

Provided for non-commercial research and education use.  
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

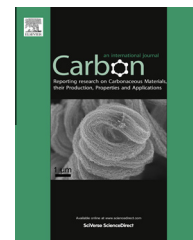
Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/authorsrights>

Available at [www.sciencedirect.com](http://www.sciencedirect.com)

SciVerse ScienceDirect

journal homepage: [www.elsevier.com/locate/carbon](http://www.elsevier.com/locate/carbon)

# Through-thickness piezoresistivity in a carbon fiber polymer-matrix structural composite for electrical-resistance-based through-thickness strain sensing

Daojun Wang, D.D.L. Chung \*

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

## ARTICLE INFO

### Article history:

Received 11 January 2013

Accepted 3 April 2013

Available online 10 April 2013

## ABSTRACT

Piezoresistivity (change of the volume electrical resistivity with strain) in continuous carbon fiber polymer-matrix structural composites allows electrical-resistance-based strain/stress sensing. Uniaxial through-thickness compression is encountered in fastening. As shown for a 24-lamina quasi-isotropic epoxy-matrix composite, compression results in (i) strain-induced reversible decreases in through-thickness and longitudinal volume resistivities, due to increase in the degree of through-thickness fiber–fiber contact, and (ii) minor-damage-induced irreversible changes in these resistivities, due to a microstructural change involving an irreversible through-thickness resistivity increase and an irreversible longitudinal resistivity decrease. The Poisson effect plays a minor role. The effects in the longitudinal resistivity are small compared to those in the through-thickness direction, but longitudinal resistance measurement is more practical. The through-thickness gage factor (reversible fractional change in resistance per unit strain) ranges from 2.6 to 5.1 and the reversible fractional change in through-thickness resistivity per unit through-thickness strain ranges from 1.5 to 4.0, both quantities decreasing with increasing strain magnitude from 0.19% to 0.73% due to the increasing irreversible effect. The irreversible fractional change in through-thickness resistivity per unit through-thickness strain ranges from  $-1.0$  to  $-1.3$  and is strain independent. The effects are consistent with the surface resistance changes previously reported for the same material under flexure.

© 2013 Elsevier Ltd. All rights reserved.

## 1. Introduction

Piezoresistivity refers to the reversible change in volume electrical resistivity with strain. This phenomenon is useful for electrical-resistance-based sensing of reversible strain.

The sensing of strain and damage of a structure is practically important for load monitoring, operation control, structural vibration control and structural health monitoring. From the scientific viewpoint, strain rather than stress is the parameter that affects a structure, but strain is a consequence

of stress application. Moreover, strain and stress are simply related in the elastic regime through the modulus of elasticity. Therefore, strain sensing allows stress sensing if the deformation is in the elastic regime.

In the elastic regime, strain is reversible. In case of a metal, elastic strain typically involves a change in the interatomic distance. In case of a composite material, elastic strain can involve more complicated geometric effects, such as a change in the degree of contact among the reinforcing units (such as fibers) in the composite. In some materials, particularly

\* Corresponding author. Fax: +1 716 645 2883.

E-mail address: [ddlchung@buffalo.edu](mailto:ddlchung@buffalo.edu) (D.D.L. Chung).

URL: <http://alum.mit.edu/www/ddlchung> (D.D.L. Chung).

0008-6223/\$ - see front matter © 2013 Elsevier Ltd. All rights reserved.

<http://dx.doi.org/10.1016/j.carbon.2013.04.005>

composite materials, strain can cause a partly irreversible change in the microstructure even if it is in the elastic regime. The irreversible change in the microstructure does not necessarily cause damage in the sense of mechanical property degradation, but it may serve as a warning for damage prior to the occurrence of the damage.

An example of a microstructural change is a change in the degree of fiber–fiber contact in a fibrous composite. The fiber–fiber contact stems from the fiber waviness and the consequent presence of points at which a fiber is locally in electrical contact with an adjacent fiber, as illustrated in Fig. 1. The electrical contact, which is to be distinguished from an actual physical contact, allows the tunneling of electrons from one fiber to another, thus resulting in percolative conduction. Tunneling requires the adjacent fibers to be separated by a sufficiently small distance (of the order of Angstroms) at the contact point. A statistical increase in the number of contact points may occur during loading (such as compression in the direction perpendicular to the general direction of the fibers) due to a very slight increase (as small as a few Angstroms) in the proximity between the adjacent fibers. This can cause a decrease in the resistivity in the direction perpendicular to the general direction of the fibers. In this paper, an increase in the number of contact points is referred to as an increase in the degree of fiber–fiber contact.

The effects of loading on the degree of fiber–fiber contact have been previously reported, as described below. For a carbon fiber epoxy-matrix composite, the contact electrical resistivity of the interlaminar interface decreases upon through-thickness compression, due to an increase in the degree of through-thickness fiber–fiber contact across the interface [1]. During flexure, one surface is under longitudinal tension while the opposite surface is under longitudinal compression. The through-thickness resistivity decreases in the compressive surface region of a composite beam upon flexure, due to an increase in the degree of through-thickness fiber–fiber contact in this region; the through-thickness resistivity in-

creases in the tensile surface region upon flexure, due to a decrease in the degree of through-thickness fiber–fiber contact in this region [2,3]. During uniaxial tension in the longitudinal (fiber) direction, the transverse resistivity increases, due to a decrease in the degree of transverse fiber–fiber contact [4].

A change in the degree of fiber–fiber contact can be reversible and/or irreversible, thereby causing a reversible and/or irreversible resistivity change. For example, the partial irreversibility of a resistivity decrease can occur, due to a partially irreversible decrease in the degree of fiber–fiber contact. In the case of a carbon fiber epoxy-matrix composite, partial irreversibility of the decrease of the contact resistivity of the interlaminar interface occurs at a through-thickness compressive stress as low as 1 MPa [1].

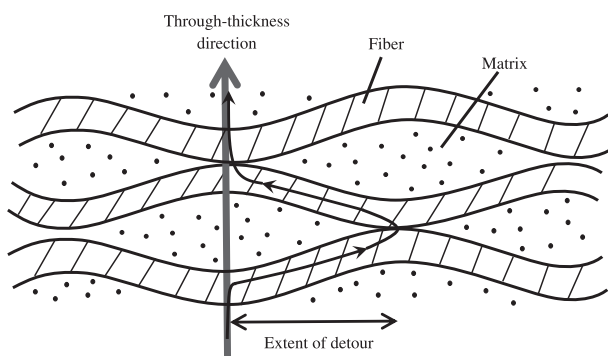
Beyond the elastic regime (i.e., in the plastic regime), strain is only partly reversible, so the irreversible effects become more severe. Moreover, in the plastic regime, damage associated with mechanical property degradation occurs with more likelihood than in the elastic regime. As the stress increases in the plastic regime, the damage becomes increasingly severe and eventually results in fracture.

