Self-sensing of Damage in Carbon Fiber Polymer–Matrix Composite Cylinder by Electrical Resistance Measurement

SHOUKAI WANG,[1] D. D. L. CHUNG[1],* AND JAYCEE H. CHUNG[2]

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

[2]*Global Contour Ltd, 1145 Ridge Road West, Rockwall, TX 75087, USA*

ABSTRACT: Self-sensing of damage, as attained by electrical resistance measurement, was found to be effective in a carbon fiber polymer–matrix composite cylinder made by filament winding. Resistance was measured in the axial, radial, oblique, and circumferential directions by using circumferential or axial electrical contacts on the outer and/or inner surfaces of the cylinder. Minor damage upon drop impact at 10 J or below caused the radial resistance to decrease irreversibly, whereas major damage upon drop impact above $\approx$10 J caused the radial, oblique, and axial resistances to increase irreversibly. The circumferential resistance ratio (ratio of the circumferential resistance of a damaged area to that away from the damaged area) was most sensitive, increasing monotonically with impact energy >1.4 J.

Key Words: composite, polymer, carbon fiber, epoxy, impact, damage, electrical resistance, cylinder.

INTRODUCTION

SELF-SENSING refers to the ability of a material, typically a structural material, to sense its own condition. A particularly important attribute that needs to be sensed is damage, as it is relevant to structural health monitoring and smart structures. The self-sensing technology uses the structural material as the sensor, so that there is no need for embedded or attached sensors, which tend to suffer from high cost, low durability, small sensing volume, and mechanical property loss. An example of an embedded sensor is a fiber optic sensor (Mitrovic and Carman, 1994; Takeda, 2000). An example of a self-sensing material is a polymer–matrix composite that contains a special reinforcing continuous fiber in the form of a cladded glass fiber, which acts as the light guide (Hayes et al., 1996, 1997; Brooks et al., 1997; Zolfaghar et al., 1998; Kister et al., 2004). Another example of a self-sensing material is a polymer–matrix composite that contains continuous carbon fiber, the electrical conductivity of which allows self-sensing through electrical resistance measurement (Ceysson, et al., 1995; Kemp et al., 1996; Wang and Chung, 1997a,b, 1998a, 1999; Wang et al., 1998a, 1999; Yanagida, 2000; Abry and Choi, 2001; Wang et al., 2001; Kupke et al., 2001; Wang and Chung, 2002; Chung and Wang, 2003; Wang et al., 2005a).

The ability of carbon fiber polymer–matrix composite laminates to sense their own damage (Wang et al., 1997a, b, 1999; Wang and Chung, 1999a, 2001, 2002), strain (Wang and Chung, 1996, 1998a, b; Wang et al., 1998b) and temperature (Wang and Chung, 1999b; Wang et al., 2004) through DC electrical resistance measurement has been previously reported. However, there has been no previous report of the self-sensing ability in composites in the form of cylinders rather than laminates. Cylinders made by filament winding are used for struts, pressure vessels, and various components of lightweight structures. Because of the difference in geometry between a laminate and a cylinder, the electrical contact configuration is not the same for the two cases and the effectiveness of the self-sensing technique may thus be different.

This article is focused on the self-sensing of damage because of the practical importance of structural health monitoring, which is needed for aircraft hazard mitigation. Carbon fiber polymer–matrix composites are dominant among structural composites for aircrafts, due to their combination of low density, high strength, and high modulus of elasticity.

This article uses drop impact to inflict damage on the composite cylinder. This is because impact is one of the common causes of damage of composite structures. The effectiveness of a composite in the form of a

---

*Author to whom correspondence should be addressed.
E-mail: ddlchung@buffalo.edu

1045-389X/06/01 00057–62 $10.00/0 DOI: 10.1177/1045389X06056072

laminate to sense its own drop impact damage has previously been demonstrated (Wang et al., in press a).

