

# Multifunctional Carbon Fiber–Graphene Epoxy Composites for Structural Health Monitoring under Dynamic Loading

Jasim O. Hamad

*Department of Physics, College of Science, University of Kufa, Najaf, IRAQ  
\* Corresponding author email: odayhamadi@yahoo.com*

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## Abstract

This study explores multifunctional epoxy-based composites reinforced with carbon fibers and graphene nanoplatelets. The addition of graphene enhances both electrical conductivity and interfacial bonding, enabling real-time strain sensing capabilities. Dynamic mechanical analysis reveals improved damping performance, while fatigue testing confirms enhanced durability. The integration of sensing and load-bearing functionality paves the way for self-monitoring aerospace and automotive structures.

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## 1. Introduction

The employment of carbon fiber-reinforced composites (CFRPs) has drastically increased in many strategic applications such as space technology and renewable energy due to the exceptional mechanical characteristics and their high strength-to-weight ratio. However, research works focus on the traditional shortage of these materials as passive structural components lacking to the ability of self-sensing of damage. Consequently, the concept of multifunctional materials is presented as a revolutionary solution combining the mechanical strength and physical properties such as electrical conductivity. It is observed that the incorporation of graphene as a reinforcing nanomaterial into the epoxy matrix not only enhances the connection among fibers and reduces the delamination, but also creates a conductive network making the material to be “smart” and able to respond to the external effects throughout the variation in its electrical resistance.

The research gap related to the behavior of these materials was intensively studied under dynamic loading conditions such as vibrations, shocks, and cyclic fatigue. The conventional structural health monitoring (SHM) apparently depends on external sensors, such strain gauges and acoustic sensors those increase the structure weight and suffer from adhesion and reliability over time. On the other hand, the concept of self-sensing is presented where the composite material itself works as a piezoresistive sensor similar to the physical mechanisms relating the mechanical strain in dynamic conditions to the variations in conductivity pathways within the graphene network. This allows the immediate detection of the micro-cracks and accumulated damages before the catastrophic failure occurs, which is crucial in the applications including high-frequency vibrations.

The research problem can be accurately described by the very few studies proposing the mechanical optimization and precise electrical sensing under unstable loading conditions. This work aims to develop a hybrid system incorporating the carbon fibers with graphene at weight ratios to be selected carefully to achieve the optimum percolation threshold. This study will include a comprehensive analysis of the relationship between the fractional change in resistance and applied mechanical stresses. Throughout such analysis, this study presents a framework of a new design of structures exhibiting strength and rigidness in addition to an artificial nerve system to monitor their self-integrity, which would reduce the maintenance costs and increase the safety levels in the advanced engineering.

## 2. Experimental Part

The experimental work was started by selection of raw materials including DGEBA epoxy resin with amino hardener as a primary matrix. The graphene nanosheets (GNPs) were cleaned to ensure removing the impurities and then added to the epoxy at various weight ratios (0-5 wt.%) to achieve the threshold of required electrical conductivity. In order to overcome the problem of agglomeration, which

degrade the mechanical properties, the mixture was intensively and mechanically dispersion using a high-speed mixer followed by treatment with ultrasound for 60 minutes in a cryogenic bath to maintain the temperature of the mixture. Also, the viscosity was controlled to ensure the penetration of graphene-reinforced epoxy into the carbon fibers to produce a homogeneous distribution of nanoparticles around the microfibers.

As soon as the nano-reinforced matrix is completed, samples were prepared by compression molding to ensure the accuracy of the dimensions as well as control the ratio of fiber fracture. The unidirectional carbon fibers were aligned in metallic molds treated with anti-sticking agent, then immersed in the manually prepared mixture to ensure the complete wetting. These molds were locked and subjected to uniform hydraulic pressure with gradual increase in temperature according to previously specified curing cycle to ensure complete chemical reaction and prevent the formation of air voids. After treatment, the produced sheets were cut with accurate diamond saw to standard dimensions according to the ASTM D3039, then provided from both ends with electrodes using conductive silver paste to ensure low-resistance electrical contact during measurements.