The sensing of all stages of deformation is valuable both for fundamental science and for technologies related to smart structures. The science pertains to the mechanism of strain, the mechanism of formation and build-up of damage, and the evolution of the damage from inception to failure. Sensing is the most basic function of a smart structure, which refers to a structure that can sense and respond to the sensed information in an appropriate fashion.

The most conventional approach for strain/damage sensing involves the embedment or attachment of a sensor, such as a fiber-optic sensor, a piezoelectric sensor and an acoustic sensor. This approach is costly due to the high cost of the sensors compared to the structural material. It also suffers from low durability, due to the tendency for attached sensors to be detached during extended use and the difficulty of repairing embedded sensors. Moreover, in case of embedded sensors, it suffers from loss of the mechanical properties of the structure.

A less conventional approach involves the use of the structural material itself as the sensor. This approach is known as self-sensing, as the structure senses itself. It does not require the use of any embedded or attached sensor, so it does not suffer from any of the problems mentioned above in relation to the use of embedded or attached sensors. However, not all structural materials can function as a sensor and the science behind the self-sensing is not well-developed yet.

Self-sensing can be conveniently achieved by the measurement of the electrical resistance of the structural material, provided that the resistance change correlates with the strain and/or damage. Resistance measurement mainly involves the use of electrical contacts and a meter, which is portable, so field implementation of the technology is relatively simple. However, electrical-resistance-based sensing is not feasible when the material is too low or too high in the electrical resistance. In case that the resistance is very low, as in the case of metals, the change in resistance is usually too small for accurate sensing. In case that the resistance is very high, as in the case of ceramics, the resistance measurement is technically difficult. Thus, an intermediate level of electrical resistivity is optimal. Carbon fiber polymer-matrix



**Fig. 1 – Schematic illustration of the electrical conduction path associated with through-thickness conduction behavior. The dotted regions are the matrix. The hatched regions are the fibers. Thick line: through-thickness direction. Thin line: a current path through fiber–fiber contacts. At a contact point, the fibers are separated by a distance (of the order of Angstroms) that is small enough for electrons to hop from one fiber to the adjacent fiber by tunneling. The degree of fiber waviness is exaggerated.**

composites are particularly suitable, because carbon fibers are intermediate in resistivity and, due to the fact that the polymer matrix is not conductive, the resistivity of the composite is sensitive to the fiber arrangement, which is affected by the strain and/or damage of the composite. Moreover, carbon fiber polymer-matrix composites are technologically important for lightweight structures, such as aircraft, due to their low density, high elastic modulus and high strength. Sensing (or monitoring) is important for aircraft for the purpose of transportation safety.

The effectiveness of electrical-resistance-based sensing of strain and damage has been reported for a 24-lamina quasi-isotropic carbon fiber epoxy-matrix composite under flexure [2–4], as shown by measuring the surface resistance of the tension/compression surface of the composite beam during flexure. An analytical model of the sensing under flexure has been developed [5], based on the notion that flexure affects the through-thickness resistivity in the surface region.

Through-thickness compression is relevant to fastening, which is a common method of joining composite components. An example is the fastened joint between the tail and the body of an aircraft. Stress monitoring of a fastened joint is valuable for joint integrity monitoring, which is a part of the structural health monitoring of the overall structure.

Through-thickness compression of the same 24-lamina composite mentioned above in relation to flexural testing [2] has been shown to cause decrease in the longitudinal resistance, which is easier to measure than the through-thickness resistance (due to the small thickness of the composite) [6]. For a unidirectional composite, which is not used for high-performance structures, the effectiveness of the sensing is lower, with relatively complex resistance changes, due to the spreading of the unidirectional fibers from one another under through-thickness compression [7]. However, due to the absence of measurement of the through-thickness resistance during through-thickness compression in the prior work [6,7], the through-thickness piezoresistivity could not be adequately characterized.

The effect of through-thickness compression on the contact electrical resistivity of the interlaminar interface of a carbon fiber polymer-matrix composite has been reported [1], but the absence of measurement of the through-thickness resistance of the composite makes the through-thickness piezoresistivity inadequately characterized. Electrical-resistance-based sensing of damage due to impact in the through-thickness direction of carbon fiber polymer-matrix composites has been reported [8,9], but this does not involve the sensing of strain and, as a consequence, does not address piezoresistivity. Flexural damage sensing by through-thickness resistance measurement has also been reported [10], but this does not involve the sensing of strain and, as a consequence, does not address piezoresistivity.

The piezoresistive effect of carbon fiber polymer-matrix composites during uniaxial longitudinal tensile loading has been studied by numerous workers [11–17]. During longitudinal loading, both the longitudinal resistance and the through-thickness resistance have been measured. However, this is to be distinguished from piezoresistivity that stems from the application of a stress in the through-thickness direction, as addressed in this paper.

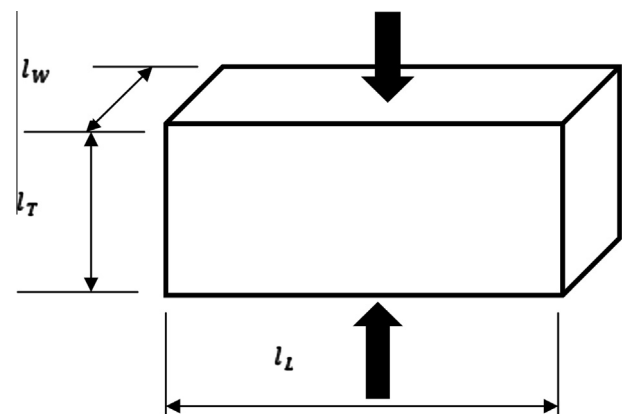
The carbon fiber polymer-matrix composite studied in this work is a conventional commercially manufactured material. The sensing technology of this work does not require any modification of the composite. This is in contrast of approaches which involve modifications such as the addition of carbon nanotubes [18] or nickel nanoparticles [19].

The objectives of this paper are (i) to extend the technology of electrical-resistance-based strain/stress/damage self-sensing of carbon fiber polymer-matrix composites from uniaxial longitudinal (in-plane) loading and flexural loading to uniaxial through-thickness loading, and (ii) to address the science behind the through-thickness piezoresistivity, with attention on the effects of through-thickness stress on the through-thickness and longitudinal resistivities.

