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Effects of composite lay-up configuration and thickness on the damage self-sensing behavior of carbon fiber polymer-matrix composite

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The lay-up configuration (unidirectional, crossply and quasi-isotropic) and thickness (8–24 laminae) affect the damage self-sensing characteristics of continuous carbon fiber epoxy-matrix composites. The damage is by drop impact directed at the top surface of the laminate. The oblique resistance (i.e., resistance at an angle between the longitudinal and through-thickness directions) is an effective damage indicator for all lay-up configurations and thicknesses. The surface resistance of the bottom surface is an effective damage indicator for thin (8-lamina) composites, though it is less sensitive to minor damage than the oblique resistance. The surface resistance of the top surface is less effective than that of the bottom surface for 8-lamina multidirectional composites. The through-thickness resistance is an effective damage indicator for 16- and 24-lamina quasi-isotropic composites, but is ineffective for 8-lamina composites of any lay-up configuration. In general, effectiveness means a monotonic and significant increase of the resistance with damage extent.

1. Introduction

Due to the concern of the structural health of aircraft, which can suffer from damage related to aging, temperature variation, lightning and mechanical abuse, there is a growing need for damage monitoring of aircraft structures. By monitoring, one can detect the damage that may be present, thereby allowing timely repair.

Aircraft structures are more and more dominated by composite materials (particularly polymer-matrix composites containing continuous carbon fibers), due to their high modulus, high strength and low density. Composite materials are commonly made by laying up continuous fiber prepreg sheets in chosen orientations with respect to one another to form a stack, followed by consolidation and matrix curing under heat and pressure. As the fibers in the resulting composite are not perfectly straight and the extent of consolidation may not be perfectly uniform throughout the composite, flaws are commonly present in a composite material after fabrication. Due to the variability in the type, distribution and concentration of flaws, there is substantial variability in the quality of a fabricated composite component. This variability makes it difficult to predict the service life of a composite component. As a result, damage monitoring of each critical composite structure during use is needed for the purpose of safety enhancement.

The sensing of damage in a composite material may be achieved by using conventional nondestructive evaluation methods. Ultrasonic inspection is one of the most sensitive of these conventional methods [1, 2]. However, it is limited to the detection of flaws that are well defined (e.g., a crack) and are large (at least a fraction of a millimeter). It is valuable to detect flaws before they evolve into cracks of substantial size.

An alternate method of damage sensing involves the embedding of sensors (e.g., fiber optic [3, 4] and piezoelectric [5, 6] sensors) in the composite. However, this method is intrusive, affecting the mechanical performance of the structure. The larger is the size of the embedded sensor, the more severe is the mechanical performance degradation. Moreover, repair of the embedded sensors is difficult.

A relatively new method of damage sensing involves using the structural composite material itself as the sensor, so that there is no embedment or attachment of any sensor. This has been achieved in carbon fiber polymer-matrix composites by the measurement of the electrical resistance, which is affected by the damage [7–19]. In other words, by measuring the electrical resistance, the

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damage can be detected and identified. By measuring the resistance distribution, the damage distribution can be determined.

Prior work in the use of DC electrical resistance measurement to assess damage in carbon fiber polymer-matrix composites has shown the effectiveness of this method in sensing damage inflicted by tension [8, 9, 12, 13, 15–19], flexure [8] and impact [7]. The resistance measured has included the volume resistance and the surface resistance. The surface resistance is obtained with electrical contacts only on one side (e.g., the tension side or the compression side of a composite under flexure), whereas the volume resistance is obtained with electrical contacts that are not only on one side of the composite. The volume resistance can be measured in the longitudinal, oblique and through-thickness directions. In case of the longitudinal volume resistance, the electrical contacts are around the whole perimeter of the composite in planes perpendicular to the longitudinal direction. In case of the through-thickness resistance, the electrical contacts are directly opposite one another on the two opposite sides of the composite. In case of the oblique volume resistance, the electrical contacts are on the two opposite sides, such that they are not directly opposite one another.

Composites that are used in practice differ in thickness and lay-up configuration. In spite of the substantial prior work in this area, no prior work has been done in studying the effect of the thickness of the composite or that of the lay-up configuration on the self-sensing behavior. The thickness relates to the number of lamina. The closest prior work [7] studied an eight-lamina unidirectional composite, an eight-lamina quasi-isotropic composite and a 24-lamina quasi-isotropic composite. In contrast, this paper provides a systematic study of the effects of thickness and lay-up configuration by investigation of (i) an eight-lamina unidirectional composite, (ii) an eight-lamina crossply composite, (iii) an eight-lamina quasi-isotropic composite, (iv) a 16-lamina quasi-isotropic composite, and (v) a 24-lamina quasi-isotropic composite. Comparison of (i), (ii) and (iii) allows investigation of the effect of the lay-up configuration. Comparison of (iii), (iv) and (v) allows investigation of the effect of thickness.

As in the closest prior work [7], damage is inflicted in this work by drop impact. This is because impact is a commonly encountered cause of damage of structural composites.

2. Experimental methods

Commercially manufactured composites in the form of continuous carbon fiber epoxy-matrix laminates were cut into strips of size 200 × 10 mm and then sanded by using 600 grit silicon carbide sand paper for the purpose of removing the surface layer (about 20 μm thick) of epoxy matrix prior to the application of electrical contacts. The contacts were in the form of silver paint in conjunction with copper wire. The sanding step is not essential, but it helps the electrical measurement by increasing the accuracy and decreasing the noise. Although the entire surface was sanded in this work, only the portions beneath the electrical contacts needed to be sanded.

