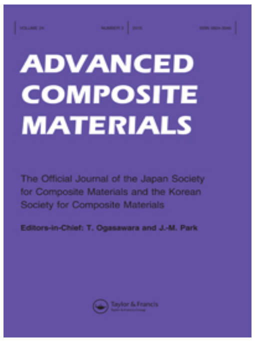

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Review of self-sensing of damage and interfacial evaluation using electrical resistance measurements in nano/micro carbon materials-reinforced composites

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Nondestructive evaluation methods have been utilized to detect and to prevent structural damage in research and development. Most such detection methods used expensive external sensors to detect damage. This paper explores the use of a less expensive electrical resistance measurement method for damage and strain sensing resulting from electrical signal variations, induced by stresses or shape changes in conductive materials. This method of damage sensing was performed first on carbon fibers composites, and in this study, its use is extended to conductive nanoparticles composites. Self-sensing can also be used to evaluate the interfacial properties of fiber-reinforced polymer composites. This electrical resistance measurement method had several advantages compared to other nondestructive evaluation methods such as better stability, lower cost, and being rather simple. Future plans are to include studies of this nondestructive method into the manufacturing and robotic fields.

Keywords: carbon fiber; polymer–matrix composites (PMCs); electrical properties; damage mechanics

1. Introduction

1.1. Methods of nondestructive Evaluation

It is important to prevent accidents, in cases where methods are available to estimate damage and potential failure, in structural materials.[1] Such damage originates from a variety of causes including accidents, natural disasters, mistakes in design, etc. A major goal in the development of nondestructive evaluation methods is to identify and clarify the status of potentially damaging structural features and changes. A number of methods have been proposed, developed, and explored for the nondestructive evaluation of composites, all with essentially this goal.[2–5]

A variety of nondestructive evaluation methods have been developed for use with different structural materials including X-ray, ultrasound, acoustic emission, analysis of electrical signals, etc.[6,7] In 1974, Huggins proposed a theory to find the cracks using the measured voltage in plate through hole (PTH). While voltage variations were dependent on crack growth, a major problem was that the crack growth resulted in relatively small changes in voltage in the crack growth direction.[8–10] Since then, due to the importance of the area, the diversity of materials used in structural applications

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(metals, plastics, composites, ceramics, etc.), the variety of different failure modes, etc., a number of nondestructive evaluation methods began to be developed. The occurrence and growth of a crack involve a variety of features and parameters; hence, evaluation methods are needed to identify the position, size, and other feature of cracks. Formally, most NDE primarily involved measurements of AE signals and events for the analysis and examination of damage. But, more recently other three-dimensional structural analysis and transmission forms are being developed to study damage location, degree of damage, and life prediction.[11–13]

1.2. Theory of electrical resistance measurement for damage sensing

Currently, application and use of composite materials are increasing in a variety of fields.[14,15] To perform nondestructive evaluation in composites, the addition of specific sensor and test systems might be viewed as a disadvantage.[16] In the case of a carbon-fiber-reinforced composite material, a new nondestructive evaluation method using electric conductivity of carbon fibers is being developed and used.[17–19] The basic electric resistance of carbon-fiber-reinforced composite is measured and used as a baseline. The change in electrical signal, due to applied stress, has been shown to be an effective means of detecting resistance-based damage. This method has been used to measure the onset and propagation of damage as well as for differentiating between different damage scenarios, in advanced composite materials.[20–22]

The changes in electrical resistance with the stress depend on the arrangement of the composite fiber array, and hence, on the direction of the measurement, that is, through the specimen thickness or in the side directions as shown in Figure 1.[23] Carbon fibers conduct electricity, and so they may be modeled as resistors in a carbon fabric in an insulating matrix as shown schematically in Figure 2. As fibers break, the current in those fibers is terminated and must find other conductive paths typically leading to an increase in electrical resistance, becoming infinite with the final fracture of the specimen.[24,25]

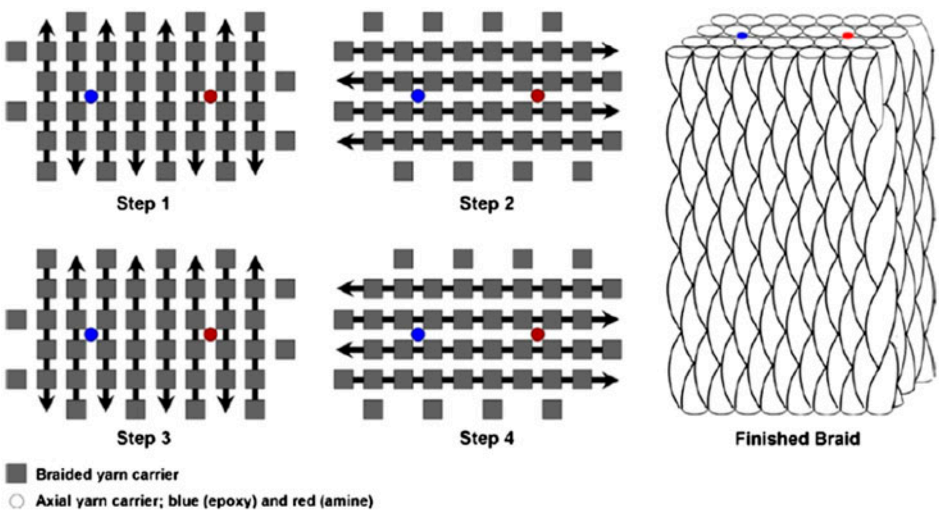

Figure 1. Four-step braid morphology.[23]

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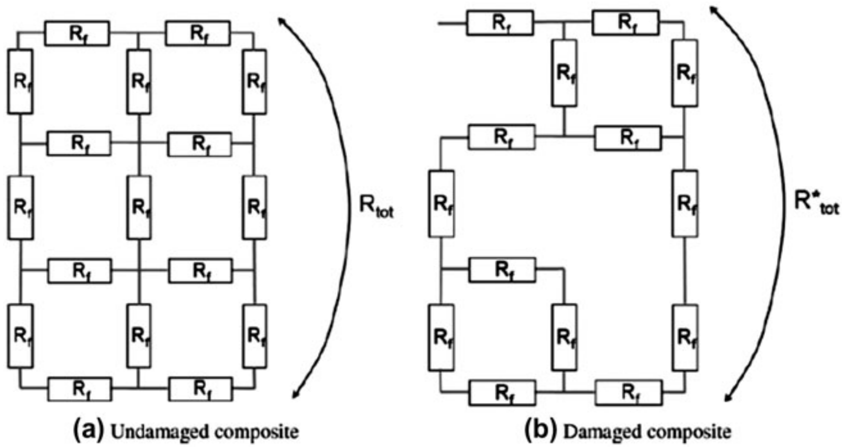

Figure 2. Electric network of resistors, representing a fabric of carbon fibres in an insulating matrix.[24]

