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Through-thickness stress sensing of a carbon fiber polymer–matrix composite by electrical resistance measurement

Daojun Wang and D D L Chung[1]

Composite Materials Research Laboratory, University at Buffalo, State University of
New York, Buffalo, NY 14260-4400, USA

E-mail: ddlchung@buffalo.edu

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Abstract

Through-thickness stress self-sensing in a quasi-isotropic carbon fiber epoxy–matrix composite by in-plane electrical resistance measurement is effective. The resistance decreases reversibly upon through-thickness compression conducted up to 67 MPa, due to an increase in the proximity between adjacent laminae. The sensing can be attained by measuring the surface resistance in the direction of the surface fibers or by measuring the volume resistance in essentially any in-plane direction. The sensing is ineffective if the transverse surface resistance is the quantity measured, due to the dominance of the surface fibers in governing the surface resistance. In the case of the longitudinal surface resistance, the decrease in resistance upon compression has a slight irreversible component, due to an irreversible increase in the proximity between adjacent laminae and the consequent increase in the degree of current penetration. This effect is smaller for the longitudinal or transverse volume resistance. The variability of the resistance from area to area in the same laminate is larger for the surface resistance than the volume resistance, due to its higher sensitivity to current spreading. The sensitivity of stress sensing, as described by the fractional change in resistance per unit through-thickness compressive stress, is -10^{-5} MPa^{-1}. The magnitude of the effectiveness is lower for the resistance away from the stressed region than that at the stressed region.

1. Introduction

Polymer–matrix composites with continuous carbon fibers as reinforcement are widely used for lightweight structures, such as aircraft, due to their combination of high strength, high modulus and low density. Since the fibers in such a composite are in the form of plies (known as laminae), the fibers are in the plane of the laminae. As a consequence, the strength and elastic modulus of the composite are much higher in the plane of the laminae (particularly in the direction of the fibers) than in the direction perpendicular to the laminae (known as the through-thickness direction). The interface between adjacent laminae (known as the interlaminar interface) constitutes a weak link, so delamination is a common form of damage in such composites.

Much attention has been given to studying the mechanical properties of composites in the plane of the laminae, but relatively little attention has been given to the properties in the through-thickness direction. Composites are designed to carry load in the plane of the laminae rather than in the through-thickness direction, but they encounter stress in the through-thickness direction under some circumstances. Such a circumstance pertains to the joining of composite components by fastening, which imposes a compressive stress in the through-thickness direction of the panels being joined. The effect of fastening on the microstructure of composites is of current aircraft safety concern, due to the 2001 Airbus accident in New York. The accident involved detachment of the tail section from the body of the aircraft [1].

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[1] Author to whom any correspondence should be addressed. http://alum.mit.edu/www/ddlchung.

Through-thickness compressive stress has been shown to decrease (with a substantial degree of reversibility) the contact electrical resistivity of the interlaminar interface [2]. The degree of reversibility is less for a composite with an epoxy matrix than for one with a thermoplastic matrix, due to the relatively brittle nature of epoxy compared to a thermoplastic polymer [3]. The decrease in contact resistivity is due to an increase in the extent of fiber–fiber contact across the interlaminar interface. The partial irreversibility of the contact resistivity decrease is due to an irreversible change in the microstructure of the interface. In the case of an epoxy–matrix composite, such partial irreversibility occurs at compressive stresses as low as 1 MPa [2]. Although the contact resistivity of the interlaminar interface is a sensitive indicator of the microstructure of the interface, its measurement on a composite with more than two laminae (as is usually the case in practical structures) is geometrically difficult, due to the need for making electrical contacts to each of two adjacent laminae, as required to pass current from one lamina to the other through the interlaminar interface and to measure the voltage between the laminae [2]. In contrast, the electrical resistance of the composite in the plane of the laminae is an attribute that is amenable to measurement in practical composite structures.

It has been shown that the longitudinal resistance (resistance in the direction of the fibers) in a unidirectional composite with a single lamina decreases upon through-thickness compression, in spite of the expected accompanying decrease in thickness tending to cause the resistance to increase [4]. This longitudinal resistance decrease is due to fiber squeezing (i.e. increase in the extent of fiber–fiber contact within the single lamina in the through-thickness direction) and the consequent decrease in the through-thickness volume electrical resistivity. The through-thickness resistivity can affect the longitudinal resistivity because of the presence of fiber imperfections and the need for the longitudinal current to detour around imperfections. Accompanying this longitudinal resistance decrease is an increase in the transverse electrical resistance. The transverse effect is due to fiber spreading (i.e. increase of the average distance between adjacent fibers in the transverse direction of this unidirectional composite) [4]. The transverse effect complicates the overall phenomenon, particularly when the applied stress is high [4].

The transverse effect is expected to be absent (or nearly absent) in the case of a multidirectional composite, such as one that has fibers in both the longitudinal and transverse directions, as the transverse fibers will restrain the composite from undergoing fiber spreading. In a typical structural composite, the fiber lay-up configuration is quasi-isotropic, with fibers in the longitudinal (0°), transverse (90°) and intermediate directions (most commonly 45°). In the absence of fiber spreading, the in-plane resistance change upon through-thickness compression is expected to become relatively simple and thus become amenable for serving as a practical indicator of through-thickness compressive stress. Therefore, this paper is aimed at investigating the effect of through-thickness compression on the resistance in the plane of the laminae of a quasi-isotropic composite for the purpose of developing a method of through-thickness stress sensing.

The use of the resistance of a composite to indicate the stress experienced by the composite means that the composite serves as a sensor. Since the structure senses itself, the technique is known as self-sensing [5]. Self-sensing is advantageous for the use of embedded or attached sensors in the low cost, high durability, large sensing volume and absence of mechanical property loss.

The self-sensing of stress or strain [5–10] is to be distinguished from the self-sensing of damage [11–23], although both can be achieved in carbon fiber polymer–matrix composites by electrical resistance measurement. This paper addresses stress sensing.

The volume resistance, as measured by using a current that goes through the entire cross section of a specimen, is an attribute that is of more scientific significance than the surface resistance, which is measured by using a current that flows in the surface region only. However, due to the fact that surface resistance measurement involves the use of electrical contacts that are on the same surface of a composite, surface resistance measurement is more suitable for practical implementation than volume resistance measurement. On the other hand, due to the 0° orientation of the fibers in the surface lamina, the surface resistance of a quasi-isotopic composite is lower in the 0° direction than the 90° direction. In contrast, due to the completeness (at least ideally) of the current penetration in volume resistance measurements, the volume resistance of a quasi-isotopic composite is the same in the two directions. Therefore, this work includes both volume resistance and surface resistance in studying the effect of through-thickness compression. Furthermore, this work includes comparison of the effect of through-thickness stress on the resistance in the 0° direction and on the resistance in the 90° direction.

