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# An electromechanical study of the transverse behavior of carbon fiber polymer–matrix composite

XIAOJUN WANG and D. D. L. CHUNG

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

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**Abstract**—The transverse behavior of continuous carbon fiber epoxy–matrix composite was studied by measuring the 0° electrical resistance of a $[90]_{32}$ composite during 0° tension and compression. The number of fiber–fiber contacts was found to decrease by 0.7% upon tension to 0.5% strain (resistance increasing) and increase by 1.1% upon compression to −0.5% strain (resistance decreasing), such that this number decreased with increasing strain and the resistance varied linearly with strain (fractional resistance change per unit strain = 2), until damage (probably matrix cracking) occurred and caused the resistance to increase with compressive strain beyond 1% (84 MPa stress) and increase abruptly with tensile strain beyond 0.5% (43 MPa stress). Prior to damage, the resistance varied with strain reversibly; slight reversibility was due to plastic deformation of the matrix.

*Keywords*: Composite; polymer; carbon fiber; electrical resistance; transverse; electromechanical.

## 1. INTRODUCTION

In a continuous fiber composite, the fibers reinforce most effectively in the longitudinal direction (parallel to the fibers) and do not reinforce in the transverse direction (perpendicular to the fibers). The transverse behavior of the composite is governed by the matrix rather than by the fibers. The mechanical weakness in the transverse direction is a shortcoming of continuous fiber composites, although this problem may be circumvented by the use of multidirectional fibers in a composite.

In a unidirectional continuous fiber composite lamina described in textbooks, the parallel fibers appear to not touch one another, as they are separated by the matrix. However, in reality, due to the imperfect alignment of the fibers and the flow of the matrix material (e.g. the polymer resin) during composite fabrication, fiber–fiber contacts always exist, as indicated by the fact that the electrical resistivity of a unidirectional carbon fiber epoxy–matrix composite in the transverse direction (in the plane of the laminae) is not infinite. Several microstructural models have been proposed to explain the electrical conductivity of a lamina in the transverse direction [1–5].

Although electrical and mechanical measurements have been used separately in previous work to study the transverse behavior of continuous fiber composites, so simultaneous electrical and mechanical measurements (i.e. electrical measurement during mechanical loading, also called electromechanical testing) have been made previously to study the transverse behavior. In this work, by using electromechanical testing, we have obtained new information on the transverse behavior, particularly in relation to the fiber–fiber contacts and damage. Fiber–fiber contacts decrease the transverse resistivity whereas damage in the form of matrix cracking increases the transverse resistivity. The effect of applied stress on fiber–fiber contacts and damage is reported.

We have previously reported the use of electromechanical testing to study continuous carbon fiber epoxy–matrix composites in the longitudinal direction and in the through-thickness direction [6, 7]. In contrast, this work addresses the behavior in the transverse direction. Thus, a [90] composite was used in this work, whereas [0] composites were used in [6, 7].

The method presented in this paper applies to composites with continuous fibers that are electrically much more conducting than the matrix. It is not limited to carbon fiber composites. However, carbon fiber polymer–matrix composites were chosen for this work because of their dominance among advanced composites.

## 2. EXPERIMENTAL METHODS

Composite samples were constructed from individual layers cut from a 12 in wide unidirectional carbon fiber prepreg tape manufactured by ICI Fiberite (Tempe, AZ). The product used was Hy-E 1076E, which consisted of a 976 epoxy matrix and 10E carbon fibers. The fiber and matrix properties are shown in Table 1.