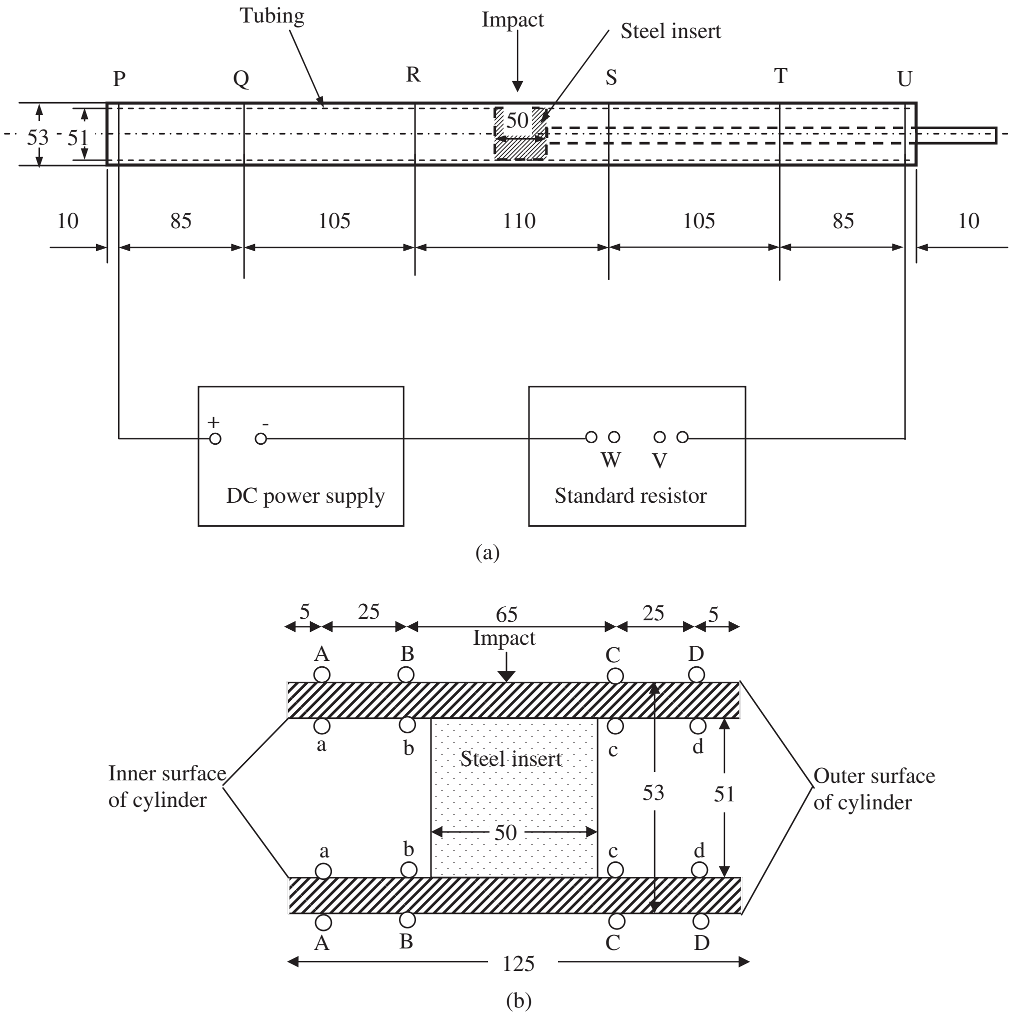
The objectives of this article are: (i) to demonstrate the effectiveness of damage self-sensing by resistance measurement in a carbon fiber polymer–matrix composite cylinder and (ii) to compare the effectiveness of various electrical contact configurations for self-sensing in a composite cylinder. The various electrical contact configurations correspond to different directions of resistance measurement. These directions include the axial, radial, oblique, and circumferential directions. These directions are explained in the next section.

