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Multifunctional Carbon Fiber Reinforced Polymer Composite Structures: Reinforcing and Sensing

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Summary: In our research, we investigated how electric current connected to multifunctional carbon fiber would affect the dynamic mechanical properties of the polymer matrix composite. The reinforcing carbon fiber, which could have additional functions as well (e.g., self-sensing) was connected to an electric circuit, then we carried out a dynamic three-point bending test. We varied the amperage and connection time of the current and measured bending stiffness and strength. Based on the results, we concluded that there is a current limit (0.5 A), under which the electric current does not modify the dynamic bending properties. We measured the generated Joule heat. We determined the same current limit where the specimen would not heat up too much, although resistance heat should be considered at any amperage connected for longer time. Usually, when carbon fibers are used multifunctionally for both reinforcing and sensing, a low current is applied (~100 mA), therefore it would not change the mechanical behavior of the composite.

Keywords: Multifunctional carbon fiber, Smart material, Self-sensing, Joule heating.

1. Introduction

Carbon fiber reinforced polymer composites (CFRP) are widely used in many industries due to their low density, high strength, load-optimized stiffness and excellent corrosion resistance. One of these industries is transportation, where electric vehicles are dynamically developing, and an important goal is to increase their range. This can be achieved by either increasing the capacity of the batteries or reducing consumption, for example by reducing the weight of the vehicle. One solution is to use reinforced plastic, such as fiber-reinforced composites. Additional weight reduction can be achieved by combining functions: a component can perform multiple tasks (e.g. load-bearing, signal transferring, self-repairing, and energy storage), therefore, the non-load-bearing part can be eliminated [1]. In our previous review article, we categorized multifunctional CFRPs based on their secondary function and application [2]. For instance, monitoring the resistance of a carbon fiber bundle in a specimen would create a structural health monitoring sensor. Bashmal *et al.* [3] investigated the linearity of the sensitivity of carbon fiber. They tested different conducting areas and lengths by varying the number and length of the carbon fiber tows they used. They concluded that specimens with a small number of filaments (3K or under) have linear characteristics and are suitable for low strain levels.

With carbon fiber-based sensors, it is possible to detect deformation, fiber breakage, delamination and failure as the resistance of the carbon fibers will increase during those effects. Wang *et al.* [4] performed drop tests on carbon fiber-reinforced polymer composites with different layer orders while measuring the change in the electrical resistance of the specimens. They investigated several configurations: in one case, surface resistance was measured, which in their opinion could be used to detect fiber breakage, in another case, the change in resistance was measured through the width of the composite specimen, which they thought was more suitable for detecting delamination. They also mentioned that by measuring the change in resistance, smaller defects can also be detected compared to other non-destructive processes (e.g. ultrasonic testing).

Luan *et al.* [5] used a novel manufacturing technique to create a multifunctional composite: they developed an additive manufacturing process with two printer nozzles and integrated an injection system. With this method they built specimens with continuous carbon fiber and thermoplastic matrix to test the reinforcing and sensing function and injected epoxy resin as curing agent separately for self-healing function. They performed compression tests and three-point bending tests on the material. They achieved continuous and *in-situ* detection of damage. They found that self-healed specimens have better mechanical properties than the original specimens because of the poor initial adhesion between the fiber and matrix and the improved adhesion after the first test caused by the cured epoxy.

With new materials, for example nanocomposites, new opportunities are available. Shape memory polymers could change their geometry triggered by heat, mechanical stress or an electric current. This additional function can be used in different applications where weight saving is crucial or the available space is limited (e.g. space structures, artificial muscles, civil applications) [6]. Other nanocarbon allotropic materials, for example graphene nanoplatelets can also be used for sensing, they can even be applied on originally non-conductive materials. Sethy *et al.* [7] spray coated a glass fiber reinforced composite beam with this material. They investigated the sensitivity of this sensor with different mechanical tests and obtained a high gauge factor, which makes it a feasible material for multifunctional applications.

In parallel with the ongoing development of electronic, information and telecommunications technologies, harmful electromagnetic radiation called electromagnetic interference (EMI) is also a growing problem. It can interfere with electronic devices, which can be particularly risky for applications such as medical technology, the aerospace and military industries, and can also be harmful to health. To avoid these, Faraday-cage-based equipment and materials are used, which partially or completely surround the device responsible for radiation, partially transmit, reflect or absorb electromagnetic radiation, thus limiting the adverse effects. Aripin *et al.* [8] used carbon fiber reinforced thermoplastic matrix tapes and made three dimensional specimens with different layer orders. Based on both electromagnetic insulation and mechanical properties, they concluded that unidirectional tapes are best for EMI shielding and structural functions. They explained it by the good through-thickness conductivity and interlaminal adhesion of the CFRP layup.

Another example of multifunctional CFRP is the resistive heating of carbon fibers, which can be used to help the crosslinking process, create the necessary heat for bonding and welding, or deice airplane wings. Weiland *et al.* [9] simulated and experimentally validated the effectiveness of self-heating CRFP. They also made mold from CFRP. They summarized their results in such a way that although CFRP is suitable for *in-situ* heated mold material by resistive heating, the induced temperature will not be homogeneous due to the relatively low thermal conductivity. With their simulation, they found that varying cross sections of the CFRP tool results in a more homogeneous heat distribution.

