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Article

Development of Self-Sensing Textile Strengthening System Based on High Strength Carbon Fiber

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Abstract: Monitoring of structures is one of the engineering challenges of the 21st century. At the same time, as a result of changes in the conditions of use, design errors, many building structures require strengthening. The article presents research on the development of the external strengthening carbon fiber textile with an option of self-sensing. The idea is based on the pattern of resistive strain gauge, where thread is provided in a zig-zag of parallel lines. Already the first laboratory tests showed the high efficiency of the system in the measurement of strains, but also revealed the sensitivity of measurement to environmental conditions. The article presents studies on the influence of temperature and humidity on the measurement. To separate those effects, resistance changes were tested on unloaded concrete and wooden samples. The models were placed in a climatic chamber and the daily cycle of temperature and humidity changes was simulated. The results of the research confirm preliminary observations. Resistivity growths with the temperature. This effect is more visible on concrete samples, presumably due to its greater natural humidity. The strain measurement with carbon fibers is very sensitive to temperature changes and application of this method in practice requires compensation.

Keywords: CFRP strengthening; textile sensor; strain gauge errors compensation

1. Introduction

About 50 years ago, Concor and Owston [1] noted that most carbon fibers behave in a simple manner of linear rise in resistance with strain. They also defined characteristics that are important for measurement as the initial stress of fibers, time-dependent and high strain rate or contact resistance [2]. Since that time idea of self-sensing carbon fibers is developed and still improved. Today, the development of two independent technologies using conductivity of carbon-based materials for strain measurement can be observed: printed gauges based on graphite carbon nanotubes [3, 4] and based on continuous carbon fiber [5-14]. It should be emphasized that only this second technology allows the use of an essential feature of carbon fibers, which is their high strength. In recent years, a technology enabling the 3D printing of carbon fiber sensors has appeared [14, 15]. It should avoid a quite laborious assembly process and will improve the sensor quality. Carbon fibers can also be used as light sensors [16].

Measurements performed using resistive strain gauges allow investigating the change in strain expressed by the change in resistance. Unfortunately, the measurement of the actual mechanical deformation overlaps with various effects disturbing the measurement signal. These include mainly environmental influences, such as thermal elongation of the measured object, temperature-dependent change in strain gauge resistance, thermal shrinkage of the strain gauge measuring film, thermal response of connecting wires, surface conductivity with increasing humidity. Carbon-based materials are much more temperature sensitive conventional strain sensor made of constantan (copper-nickel alloy) [17]. The above factors may be influenced by the method of laying the wire, the material from which the strain gauge was made, the ground material as well as

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the type of adhesive that fixes the strain gauge. In the case of carbon fibers, their straightness may also be important [2, 9], or the contact resistance [10] limited by the matrix material and the method of assembling electrodes

Typically, the effect of temperature and humidity is compensated in the measurements, by combining several strain gauges to form a half or full bridge. Through the skillful combination of strain gauges of the usually used Wheatstone bridge circuit [18], where strains from the measuring strain gauges and compensation strain gauges are reflected in the measurement signal with opposite signs (positive and negative), the bridge voltage only represent mechanical strains, and the temperature/humidity dependent effects abolish each other.

Identical or even similar working conditions of measuring and compensating strain gauge may not always be met, which is why modern computational compensation systems adapted to the thermal and moisture response of strain gauges are increasingly being used today. In this type of measurements, a quarter-bridge circuit is sufficient, but knowledge of the temperate and humidity response functions is necessary.

Paper describes preliminary works on the temperature-resistance dependence of developed external strengthening carbon fiber textile sensor. These tests are to be used in the future to build a temperature change compensation functions necessary to use the discovered device in engineering practice.

2. The idea of self-sensing strengthening system

The developed system takes advantage of two features of carbon fibers, their superb strength and electrical conductivity. The idea of measuring strains by recording changes in the resistance is based on operation principles of strain gauge invented in 1938 by Edward E. Simmons and Arthur C. Ruge [19]. Such strain gauge contains a long, thin conductive wire arranged in a zig-zag pattern of parallel lines. The parallel orientation of wires multiplies the reading which allows increasing the accuracy of the measurement of small strains. The same concept was used to create smart textile. Carbon fiber tow commonly used as a reinforcement of FRP strengthening systems at the same time can act as an electric conductor. Deformation leads to change in electrical resistance allowing self-monitoring of the fabric. How can be assumed already the first tests have shown that changes in resistance for a single tow is too small compared to the technical abilities of recording equipment used (Wheatstone bridge). Increasing the length of the tow by its wiggly lead (copy of zig-zag pattern of strain gauge) significantly improved the sensitivity of the system.