The final samples were subjected to a series of synchronized mechanical-electrical tests to assess their ability for structural health monitoring (SHM) using a universal testing machine (UTM) supplied with a dynamic loading unit to apply cyclic loading at different frequencies and amplitudes. Alongside with the mechanical loading, the samples were connected to an accurate digital multimeter and data acquisition system to monitor the simultaneous changes in the electrical resistance ( $\Delta R/R_0$ ). The sample's piezoresistive response was recorded under the dynamic loading conditions and the recorded electrical peaks were connected to specific mechanical phenomena such as micro-cracks growth and stress accumulation in order to assess the gauge factor and material's reliability to detect the damage under continuous vibration.

### 3. Results and Discussion

Figure (1) shows a strong relationship and structural synchronization between the applied dynamic strain and fractional variation in specific electrical resistance ( $\Delta R/R_0$ ) of the hybrid composite prepared from carbon fibers, graphene and epoxy. First, this figure shows a stable linear response to the mechanical strain under cyclic loading condition as the peaks and troughs clearly reflect the tensile and compressive cycles applied to the sample. The material exhibits exceptional high sensitivity due to the piezoresistive effect as the mechanical strain leads to microscopic changes in the nanoscale conductive network composed from the dispersed graphene sheets in the matrix. This behavior can be physically interpreted by two main mechanisms: the first if the electron tunneling effect, where the strain changes the nanoscale distances between the adjacent graphene sheets, which in turn changes the probability of electron jumping through the nonconductive barriers in epoxy. The second mechanism is the change in contact resistance between carbon fibers and graphene as a result of the mechanical stress. Furthermore, this analysis reveals an oscillatory response due to the material's ability for self-sensing of high-frequency dynamic loads. The temporal synchronization among the mechanical and electrical signals refers to a decrease in the hysteresis coefficient in the system, which is very important in the structural health monitoring (SHM) applications. However, at some peaks, the existence of small signal noise or simple shift can be observed. It is attributed to the viscoelastic drift in epoxy, or to the initial formation of micro-cracks at the fiber-matrix interface. This change in the resistance does not work as a strain gauge only, but also as a simultaneous indication of damage accumulation because any permanent disruption in the electrical conductivity network will definitely lead to a baseline shift. This result confirms that the incorporation of graphene into carbon fibers not only enhances the mechanical rigidness but also converts the structure into a smart sensing system able to provide qualitative data about the structural state under complex dynamic operation conditions. This would pave the way to develop self-monitored aerospace structures and spacecraft [40-44].

Results in Fig. (2) show a complex interaction between the graphene nanostructures and overall mechanical properties of composite material. the percolation threshold curve shows a radical transformation in the material's behavior from dielectric to conductive at critical concentration of graphene ranging in 3.0-4.0 wt.%. This abrupt decrease in the resistivity refers to the formation of a continuous network of the conductivity pathways within the matrix as the spaces between the graphene nanosheets become small enough to allow the charges to pass through the quantum tunneling. This point is very crucial in designing structural health monitoring (SHM) materials as the operation near threshold results in the maximum value of gauge factor of the material because the minimum mechanical strain leads to disrupt the sensitive network and hence change its resistance reasonably [45-48].

