DAMAGE DETECTION AND AMELIORATION BY ELECTRICAL RESISTANCE FOR SMART COMPOSITES

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1 Introduction

A practical method is presented which enables damage to be reliably detected and located in a carbon fibre reinforced polymer composite (CFRP) structure. The resistivity of CFRP is known to change as a result of damage [1] and [2], partly due to the piezo-resistive nature of carbon fibres themselves and partly due to disruption of conductive pathways within the structure of the material such as cracks and delaminations. Since the resistance of CFRP is orthotropic the basis of a structural health monitoring system is inherent within the material itself; damage can be detected by recording changes in resistance and the location of the damage inferred due to the inherent directionality of the material's properties. These changes in resistance are recorded by a network of contacts which are embedded into the structure during manufacture in the form of flexible printed circuit board interleaves.

The geometry and location of these electrical contacts within the laminate was found to be important for the efficiency of the sensing system. The effects of contact offset and through thickness location was investigated in this work.

If a higher current is applied via these contacts the electrical resistance of the carbon fibres causes them to act as heating elements. It is thus possible to apply heat to a local area of the structure. If a heat-activated self healing resin is used, such as that described by Hayes et al [3], [4] and [5] this heating effect can be used to ameliorate damage in the structure. Contact geometry was again found to be an important factor in delivering heat to the correct area of the specimen. Wider contacts were found to reduce the undesirable heating at the contact location, and so allow higher temperatures to be achieved in the location of the actual damage.

Barely visible impact damage (BVID) represents an obstacle to the wider adoption of composite materials within the aerospace industry [6]. A minor impact which would produce a visible dent in a metallic panel can cause internal damage to a composite panel which is difficult or impossible to observe visually [6]. Although damage resulting from such low energy impacts is unlikely in itself to result in failure of the structure, it can result in reduced fatigue life, reduced compressive strength and enhanced degradation due to environmental effects or moisture ingress. The threat of BVID leads to composite structures which are designed over-conservatively and/or subjected to expensive and time-consuming non-destructive testing (NDT) regimes.

Barely visible impact damage has been reliably detected and located using the system described in this paper. The effects of some aspects of contact geometry and location have been investigated. Application of higher electrical currents have been shown to increase temperatures in the region of the damage to a sufficient level to induce healing in a thermally activated self healing resin. A smart material which is able to semi-autonomously detect and heal, or at least ameliorate, damage is thus shown to be achievable.

2. Experimental

Panels were laminated in a cross-ply stacking sequence from a commercially available aerospace grade unidirectional carbon fibre pre-preg (Cytec 977-2/Tenax HTS fibres). During lamination, flexible printed circuit boards (FPCBs) were included between certain plies as interleaves. The FPCBs comprised of 40 μm thick copper tracks on a 50 μm thick polyimide film. These were produced using standard photo-lithographic techniques with a variety of contact spacings, geometries and alignments. In order to get location information in both x and y directions, two FPCBs were typically included in each panel to make contact with orthogonal plies. These plies are referred to as the sensing plies. The polyimide film which comprised the substrate of the FPCB also served the purpose of electrically isolating the sensing ply from its neighbours. Where extra interleaves were necessary for electrical insulation these were 25 µm thick Kapton film. An example of a panel produced in this way, showing the external connections is shown in Figure 1. Panels were also produced with other arrangements of contacts. These included panels with contacts in every ply to investigate the effect of through thickness location of the sensing ply and panels with contact pairs offset transversely.

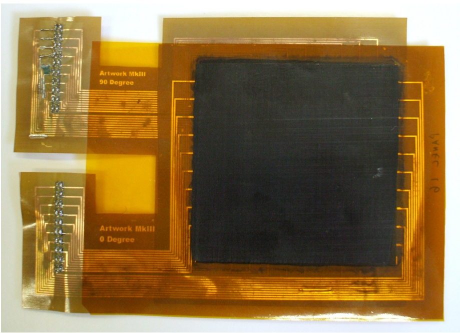

Fig 1: CFRP panel containing flexible printed circuit board interleaves.

For sensing a small (400 µA) current was applied to the contacts. This very low current resulted in no measurable heating effect. Data was recorded from the panels by one of two modes. Direct measurements of resistance were obtained by recording the voltage across the pair of contacts to which was excitation current was applied, this is effectively a conventional 2 wire resistance meter. However, in addition to these measurements, voltages were also recorded from all contacts while the excitation current was applied to each contact pair in turn. In this way a more comprehensive set of of data could be obtained, for example 10 pairs of contacts results in the collection of 100 data points. Damage was observed in the form of a change in resistance or voltage.
Impact damage was induced by means of a falling dart impactor. Incident energy was calculated by the mass and height used, and energy absorbed was measured from a force/time trace from a load cell on the impactor.
For heating experiments, two pairs of contacts (one in each orthogonal ply) were connected to a laboratory power supply and various currents (up to 2 A) were applied. The heating was monitored by a thermocouple probe on the surface of the panel and by an Electrophysics PV320L thermal imaging camera.

