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Electric resistance measurement–based structural health monitoring with multifunctional carbon fibers: Predicting, sensing, and measuring overload

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ABSTRACT

Polymer matrix composites that also contain carbon fiber reinforcement can be given a secondary function in addition to load bearing due to the electrical conductivity of the reinforcing fiber. We investigated how to measure the deformation of a composite by measuring the resistance of the carbon fiber and indicate its current or previous overload. We found that the resistance of the carbon fiber bundle initially increases linearly and then progressively during the testing of the specimens, and finally, when the fiber bundle snaps, the circuit breaks. We have shown by cyclic testing that overload exceeding reversible deformation can be detected and measured by examining the first derivative of the resistance change with respect to deformation. Based on our results, electric measurements of either an only carbon fiber-reinforced composite or a hybrid composite can be used to detect a possible previous overload of a component with an unknown load history.

1. Introduction

Carbon fiber-reinforced polymer matrix composites are increasingly used due to their advantageous properties, such as low weight [1] and good machinability [2], in addition to load-specific stiffness properties. In addition to their load-bearing capacity, these materials can be provided with several secondary functions due to their electrical conductivity. By measuring the electrical resistance of carbon fibers, a structural health monitoring system can be created to detect the consequences of environmental impacts on the composite component (e.g., deformation, cracking, etc.) even from the beginning of production. As we previously discussed [3], the crosslinking of the epoxy resin can be monitored by measuring the resistance of the carbon fiber bundle used as reinforcement since the resistance of the fiber bundle depends on the surrounding medium and temperature.

The electrical resistance of the carbon fiber used as a reinforcing fiber and its change under load have already been studied by Schulte and Baron [4]. They found that initially, the resistance increases linearly according to the geometric change, and then the value of the resistance suddenly jumps as the fibers break. Chung [5] investigated joints by electric resistance measurement. Based on the article, it is possible to detect and to characterize the failure of the joints by electric resistance measurement. Prasse et al. [6] studied the change in the electrical resistance of carbon fiber under cyclic loading. They found that with increasing load, when the load level reaches the maximum of the previous cycle, there is a breakpoint in the electrical resistance curve. This can be due to the cracks that form during loading and then close during unloading, as the cracks that have already been created will open first during reloading (this is only slightly visible in the change in electrical resistance) and then, at higher stresses, the system resistance starts to increase more intensively due to new cracks forming. Luan et al. [7] created a composite specimen containing carbon fiber using additive manufacturing technology. In their experiments, they investigated how the resistance of a sample loaded asymmetrically with three-point bending changes under the effect of deformation. They found that the sensitivity of the carbon fiber sensor can be well determined for different load conditions. Vavouliotis et al. [8] investigated fatigue fracture of quasi-isotropic carbon fiber reinforced epoxy resin matrix composite specimens filled with carbon nanotubes (CNT). As a result of their experiments, they discovered correlations between load level, the number of cycles, and resistance change, which can be used to predict specimen failure.

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Several studies [9–13] have also investigated electrically insulating fiberglass-reinforced epoxy composite plates by resistance measurement. For this, they added nanoparticles (e.g. CNT, carbon black) to make the specimens conductive. By testing the electrical resistance of the samples, they demonstrated that a fundamentally insulating material could also be modified to allow continuously and *in situ* structural health monitoring, thereby (based on previous calibrating measurements) predicting specimen failure. For this type of test, it is necessary to reach a specific concentration of the filler, the so-called percolation threshold, the concentration at which a cohesive conductive network is formed from the contacting particles. According to Alipour et al. [14], the percolation threshold is related to the viscosity of the epoxy, as the nanoparticle is easier to distribute in the matrix with better flowability, agglomerations are more challenging to form; thus the required conductivity can be achieved even with lower graphene content. A carbon-based additive for strain measurement can also be used for higher elongations. Nakaramontri et al. [15] mixed carbon nanotubes and carbon black into different rubbers, making the material conductive. They were able to measure the resistance of the sample even during high deformation of the rubber (up to 250%), thus creating a material suitable for condition monitoring.

A condition monitoring sensor can be created using the electrical properties of carbon fiber or carbon-based nanoparticles. Deformations, fiber breakage, matrix cracks, and delamination in a specimen or product can be examined with an appropriate measurement arrangement and the proper use of materials. In addition to qualitative indication, information can also be obtained on the size and location of the failure. Based on the literature research, we aimed to develop a measurement and evaluation method in which measuring the resistance of the reinforcing carbon fiber bundle can predict possible overload and determine the potential previous overload of the composite specimen.

