Method of sensing impact damage in carbon fiber polymer-matrix composite by electrical resistance measurement

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The method of sensing impact damage in carbon fiber polymer-matrix structural composite by DC electrical resistance measurement was evaluated by measuring the resistance of the top surface (surface receiving impact). The resistance obtained by using the four-probe method is a more sensitive, more precise (less data scatter) and more accurate indicator of composite damage than that obtained by using the two-probe method. The data scatter is low for both four-probe and two-probe resistances for impact energy up to 5 J, but it is lower for the four-probe resistance than the two-probe resistance. The data scatter increases with damage. It is attributed to electrical contact degradation. The four-probe resistance of the 8-lamina composite increases upon impact, such that the fractional increase diminishes as the distance from the point of impact increases. The four-probe resistance of the 24-lamina composite increases upon impact for the specimen segment containing the point of impact, but decreases slightly upon impact for the segments within about 20 mm from the point of impact. The two-probe resistance has less tendency to decrease upon impact than the four-probe resistance.

1. Introduction

Impact is a commonly encountered cause of damage of a structure. For strategic structures such as aircraft, it is particularly important to assess the damage so as to mitigate hazards. Polymer-matrix composites with continuous fiber reinforcement are dominant among lightweight structural materials, due to their low density, high strength and high modulus of elasticity. Thus, impact damage of such composites has received considerable recent attention [1–4].

The evaluation of impact damage has been conducted destructively by residual strength measurement [5–7] and nondestructively by electrical resistance measurement [8–11] and ultrasonic inspection [11], as damage decreases the residual strength, increases the electrical resistivity and hinders ultrasonic wave propagation. The electrical resistance technique is more sensitive than the ultrasonic method [11]. In addition, the nature of the damage has been examined by microscopy [12] and the process of damage infliction has been studied by analysis of the transient strain response [13]. The above techniques do not require modification of the material to be evaluated. However, modification in the form of optical fiber embedment allows damage evaluation too [14]. Nondestructive evaluation methods that do not require modification of the material are attractive, as the need to modify limits the field of application and the embedded devices are expensive and quite impossible to maintain or repair. Therefore, this paper is focused on the electrical resistance method, which allows the composite to sense its own damage (i.e., self-sensing).

Due to the low electrical resistivity of carbon fibers compared to polymer matrices, the electrical resistance method is particularly valuable for evaluating carbon fiber polymer-matrix composites, which are important for aircraft structures. This method has been used to evaluate flexural damage [15], tensile damage [16–19], thermal damage [20] and impact damage [9–11] in carbon fiber epoxy-matrix composites, which are dominant among carbon fiber polymer-matrix composites.

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Prior work on the use of the electrical resistance method for sensing strain or damage in carbon fiber polymer-matrix composites primarily used the four-probe method [15–22]. This is due to the well-known superiority of the four-probe method over the two-probe method. The four-probe method refers to a resistance measurement method in which four electrical contacts are utilized. The outer two contacts are for passing a current, while the inner two contacts are for voltage measurement. By separating the current and voltage contacts, the electrical resistance associated with the voltage contacts is not included in the resistance measured for the part of the specimen between the voltage contacts. In contrast, the two-probe method, which is an inferior but more convenient method, uses two electrical contacts, such that each contact serves both functions of current application and voltage measurement. The resistance obtained by using the two-probe method includes the contact resistance with the specimen resistance and is thus sensitive to the quality of the electrical contacts.

Although the superiority of the four-probe method over the two-probe method is well-known in the field of electrical resistance measurement, comparative evaluation of these two methods in the case of carbon fiber polymer-matrix composite self-sensing has received little attention [22, 23]. Prior comparative evaluation [22, 23] addressed the accuracy of the resistance measurement and did not address the precision (i.e., the extent of data scatter). Moreover, prior work [22, 23] addressed strain sensing rather than damage sensing. Therefore, this paper is partly aimed at comparative evaluation of the four-probe and two-probe methods in relation to the sensitivity, precision and accuracy for composite damage self-sensing.

Prior use of the electrical resistance method of impact damage self-sensing of composites was limited to the use of the four-probe method and impact energy up to 5 J [11]. In contrast, this paper used both four-probe and two-probe methods and included a wide range of impact energy (from 0.73 to 18.1 J). Because of the increased chance of damage to the electrical contacts as the impact energy increases, investigation that covers a wide range of impact energy allows study of the effect of electrical contact degradation on the composite self-sensing. Such a study constitutes a secondary aim of this paper.

Related to the electrical resistance method is the electrical potential method, which involves measuring the potential at various points of a specimen during current application of a fixed current in a particular direction in the specimen. The potential method has been used for locating impact damage in the plane of the fiber layers of a carbon fiber epoxy-matrix composite for impact energy in the range from 2 to 12 J [9, 10].