Made in this way the first prototype was tested on small models of concrete slabs. To verify the accuracy of the measurement, the device was accompanied by paper strain gauges adhered along its length (Fig. 1). A more detailed description of these studies is described in [20]. This initial trials confirmed capabilities of developed smart textile. However, the sensitivity of the device still proved to be insufficient, especially for measuring small changes in strain. The modification allowing to increase the accuracy of the measurement was the introduction of two parallel threads of carbon fibers placed end to end. When the measuring bridge was connected to the two ends of independent threads, the measured resistance increased, because, beside the previous volume resistance (growing with elongation of carbon fiber), the phenomenon of contact resistance appeared at the interface of parallel fiber threads. Despite the controversy, mainly related to the accuracy of the measurement of large deformations, at which micro-cracks may appear, and with them rapid increases in contact resistance, the results of the first tests turned out to be quite promising. The developed textile sensor was checked as an independent external reinforcement and local strengthening of existing reinforcement. Achieved strengthening effectiveness can be assessed at the level of a single layer of carbon sheet while maintaining the ability to measure strains until failure. The results of these studies can be found in the work [21].

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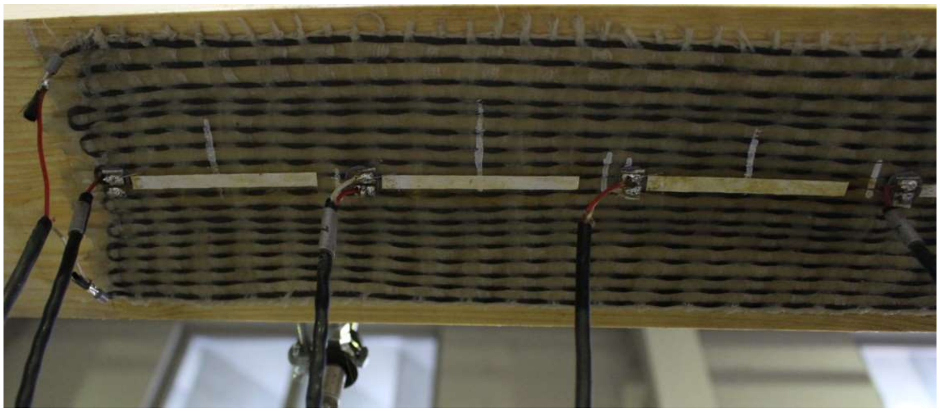

Figure 1. The second generation of textile sensor adhered to timber specimen.

Provided production method was based on traditional plain weaving, where alternating carbon and acrylic threads arranged as warp and are stabilized by the weft made of cotton. This technology has several significant disadvantages. The carbon fiber must be continuous and well stressed during weaving. This hinders the automation of production, and only the classic weaving loom can be used. The fiber types used makes the textile sensor soft. This facilitates its application, however, after adhering, the carbon fibers may not be sufficiently stressed, which worsens the strengthening efficiency and changes the gauge factor. Specifying the gauge factor value is one of the biggest drawbacks of the developed solution. In trial tests, paper strain gauges were used for this purpose. It was observed that resistance largely depends not only on the total length of the carbon fiber thread but also on the lamination conditions. Most likely, this is related to the change in contact resistance conditions.