In practical implementation of the self-sensing technology in a structure, it is more convenient to measure the resistance away from the stressed region than that at the stressed region. For example, the stressed region may be the area where the fastening takes place and measurement of the resistance of an area where a fastener is located is less convenient than measurement of the resistance of an area away from the fastener. Therefore, this paper includes investigation of the effectiveness of the self-sensing away from the stressed region.

The objectives of this paper are (i) to investigate the effectiveness of through-thickness stress self-sensing in a quasi-isotropic carbon fiber epoxy–matrix composite, (ii) to compare the effectiveness of stress sensing by volume resistance measurement and that by surface resistance measurement, (iii) to compare the effectiveness of stress sensing by resistance measurement in the 0° (longitudinal) and 90° (transverse) directions, and (iv) to compare the effectiveness of stress sensing by resistance measurement at and away from the stressed region.

2. Experimental methods

The composite is a commercially manufactured 24-lamina quasi-isotropic $[0/45/90/-45]_{3s}$ laminate with IM7 carbon fiber (Hexcel Corp., PAN-based, intermediate modulus of 290 GPa, diameter 5 μm, 12 000 fibers per tow) and 977-3 epoxy (CYCOM, toughened epoxy resin with a curing temperature of 177 °C). The thickness is 3.2 mm. The composite is cut into specimens in the shape of a cross in the plane of the laminate, as illustrated in figure 1(a), where the

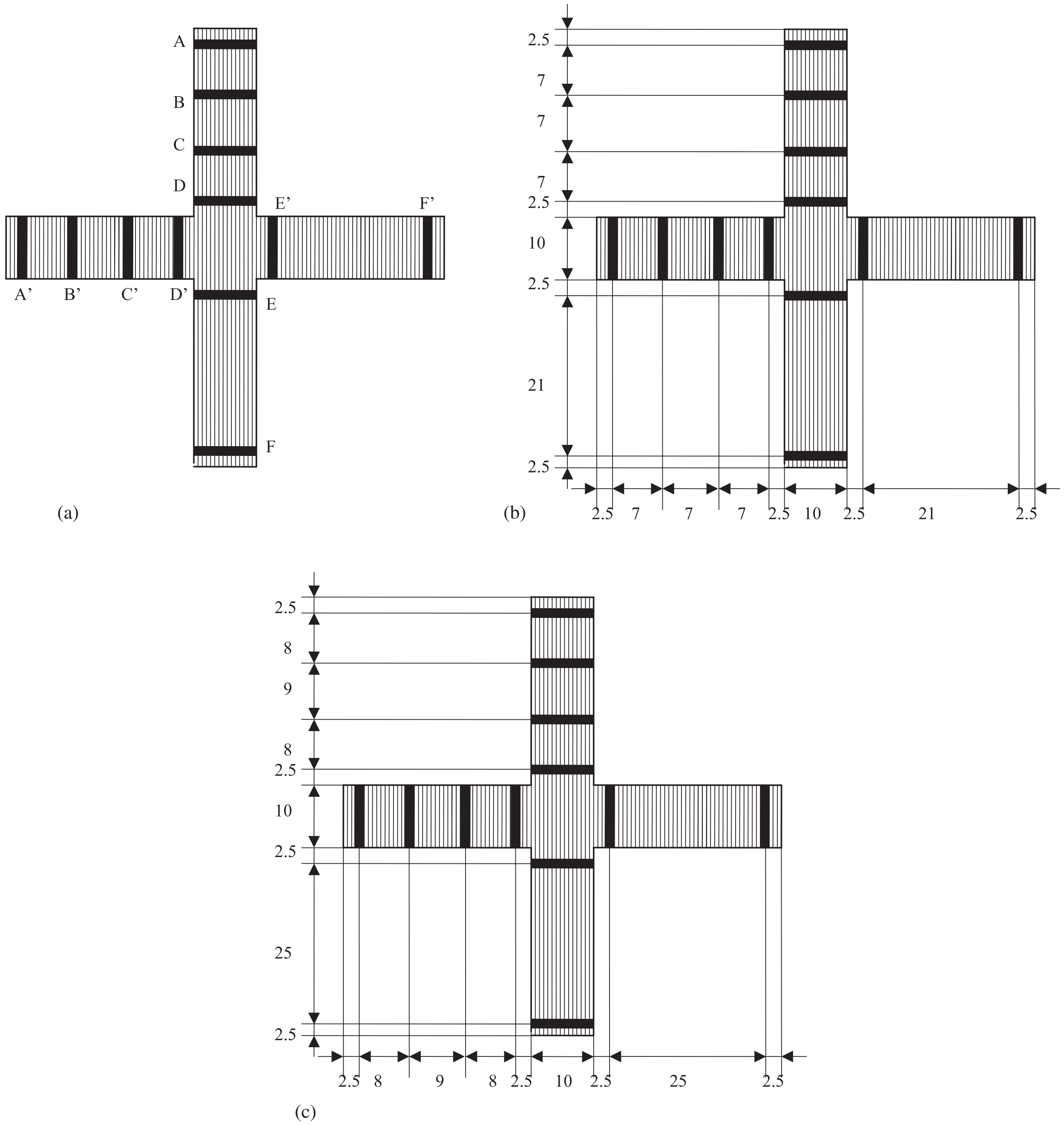

Figure 1. (a) Composite configuration for measuring the volume/surface electrical resistance of the stressed region (the central square) of a quasi-isotropic composite in both the 0° (longitudinal) and 90° (transverse) directions. Contacts A and D are current contacts, while contacts B and C are voltage contacts, for measuring the 0° resistance away from the stressed region (the central square). Contacts A′, B′, C′ and D′ can be used in place of contacts A, B, C and D for the same purpose. Contacts A and F are current contacts, while D and E are voltage contacts, for measuring the 0° resistance at the stressed region. Contacts A′, D′, E′ and F′ can be used in place of contacts A, D, E and F for the same purpose. (b) Dimensions (all in millimeters) for configuration used for volume resistance measurement. All contacts are around the perimeter. (c) Dimensions (all in millimeters) for configuration used for surface resistance measurement. All contacts are on the top surface only.

thin parallel lines indicate the direction of the 0° fibers on the top surface of the quasi-isotropic composite. During testing, compressive stress is applied at the central square of the cross, while electrical resistance is measured using electrical contacts at one or more of the four legs of the cross.

The DC resistance is measured by using the four-probe method. In this method, the outer two contacts are for passing the current, while the inner two contacts are for measuring the voltage. Figure 1 shows the electrical contact configuration for measuring the resistance of the stressed (pressed) region, which is the central square of the cross-shaped specimen and that for measuring the resistance away from the stressed region. For measuring the resistance of the stressed (pressed) region, the contacts are A, D, E and F, with A and F serving as current contacts and D and E serving as voltage contacts, in the case of longitudinal (0°) resistance measurement, and are A′, D′, E′

and F′ in the case of transverse (90°) resistance measurement. For measuring the resistance away from the stressed region, the contacts are A, B, C and D, with A and D serving as current contacts and B and C serving as voltage contacts, in the case of longitudinal resistance measurement, and are A′, B′, C′ and D′ in the case of transverse resistance measurement.