Resistance measurement using a resistance meter usually does not involve a fixed current, as the current is set by the meter to decrease in steps with increasing resistance. In contrast, the current must be fixed and known in the potential method.

The objective of this paper is to evaluate the effectiveness of the resistance method for sensing impact damage of carbon fiber polymer-matrix composite in real time. This evaluation includes (i) studying the effects of electrical contact configuration (two-probe vs. four-probe methods), specimen damage and electrical contact degradation (which may accompany specimen damage) on the data scatter—a subject that has not been addressed in prior related work, (ii) investigating the relationship between impact energy and electrical contact degradation—also a subject that has not been addressed in prior related work, and (iii) comparing the effect of impact damage on the resistance of the part of the specimen including the point of impact and the effect of impact damage on the resistance of the part of the specimen adjacent to but not including the point of impact—a subject that has been previously addressed in the regime of minor damage resulting from impact at energy up to 5 J [11], in contrast to the wide range of impact damage studied in this work. Objectives (ii) and (iii) relate to investigation of possible degradation of the electrical contacts by the impact on the specimen.

2. Experimental methods

Commercially manufactured composites in the form of continuous carbon fiber epoxy-matrix laminates were cut into strips of size 200 × 12 mm. The length of 200 mm was limited by the size of the steel block at the base of the drop impact instrument. The width of 12 mm was chosen partly to provide a substantial resistance of the specimen in the longitudinal direction; the wider the specimen, the lower is the resistance. On the other hand, a large width is desirable for diminishing the edge effect. Thus, a compromise was made by using a width of 12 mm. That the edge effect was small, if any, is shown by the absence of observable change at the edge surface before and after impact.

Each strip was lightly 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 sanding would not be necessary if the surface epoxy layer were negligible. In general, the thickness of the surface epoxy layer depends on the composite fabrication process. In a separate study [24], it was found that sanding improved the accuracy and precision of the resistance measurement, though it was not essential. In case of a painted composite, the paint may be removed by the use of a suitable solvent, though it may also be removed in a way similar to the removal of the surface epoxy layer. Although the entire surface was sanded in this work, only the portions beneath the electrical contacts needed to be sanded. The contacts were in the form of silver paint in conjunction with copper wire. Each contact was protected with an epoxy coating so as to enhance its mechanical integrity.

Two laminates were studied, namely a 8-lamina quasi-isotropic $[0/45/90/-45]_s$ laminate (thickness = 1.0 mm)

