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# The interlaminar interface of a carbon fiber epoxy-matrix composite as an impact sensor

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The interlaminar interface of a crossply carbon fiber epoxy-matrix composite was found to be an impact sensor, with sensitivity to impact from 0.8 mJ to 5 J (though no indentation was observed) and to multiple (up to 35) impacts at the same energy. However, the sensing of a small impact after a large one was not effective if the small impact was much lower in energy than the large one. The higher the impact energy, the lower was the contact electrical resistivity of the interlaminar interface after impact. Above 1 J, the resistance tended to increase with partial or complete reversibility upon impact, though this effect was minor compared to the irreversible resistance decrease mentioned above.


## 1. Introduction

The interlaminar interface refers to the interface between laminae (i.e., fiber layers) in a continuous fiber composite. Each lamina is typically thousands of fibers thick, due to the thousands of fibers in a tow. In spite of the presence of the matrix material (e.g., a polymer matrix) at the interlaminar interface, this interface is mechanically the weakest part of a composite. Damage of a composite most commonly occurs at this interface. Such damage includes delamination and subtle microstructural changes that occur at the interface without delamination.

A particularly sensitive method of detecting damage at an interlaminar interface is the measurement of the contact electrical resistivity of the interface [1]. This method is applicable to composites in which the fibers are much more conductive than the matrix, as in the case of carbon fiber epoxy-matrix composites, which are important for lightweight structures.

Delamination causes local separation of adjacent laminae, thereby decreasing the number of contacts between fibers of adjacent laminae and causing the contact resistivity of the interlaminar interface to increase. The increase in contact resistivity results in increase in the through-thickness volume resistivity of the composite, as reported for carbon fiber epoxy-matrix composite laminates under longitudinal tension-tension fatigue loading [2].

An example of a subtle microstructural change that occurs at the interface without delamination is an irreversible increase of the number of contacts between fibers of adjacent laminae. This microstructural change occurs upon compression of the laminate in the direction perpendicular to the plane of the laminate and results in an irreversible decrease in the contact resistivity, as shown for a carbon fiber epoxy-matrix composite [1].

Temperature cycling (i.e., thermal fatigue) can also cause damage in the form of delamination, thereby resulting in an increase in the contact electrical resistivity of the interlaminar interface. This has been shown for a carbon fiber epoxy-matrix composite [1].

Impact is a commonly encountered cause of damage. There is a practical need to sense the impact that a structure sustains, as the information is useful for identification of the cause, location and severity of damage. Previously reported impact sensors involve the use of embedded devices, such as fiber optics [3, 4] and piezoelectric sensors [5, 6]. In contrast, this paper investigates the use of the interlaminar interface as an impact sensor by studying the change of the contact electrical resistivity of the interlaminar interface upon impact in the direction perpendicular to the plane of the interface. Previous work related to the sensing of impact damage in carbon fiber epoxy-matrix composites involved measurement of the volume electrical resistance in various directions of the laminate [7]. By measuring the contact resistance rather than the volume resistance, this work focuses on the microstructural change of the interlaminar interface, thereby providing new information on the susceptibility of the interlaminar interface to irreversible microstructural change.

An advantage of the interlaminar interface as sensor is that two crossply laminae provide a two-dimensional array of sensors, thereby allowing spatial distribution sensing [1]. In contrast to the fiber optic or piezoelectric sensors [3–6] that are embedded in a structure, the interlaminar interface is a sensor that is an inherent part of the structural material, thereby avoiding the problems

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TABLE I Carbon fiber and epoxy matrix properties (according to Cape Composites Inc., San Diego, CA)

| | |
|---|---|
| Fortafil 555 continuous carbon fiber | |
| Diameter | 6.2 $\mu$m |
| Density | 1.8 g/cm$^3$ |
| Tensile modulus | 231 GPa |
| Tensile strength | 3.80 GPa |
| Cape C2002 epoxy | |
| Processing temperature | 121°C |
| Flexural modulus | 99.9 GPa |
| Flexural strength | 1.17 MPa |
| $T_g$ | 129°C |
| Density | 1.15 g/cm$^3$ |

of high cost, low durability, limited sensing volume and mechanical property loss.