2. Materials and methods

For our experiments, we used Sigrafil C T24-5.0 / 270-E100 carbon fiber (PAN precursor, 24 thousand elementary fibers per roving, 7 μm diameter, 5 GPa tensile strength, 270 GPa tensile modulus, 1.9% elongation at break, specific resistance 14 μΩm [16]) manufactured by the automotive supplier SGL Carbon SE (Germany). We used epoxy resin (aliphatic reactive diluent-based MR 3016 resin and cycloaliphatic amine-based MH 3124 crosslinker 100:40, Ipox Chemicals Kft., Hungary) for the composite specimens. We used glass fabric (225 g / m^2 area density, Owens-Corning Composites LLC, USA) as a base layer for the composite samples. During the production of the 300*25*2 mm specimens, we took care to ensure that the measured carbon fiber bundle remained tight throughout the lamination process. The embedded carbon fiber bundle extended beyond the glass fabric, parallel to the longitudinal axis of the specimen. We choose glass fabric as the enclosing layer (2 layers below and above the carbon fiber bundle) because it is an electrical insulator; thus, we measured the change in carbon fiber resistance and avoided contact with the environment. The specimens were heat-treated in an oven (Despatch LBB-27-1CE, Despatch Industries, USA) at 80 °C for 4 h.

We measured the resistance of the embedded carbon fiber bundle with an Agilent 34970A (Agilent Technologies, USA) data acquisition device using the four-wire method. Based on our previous experiences [17], we used a copper block to establish contact between the measuring device and the carbon fiber bundle to minimize specimen preparation and replacement time. From the resistance values we measured in this way, we calculated the relative change in resistance ($R_{\%}$) according to formula (1). R_i is the current resistance, and R_0 is the initial resistance at the beginning of the measurement.

$$R_{\%} = \frac{R_i - R_0}{R_0} \tag{1}$$

We performed tensile tests with a Zwick Z250 (Zwick, Germany) universal tensile machine. We monitored the force with a force-measuring cell with a measuring range of 20 kN, and the tensile speed was 2 mm/min. We measured the deformation by digital image correlation (DIC) with a Mercury Monet (Sobriety, Czech Republic) type optical strain measuring equipment during the tensile tests.

3. Results and discussion

In our first series of experiments, we broke five specimens in a one-step tensile test while measuring resistance and deformation. We plotted the measured results on a deformation-resistance change diagram (Fig. 1).

Fig. 1.d shows that initially (up to about 0.8% elongation), the resistance changes linearly with increasing deformation due to the reversible deformation. The slope of this section is called the gauge factor, and in our experiments, it was 1.05 ± 0.10%/%. By further increasing the deformation, we found that the change in resistance of the carbon fiber progressively moves away from linear. This is due to the irreversible elongation, at which the elementary fibers begin to break or pull out of the matrix, thereby reducing the conducting cross-section and increasing the resistance of the fiber bundle. As we proved in our later measurements, this change in resistance is no longer recovered after unloading. The carbon fiber bundles broke at a deformation of 1.61 ± 0.12%, at which point the electric circuit broke (Fig. 1b). Because the elongation at break of the glass fiber is greater than that of the carbon fiber, the specimen bore even more stress before the glass fabric broke (Fig. 1c). In addition, the carbon fiber bundle is not broken in the same place as the glass fabric (Fig. 1e), suggesting that the failure took place not in one but in two stages, which means that the higher modulus, lower elongation carbon fiber broke earlier than the more flexible fiberglass fabric. Based on the above, in a fiberglass-carbon fiber reinforced hybrid composite structure, overloading or failure due to excessive deformation can be predicted by resistance measurement, thus preventing catastrophic failure. A similar signaling mechanism can be developed by incorporating a bundle of carbon fiber with a lower elongation at break into a carbon fiber-reinforced composite and measuring only the resistance of that bundle.

We also performed cyclic loads on five specimens to better understand the correlation between reversible and irreversible deformation and resistance change. To clearly define the boundary of the two sections, we subjected the specimens to various increasing deformations as a percentage of the average elongation at break (10; 20; 30; 40; 50; 60; 70; 80; 90; 100%) while we measured the resistance of the fiber bundle (Fig. 2).