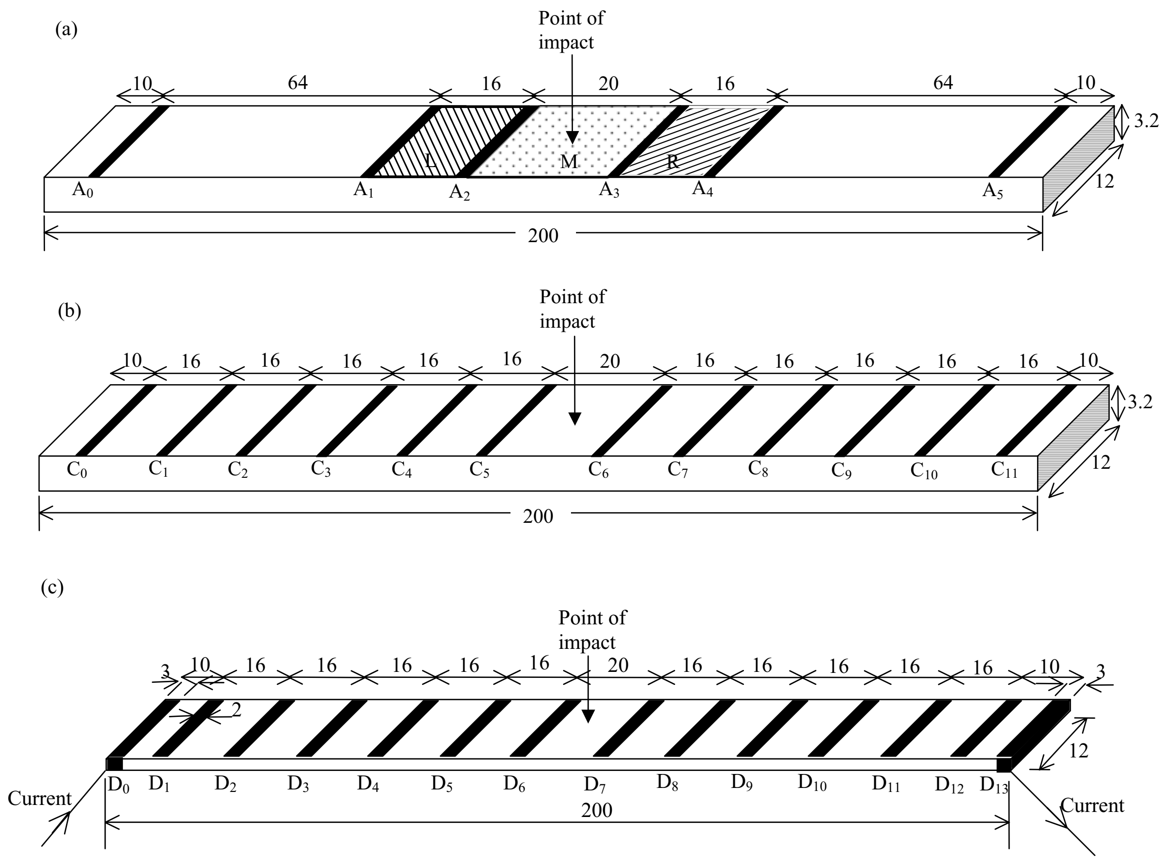

Figure 1 Specimen configuration for impact damage sensing. All dimensions are in mm. (a) Specimen 1 of the 24-lamina composite. (b) Specimen 2 of the 24-lamina composite. (c) The 8-lamina composite.

and a 24-lamina quasi-isotropic $[0/45/90/\text{-}45]_{3s}$ laminate (thickness = 3.2 mm).

For the 24-lamina composite, Specimens 1 and 2 were used. Specimen 1 (Fig. 1a) involved six electrical contacts, which were applied on one side (the top side of Fig. 1a). Six contacts rather than four contacts were used in order to obtain information of the spatial distribution of damage. Each contact was in the form of a line along the 12-mm width of the specimen. Specimen 2 (Fig. 1b) involved 12 electrical contacts that were applied on one side (the top side of Fig. 1b) in order to obtain more detailed information on the spatial distribution of damage. For the 8-lamina composite (Fig. 1c), 12 electrical contacts were applied on one side (the top side of Fig. 1c), whereas the two end contacts covered the top, bottom and edge surfaces at the two end regions of the specimen. In Fig. 1c, there were a total of 14 electrical contacts.

DC electrical resistance measurement was conducted using the four-probe method, unless noted otherwise. A Keithley 2002 multimeter was used. The surface resistance of the top side (the side receiving the impact) was measured. The two end contacts (i.e., A_0 and A_5 in Fig. 1a, C_0 and C_{11} in Fig. 1b, and D_0 and D_{13} in Fig. 1c) were used to pass current. Various adjacent pairs of the remaining contacts were used to measure the potential difference. For example, in Fig. 1a, (i) A_2 and A_3 were used as voltage contacts for measuring the resistance of the middle segment (labeled M in Fig. 1a), (ii) A_1 and A_2 were used as voltage contacts for measuring the resistance of the left segment (labeled L in Fig. 1a), and (iii) A_3 and A_4 were used as voltage contacts for measuring the resistance of the right segment (labeled R in Fig. 1a). In addition to the four-probe method mentioned above, the surface resistance of the top side was measured by using the two-probe method for the case of Fig. 1a. In the two-probe method, contacts A_1 and A_2 were used for segment L, contacts A_2 and A_3 were used for segment M, contacts A_3 and A_4 were used for segment R, and contacts A_0 and A_5 were used for the segment from A_0 to A_5 (almost the entire length of the specimen).

Before, during and after impact using a steel hemisphere (19 mm or 0.75 in diameter) dropped from a controlled height, four-probe and two-probe resistance measurements were made using a resistance meter with a variable DC current and potential difference measurement was made with a fixed DC current (10, 50 or 100 mA, applied through contacts A_0 and A_5) for each of the segments L, M and R. In addition, two-probe resistance measurement was made using a resistance meter for the segment from A_0 to A_5. The impact energy was calculated from the weight of the ball assembly (either 0.740 or 2.640 kg) and the initial height of the ball (up to 760 mm). The impact was directed at the same point of the specimen at progressively increasing energy. Hence, the cumulative damage was analyzed. Although cumulative damage is more than damage resulting from a single impact at the maximum impact energy used in inflicting cumulative damage, it is meaningful in providing the damage evolution for the same specimen as the impact energy progressively increased.

In the case of the configuration of Fig. 1a (i.e., Specimen 1 of the 24-lamina composite), after each impact, the resistance or potential difference was measured 20 times (0.3 s between successive measurements). The standard deviation was then computed using these 20 values.