## 2. Experimental methods

Two laminae of unidirectional carbon fiber epoxy-matrix prepregs (provided by Cape Composites Inc., San Diego, CA) (Table I) in the form of strips crossing one another, with one strip on top of the other (Fig. 1), were fabricated into a composite at the overlapping region (4.0 mm × 4.0 mm) of the two laminae by applying pressure (0.2 MPa) and heat to the overlapping region (without a mold). The pressure was provided by a weight, which was varied in order to vary the pressure. A glass fiber epoxy-matrix composite spacer was placed between the weight and the junction (the overlapping area region of the two strips). The heat was provided by a Carver hot press. A Watlow model 981C-10CA-ARRR temperature controller was used to control the temperature and the ramping rate. Each of the specimens was put between the two heating platens of the hot press and heated linearly up to 121 ± 2°C at the rate of 2°C/min. Then it was cured at that temperature for 3 h and subsequently furnace cooled to room temperature.

A specimen to be impacted was mounted on a steel plate that had been covered with an electrically insulating sheet (a flexible sheet of thickness 0.064 mm, in the form of a glass fiber Teflon-matrix composite). The mounting involved the use of adhesive tape applied away from the area corresponding to the interlaminar interface.

Before, during and after impact using a steel ball or a steel hemisphere assembly dropped from a controlled height up to 870 mm, resistance measurement was made. The impact energy was calculated from the weight of the impactor and the initial height of the impactor. For impact energies below 0.2 J, the impactor was a ball of diameter 16 mm (5/8 in) and weight 16.3 g. For impact energies above 0.2 J, the impactor was a hemisphere assembly of diameter 19 mm (3/4 in) and weight 740 g. The impact was directed at the same point of a specimen at progressively increasing energy. The impact area of the specimen was electrically insulated from the steel ball by using plastic adhesive tape on the specimen surface.

All the time, the contact electrical resistance was measured by using a Keithley 2001 multimeter. Electrical contacts were made to the four ends of the two strips, so as to measure the contact electrical resistivity (resistance multiplied by contact area, which is the area of the overlapping region) between the two laminae in the composite, using the four-probe method (Fig. 1). The epoxy at the ends of each prepreg strip was burned out to expose the carbon fibers for the purpose of making electrical contacts. These exposed fibers were wrapped by pieces of copper foil, with silver paint between the copper foil and the fibers. The electric current flowed from A to D. The voltage between B and C is the voltage between the two laminae. The contact resistance was obtained by dividing the voltage by the current. Five specimens were tested and the reproducibility of the data trends were ascertained. The specimen of initial contact resistance 0.2792 Ω was 0.292 mm thick. The specimen of initial resistance 0.3221 Ω was 0.305 mm thick. The specimen of initial resistance 0.4298 Ω was 0.290 mm thick. The specimen of initial resistance 0.4247 Ω was 0.330 mm thick. The specimen of initial resistance 0.4755 Ω was 0.310 mm thick. Since the geometric area of the contact was not changed by the impact, the fractional change in contact resistance due to impact was the same as the fractional change in contact resistivity.

## 3. Results and discussion

Fig. 2 shows the fractional change in contact resistance before, during and after impact at progressively increasing levels of energy from 16 to 139 mJ for a specimen

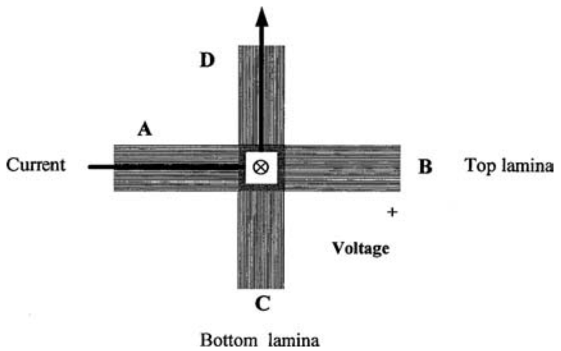


*Figure 1* Composite configuration for testing contact resistivity.

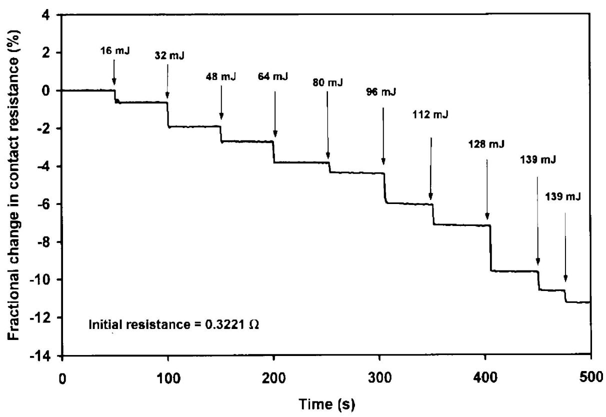


*Figure 2* Contact resistance vs. time during impact at progressively increasing energy from 16 to 139 mJ.