In the case of volume resistance measurement, each of the four electrical contacts is around the entire perimeter of a leg of the cross-shaped specimen. Thus, the electric current emanating from the current contacts penetrates to essentially the entire cross section in the region between the voltage contacts. In the case of surface resistance measurement, all of the four electrical contacts are on one side (i.e. the top side in figure 1(a)). Thus, the current is only in the surface region of the specimen.

All electrical contacts are in the form of silver paint in conjunction with stranded tin-coated copper wire. A Keithley 2002 multimeter (Keithley Instruments Inc., Cleveland, OH) is used for the resistance measurement.

Figure 1(b) gives the dimensions for the volume resistance testing configuration, whereas figure 1(c) gives the dimensions for the surface resistance testing configuration. The two configurations are identical, other than that the specimen legs are slightly shorter in figure 1(b) than figure 1(c). In both cases, the central square region of the square is 10 × 10 mm^2.

Compressive stress is applied on the square region in the center of figure 1(a) via a glass fiber reinforced epoxy piston in the form of a slab of size equal to the square region. The stress was provided by a screw-action mechanical testing system (Sintech 2/D, MTS Systems Corp., Marblehead, MA). The stress was either cycled at a fixed amplitude of 67 MPa or progressively increased (with three cycles conducted at each stress amplitude). The resistance was measured during the stress variation. The longitudinal and transverse resistances were measured essentially simultaneously by digital data acquisition. At least three specimens were tested in terms of the longitudinal and transverse volume resistance and at least three other specimens were tested in terms of the longitudinal and transverse surface resistance, in order to ascertain the general reproducibility of the results reported here.

Because the compressive strain in figure 1 is not measured, the volume resistivity has not been determined. Nevertheless, the measured volume resistance gives valuable information in relation to stress sensing. The surface resistance is less valuable from a scientific point of view, but it is more relevant for practical implementation.

3. Results and discussion

3.1. Under stress cycling

Figure 2(a) shows the longitudinal volume resistance at the stressed region during through-thickness stress cycling at progressively increasing stress amplitudes, with three cycles at each stress amplitude. The resistance decreases reversibly upon loading in each cycle, such that the resistance decrease becomes more significant as the stress amplitude increases. This is due to the increase in the proximity between adjacent laminae upon through-thickness compression, the consequent decrease in the through-thickness resistivity and the still consequent decrease in the in-plane resistivity, as explained in section 1. Figure 2(b) shows the correlation between the fractional change in resistance in a cycle and the stress amplitude up to 67 MPa. The correlation is roughly linear, though the data scatter is substantial.

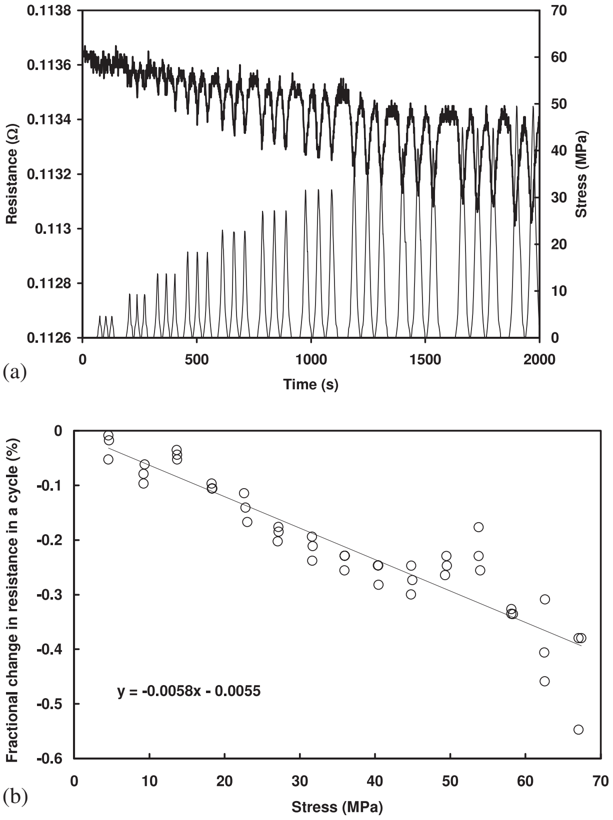

Figure 2. (a) Variation of the longitudinal volume resistance (at the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at progressively increasing stress amplitudes (3 cycles for each amplitude). (b) Variation of the fractional change in longitudinal volume resistance (at the stressed region) in a cycle with the through-thickness compressive stress amplitude.

Figure 3 shows the corresponding results for the longitudinal volume resistance away from the stressed region. The results are similar to those in figure 2, but the resistance variation (figure 3(a)) is more noisy and the correlation between the fractional change in resistance in a cycle and the stress amplitude is weaker (figure 3(b)).

Figure 4 shows the corresponding results for the transverse volume resistance at the stressed region. The results are similar to those in figure 2 for the longitudinal volume resistance at the stressed region.

Figure 5 shows the corresponding results for the transverse volume resistance away from the stressed region. The results are similar to those in figure 3 for the longitudinal volume resistance away from the stressed region.

The results in figures 2–5 mean that self-sensing of the through-thickness stress by resistance measurement is similarly effective for longitudinal and transverse volume resistance. The effectiveness relates to the ability to distinguish between stresses that are close. In other words, it relates

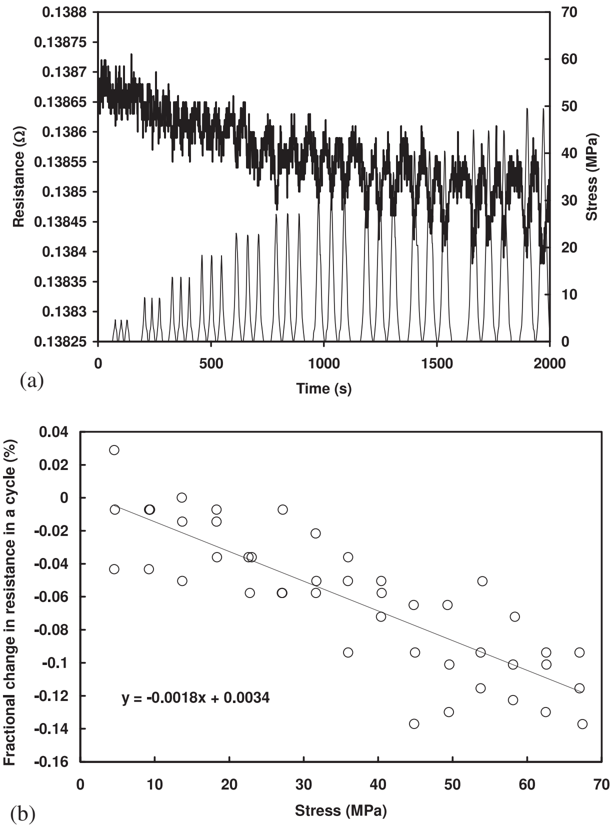

Figure 3. (a) Variation of the longitudinal volume resistance (away from the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at progressively increasing stress amplitudes (3 cycles for each amplitude). (b) Variation of the fractional change in longitudinal volume resistance (away from the stressed region) in a cycle with the through-thickness compressive stress amplitude.