All the data reported in this paper for the 24-lamina composite were obtained on Specimen 1, unless noted otherwise. For each of the three configurations illustrated in Fig. 1a–c, testing had been performed on multiple specimens in order to ascertain the general reproducibility of the results.

3. Results and discussion

3.1. 24-lamina composite

The occurrence of damage after impact is shown by the indentation at the point of impact. The measured diameter of the indentation was used to calculate the depth of the indentation. The depth was thus found to be 0.01, 0.03, 0.06, 0.08, 0.11, 0.15 and 0.20 mm after single impacts at energies 0.73, 1.45, 2.18, 2.90, 3.63, 4.36 and 5.08 J respectively. For the 24-lamina composite of thickness 3.2 mm, an indentation depth of 0.20 mm exceeded the thickness of one lamina. This implies that the resistance method involving surface electrical contacts, as used in this work, is not limited to sensing damage in the first lamina.

The resistance was measured in this work in the same specimen as the impact energy was progressively increased. This means that the resistance reflected the cumulative damage rather than damage due to a single impact. Thus, the indentation depths mentioned in the last paragraph for single impacts are underestimates of the indentation depths for the cumulative damage case.

TABLE I Fractional change in four-probe resistance of each of the segments *L*, *M* and *R*

	Fractional change (%)		
Impact energy (J)	*L*	*M*	*R*
0.73	–0.09	0.10	0.07
1.45	–0.14	0.14	–0.04
2.18	–0.13	0.22	–0.02
2.90	–0.30	0.46	–0.15
3.63	–0.35	0.64	–0.12
4.36	–0.45	0.75	–0.25
5.08	–0.46	0.87	–0.22
7.77	–0.64	1.16	–0.41
10.4	–1.04	40.7	–0.06
12.9	–1.28	85.2	–0.21
15.5	–18.2	437	–10.8
18.1	–145	1280	–103

Fig. 2 shows the four-probe resistance vs. impact energy for Specimen 1 of the 24-lamina composite. The resistance of segment *M* increases with impact energy monotonically, while those of segments *L* and *R* decrease slightly with increasing impact energy, as clearly shown in Table I.

Fig. 3 and Table 2 show the two-probe resistance vs. impact energy for Specimen 1 of the 24-lamina composite. The resistances for segment *M* increase more or less monotonically with increasing impact energy, whereas those for segments *L* and *R* and the segment from A_0 to A_5 show a decrease at low impact energies, followed by an increase at high impact energies. The increase is more

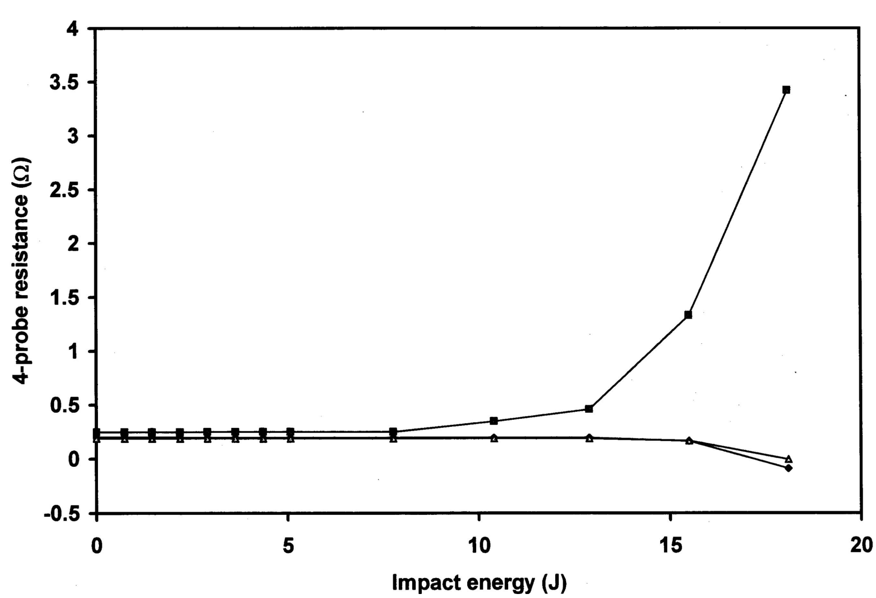

Figure 2 Variation of the four-probe resistance with impact energy as the energy is increased for Specimen 1 of the 24-lamina composite. ♦: Segment L;■: Segment M; △: Segment R.