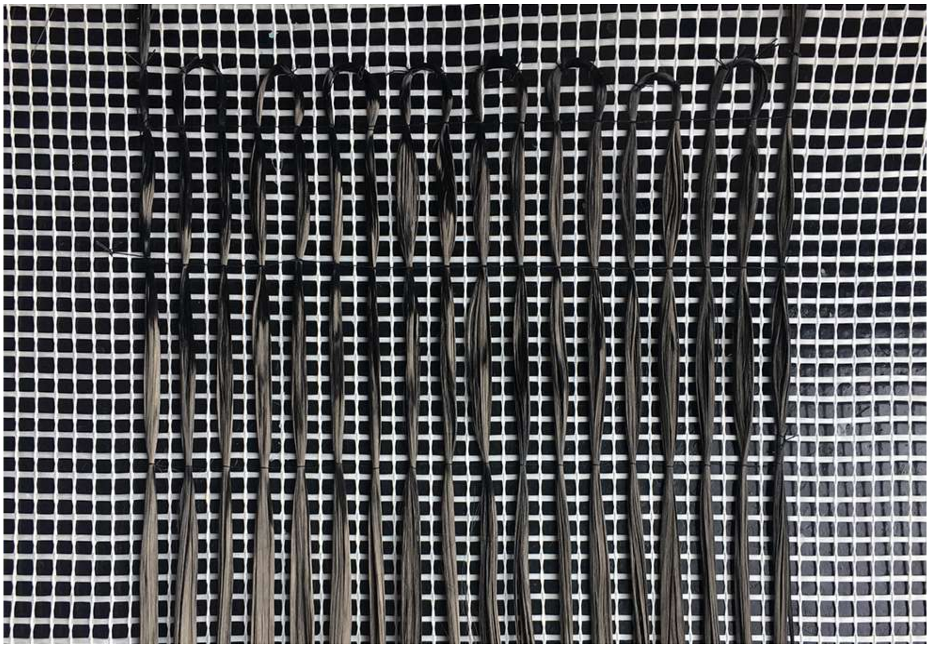

Figure 2. The third generation of textile sensor during fabrication.

The third generation of the intelligent textile is currently being tested. The concept of the parallel arrangement of a double fiber thread was abandoned, which means that the volumetric resistance is directly responsible for the measurement. However, the main modification concerns the production method. Weaving was replaced by fiber stabilization by fastening to the composite mesh matrix. For this purpose, a glass fiber plaster reinforcing mesh was used. The dry carbon thread is

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stitched to the mesh strands as shown in Figure 2. This stabilization method reduces the risk of accidental short-circuiting during the assembly of the sensor. There is no need for additional separating acrylic threads. The sensor can be manufactured even in construction site conditions, no machines are needed, such as a weaving loom. The change in the resistance of this type of sensor should depend mainly on the total length and cross-section of the carbon fibers, therefore its gauge factor should be easier to determine.

3. Tests of the influence of temperature on the resistance

The research described in the chapter concerns two types of the sensor. Woven, the second generation adhered to the wooden substrate, mesh stabilized, latest generation adhered to the concrete substrate. Table 1 presents the basic parameters of both types of the sensor.

Table 1. Properties of the textile sensor.

Sensor generation	**Woven (2nd)**	**Mesh stabilized (3rd)**
construction	Two parallel threads of conductive carbon fiber, separated by thread of acrylic fiber (1.17 g/cm^3) and stabilized by cotton weft (1.54 g/cm^3)	A single thread of conductive carbon fiber fastened to the glass fiber plaster reinforcing mesh (8 x 8 mm; 145 g/cm^3)
number of loops	18	18
length of the sensor	1000 mm	1000 mm
rowing	2 x 24000 filaments / thread 2 x 1600 tex	24000 filaments / thread 1600 tex
strength of carbon fiber	5000 MPa	
modulus of elasticity	270 GPa	
elongation at break	1.9 %	
filament resistivity	14 μΩm	
initial resistance	174,8 Ω [1]	212 Ω
gauge factor	1,24	1,19

[1] before lamination of fibers.

The test samples were placed in a climatic chamber (Fig. 3). Humidity and temperature were changed in four different cycles:

- heating from + 20^{0}C to + 40^{0}C with a simultaneous humidity change from 60% to 65%,
- heating from +20^{0}C to + 60^{0}C with a simultaneous change in humidity from 60% to 65%,
- cooling from + 20^{0}C to 0^{0}C with a simultaneous reduction of humidity from 60% to 55%,
- cooling from +20^{0}C to -20^{0}C with a simultaneous reduction of humidity from 60% to 55%.

