Short-carbon-fiber-reinforced epoxy as a piezoresistive strain sensor

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Short-carbon-fiber-reinforced epoxy as a piezoresistive strain sensor

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Abstract. Epoxy containing 5.5 vol.% short carbon fibers was found to be piezoresistive strain sensor, such that the magnitude of the reversible fractional increase in electrical resistance per unit strain was 6–23 under tension and 29–31 under compression. These values are much higher than those of previously reported composite piezoresistive materials. The reversible fractional increase in resistance was positive under tension and negative under compression, but the irreversible fractional increase in resistance was positive under both tension and compression. Both reversible and irreversible fractional increases in resistance increased in magnitude with increasing stress/strain amplitude. The reversible portion was due to piezoresistivity, while the irreversible portion was due to damage.

1. Introduction

Strain sensing is a basic ability of smart structures. For this purpose, strain sensors are commonly embedded in or attached to a structure. Strain sensors include piezoelectric, electrostrictive, magnetostrictive, piezoresistive, acoustic and optical fiber sensors. In response to strain, these sensors give a signal, which can be electrical, magnetic, optical or acoustic. The sensing of damage is less demanding than that of reversible strain. For example, acoustic emission detectors can sense damage, but not reversible strain.

Among the various strain sensors, piezoresistive sensors are particularly attractive because (i) they can sense reversible strain and (ii) in the form of a polymer–matrix composite with an electrically conducting filler, they are relatively inexpensive and can be easily molded or even applied as coatings. Composite piezoresistive sensors work because strain changes the proximity between the conducting filler units, thus affecting the electrical resistivity. Tension increases the distance between the filler units, thus increasing the resistivity; compression decreases this distance, thus decreasing the resistivity.

Previously investigated composite piezoresistive materials include polymer–matrix composites containing continuous carbon fibers [1], carbon black [2–4], metal particles [3] and short carbon fibers [4], and ceramic–matrix composites containing silicon carbide whiskers [5]. The sensing of reversible strain had been observed only in polymer–matrix composites [1–3]. In spite of the previous work mentioned above, a quantitative description of the sensitivity to reversible strain and the effect of sensor damage during straining on the sensor response was not available to allow comparison among the various piezoresistive materials. Furthermore, the strain sensitivity (i.e., fractional increase in resistivity per unit strain) could be obtained from the published data only for the case of materials under tension (not under compression). In addition, the strain was contained only in the data for polymer–matrix composites with continuous carbon fibers [1] or carbon black [2]. The field of piezoresistive materials is clearly still in its infancy.

In this work, the piezoresistive behavior of polymer–matrix composites containing short carbon fibers was studied, with the purpose of developing a strain sensor that has high strain sensitivity and that can be used as coatings as well as bulk materials. In contrast, composites with continuous fibers can not be applied as coatings. The applicability as a coating enhances the practical usefulness of the sensor, as the coating may be applied to a large range of materials. Moreover, the discontinuous and randomly oriented nature of the fibers is expected to enhance the strain sensitivity compared to continuous fibers; the large aspect ratio of the short fibers compared to carbon black is expected to enhance the strain sensitivity compared to the carbon black composites. Indeed, by the use of short carbon fibers, we have attained strain sensitivities that are much higher than all that had previously been reported.

2. Experimental details

The electrical resistance R was measured with a Keithley 2001 multimeter using the four-probe method while cyclic tension or cyclic compression was applied. Silver paint was used for electrical contacts. The four probes consist of two outer current probes and two inner voltage probes. The resistance R refers to the sample resistance between the inner probes. The distance between the inner probes was 50 and 25 mm for tensile and

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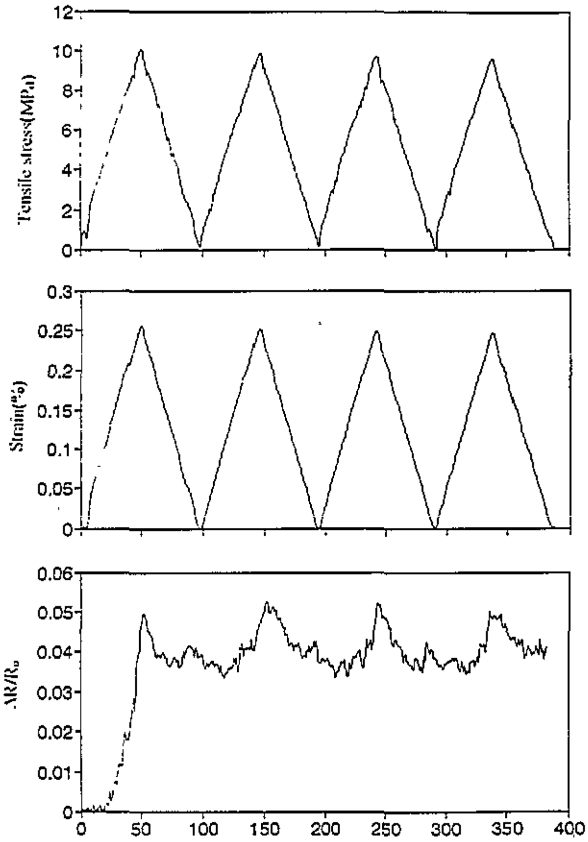