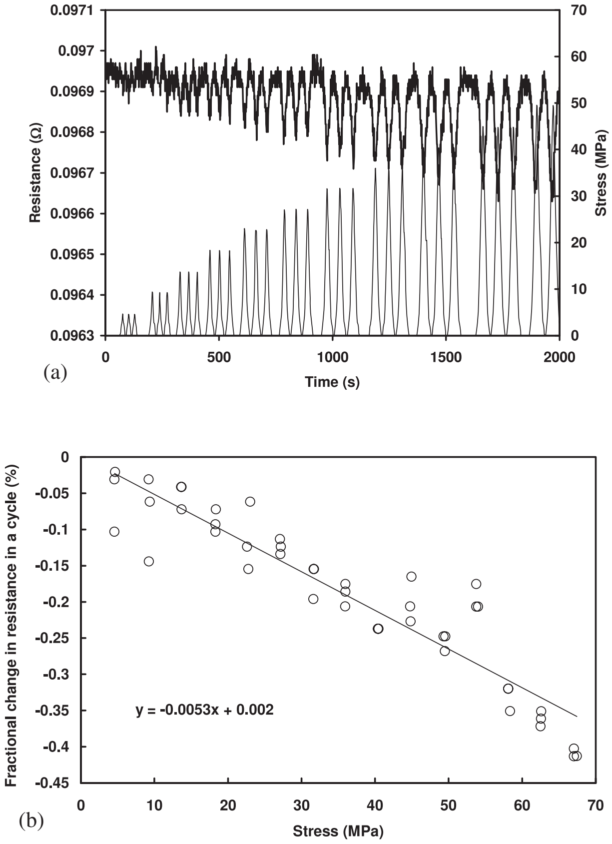

Figure 4. (a) Variation of the transverse volume resistance (at the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at progressively increasing stress amplitudes (3 cycles for each amplitude). (b) Variation of the fractional change in transverse volume resistance (at the stressed region) in a cycle with the through-thickness compressive stress amplitude.

Table 1. The stress sensitivity, i.e. the fractional change in resistance in a cycle per unit stress (10^{-5} MPa^{-1}).

	Longitudinal		Transverse	
	Volume	Surface	Volume	Surface
At the stressed region	-5.8^{a}	-4.4^{a}	-5.3^{a}	d
	-5.6^{b}	-5.6^{b}	-4.8^{b}	d
Away from the stressed region	$-1.8^{a,c}$	-1.6^{b}	$-2.5^{a,c}$	d

[a] Determined from the slope of the plot of fractional change in resistance in a cycle versus stress amplitude.

[b] Determined from the average fractional change in resistance per cycle for a stress amplitude of 67 MPa.

[c] Relatively large scatter in the data in the plot of fractional change in resistance in a cycle versus stress amplitude.

[d] No correlation of resistance with stress within each cycle.

to the resolution. It is indicated by a high value of the fractional change in resistance in a cycle per unit stress (i.e. the magnitude of the slope of the curve in figures 2(b), 3(b), 4(b) or 5(b)) and by a low degree of data scatter in the correlation between resistance and stress, which is superior at the stressed region compared to that away from the stressed region.

Figures 6(a) and (b) show corresponding results for the longitudinal surface resistance at the stressed region. The resistance variation is more noisy than that in figure 2(a) for the longitudinal volume resistance at the stressed region. This means that the volume resistance is a better indicator of the through-thickness stress than the surface resistance.

The transverse surface resistance at the stressed region (figure 7) did not show any systematic variation with the through-thickness stress. The negative observation for the transverse surface resistance is attributed to the dominance of the surface transverse fibers in the resistance measurement. This means that the transverse surface resistance is not able to indicate the through-thickness stress.

The stress sensitivity, as described by the fractional change in resistance in a cycle per unit stress amplitude, is shown in table 1. The stress sensitivity determined from the slope of plots such as figure 2(b) is comparable to that determined from the average of the values for various cycles at a fixed stress amplitude of 67 MPa. The magnitude of the stress sensitivity is higher at the stress region than that away from the stress region, whether the resistance is longitudinal or transverse, and whether the resistance is volume or surface. For the same region, it is comparable for the volume resistance and the surface resistance.

The sensitivity values shown in table 1 are lower in magnitude than the value of about -6×10^{-4} MPa^{-1} associated

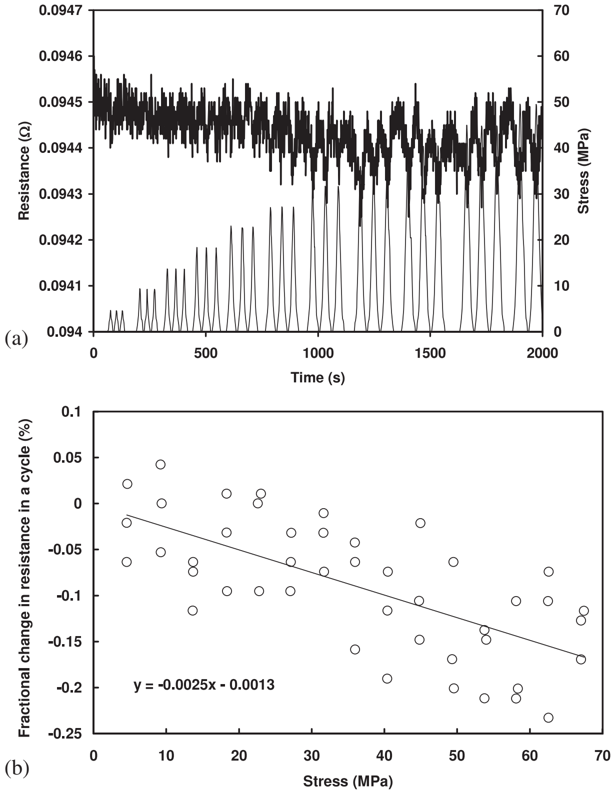

Figure 5. (a) Variation of the transverse volume resistance (away from the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at progressively increasing stress amplitudes (3 cycles for each amplitude). (b) Variation of the fractional change in transverse volume resistance (away from the stressed region) in a cycle with the through-thickness compressive stress amplitude.