EXPERIMENTAL METHODS

Axial Resistance

A filament-wound cylindrical specimen of wall thickness 1.3 mm (inner diameter 51 mm, length 510 mm, winding sequence [+45/−45]/0/[+45/−45], external woven, tensile strength 227 MPa, Grafil 34-600 carbon fiber, Epon 862 epoxy matrix, 315°F cure temperature, manufactured by MacLean Quality Composites) with six circumferential electrical contacts (labeled P, Q, R, S, T, and U) in the form of silver paint in conjunction with the copper wire (applied after sanding the outer surface of the cylinder) was subjected to impact at the same point at the center of the length of the cylinder, with the force in the radial direction. The impact energy was progressively increased, while the resistance was measured by using the four-probe method. The experimental setup is shown in Figure 1(a). The same cylinder was used for all impact energies.

For measuring the axial resistance of the cylinder, circumferential electrical contacts A, B, C, and D on the outer surface (lightly sanded by using a 600-grit SiC paper to remove the surface epoxy layer) were used (Figure 1(b)). For measuring the radial resistance, circumferential contacts A, B, C, and D on the outer



(a)

(b)

Figure 1. *Method for testing the filament-wound cylinder: (a) experimental setup; (b) circumferential electrical contacts for axial, radial and oblique resistance measurement; and (c) axial electrical contacts for circumferential resistance measurement. All dimensions are in mm.*

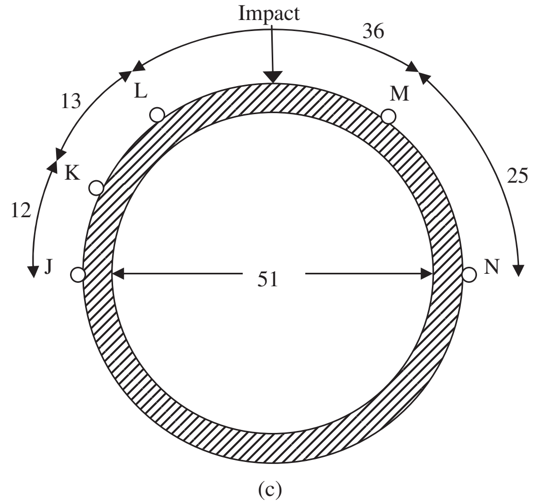


Figure 1. *Continued.*

surface (similarly sanded to remove the surface epoxy layer) and circumferential contacts a, b, c, and d on the inner surface (similarly sanded to remove the surface epoxy layer) were used, such that A and D electrically connected together were used as one of the two current contacts, a and d electrically connected together were used as the other current contact, B and C electrically connected together were used as one of the two voltage contacts, and b and c electrically connected together were used as the other voltage contact (Figure 1(b)). The radial resistance is the volume resistance in the radial direction between the inner surface and the outer surface of the cylinder. For measuring the oblique resistance, A and d were the current contacts, while B and c were the voltage contacts (Figure 1(b)). The oblique resistance is the volume resistance in a direction between the axial direction and the radial direction.

The specimen of dimensions shown in Figure 1(a) was used for axial resistance study. The axial electrical current, as provided by a DC power supply, was passed to the specimen through contact P and out of the specimen through contact U. The voltages between contacts Q and R, between contacts R and S, and between contacts S and T were measured using a Keithley 2002 multimeter. A standard resistor with a known resistance of 0.001 Ω was connected in series to the specimen. The voltage between the two terminals V and W of the standard resistor was also measured. This voltage, divided by the resistance of the standard resistor, gave the electrical current, which was 890 mA on the average. The large current was necessitated by the small values of the specimen resistance, which was low due to the geometry of the cylindrical specimen. In contrast, the specimen resistance was much higher for the laminate composites of the prior work of the present authors (Wang et al., 2005b). In spite of the high current, the specimen temperature was negligibly affected. After all, the corresponding axial current density was only 5.46 mA/mm^2 (average value, since the current density may not be the same for the various layers of fiber), due to the large cross-sectional area (163 mm^2) of the cylinder wall. The resistance of the section QR (RS or ST) was calculated by dividing the voltage between Q and R (between R and S, or between S and T) by the current.