Figure 1. Plots against time of $\Delta R/R_0$, tensile strain and tensile stress obtained during cyclic tensile testing at a stress amplitude of 27%.

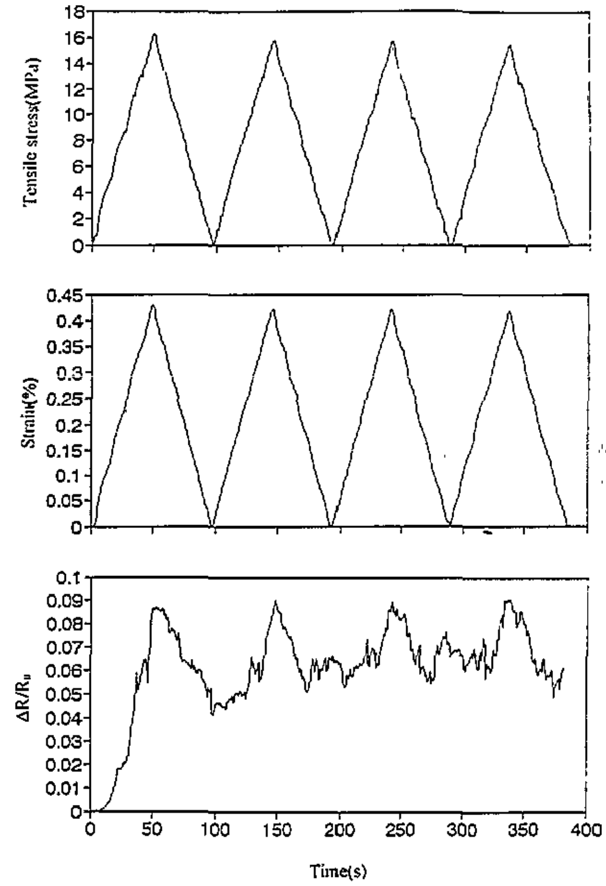

Figure 2. *Plots against time of $\Delta R/R_0$, tensile strain and tensile stress obtained during cyclic tensile testing at a stress amplitude of 44%.*

compressive samples respectively. The tensile samples were of size 80 mm×8.5 mm×3.8 mm; the compressive samples were of size 32 mm×9 mm×6 mm. The resistance was measured along the stress axis. The current (DC) used was 0.5–1.0 mA; the voltage used was 2.0–2.4 V. The displacement rate was 1.0 mm min^{-1} under tension and 0.5 mm min^{-1} under compression. The strain under tension was measured by a strain gage; the strain under compression was measured using the displacement. Tensile testing was conducted using a hydraulic mechanical testing system (MTS 800); compressive testing was conducted using a screw type mechanical testing system (Sintech 2/D).

The composite samples had epoxy (Epon(R) 862 bisphenol F/epichlorohydrin epoxy resin and 3274 curing agent (a mixture of polyoxyalkyleneamine and nonyl phenol), from Shell Chemical Co.) as the matrix and short carbon fibers (5 mm long, resistivity 3×10^{-3} Ω cm, pitch based, unsized, from Ashland Petroleum Co., Ashland, KY) as the filler. The fiber volume fraction was 5.5 vol.%. The composites were fabricated by mixing the fibers with the epoxy resin, putting the mixture in a rough vacuum to remove bubbles, and then curing at room temperature for 24 h.