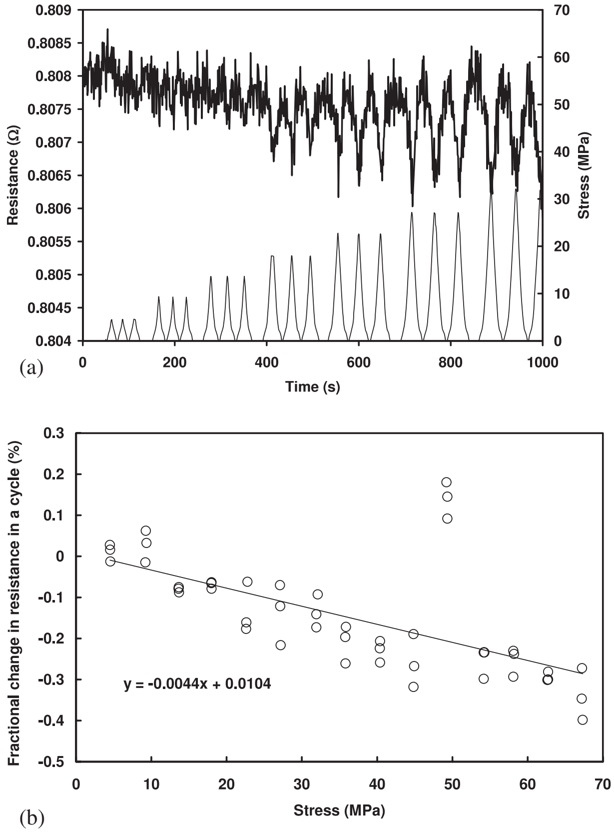

Figure 6. (a) Variation of the longitudinal surface resistance (at the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at progressively increasing stress amplitudes (3 cycles for each amplitude). (b) Variation of the fractional change in longitudinal surface resistance (at the stressed region) in a cycle with the through-thickness compressive stress amplitude.

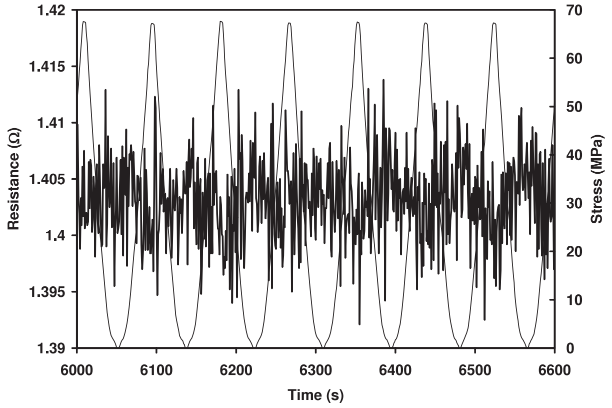

Figure 7. Variation of the transverse surface resistance (at the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at a fixed stress amplitude of 67 MPa.

with the use of the contact resistance of the interlaminar interface to indicate the through-thickness stress [3]. That the interlaminar interface is a better sensor than the overall composite is consistent with the notion that the decrease of the through-thickness resistivity upon through-thickness compression is due to increase in the proximity between the adjacent laminae. Although the interlaminar interface is a better sensor, measurement of the contact resistance of the interlaminar interface requires the making of two electrical contacts to each of the two adjacent laminae [3]. As a consequence, interlaminar interface contact resistance measurement is less amenable to structural implementation than the measurement of the resistance of the overall composite.

Figures 8–11 show the resistance variation during through-thickness stress cycling at a fixed stress amplitude of 67 MPa. The resistance decreases reversibly in every cycle, though there is a slight irreversible decrease in resistance at the end of each cycle. This slightly irreversible behavior is not desirable from the viewpoint of practical stress sensing. Although the behavior up to 80 cycles is shown in figures 8 and 9, behavior up to 200 cycles is shown in figures 10 and 11.

The fractional change in the minimum resistance of a cycle per cycle during stress cycling is listed in table 2. These values are obtained from the data in figures 8–11. The fractional decrease in this resistance is smaller for the volume resistance (whether longitudinal or transverse) than the surface resistance. In other words, the resistance change is more reversible for the volume resistance than the surface resistance. This means

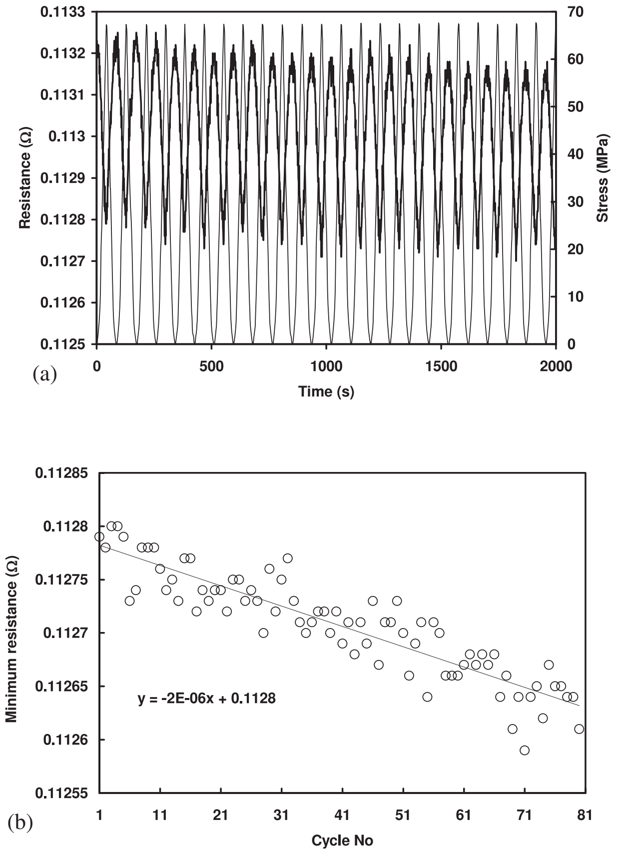

Figure 8. (a) Variation of the longitudinal volume resistance (at the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at a fixed stress amplitude of 67 MPa. (b) Variation of the minimum longitudinal volume resistance (at the stressed region) in a cycle with the cycle number during stress cycling at a fixed stress amplitude of 67 MPa.

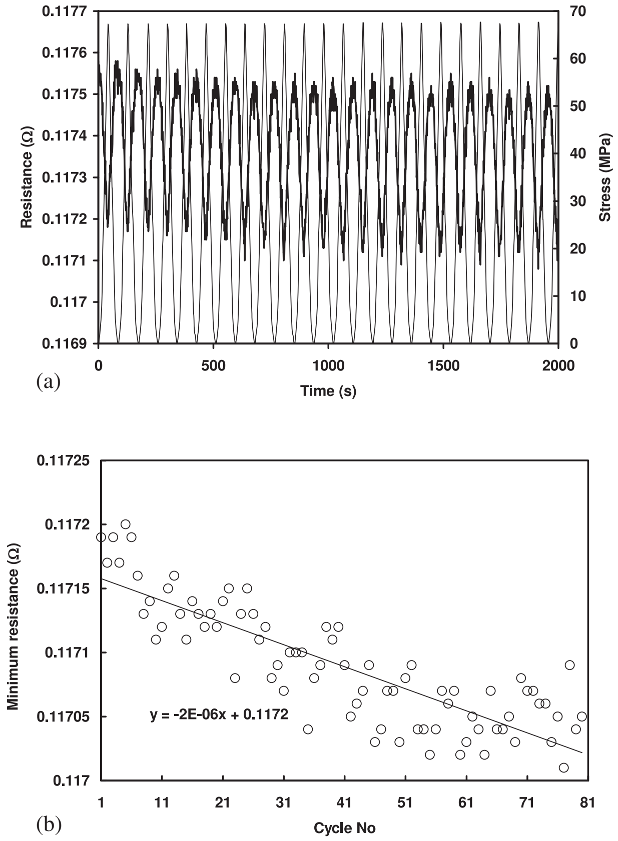

Figure 9. (a) Variation of the transverse volume resistance (at the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at a fixed stress amplitude of 67 MPa. (b) Variation of the minimum transverse volume resistance (at the stressed region) in a cycle with the cycle number during stress cycling at a fixed stress amplitude of 67 MPa.

that the volume resistance is more suitable for accurate stress sensing than the surface resistance.