When calculating the change in resistance, we took the resistance of the unloaded specimen before the given deformation load level as a reference point in each case. During the test, the resistance followed the deformation in each cycle. The difference in the two values visible at the maxima was because of the gauge factor of the carbon fiber bundle. After correction with the gauge factor, the deformation calculated from the resistance of the carbon fiber bundle was approximately the same as the deformation measured with the DIC device. We assigned resistance and deformation to each other based on test time and then plotted the values on a diagram (Fig. 3).

In the reversible deformation phase ($\varepsilon \leq 0.8\%$), the resistance change–deformation curve during cyclic loading can also be characterized by a line with a slope equal to the gauge factor determined during the quasi-static tensile test. At each load, the resistance changes linearly until it reaches the previous maximum deformation and then begins to increase progressively due to the breakage of the individual fibers. Based on these, a test can be performed on a carbon fiber-reinforced composite component, in which the previous possible overload and its magnitude can be determined from the resistance measurement by continuously deforming the specimen. The way to do this is to continuously measure the resistance of the carbon fiber-reinforced component with an unknown history during a tensile test with a constant deformation rate, and

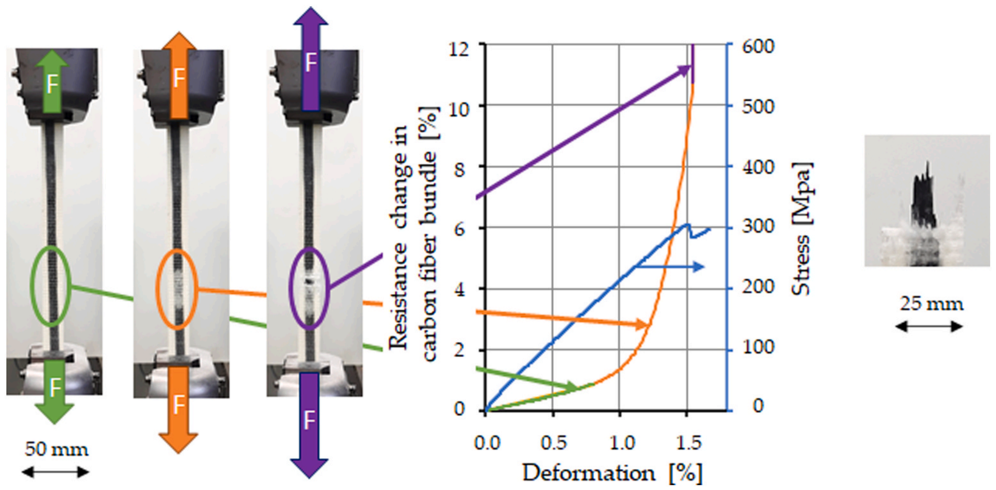


Fig. 1. Tensile specimen before failure (a), breakage of the carbon fiber bundle (b), breakage of the glass fabric (c), change in resistance of the carbon fiber bundle as a function of deformation with the measured stress data during a typical tensile test (d), and enlarged image of the failure environment (e). Reversible deformation phase (green), irreversible deformation phase (orange), and fracture (purple), and the stress in the specimen (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

