Electrical Self-Sensing of Damage within Composite Structures

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Abstract

When damage occurs in carbon fibre composite materials, there is an associated change in the electrical resistance. Previously, edge mounted and surface mounted contact arrangements have been used to monitor the change in the resistance, and it has proved possible to detect and locate the presence of damage [1-3]. However, accuracy has been limited due to the small changes in resistance that are involved, and to date it has not been possible to assess the damage within woven structures. One reason for this is that in woven structures, the resistance in-plane is generally uniform, unlike the case with unidirectional systems, where a degree of non-uniformity is expected due to the differences in resistance in the two principle directions. This study extends the application of the electrical resistance change method to woven fabric/epoxy composite laminates. Woven carbon fibre/epoxy laminate was targeted because it is used in many practical structures to support impact and peeling loads. A practical sensing procedure was therefore applied on laminated plate specimens to overcome the identified issues. The contact arrangement selected in this study was surface mounted, as this would minimize the conduction length of the measurements and thus maximize the chances of detecting local changes in the panel. A sensing ply was attached to the bottom surface of the specimens to simulate a thin shell type structure. Static indentation and impact testing were used to generate the damage, introducing delamination in to the plate in a controlled fashion. A data acquisition device was used to collect the data and a dedicated programing code was written to perform the analysis. Data analysis allowed the identification of the damage location, with a resolution good enough to facilitate targeted investigation using conventional NDT methods. As a result, this method was effective in locating damage inside a composite laminate.

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1. Introduction

Carbon fibre composite laminates have been used widely in both military and civil applications due to their light weight and high specific properties [4] [5]. Military applications, in particular, require high strength-to-weight ratio and high stiffness to maximize the efficiency and minimize the fuel consumption. Carbon fibre/Epoxy composites consist of, at least, two different components that are the epoxy, which is highly insulating, and the carbon fibre, which is highly conductive. That makes it potentially a smart material by utilizing one or more of its components, carbon fibre/epoxy composite can be monitored during the manufacturing process [6-9] or in-service [3, 10]. As composite materials are susceptible to damage due to low amounts of loads, new challenges are imposed. Normally low amounts of loads such as low velocity impact loads, could produce barely visible impact damage (BVID). That, in turn, reduces the reliability of fibre reinforced composites as it decreases the compressive strength and stiffness of the fibre reinforced composites drastically. To overcome this problem non-destructive testing methods have been developed. The main advantages of these techniques such as C-scanning, eddy current, X-ray is that they are quick and efficient. C-scanning, eddy current and X-Ray might provide precise results about damage size, shapes and locations. However, they need special equipment and surface preparations. In reality, it might be difficult to use these techniques to test composite structures in-service due to complexity of laminated composite materials, which are normally formed by layers of dissimilar materials, but they can be used to detect damage in certain parts of composite structures. To reduce the cost of taking parts out-of-service to test and improve reliability of composites, in-service testing systems such as fiber-optic methods have been developed [11-14]. Optical strain sensors like Fabry-Perot interferometers and Bragg grating sensors are used to monitor strain and the damage occurrence of damage in carbon fiber composite laminates [15]. These sensors can be integrated into carbon fibre composite laminate but can potentially cause local distortion or resin-rich regions, when the optic sensor diameter is bigger than the thickness of the ply [11]. Further development have been undertaken allowing the optical strain sensors to be attached to the surface of the carbon fibre composite laminates, however that could reduce the accuracy of the sensors. Other optical methods have been used, but they are built on the principle that crack or delamination will fracture an embedded optical fibre causing a loss of light, but this is not always reliable [16].

The electrical resistance method has been used successfully to monitor strain and damage in carbon fiber composites [17-19]. The electrical resistance method does not require expensive equipment as it employs the reinforced carbon fiber as a sensor to detect the damage, as a result there is no reduction in mechanical, static or dynamic, strength. By measuring the electrical resistance change between electrodes, which are mounted on the

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surface of carbon fiber composite laminates, damage such as delamination, matrix cracks, and fibre breakage can be detected.

In this study, therefore, the ability to detect the BVID by using a four-probe electrical resistance change method is investigated. Woven carbon fiber composite laminated plate-type specimen was used. Impact and indentation loads were used to create the damage. The effect of specimen thickness and distances between electrodes were studied. A preliminary code developed by the authors was used to locate the damaged area.

2. Experimental Procedure

2.1. Specimen Preparation

The material employed in this study was VTF 261 fabric carbon fiber/epoxy prepreg by CYTEC Co., Ltd. 140X240 mm plies were stacked to make laminates of four or eight plies (thickness of the laminate is ~1mm or 2mm). The laminate was cured in an autoclave at $135^{o}C$ X 90 psi for 1 hour.