The composite laminates were laid up in a 4 × 7 in (102 × 178 mm) platen compression mold with laminate configuration $[90]_{32}$. The individual 4 × 7 in unidirectional

**Table 1.**
Carbon fiber and epoxy matrix properties (according to ICI Fiberite)

| | |
|---|---|
| 10 E – Torayca T-300 (6K) untwisted, UC-309 sized | |
| Diameter | 7 $\mu$m |
| Density | 1.76 g/cm$^3$ |
| Tensile modulus | 221 GPa |
| Tensile strength | 3.1 GPa |
| 976 Epoxy | |
| Process temperature | 350°F (177°C) |
| Maximum service temperature | 350°F (177°C) dry |
| | 250°F (121°C) wet |
| Flexural modulus | 3.7 GPa |
| Flexural strength | 138 MPa |
| $T_g$ | 232°C |
| Density | 1.28 g/cm$^3$ |

fiber layers (32 per laminate) were cut from the prepreg tape. The layers were stacked in the mold with a mold release film on the top and bottom of the layup. No liquid mold release was necessary. The density of the laminate was $1.52 \pm 0.03$ g/cm$^3$. The thickness of the laminate was 4.5 mm. The volume fraction of carbon fibers in the composite was 58%. The laminates were cured using a cycle based on the ICI Fiberite C-5 cure cycle. The curing occurred at $179\pm6$°C ($355\pm10$°F) and 0.61 MPa (89 psi) for 120 min. Afterwards, they were cut to pieces of size $160 \times 14$ mm for tensile testing and $100 \times 10$ mm for compressive testing. Glass fiber reinforced epoxy end tabs were applied to both ends on both sides of each piece, such that each tab was 30 mm long and the inner edges of the end tabs on the same side were 100 mm apart. The tensile strength was $62\pm4.9$ MPa. The tensile ductility was $(0.74\pm0.08)$%. The Poisson ratio was 0.05. The electrical resistivity in the 0° direction was 5.74 Ω cm; that in the through-thickness direction was 6.25 Ω cm.

The electrical resistance $R$ was measured in the 0° direction using the four-probe method while either static or cyclic tension or compression was applied in the 0° direction. The fibers were in the 90° direction. Silver electrically conducting paint was used for all electrical contacts. The four probes consisted of two outer current probes and two inner voltage probes. The resistance $R$ refers to the sample resistance between the inner probes. To measure $R$ in the 0° direction (the stress axis), the four electrical contacts were placed around the whole perimeter of the sample in four parallel planes that were perpendicular to the stress axis, such that the inner probes were 60 mm apart and the outer probes were 80 mm apart. A Keithley 2001 multimeter was used for DC electrical measurement. The displacement rate was 0.5 mm/min. A hydraulic mechanical testing system (MTS 810) was used for loading in the 0° direction. A resistive strain gage (Micromeasurements Group, #991117) was attached to the center of each specimen on a surface parallel to the applied stress for measurement of strain in the stress direction.

## 3. RESULTS AND DISCUSSION

### *3.1. Static loading*

The fractional change in electrical resistance ($\Delta R/R_o$) in the loading (0°) direction was measured during static tensile and compressive loading up to fracture. Figures 1 and 2 show the tensile stress, strain and $\Delta R/R_o$ in the loading direction, obtained simultaneously during tensile and compressive testing, respectively. The $\Delta R/R_o$ in the loading direction increases nearly linearly with tensile strain up to 0.5% (Fig. 1), and then increases more shaxply with strain until failure. In the compressive case, as shown in Fig. 2, $\Delta R/R_o$ in the loading direction decreases linearly with compressive strain up to 0.9%, reaches a minimum, and beyond 1.1% strain, $\Delta R/R_o$ sharply increases until the specimen fails.