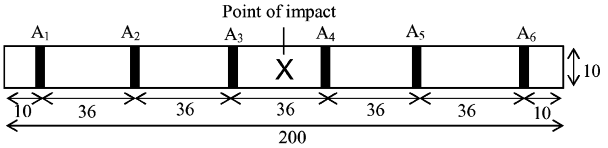


Figure 1 Composite specimen testing configuration (top view). Contacts A_1, A_2, A_3, A_4, A_5 and A_6 are on only the top side of the specimen. Contacts B_1, B_2, B_3, B_4, B_5 and B_6 (not shown) are on the bottom side, such that B_1 is directly opposite A_1, B_2 is directly opposite A_2, B_3 is directly opposite A_3, B_4 is directly opposite A_4, etc. The point of impact is at the center of the specimen along its 200-mm length. All dimensions are in mm.

Five types of laminate were studied, namely an eight-lamina unidirectional $[0]_8$ laminate (thickness = 1.0 mm), an eight-lamina crossply $[0/90]_{2s}$ laminate (thickness = 1.0 mm), a quasi-isotropic $[0/45/90/-45]_s$ laminate (thickness = 1.0 mm), a 16-lamina quasi-isotropic $[0/45/90/-45]_{2s}$ composite (thickness = 2.1 mm), and a 24-lamina quasi-isotropic $[0/45/90/-45]_{3s}$ laminate (thickness = 3.2 mm).

For each composite, six electrical contacts were applied on each of the two sides. Each contact was in the form of a line along the 10-mm width of the specimen, as shown in Fig. 1. The point of impact was at the center along the specimen length.

DC electrical resistance measurement was conducted using the four-probe method. A Keithley 2002 multimeter was used. The surface resistance of the top side (referred to as the top resistance) was measured by using A_1 and A_6 as current contacts and A_2 and A_5 as voltage contacts; the surface resistance of the bottom side (referred to as the bottom resistance) was measured by using B_1 and B_6 as current contacts and B_2 and B_5 as voltage contacts; the oblique resistance was measured using A_1 and B_6 as current contacts and A_2 and B_5 as voltage contacts; the through-thickness resistance was measured using A_3 and B_3 as current contacts and A_4 and B_4 as voltage contacts (Fig. 1).

During impact at progressively increasing energy, using a steel hemisphere (diameter 19 mm or 0.75 in) dropped from a controlled height, measurement of the top, bottom, oblique and through-thickness resistances was continuously made. The impact energy was calculated from the weight of the hemisphere assembly (0.698 kg) and the initial height of the hemisphere (up to 850 mm). After an impact, the hemisphere bounced back to a height up to 1/3 of the initial height. Hence, the energy absorbed by a specimen due to an impact was smaller than the energy calculated from the initial height. Impact was directed at the same point of the specimen at progressively increasing energy.

The damage resulted in an indentation, the diameter of which was measured by using calipers in order to provide a rough indication of the extent of damage. The depth of the indentation was calculated from the diameter of the indentation and the diameter of the impacting hemisphere. Each indentation was made with a single impact at a selected impact energy, in contrast to the multiple impacts made at the same point at successively increasing energies for the electrical resistance monitoring.

Multiple specimens of each type were similarly tested by resistance measurement in order to ascertain the reproducibility of the results.

3. Results

Figs 2–6 show the fractional changes in resistance (top, bottom, oblique and through-thickness resistances) during impact at progressively increasing energy respectively for the unidirectional, crossply and quasi-isotropic eight-lamina composites and the quasi-isotropic 16-lamina and 24-lamina composites.