3. Results

Damage was reliably detected as a change in the electrical resistance, even in the case of very low energy impacts where there was no discernible dent in the front face and only very slight splitting of the back face. An example of the changes in directly measured resistance recorded in a panel when impacted at either 7.4 or 14.7 J is shown in Figure 2. It can be seen that at higher impact energies there is a large increase in resistance at the location of the impact, accompanied by a much smaller decrease in resistance adjacent to the impact. At lower energies there is still a decrease in resistance adjacent to the damage, of similar magnitude to that recorded for higher impact energies, however the increase in resistance at the impact location is much lower. It is thought that the increase in resistance at the impact location is a result of breaks in fibres or in inter-fibre contacts. The slight decrease adjacent to the damage is thought be a result of the resistance of the fibres responding to the changed strain state in the material following impact, largely as a result of relaxation of residual thermal stresses.

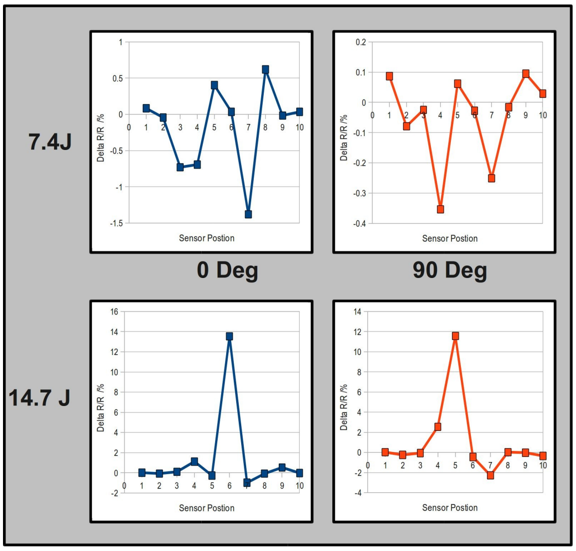

Fig 2: Changes in resistance of 0 and 90 degree plies of CFRP panels impacted at an energy of either 7.4 or 14.7J

The full-field voltage measurements could be used to create a map of the changes in resistance of the panel. An example of such a map is shown in Figure 3, the damage is clearly identifiable by the brighter colours, indicating increased resistance, at the impact site and darker colours, indicating decreased resistance adjacent to it.

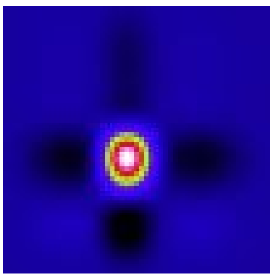

Fig 3: Map of change in electrical resistance after damage. The damage location is clearly visible as an increase in resistance.

The through-thickness location of the contacts was found to be an important parameter to sensing efficiency. Maps of resistance changes in each pair of plies of a laminate are shown in Figure 4. When the panel is impacted at high energy it can be seen that the impact location is unambiguously identified in all plies. However when lower impact energy is used, the location can only be identified in certain plies of the laminate.

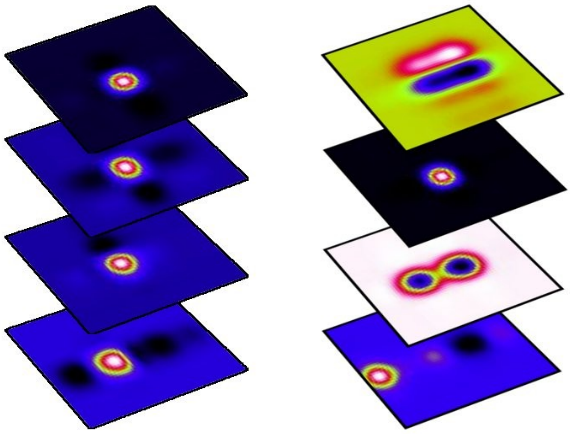

Fig 4: Maps of changes in electrical resistance in each pair of plies in a cross ply laminate, impacted at 14.7 J (left) and 11 J (right).

The effect of through-thickness location of the sensing ply on sensing efficiency is shown in Figure 5. It can be seen that the greatest increases in resistance at the impact location are recorded for a sensing ply towards the back face of the specimen. This is to be expected since impact damage in a composite laminate typically results in a cascade of damage with the greatest splitting and delamination visible on the back face of the laminate. However, it is not understood why the lowest response to damage should be in the rearmost ply (ply 8) of the laminate.