The 0° $\Delta R/R_o$ was calculated by using the equation

$$\frac{\Delta R}{R_o} = \frac{\rho(1+\varepsilon)}{\rho_o(1-2\nu\varepsilon)} - 1,$$

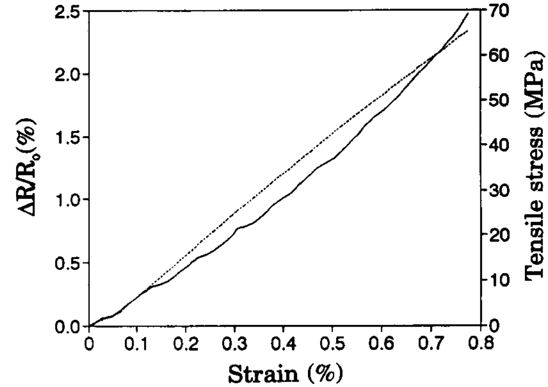


**Figure 1.** Tensile stress, strain and $\Delta R/R_0$ in the 0° direction of unidirectional [90] composite obtained simultaneously during static tension up to fracture, which occurs at the highest strain in the curve. Solid curve: $\Delta R/R_0$ *vs* strain. Dashed curve: tensile stress *vs* strain.

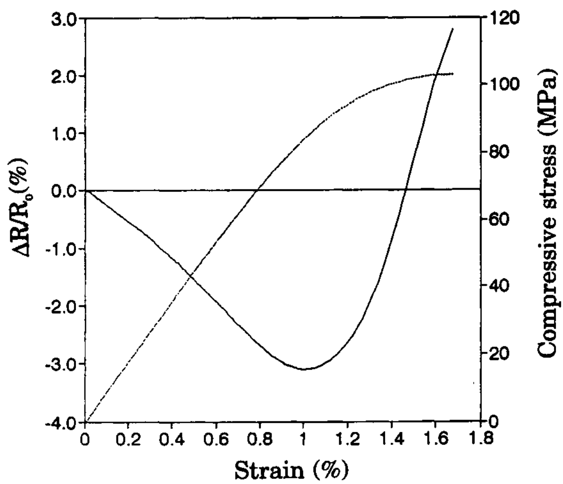


**Figure 2.** Compressive stress, strain and $\Delta R/R_0$ in the 0° direction of unidirectional [90] composite obtained simultaneously during static tension up to fracture, which occurs at the highest strain in the curve. Solid curve: $\Delta R/R_0$ *vs* strain. Dashed curve: tensile stress *vs* strain.

where $\rho = 0°$ resistivity under load, $\rho_0 = 0°$ resistivity under no load, $\varepsilon = 0°$ strain, and $\nu =$ Poisson ratio, such that it was assumed that $\rho = \rho_0$, i.e. the resistivity was assumed to be constant. In other words, $\Delta R/R_0$ was calculated by assuming that the resistance change was all due to dimensional change and not due to resistivity change. Furthermore, the material was assumed to be homogeneous. Table 2 shows the calculated and measured $\Delta R/R_0$ values. The magnitudes of the calculated $\Delta R/R_0$ values are less than the magnitudes of the measured values, indicating that dimensional changes cannot totally explain the observed resistance increase.

The 0° conduction for the [90] composite depends on the fiber–fiber contacts. As the polymer matrix is not conductive, the contact resistivity of the fiber–matrix interface does not affect the 0° resistance, even though the contact resistivity is expected to

**Table 2.**
0° $\Delta R/R_o$ and $\Delta\rho/\rho_o$ ($R$ = resistance, $\rho$ = resistivity) for unidirectional [90] composite during 0° static tensile and compressive testing

| Strain (%) | Calculated $\Delta R/R_o$ (%) | Measured $\Delta R/R_o$ (%) | Measured $\Delta\rho/\rho_o$ (%) |
|---|---|---|---|
| Tension | | | |
| 0.1 | 0.11 | 0.18 | 0.07 |
| 0.2 | 0.22 | 0.34 | 0.12 |
| 0.3 | 0.33 | 0.63 | 0.30 |
| 0.4 | 0.44 | 1.01 | 0.56 |
| 0.5 | 0.55 | 1.23 | 0.68 |
| Compression | | | |
| −0.2 | −0.21 | −0.51 | −0.30 |
| −0.3 | −0.32 | −0.82 | −0.50 |
| −0.4 | −0.42 | −1.23 | −0.81 |
| −0.5 | −0.53 | −1.61 | −1.08 |
| −0.6 | −0.63 | −2.11 | −1.48 |
| −0.8 | −0.88 | −2.51 | −1.65 |