3.1. Eight-lamina composites

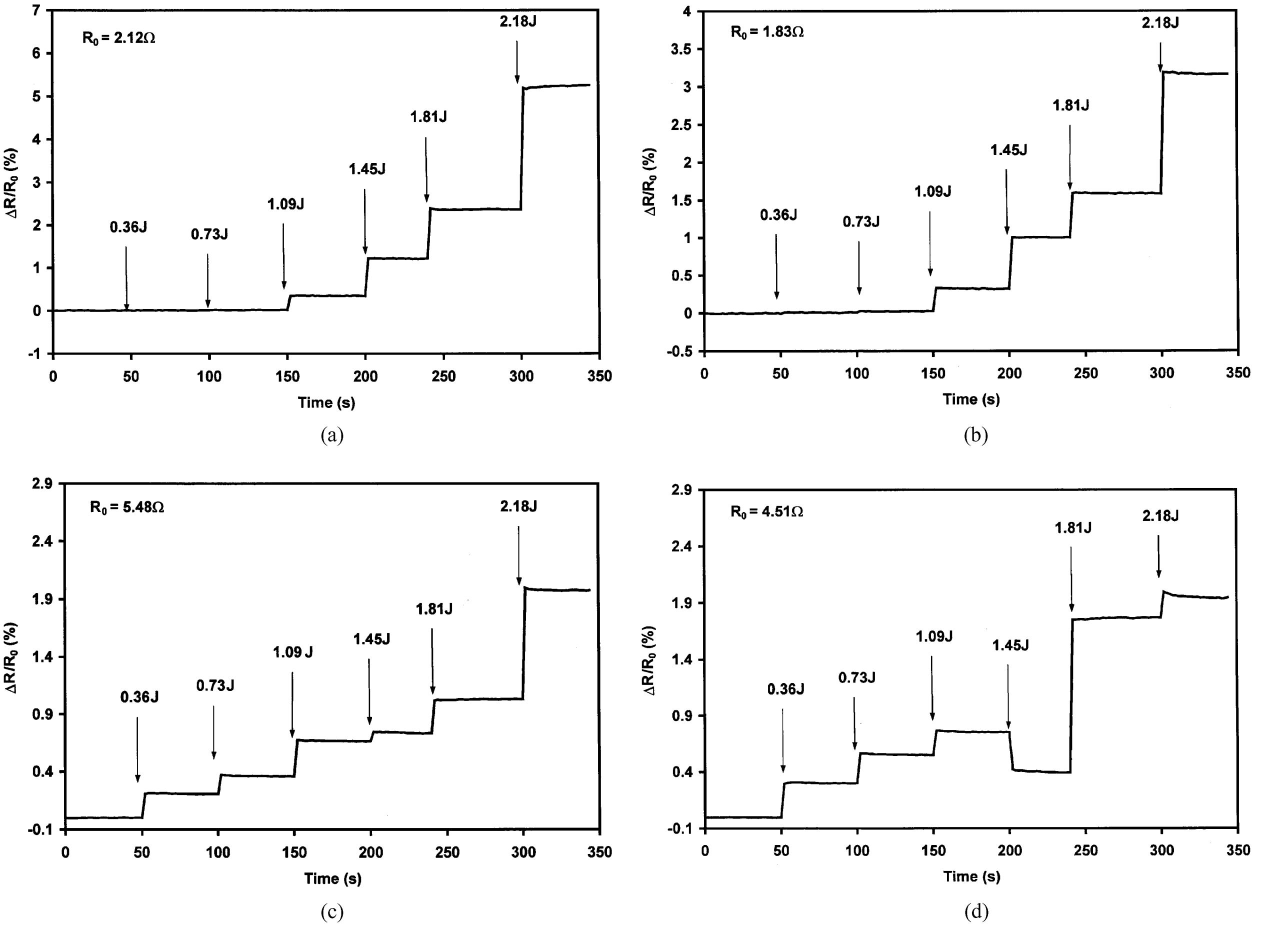
For the eight-lamina unidirectional composite, the fractional change in resistance ($\Delta R/R_0$) increases monotonically with increasing impact energy for the top, bottom and oblique resistances. For the through-thickness resistance, the fractional change in resistance has a tendency to decrease upon impact when the impact energy is high. This tendency is absent for the top, bottom and oblique resistances.

The oblique resistance is more sensitive to minor damage than the top or bottom resistance for unidirectional, crossply and quasi-isotropic composites. The through-thickness resistance is as sensitive as the oblique resistance, but it suffers from a variation of $\Delta R/R_0$ with impact energy that is not monotonic.

For the eight-lamina crossply and quasi-isotropic composites, the trends for the variation of $\Delta R/R_0$ with impact energy are similar to those for the eight-lamina unidirectional composite, except that the through-thickness resistance decreases with increasing impact energy much more clearly. The values of $\Delta R/R_0$ are much higher for the bottom resistance than the top resistance for both crossply and quasi-isotropic composites, but are comparable for the unidirectional composite. The values of $\Delta R/R_0$ for the through-thickness resistance are much higher for the unidirectional composite than the crossply or quasi-isotropic composite.