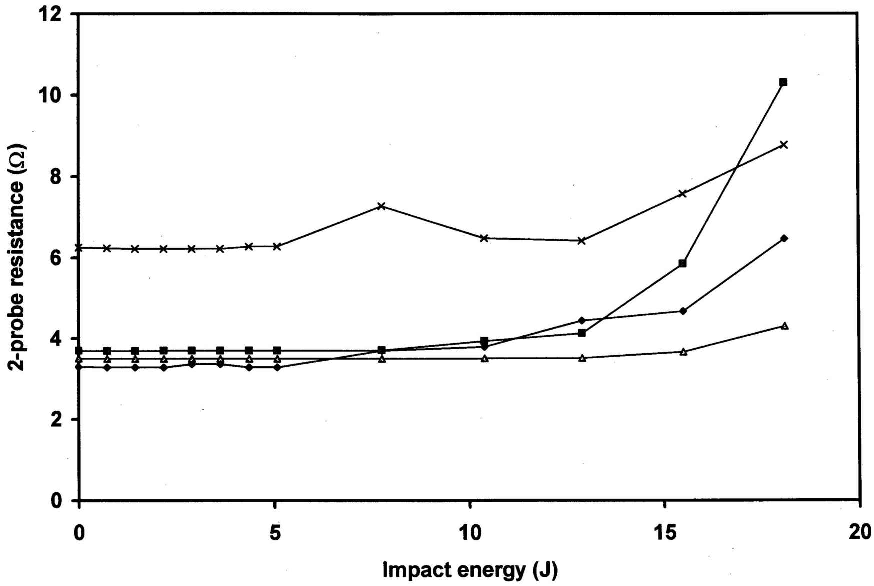

Figure 3 Variation of the two-probe resistance with impact energy as the energy is increased for Specimen 1 of the 24-lamina composite. ♦: Segment L; ■: Segment *M*; △: Segment *R*; ×: Segment from A_0 to A_5.

significant for segment *M* than the other segments. In particular, the increase is more significant for segment *M* than the segment from A_0 to A_5, though both of these segments contain the point of impact. Thus, proximity of the electrical contacts to the point of impact helps increase the sensitivity. The increase is more significant for segment *L* than for segment *R*, suggesting that contact A_1 and/or A_2 to be more prone to degradation (due to impact) than contact A_3 and/or A_4. In other words, different contacts differ in quality and these differences affect resistance values obtained by the two-probe method. The asymmetry is not due to misalignment in the impact tester.

The trend of the fractional change in resistance (relative to the value before any impact) increasing with increasing impact energy is exhibited by segment *M* for the four-probe resistance over the whole range of impact energy from 0.73 to 18.1 J. This is consistent with prior work from 0.73 to 5.08 J [11]. This trend is also exhibited by segment *M* for the two-probe resistance over the whole range of impact energy, though the fractional change is negative for impact energy ranging from 0.73 to 2.90 J. It is also exhibited by segments *L* and *R* and the segment from A_0 to A_5 for the two-probe resistance in the regime of high impact energy (e.g., above 7.77 J for segment *L* and above 12.9 J for segment *R*). A negative value means that the resistance is less after impact than beforeM impact.

The trend of the fractional change in resistance decreasing (becoming more negative) with increasing impact energy is exhibited by segment *L* for the four-probe resistance over the whole range of impact energy from 0.73 to 18.1 J. This trend had been previously observed to a small degree in segment *L* (similarly defined as in this paper) below 2.18 J [11]. This trend is also exhibited in the present work by segment *R* for the four-probe resistance, although the trend is less regular than that for segment *L*. It is also exhibited by segments *L* and *R* and the segment from A_0 to A_5 for the two-probe resistance in the low impact energy regime (e.g., below 2.18 J for segment *L* and below 1.45 for segment *R*). In the case of the four-probe resistance, the greater is the damage in segment *M* (as shown by a high value of the fractional increase in resistance), the more negative is the fractional change in resistance in segment *L* or R.

The trend of the fractional change in resistance increasing with increasing impact energy is attributed to major damage (such as delamination and fiber fracture), which is encountered by the segment containing the point of impact (i.e., segment *M*). The opposite trend, as mainly exhibited by the segments adjacent to the segment containing the point of impact, may be due to several reasons. One possible reason relates to the distortion of the current path away from the top surface due to the major

TABLE II Fractional change in two-probe resistance of each of the segments *L*, *M* and *R* and the segment from A_0 to A_5

	Fractional change (%)			
Impact energy (J)	*L*	*M*	*R*	From A_0 to A_5
0.73	–0.34	–0.24	–0.29	–0.18
1.45	–0.42	–0.12	–0.39	–0.52
2.18	–0.42	–0.08	–0.38	–0.51
2.90	1.89	–0.05	–0.31	–0.52
3.63	1.90	0.02	–0.31	–0.51
4.36	–0.40	0.07	–0.34	0.39
5.08	–0.41	0.13	–0.33	0.41
7.77	12.0	0.28	–0.34	16.4
10.4	15.0	6.40	–0.02	3.71
12.9	34.7	11.7	0.18	2.73
15.5	41.6	58.2	4.50	21.2
18.1	96.1	179	22.5	40.4