The fractional decrease in the minimum resistance of a cycle per cycle during stress cycling is smaller away from the stressed region than that at the stressed region (table 2). This gives an attraction for using the resistance away from the stressed region for stress sensing. However, the resistance away from the stressed region is more noisy than that at the stressed region, as shown by comparing figures 10(a) and 11(a).

The partially irreversible effect described in table 2 is attributed to a partially irreversible decrease in the through-thickness resistivity as cycling progresses and the consequent increase in the degree of surface current penetration as cycling progresses. A partially irreversible decrease in the through-thickness resistivity is consistent with prior observation of partially irreversible decrease in the interlaminar contact resistivity during through-thickness compression [3]. The irreversible decrease in through-thickness resistivity is in turn attributed to the irreversible increase in proximity between adjacent laminae. This irreversible effect is small for the longitudinal and transverse volume resistances, because of the essentially complete penetration of the current in volume resistance measurement.

The resistance per unit length prior to loading is listed in table 3. The length is the distance between the voltage contacts in the direction of current application, as measured for each specimen. The thickness (3.2 mm) and width (10 mm) are the same for all the specimens.

The volume resistance per unit length is substantially lower than the surface resistance per unit length for the same direction (whether longitudinal or transverse) (table 3). This is due to the limited degree of current penetration in the depth direction for the surface current used in the surface resistance measurement. As a higher resistance is easier to measure, the higher value of the surface resistance is attractive.

The volume resistance per unit length is comparable in the longitudinal and transverse directions for the same region of the same specimen (table 3). This is consistent with the quasi-isotropic nature of the composite and the essentially complete penetration of the current into the specimen. For the same specimen, the resistance per unit length is lower at the stressed region than the area away from the stressed region (table 3). This is due to current spreading [15, 16] in both the longitudinal and transverse directions at the stressed region. The current spreading decreases the measured resistance.

Away from the stressed region for the same specimen, the surface resistance per unit length is much higher in the

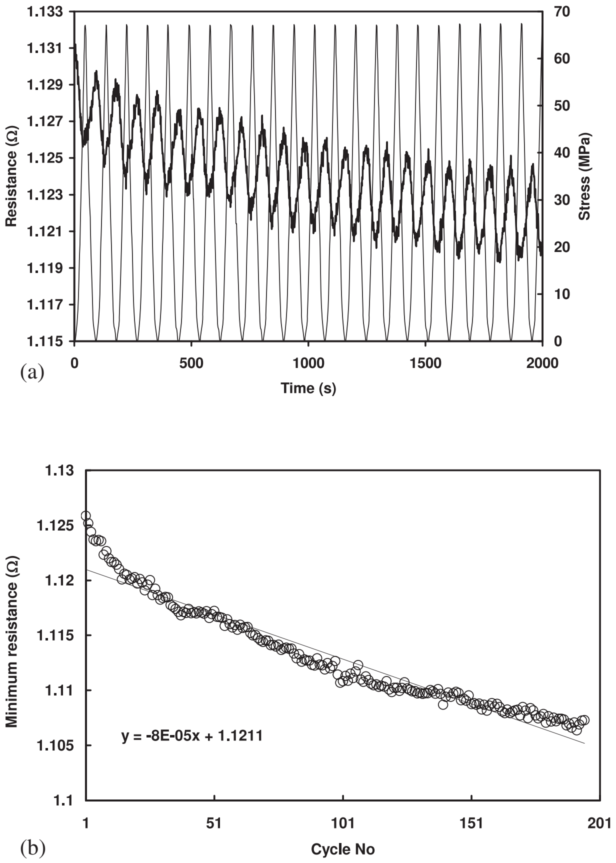

Figure 10. (a) Variation of the longitudinal surface resistance (at the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at a fixed stress amplitude of 67 MPa. (b) Variation of the minimum longitudinal surface resistance (at the stressed region) in a cycle with the cycle number during stress cycling at a fixed stress amplitude of 67 MPa.

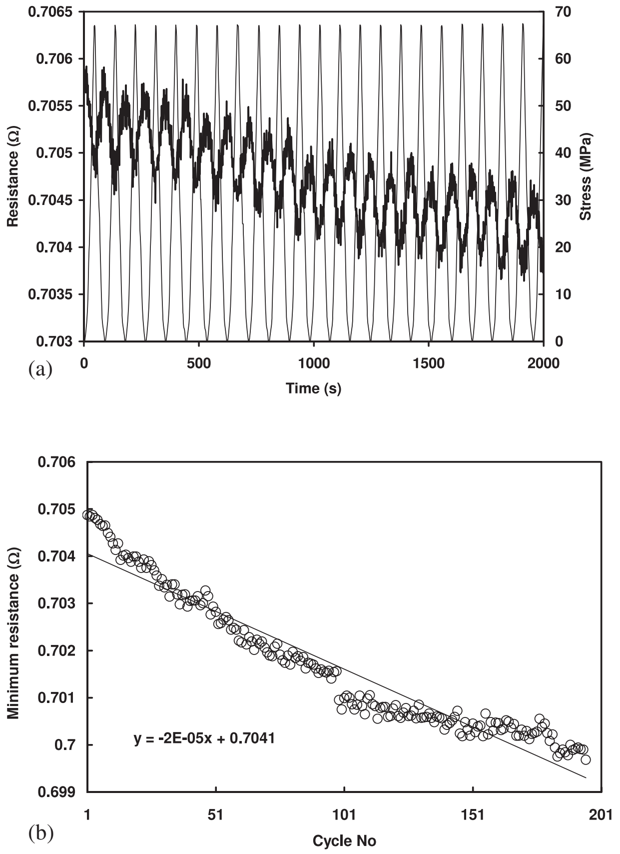

Figure 11. (a) Variation of the longitudinal surface resistance (away from the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during stress cycling at a fixed stress amplitude of 67 MPa. (b) Variation of the minimum longitudinal surface resistance (away from the stressed region) in a cycle with the cycle number during stress cycling at a fixed stress amplitude of 67 MPa.

Table 2. Fractional change (10^{-5}) in minimum resistance per cycle during cyclic loading at a fixed stress amplitude of 67 MPa.