## 2. Analytical models

This section describes analytical models that relate the through-thickness stress input to the electrical, strain and damage effects. The electrical effects include the through-thickness and longitudinal electrical resistivities. The strain includes the through-thickness, longitudinal (in-plane) and transverse (in-plane) strains. Strain without damage is associated with a reversible change in the resistivity. In contrast, damage is associated with an irreversible change in the resistivity. In this work, damage pertains to minor subtle damage that includes irreversible microstructural changes. The models are useful for analyzing the experimental results for (i) determining the quantities that describe the effects of strain and damage on the electrical resistivity and (ii) converting the measured resistance change to resistivity change.

As illustrated in Fig. 2, the specimen dimensions are  $l_T$ ,  $l_W$  and  $l_L$  for the through-thickness, width and length directions respectively. Let  $R_L$  and  $R_T$  be the volume resistance in the longitudinal and through-thickness directions respectively. Let  $\rho_L$  and  $\rho_T$  be the volume resistivity in the longitudinal and through-thickness directions respectively. Let  $\varepsilon_T$ ,  $\varepsilon_W$  and  $\varepsilon_L$  be the strain in the through-thickness, width and longitudinal directions respectively. Let  $\nu$  be the Poisson ratio  $\nu_{31}$ , where the subscript 3 signifies the through-thickness direction and



**Fig. 2 – Schematic illustration of the composite specimen, showing the through-thickness stress (thick arrows) and the composite dimensions. The laminae are in the plane perpendicular to the stress.**

the subscript 1 signifies the longitudinal direction. For the quasi-isotropic composite studied, the longitudinal and transverse directions are equivalent under through-thickness stress application. The Poisson ratio thus is given by

$$\nu = -\frac{\varepsilon_L}{\varepsilon_T} \quad (1)$$

In general, the resistance/resistivity (whether through-thickness or longitudinal) changes upon stress application, such that the change due to reversible strain is reversible and the change due to damage is irreversible. Thus, distinction of the reversible and irreversible effects allows the sensing of both strain and damage.

### 2.1. Strain effect

Let  $\alpha$  be the proportionality constant that relates the fractional reversible change in through-thickness resistivity (i.e., the reversible change in the resistivity divided by the resistivity prior to loading in the loading cycle under consideration) and the through-thickness strain, as defined by the equation

$$\left(\frac{\Delta\rho_T}{\rho_T}\right)_{\text{Reversible}} = \alpha\varepsilon_T \quad (2)$$

In other words,  $\alpha$  (hereby referred to as the strain coefficient) describes the severity of the effect of through-thickness strain on the through-thickness resistivity.

Since the resistance is related to the resistivity and the dimensions, the through-thickness resistance  $R_T$  is given by

$$R_T = \frac{\rho_T l_T}{A} = \frac{\rho_T l_T}{l_w l_L} \quad (3)$$

By taking the derivative, Eq. (3) gives

$$\frac{\Delta R_T}{R_T} = \frac{\Delta\rho_T}{\rho_T} + \varepsilon_T - \varepsilon_L - \varepsilon_w = \frac{\Delta\rho_T}{\rho_T} + \varepsilon_T - 2\varepsilon_L \quad (4)$$

Combination of Eq. (1) and (4) gives

$$\begin{aligned} \frac{\Delta R_T}{R_T} &= \frac{\Delta\rho_T}{\rho_T} + \varepsilon_T - \varepsilon_L - \varepsilon_w = \frac{\Delta\rho_T}{\rho_T} + \varepsilon_T - 2\varepsilon_L \\ \frac{\Delta R_T}{R_T} &= \frac{\Delta\rho_T}{\rho_T} + \varepsilon_T(1 + 2\nu) \end{aligned} \quad (5)$$

Combination of Eqs. (2) and (5) gives

$$\frac{\Delta R_T}{R_T} = \varepsilon_T(1 + \alpha + 2\nu) \quad (6)$$

Rearrangement gives

$$\varepsilon_T = \frac{\left(\frac{\Delta R_T}{R_T}\right)}{1 + \alpha + 2\nu} \quad (7)$$

Similarly, the longitudinal resistance is given by

$$R_L = \frac{\rho_L l_L}{A} = \frac{\rho_L l_L}{l_w l_T} \quad (8)$$

where  $A = l_w l_T$  is the area perpendicular to the longitudinal direction. Taking the derivative gives

$$\frac{\Delta R_L}{R_L} = \frac{\Delta\rho_L}{\rho_L} - \varepsilon_T \quad (9)$$

Combination of Eqs. (7) and (9) gives

$$\frac{\Delta R_L}{R_L} = \frac{\Delta\rho_L}{\rho_L} - \frac{\left(\frac{\Delta R_T}{R_T}\right)}{1 + \alpha + 2\nu} \quad (10)$$

### 2.2. Damage effect

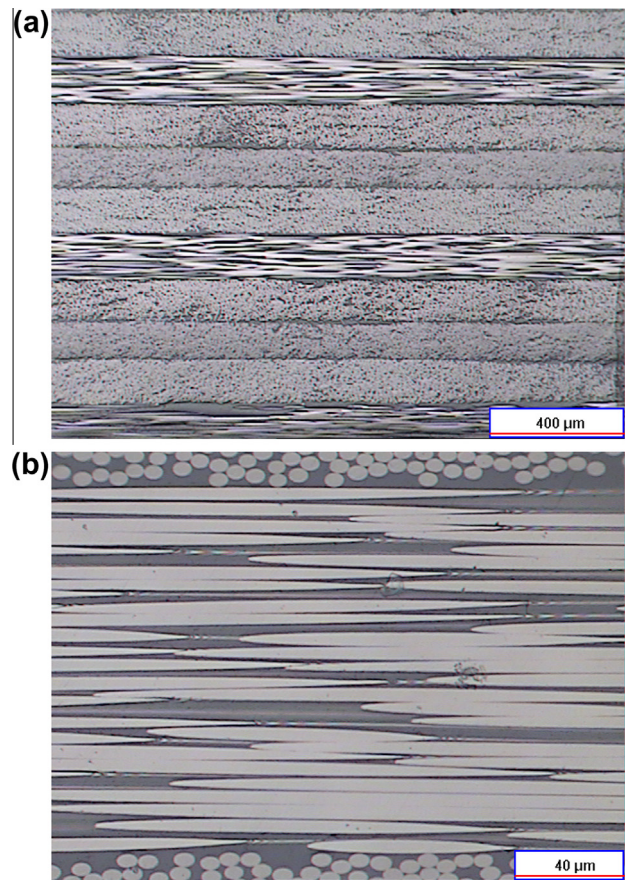
Let  $\beta$  be the proportionality constant that relates the irreversible fractional change in through-thickness resistivity (i.e., the irreversible change in the resistivity divided by the resistivity prior to loading in the loading cycle under consideration) and the through-thickness strain, as defined by the equation

$$\left(\frac{\Delta\rho_T}{\rho_T}\right)_{\text{Irreversible}} = \beta\varepsilon_T \quad (11)$$

Eqs. (3)–(10) apply, provided that  $\alpha$  is changed to  $\beta$  and the fractional changes in resistance and in resistivity are all in terms of the irreversible changes.