In ‘polymer–matrix composites’, the conductive carbon fibers provide the only electrical conductive path in the material. For unidirectional fiber composites, the electrical conductivity is markedly maximum parallel to the reinforcement axis, while the transverse conductivity may be attributed to relatively random contacts between the aligned carbon fibers. The initial decrease in this electrical resistance is attributed to a Poisson’s ratio effect in which the reduction in cross-sectional area increases the probability of random contacts between the longitudinal fibers as illustrated schematically in Figure 3. This short-circuiting leads to overall increase in conductivity or decrease in electrical resistance.[26] Fiber breakage is one basic type of damage. The broken fibers lose their load-carrying capability and the load is transferred to the unbroken fibers.[27]

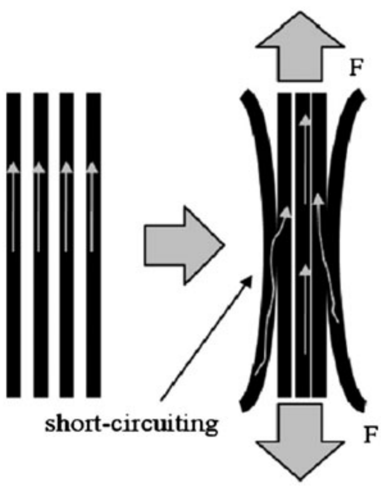

Figure 3. Short-circuiting induced by the applied load to the longitudinal axis (Poisson’s ratio effect).[26]

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The different forms or modes of damage in a composite are schematically illustrated in Figure 4. The discontinuation of electrical conductivity due to the broken fibers results in a general increase of electric resistivity along the fiber direction. The sketches in Figure 5 schematically illustrate the potential coupling between the mechanical and electrical networking. The second form of damage is matrix structural damage, which is more common than the fiber breaking damage. Since fiber strength is substantial than that of the matrix, damage usually involves the matrix earlier than the fibers, for laminate composites.[28]

Electrical resistance measurement has recently been widely employed for damage sensing. These simple electrical resistance measurements have several advantages for damage detection in composite materials. In the further development of the electrical resistance measurement as a nondestructive evaluation method, structural models that can be correlated with the observed changes in electrical resistance would likely prove very useful.[29]

2. Experimental

2.1. Theory of self-sensing using electrical resistance measurement

The sketches shown in Figure 5 schematically illustrate the potential coupling between the mechanical and electrical networking modeling. Moreover, explicit random locations of fiber/fiber contact are introduced in the electrical model. Fiber damage occurring in the mechanical model should result in concomitant changes in the model of the electrical network.[30] Real-time sensing using the composite electrical response appears feasible and holds the advantages of low cost and total component sensing.[31] Nanotechnology provides new materials that might be useful in the development of novel composites. Carbon nanofiber (CNF) composites have been developed with good electrical properties as well as increased strength and stiffness, but still somewhat inferior to the properties of carbon nanotubes (CNTs) composite.[32–34]

Consideration has been given to introducing CNTs into conventional fiber-reinforced composites, forming a hierarchical structure, where nanoscale reinforcement is made to

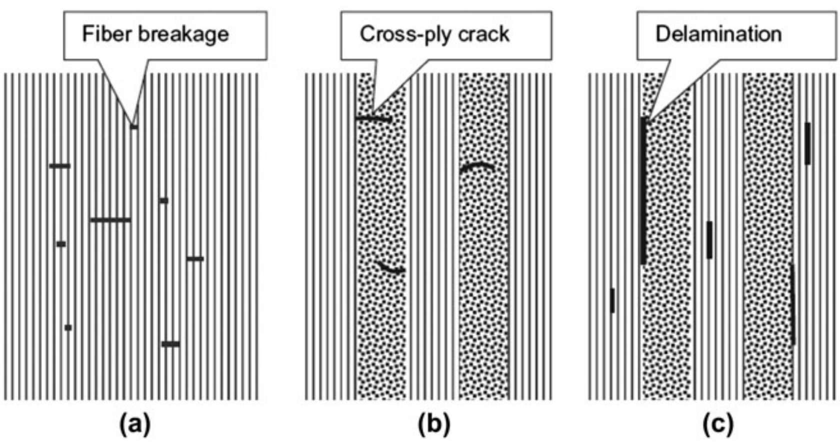

Figure 4. Three types of damage in CFRPs: (a) fiber breakage; (b) cross-ply crack; and (c) delamination.[27]

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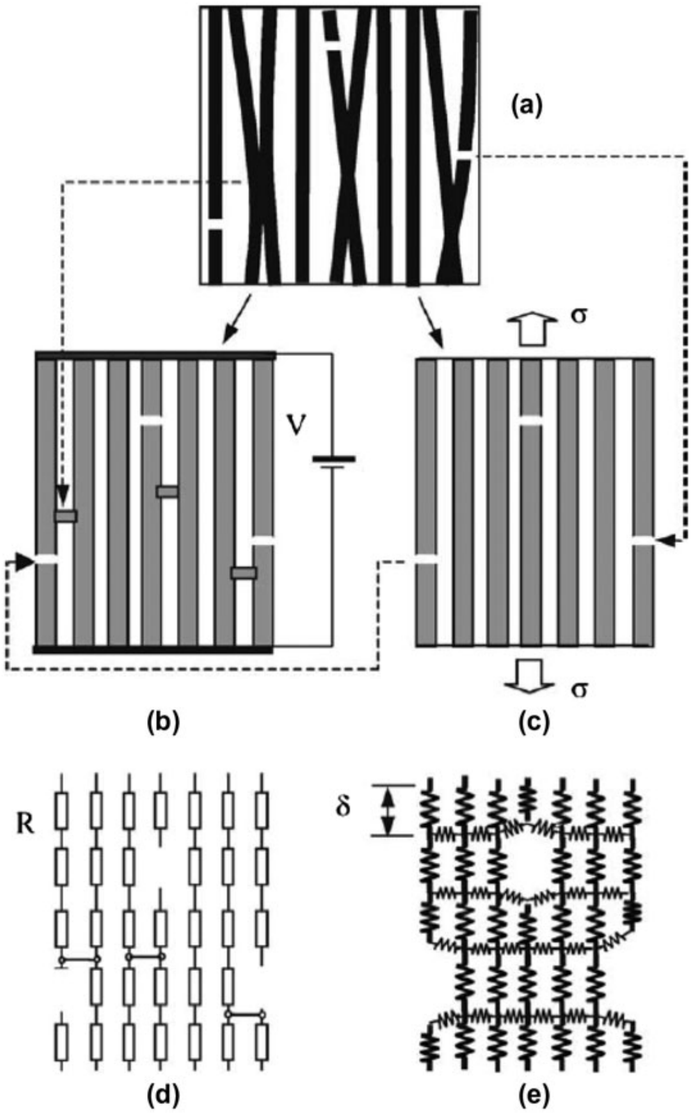

