current normalized by an input current (= 10mA), and the horizontal axis is the location of damaged area. Results for different distances between electrodes are plotted by different symbols.

The electrical current ratio in the fiber direction and through-thickness direction are a few %. These currents are not negligible, and the occurrence of delamination and fiber breaking might result in the electrical resistance change. On the contrary, the electrical current ratio in the transverse direction is less than 1%. This suggests that the influence of matrix cracking might be much smaller than that of fiber breaking and matrix cracking.

In addition, the current ration decreased as increase of the distance between electrodes and the distance between electrodes and damage. These figures show that a compromise between sensitivity and distance are required, but it is possible to detect damage that exists at the distance of a few cm from electrodes by using the electrical resistance change method.



(a) Fiber direction

(b) Transverse direction

(c) Through-thickness direction

(d) Through-thickness direction of $[(\pm 45)_2]_S$

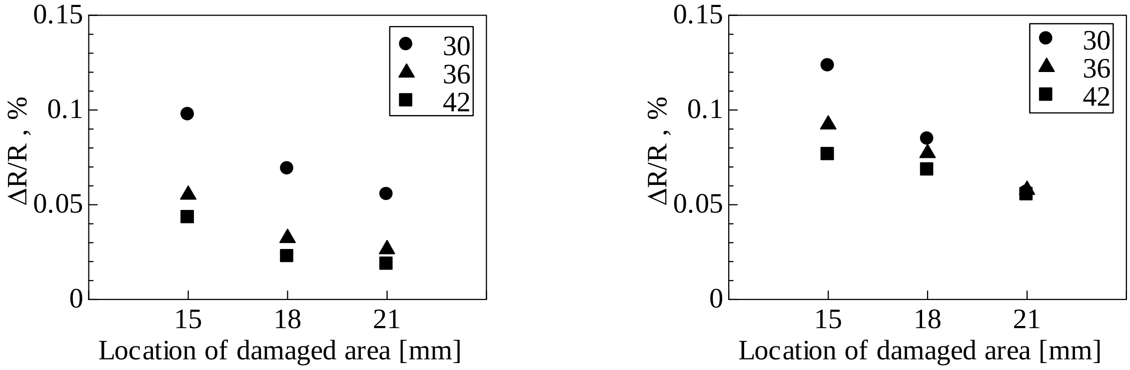
Fig.4 Electrical current ratio through different internal cross sections that correspond to delamination, fiber breaking and matrix cracking

The influence of the stacking sequence was also conducted by using an angle-ply laminate. The current ratio through an internal cross-section that corresponds to delamination is shown in Fig.4(d). The difference between Fig.4(c) and (d) is small. This implies that the fiber angle of the outmost layer dominates the current path of laminates.

Electrical resistance change by fiber breaking and delamination

Electrical resistance change of $[45/0/-45/90]_S$ laminate by damage was analyzed. In order to model delamination and fiber breaking, the electrical conductivity in the through-thickness or the fiber direction of elements at the respective cross-sections was set to 0. The results are shown in Fig.5. The vertical axis is the electrical resistance normalized by the initial electrical resistance, and the horizontal axis is the location of damaged area. The both resistance changes are on the order of 0.1%, and the order of resistance changes agrees with experimental results for CFRP bolted joints as shown in Fig.6 [30].

It is noteworthy that the magnitude of the electrical resistance change by delamination is on the same order of that by fiber breaking. This is because the electrical currents through the respective internal cross sections are on the same order. Bearing failure is not dominated by fiber breaking, but induces delamination and shear matrix-cracking that prevent current flow in the through-thickness direction. Thus the electrical resistance change method is effective to detect bearing failure.



(a) Fiber breaking (b) Delamination

Fig.5 Electrical resistance change

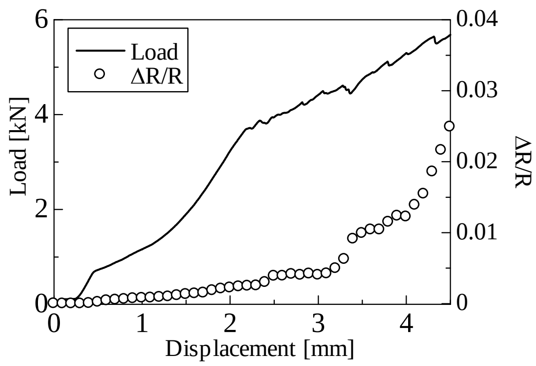


Fig.6 Experimental electrical resistance change by bearing failure [30]

Concluding remarks

In this study, the detectablity of the remote damage detection of CFRP plates, which includes bearing failure, by the electrical resistance change method was investigated by using finite element analysis. The results show that fiber breaking and delamination induce permanent increase in the electric resistance of composite laminates, and that the proposed method, which involves measuring electric resistance, is effective for detecting bearing failure.

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