## 3. 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  $\mu\text{m}$ , 12,000 fibers per tow) and 977-3 epoxy (CYCOM, toughened epoxy resin with a curing temperature of 177  $^{\circ}\text{C}$ ). Optical micrographs of the mechanically polished edge (surface perpendicular to the plane of the laminate) are shown in Fig. 3. The laminate thickness is 3.2 mm. The



**Fig. 3 – Optical micrographs of the polished edge of the quasi-isotropic composite. (a) Lower magnification view showing 10 laminae, with the three 0° laminae being brightest. (b) Higher magnification view showing mainly a single 0° lamina.**

thickness of a lamina is 130  $\mu\text{m}$  (Fig. 3(b)). The thickness of four laminae is 530  $\mu\text{m}$  (Fig. 3(a)). The composite properties, as obtained from CompositePro (software based on laminate theory), include the Poisson ratio  $\nu_{31} = 0.0464$  and the through-thickness elastic modulus = 9.59 GPa.

For the through-thickness resistance measurement, the specimen is square-shaped in the plane of the laminate, of size 10.0  $\times$  10.0 mm. The four-probe method is used for electrical resistance measurement. It involves two current contacts and two voltage contacts. The two current contacts are centered at the two surfaces perpendicular to the stress direction, as made by using silver paint in conjunction with an 8.0  $\times$  8.0 mm copper foil (thickness 0.001 in or 25  $\mu\text{m}$ , with the silver paint applied between the specimen and the copper), such that each contact is of size 8.0  $\times$  8.0 mm and the copper foil has an integral leg protruding out of the 10.0  $\times$  10.0 mm area in the plane of the surface for facilitating electrical connection (Fig. 4). The two voltage contacts, as made by silver paint in conjunction with copper wire, are perimetric around the specimen in two planes that are perpendicular to the stress direction, such that the two planes are symmetrically positioned and are separated by 1.5 mm. Due to its substantial width, each voltage contact is in contact with more than a single lamina. The load during the piezoresistivity testing is applied through a glass fiber reinforced epoxy piston (chosen due to its electrical nonconductivity) in the form of a slab of size 10.0  $\times$  10.0 mm. Although the load is applied to the 8.0  $\times$  8.0 mm copper foil, the entire specimen cross-sectional area of 10.0  $\times$  10.0 mm is considered to receive the load, due to the strong mechanical anisotropy of the composite material. Similarly, due to the strong electrical anisotropy of the composite, the entire specimen cross-sectional area of 10  $\times$  10 mm is considered to receive the current.

The stress is provided by a hydraulic mechanical testing machine (MTS Systems Corp., Eden Prairie, MN). The through-thickness strain is not measured because of the

thickness is too small for strain gage attachment, but the longitudinal strain is measured using a strain gage that is attached to one of the four legs of a cross-shaped specimen for through-thickness compression directed at the square middle area of the cross, as in prior work [6]. The strain gage is located just outside the square area, so the strain measured is the strain just away from the stressed region. For the longitudinal strain measurement, the specimen geometry shown in Fig. 4 is not used.

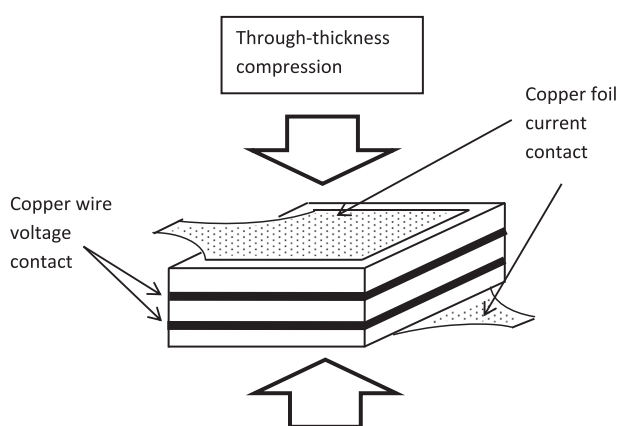
The through-thickness resistance is measured during through-thickness compression at progressively increasing stress amplitudes, with three cycles conducted at each stress amplitude. Although the longitudinal resistance (prior work using the same composite material [6]) and the through-thickness resistance (this work) are measured in different specimens during through-thickness stress application, correlation of these two quantities can be made at the same value of the through-thickness stress.

In relation to both through-thickness resistance measurement (this work) and longitudinal resistance measurement (prior work using the same composite [6]), the through-thickness strain is not measured. The value based on the cross-head displacement is excessive and is not reliable. However, a reliable value is obtained by calculation based on the applied through-thickness stress and the through-thickness modulus, which is calculated based on laminate theory and the constituent properties, using commercial software (CompositePro).