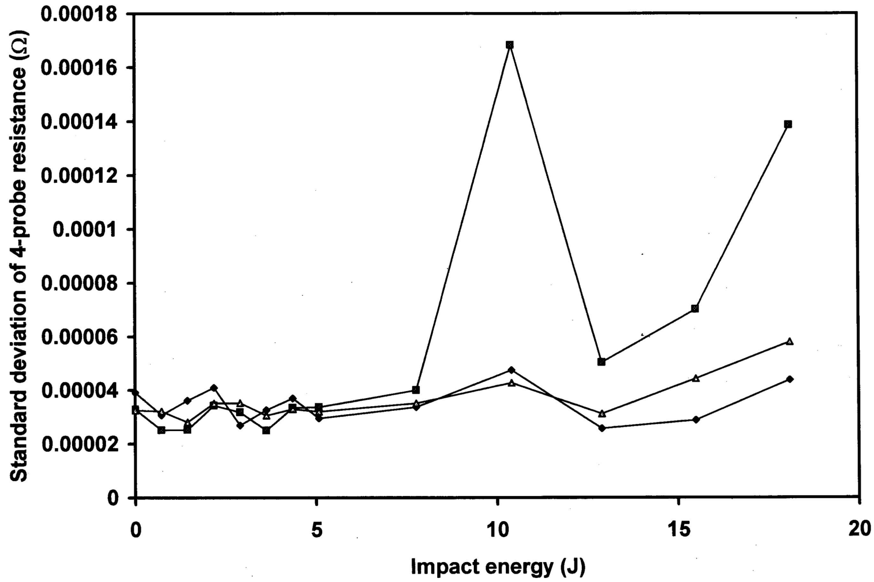

Figure 4 Variation of the standard deviation of the four-probe resistance with impact energy as the energy is increased for Specimen 1 of the 24-lamina composite. ♦: Segment *L*; ■: Segment *M*; Δ: Segment *R*.

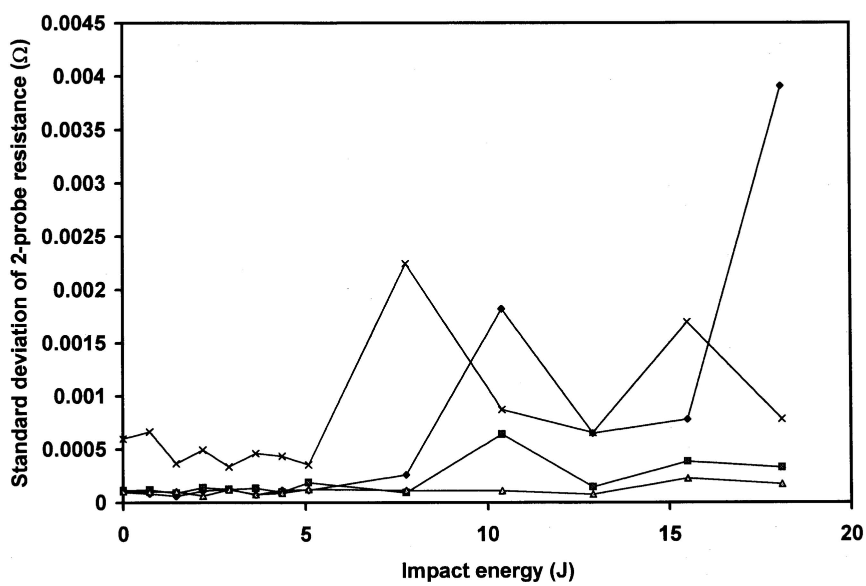

Figure 5 Variation of the standard deviation of the two-probe resistance with impact energy as the energy is increased for Specimen 1 of the 24-lamina composite. ♦: Segment L; ■: Segment M; Δ: Segment R; ×: Segment from A_0 to A_5.

damage at the top surface nearby. This distortion can involve the current crossing from one lamina to the adjacent one, since the contact resistivity of the interlaminar interface is limited [25]. The distortion results in less current at the top surface and hence a decrease of the measured resistance at the top surface. Another possible reason relates to residual stress relief in the segments adjacent to the segment containing the point of impact, due to the damage in the segment containing the point of impact. Yet another possible reason, though the least likely, relates to minor damage in the form of increased proximity between the laminae in the segments adjacent to the segment containing the point of impact. The increased proximity causes the through-thickness resistance to decrease [25]. A decrease in through-thickness resistance can cause the longitudinal resistance to decrease, since current can more easily detour from one lamina to another.