Figures 1–4 show the stress, strain and fractional resistance increase ($\Delta R/R_0$) obtained simultaneously during cyclic tension to a maximum stress equal to $27\%, 44\%, 61\%$ and 72% of the breaking stress respectively. The strain is totally reversible at all these stress amplitudes. Because of the small strains involved, $\Delta R/R_0$ is essentially equal to the fractional increase in resistivity. The value of $\Delta R/R_0$ increases upon first tensile loading and then decreases upon unloading to a level above the initial zero value. Reloading causes $\Delta R/R_0$ to increase again and subsequent unloading behaves in a manner similar to the first unloading. That $\Delta R/R_0$ does not return to the original value after the first cycle indicates the occurrence of irreversible damage during the first loading, even though the strain is totally reversible. Figures 1–4 show that there are two portions to $\Delta R/R_0$—one portion is irreversible while the other portion is reversible. Table 1 lists these portions to various stress/strain amplitudes. The irreversible portion increases with strain amplitude up the highest strain amplitude used, whereas the reversible portion increases with strain amplitude up to a strain amplitude of 62% of the fracture strain. The irreversible portion exceeds the reversible portion at the lowest stress amplitude (27%), but is less than the reversible portion for all other stress amplitudes (44%, 61% and 72%). Consistent with the cyclic tension results of figures 1–4 is the static tension result (up to fracture) of figure 5. $\Delta R/R_0$ increases monotonically with strain up to fracture. At low strains, $\Delta R/R_0$ is mainly due to piezoresistivity; at high strains, $\Delta R/R_0$ is mainly due to fiber breakage.

Figures 6–9 show the stress, strain and $\Delta R/R_0$ obtained simultaneously during cyclic compression to a maximum

Table 1. Reversible and irreversible portions of $\Delta R/R_0$ for various stress/strain amplitudes during cyclic tension.

Maximum stress Fracture stress (%)	Maximum strain Fracture strain (%)	Maximum strain (%)	$\Delta R/R_0$	
			Reversible	Irreversible
27	26	0.25	0.015	0.035
44	44	0.42	0.047	0.043
61	62	0.61	0.140	0.060
72	72	0.71	0.135	0.11

Table 2. Reversible and irreversible portions of $\Delta R/R_0$ for various stress/strain amplitudes during cyclic compression.

Maximum stress / Fracture stress (%)	Maximum strain / Fracture strain (%)	Maximum strain (%)	$\Delta R/R_0$	
			Reversible	Irreversible
27	23	0.81	−0.25	0.11
44	38	1.32	−0.38	0.23
61	52	1.83	−0.56	0.35
72	62	2.16	−0.66	0.48

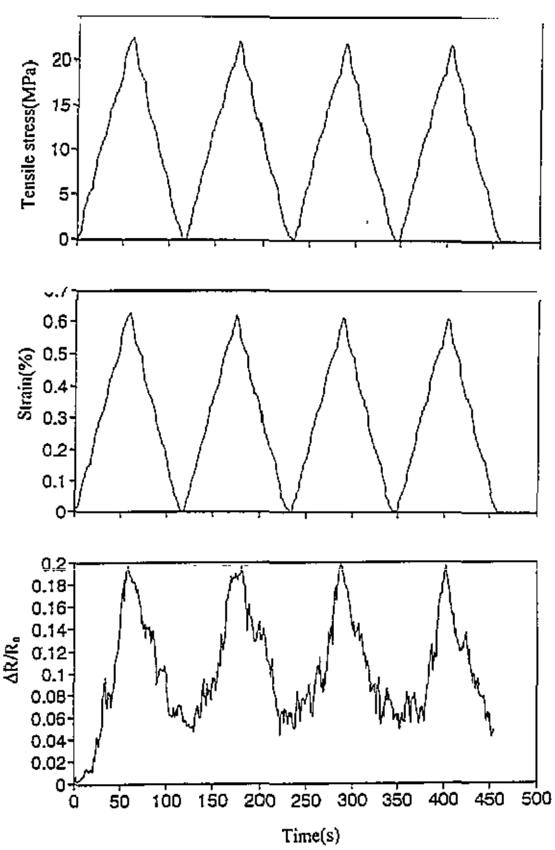

Figure 3. *Plots against time of $\Delta R/R_0$, tensile strain and tensile stress obtained during cyclic tensile testing at a stress amplitude of 61%.*