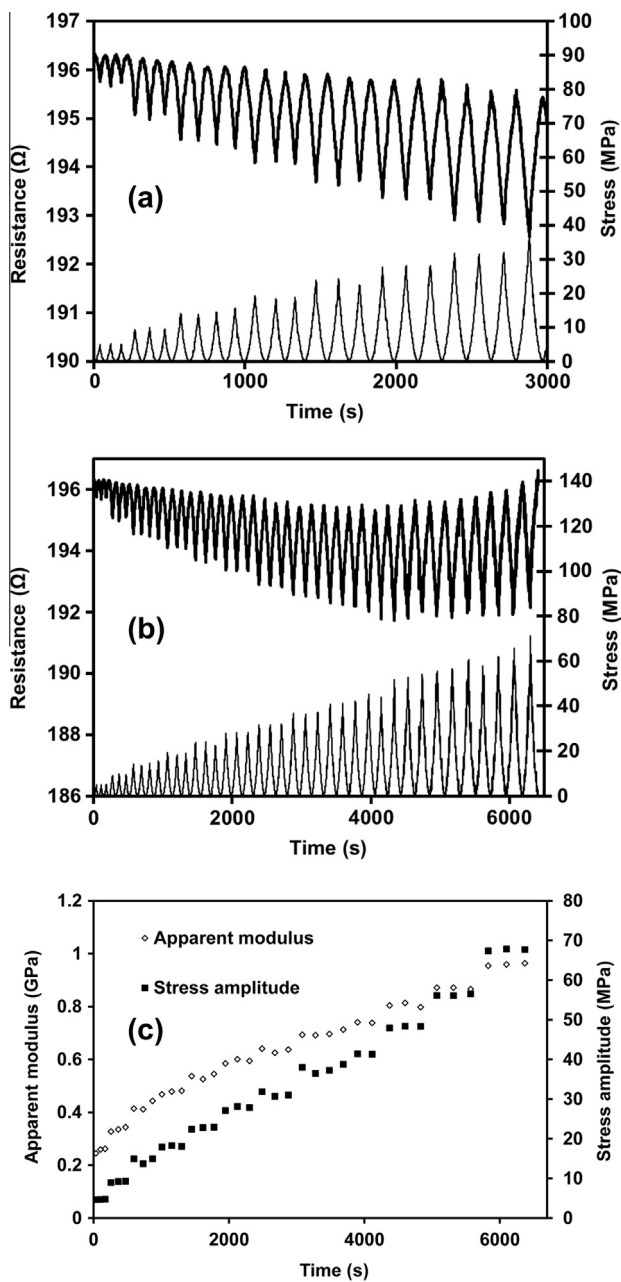
#### 4. Results and discussion

The through-thickness resistance and resistivity without loading are  $196.32 \pm 0.01 \Omega$  and 1300  $\Omega \text{ cm}$  respectively. The limited accuracy of the resistivity is due to the error in the measurement of the distance between the voltage contacts.

The effect of the through-thickness stress on the through-thickness resistance is shown in Fig. 5. The through-thickness resistance decreases upon through-thickness compression in every stress cycle. The higher is the stress amplitude, the greater is the resistance decrease. Up to a stress of 50 MPa, the resistance baseline (upper envelope) decreases with increasing stress amplitude and has a tendency to decrease upon repeated loading at the same stress amplitude. This means that the through-thickness compression up to about 50 MPa causes a small degree of irreversible through-thickness resistance decrease, although the resistance decrease is mainly reversible. This baseline decrease is consistent with that observed for the longitudinal resistance at similar through-thickness stress levels (Fig. 6) [6]. It is attributed to an irreversible change in the microstructure, specifically an irreversible increase in the extent of fiber–fiber contact in the through-thickness direction, as previously reported based on an irreversible decrease of the contact electrical resistivity of the interlaminar interface upon through-thickness compression [1]. At and above a stress of about 50 MPa (Fig. 5(b)), the resistance baseline (upper envelope) increases with increasing stress amplitude. Since, in general, the defects resulting from damage tend to cause the resistance to increase, this baseline resistance increase suggests



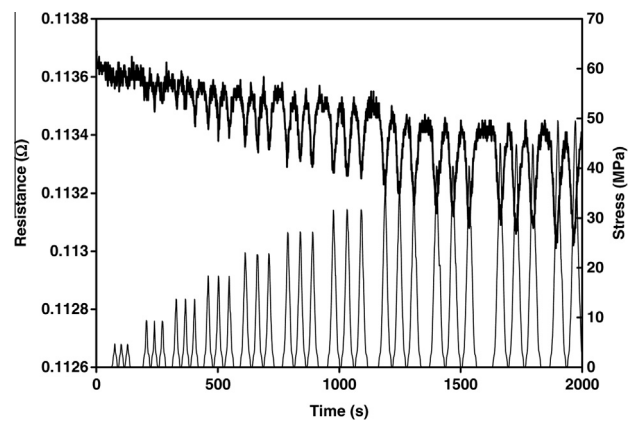
**Fig. 4 – Schematic illustration of the configuration for through-thickness resistance measurement during through-thickness compression. The arrows indicate the applied force. The shaded regions are the copper foils. Each copper foil or wire is attached to the specimen by using silver paint. The bold solid lines indicate the copper wires, which are around the entire perimeter of the specimen at two planes that are perpendicular to the force direction.**



**Fig. 5** – (a) The effect of through-thickness stress (thin lower curve) on the through-thickness resistance (thick upper curve) up to a stress amplitude of 35 MPa. (b) The effect of through-thickness stress (thin lower curve) on the through-thickness resistance (thick upper curve) up to a stress amplitude of 70 MPa. (c) The correlation of the through-thickness stress amplitude and the apparent modulus for each cycle of loading up to a stress amplitude of 70 MPa.

the occurrence of minor damage or the precursor of damage, as previously reported based on an irreversible increase of the through-thickness resistance upon longitudinal tension-tension fatigue [17].

The apparent modulus is defined as the magnitude of the through-thickness stress amplitude divided by the longitudinal strain amplitude just away from the stressed region. The apparent modulus is related to the true through-thickness



**Fig. 6** – Variation of the longitudinal volume resistance (at the stressed region) (thick upper curve) with time and of the through-thickness compressive stress (thin lower curve) with time during stress cycling at progressively increasing stress amplitudes (3 cycles for each amplitude) [6].

modulus, because the longitudinal strain is related to the through-thickness strain through the Poisson ratio and the longitudinal strain just away from the stressed region is related to that in the stressed region. The apparent modulus increases with increasing stress amplitude up to about 70 MPa, as shown in Fig. 5(c). This trend is attributed to the increasing difficulty to deform the polymer matrix further by through-thickness compression as the strain increases. Hence, the resistance baseline increase, which starts at about 50 MPa (Fig. 5(b)), is not accompanied by a decrease in the apparent modulus. This means that, the damage (or damage precursor) suggested by the resistance baseline increase is so subtle that it does not affect the modulus.

Table 1 shows the measured reversible/irreversible fractional change in through-thickness resistance and the measured reversible/irreversible fractional change in longitudinal resistance at various strain amplitudes. The model described in Section 2.1 is used to relate the through-thickness and longitudinal reversible resistance changes, thus allowing determination of the strain coefficient  $\alpha$  (Eq. (2)). The model described in Section 2.2 is used to relate the through-thickness and longitudinal irreversible resistance changes, thus allowing determination of the damage coefficient  $\beta$  (Eq. (11)). Furthermore, the models allow determination of the through-thickness and longitudinal resistivities from the measured resistances.

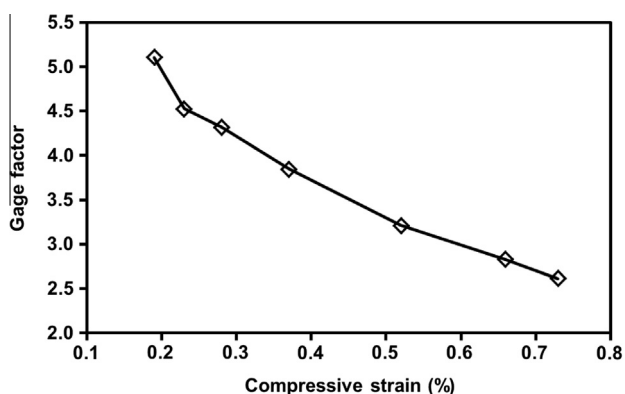
Table 1 summarizes the experimental results at seven through-thickness stress levels in terms of both the through-thickness resistance and the longitudinal resistance. In addition, it shows the fractional changes in the through-thickness and longitudinal resistivities, the coefficients  $\alpha$  and  $\beta$ , as obtained by using the models (Section 2), and the through-thickness gage factor, which is given by the reversible fractional change in through-thickness resistance per unit through-thickness strain.