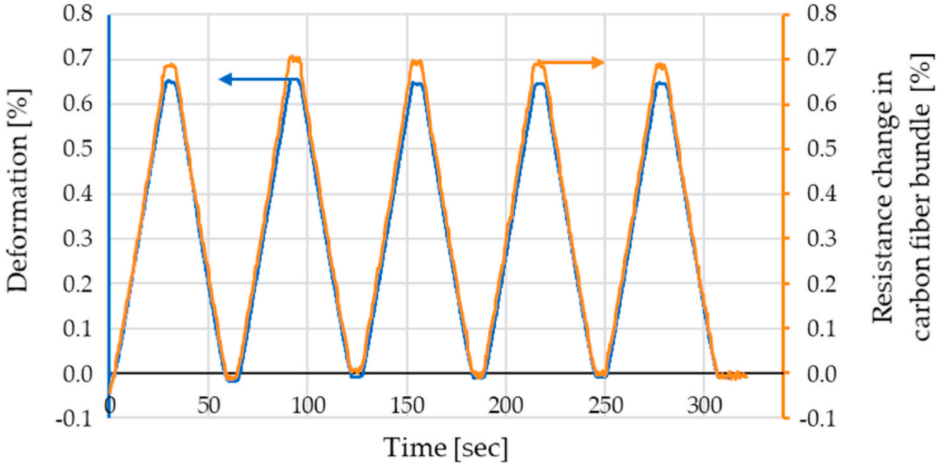
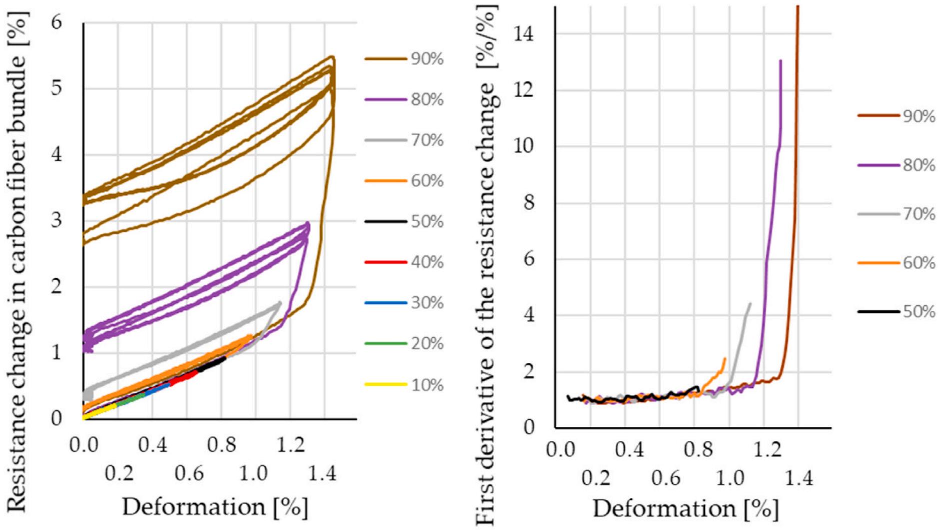


Fig. 2. Deformation (measured by DIC) and resistance change measured. under cyclic loading of a carbon fiber bundle specimen. The result of a typical sample at a deformation load of 40% of the elongation at break.



a)

b)

Fig. 3. The resistance change of a carbon fiber bundle specimen under cyclic loading normalized to the pre-cycle value (a) and the first derivative of the resistance change during irreversible loading (b)—values of a typical specimen.

then to form a numerical derivative of the measured resistance change by central differentiation (Fig. 3b). The value of the first derivative moves around the gauge factor (1.05%/%) of the carbon fiber in the initial, linear section and then increases as the fibers break. In a previously not overloaded carbon fiber bundle, this breaking point coincides with the end of the reversible section. On the other hand, the breaking point occurs at the maximum of the previous overload in the first derivative in the case of an overloaded composite. It can also be seen in Fig. 3.b that the first derivative of the 60% specimen indicates damage which is barely visible in Fig. 3.a. Based on these, the degree of previous maximum irreversible deformation of a composite can be determined by measuring the resistance of the carbon fiber bundle.

4. Conclusion

By measuring the electrical resistance of the carbon fiber bundle, the deformation and load of a composite can be monitored. In our experiments, we laminated a carbon fiber bundle to a glass fabric-reinforced composite, and measured its resistance during a tensile test. We have developed a test method to indicate the overload of a glass fabric–carbon fiber-reinforced composite component in the initial stage of residual deformation. This requires continuous measurement of the resistance of the carbon fiber bundle and calculation of the first derivative according to the deformation.

We have also developed a material testing method based on resistance change analysis, which can be used to determine the possible overload of a component with an unknown history and its extent. The first derivative of the resistance change assumes a constant value until the reversible deformation section or the maximum of the previous overload is reached, then this value increases.

Since the elongation at break of the glass fabric is greater than that of the carbon fiber bundle, the glass fabric was not torn immediately but could be further loaded when the carbon fiber bundle broke. Based on these, the failure of the composite can be predicted by measuring the resistance of the carbon fiber bundle. This requires a bundle of carbon fibers that can also be used as a sensor and has a lower elongation at break than the reinforcing fibers in the composite component. Thus, in either a hybrid composite or a carbon fiber-reinforced composite, the carbon fiber bundle used as a sensor achieves irreversible deformation earlier than the component itself, which means overload and damage can be indicated even before the structure is seriously damaged.

CRediT authorship contribution statement

N. Forintos: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **T. Sarkadi:** Conceptualization, Writing – original draft. **T. Czigany:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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