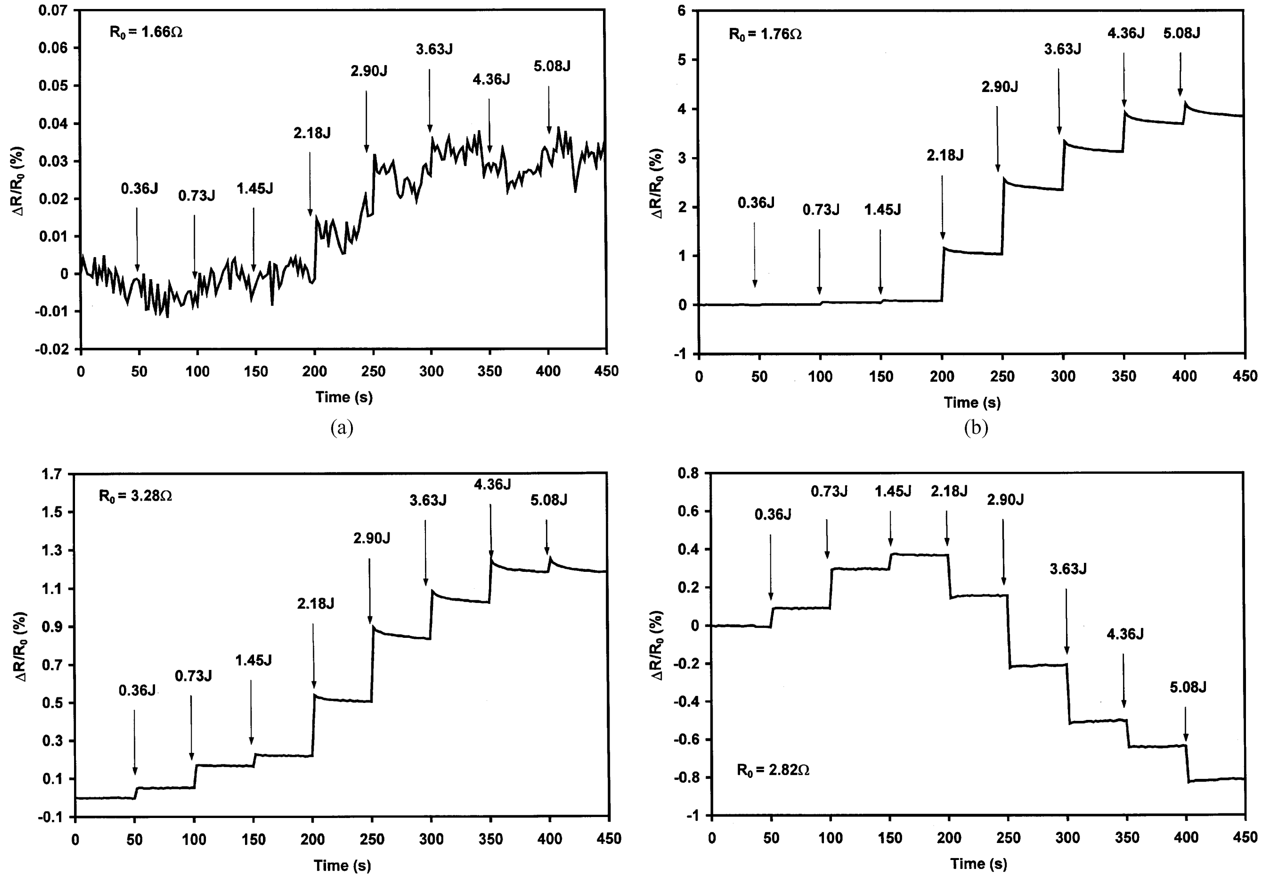
3.2. 16-Lamina and 24-lamina composites

For the 16-lamina and 24-lamina quasi-isotropic composites, the top, bottom, oblique and through-thickness resistances all increase monotonically with increasing impact energy, in contrast to the decrease of the through-thickness resistance with impact energy for the 8-lamina quasi-isotropic composite. The oblique and through-thickness resistances of the 16-lamina and 24-lamina quasi-isotropic composites exhibit much higher $\Delta R/R_0$ values than the corresponding top or bottom resistance. The oblique and through-thickness



(a) (b) (c) (d)

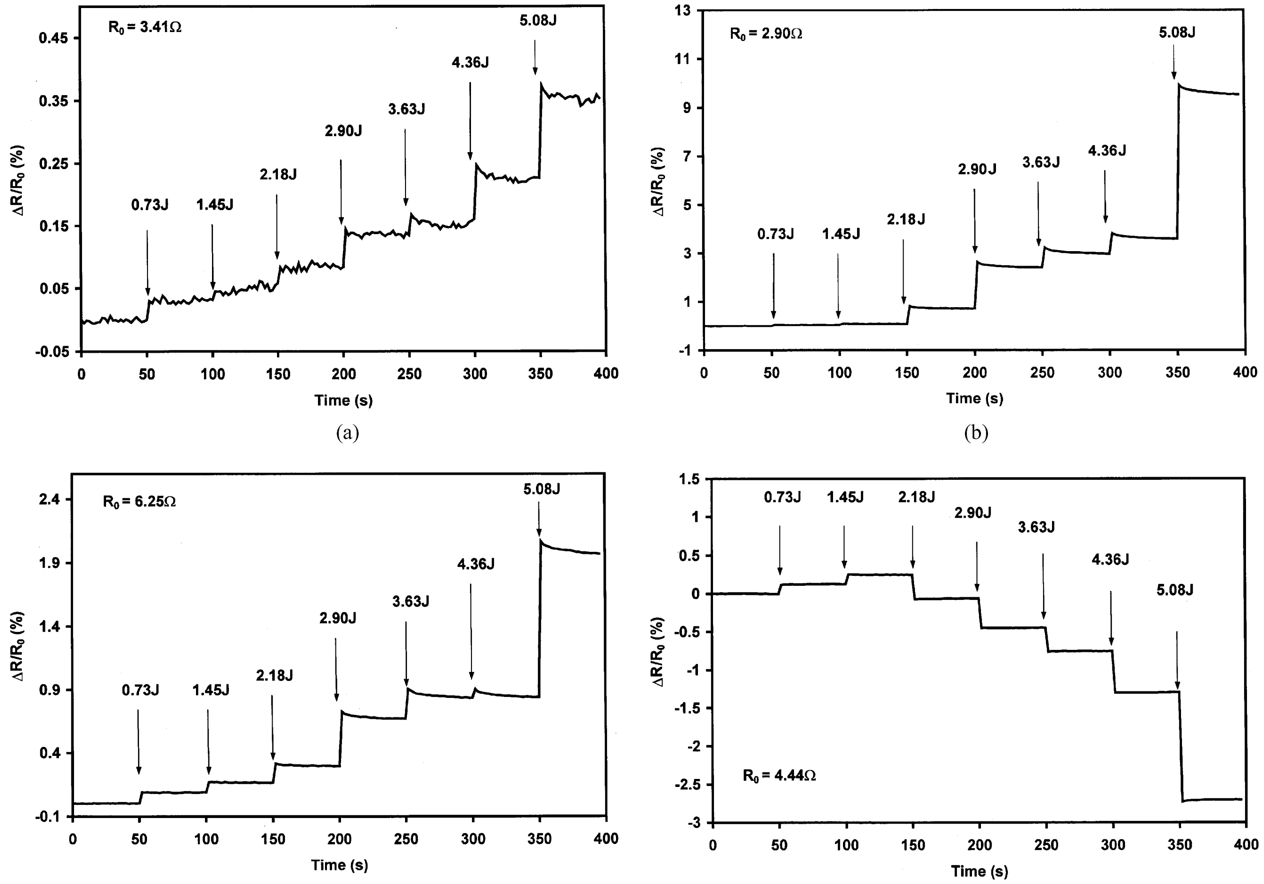
Figure 2 Fractional change in resistance ($\Delta R/R_0$) vs. time during impact at progressively increasing energy for the eight-lamina unidirectional composite: (a) Top resistance, (b) bottom resistance, (c) oblique resistance, and (d) through-thickness resistance.