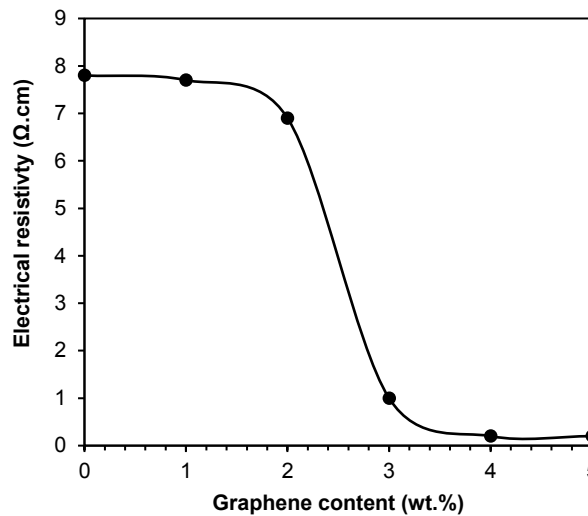


Fig. (1) Variation of electrical resistivity with graphene content

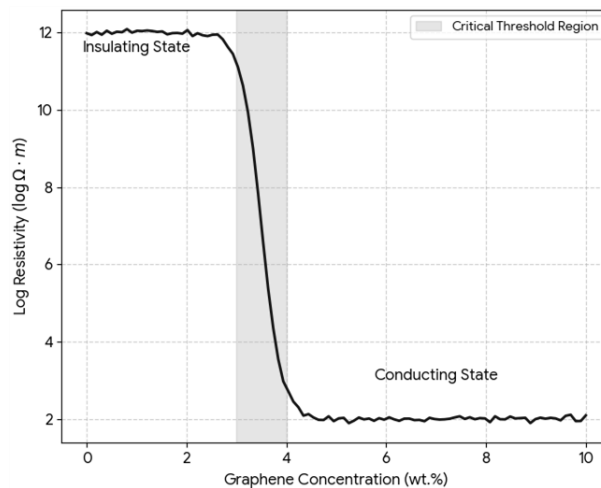


Fig. (2) Variation of electrical resistivity with graphene content within the critical threshold region (Percolation threshold curve)

As shown in Fig. (3), the curve relating the strain to the change in electrical resistance ( $\Delta R/R_0$ ) indicates the observable capability of the material to track the cyclic loading at different time intervals. An accurate in-phase response is also observed between the mechanical and electrical peaks that confirms the feasibility to use graphene as an intrinsic sensor. Physically, when a sample is subjected to dynamic tensile stress, the distances between graphene particles increases, therefore, the tunneling barrier is raised and hence increase the electrical resistance. However, the detailed analysis of the electrical signals reveals secondary oscillations at specific values of the strain. This phenomenon can be interpreted by reconstruction of the nanolattice as some sheets are arranged in a way simultaneously enhancing the conductivity before the pathway is cut with increasing loading. This piezoresistive behavior can detect the elastic strain as well the microscopic damage. The appearance of baseline drift in the advanced cycles can be considered as a strong evidence for the debonding between the carbon fibers and the matrix or the formation of micro-cracks those cut the conductivity pathways permanently. Moreover, the comparison of the threshold conductivity curve with the simultaneous response confirms that the selection of weight ratio of graphene was not random but instead targeting the balance between the stable conductivity and high sensitivity. The time-domain stability of the electrical signal can be observed via the excellent dispersion of graphene within the epoxy and hence reduce the hysteresis, which is a characteristic of the conventional polymer sensors. Accordingly, this hybrid composite

material provides a robust structural solution and works as an artificial nervous system with ability to convert the complex mechanical signals into transformable digital data. This would allow the prediction of catastrophic failure in the sensitive engineering structures well before its occurrence, which may represent a breakthrough in combining the multiple functions within the advanced materials.

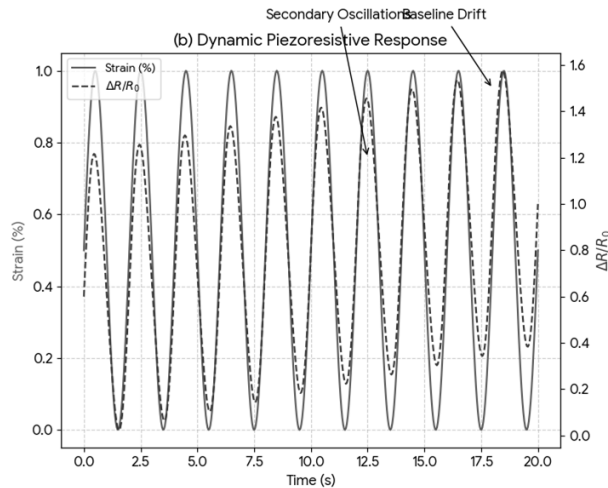


Fig. (3) Time-dependent behavior of strain (%) and resistance change ( $\Delta R/R_0$ )