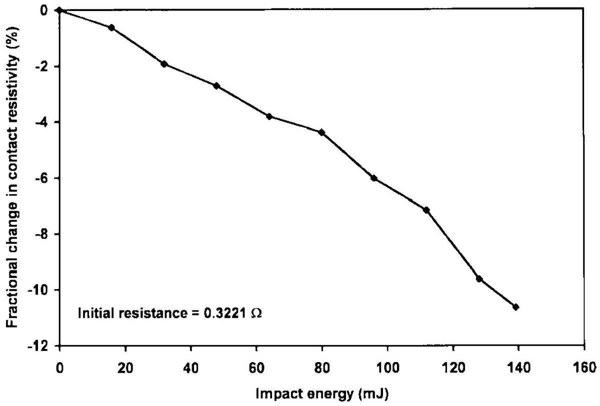


*Figure 3* Contact resistance vs. impact energy during impact at progressively increasing energy from 16 to 139 mJ.

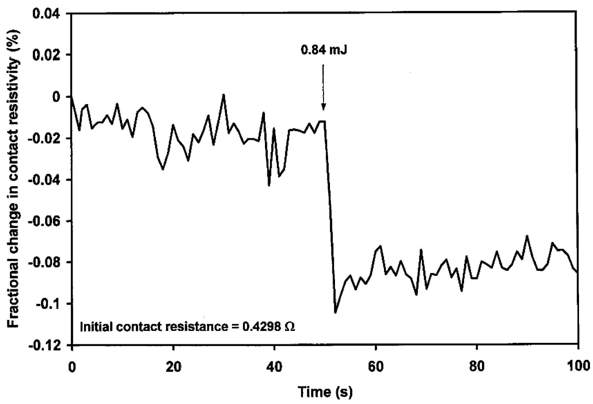


*Figure 4* Contact resistance vs. time due to impact at an energy of 0.84 mJ.

that had not been subjected to prior impact. The resistance decreased irreversibly at every impact, though the impact caused no indentation. The higher the impact energy, the lower was the resistance, as shown in Figs 2 and 3. The highest impact energy of 139 mJ was applied twice (Fig. 2). The resistance decreased irreversibly at both the first and second impacts at this energy. Although the effect of impact energies less than 16 mJ is not shown in Fig. 2, irreversible resistance decrease upon impact was observed at energies as low as 0.84 mJ, as shown in Fig. 4.

At impact energies above 0.3 J (300 mJ), irreversible resistance decrease upon impact was observed at energies up to 5.08 J, as shown in Fig. 5 for a specimen which had not been subjected to prior impact. The fractional decrease in contact resistivity at 5.08 J was 30% (Fig. 5), compared to 11% for 139 mJ (Fig. 2). However, in the regime above 1 J, the resistance had a tendency to increase (with partial or complete reversibility) upon impact, as observed at impact energies of 1.09, 2.18, 2.90, 3.63, 3.99 and 4.72 J. The higher was the impact energy, the greater was the tendency for the resistance to increase, though the increase remained a minor effect compared to the irreversible resistance decrease. Fig. 6 shows that the trend in which the resistance decreased with increasing impact energy is clear, in spite of the slight tendency for the resistance to increase at some of the impacts.

Fig. 7 shows the effect of numerous impacts at the same energy of 16 mJ on a specimen that had not been

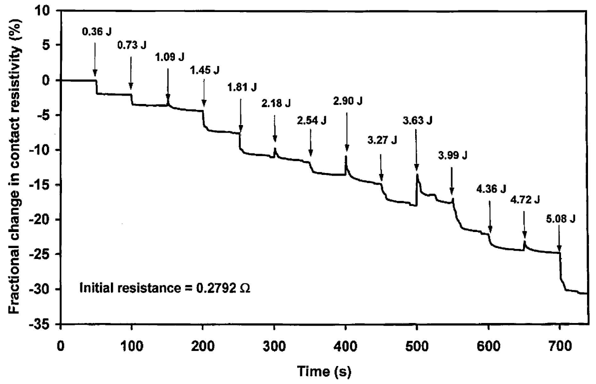


*Figure 5* Contact resistance vs. time due to impact at progressively increasing energy from 0.36 to 5.08 J.

