Diagnosis for CFRP aircraft by Joule heating using lightning protection system

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Abstract

Rapid and automatic inspection of composite aircraft after every flight would reduce the safety factor and allow for more flights. Although, an electrical resistance change method (ERCM) has been proposed, there are many problems with its practical application. In this study, a new diagnostic method, impact–damage visualization, was developed. Indentation damage increases fiber–fiber contact at the interlaminar interface and electrical conductivity. Consequently, electrical current applied to the material will concentrate around the damaged area, and lead to selective and intense resistive heating. This temperature increase can be observed by thermography or detected as a change in electrical resistance caused by the temperature difference. The proposed method had sufficient reliability and sensitivity for practical application as a damage inspection method.

1. Introduction

Carbon fiber reinforced polymer (CFRP) materials have been widely used in aerospace because of their high mechanical properties. However, the interlaminar strength of the laminated composites is a weakness with these materials. When the laminated composites are subjected to even slight impacts delamination occurs, which results in cracks that reduce the structural strength. The electrical resistance change method (ERCM) has been proposed as an automatic diagnostic system to detect or identify impact damage in CFRP composite structures[1–6]. For the ERCM, carbon fibers as structural reinforcement of the structure can be used as sensors by making use of their electrical conductivity. The electrical resistance between electrodes mounted on the CFRP structure’s surface can be used to evaluate the structural integrity of the composite. Because we only have to measure electrical resistance for the inspection, the ERCM could be applied to inspection of large structures, such as the primary components of commercial aircraft, in a short time without expensive equipment. However, there are still problems with using the ERCM for in situ inspection of actual aircraft structures in hangers or outside. These problems include reduced accuracy because of fluctuations in the electrical properties of the composites caused by air disturbances. The applicability of this method to commercial aircraft structures is also hindered by the large number of segments that measurements need to be conducted on and the large amount of wiring required to enhance the sensitivity and accuracy of damage detection.

To overcome these problems, a new diagnostic method was proposed. This method was based on increases in the fiber–fiber contact at the interlaminar interface and the electrical conductivity through the thickness of the composite after indentation damage from an impact load. Figure 1 shows the schematic setup for measuring the decrease in electrical resistance between the outer two layers caused by an indentation. In this method, the two outer layers of a continuous graphite fiber laminate have the conductive fibers orientated at different angles (orthogonal each other). The lower section of the laminate does not have the first 0° layer on it, so that direct electrical contacts can be placed on the second 90° layer. When an electrical
current is applied between electrodes B and 3, the maximum through–thickness current occurs around the intersection of the carbon fibers connected these electrodes, which is called segment B3. Therefore, a decrease in electrical resistance can be sensitively measured when an impact load creates an indentation on segment B3. However, in this measurement, sufficient sensitivity could not be obtained in larger structures because the resistance change was relatively small when the interval for electrical resistance measurement was larger. This also makes it difficult to identify the segment that is damaged. The electrical resistances of the surrounding undamaged segments, such as A3 and B4, also decrease to the same degree as the damaged segment. This will be discussed further in Section 3.2.

To overcome these problems, a method for impact–damage visualization is proposed here. For the visualization of impact damage, the area around an indentation is selectively and intensely heated by resistive heating like Fig. 2. This area has much lower through–thickness electrical resistivity than undamaged areas, and the electrical current from all in–plane directions concentrates here. The indentation increases both the through–thickness current flow through itself and the in–plane current density in the surrounding area. Consequently, the segment with the indentation generates the maximum amount of electrical heat and has the maximum temperature. Application of an appropriate amount of current to the structure produces a sufficient change in the temperature at the damaged area even in large structures that are subject to disturbances from ambient air. This allows highly sensitive detection and location of small impact damages. This method can be applied to laminates with other stacking sequences as long as there is a difference in the fiber orientation angle between the two outermost layers. Indentations always occur at the interface near the structure surface, which can make our proposed method easy to diagnose thick laminates. Moreover, the visualization method could be used with existing aircraft lightning protection systems, which consist of metal mesh or strips mounted on the composite aircraft surface as shown in Fig. 3.

2. Electrical resistance change caused by an indentation or delamination cracking

The electrical resistance change caused by an indentation was measured by experiment, and subsequent analyses were conducted for the estimation of the electrical resistivity around the indentation, so it could be used in coupled electrothermal analysis of the CFRP structure.