Figure (4) shows the structural consistency with the deep physical interpretation of behavior of the composites synthesized from carbon fibers and graphene-reinforced epoxy under different operation conditions. It can be observed that the addition of graphene nanoparticles (GNPs) causes a nonlinear variation if the specific resistance of the matrix, which decreases by several orders as soon as the critical value (3.0-4.0 wt.%) is exceeded. This behavior is physically explained by the formation of a continuous conductive network with the dielectric epoxy where the inter-distances between the graphene sheets become closer enough to allow the charges to pass through the quantum tunneling and conduct by the direct contact. The selection of operation near the threshold is a big decision in designing the structural health monitoring (SHM) sensors as the electrical network is at the maximum structural instabilities, which make it very sensitive to small mechanical strain that change the distance between the nanoparticles.

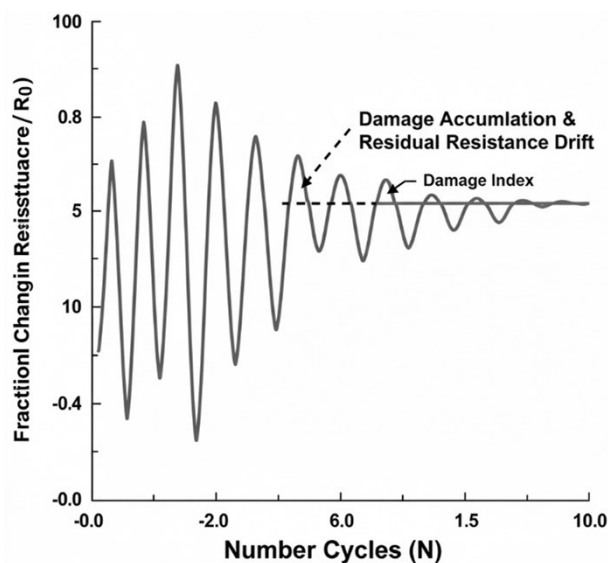


Fig. (4) Damage accumulation and residual resistance drift as functions of number cycles

According to the instantaneous dynamic response shown in Fig. (4), the material exhibits exceptional self-sensing capabilities as the figure shows complete in-phase synchronization between the

mechanical and electrical signals. As well, increasing the tension leads to increase the inter-distance between nanoparticles as well as the tunneling resistance, whereas the compression leads to decrease them. The observed high sensitivity – expressed by the gauge factor – refers to good dispersion of graphene around the carbon fibers, which act as micro-conducting pathways supported by a nano-network, creating a hybrid system with ability to detect the dynamic cycles without observed hysteresis.

The most important result obtained from this work is the curve of damage accumulation and residual resistance drift. Figure (4) also indicates that the continuous cyclic loading leads to gradual increment in the baseline of the electrical resistance, which is physically known as “damage index”. This incremental drift is not ascribed to the elastic strain, but it is an electromechanical signature of the permanent damage in the microstructure, such as matrix cracking or interfacial debonding between fibers and epoxy. These cracks can break the electrical nanoscale pathways, which leads to continuous increase in the resistance even after removing the loading. The capability to detect such electrical creep provides a novel way to predict the functional life of the system as the resistance shift rate can be related to the crack growth rate that allows the transformation from the periodic maintenance to condition-based maintenance.

#### 4. Conclusions

In conclusions, the results obtained from this work confirm that the incorporation of graphene nanosheets with carbon fibers in epoxy matrix may lead to a substantial change in the nature of the composite material by converting it from a passive structural components into multifunctional smart systems. An active nano-conductive network was successfully formed at a critical conductivity threshold of 3.0-4.0 wt.% graphene nanosheets as such contents lead to reasonable decrease of several order of magnitudes in the specific resistivity due to the activated electron tunneling mechanisms and direct contact of particles. High efficiency of the composite material was recorded in the SHM under dynamic loading conditions. This confirms the superiority of these hybrid systems over the conventional sensors by the reliability and weight saving. This work reveals that the synergy between carbon fibers and graphene creates an artificial nervous system within the structure, which prepares to new applications in space and aerospace technologies.

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