During the test, textile sensors were connected to the Wheatstone bridge. Resistance changes were recorded every 60 seconds. This measurement corresponds to the sum of the actual thermal deformation of the sample and apparent deformation, which expresses the wanted change in the sensor's resistance under the influence of temperature and humidity.

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(**a**) (**b**)

Figure 3. Samples inside climate chamber during the test: (**a**) second generation of sensor and timber sample; (**b**) third generation of sensor and concrete sample.

4. Test results

The test results were presented in diagrams in the form of dependence of temperature changes on the measured apparent deformation. Figures 4 and 5 show the test results for the sensor on a wooden sample, Figures 6 and 7 on a concrete sample. The situation of the rising temperature and the decreasing temperature is shown independently in separate diagrams.

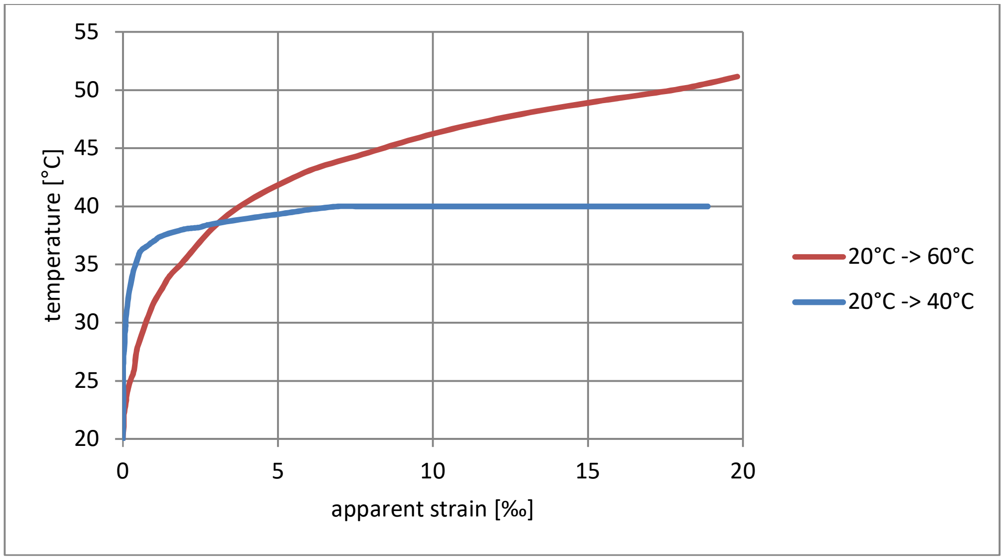

Figure 4. Dependence of apparent strain on rising temperature for the wooden sample.

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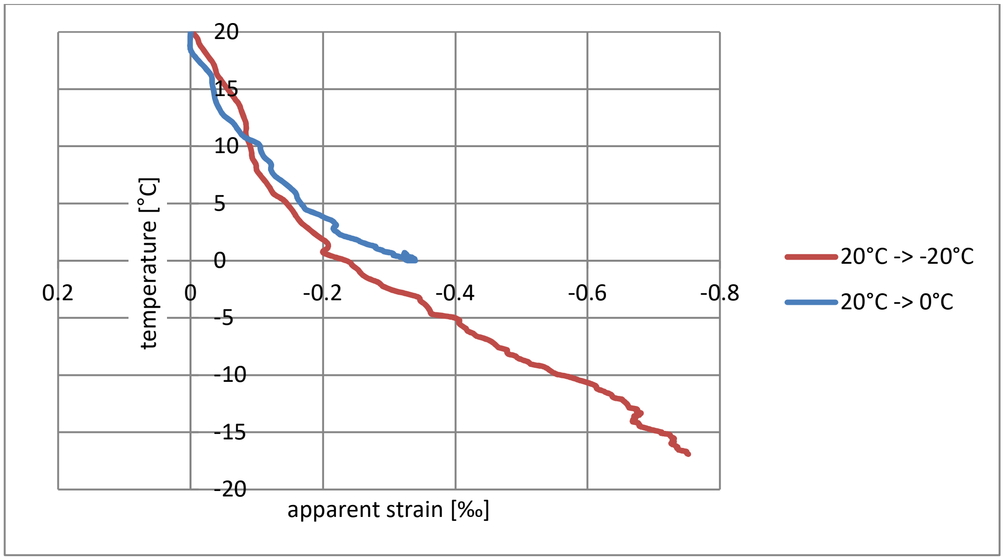

Figure 5. Dependence of apparent strain on decreasing temperature for the wooden sample.

