DETECTION OF INCIPIENT HEAT DAMAGE IN AIRCRAFT COMPOSITES USING ELECTRICAL RESISTANCE MEASUREMENTS

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Abstract

This paper presents a preliminary investigation into the use of changes in electrical resistivity to detect incipient heat damage in carbon-epoxy composite. Specimens made of IM7/977-3 were exposed to a range of temperatures varying from 0°C to 100°C above the composite's curing temperature. Their electrical resistance was then measured along and perpendicular to the fibre direction to characterize the relationship between resistance and overheating damage. The results revealed that the electrical conductivity increased with the level of thermal exposure. This is likely due to an improvement in crystalline structure with prolonged exposure to temperatures above the cure temperature of the carbon-epoxy composite. These results show that electrical conductivity is a promising technique for detecting incipient heat damage in carbon fibre composites employed in aircraft construction.

1. Introduction

Carbon fibre-reinforced polymer matrix composites (CFRPs) are susceptible to damage by overheating due to fires, lightning strikes, supersonic dashes, and jet engine exhaust in service [1]. At present, visible damage such as paint peeling, charred surfaces and delamination cracking can be detected using existing non-destructive evaluation (NDE) techniques, whereas non-visually apparent or barely visible damage remains difficult to identify and quantify [2]. McShane et al [3] identified incipient heat damage as degradation in material properties without visible signs of damage to the composite as a result of thermal exposure.

The concept of monitoring changes in electrical resistance for damage detection in CFRPs is not new [4-8]. Electrical resistance measurements require only simple equipment and are suitable as a field interrogation technique for composite parts. Previous work exploited the presence of electrically conductive fibres in a dielectric polymer matrix, whereby resistance was measured via continuous carbon fibres in the fibre direction as well as in the transverse direction via contact points along the fibres [7, 9]. The effect of internal stresses and strains [10] as well as changes to the internal structure of the laminate on the resistance of the carbon fibres allows the detection of damage such as delamination [11], cracking [12] or fibre fracture [6, 8, 11], by monitoring changes in the electrical resistance.

Mei and Chung [13] and Schulte and Baron [8] have reported links between the thermal history and the electrical resistance of CFRPs, indicating that the electrical resistance has the potential to be a useful in-situ monitoring technique in high temperature conditions. However, all of these studies have monitored the change in electrical resistance as the temperature increases. This paper presents an experimental study of the effect of overheating damage on the electrical resistance of carbon fibre/epoxy composites, with a view of identifying a non-destructive inspection method to detect incipient heat damage of composite materials.

2. Experimental Details

Carbon fibre composite laminates were manufactured from Cytec IM7/977-3 carbon/epoxy unidirectional prepreg. Laminates consisting of 24 plies were manufactured in two lay-ups: unidirectional (UD) and quasi-isotropic (QI) $[+45/0/-45/90]_{3S}$. The laminates were cured at 177°C for six hours as per the manufacturer's recommendations. Laminate plates were then cut to yield specimens of dimension 18 x 6 x 3 mm for the Short-Beam Shear (SBS) specimens and 100 x 25 x 3 mm for the resistivity measurements. All specimens were then heat treated in a digitally controlled furnace for one hour at 180°C, 205°C, 230°C, 255°C and 280°C. Short-beam shear (SBS) testing was carried out according to ASTM D2344 [14].

To reduce the contact resistance between the probes and the carbon fibre laminates, resistivity specimens were sanded to remove the resin layer from the surface and expose the carbon fibres. Conductive silver paint was then applied to all surfaces and wires were adhered to each surface via conductive epoxy [10]. Care was taken to ensure that no two surfaces of conductive paint met. Probes were connected to wires adhered to conductive silver paint via conductive epoxy as per the schematic in Figure 1, to measure resistance in three directions: longitudinal, transverse through-width and transverse through-thickness. Conductivity measurements were obtained via a Keithley 2100 6 ½ digit multimeter.