The through-thickness gage factor decreases with increasing through-thickness compressive strain (Table 1 and Fig. 7). The strain coefficient  $\alpha$  also decreases with increasing through-thickness compressive strain (Table 1 and Fig. 8). This

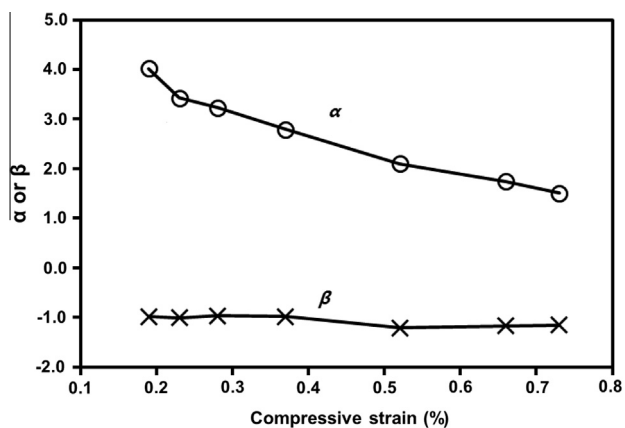
**Table 1 – Correlation of the through-thickness and longitudinal resistance/resistivity changes, with separation of the reversible and irreversible effects. The fractional changes are all relative to the unloaded state. Stress and strain shown are negative, corresponding to those under compression.**

Through-thickness stress (MPa)	–18	–22	–27	–35	–50	–63	–70
Through-thickness strain (%)	–0.19	–0.23	–0.28	–0.37	–0.52	–0.66	–0.73
Reversible fractional change in through-thickness resistance (%)	–0.97	–1.04	–1.21	–1.42	–1.67	–1.86	–1.91
Irreversible fractional change in through-thickness resistance (%)	–0.021	–0.017	–0.036	–0.042	+0.010	0.050	0.040
Reversible fractional change in through-thickness resistivity (%)	–0.76	–0.79	–0.90	–1.02	–1.10	–1.14	–1.10
Irreversible fractional change in through-thickness resistivity (%)	0.18	0.23	0.27	0.36	0.64	0.77	0.84
Reversible fractional change in longitudinal resistance (%)	–0.014	–0.029	–0.022	–0.17	–0.21	–0.29	–0.32
Irreversible fractional change in longitudinal resistance (%)	–0.007	0.000	0.014	–0.005	–0.000	0.010	0.013
Reversible fractional change in longitudinal resistivity (%)	–0.20	–0.26	–0.30	–0.53	–0.74	–0.95	–1.05
Irreversible fractional change in longitudinal resistivity (%)	–0.19	–0.23	–0.26	–0.37	–0.52	–0.65	–0.72
$\alpha$	4.02	3.43	3.23	2.79	2.10	1.74	1.51
$\beta$	–0.98	–1.01	–0.97	–0.98	–1.21	–1.17	–1.15
Gage factor*	5.1	4.5	4.3	3.8	3.2	2.8	2.6

\* Reversible fractional change in through-thickness resistance per unit through-thickness strain.



**Fig. 7 – Effect of the through-thickness compressive strain on the through-thickness gage factor.**



**Fig. 8 – Effect of through-thickness compressive strain on the strain coefficient  $\alpha$  (upper curve) and the damage coefficient  $\beta$  (lower curve).**

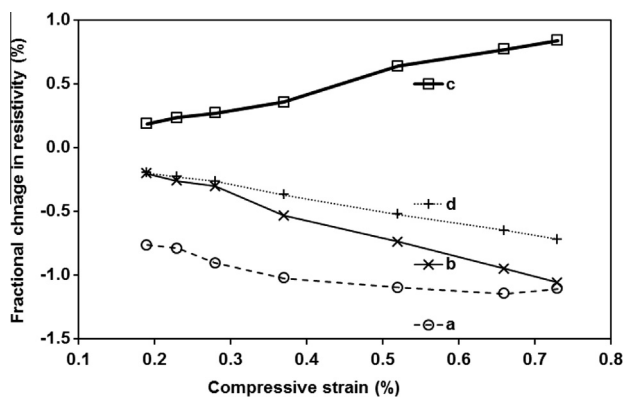
means that the strain sensitivity associated with the piezoresistivity decreases with increasing strain, probably due to the minor irreversible effect of strain becoming more significant as strain increases. Since the irreversible effect is associated with an irreversible increase in the degree of fiber–fiber contact, its occurrence lessens the subsequent strain-induced reversible decrease in the degree of fiber–fiber contact. The strain mechanism is further discussed below.

The damage coefficient  $\beta$  is quite independent of the strain (Table 1 and Fig. 8), indicating that the damage sensitivity is quite independent of the strain. The damage is indicated by the irreversible fractional change in resistivity (Table 1), with the through-thickness resistivity increasing irreversibly with increasing strain (curve c in Fig. 9) and the longitudinal resistivity decreasing irreversibly with increasing strain (curve d in Fig. 9). The damage mechanism is further discussed below.

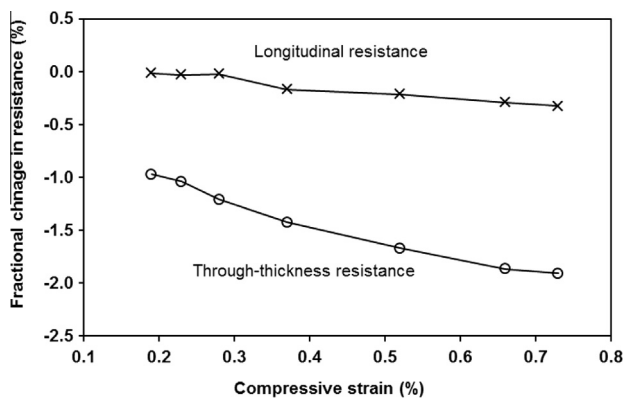
For the entire strain range studied, the gage factor is 2.6 or above. This is consistent with the fact that the through-thickness resistivity reversibly decreases upon through-thickness compression (Table 1 and curve a in Fig. 9), i.e., the observed resistance change is not just due to dimensional changes, but is also due to a resistivity change. For the sake of comparison, a conventional metallic strain gage, which is not piezoresistive and has its resistance changing due to the dimensional changes only, has gage factor around 2.0.