A steel rod of diameter 51 mm (2.0 in.) was inserted into the center of the cylindrical specimen, such that the rod was symmetrically positioned relative to the midpoint along the length of the cylindrical specimen. The insert was for supporting the cylinder from its interior during impact. A steel bracket (not shown in Figure 1(a)) was placed under the cylindrical specimen to support the specimen. The insert and the bracket were all made from 4340 stainless steel and designed to fit the size and curvature of the cylindrical specimen. An electrically insulating film was placed between the insert and the inner surface of the cylindrical specimen and between the bracket and outer surface of the cylindrical specimen. It is possible for the design of the insert to affect the damage upon impact. Investigation of the dependence of the damage on the insert design is beyond the scope of this article.

Radial and Oblique Resistance

The specimen for radial and oblique resistance study was of the same diameter as that for axial resistance measurement (Figure 1(a)), but its length was only 125 mm. The contacts A (outer surface) and a (inner surface) were at a distance of 5 mm from one end of the cylinder (Figure 1(b)). The contacts D and d were at a distance of 5 mm from the other end. The distance between A and B was 25 mm; that between C and D was also 25 mm. Hence, the distance between B and C was 65 mm.

For the radial resistance measurement, the radial current was 810 mA, which corresponded to a radial current density of 0.0396 mA/mm^2. For the oblique resistance measurement, the current was 730 mA, but the current density could not be calculated due to the difficulty of estimating the area of the oblique current path.

Circumferential Resistance

Specimen A for circumferential resistance study was of the same diameter as those for axial, radial, and oblique resistance measurements, but its length was only 115 mm. The steel insert of length 50 mm was at the center of the cylinder, as in Figure 1(b). Five electrical contacts, labeled J, K, L, M, and N in Figure 1(c), were applied on the outer surface of the cylinder. Each contact was a straight line parallel to the axis of the cylinder, such that the line extended for the whole length of the cylinder. Contacts J and N were for passing current, which split into two paths – one along the half of the cylinder that was to receive the impact (top half of Figure 1(c)) and the other along the half of the cylinder that was not to receive the impact (bottom half of Figure 1(c)). Upon damage, the half that received the impact would increase in resistance, whereas the other half would not. Thus, after damage, the current would not be equally split between the two paths. The current in the two paths could not be separately measured; only the total current was measured. With the current unclear, the resistance could not be determined. To circumvent this problem, three voltage contacts (K, L, and M in Figure 1(c)) were used, thereby allowing the ratio of the resistance between L and M (referred to as R_2) to that between K and L (referred to as R_1) to be measured. Since the point of impact was between L and M, as shown in Figure 1(c), R_2 would increase upon damage while R_1 would not (assuming that there was no damage between K and L). Therefore, the R_2/R_1 ratio was used as the quantity for indicating impact damage.

Specimen B for circumferential resistance study was larger than Specimen A. It had an outer diameter of 97 mm, inner diameter of 89 mm, and a length of 75 mm. The steel insert at the center of the cylinder was 25 mm in length. The five electrical contacts were as in Figure 1(c), except that the distances were 25 mm between contacts J and K, 25 mm between K and L, 51 mm between L and M, and 51 mm between M and N.

RESULTS AND DISCUSSION

Axial Resistance

Figure 2 shows the axial resistance of the filament-wound cylindrical specimen for the middle section (RS of Figure 1(a)) upon impact at progressively increasing energy up to 18.9 J. The resistance showed abrupt increases at impact energies >5 J. The higher the impact energy, the greater was the axial resistance. The sensitivity of the resistance for damage improved as the impact energy reached 10 J or more. The resistance of the other sections (i.e., QR and ST) did not show any change upon impact at any of the energies, due to the negligible damage in these sections that were away from the point of impact.

Drop impact damage of the filament-wound cylinder was effectively monitored in this work for impact energy at or >5 J. In a prior work of the present authors (Wang, et al., in press a), drop impact damage of laminates was effectively monitored for impact energy at or >1 J. The higher effectiveness for laminates is due to the large diameter of the indentation relative to the dimension of the specimen in the direction transverse to the resistance measurement direction. For the cylinder, the transverse direction is the circumferential direction and the circumference is large compared to the width of a laminate specimen.