Figure 5. Schematics of coupled mechanical and electric models showing how a ‘real’ composite (a) is represented by an electrical network of resistors (b and d) and a mechanical network of elastic elements (c and e) with common damage states.[30]

work alongside more traditional microscale architectures. Since conventional glass fibers are electrically insulating materials, the electrical resistance methods described here would be ineffective. Traditionally, therefore, external sensors are used to monitor damage in glass-fiber-reinforced plastics (GFRPs) with the associated attached sensor’s alteration of mechanical properties and increased cost. There is a growing interest in techniques without the requirement of additional sensors to study composites; therefore, the development of new GFRPs with an *in situ* self-detecting function is desirable. CNTs grafting onto fiber surfaces has been used to create electrically conductive interphases for introducing sensing capabilities into bulk nanocomposites. The morphologies of CNT coatings on the glass fiber surface were investigated using scanning electron microscopy. Figure 6 shows SEM micrographs of bare and coated GFs, on annealed GFs using the charge contrast imaging technique. It was observed that the CNTs are well dispersed and distributed on the glass fiber surface. A similar distribution and state of dispersion of CNTs may be expected for all areas on the GF covered by such films. Hence, in the case of interphase sensors based on CNT networks on the GF surface, any change in electrical resistance as a function of applied stress involves information of all continuously connected areas on the GF covered fiber with the CNT coating as well as conductive paths between adjacent fibers.[35,36]

Nanocomposites filled with CNT have high stiffness, strength, and good electrical conductivity at relatively low concentrations of the reinforcing material. Adding a small amount of CNT to form an electrically conductive network has been found to be a promising approach for monitoring damage initiation and propagation in fiber-reinforced composites. As microcracks propagate in the matrix, the conductive pathways are disrupted in the percolating network, resulting in changes in electrical resistance.[37] Although only comparably little volume is affected when CNTs are concentrated in the composites interphase, this modification results in significantly improved mechanical properties.[38] Carbon nanomaterials have attracted considerable attention in both research and industrial fields due to their unique mechanical and electrical properties which might be used for damage sensing purposes. The conductivity and high aspect ratios of CNT are attractive properties for producing conductive composites with minimum added constituents.

Nondestructive monitoring of the damage developed in continuous carbon-fiber-reinforced composites during mechanical loading is a key issue in many applications. The optimal way to proceed for structural health monitoring is to use the material itself as a sensor of its own damage. To this end, the electrical resistance change method is appropriate since it employs the electrical conductivity, an inherent material property, to identify internal damage.[39] Electrical conduction in CFRPs is primarily realized directly through the conductive carbon fibers, but also indirectly through the electrical contacts between the neighboring fibers as shown schematically in Figure 7.[40] The electrical resistance change method does not require expensive equipment for instrumentation and does not cause any deterioration of the structure under monitoring. Furthermore, the structural weight is not changed. In the case of CFRPs, it has been proven that the electrical resistance, the mechanical deformation and damage are interconnected. To date, such investigations of detecting damage have primarily utilized strain sensors in electrical conductive carbon fiber composites.

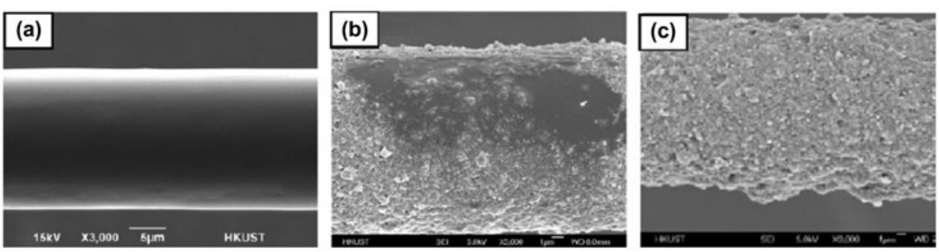

Figure 6. Typical SEM images of different glass fibres (a) without coating, (b) with coating containing 0.12 wt.% CNTs, and (c) with coating containing 0.50 wt.% CNTs).[36]

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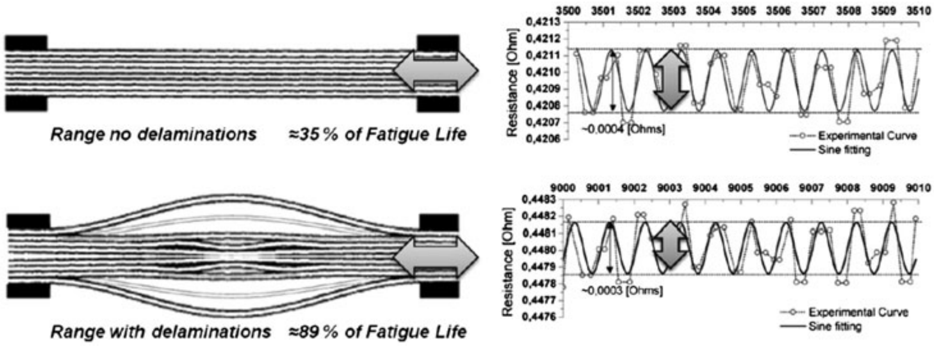

Figure 7. On-line response of electrical resistance and load versus fatigue cycles at 35% (right) and 89% (left) of fatigue life.[40]

2.2. *Electrical resistance measurement and signal analysis*

Electrical resistance can be measured using either a two-probe or a four-probe method.[24] For the two-probe method as shown in Figure 8, the specimen is kept at a certain potential, and the conductivity is measured by applying a small AC or DC voltage between two probes.[41,42] The electrical resistance measured by this technique includes both the volume resistance of the composite and the contact resistance between the contacting probes and the composite as illustrated by the graphs in Figure 9. As a consequence, the results obtained by the two-probe method may exhibit relatively large errors due to the contribution of the contact resistance.[43] On the other hand, in the four-probe method, a constant current is introduced between two outer probes, and the potential difference between the inner probes is measured by a voltmeter. Since the current through typical voltmeters is very nearly zero, the contact resistance between the two inner probes and the composites has almost no influence on the electrical resistance measurement of the composite. The four-probe method does not measure the contact resistance between probes and composite and so if the value of the contact resistance is desired, it must be determined by another method.[44]

The electrical contact between fibers in the composite, which is very often important for the electrical resistance measurement, involves the 'tunneling' of electrons from one fiber to another, thus resulting in percolative conduction.[45] This tunneling requires that adjacent fibers be separated by a sufficiently small distance at the point of conduction. An increase in the number of the 'contact points' may occur during

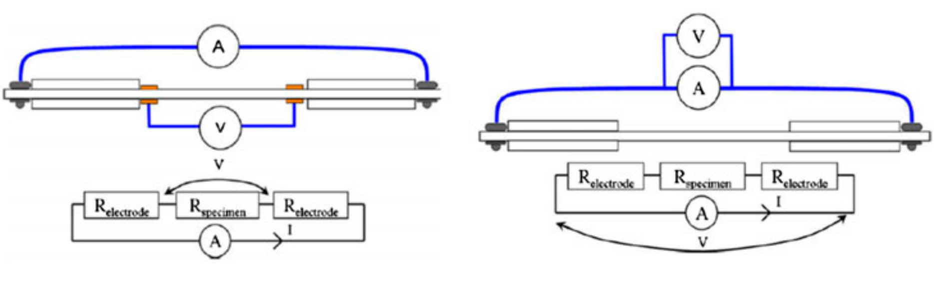

Figure 8. Four-probe method (a) and two-probe method (b) of resistance measurement.[24]