increase during 0° tension due to transverse residual compressive stress reduction. The 0° tensile loading tends to decrease the fiber–fiber contacts. Therefore, the 0° resistivity increases with tensile strain (Table 2). In the case of 0° compression, the compressive loading tends to increase the fiber–fiber contacts. Therefore, the resistance decreases with compressive strain. The magnitude of the measured $\Delta R/R_o$ is larger than that of the calculated $\Delta R/R_o$, as shown in Table 2. This is because compression not only reduces the distance between adjacent carbon fibers, but also causes some contacts between neighboring fibers.

Beyond 1.1% compressive strain, the resistance increases due to the damage (presumably in the form of matrix cracks), as indicated by the slope change of the stress–strain curve at ~ 1% strain (Fig. 2). The more abrupt increase in resistance beyond 0.5% tensile strain (Fig. 1) is also due to damage (presumably in the form of matrix cracks). Matrix cracks cutting off fiber–fiber contacts cause local open circuit conditions in relation to 0° conduction, so they cause the 0° resistance to increase.

Each 0° conduction path is actually a tortuous path involving conduction through the fiber–fiber contacts as well as conduction through the 90° fibers. However, the resistance of each path is dominated by the resistance of the fiber–fiber contacts. The number of tortuous conduction paths ($N$) is huge and different paths are different in resistance. Nevertheless, for simplification, we consider an average value ($R_i$) for the resistance of a path and assume that all the paths exhibit the average resistance.

Prior to damage, the resistance ($R$) change upon strain is partly due to dimensional changes and partly due to the change in the number of fiber–fiber contacts. The resistivity ($\rho$) change, on the other hand, is just due to the change in the number of fiber–fiber contacts. Hence, the resistivity change is related to the change in the number of fiber–fiber contacts, as shown mathematically below by considering that there are $N_o$ 0° conduction paths at strain = 0 (resistivity = $\rho_o$) and $N$ 0° conduction paths at a general value of strain (resistivity = $\rho$), and that the average resistance of each 0° conduction path is $R_i$. Since the various 0° conduction paths are electrically equivalent to resistors in parallel, the total resistance $R$ is given by

$$R = \frac{R_i}{N}.$$

The change in resistivity $\Delta\rho$ is proportional to the change in the total resistance, so

$$\Delta\rho \propto \frac{R_i}{N} - \frac{R_i}{N_o}.$$

Thus,

$$\frac{\Delta\rho}{\rho_o} = \frac{N_o}{N} - 1,$$

or

$$\frac{N}{N_o} = \frac{\rho_o}{\Delta\rho + \rho_o}. \tag{1}$$

Since the number of 0° conduction paths is proportional to the number of fiber–fiber contacts, $N/N_o$ is equal to the ratio of the number of fiber–fiber contacts to the number at strain = 0. By measurement, $\rho_o = 5.74\ \Omega\,\text{cm}$. Hence, $N/N_o$ can be calculated from $\Delta\rho$, which is measured at each strain (Table 2), using equation (1). The result is shown in Fig. 3, where $N/N_o$ is plotted *vs* strain (positive for tension and negative for compression). Figure 3 shows that the number of fiber–fiber contacts decreases by 0.7% upon tension to 0.5% strain and increases by 1.1% upon compression to −0.5% strain. This number decreases monotonically with increasing strain, such that it is affected by compression more severely than by tension at the same strain magnitude.