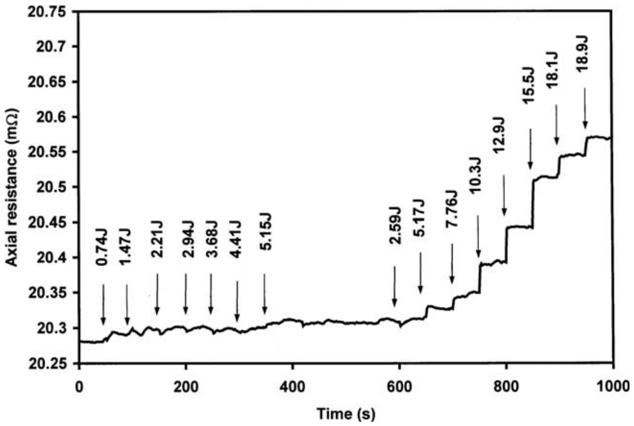


Figure 2. Variation of the axial resistance of the middle section (RS in Figure 1(a)) upon damage at progressively increasing impact energy up to 18.9 J.

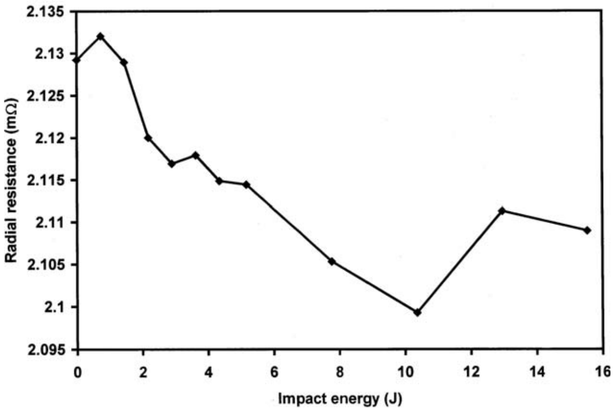


Figure 3. Variation of the radial resistance upon damage at progressively increasing impact energy up to 15.5 J. Only one data point was taken at each impact energy, in contrast to the continuous monitoring in Figure 2.

Figures 2 and 3 show the axial resistance and the radial resistance, which were obtained by using circumferential electrical contacts that were only on the outer surface of the cylindrical specimen. The axial resistance is akin to the longitudinal resistance in the case of laminates.

Radial and Oblique Resistances

Figures 3 and 4 show the radial resistance and oblique resistance of the cylinder, respectively. The radial resistance is akin to the through-thickness resistance in the case of laminates. The radial resistance decreased with increasing impact energy up to 10 J, beyond which it increased somewhat linearly (Figure 3). The oblique

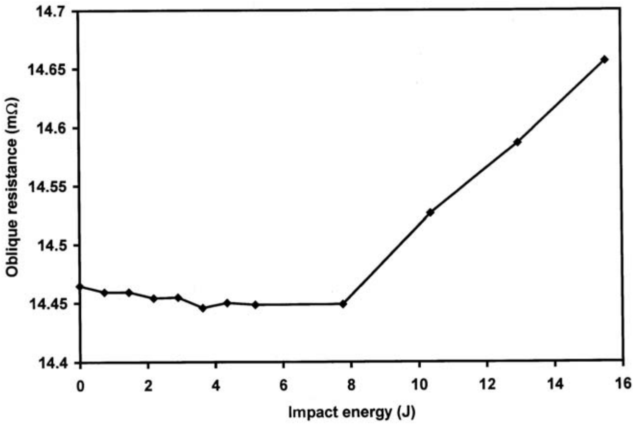


***Figure 4.** Variation of the oblique resistance upon damage at progressively increasing impact energy up to 15.5 J. Only one data point was taken at each impact energy, in contrast to the continuous monitoring in Figure 2.*

Table 1. Diameter and depth of the indentation at various levels of impact energy for the filament-wound cylinder. The impact was directed at different points on the outer surface of the cylinder.