(a) (b)

(c) (d)

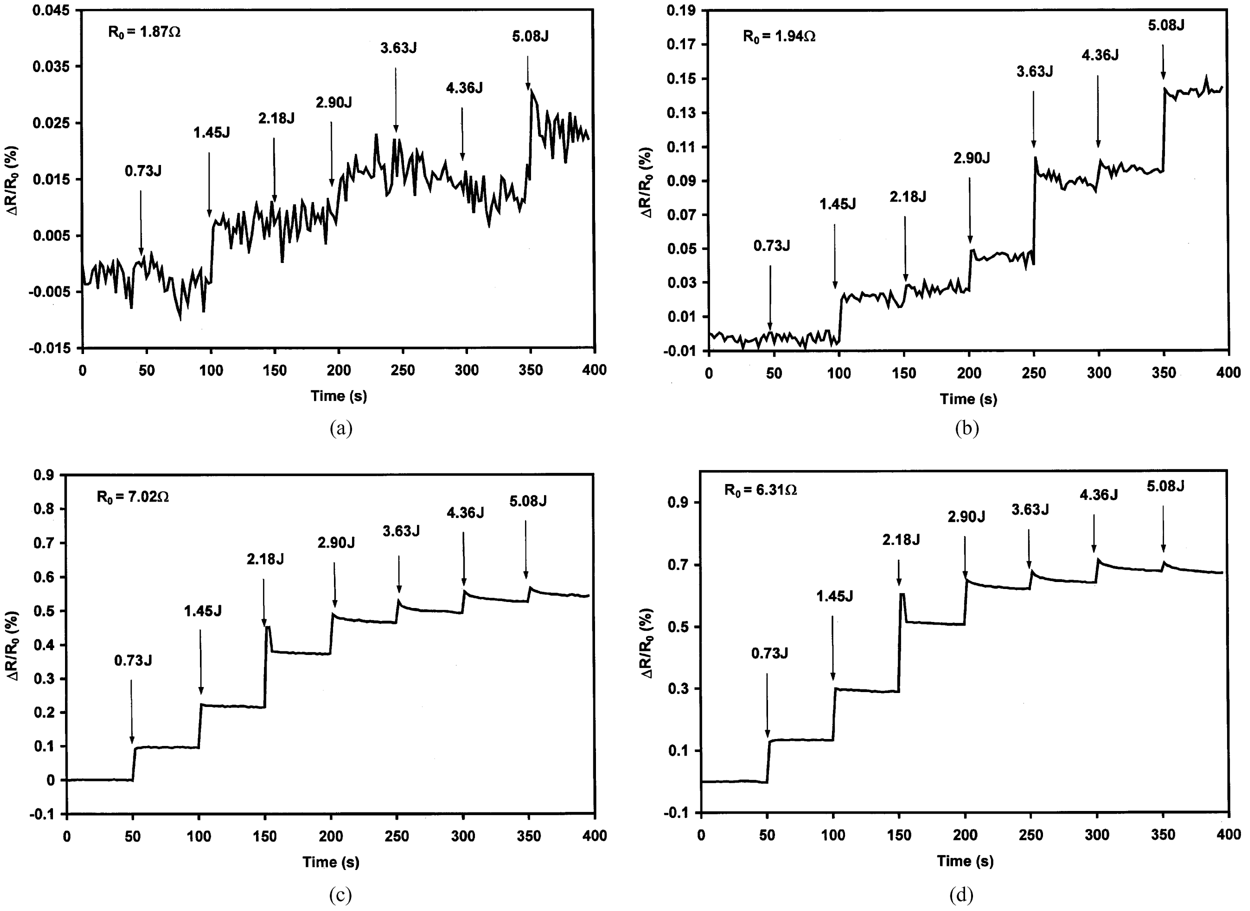
Figure 3 Fractional change in resistance ($\Delta R/R_0$) vs. time during impact at progressively increasing energy for the eight-lamina crossply composite: (a) Top resistance, (b) bottom resistance, (c) oblique resistance, and (d) through-thickness resistance.