	Longitudinal		Transverse	
	Volume	Surface	Volume	Surface
At the stressed region	−2	−7	−2	[a]
Away from the stressed region	/	−3	/	[a]

[a] No correlation of resistance with stress within each cycle.

transverse direction than the longitudinal direction (table 3). This is due to the high resistivity of the surface lamina in the transverse direction. At the stressed region for the same specimen, the surface resistance per unit length is relatively close to one another, such that the longitudinal resistance per unit length may be lower or higher than the transverse resistance per unit length (table 3). This is due to the extensive current spreading of the transverse current in the longitudinal direction at the stressed region and the consequent decrease of the measured transverse resistance. The current spreading is less in the transverse direction (figure 12), so the longitudinal surface resistance is less affected by current

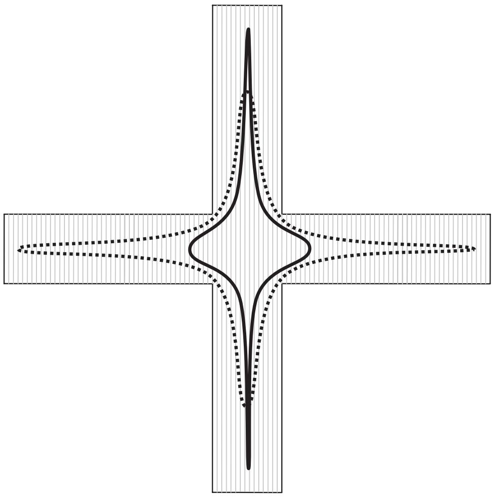

Figure 12. Current spreading in a cross-shaped specimen. The fibers of the surface lamina are along the parallel thin solid lines. Bold solid line: current applied in the longitudinal direction spreading slightly in the transverse direction. Dotted line: current applied in the transverse direction spreading extensively in the longitudinal direction.

Table 3. Resistance per unit length ($\Omega\ m^{-1}$) prior to loading. The length is the distance between the voltage contacts in the direction of current application, as measured for each specimen. The thickness (3.2 mm) and width (10 mm) are the same for all the specimens.

	Longitudinal		Transverse	
	Volume	Surface	Volume	Surface
At the stressed region	7.10^{a}	42.53^{d}	6.06^{a}	74.75^{d}
	7.08^{b}	42.53^{e}	7.35^{b}	75.00^{e}
	4.60^{c}	44.89^{f}	4.81^{c}	78.73^{f}
		60.88^{g}		89.69^{g}
		61.91^{h}		89.49^{h}
		102.04^{i}		47.32^{i}
		91.15^{j}		53.73^{j}
		65.65^{k}		48.22^{k}
Away from the stressed region	19.81^{a}	135.36^{i}	13.50^{a}	697.67^{i}
		89.91^{j}		589.60^{j}
		70.18^{k}		630.72^{k}

[a] Specimen a.
[b] Specimen b.
[c] Specimen c.
[d] Specimen d.
[e] Specimen e.
[f] Specimen f.
[g] Specimen g.
[i] Specimen i.
[j] Specimen j.
[k] Specimen k.
[h] Specimen h.

spreading than the transverse surface resistance. In the absence of current spreading, the transverse surface resistance per unit length is higher than the longitudinal surface resistance per unit length, as shown by the fact that the transverse surface resistance per unit length is much higher than the longitudinal surface resistance per unit length away from the stressed region (table 3). However, the current spreading at the stressed region decreases the measured transverse surface resistance for this region, thereby making the surface resistance to be comparable in the longitudinal and transverse directions. Due to the variability in the extent of fiber alignment among specimens (even though they all come from the same laminate), the extent of current spreading varies among the specimens, thereby causing the surface transverse resistance per unit length to exceed the surface longitudinal resistance per unit length for some specimens and vice versa for the other specimens.

In spite of the variability of the surface resistance prior to loading among specimens, the surface longitudinal resistance varies in a systematic way with the stress, thus allowing stress sensing. This variability means that the surface resistance prior to loading needs to be measured for each area of a composite structure prior to implementing the stress sensing technology to the different areas. It is the fractional change in resistance (table 1) rather than the resistance itself that relates to the stress.

The variability of the volume resistance prior to loading among specimens is small compared to that for the surface resistance (table 3). Nevertheless, the volume resistance prior to loading should be measured for each area of a composite prior to implementing the stress sensing technology.

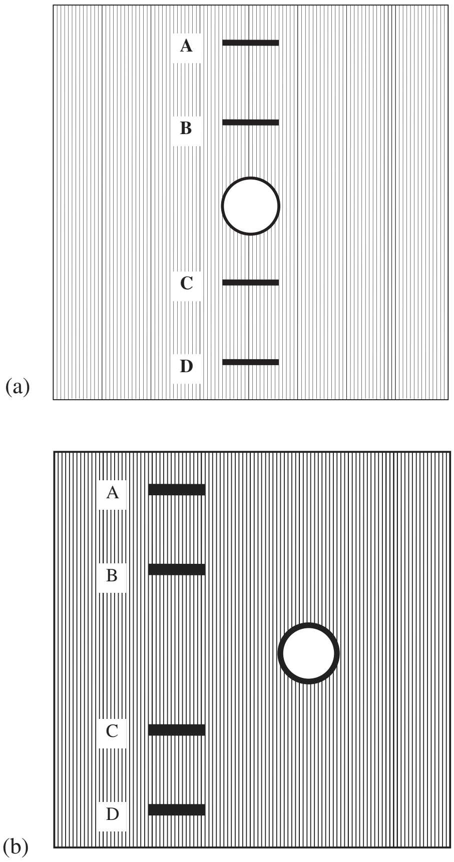

Figure 13. Possible electrical contact configuration for implementing the stress sensing technology to a composite sheet. The circle is the stressed region. The longitudinal surface resistance is measured. The fibers of the surface lamina are along the thin parallel lines. The four electrical contacts (A, B, C and D, with A and D being current contacts and B and C being voltage contacts) are indicated by the four thick lines, which are perpendicular to the fibers of the surface lamina. (a) Measuring the resistance at the stressed region. (b) Measuring the resistance away from the stressed region.

The surface transverse resistance does not vary systematically with the stress (figure 7), due to the absence of longitudinal surface fibers in the transverse direction. Hence, the data in the last column of table 3 are not useful for stress sensing.

In practical implementation of the sensing technology, the composite is a sheet rather than being in the shape of a cross (figure 1). In figure 1, each electrical contact is a line that extends across the entire width of the specimen. For a composite sheet that is not cross-shaped, the four electrical contacts may be in the form of four parallel lines, each of which is not all the away across the width of the laminate, as illustrated in figure 13. As a consequence of this contact configuration for a composite sheet, current spreading is bound to occur, both for the stressed region (figure 13(a)) and the area away from the stressed region (figure 13(b)). The stressed region is indicated by a circle in figure 13. In contrast, for the cross-shaped specimen of this work, current spreading occurs at the stressed region only, due to the stress being applied at the central square of the cross. Thus, for the case of a composite sheet (figure 13), the measured resistance (whether volume resistance or surface resistance) will be decreased by the current spreading, whether the resistance is measured at the stressed region or not.