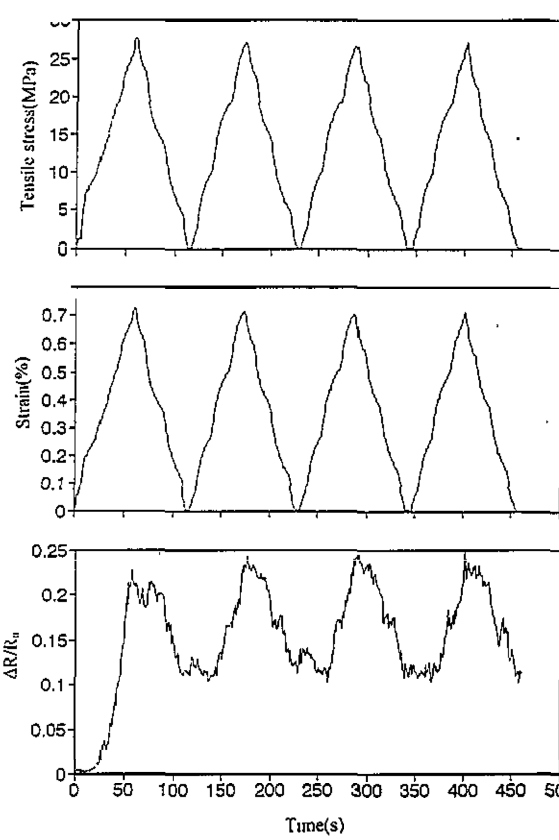

Figure 4. Plots against time of $\Delta R/R_0$, tensile strain and tensile stress obtained during cyclic tensile testing at a stress amplitude of 75%.

stress equal to 27%, 44%, 61% and 72% of the breaking stress respectively. The strain is totally reversible at all these stress amplitudes. Because of the small strains involved, $\Delta R/R_0$ is essentially equal to the fractional increase in resistivity. The value of $\Delta R/R_0$ decreases upon first compressive loading and then increase upon unloading to a level above the initial zero value. Reloading causes $\Delta R/R_0$ to decrease to the same low level as that during first loading and subsequent unloading causes $\Delta R/R_0$ to increase to the same high level as that after first unloading. Subsequent cycles are all similar in behavior. That $\Delta R/R_0$ does not return to the original zero value

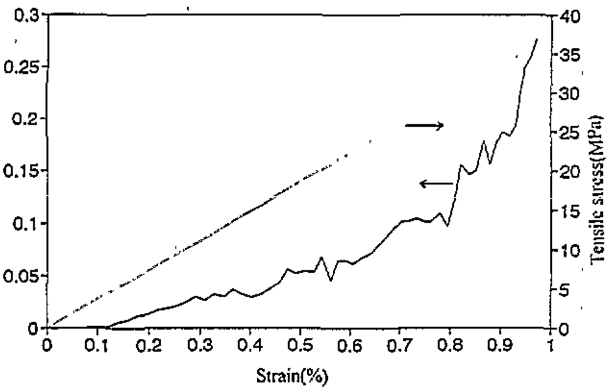

Figure 5. Plots against strain of tensile stress and $\Delta R/R_0$ during static tensile testing up to fracture.

Table 3. Strain sensitivity.

Maximum stress	Strain sensitivity	
Fracture stress (%)	Tension	Compression
27	6	31
44	11	29
61	23	31
72	19	31

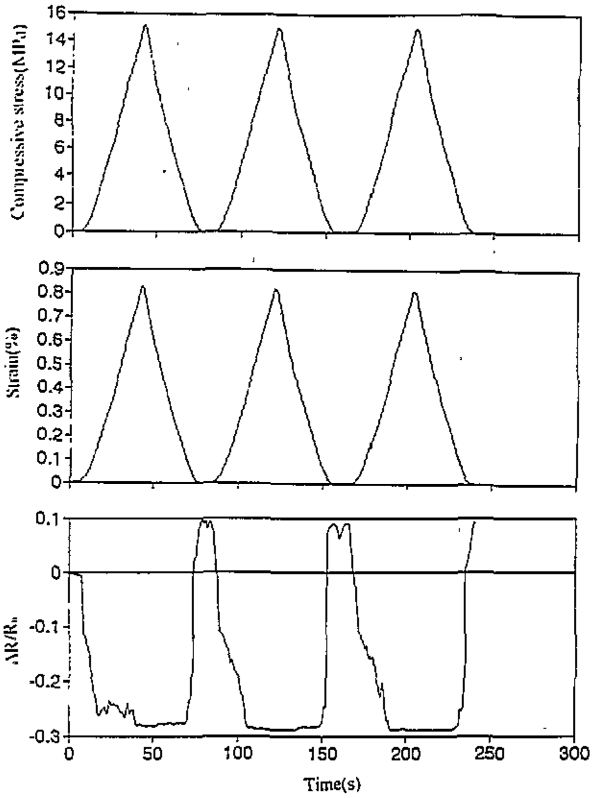

Figure 6. Plots against time of $\Delta R/R_0$, compressive strain and compressive stress obtained during cyclic compressive testing at a stress amplitude of 27%.