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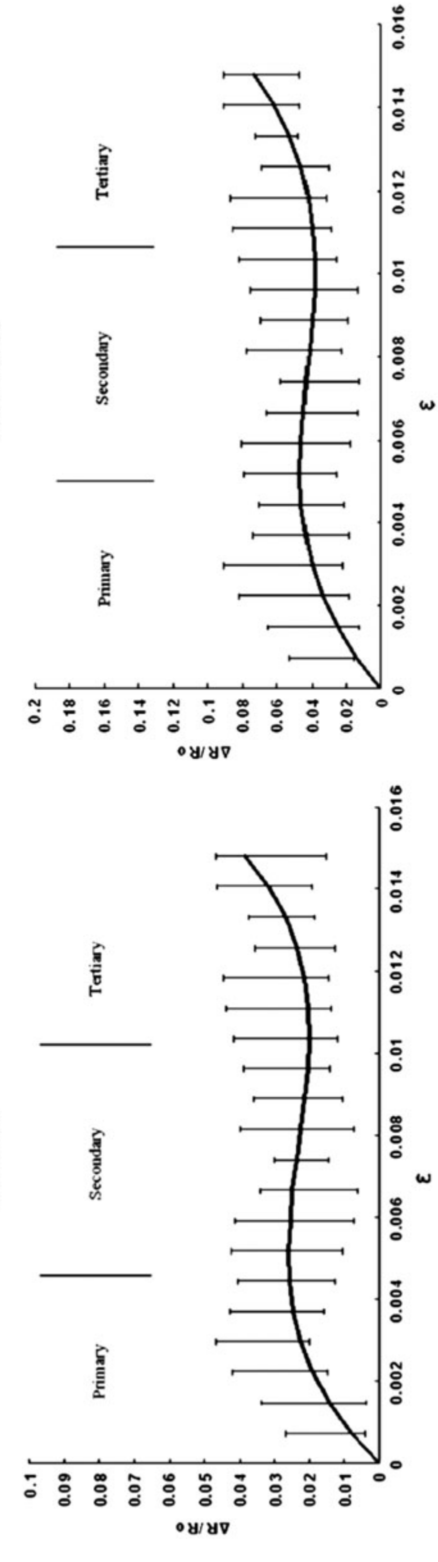

Figure 9. Relative change in resistance versus applied tensile strain using two-probe method and four probe method.[41]

loading, perhaps resulting from compression in the direction perpendicular to the general direction of the fibers causing a very slight increase in the proximity between adjacent fibers. This can cause a decrease in the resistivity in the direction perpendicular to the general direction of the fibers.

Lastly, the significance of the electric contact points on the electrical resistance measurement (on the specimen surface in contrast to that between fibers as discussed in the last paragraph) should be checked. Electrical contact points should be hard and not significantly affect the test specimen. In practice, both physical and chemical methods have been used to fix the electrical contact points to specimens. In general, the electrical contact section can be affected by induced stress, and for practical applications, this influence should be minimized. Recently, the results of several studies of electrical resistance measurements on nanocomposites, as shown in Figure 10, have been published.[46] It is important to minimize the electrical contact resistance between the test specimen and the copper wire electrodes when making electrical measurements on composites.[47] Figure 11 shows a method of physically fixing an electrical contact to a composite. To the extent possible, these probes should be situated outside the mechanical test region, and in general, reducing the contact resistance results in more stable and reliable electrical resistance signals.

3. Damage sensing analysis using electrical resistance measurements

3.1. Electrical resistance measurements for damage sensing applications

The application of a stress to a nanotube-based composite is expected to cause resistance changes as a result of the deformation and extension of the composite and its nanostructure. Figure 12 shows the electrical resistance response to applied stress (in this case cyclic loading).[48] When a mechanical force is applied to such a composite, morphological changes occur in the network structure of the filler and polymeric matrix leading to changes in the material's resistivity.[49] As a result, electrical resistance measurements can usually be used to detect uniaxial tensile stress. Figure 13 shows the further development and refinement of the method, which facilitated its use for detecting biaxial stress loading.[50] These conductive networks in composites facilitate

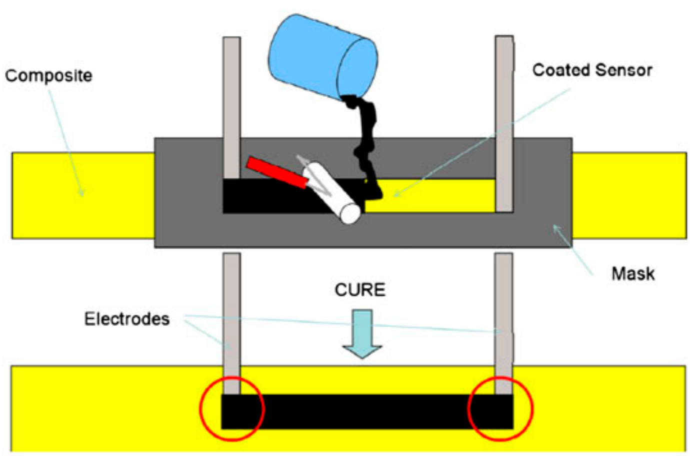

Figure 10. Application of the reactive mixture on top of the insulated CFRC specimen.[46]

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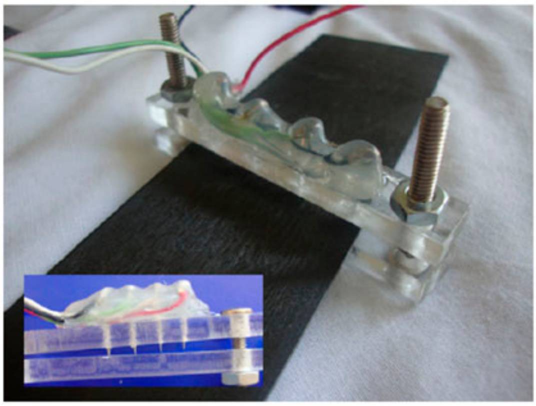

Figure 11. Four probe resistance measurement set-up for directly embedded samples.[47]

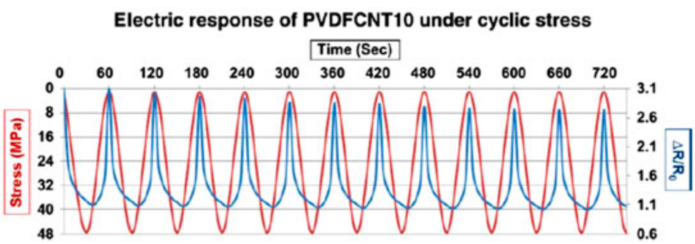

Figure 12. Resistance response under cyclic loading.[48]