A standard photo-lithographic technique with a photoresist dry film was used to make a sensing ply. A commercial laminated material, DuPont Pyralux FR8510R, consists of 18 μm copper and 25 μm polyimide was used. The mask of the sensing patterns is shown in Figure 1, 10X10mm electrode size was used to ensure the best connection between the fiber bundles and the sensing ply in Figure 2. The sensing ply was co-cured with the panel to ensure a perfect connection between the panel and the sensing ply as shown the Figure 3.

During the curing cycle the excess resin squeezes out from the woven laminate towards the upper surface due to vacuum pressure that would cause epoxy-rich layer on the top surface of the laminate, the sensing ply was placed on the bottom surface of the panel.

Once cured, pin headers were soldered to the panel using a lead free solder which contains 3% silver, shown in Figure 4, to make a connection with a data acquisition device. National Instruments NI9219 modules in an NI cDAQ-9172 chassis were used to collect the data. The devices were configured to four-wire resistance mode (four-probe technique). The four-probe technique injects the current through two electrical contacts (normally outer electrodes) on the specimen and measures the voltage between two different electrodes. A default excitation current 500 μA was applied between each pair of electrodes, it is found that this amount of current will not generate Joule heating in the sample. According to the data published by the manufacturer the T300 low modulus fibers used in this work have a resistivity of 17 $\mu\Omega.m$. By multiplying the electrical resistivity of the carbon fibres by carbon fibres volume fraction, the ideal electrical resistivity of the composite panels calculated 9.73 $\mu\Omega.m$.

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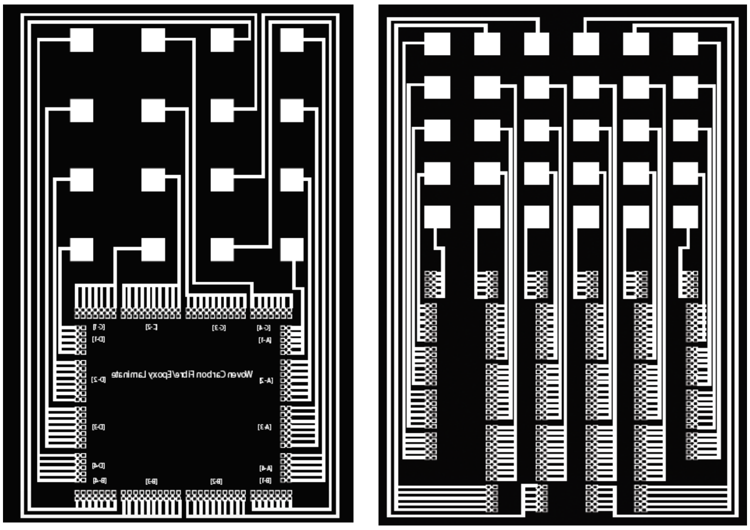

(a) (b)

Figure 1. Mask used to produce flexible circuit boards (a) shows the 20mm grid sensing pattern and (b) shows 10mm grid sensing pattern.

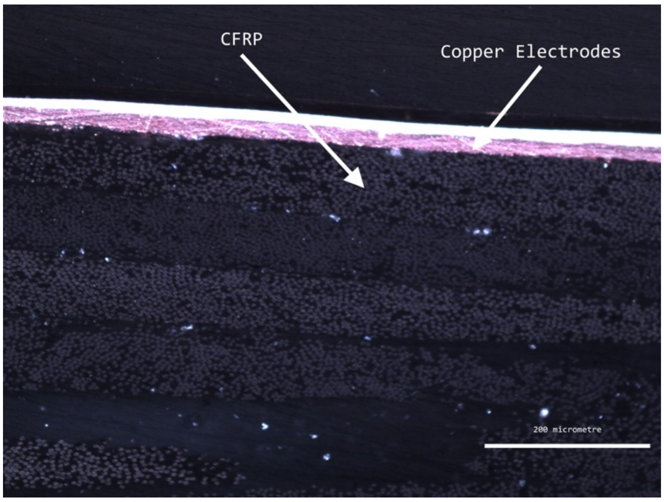

Figure 2. Cross-section view shows the interface between the electrode and CFRP.

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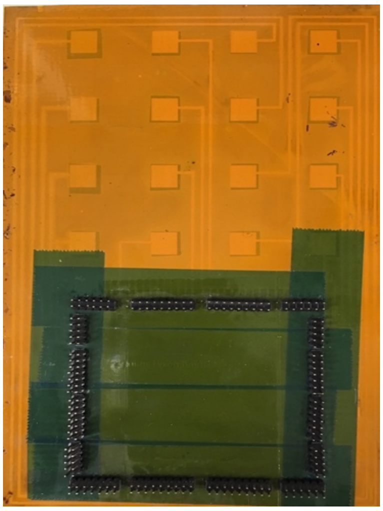

Figure 3. The backside of the panel where the sensing ply attached.