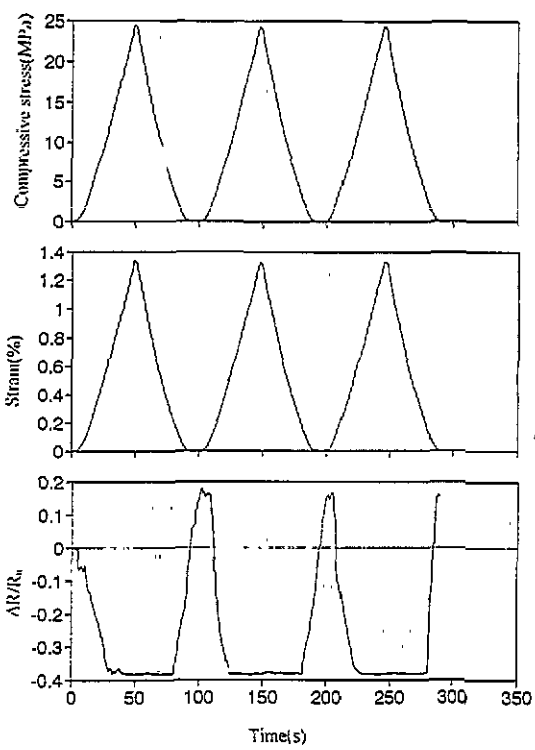

Figure 7. Plots against time of $\Delta R/R_0$, compressive strain and compressive stress obtained during cyclic compressive testing at a stress amplitude of 44%.

after the first cycle indicates the occurrence of irreversible damage during the first loading, even though the strain is totally reversible. Figures 6–9 show that there are two portions of $\Delta R/R_0$—one portion is irreversible while the other portion is reversible. Table 2 lists these portions for various stress/strain amplitudes. The magnitudes of both portions increase with strain amplitude up to the highest strain amplitude used. The irreversible portion is less than the magnitude to the reversible portion for all stress amplitudes. Consistent with the cyclic compression results of figures 6–9 is the static compression result (up to fracture) of figure 10. $\Delta R/R_0$ decreases with strain up to 2.3% due to piezoresistivity and then increases with strain (probably due to fiber breakage) when the strain exceeds 2.3%. Note that the strain of 2.3% is higher than any of the strains of table 2.

The irreversible portions in figures 1–5 and 6–9 are attributed to damage, probably related to a fiber–matrix contact resistivity increase (interface weakening) rather than fiber breakage, since the stress–strain relationship does not change during cycling in figures 1–5 and 6–9. The reversible portions are attributed to piezoresistivity.

Table 3 compiles the strain sensitivity under tension and compression. The strain sensitivity is defined as the reversible portion of $\Delta R/R_0$ per unit strain. It is also known as the gage factor. It is lower under tension than compression. Under compression, it is essentially independent of the stress amplitude (ratio of the maximum stress to the fracture stress). Under tension, it increases with stress amplitude up to 61%. The strain sensitivity obtained in this work is much higher than that of previous work, which attained strain sensitivity under tension in the range from 0.05 to two [1, 2]. This is attributed to the short fibers used in this work, in contrast to the continuous fibers used in [1] and carbon black used in [2]. The combination of a large aspect ratio and discontinuous nature of the filler favors a large strain sensitivity. The piezoresistive composites of