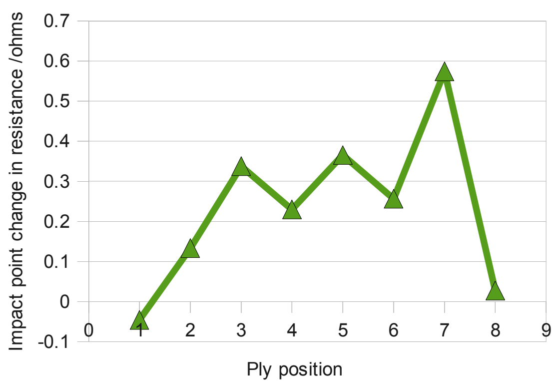

Fig 5: The change in resistance at the impact point versus the through-thickness location (ply number) of the sensing ply. Results averaged across 3 panels at 3 levels of impact energy (7.4, 11 and 14.7 J)

Laminates were also produced in which opposing contacts were offset transversely. It was thought that this would increase the sensed area of a contact pair while possibly increasing the sensitivity by forcing the electrical current to travel diagonally through the ply. The results of these offset contacts are shown in Figure 6. It can be seen that while the magnitude of the change in resistance did increase slightly at moderate levels of offset (not for the highest amount of offset), the higher initial resistance meant that the percentage change in resistance was actually lower at increased offset distances. Thermal images of the panels when higher currents were applied did indicate a greater spread of the current across the ply, so it is thought that the sensed area, if not the sensitivity can be increased by the use of moderate offset distances between the contacts.

Localised heating was found to be possible by applying larger currents (up to 1 amp) to the contacts. Temperatures of up to 200 ºC were found to be achievable, and the region of elevated temperature could be highly localised as can be seen in the thermal images shown in Figure 7. As was the case for sensing, the geometry of the contacts was found to be an important factor in heating efficacy.

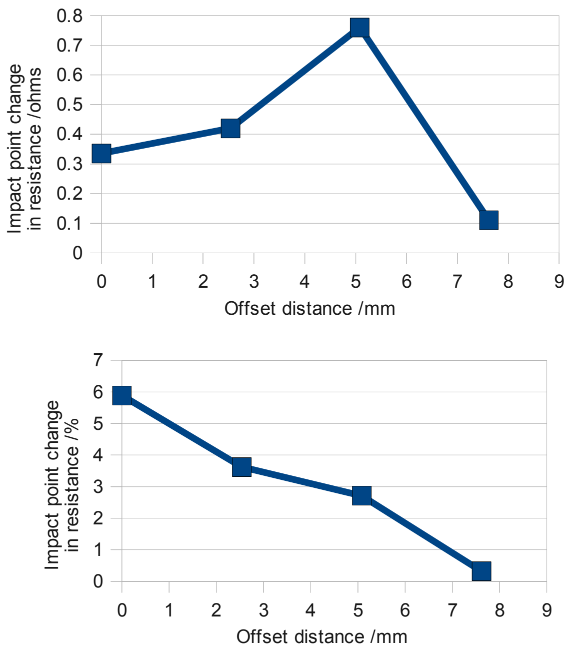

Fig 6: The change in resistance at the impact point versus the offset distance for a 7.4 J impact. Absolute change in resistance (top), percentage change in resistance (bottom).

It was found that the narrow (2.5 mm wide) contacts which had been used to carry the low currents used for sensing were inefficient at applying the higher currents used to heat the panel. A high degree of localised heating was observed at the contacts, which resulted in the area of the contacts reaching a higher temperature than the desired heating point. Wider (10 mm wide) contacts were found to reduce the localised heating at the contacts, resulting in the area of increased temperature being contained to the desired area, as can be seen in Figure 7.

It was also noted that the increased resistance resulting from damage caused a greater local increase in temperature at the damage location, as can be seen in Figure 7 in the case of both narrow and wide contacts.

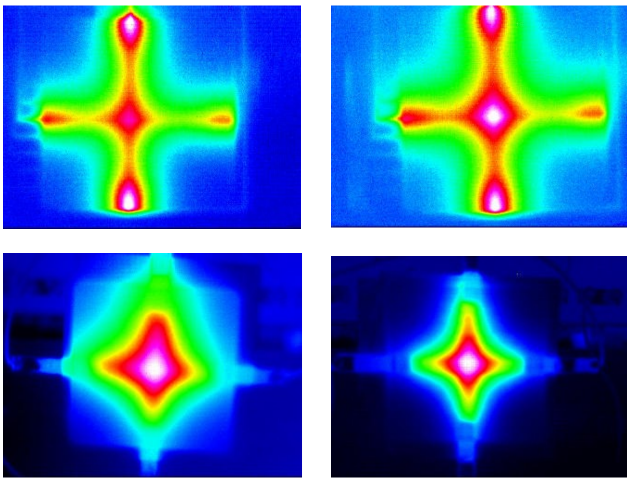

Fig 7: Thermal images of CFRP panels heated by electrical currents applied to the embedded contacts. 2.5 mm wide contacts were used for the panel shown in the top row, before impact (left) and after impact (right). 10 mm wide contacts were used for the panel shown in the bottom row, before impact (left) and after impact (right). 1 watt of electrical power applied in every case.

4. Conclusions

It has been demonstrated that effective detection and location of barely or invisible damage is both possible and practical. It has been demonstrated that temperatures of a sufficient level to activate a self healing resin can be generated in the locality of the damage with very little increase in temperature elsewhere in the laminate.

A smart structure able to sense and heal, or at least ameliorate, damage is therefore achievable using electrical resistance measurements and resistive heating of heat-activated self healing resins.

References

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