Wooden sample was made of pinewood. Thermal expansion coefficient along the fibers of that kind of wood is equal around 3 $\times 10^{-6}$/°C. Similarly, the coefficient of thermal expansion of concrete is equal to 1.2 $\times 10^{-6}$/°C.

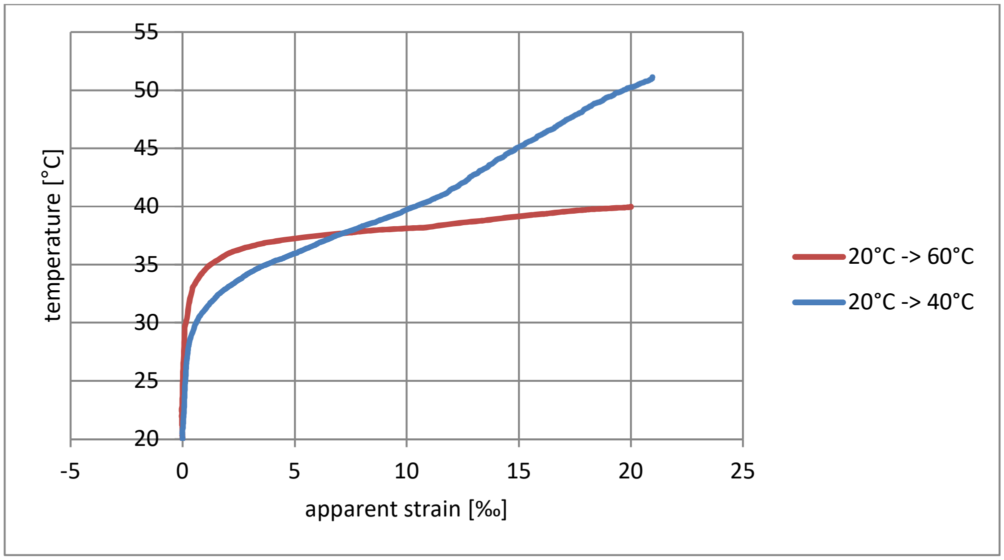

Figure 6. Dependence of apparent strain on rising temperature for the concrete sample.

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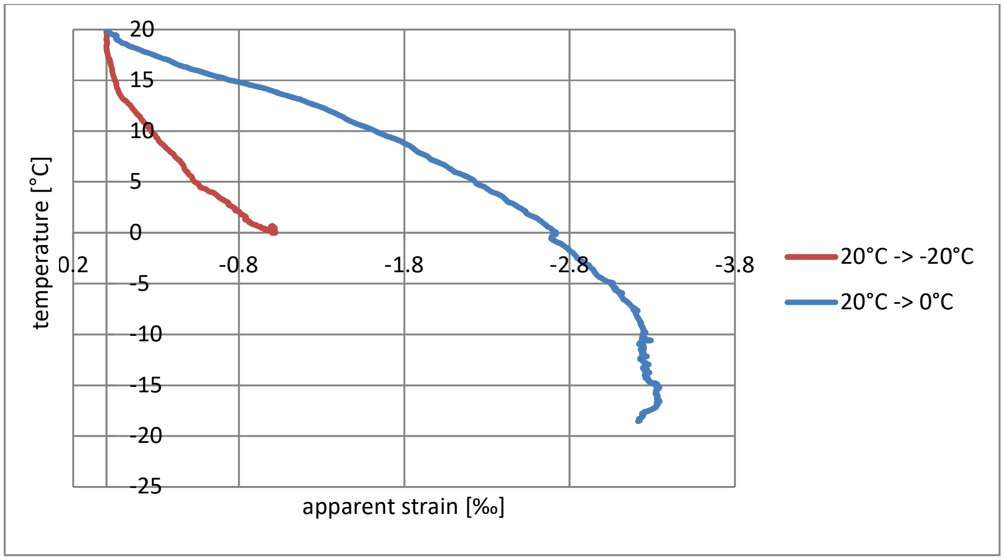

Figure 7. Dependence of apparent strain on decreasing temperature for the wooden sample.