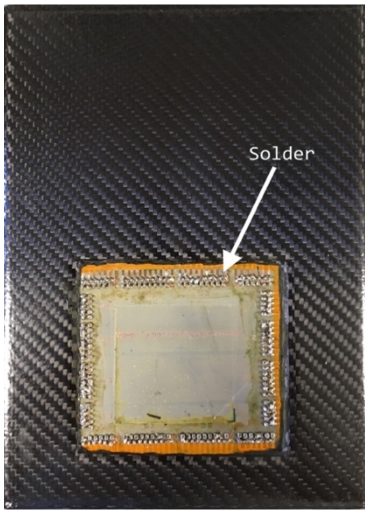

Figure 4. A 2mm CFRP laminate where flexible circuit board is attached to the backside of the panel and soldered with pin headers.

2.2. Indentation and impact Testing

Eight specimens with different thicknesses (1mm and 2mm) were used, four samples each. Two samples of four specimens were indented and the other two were impacted by using different loads. The specimens were indented and impacted by instrumented force head, a 15 mm hemispherical impactor was used. The samples were placed on a steel plate with 75 mm hole, and clamped using U clamps to prevent sample movements during the tests. From obtained information, the energy absorbed by the panel (E_a) can be calculated by using the following formula

$$E_a = \int F \, v dt \quad (1)$$

where F was the instantaneous force, v was the instantaneous velocity and dt was the time interval. The indentation load was 2kN while the impact loads were 3.5 and 5J

3. Results and Discussion

A fully automated custom-built experimental setup was used. It is found that the proposed sensing system could replace expensive testing methods such as C-scanning and X-ray and could be more efficient than aforementioned methods. To achieve that goal and to test the feasibility of the proposed sensing system, it

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has been tested on the different panel thicknesses as well as the proposed sensing system being optimised to reduce the operation cost.

3.1. Panel thickness

In order to test the effectiveness of the system at detecting damage in panels, different panels thicknesses were used. A 1 and 2 mm panel thickness was used with both 10 and 20 mm grid sensing patterns. For the 10 mm pattern the undamaged resistance of the panels was 6.5 Ohm and 4.3 Ohm respectively. While, 1 and 2mm with 20 mm pattern the undamaged resistance of the panels was 8.22 Ohm and 3.39 Ohm respectively. Changes in the sample thickness are noticed to reduce their electrical resistance due to increasing the paths that the electrical current uses to travel from electrode to another. The damage was introduced in different regions of the panels, and located precisely using a preliminary code written by the authors. The code divides the panel into multiple sub-regions and calculates the mean electrical resistance changes. A region with highest electrical resistance changes is considered as a damaged region, which is shown on the contour plots in Figure 5. The predictive capabilities of the code depend on the efficiency of the electrical contacts between the panel and the sensing layer on the other hand between pin headers and the sensing ply.

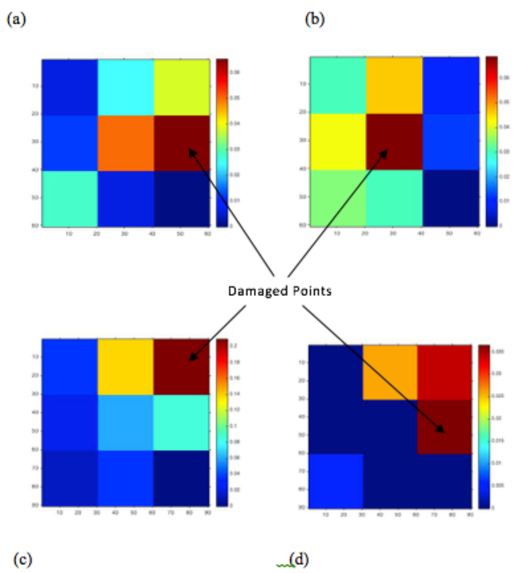

Figure 5. Damage contour plots as a function of electrical resistance change. a) A 1 mm, 10mm grid sensing indented with 2kN, b) A 2mm, 10mm grid sensing indented with 2kN, c) A 1mm, 20mm grid sensing impact with 3.5J and d) A 2mm, 20mm grid sensing impact with 5J

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3.2. Spacing between electrodes

For the proposed technique to be utilized on an industrial scale, the space between electrodes needs to be increased, as that would facilitate the manufacturing process of the sensing ply as well as reducing the number of dedicated data acquisition devices and reducing the operation cost consequently. As damage detecting in woven fibre composite laminates is a property of the arrangement of carbon fibre in a textile. It is found that increased spacing between electrodes would compromise the accuracy of the system, however the authors are working on developing a complementary mathematical model that would locate the damage in a sensitized damage region precisely.

4. Conclusion

The present study demonstrated for the first time the applicability of the electrical resistance change technique in detecting damage in woven CFRP panels on an industrial scale. A newly developed sensing system with four-probe electrical resistance change technique was used, measurable changes in resistance occurred after BVID was introduced. The effects of panel thickness as well as the spacing between electrodes on the proposed sensing system were investigated. The proposed sensing patterns were effective in detecting damage in 1 and 2mm thick panels. It is found that increasing the spacing between electrodes would reduce the operation cost but it is associated with compromising on sensing system accuracy.

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