The effect of the resistance increasing upon impact is the primary phenomenon observed; the latter effect of the resistance decreasing upon impact is a secondary phenomenon. The secondary phenomenon complicates the interpretation of resistance data in regions not including, but close to, the point of impact. Although not shown by the data above, the secondary phenomenon is small in regions that are not immediately adjacent to the segment containing the point of impact, as shown by a separate experiment involving Specimen 2 of the 24-lamina composite, where the resistance essentially does not change up to 10 J for

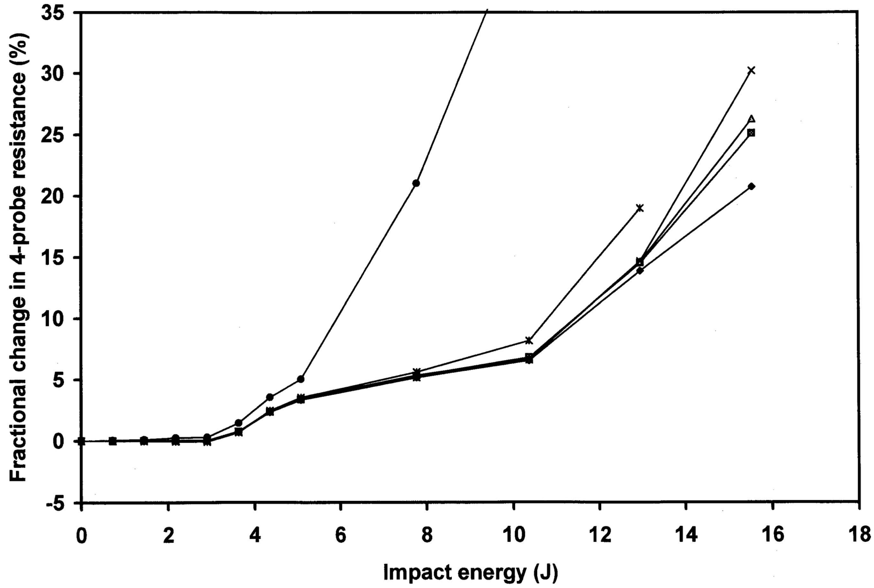

Figure 6 Variation of the fractional change in four-probe resistance with impact energy as the energy is increased for the 8-lamina composite. Data for the various segments are shown by the symbols below. □ : D_0D_1, ■ : D_1D_2, Δ : D_2D_3, × : D_3D_4, ✳ : D_4D_5, • : D_5D_6.

the segments that are not immediately adjacent to the segment containing the point of impact. Above 10 J, the resistance decreases more appreciably, but the decrease remains small compared to the decrease for the segment that is immediately adjacent to the segment containing the point of impact. Thus, the complication mainly applies to the segment immediately adjacent to the segment containing the point of impact, i.e., regions within about 20 mm from the point of impact but not containing the point of impact.

For the same impact energy, the two-probe resistance (Fig. 3) is much higher than the four-probe resistance (Fig. 2), due to the contribution of the contact resistance to the two-probe resistance. Since the damage of the specimen rather than that of the electrical contacts is the attribute to be investigated, the four-probe resistance is a more accurate indicator of damage than the two-probe resistance. For the same impact energy, the fractional change in resistance is higher for the four-probe resistance than the two-probe resistance, as clearly shown by comparing Tables I and II. Thus, the four-probe resistance is a more sensitive indicator of damage than the two-probe resistance.

Figs. 4 and 5 show the standard deviations for the four-probe and two-probe resistances respectively (Specimen 1). For the same impact energy, the standard deviation is much less for the four-probe resistance than the two-probe resistance. This means that the four-probe resistance is a more precise indicator of damage than the two-probe resistance. The standard deviation of the four-probe resistance is large (relative to the value prior to any impact) at impact energy of 10 J and above, whereas that of the two-probe resistance is large (relative to the value prior to any impact) at impact energy of 7.8 J and above. In other words, the standard deviation is low for both four-probe and two-probe resistance if the impact energy is low (less than 7 J). For the four-probe resistance, the rise in standard deviation is much more significant for segment *M* than segment *L* or *R*, due to more damage in segment *M* and the observed relationship of damage degree to standard deviation. For the two-probe resistance, the rise in standard deviation is larger for segment *L* and the segment from A_0 to A_5 than for segment *M* or *R*, probably due to the higher degradation tendency for contact A_1 than contact A_4 (as mentioned above). That the standard deviation is higher for the two-probe resistance than the four-probe resistance and is higher for greater impact energy suggests that the data scatter is due to electrical contact degradation.

The four-probe resistance of segment *M* (Table I) shows that damage abruptly increases at an impact energy of 10.4 J. At and above 10.4 J, the fractional change in resistance is much higher than the value below 10.4 J. The two-probe resistance of segment *M* (Table II) shows a similar but weaker effect.