Impact energy (J)	Diameter (mm, ±0.1)[a]	Calculated depth (mm)[b]
0.73	1.8	0.04
1.45	2.1	0.06
2.18	2.9	0.11
2.90	3.4	0.15
3.63	3.7	0.18
4.36	3.6	0.17
5.18	4.0	0.21
7.77	4.4	0.26
10.4	4.8	0.31
12.9	5.6	0.42
15.5	6.5	0.56

[a] Measured in the axial direction of the cylinder.
[b] Depth at the center of the indentation.

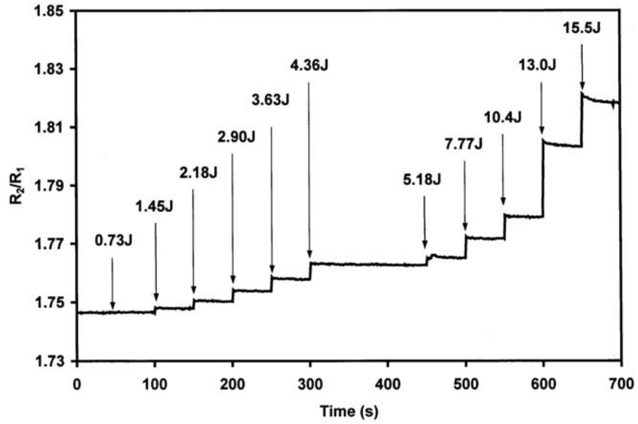


***Figure 5.** Variation of the circumferential resistance ratio R_2/R_1 upon damage at progressively increasing impact energy up to 15.5 J for Specimen A. Monitoring was continuous, as in Figure 2.*

resistance showed negligible change < 8 J (Figure 4). Above 8 J, it increased with increasing impact energy.

The decrease in radial resistance with increasing impact energy up to 10 J is attributed to the minor impact damage that caused the fiber layers in the wall of the cylinder to contact one another more directly. The increase in radial resistance beyond 10 J is attributed to the major impact damage that involved delamination. This major damage also caused the oblique resistance to increase. The radial resistance is more sensitive to minor damage than the oblique resistance, but the oblique resistance is more sensitive to major damage.

Table 1 shows the measured diameter and calculated depth of the indentation at various levels of impact energy. The largest depth of 0.56 mm was still small compared to the wall thickness of 1.3 mm.

The resistance values for the cylinder were small compared to those for the laminates of the prior work (Wang et al., in press a), due to the large cross-sectional area of the cylinder wall compared to that of the laminate strip. As a result, the noise in the resistance measurement was higher for the cylinder than for the laminates.

Circumferential Resistance

Figure 5 (for Specimen A) shows that the circumferential resistance ratio R_2/R_1 increased monotonically with increasing impact energy. Impact damage at energy 1.45 J and above were detected. Comparison of Figure 5 with Figures 2–4 shows that R_2/R_1 is attractive in its high sensitivity to minor damage and its simple monotonic increase with increasing damage. A further attraction of circumferential resistance measurement lies on the greater convenience of applying axial electrical contacts compared to circumferential contacts.

Results for Specimen B were qualitatively similar to those of Specimen A. The resistance values were lower for Specimen B, due to the larger wall thickness. Because of the lower signal-to-noise ratio and the smaller extent of damage for Specimen B (both due to the larger wall thickness), increase in the R_2/R_1 ratio was observed clearly at impact energy of 7.77 J and above (in contrast to 1.45 J for Specimen A).

CONCLUSIONS

Damage of continuous carbon fiber epoxy–matrix composite in the form of a filament-wound cylinder was effectively monitored by the electrical resistance measurement. The four-probe method was used. Circumferential electrical contacts on the outer and/or inner surfaces of the cylinder were used for axial, radial, and oblique resistance measurements. Axial electrical contacts on the outer surface were used for circumferential resistance ratio (R_2/R_1) measurement. This ratio was the ratio of the circumference resistance of a damage area to that of an area away from the damaged area.