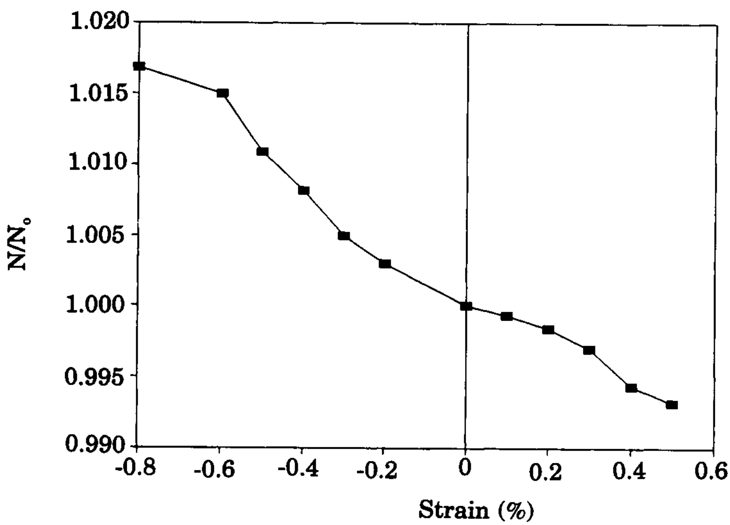


**Figure 3.** Plot of $N/N_o$ *vs* strain, where $N$ is the number of fiber–fiber contacts and $N = N_o$ at strain = 0.

### *3.2. Dynamic loading*

Both dynamic tensile loading and compressive loading were conducted on the [90] composite. Figure 4 shows the 0° tensile stress, 0° tensile strain and 0° $\Delta R/R_0$ obtained simultaneously during cyclic 0° tension at a stress amplitude of 66% of the fracture stress. The 0° resistance increases linearly upon tensile loading and decreases linearly upon unloading. The strain is not totally reversible due to plastic deformation, which is attributed to the polymer matrix, as the polymer matrix dominates the transverse mechanical properties. As a result, the resistance increase is not totally reversible. The values of both reversible and irreversible parts of $\Delta R/R_0$ increase with the stress amplitude, as shown in Table 3.

Figure 5 is a plot of 0° compressive stress, 0° compressive strain and 0° $\Delta R/R_0$ obtained simultaneously during cyclic 0° compression at a stress amplitude of 45% of the fracture stress. The $\Delta R/R_0$ decreases linearly upon compressive loading and increases upon unloading. There is a small irreversible part in the resistance change. Table 3 lists the reversible and irreversible parts at different stress levels. Both reversible and irreversible parts of $\Delta R/R_0$ increase with the stress amplitude.

The reversible change in resistance during cyclic tension and compression (Figs 4 and 5) is attributed to dimensional changes and change in the number of fiber–fiber contacts. The irreversible change, though slight, is attributed to plastic deformation of the matrix.

The strain sensitivity ($\Delta R/R_0$ per unit strain) is indicated in Table 3. For both tension and compression, the value is about 2 and is independent of the strain. This

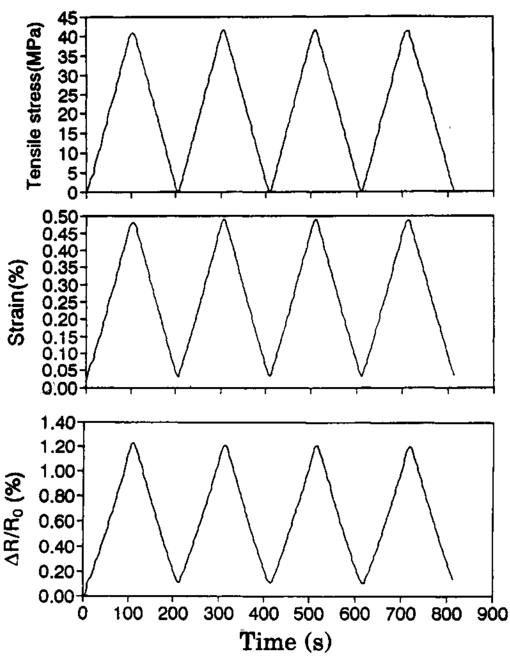


**Figure 4.** Tensile stress, strain and $\Delta R/R_0$ in the 0° direction of unidirectional [90] composite obtained simultaneously during cyclic tension at a stress amplitude equal to 66% of the fracture stress.