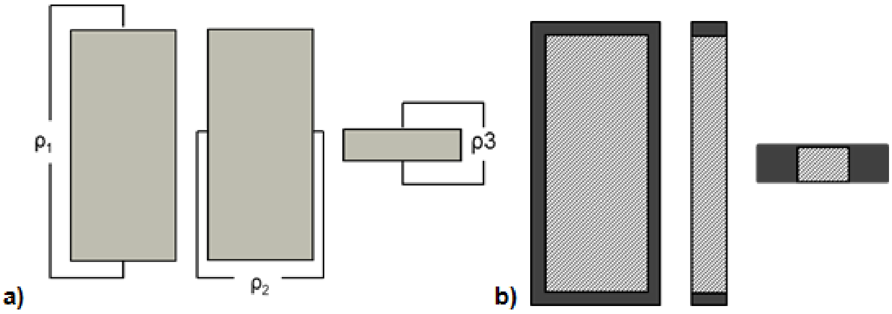


Figure 1. Position of wires connecting to multimeter probes to obtain the three resistivity measurements, ρ_1 is the longitudinal resistivity, ρ_2 is the transverse resistivity through the width of the specimen and ρ_3 is the transverse resistivity through the thickness of the specimen.

Once the resistance measurements were obtained, the volumetric resistivity ρ was calculated via the following relation,

$$\rho = R\frac{A}{L} \tag{1}$$

where L denotes the distance between the probes, A the cross-sectional area of the sample perpendicular to the current direction.

3. Results and discussion

3.1. Results

The reductions of SBS strength due to varying levels of overheating damage are presented in Figure 2, showing a steady decrease in SBS strength with increasing exposure temperature up to 280°C. The UD specimens suffered a 34.33% loss in SBS, while the QI specimens saw a 43.77% reduction in SBS at 280°C. Figure 3 shows the measured electrical resistivity results as a function of exposure temperature. Each data point represents the average value of three measurements. As expected, the longitudinal resistivity for both the UD and the QI specimens were quite low, being 0.25 Ω.m and 0.63 Ω.m in the pristine specimens respectively. The longitudinal resistivity of the QI laminate was slightly higher than the value pertinent to the UD laminate as the QI laminates contain only a quarter of the fibres in the 0° direction. The transverse-resistivity in the UD laminates was much higher than the QI as expected. For QI laminates, the 90° fibres provide a conductive pathway in the width direction, reducing the width-wise resistivity to below the transverse resistivity of the UD laminates. The through-thickness resistivity for the pristine UD and QI specimens are 8818 Ω.m and 10436.98 Ω.m respectively, both of which decreased with exposure damage. While the quasi-isotropic specimens exhibited an initial drop in resistivity after being subjected to 180°C exposure and an increase with increasing temperature, the UD specimens showed a smaller drop in resistivity with the 180°C exposure which continued to decrease with increasing temperature until 255°C, where there is an increase in resistivity at 280°C. The through-thickness resistivity dropped 4344.76 Ω.m and 4333.35 Ω.m from the pristine value for the UD and QI lay-ups respectively as a result of exposure to 280°C for one hour, indicating that thermal exposure resulted in a non-monotonic reduction in the through-thickness resistance. Only the transverse resistivity through the thickness of the laminates experiences a consistent drop over the range of thermal exposures.

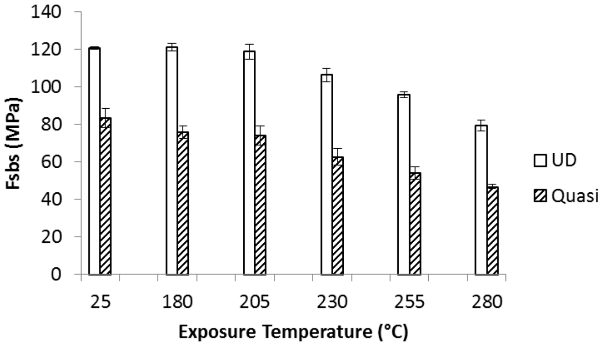
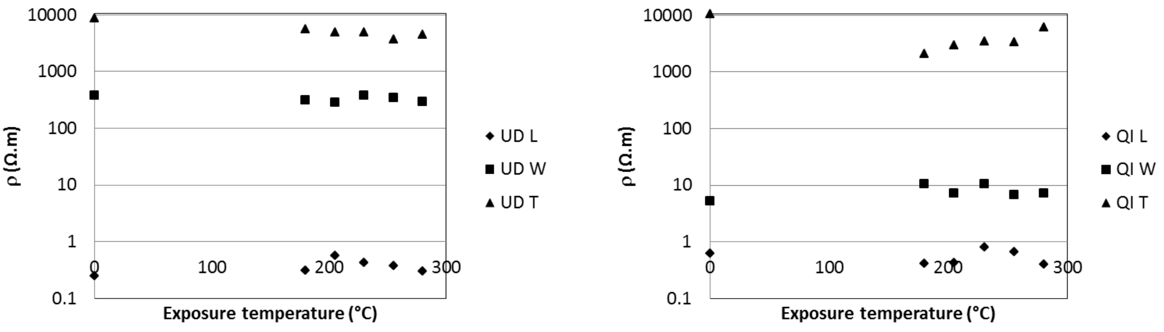