The reversible fractional change in through-thickness resistance is greater in magnitude than the reversible fractional change in through-thickness resistivity for each stress level. This is because the resistance change is due to both the resistivity change and the dimensional changes. As the stress magnitude increases, the reversible fractional change in through-thickness resistance/resistivity becomes more and more negative (curve a in Fig. 9 and Fig. 10), thus indicating piezoresistivity (a strain effect).





**Fig. 9 – Effect of through-thickness compressive strain on the reversible/irreversible fractional change in resistivity. Curve a (○): reversible fractional change in through-thickness resistivity. Curve b (x): reversible fractional change in longitudinal resistivity. Curve c (□): irreversible fractional change in through-thickness resistivity. Curve d (+): irreversible fractional change in longitudinal resistivity.**



**Fig. 10 – Effect of through-thickness compressive strain on the reversible/irreversible fractional change in resistance. Upper curve: reversible fractional change in longitudinal resistance. Lower curve: reversible fractional change in through-thickness resistance. The irreversible fractional changes (not shown) are essentially independent of the strain.**

The irreversible fractional change in through-thickness resistance is much smaller in magnitude than the corresponding reversible fractional change. This means that the damage is very minor and the observed resistance decrease is mainly due to strain rather than damage. As shown in both Fig. 5 and Table 1, the irreversible fractional change in through-thickness resistance becomes more and more negative as the strain magnitude is increased up to about 0.5% (corresponding to a stress magnitude of about 50 MPa), above which this quantity becomes more and more positive. This change in the trend for the irreversible change in the resistance corresponds to the smooth increase of the irreversible change in the resistivity as strain increases in the range including values below and above 0.5% (Table 1 and curve c in Fig. 9) and reflects the fact that both resistivity change and dimensional changes affect the resistance change.

The irreversible fractional change in through-thickness resistivity is positive (curve c in Fig. 9), whereas the corresponding reversible fractional change is negative (curve a in Fig. 9), such that the magnitude is much higher for the reversible fractional change than the irreversible fractional change. This again indicates dominance of the strain rather than damage in affecting the resistance change. That the signs are opposite is due to the effect of the dimensional changes on the resistance being more significant when the fractional change in resistivity is small. It should be noted that, upon uniaxial compressive stress application, dimensional changes in the absence of a resistivity change always cause the resistance to decrease.

The irreversible fractional change in through-thickness resistance is negative, whereas the corresponding fractional change in resistivity is positive (curve c in Fig. 9), such that the magnitude is much higher for the resistivity than the resistance. This means that the irreversible resistance change is mainly due to the resistivity change rather than the dimensional changes. The dimensional changes in the absence of a resistivity change would cause the through-thickness resistance to decrease. This decrease opposes the resistance increase due to the damage, which increases the resistivity. As a consequence, the fractional change is negative for the resistance and is positive for the resistivity.

As the stress level increases, the irreversible fractional change in through-thickness resistance/resistivity becomes less negative and more positive, indicating increasing damage, which remains minor. It should be noted that damage (such as cracks) typically causes the resistivity of a material to increase.

Due to the abovementioned strain effect,  $\alpha$  is positive. Due to the abovementioned minor damage effect,  $\beta$  is negative. The magnitude of  $\alpha$  is much higher than that of  $\beta$ , indicating that strain sensing is more effective than damage sensing, as expected for the very minor damage associated with this range of stress.

The reversible fractional change in longitudinal resistance/resistivity is negative (curve b in Fig. 9), such that the magnitude is much higher for the resistivity than the resistance. This reflects the Poisson effect, which results in a dimensional change that causes the longitudinal resistance to increase. This resistance increase opposes the resistance decrease that is due to the piezoresistive effect. This further means that the piezoresistive effect observed in the longitudinal direction is distinct from the Poisson effect. The reversible fractional change in longitudinal resistance/resistivity increases in magnitude as the stress level increases, such that the trend is clearer for the resistivity (curve b in Fig. 9) than the resistance. That the trend is clearer for the resistivity is consistent with the notion that this is a piezoresistive effect. For similar reasons, the irreversible fractional change in longitudinal resistance/resistivity (curve d in Fig. 9) is negative, such that the magnitude is much higher for the resistivity than the resistance.

For both through-thickness and longitudinal resistivities, the reversible fractional change becomes more negative as the stress magnitude increases (curves a and b in Fig. 9). This means that the strain causes both resistivities to decrease, i.e., a piezoresistive effect. However, the fractional change is

much higher in magnitude for the through-thickness resistivity (curve a in Fig. 9) than the longitudinal resistivity (curve b in Fig. 9), as expected due to the applied stress being in the through-thickness direction.

The effect of strain on the through-thickness resistivity is attributed to the increase in the degree of fiber–fiber contact in the through-thickness direction as the stress magnitude increases. The effect of strain on the longitudinal resistivity is partly due to the decrease in the degree of fiber waviness and partly due to the increasing degree of fiber–fiber contact and the consequent increasing ease of the longitudinal current to detour from one fiber to another when a defect is encountered in a fiber.

The irreversible fractional change in the through-thickness resistivity (curve c in Fig. 9) becomes more positive as the stress magnitude increases, whereas that in the longitudinal resistivity (curve d in Fig. 9) becomes more negative as the stress magnitude increases. This means that the damage causes the through-thickness resistivity to increase but causes the longitudinal resistivity to decrease. This suggests that the damage is akin to delamination, which increases irreversibly the through-thickness resistivity [17], such that the through-thickness compression causes some through-thickness-strain-induced irreversible decrease in the fiber waviness in the through-thickness direction, thereby decreasing irreversibly the longitudinal resistivity.

The irreversible fractional change in longitudinal resistance is almost zero, but it becomes more positive as the stress magnitude increases. The irreversible fractional change in longitudinal resistivity is negative and becomes more negative as the stress magnitude increases (curve d in Fig. 9). This is consistent with the notion that the damage causes the longitudinal resistivity to decrease, whereas dimensional changes due to the Poisson effect cause the longitudinal resistance to increase.

## 5. Correlation of flexure results of prior work and through-thickness compression results of this work

This paper pertains to carbon-fiber polymer-matrix composite self-sensing during through-thickness compression for a 24-lamina quasi-isotropic epoxy-matrix composite. Self-sensing during flexure for the same composite has been previously reported [2]. This section is aimed at correlating the flexural results of the prior work and the through-thickness compression results of this work for the same material.

Upon flexure (three-point bending), the tension surface resistance increases reversibly [2], due to decrease in the degree of fiber–fiber contact in the through-thickness direction and the consequent decrease in the degree of current penetration, while the compression surface resistance decreases reversibly [2], due to increase in the degree of fiber–fiber contact in the through-thickness direction and the consequent increase in the degree of current penetration. The explanation of the results in terms of the degree of current penetration is supported by an analytical model [5].