2.1 Estimation of the electrical resistivity around the indentation

Figure 4 shows the experimental set up for the indentation test (left) and the sample configuration for measurement of the change in electrical resistance between the two outermost layers caused by the indentation load.

The stacking sequence was [0/90]_4S. The lower third of the laminate did not have the first 0° layer, which allowed electrical contacts to be placed on the surface of the second 90° layer. When current was applied to electrode 1 on the first layer at 30 mA, and the difference in

![Fig. 1 Schematic of the system for measuring the decrease in electrical resistance between the outer two layers caused by an indentation in a multi–segment CFRP laminate.](image1)

![Fig. 2 Schematic of the system for resistive heating an indentation selectively by making use of decrease in electrical resistance caused by the indentation.](image2)
potential between electrodes 2 and 3 was used to measure the electrical resistance between the first and second layers, $R_{23}$, of the structure (the four-probe method). To create an indentation in material and not cause delamination cracking at the same time, a quasi-static indentation was applied to the center of the sample on the jig plate, which constrained through-thickness deformation of the sample.

Figure 5 shows the results of the average of $\Delta R_{23}/R_{23}$ (left) and the average indentation depth (right). In the indentation test, the resistance between the outer two layers decreased because of the indentation. The resistance decreased by >10 % with the 0.15 mm depth of indentation. These substantial changes caused by even small subcritical damage have not been observed in the conventional ERCM, which focuses on delamination, matrix cracking, or fiber breakage. These changes in resistance are comparable to those caused by delamination cracking in Section 2.3.

### 2.2 Analytical estimation of the electrical resistivity around the indentation

Finite element analysis (ANSYS Version 11.0) for estimating the through-thickness resistivity around the indentation was conducted with the following three assumptions: only the through-thickness electrical resistivity is different in intact parts from the indentation; the resistivity in the indentation is constant; and the size (2 mm × 2 mm, 0.30 mm thick) and shape (rectangular solid) of the indentation are constant. An analytical model has the same dimensions and stacking sequence as the sample shown in Fig. 4 used for the experimental measurements. The central nodes on the top of electrode 1 and 4 had current applied at $I$ ($I=1$ A) and 0 V, respectively. $R_{23}$ is defined as the electrical resistance between electrodes 2 and 3 and it was calculated using $V_{23}$, which is the average of the difference in potential distribution between the top of electrode 2 and that of electrode 3 as follows:

$$R_{23}=V_{23}/I$$  \hspace{1cm} (1)

$R_{23}$ for the undamaged structure was calculated first, and the analysis was then repeated with the through-thickness resistivity of the indentation ($\rho_{dent}$), which diminished gradually. By
trial and error, \( \rho_{\text{dent}} \) was determined for an indentation of each scale to determine the fractional change in \( R_{23} \) caused by the indentation corresponding to the experimental results presented in Fig. 5(left). The properties used in the analysis were taken from reference 8.

The analytical results are presented in Fig. 6. The vertical axis is the electrical resistance and the horizontal axis shows the through–thickness resistivity around the indentation. If the three assumptions discussed earlier are true, the through–thickness resistivity rapidly diminishes to less than 30% and 10% that of the unloaded sample after occurrence of 0.041 and 0.074 mm depth of indentations, respectively. The resistivity finally decreases to 1–2% that of the undamaged areas. Such a large decrease is crucial to reliability and efficiency of the diagnosis in actual large structures that are subject to disturbances by ambient air.

### 2.3 Analytical estimation of the change in electrical resistance caused by delamination

To compare the electrical resistance change caused by an indentation to that caused by delamination, we calculated the resistance for a delamination analytical model. Square delamination cracks (4 mm, 8 mm, 12 mm, and 16 mm in size) were placed at the center of the sample. The delamination cracks were simulated as an electrical insulator sheet by two sets of nodes at the same coordinates on the interlaminar interface between the first and second layers. One was placed on the bottom surface of the first layer and the other on the top surface of the second layer, so that the delamination crack disconnected the electrical current paths. The resistance changes caused by delamination are shown in Fig. 7, and can be compared with the results in Fig. 5(left). The indentation changed the electrical resistance much more than the delamination crack.