As expected, the absence of fiber spreading in a quasi-isotropic composite (this work) under through-thickness compression makes the in-plane resistance variation much simpler than that in a unidirectional composite (prior work) [4]. The simplicity makes practical application of the stress sensing technique feasible.

The results of this work mean that practical through-thickness stress self-sensing can be effectively attained by volume or surface resistance measurement. In the case of surface resistance measurement, the resistance should be measured in the direction of the surface fibers. In the case of volume resistance measurement, the resistance can be measured in essentially any in-plane direction. The surface resistance method is more convenient for practical implementation than the volume resistance method, but it is complicated by greater noise, the slightly irreversible decrease of the longitudinal surface resistance upon through-thickness compression, and the greater variability of the resistance from area to area in the same laminate.

4. Conclusion

Through-thickness stress self-sensing in a quasi-isotropic carbon fiber epoxy–matrix composite by in-plane electrical resistance measurement is effective. The variation of the resistance with stress is much simpler than the previously reported case of a unidirectional composite, which suffers from complication due to fiber spreading upon compression.

The in-plane resistance of the quasi-isotropic composite decreases reversibly upon through-thickness compression conducted up to 67 MPa, due to increase in proximity between adjacent laminae. The sensing can be attained by measuring the surface resistance in the direction of the surface fibers or by measuring the volume resistance in essentially any in-plane direction. Compared to the longitudinal or transverse volume resistance, the longitudinal surface resistance is higher, noisier and more variable for different areas of the same laminate (due to its sensitivity to current spreading). The sensing is ineffective if the transverse surface resistance is the quantity measured, due to the dominance of the surface fibers in governing the surface resistance. In the case of the longitudinal surface resistance, the decrease in resistance upon compression has a slight irreversible component. This irreversible effect is due to irreversible increase in the proximity between adjacent laminae and the consequent increase in the degree of current penetration. This effect is smaller for the longitudinal or transverse volume resistance.

The longitudinal surface resistance away from the stressed region allows stress sensing, though it is not as sensitive as that at the stressed region. The sensitivity, as described by the fractional change in volume resistance per unit through-thickness compressive stress, is lower in magnitude than the value previously reported for sensing based on measurement of the contact resistance of the interlaminar interface.

References

[1] Investigation of the Crash of American Airlines Flight 587 http://www.airsafe.com/events/aa587.htm

[2] Wang S, Kowalk D P and Chung D D L 2002 Effects of the temperature, humidity and stress on the interlaminar interface of carbon fiber polymer–matrix composites, studied by contact electrical resistivity measurement *J. Adhes.* **78** 189–200

[3] Wang S, Kowalk D P and Chung D D L 2004 Self-sensing attained in carbon fiber polymer–matrix structural composites by using the interlaminar interface as a sensor *Smart Mater. Struct.* **13** 570–92

[4] Leong C, Wang S and Chung D D L 2006 Effect of through-thickness compression on the microstructure of carbon fiber polymer–matrix composites, as studied by electrical resistance measurement *J. Mater. Sci.* **41** 2877–84

[5] Chung D D L 2001 Continuous carbon fiber polymer–matrix composites and their joints, studied by electrical measurements *Polym. Compos.* **22** 250–70

[6] Wang S and Chung D D L 2007 Negative piezoresistivity in continuous carbon fiber epoxy–matrix composite *J. Mater. Sci.* at press

[7] Wang S and Chung D D L 2006 Self-sensing of flexural strain and damage in carbon fiber polymer–matrix composite by electrical resistance measurement *Carbon* **44** 2739–51

[8] Schulte K and Baron Ch 1989 Load and failure analyses of CFRP laminates by means of electrical resistivity measurements *Compos. Sci. Technol.* **36** 63–76

[9] Todoroki A and Yoshida J 2004 Electrical resistance change of unidirectional CFRP due to applied load *JSME Int. J.* **47** 357–64

[10] Todoroki A and Yoshida J 2005 Apparent negative piezoresistivity of single-ply CFRP due to poor electrical contact of four-probe method *Key Eng. Mater.* **297–300** 610–5

[11] Wang S and Chung D D L 2005 The interlaminar interface of a carbon fiber epoxy–matrix composite as an impact sensor *J. Mater. Sci.* **40** 1863–7

[12] Wang S, Chung D D L and Chung J H 2005 Impact damage of carbon fiber polymer–matrix composites, monitored by electrical resistance measurement *Composites* A **36** 1707–15

[13] Wang S, Wang D, Chung D D L and Chung J H 2006 Method of sensing impact damage in carbon fiber polymer–matrix composite by electrical resistance measurement *J. Mater. Sci.* **41** 2281–9

[14] Wang D, Wang S, Chung D D L and Chung J H 2006 Comparison of the electrical resistance and potential techniques for the self-sensing of damage in carbon fiber polymer–matrix composites *J. Intell. Mater. Syst. Struct.* **17** 853–61

[15] Wang D, Wang S, Chung D D L and Chung J H 2006 Sensitivity of the two-dimensional electric potential/resistance method for damage monitoring in carbon fiber polymer–matrix composite *J. Mater. Sci.* **41** 4839–46

[16] Wang S, Chung D D L and Chung J H 2005 Self-sensing of damage in carbon fiber polymer–matrix composite by measurement of the electrical resistance or potential away from the damaged region *J. Mater. Sci.* **40** 6463–72

[17] Abry J C, Choi Y K, Chateauminois A, Dalloz B, Giraud G and Salvia M 2001 *In situ* monitoring of damage in CFRP laminates by means of ac and dc measurements *Compos. Sci. Technol.* **61** 855–64

[18] Todoroki A, Tanaka M and Shimamura Y 2005 Electrical resistance change method for monitoring delaminations of CFRP laminates: effect of spacing between electrodes *Compos. Sci. Technol.* **65** 37–46

[19] Todoroki A, Tanaka Y and Shimamura Y 2004 Multi-prove electric potential change method for delamination monitoring of graphite/epoxy composite plates using normalized response surfaces *Compos. Sci. Technol.* **64** 749–58

[20] Todoroki A and Ueda M 2006 Low-cost delamination monitoring of CFRP beams using electrical resistance changes with neural networks *Smart. Mater. Struct.* **15** N75–84

[21] Kang J H, Paty S, Kim R Y and Tandon G P 2006 Self-diagnosis of damage in fibrous composites using electrical resistance measurements *Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure V*; *Proc. SPIE* **6176** 617602

[22] Xia Z, Okabe T, Park J B, Curtin W A and Takeda N 2003 Quantitative damage detection in CFRP composites: coupled mechanical and electrical models *Compos. Sci. Technol.* **63** 1411–22

[23] Chung D D L 2007 Damage detection using self-sensing concepts *J. Aerosp. Eng.* G at press