The reversible increase in the longitudinal tension surface resistance upon flexure [2] appears to be inconsistent with

the reversible decrease in the longitudinal volume resistivity upon through-thickness compression (this work). However, this apparent inconsistency can be explained by consideration of the difference in microstructural effects of these two manners of loading. Upon flexure, the tension surface region experiences a decrease in the degree of fiber–fiber contact in the through-thickness direction; upon through-thickness compression, the through-thickness direction of the overall composite experiences an increase in the degree of fiber–fiber contact, thereby decreasing both through-thickness and longitudinal volume resistivities, with the accompanying decrease in the degree of fiber waviness causing the longitudinal direction of the overall composite to experience an irreversible resistivity decrease.

## 6. Conclusion

Through-thickness strain/stress self-sensing in a quasi-isotropic carbon fiber epoxy-matrix composite by through-thickness or longitudinal electrical resistance measurement is effective. The strain causes both the through-thickness and longitudinal resistivities to decrease reversibly, due to piezoresistivity. Due to the Poisson effect, the reversible fractional decrease in the longitudinal resistance is smaller than the corresponding fractional decrease in the resistivity. In contrast, the reversible fractional decrease in the through-thickness resistance is relatively close to the corresponding fractional decrease in the resistivity.

The associated irreversible microstructural change (minor damage or precursor or damage) causes the through-thickness resistivity to increase irreversibly and causes the longitudinal resistivity to decrease irreversibly. The irreversible fractional change in resistivity is small in magnitude compared to the corresponding reversible fractional change.

The through-thickness gage factor (reversible fractional change in resistance per unit strain) ranges from 2.6 to 5.1, such that it decreases with increasing strain magnitude ranging from 0.19% to 0.73%. The strain coefficient  $\alpha$ , which is the reversible fractional change in through-thickness resistivity per unit through-thickness strain, is positive and ranges from 1.5 to 4.0 for through-thickness strain in the same range, such that  $\alpha$  decreases with increasing strain magnitude. The damage coefficient  $\beta$ , which is the irreversible fractional change in through-thickness resistivity per unit through-thickness strain, is negative and ranges from  $-1.0$  to  $-1.3$  for the same strain range, such that  $\beta$  is essentially independent of the strain.

The reversible and irreversible effects of through-thickness compression on the longitudinal volume resistivity are consistent with those of flexure (prior work [2]) on the surface resistance of the tension/compression surface. Upon flexure and due to strain, the compression surface region experiences a reversible increase in the degree of fiber–fiber contact in the through-thickness direction, thereby resulting in a reversible decrease in the compression surface resistance. Upon through-thickness compression and due to strain, the overall composite experiences a reversible increase in the degree of fiber–fiber contact, thereby resulting in a reversible decrease in the through-thickness and longitudinal resistivities.

## REFERENCES

- [1] Wang S, Kowalik DP, Chung DDL. Self-sensing attained in carbon fiber polymer-matrix structural composites by using the interlaminar interface as a sensor. *Smart Mater Struct* 2004;13(3):570–92.
- [2] Wang S, Chung DDL. Self-sensing of flexural strain and damage in carbon fiber polymer-matrix composite by electrical resistance measurement. *Carbon* 2006;44(13):2739–51.
- [3] Wang S, Chung DDL. Negative piezoresistivity in continuous carbon fiber epoxy-matrix composite. *J Mater Sci* 2007;42(13):4987–95.
- [4] Wang X, Chung DDL. An electromechanical study of the transverse behavior of carbon fiber polymer-matrix composite. *Composite Interfaces* 1998;5(3):191–9.
- [5] Zhu S, Chung DDL. Analytical model of piezoresistivity for strain sensing in carbon fiber polymer-matrix structural composite under flexure. *Carbon* 2007;45(8):1606–13.
- [6] Wang D, Chung DDL. Through-thickness stress sensing of carbon fiber polymer-matrix composite by electrical resistance measurement. *Smart Mater Struct* 2007;16:1320–30.
- [7] Leong C, Wang S, Chung DDL. Effect of through-thickness compression on the microstructure of carbon fiber polymer-matrix composites, as studied by electrical resistance measurement. *J Mater Sci* 2006;41(10):2877–84.
- [8] Wang S, Wang D, Chung DDL, Chung JH. Method of sensing impact damage in carbon fiber polymer-matrix composite by electrical resistance measurement. *J Mater Sci* 2006;41(8):2281–9.
- [9] Wang S, Chung DDL, Chung JH. Impact damage of carbon fiber polymer-matrix composites, monitored by electrical resistance measurement. *Composites: Part A* 2005;36:1707–15.
- [10] Ngabonziza Y, Ergun H, Kuznetsova R, Li J, Liaw BM, Delale F, et al. An experimental study of self-diagnosis of interlaminar damage in carbon-fiber composites. *J Intell Mater Syst Struct* 2010;21(3):233–42.
- [11] Boschetti-de-Fierro A, Pardey R, Savino V, Muller AJ. Piezoresistive behavior of epoxy matrix-carbon fiber composites with different reinforcement arrangements. *J Appl Polym Sci* 2009;111(6):2851–8.
- [12] Todoroki A, Samejima Y, Hirano Y, Matsuzaki R. Piezoresistivity of unidirectional carbon/epoxy composites for multiaxial loading. *Compos Sci Technol* 2009;69(11–12):1841–6.
- [13] Gordon DA, Wang S, Chung DDL. Piezoresistivity in unidirectional continuous carbon fiber polymer-matrix composites: single-lamina composite versus two-lamina composite. *Compos Interfaces* 2004;11(1):95–103.
- [14] Wang S, Chung DDL. Piezoresistivity in continuous carbon fiber polymer-matrix composite. *Polym Compos* 2000;21(1):13–9.
- [15] Wang X, Chung DDL. Fiber breakage in polymer-matrix composite during static and dynamic loading, studied by electrical resistance measurement. *J Mater Res* 1999;14(11):4224–9.
- [16] Wang X, Wang S, Chung DDL. Sensing damage in carbon fiber and its polymer-matrix and carbon-matrix composites by electrical resistance measurement. *J Mater Sci* 1999;34(11):2703–14.
- [17] Wang X, Chung DDL. Sensing delamination in a carbon fiber polymer-matrix composite during fatigue by electrical resistance measurement. *Polym Compos* 1997;18(6):692–700.
- [18] Wu AS, Na W, Yu W, Byun J, Chou T. Carbon nanotube film interlayer for strain and damage sensing in composites during dynamic compressive loading. *Appl Phys Lett* 2012;101(22):221909/1–5.
- [19] Johnson Timothy M, Fullwood David T, Hansen George. Strain monitoring of carbon fiber composite via embedded nickel nanoparticles. *Compos Part B: Eng* 2012;43(3):1155–63.