### 3. Verification of the effectiveness of the impact–damage visualization

#### 3.1 Feasibility of detection of an indentation

To verify the effectiveness of the visualization of an indentation, a coupled thermal–electrical analysis was conducted for both indentation and delamination models. The boundary conditions of both natural convection and radiation were applied to all the surfaces at an ambient temperature of 27 °C (300 K). The heat transfer coefficient was 8.334 Wm\(^{-2}\)K\(^{-1}\). The thermal properties of the IM600/133 laminate (fiber volume fraction, \( V_f = 0.47 \)) were taken from the work of Ogasawara et al.[9]. The thermal contact conductance (TCC) at the delaminated interface was calculated from the thermal conductivity of dry air as follows:

\[
TCC = \frac{k}{t} = \frac{26.14 \times 10^{-3}[\text{Wm}^{-1}\text{K}^{-1}]}{0.02 \times 10^{-3}[\text{m}]} = 1307[\text{Wm}^{-2}\text{K}^{-1}]
\]

where \( t \) is the thickness of the delamination crack. A coupled thermal–electrical analysis was
performed with 0 V and 10 V at the center nodes of electrode 1 and 4, respectively.

The temperature distribution results for an indentation and delamination are shown in Fig. 8. The temperature around the indentation was higher than that in undamaged areas. With an indentation depth of 0.15 mm that needs to be detected, the maximum temperature changed by >31 °C in the damaged state compared to the undamaged state. The change in temperature of >6.6 °C was easy to detect with an indentation depth of >0.074 mm. The experimental results as shown in Fig. 9 were similar to the analytical ones. Conversely, the surface temperature in the presence of delamination was not very different from that of the surrounding undamaged material.

### 3.2 Feasibility of identification of indentation location in a multi–segment structure

Indentation identification was conducted in a two–segment model ([0/90/+45/45]_25) as shown in Fig. 10. An indentation model (rectangular solid, 2 mm × 2 mm by 0.3 mm thick) with a through–thickness resistivity of 5.084 % (indentation load of 9 kN, indentation depth of 0.11 mm) of the undamaged structure was located at the center of segment 23. The dimensions of regular rectangular solid mesh were 2 mm × 2 mm by 0.15 mm thick. After analyzing both an undamaged model and a model with an indentation, the fractional change in resistance between electrodes 2 and 3, \( \Delta R_{23}/R_{23} \), and that between electrodes 2 and 5, \( \Delta R_{25}/R_{25} \), were calculated as follows:

\[
\Delta R_{23}/R_{23} = -0.05902, \quad \Delta R_{25}/R_{25} = -0.05747
\]

Because an indentation had the same influence on the resistance change of both segments 23 and 25, it was difficult to identify the segment with the indentation in it from the resistance
change. This can be explained by considering the electrical current flow. The electrical paths in the structure with an indentation in segment 23 would look something like Fig. 1. Once an indentation occurs and generates a low–resistance electrical path through an interlaminar resin–rich area, most of the electrical current applied between the first and second layers concentrates around the indentation. Therefore, the electrical resistances of the damaged area and the surrounding undamaged segments decrease by a similar level. Similar problems occur in other ERCMs using electrical resistance between two sets of electrical contacts located on the top and bottom surfaces. In the proposed diagnostic technique, identifying the segment with the indentation is relatively easy because a temperature increase caused by concentration of electrical current can be detected around the indentation. In the analytical model (Fig. 10), the center nodes of electrodes 1, 4, and 6 had applied voltages of 10 V, 0 V, and 0 V, respectively. The highest temperatures were observed in the areas around the indentation as shown in the structural temperature distribution (Fig. 12).

4. Conclusion
To detect a >0.15 mm depth of indentation in carbon fiber composites that may lead to a large reduction in CAI strength, a new automatic self–monitoring method called impact–damage visualization was proposed. The electrical properties of IM600/133 (graphite/epoxy, Toho Tenax, Tokyo, Japan) were determined experimentally and estimated analytically. To verify the effectiveness of the impact–damage visualization, temperature distributions were compared in undamaged, indented, and delaminated IM600/133 structures after application of resistive heating. The following results were obtained:

1. The resistivities in 90° direction and thickness direction of IM600/133 were $2.843 \times 10^4$ and $1.069 \times 10^7$ times larger than that in fiber direction, respectively.

2. In the indentation test (indenter ø 15.9 mm) the through–thickness resistivity decreased to <30 % and <10 % of that without indentation after occurrence of 0.041 and 0.074 mm depth of indentations, respectively.

3. The differences in the maximum steady–state temperature between the undamaged structure and that has a 0.074, 0.11, 0.15 mm depth of indentations were calculated analytically at 6.6, 13 and 31 °C, respectively. The temperature change was easy to detect with an indentation depth of >0.074 mm.

References