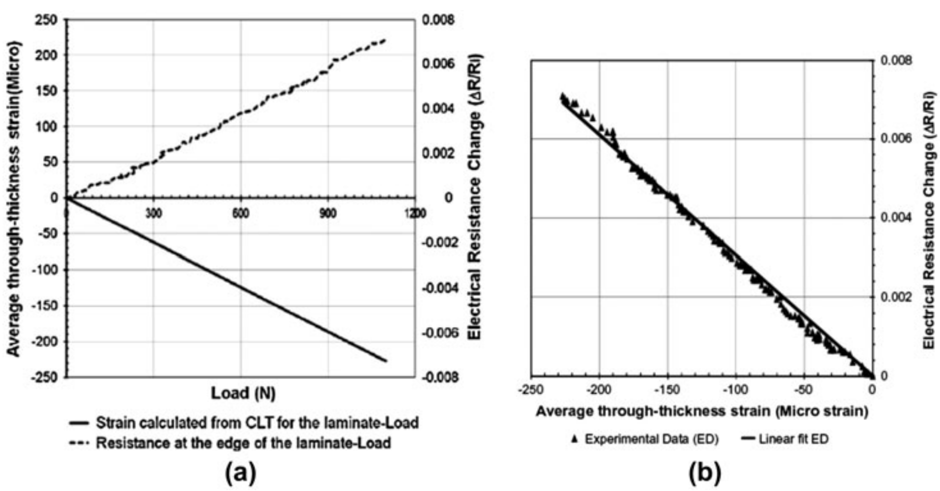

Figure 13. (a) Calculated ATTS and measured ERC versus load for the total thickness. (b) Measured ERC vs. calculated ATTS for the total thickness.[50]

the creation of matrix-dominated damage sensing capabilities. Research has demonstrated that the above approach can be highly effective at sensing damage in composites.[51] To date, however, most of the available studies using this method of damage sensing have been limited to experimental studies, and there is still a lack of theoretical studies. A thorough and comprehensive research on damage sensing mechanism composites are, therefore, needed to facilitate the development of self-sensing composite systems for engineering applications such as that shown in Figure 14.[52]

The electrical behavior of thin films when subjected to mechanical loading has also been investigated.[53] In this study, in a tensile test, the electrical resistance was continually measured as the specimen was stretched to a certain limit. In a bending test, the substrate was bent between parallel plates and the electrical resistance was measured at different degree intervals.[53] The failure in the thin film was different than the failure in more bulky materials. In the bulky materials, failure is characterized by sudden fracture, where apparently a single crack initiates and propagates to fracture in a very short time. Failure in the thin film, on the other hand, is usually characterized by relatively slow propagation of many cracks. Other types of failure modes have also been observed in the thin films under mechanical loading such as the occurrence of extrusions and intrusions.

3.2. Electrical resistance measurement for strain sensing application

Figure 15 shows the relationship between tensile strain and change of electrical resistance for composite layers of carbon fibers and cement paste deposited on PET.[54] The authors not only documented the specimens' increased strength, stiffness, and impact resistance, but also correlated this behavior to a documented higher sensitivity to identify tensile and impact damage. The increased strength and stiffness are coupled with the improved sensitivity in detecting fatigue and impact damage in the fiber-reinforced panels.[55] The electrical resistance is a function of the applied strain and allows *in situ* monitoring of the specimens strain and other events possibly associated with damage in the composite. Recently, results of other studies have been published dealing with different aspects of *in situ* strain sensing by recording the change in electrical resistance associated with variation of mechanical strain, a few of which are shown in Figure 16.[56,57] The electrical resistance measurement method has also been used to detect the cracks where sufficient tensile strain (typically more than 1%) was applied to polymer–matrix composites, some results of which are shown in Figure 17.[58] For rubber CNT composites, use of the method produces residual

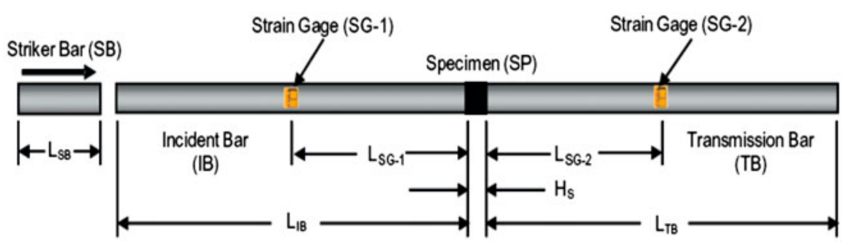

Figure 14. Split Hopkinson pressure bar experimental apparatus.
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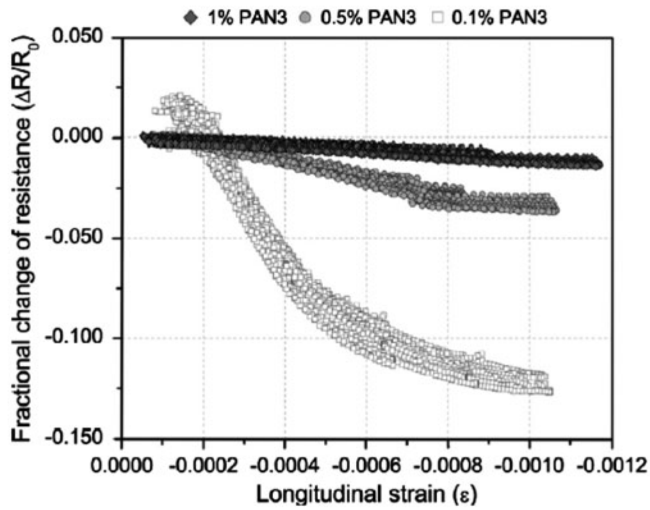

Figure 15. Resistance fractional change versus longitudinal strain for all tests made on cement pastes reinforced with 3 mm long CF at different dosages and hence different percolation status: 0.1, 0.5 and 1.0% CF with respect to cement mass.[54]

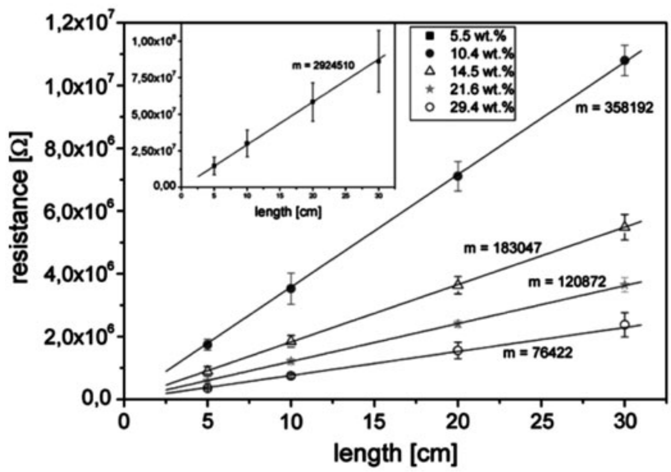

Figure 16. Dependence of resistance of CNT-coated GF on the yarn length for different coating contents. Linear lines show least square fit through the origin of the resistance data and the corresponding slopes.[57]

electrical resistance after every unloading step. There will typically be some errors in the electrical resistance measurements, during unloading in fatigue tests.[59]

Figure 18 shows some typical result from a study using the CNT-glass fibers as real-time *in situ* sensors. It was found that the fibers were able to detect and make use of microcracks for potential early warning catastrophic failure in materials and for switches for sensitive controlling of microsystems.[60] The authors feel that this pilot study, using self-diagnosing CNT-glass fibers, suggests that there is a unique