The minor damage upon drop impact at 10 J or less caused the radial resistance to decrease, but negligible change in the axial and oblique resistances, due to increase in proximity of the fiber layers to one another, whereas major damage upon drop impact above $\approx$10 J caused the radial resistance, the oblique resistance, and the axial resistance to increase, due to delamination. The circumferential resistance ratio R_2/R_1 was most sensitive, increasing monotonically upon damage (whether minor or major) at impact energy $>$1.4 J.

REFERENCES

Abry, J.C. and Choi, Y.K. 2001. "*In situ* Monitoring of Damage in CFRP Laminates by Means of AC and DC Measurements," *Compos. Sci. Technol.*, 61(6):855–864.

Brooks, D., Hayes, S., Khan, N., Zolfaghar, K., Fernando, G.F. and Bellingham, W.A. 1997. "Self-Sensing E-Glass Fiber Reinforced Composites," In: *Proc. of SPIE – The International Society for Optical Engineering, Smart Sensing, Processing and Instrumentation*, Vol. 3042, pp. 111–119.

Ceysson, O., Salvia, M. and Vincent, L. 1995. "*In situ* Study of the Evolution of Various Damage Factors in Long Carbon Fiber/Polymer Matrix Composites to Measure Electric Resistance and Acoustic Emission," In: *Annales des Composites, Micromecanique et Mechanismes de lEndommagement des Composites*, Vol. 4, Paris, pp. 173–182.

Chung, D.D.L. and Wang, S. 2003. "Self-Sensing of Damage and Strain in Carbon Fiber Polymer-Matrix Structural Composites by Electrical Resistance Measurement," *Polym. & Polym. Compos.*, 11(7):515–525.

Hayes, S., Brooks, D., Liu, T., Vickers, S. and Fernando, G.F. 1996. "*In situ* Self-Sensing Fiber-Reinforced Composites," In: *Proc. of SPIE – The International Society for Optical Engineering, Smart Sensing, Processing, and Instrumentation*, Vol. 2718, pp. 376–384.

Hayes, S., Liu, T., Brooks, D., Monteith, S., Ralph, B., Vickers, S. and Fernando, G.F. 1997. "*In situ* Self-Sensing Fiber Reinforced Composites," *Smart Mater. Struct.*, 6(4):432–440.

Kemp, R.M.J., Williamson, N.J. and Curtis, P.T. 1996. "Self-Sensing Smart Polymer Composites," *IMechE Seminar, Aircraft Structures and Materials*, 10:47–54.

Kister, G., Ralph, B. and Fernando, G.F. 2004. "Damage Detection in Glass Fibre-Reinforced Plastic Composites using Self-Sensing E-Glass Fibres," *Smart Mater. Struct.*, 13(5): 1166–1175.

Kupke, M., Schulte, K. and Schuler, R. 2001. "Non-Destructive Testing of FRP by D.C. and A.C. Electrical Methods," *Compos. Sci. Technol.*, 61(6):837–847.

Mitrovic, M., Carman, G.P. and Covina, C.A. 1994. "Monitoring the Fatigue Behavior of Composite Materials With Fiber Optic Sensors," In: *International SAMPE Symposium and Exhibition, Moving Forward with 50 Years of Leadership*, Vol. 39, pp. 3078–3090.

Takeda, N. 2000. "Structural Health Monitoring for Smart Composite Structure Systems in Japan," *Annales de Chimie (Paris)*, 25(7):545–549.

Wang, X. and Chung, D.D.L. 1996. "Continuous Carbon Fiber Epoxy-Matrix Composite as a Sensor of Its Own Strain," *Smart Mater. Struct.*, 5(6):796–800.

Wang, X. and Chung, D.D.L. 1997a. "Sensing Delamination in a Carbon Fiber Polymer-Matrix Composite During Fatigue by Electrical Resistance Measurement," *Polymer Composites*, 18(6):692–700.