**Table 3.**
Reversible and irreversible parts of 0° $\Delta R/R_0$ for unidirectional [90] composite at various stress/strain amplitudes during 0° cyclic tension and compression

| Maximum stress / Fracture stress | Strain (%) | $\Delta R/R_0$ (%) Reversible | $\Delta R/R_0$ (%) Irreversible | Strain sensitivity |
|---|---|---|---|---|
| Tension | | | | |
| 18% | 0.13 | 0.32 | 0.04 | 2.4 |
| 47% | 0.34 | 0.80 | 0.08 | 2.4 |
| 66% | 0.47 | 1.13 | 0.11 | 2.4 |
| Compression | | | | |
| 20% | −0.22 | −0.48 | −0.02 | 2.2 |
| 31% | −0.34 | −0.74 | −0.03 | 2.2 |
| 45% | −0.48 | −1.03 | −0.05 | 2.1 |

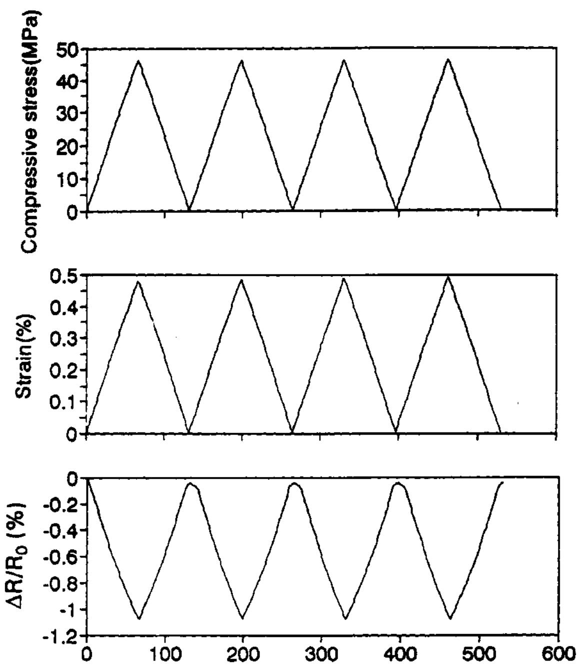


**Figure 5.** Compressive stress, strain and $\Delta R/R_0$ in the 0° direction of unidirectional [90] composite obtained simultaneously during cyclic compression to a stress smplitude equal to 45% of the fracture stress.

independence is consistent with the observed linear relationship between $\Delta R/R_0$ and strain (Figs 4 and 5). Although the strain sensitivity (also called gage factor) is not particularly large, the linearity makes the [90] composite a potentially attractive strain sensor. The strain sensitivity is higher for the [0] composite, but the linearity is worse [6].

## 4. CONCLUSION

The transverse behavior of continuous carbon fiber epoxy–matrix composite was studied on a [90] unidirectional composite by electromechanical testing, in which the electrical resistance in the 0° (transverse) direction was measured during tension and compression in the same direction. The number of fiber–fiber contacts was found to decrease by up to 0.7% upon tension up to 0.5% strain (resistance increasing) and increase by up to 1.7% upon compression up to 0.8% strain (resistance decreasing), such that the resistance varied linearly with strain/stress. This linearity corresponds to a strain sensitivity of about 2 and allows the [90] composite to function as a strain sensor. The slight irreversibility of strain and resistance changes was due to plastic deformation of the epoxy matrix. Damage, presumably in the form of matrix cracks, was found to begin at a compressive strain of 1% (compressive stress of 84 MPa), as shown by resistance increasing with strain, in contrast to the decrease of the resistance with strain at lower strains. Similar damage probably began at a tensile strain of 0.5% (tensile stress of 43 MPa), as the resistance increased with strain more sharply than linearly when the tensile strain exceeded 0.5%.

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