Accompanying large increases in the four-probe resistance of segment *M* are significant decreases of the four-probe resistance of segments *L* and *R*, as shown at an impact energy of 15.5 J and above. In contrast, large increases in the two-probe resistance of segment *M* are accompanied by significant increases of the two-probe resistance of segments *L* and *R*. Hence, the four-probe resistances of segments *L* and *R* have higher tendency to decrease with increasing impact energy than the corresponding two-probe resistances. This is attributed to the contribution of the contact resistance to the two-probe resistance; degradation of an electrical contact can only increase the contact resistance, whereas degradation of the composite specimen can increase or decrease the specimen resistance. For example, the squeezing of the laminae

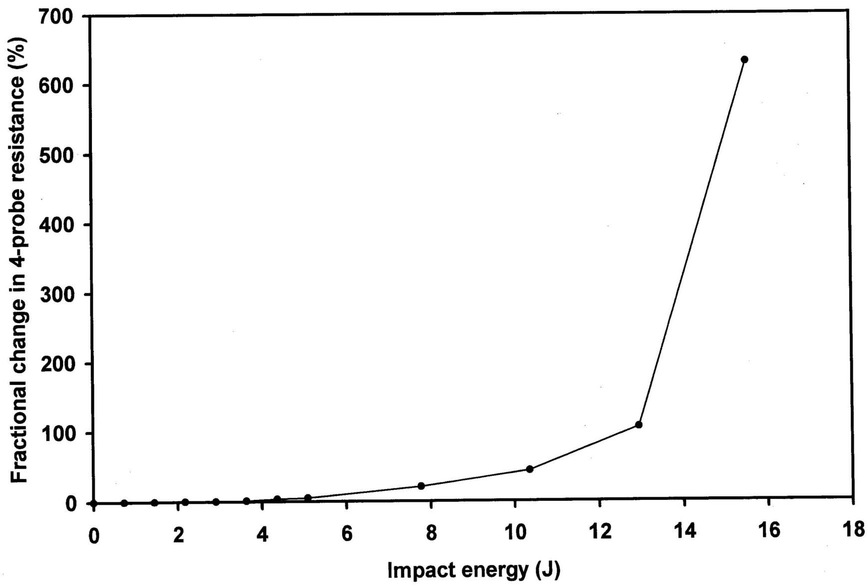

Figure 7 Variation of the fractional change in four-probe resistance with impact energy as the energy is increased for the 8-lamina composite. Only data for the segment containing the point of impact (D_5D_6) are shown.

together causes the resistance associated with the interlaminar interface to decrease [25], whereas delamination causes the through-thickness resistance to increase [19].

3.2. 8-lamina composite

The 8-lamina composite was studied using the configuration of Fig. 1c. Fig. 6 shows the fractional change in four-probe resistance vs. impact energy. The resistance increases monotonically with increasing impact energy. At the same impact energy, the closer the segment is to the point of impact, the greater is the fractional change in resistance. The higher is the impact energy, the more are the differences in fractional change in resistance among the various segments. The segment containing the point of impact exhibits exceptionally high fractional change in resistance compared to the other segments. Fig. 7 shows the complete curve for the segment containing the point of impact.

All segments of the 8-lamina composite do not show any decrease in resistance upon impact, in contrast to the tendency for the segments adjacent to the segment containing the point of impact to decrease in the case of the 24-lamina composite. The absence of the resistance decrease phenomenon for the 8-lamina composite is because the small thickness of the 8-lamina composite makes the damage more extensive, thus causing the current path distortion, residual stress relief and minor damage (as mentioned in the last section as possible origins of the resistance decrease phenomenon) to occur insignificantly.

4. Conclusion

The two-probe resistance is much higher than the four-probe resistance both before and after impact, due to the contribution of the contact resistance to the two-probe resistance. The four-probe resistance is a more sensitive (greater fractional change upon impact), more precise (less data scatter) and more accurate indicator of composite damage than the two-probe method. For impact energy up to 5 J, the data scatter is low for both four-probe and two-probe resistances, although it is lower for the four-probe resistance than the two-probe resistance. The more severe is the damage, the greater is the data scatter. The data scatter is attributed to electrical contact degradation, which accompanies specimen damage above 5 J.

The four-probe resistance of the 24-lamina composite increases upon impact for the segment containing the point of impact, but decreases upon impact for the segments within about 20 mm from the point of impact. However, the two-probe resistance has less tendency to decrease upon impact than the four-probe resistance. The four-probe resistance of the 8-lamina composite increases upon impact for all the segments, such that the fractional increase diminishes as the distance from the point of impact increases.

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