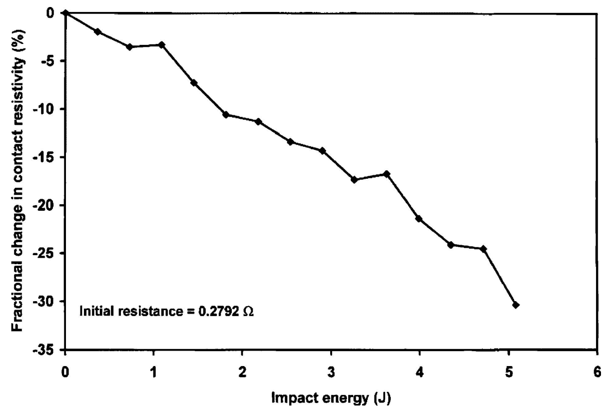


*Figure 6* Contact resistance vs. impact energy during impact at progressively increasing energy from 0.36 to 5.08 J.

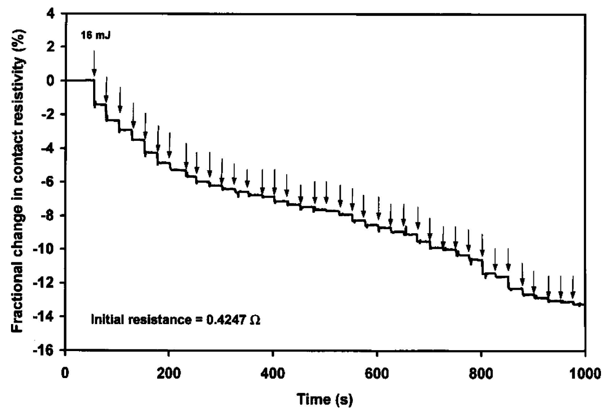


*Figure 7* Contact resistance vs. time during repeated impact at an energy of 16 mJ.

subjected to prior impact. The resistance decreased irreversibly at every impact, though the extent of resistance decrease tended to lessen as the number of impacts increased. After about 35 impacts, the resistance decrease upon impact became too small for effective impact sensing.

Fig. 8 shows the effect of numerous impacts at the same energy of 139 mJ on a specimen that had not been subjected to prior impact. The resistance decreased irreversibly at every impact, such that the decrease was clear up to about 22 impacts. Comparison of Figs 7 and 8 indicates that the number of impacts at a particular energy that can be sensed is lower when the impact energy is higher.

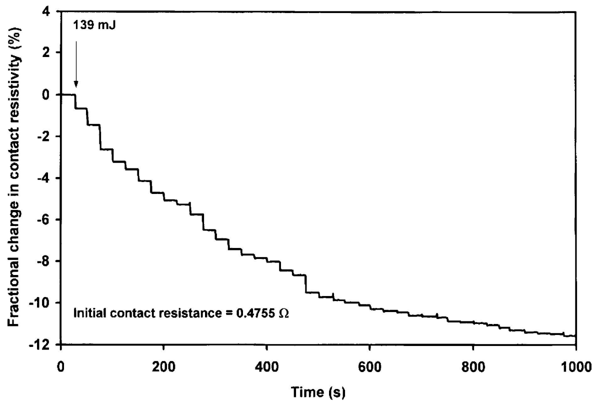


*Figure 8* Contact resistance vs. time during repeated impact at an energy of 139 mJ.

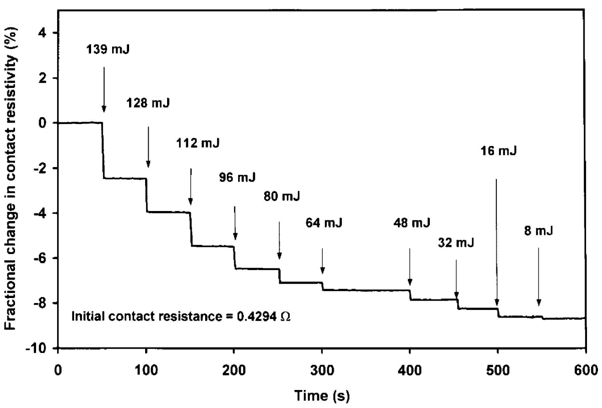


*Figure 9* Contact resistance vs. time during impact at progressively decreasing energy from 139 to 8 mJ.