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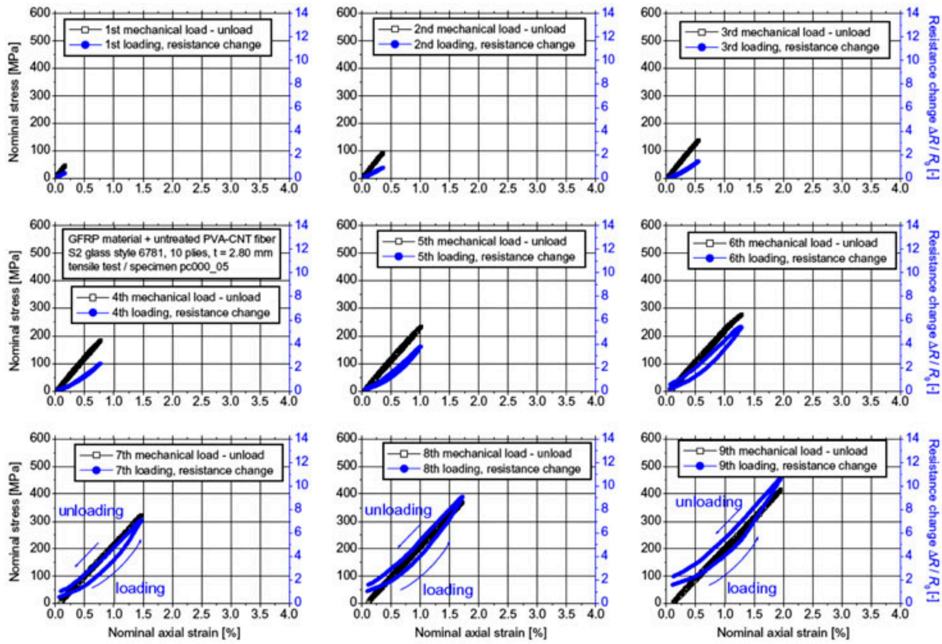

Figure 17. Typical tensile mechanical and resistance results of a GFRP specimen with embedded untreated PVA–CNT fiber for different incremental loading–unloading steps.[58]

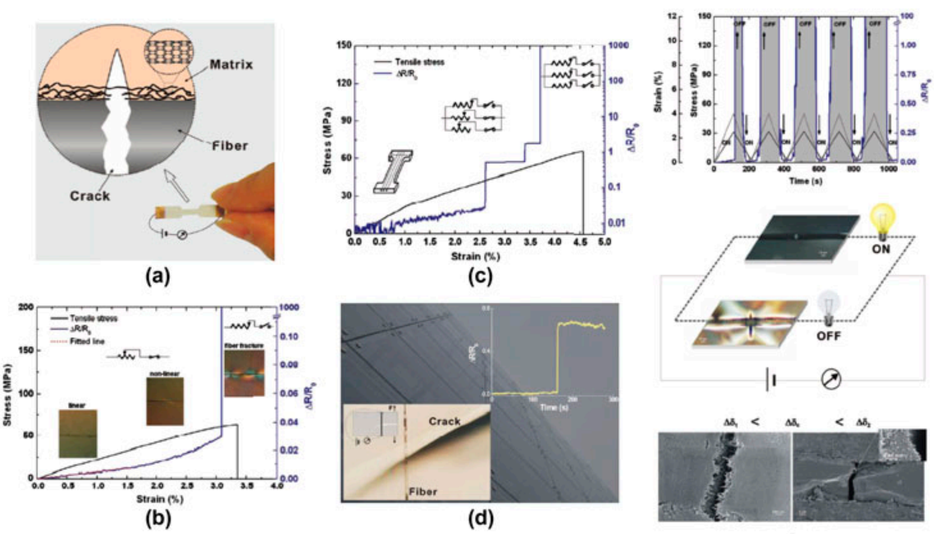

Figure 18. Performance of in situ sensor of a single fiber model composite. (a) Schematic of microcrack bridged. (b) Simultaneous change of electrical resistance and tensile stress as a function of tensile strain. (c) The function of early warning. (d) The resistance of the single fiber sensor.[60]

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opportunity for *in situ* loading and damage detection in such composites. In the first stage of the tensile test, relatively linear behavior was observed in which the electrical resistance increased proportional to the strain up to approximately 1.5% strain, which is possibly linked to the elastic deformation of the interphase. For strains higher than 1.5%, the slope of the resistance–strain curve increased exponentially with strain. This exponential behavior of electrical resistance change is likely related to the interphase plastic deformation of CNT networks, associated with stress concentrations just before fiber breakage. This may result in increases in the CNT interspace and loss of junction points arising from permanent changes in the network shape during loading. This interphase deformation caused apparent irreversible resistance changes. In the third stage of deformation, the interphase failed completely accompanied by an infinite jump in resistance. As the strain was further increased, after interphase fracture, the coated fiber/epoxy composites failed at a strain of about 3.4%. An important feature, observed during these measurements, was that the three stages of the resistance variation were highly consistent and reproducible; therefore, indicating that such single-coated glass fibers can find uses as small and sensitive rapid response mechanical sensors. The results of these tensile tests also suggest that all the resistance change occurring during testing is related to interphase damage, rather than to failure of the reinforcement fibers.[61]

3.3. *Interfacial evaluation using electrical resistance measurement*

Electrical resistance measurement was used to evaluate the state of dispersion of the nanoparticles in composite matrices; some results of which are shown in Figures 19 and 20. The electrical resistance changed under loading due to changes in the nanoparticle contact point density.[68] Interfacial properties of fiber-reinforced polymer composites may also be evaluated by acoustic emission (AE).[68] Figures 21 and 22 show

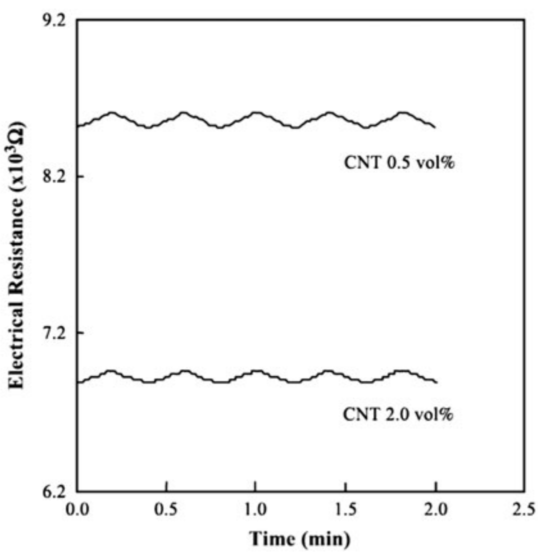

Figure 19. The change in electrical resistance for fiber tension with CNT content under electro-pullout test.[68]