(a) (b)

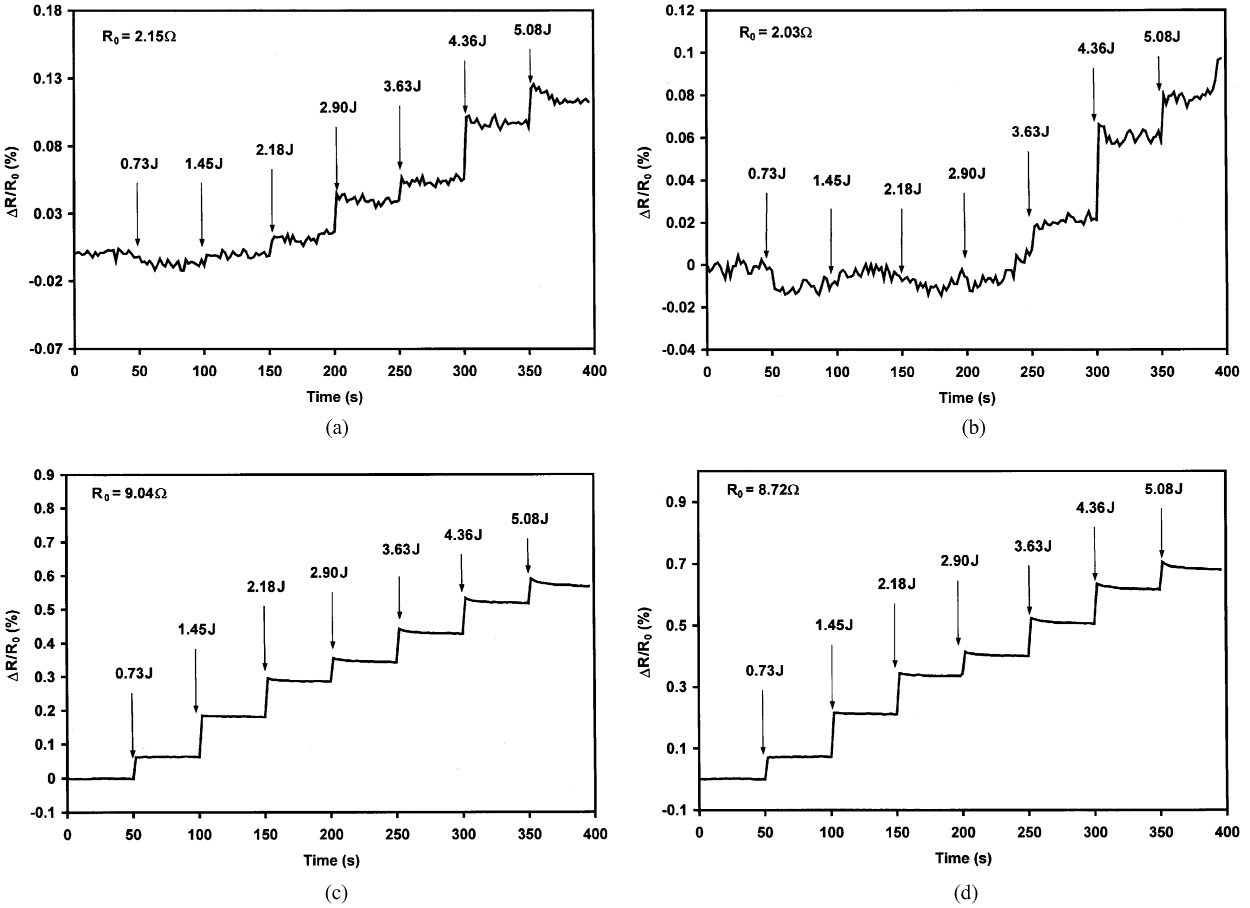
(c) (d)

Figure 4 Fractional change in resistance ($\Delta R/R_0$) vs. time during impact at progressively increasing energy for the eight-lamina quasi-isotropic composite: (a) Top resistance, (b) bottom resistance, (c) oblique resistance, and (d) through-thickness resistance.



(a) (b) (c) (d)

Figure 5 Fractional change in resistance ($\Delta R/R_0$) vs. time during impact at progressively increasing energy for the 16-lamina quasi-isotropic composite: (a) Top resistance, (b) bottom resistance, (c) oblique resistance, and (d) through-thickness resistance.



(a) (b) (c) (d)

Figure 6 Fractional change in resistance ($\Delta R/R_0$) vs. time during impact at progressively increasing energy for the 24-lamina quasi-isotropic composite: (a) Top resistance, (b) bottom resistance, (c) oblique resistance, and (d) through-thickness resistance.

resistances are particularly sensitive to minor damage, which cannot be indicated by the top or bottom resistance.

The values of $\Delta R/R_0$ for the top, bottom and oblique resistances are much higher for the 8-lamina quasi-isotropic composite than the 16-lamina and 24-lamina quasi-isotropic composites. However, the $\Delta R/R_0$ values for the through-thickness resistance are comparable for the 8-lamina, 16-lamina and 24-lamina quasi-isotropic composites.