Wang, X. and Chung, D.D.L. 1997b. "Real-Time Monitoring of Fatigue Damage and Dynamic Strain in Carbon Fiber Polymer-Matrix Composite by Electrical Resistance Measurement," *Smart Mater. Struct.*, 6(4):504–508.

Wang, X., Fu, X. and Chung, D.D.L. 1998a. "Electromechanical Study of Carbon Fiber Composites," *J. Mater. Res.*, 13(11):3081–3092.

Wang, X. and Chung, D.D.L. 1998a. "Self-Monitoring of Fatigue Damage and Dynamic Strain in Carbon Fiber Polymer-Matrix Composite," *Composites: Part B*, 29B(1):63–73.

Wang, X. and Chung, D.D.L. 1998b. "An Electromechanical Study of the Transverse Behavior of Carbon Fiber Polymer-Matrix Composite," *Composite Interfaces*, 5(3):191–199.

Wang, S., Shui, X., Fu, X. and Chung, D.D.L. 1998b. "Early Fatigue Damage in Carbon-Fiber Composites Observed by Electrical Resistance Measurement," *J. Mater. Sci.*, 33(15):3875–3884.

Wang, X. and Chung, D.D.L. 1999. "Fiber Breakage in Polymer-Matrix Composite During Static and Dynamic Loading, Studied by Electrical Resistance Measurement," *J. Mater. Res.*, 14(11):4224–4229.

Wang, S. and Chung, D.D.L. 1999a. "Interlaminar Shear in Carbon Fiber Polymer-Matrix Composites, Studied by Measuring the Contact Electrical Resistance of the Interlaminar Interface During Shear," *Composite Interfaces*, 6(6):507–518.

Wang, S. and Chung, D.D.L. 1999b. "Temperature/Light Sensing Using Carbon Fiber Polymer-Matrix Composite," *Composites: Part B*, 30(6):591–601.

Wang, X., Wang, S. and Chung, D.D.L. 1999. "Sensing Damage in Carbon Fiber and Its Polymer-Matrix and Carbon-Matrix Composites by Electrical Resistance Measurement," *J. Mater. Sci.*, 34(11):2703–2714.

Wang, S. and Chung, D.D.L. 2001. "Thermal Fatigue in Carbon Fiber Polymer-Matrix Composite, Monitored in Real Time by Electrical Resistance Measurement," *Polym. & Polym. Compos.*, 9(2): 135–140.

Wang, S., Mei, Z. and Chung, D.D.L. 2001. "Interlaminar Damage in Carbon Fiber Polymer-Matrix Composites, Studied by Electrical Resistance Measurement," *Int. J. Adh. Adh.*, 21(ER6):465–471.

Wang, S. and Chung, D.D.L. 2002. "Mechanical Damage in Carbon Fiber Polymer-Matrix Composite, Studied by Electrical Resistance Measurement," *Composite Interfaces*, 9(1):51–60.

Wang, S., Kowalik, 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(3):570–592.

Wang, S., Chung, D.D.L. and Chung, J.H. 2005a. "Effects of Composite Lay-Up Configuration and Thickness on the Damage Self-Sensing Behavior of Carbon Fiber Polymer-Matrix Composite," *J. Mater. Sci.*, 40(3):561–568.

Wang, S., Chung, D.D.L. and Chung, J.H. 2005b. "Impact Damage of Carbon Fiber Polymer-Matrix Composites, Monitored by Electrical Resistance Measurements," Composites: Part A, 36:1707–1715.

Yanagida, H. 2000. "Intelligent Materials for Environment and People," *Materials & Design*, 21(6):507–509.

Zolfaghar, K., Khan, N., Brooks, D., Hayes, S., Liu, T., Roca, J., Lander, J., Fernando, G.F. and Bellingham, W.A. 1998. "Quartz and E-Glass Fiber Self-Sensing Composites," In: *Proc. of SPIE – The International Society for Optical Engineering, Smart Materials, Structures, and MEMS*, Vol. 3321, pp. 314–328.