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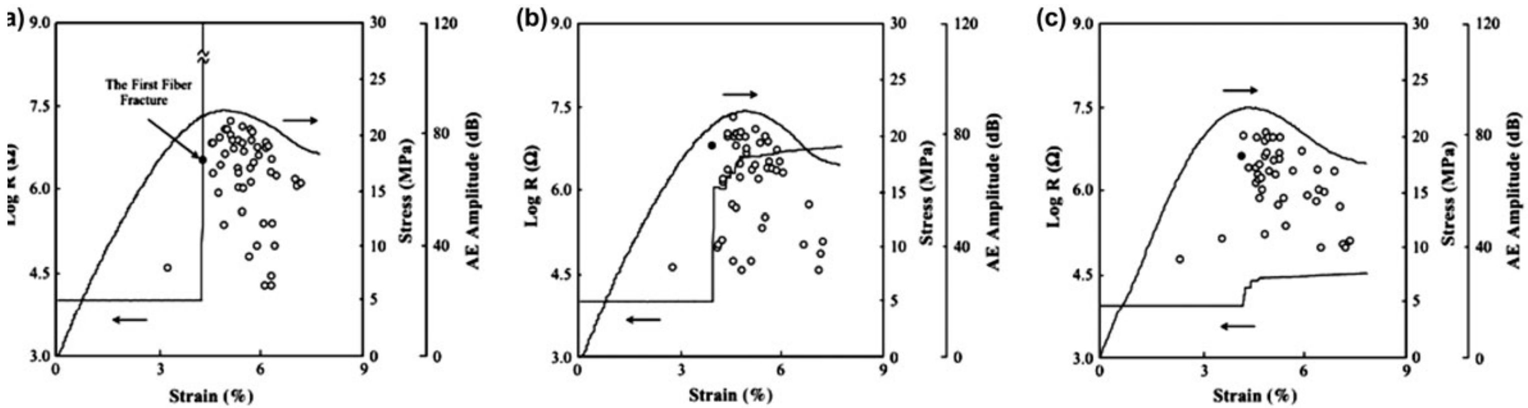

Figure 20. Damage sensitivity of fiber fracture for (a) 0.1 vol% CNT, (b) 0.5 vol% CNT and (c) 2.0 vol% CNT under DMC test.[68]

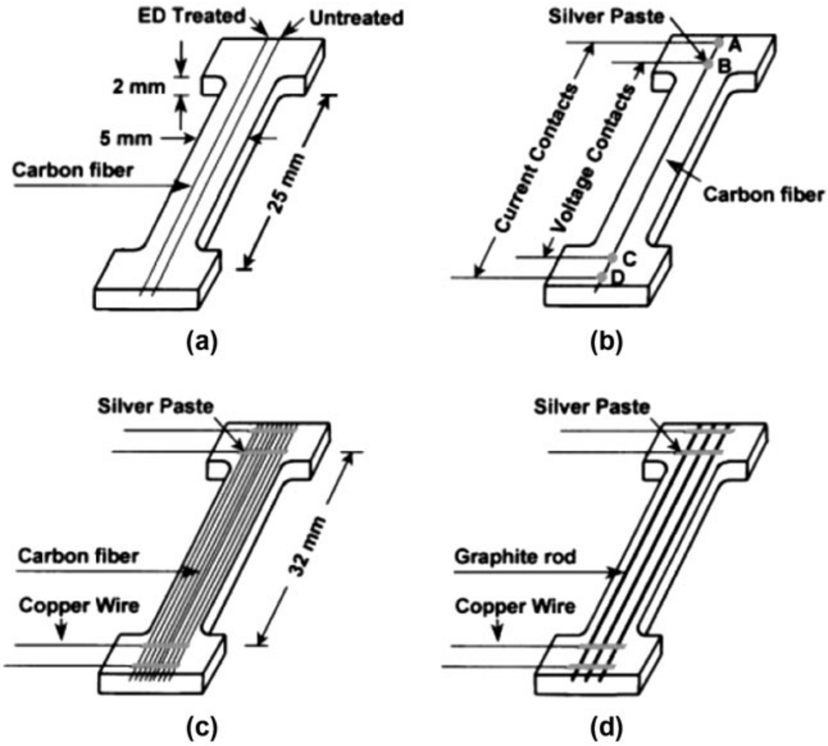

Figure 21. Dimensional scheme of four types of test composites for fragmentation, the electro-micromechanical test, and AE.[62]

some results from research using AE and electrical mechanical tests.[62] The relationship between electrical resistance and fiber breakage/delamination in carbon-fiber-reinforced plastic (CFRP) laminate was studied in tensile and fatigue tests. In the case of composite materials, the tensile load in the specimen is transferred to the fiber by shear stresses in the matrix through the interphase. During tensile testing to failure, the fiber keeps breaking until the fragments become too short to build up sufficiently high tensile load to cause further fragmentation with increasing specimen strain.

AE sensors can be used to monitor the fracture behavior of composite materials, and the AE parameters can be used to aid in understanding the types of micro failure sources during fracture progression. The AE method may be used to check the accuracy of electrical resistance measurement for the interfacial evaluation.[68] When tensile loading is applied to a composite, AE signal may occur from fiber fracture, matrix cracking, and debonding at the fiber–matrix interface. The AE energy released by the fiber fracture is typically greater than that associated with debonding or matrix cracking. The authors feel that it has been demonstrated that electrical resistance measurements can monitor internal damage as an alternative to more expensive AE sensors.

For specimens to be used with electrical resistance measuring method, two pairs of narrow copper wires were fixed transversely on a mold-released Teflon film with attaching guiding tapes, and then, a single fiber was laid down in a longitudinal direction. Silver paste was used for the electrical connection at the intersecting points between the carbon fiber and the copper wires as shown in Figures 23 and 24.[63] Apparent

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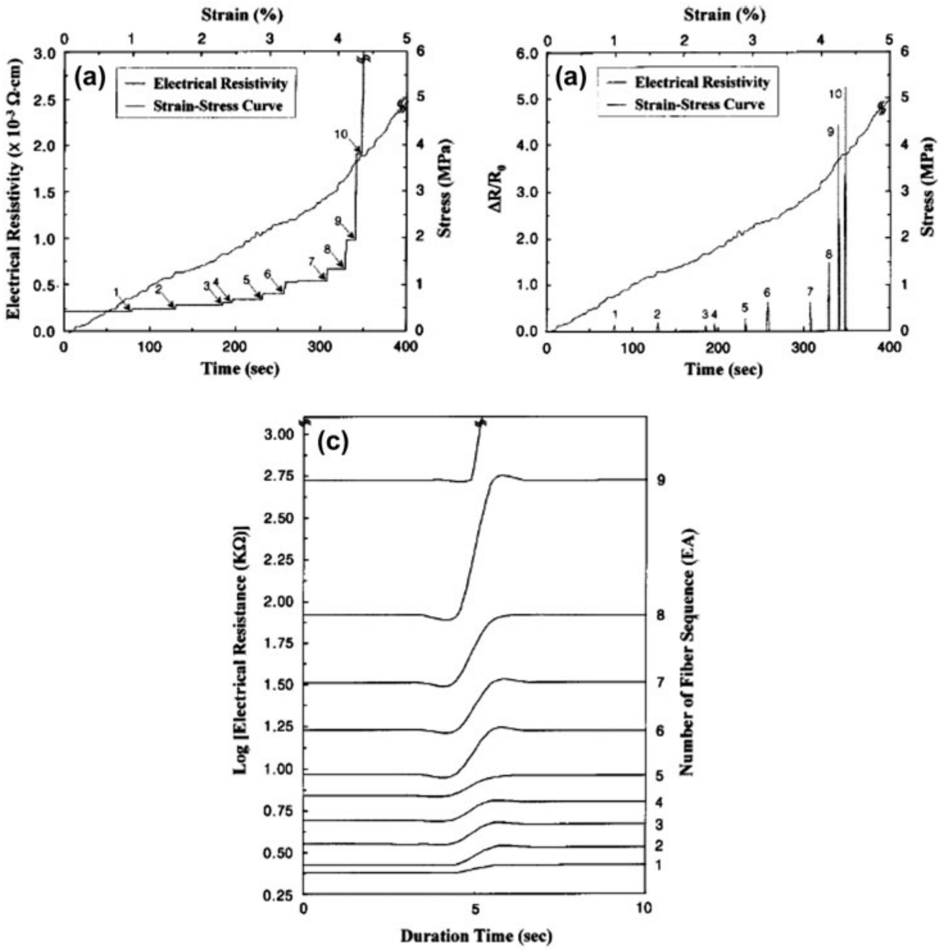