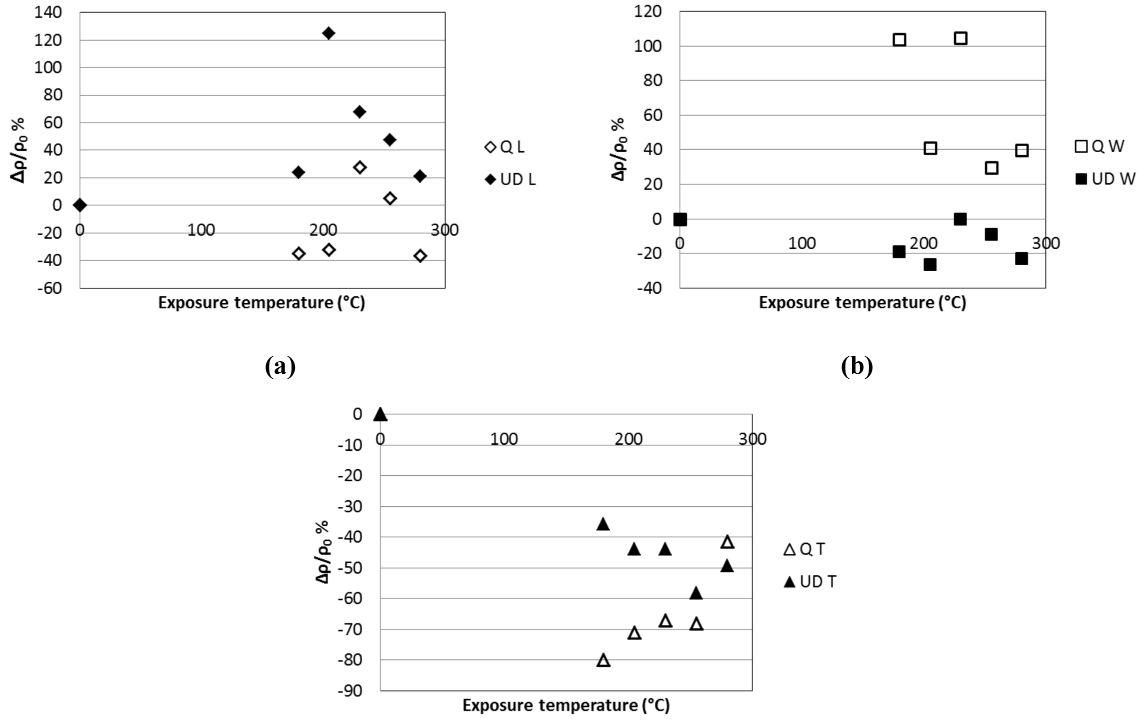
Figure 2. Short-Beam Shear (SBS) results for IM7/977-3 with increasing temperature.



(a) **(b)**

Figure 3. Measured resistivity for (a) UD and (b) QI laminates in three directions: L = longitudinal, W = width-direction and T = through-thickness.

To illustrate the effect of thermal damage on the electrical resistivity more clearly, the percentage of change in resistivity is shown in Figure 4.



(a) **(b)**

(c)

Figure 4. Percentage change in resistivity vs. exposure temperature in three directions: (a) L = longitudinal, (b) W = width-direction and (c) T = through-thickness.

Figure 5 shows the relationship between the reductions in Short-Beam Shear (SBS) strength with increasing temperature and the through-thickness resistivity of IM7/977-3 laminates. It can be seen than there is a strong correlation between the through-thickness resistivity with the short beam shear strength: reduction in resistivity indicates decrease in SBS strength.