3.3. Contrast of 8-lamina and 16-lamina quasi-isotropic composites

The behavior of the 16-lamina and 24-lamina quasi-isotropic composites is quite different from that of the 8-lamina quasi-isotropic composite. Figs 7 and 8 show the contrast between the 8-lamina and 16-lamina composites. The $\Delta R/R_0$ values for the top, bottom and oblique resistances are much higher for the 8-lamina composite than the 16-lamina composite at the same impact energy. The through-thickness resistance increases monotonically with increasing impact energy for the 16-lamina composite (Fig. 8), but mainly decreases with increasing impact energy for the 8-lamina composite. On the other hand, the top, bottom and oblique resistances all increase monotonically with increasing impact energy for both 8-lamina and 16-lamina composites, except for minor irregularity for the top resistance of the 16-lamina composite.

3.4. Depth of indentation

Table I shows the depth of indentation for various composite configurations at various impact energies. In the regime of low impact energy (less than about 1 J), the depth of indentation is so small that the indentation is almost invisible to the naked eyes. Even at the highest impact energy of 5.08 J, the depth of indentation is small compared to the thickness of the composite.

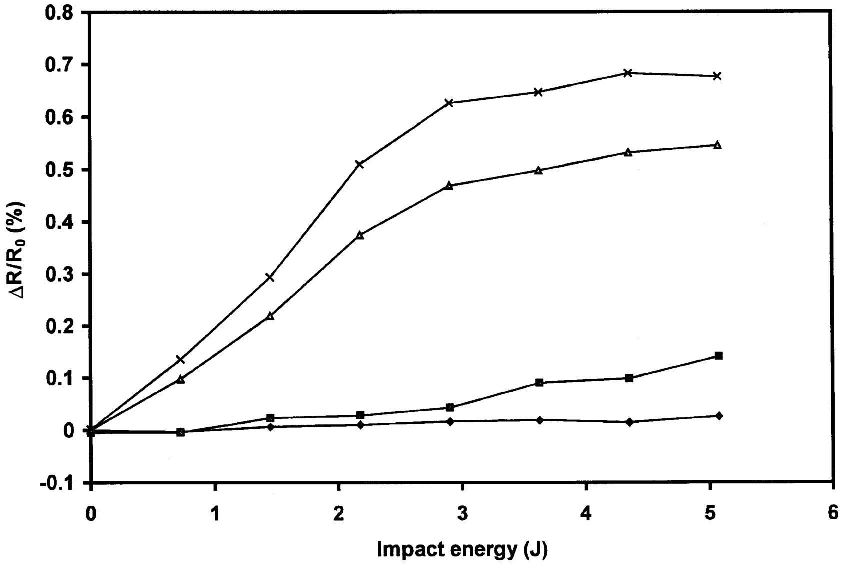


Figure 7 Fractional change in resistance vs. impact energy for the 8-lamina quasi-isotropic composite: ◆ Top, ■ bottom, △ oblique, and × through-thickness.

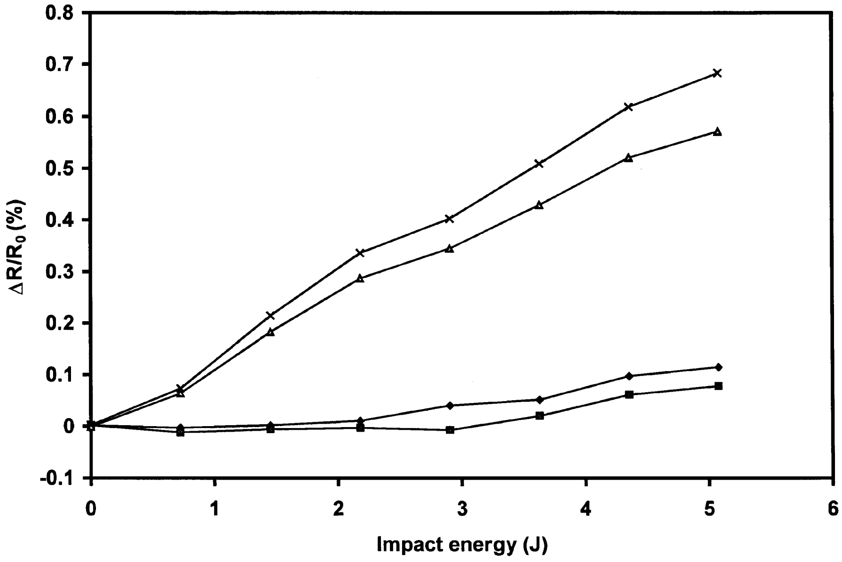


Figure 8 Fractional change in resistance vs. impact energy for the 16-lamina quasi-isotropic composite: ◆ Top, ■ bottom, △ oblique, and × through-thickness.

TABLE I Depth of indentation for various composite configurations at various impact energies

	$[0]_8$		$[0/90]_{2s}$		$[0/45/90/-45]_s$		$[0/45/90/-45]_{2s}$		$[0/45/90/-45]_{3s}$	
Impact energy (J)	Diameter[a] (mm)	Depth[b] (mm)	Diameter[a] (mm)	Depth[b] (mm)	Diameter[a] (mm)	Depth[b] (mm)	Diameter[a] (mm)	Depth[b] (mm)	Diameter[a] (mm)	Depth[b] (mm)
0.36	0.9	0.011								
0.73	1.6	0.034	1.4	0.026	1.5	0.029	1.1	0.016	1.0	0.013
1.09	1.9	0.047								
1.45	2.3	0.069	1.8	0.043	1.9	0.047	1.2	0.019	1.1	0.016
1.81	2.5	0.082								
2.18	3.3	0.14	2.6	0.089	2.5	0.082	1.9	0.047	2.1	0.058
2.90			2.9	0.11	2.7	0.096	3.1	0.13	3.2	0.14
3.63			3.2	0.14	3.2	0.14	3.3	0.14	3.4	0.15
4.36			3.4	0.15	3.7	0.18	3.4	0.15	3.5	0.16
5.08			4.2	0.23	4.1	0.22	3.5	0.16	3.5	0.16

[a] Measured.