Figs 7 and 8 also show that the maximum fractional changes in contact resistivity for impact energies of 16 mJ and 139 mJ were about the same (about 12%). This indicates that there is a saturated change in contact resistivity and the saturated change seems not to depend on the impact energy.

Fig. 9 shows the effect of multiple impacts at progressively decreasing levels of energy from 139 to 8 mJ for a specimen that had not been subjected to prior impact. The ability to sense impact was diminished by prior exposure to impact at a higher energy. For prior impact at energy up to 139 mJ, impact at energy less then 16 mJ could not be clearly sensed.

No indentation was observed, even at the highest energy of 5.08 J. This is attributed to the small thickness of the two-lamina composite and the slightly resilient nature of the substrate.

Prior work [3] showed that the electrical resistance (volume resistance rather than contact resistance) of a laminate with 8–24 laminae increased irreversibly upon impact at 0.68 J or above. Below 0.68 J (e.g., at 0.34 J), the volume resistance was not affected by impact. Comparison of the results of prior work and those of this work shows that the contact resistance of the interlaminar interface is a much more sensitive indicator of microstructural change than the volume resistance of a laminate. This means that the interlaminar interface rather than the interior of a lamina is the primary site of microstructural change. By focusing on this interface, the contact resistance is sensitive to even a very minor level of microstructural change (e.g., level corresponding to an impact energy of 0.8 mJ, as shown in Fig. 3).

The contact resistance of the interlaminar interface decreased irreversibly upon impact because of the irreversible increase in the chance of fibers of one lamina to touch those of the other lamina. In other words, there was an irreversible change in the microstructure of this interface. This effect had been previously observed upon compression (not impact) in the direction perpendicular to the plane of the interface [2].

The minor effect in which the contact resistance increased upon impact is attributed to damage, which may be in the form of delamination or the precursor of a delamination crack. Delamination decreases the number of fibers touching each other across the interlaminar interface, thereby increasing the contact resistance. Indeed, the volume resistance of a laminate in the oblique direction (i.e., a direction at an angle between the longitudinal and through-thickness directions) increased irreversibly and monotonically with increasing impact energy at or above 0.68 J [3].

The microstructural change in the regime of low impact energy (as low as 0.8 mJ) was observed by contact resistance measurement (this work), but was not observed by volume resistance measurement [3]. The microstructural change of the interlaminar interface, which caused the contact resistance to decrease, preceded the damage, which caused the contact resistance to increase.

This work shows that the interlaminar interface is a highly sensitive sensor of impact. The resistance after impact decreased monotonically with increasing impact energy from 0.8 mJ to 3 J. Due to the absence of the resistance increase tendency, the interface is a particularly good impact sensor below 1 J. The sensing of multiple impacts (as many as 35 impacts) at the same energy is also effective, though the number of multiple impacts at a particular energy that can be sensed decreases with increasing impact energy. However, the sensing of a small impact after a large impact is not effective if the energy of the small impact is much less than that of the prior large impact. This is due to the substantial and irreversible microstructural change caused by the large impact. The interlaminar interface is more sensitive than the overall laminate for sensing impact, although both the interlaminar interface and the overall laminate can serve as sensors. Furthermore, the irreversible microstructural change observed by contact resistance measurement serves to provide an early indication of damage that is to come. The lower the contact resistivity is compared to the initial value, the more is the extent of microstructural change at the interlaminar interface, and the closer is the onset of damage.

## 4. Conclusion

The interlaminar interface of a crossply carbon fiber epoxy-matrix composite is affected irreversibly upon impact at energies as low as 0.8 mJ. The effect is an irreversible microstructural change that is characterized by an irreversible decrease of the contact electrical resistivity of the interlaminar interface. Indentation was not observed. At impact energies above 1 J, there was tendency for the contact resistivity to increase (with partial or complete reversibility) upon impact, due to damage or the precursor of damage. The higher the impact energy, the greater was this tendency, though the resistance increase remained a minor effect compared to the irreversible resistance decrease. The resistance decrease allows the interlaminar interface to be an impact sensor, which is effective in sensing impacts from 0.8 mJ to 5.08 J, in addition to multiple (up to 35) impacts at the same energy. However, the sensing of a small impact (such as 8 mJ) after a large impact (such as 139 mJ) is not effective.

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