Figure 22. Behavior of (a) electrical resistivity, (b) electrical resistance difference (1R = R0); and (c) logarithmic electrical resistance due to the first fracture of the individual fiber in 10-carbon fiber composite.[62]

modulus is defined as the elastic modulus of a single fiber embedded in an epoxy composite obtained from the slope of the strain–stress curve compared with the modulus of a bare fiber. For both monotonic and cyclic loadings, electrical resistivity responded well with the changes in strain (or stress), indicating the feasibility of its use as a kind of strain–stress sensing material. The electro-micromechanical test might be defined as a simultaneous measurement of electrical resistance as well as micromechanical properties during application of a load.[64]

It is planned to continue the development of the electrical resistance measurement method since it show promise of being and effective and inexpensive method of NDE for composites but still in need of refinement. To obtain damage sensing results without external sensors is important for materials such as composites and raw materials.[65] As an example, the complex sensing system currently used on robot skin is very inconvenient, while a self-sensing composite ski might be able to detect, by electrical

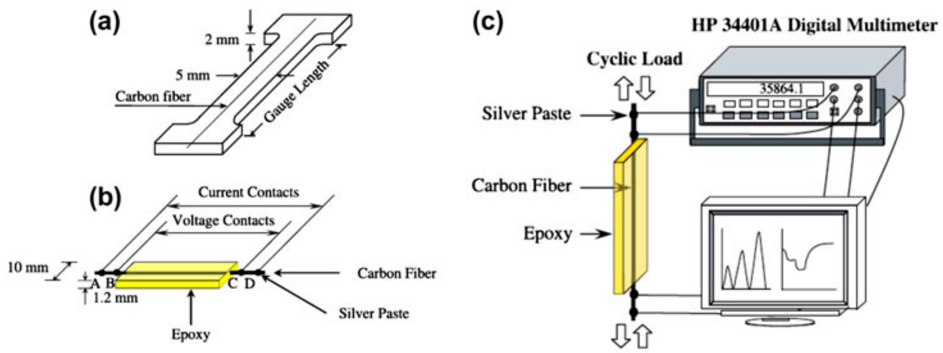

Figure 23. Schematic illustration of two-type testing composites for (a) fragmentation test (b) strain–stress sensing and (c) Experimental system for the measurement of electrical resistance and strain–stress curve for single carbon fiber composite under cyclic loadings.[63]

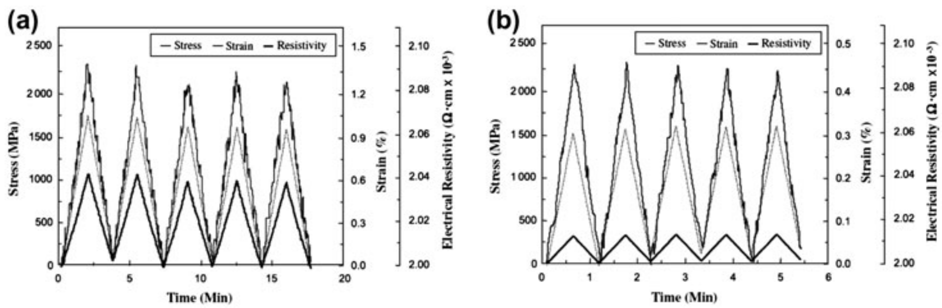

Figure 24. Comparison of the strain–stress–electrical resistivity between (a) a bare carbon fiber and (b) single carbon fiber/epoxy composite under five cyclic loadings.[63]

resistance measurement, significant information such as damage location, temperature, strength, and strain.[66,67]

As illustrated in Figures 25 and 26, for composite materials, elastic strains can involve a number of complicated geometric effects, such as a change in the degree of contact among the reinforcing materials in the composite.[69,70] In some materials, particularly 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 actual damage mechanism. An example of such 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 consequential presence of points at which a fiber is locally in electrical contact with an adjacent fiber. A statistical increase in the number of contact points may occur during loading due to a very slight increase 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. 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.

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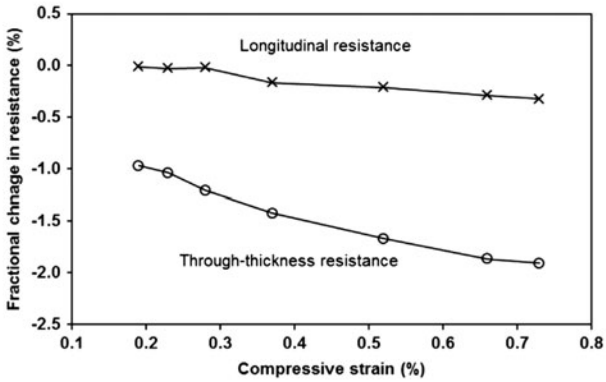

Figure 25. Effect of through-thickness compressive strain on the reversible/irreversible fractional change in resistance.[69]

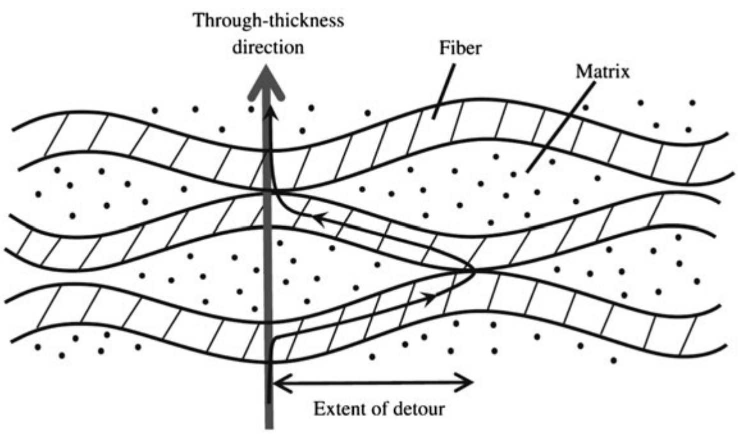

Figure 26. Schematic illustration of the electrical conduction path associated with through-thickness conduction behavior.[69,70]

4. Conclusions

Carbon fiber composites are used as skin/cover materials in both the aircraft and automobile industries. The damage sensing and parts exchange can be evaluated by electrical resistance measurement due to the conductive nature of carbon fibers. This method can also be used in the construction field. Electrical resistance changes of parts of or the whole building can be measured in real-time monitoring. The information of strain and temperature can be obtained to improve the safety of buildings. There are a variety of expensive sensors and black boxes in aircraft for sensing functions and real-time detection of possible damage. Some of these might be effectively replaced with the electrical resistance measurement method, which has advantages in economics and simplicity. Further improvements of the method will likely include theoretical studies and models to better understand the mechanisms and phenomena involve as well as development of three-dimensional methods.

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