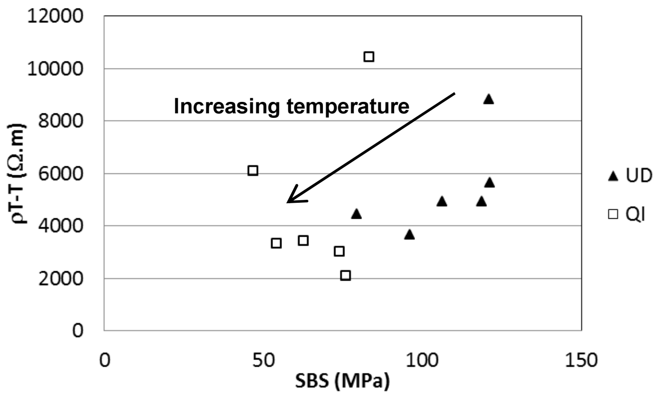


Figure 5. Through-thickness resistivity vs. reduction in SBS strength with increasing temperature.

3.2. Discussion

As the SBS strength is a matrix-dominated property, Figure 2 shows that there is matrix degradation present in the exposed specimens consistent with what was reported by Duvall and Roach [15], with further insights into the SBS strength reduction available in [16]. The results showed that there were no noticeable changes in the longitudinal resistivity of UD laminates, which was expected, as the exposure temperatures were insufficient to cause any physical or chemical changes to the carbon fibres. Chung [7] noted that the residual stresses are higher between plies in quasi-isotropic laminates in comparison to UD laminates due to the mismatch in fibre direction. This residual stress state results in a higher activation energy required by the electrons to jump from one ply to the next in the through-thickness direction. Initial decreases in resistivity with thermal exposure can be attributed to the relaxation of residual thermal stresses from the curing process [7, 13], the effect of which can be seen more clearly in the case of the QI laminates in Figure 3.

Ideally, unidirectional composite materials should be transversely isotropic in terms of conductivity however Figure 3 (a) shows a higher value for the through-thickness resistivity when compared with the resistivity in the width direction. This may be attributed to the reduced fibre-to-fibre contact at the interfaces of plies compared to within the plies. Due to the manual lay-up of the composite, there is also the possibility that small variations in the angles of 0° plies contributes further to a higher through-thickness resistivity of the material than the width-wise resistivity of UD laminate. This same mechanism may also be responsible for the through-thickness resistivity of QI laminate being higher than the width-wise resistivity.

Transverse measurements through the thickness of the laminates showed an overall reduction in electrical resistance with increasing exposure temperature. Given that the main type of damage at these temperatures has been reported to be matrix embrittlement and fibre-matrix interface degradation [8], the transverse electrical resistance could be a good indicator of incipient heat damage. The fluctuations in the through-thickness resistivity of the laminates can be attributed to a complex combination of increasing levels of crystallinity and changes in the residual thermal stresses due to temperature exposure after curing [7, 13], as well as thermal degradation effects such as matrix cracking [12] and fibre-matrix interface damage with exposure to increasing temperature.

At lower temperatures, crystallization occurs on the fibre surface decreasing the electrical resistivity by decreasing fibre-waviness and improving the bond between the fibre and the matrix [17]. There is however a maximum level of crystallinity, above which the benefits are no longer seen. At the same time, returning the composite to the cure temperature can relieve residual thermal stresses as shown by Chung [7], further decreasing the resistivity. Heating the composite to higher temperatures may induce further thermal stresses in the composite resulting in an increase in resistivity. Evidence of these effects in the matrix can be seen in the behaviour at 230°C where the reduction in resistivity due to improving crystalline structure starts being affected by the increase in resistivity due to thermal degradation at higher temperatures, including the possible breakdown of this crystalline structure. Figure 4 (c) shows that the through-thickness resistivity of both the UD and QI laminates experience an increase at 280°C as a result of thermal degradation.

4. Conclusion

Based on the findings included in this paper, the transverse resistivity in the through-thickness direction of IM7/977-3 carbon-fibre epoxy composite has been found to be sensitive to incipient heat damage. Damage mechanisms of incipient heat damage experienced by the composite within 100°C of the cure temperature, including matrix and fibre-matrix interface degradation affect the transverse resistivity by altering the activation energy required for the electrons to pass through the matrix at fibre contact points through the thickness of the laminate. The through-thickness resistivity showed a 49% drop in resistivity for the UD and a 41% drop for the quasi-isotropic laminates after a 280°C exposure. These results show that electrical resistivity is a promising diagnostic indicator for determining if a carbon fibre composite has experienced any incipient heat damage.

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