[b] Calculated from the measured diameter.

4. Discussion

The trend of increasing resistance with increasing impact energy, as observed for all composites of this work (except for the through-thickness resistance of the 8-lamina composites) is attributed to damage, which can be associated with the separation of fibers of different laminae (i.e., delamination), the separation of fibers of different tows within the same lamina, and fiber breakage. The trend of decreasing resistance with increasing impact energy, as observed for the through-thickness resistance of 8-lamina composites (particularly the crossply and quasi-isotropic ones) at relatively high values of the impact energy, is attributed to the fact that the current and voltage probes are at a distance from one another on each of the two opposite surfaces. Due to this distance, the voltage given by the voltage probes can be reduced when the bent current emanating from the current probes (the bending being due to the high longitudinal conductivity compared to the through-thickness conductivity) is partially cut off from the position of the voltage probes by fiber fracture or off-axis fiber separation at a location between the current and voltage contacts. By using current contacts in the form of a loop and voltage contacts in the form of a dot inside the loop [17], the problem mentioned above is removed and the true through-thickness resistance is measured [15]. In a companion paper [20], we show that the true through-thickness resistivity increases as the level of impact damage increases.

For the 16-lamina and 24-lamina quasi-isotropic composites, the through-thickness resistance increases monitonically with increasing impact energy, in contrast to the decreasing trend for the 8-lamina quasi-isotropic composite at relatively high impact energies. This is because of the relatively large thicknesses of the 16-lamina and 24-lamina composites making the through-thickness damage less severe.

For the 8-lamina crossply and quasi-isotropic composite and the 16-lamina quasi-isotropic composite, the values of $\Delta R/R_o$ are much higher for the bottom resistance than the top resistance. This is due to the impact at the top surface causing the specimen to be effectively subject to slight flexure, such that the bottom surface is under tension. Even though the indentation is directed at the top surface, $\Delta R/R_o$ is larger at the bottom surface. However, for the 24-lamina composite, the top and bottom resistances are comparable in the $\Delta R/R_o$ values, because the large specimen thickness makes the bottom surface less prone to being damaged and makes the specimen less prone to flexure. For the 8-lamina unidirectional composite, the top and bottom resistances are comparable in the $\Delta R/R_o$ values, because the damage involves separation of the unidirectional fibers along cracks that are in the longitudinal direction, i.e., longitudinal matrix cracking. This cracking, as visually observed, eventually affects the whole thickness of the composite, due to the small thickness of the 8-lamina composite.

Among the quasi-isotropic composites of the three different thicknesses, the $\Delta R/R_o$ values for the top, bottom and oblique resistances are much higher for the 8-lamina composite than the 16-lamina or 24-lamina composite. This is because of the more severe damage in the 8-lamina composite, which is small in thickness.

In relation to practical self-sensing, the results of this work mean the following. (i) For thick composites with 16 or more laminae, the oblique and through-thickness resistances are more sensitive to damage than the top or bottom resistance, presumably due to the subsurface nature of the dominant damage. (ii) For thin multidirectional composites with around 8 or less laminae, the bottom resistance is more sensitive to damage than the top, oblique or through-thickness resistance, presumably due to the flexure experienced by the composite and the consequent tension at the bottom surface. (iii) For thin composites with around 8 or less laminae, the through-thickness resistance is not suitable for damage sensing, due to the fact that the variation of the resistance with damage level is not monotonic. (iv) The oblique resistance is the overall best attribute for indicating damage, as it is suitable for all lay-up configurations and all thicknesses, in addition to being sensitive to both minor and major damage.

5. Conclusion

Damage self-sensing by electrical resistance measurement is effective in carbon fiber epoxy-matrix composites irrespective of lay-up configuration or thickness (number of laminae), as shown for impact damage. However, the lay-up configuration and thickness affect the self-sensing characteristics and the recommended resistance measurement configuration.

The oblique resistance is a particularly effective indicator of damage. Although the through-thickness resistance is as sensitive to damage as the oblique resistance, its variation with the impact energy tends to increase and then decrease as the impact energy is increased, when the composite has only 8 laminae. In contrast, the oblique, top and bottom resistances all increase monotonically with increasing impact energy, irrespective of the lay-up configuration or the number of laminae. For multidirectional composites with 8 or 16 laminae, the bottom resistance is more sensitive to damage than the top resistance. For 8-lamina multidirectional composites, the bottom resistance is more sensitive to damage than the top, oblique or through-thickness resistance. For the 8-lamina unidirectional composite, the top and bottom resistances are comparably sensitive to damage, due to damage in the form of longitudinal matrix cracking. For 16-lamina and 24-lamina quasi-isotropic composites, the oblique and through-thickness resistances are comparably sensitive and both increase monotonically with increasing impact energy.

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