5. Discussion

The measured strain consists of a real elongation of the sample as a result of thermal expansion and apparent strain resulting from the temperature sensitivity of the textile sensor. The direction of observed resistance changes is correct. The increase in temperature is indicated as elongation, while the temperature decrease is indicated as shortening. If the shown changes were purely the result of thermal deformability, then for wood the measured deformation should not exceed 0.003 ‰/°C, whereas for concrete 0.0012 ‰/°C. The obtained strains are much greater, in addition, the temperature-strain relationship is not linear.

The tendency to indicate apparent strain is particularly visible for rising temperatures. Taking into account the elasticity coefficient of carbon fibers, the measured strain > 20‰ theoretically correspond to a stress of 5.4 GPa, in practice breaking the carbon fibers. The situation is slightly better in the case of decreasing temperatures, where the error for wood does not exceed 0.75‰, while for concrete 3.3‰. The difference can result from a slightly different type of textile sensor used in both cases. A faster increase in the conductivity of concrete samples may also result from humidity changes on their surface. Due to the better thermal conductivity, the concrete surface can promote condensation of water vapor.

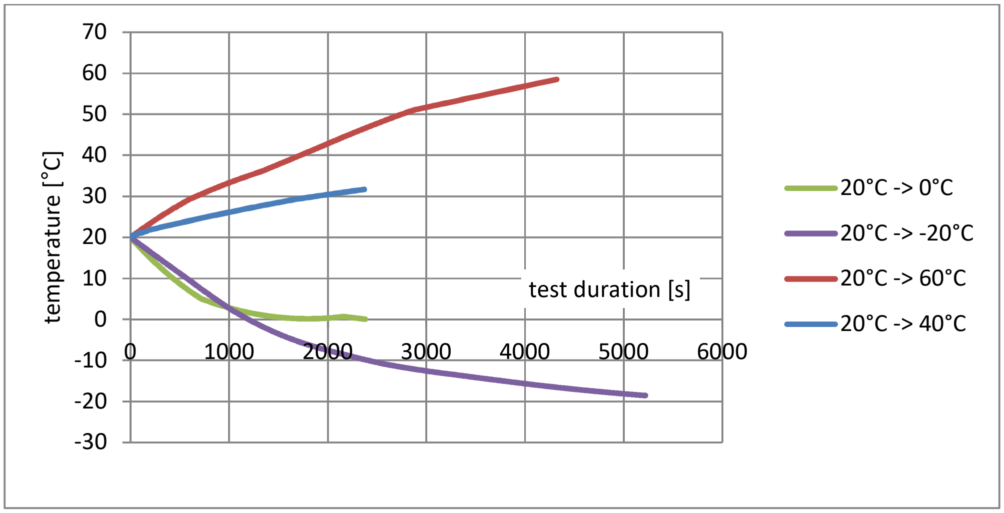

Figure 8. Paths of the temperature change during the heating or cooling inside the climate chamber.

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Another interesting observation is related to the speed of temperature changes. Heating tests 20 °C -> 40 °C and 20 °C -> 60 °C, as well as cooling 20 °C -> 0 °C and 20 °C -> -20 °C were running at different rates (shown in Figure 8). The paths of strain increments in the same temperature ranges shown in the diagrams (Figure 4 – 7) are totally different. At the current level of research, it is difficult to explain the reason for this phenomenon. Further research is needed for different rates of temperature change in various ranges. The problem of the influence of humidity, including its condensation, also needs to be solved. The physical mechanisms of such a high sensitivity of the sensor to temperature changes also require clarification. Perhaps it will be necessary to modify the concept of developed textile sensor, for example by introducing an additional isolating layer that cuts off carbon fibers from moisture.

6. Conclusions

Due to the small number of samples, the presented tests are only preliminary and do not allow to determine the relationship between temperature and resistance change. However, even such limited research shows the importance and complexity of the problem. Resistance changes are not only a function of temperature changes, but also the speed of these changes or the type of substrate. Caused by increasing temperature indication error exceeding 5.4 GPa very well illustrates how important for the development of measurement methods using carbon fibers is the development of effective methods to compensate for the temperature changes.

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