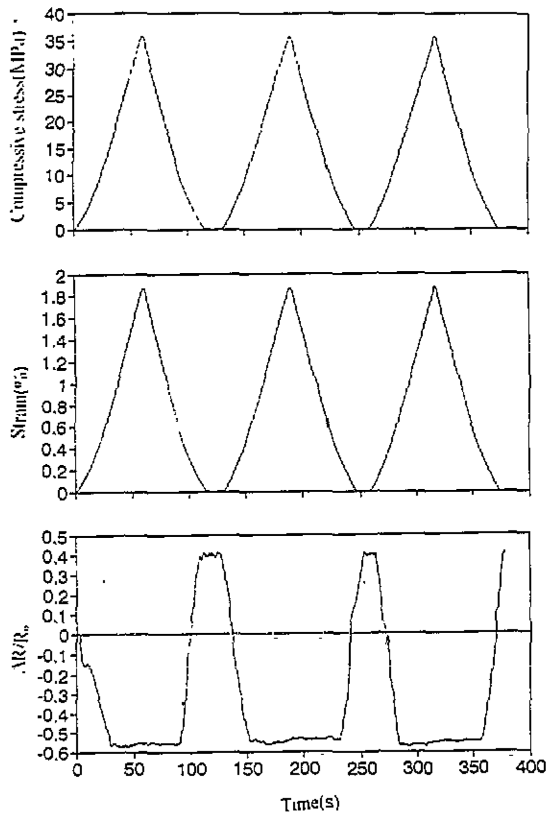

Figure 8. Plots against time of $\Delta R/R_0$, compressive strain and compressive stress obtained during cyclic compressive testing at a stress amplitude of 61%.

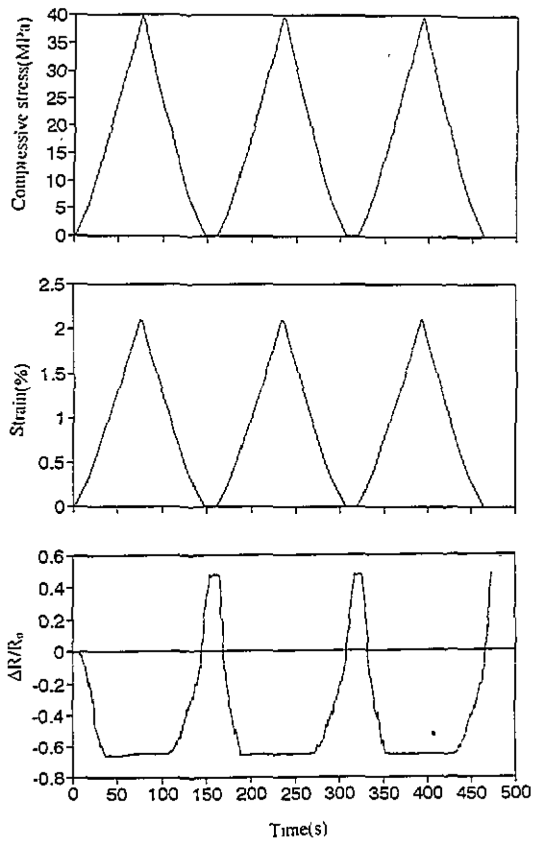

Figure 9. Plots against time of $\Delta R/R_0$, compressive strain and compressive stress obtained during cyclic compressive testing at a stress amplitude of 75%.

this work are attractive from the performance, cost and processability points of view.

3. Conclusion

Epoxy containing 5.5 vol.% short carbon fibers was found to be a piezoresistive strain sensor with a higher strain sensitivity than previously reported piezoresistive strain sensors. The strain sensitivity (reversible $\Delta R/R_0$ per unit strain) is 6–23 under tension and 29–31 under compression within the elastic deformation regime. The reversible $\Delta R/R_0$ is positive under tension and negative under compression, but the irreversible $\Delta R/R_0$ is positive under both tension and compression. Both reversible and irreversible portions of $\Delta R/R_0$ increase in magnitude with increasing stress/strain amplitude. Except for cyclic tension at a low stress amplitude (27%), the irreversible portion is less than the reversible portion. The reversible portion is due to piezoresistivity, while the irreversible portion is due to damage (probably fiber–matrix interface weakening).

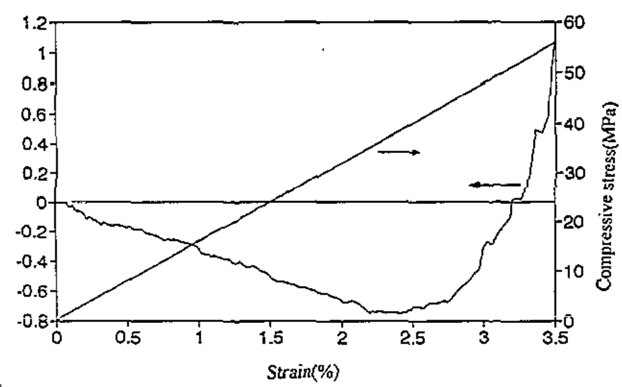

Figure 10. Plots against strain of compressive stress and $\Delta R/R_0$ during static compressive testing up to fracture.

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