Welding components together requires pressure and heat. Using the self-heating property of CFRP makes it possible to locally heat the parts to weld them. Flanagan *et al.* [10] used carbon fiber reinforced polyether ether ketone (PEEK) composite parts and they heated them by Joule-heating generated by induced alternating current. They inspected the welded assembly by mechanical testing and optical microscopy and concluded that although it had similar mechanical properties to adhesive bonded parts, it had voids, delamination and warpage caused by the welding process. They predict that this manufacturing process could be used in different industries, for example for automotive component assembling.

Pan *et al.* [11] also used the self-heating effect of carbon fiber reinforced PEEK. They added graphene to enhance conductivity and to achieve better heat distribution, therefore decreasing the power needed for larger scale parts. In their research, they tested the self-heating function by simulating cold application, where icing of the part can occur, therefore efficient deicing is needed. They achieved rapid heating and deicing by using the *in-situ* heating concept.

The generated heat can be a disadvantage in the case of the electrical multifunctional application of CFRP: when the carbon fibers are used as sensors, the generated heat changes the resistance of the sensor, which would cause inaccurate sensing. In our recent article, we presented how a change in temperature would result in a change in resistance (Fig. 1).

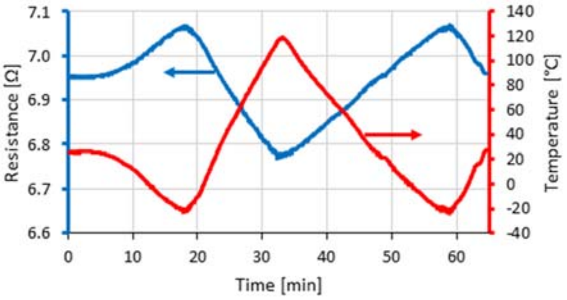

Fig. 1. Resistance as a function of temperature during a heating-cooling cycle for heat dependence measurement [12].

In that article, we showed that carbon fibers have a negative linear temperature coefficient, which means that with increasing temperature the resistance of carbon fibers decreases. Their heat sensitivity is significant, a temperature difference of 100 °C results in the same resistance change as breaking the specimen would cause, therefore this effect should be taken into account and it should be compensated for in sensing applications [12].

The development of electric vehicles includes examining possibilities of how the body could also be an energy storage component. The so-called structural supercapacitor is a capacitor-like energy storage unit in which the electrodes are usually activated carbon fiber layers with an electrically insulating layer between them. In addition to energy storage, they also have load-bearing capacity [13].

Using structural batteries, for example combining lithium-ion battery with carbon fiber reinforced polymer composite is ideal for weight and volume saving. Moyer *et al.* [14] used the carbon fiber's mechanical properties for the structural function and the electric properties for the current collector function. They used this concept in a CubeSat, which is a miniature satellite type. As the outer dimensions are strictly given, all the necessary parts should fit inside. They eliminated the traditional battery by using their multifunctional composite, therefore saving volume for other instruments.

The use of supercapacitors and structural batteries raises several safety issues: what happens to the stored electrical energy in the event of a collision, and how electric current affects the dynamic mechanical properties of CFRP.

Sierakowski *et al.* [15] investigated the relationship between the impact resistance of composites and the electric current conducted through samples using drop tests. A direct current of 25 A and 50 A was passed through the pieces for different times. They observed that if the current is passed through the specimens immediately before the mechanical impact, the impact resistance increases, but if they connected the current for longer, impact resistance decreases. The negative effect of prolonged current was explained by resistance heating, but the authors did not explain why a brief electric current would improve the mechanical properties.

Barakati and Zhupanska [16] modelled the behavior of composite plate under a mechanical impact load. They used the model to investigate the response of a composite plate during the impact, as they subjected the specimen to an electric current and placed it in a magnetic field. Their calculated results showed that the applied electromagnetic field reduced the magnitude of vibration and improved damping properties. They also claimed that maximum deflection and stress are also affected by the electromagnetic field, but it also depends on the layer order.

Amaro *et al.* [17] investigated the effect of electric current on carbon fiber-reinforced composites, with particular reference to their impact resistance. In their experiments, unidirectional prepregs were used, from which composites of different layer orders were formed, and then subjected to drop tests. The electric current flowed through the thickness of the specimens, perpendicular to fiber orientation. A decrease in impact resistance was observed on specimens in which the electric current flowed for a longer time. They repeated the drop test on the same specimen until the tup (the tip of the falling weight) fully broke through the specimen. Based on those results, they concluded that electric current has a negative effect on impact fatigue life.

The aim of this study is to show how electric current affects the mechanical properties of a carbon fiber composite structure as there are opposing results. Therefore, we investigated short and long connection times and different amperage.

2. Experiments

In our experiments, we investigated how the electric current flowing through the specimen would affect impact bending stiffness. We made glass fiber (225 g/m^2 areal density, Owens-Corning Composites LLC, USA) reinforced epoxy (MR 3016 with MH 3124 hardener, 100:40 mixing ratio, Ipox Chemicals, Hungary) specimens and laminated a carbon fiber (Sigrafil C T24-5.0/270-E100, SGL Carbon SE, Germany) layer into them as the penultimate layer (Fig. 2). We cured the specimens at 80 °C for 4 hours.

We tested the specimens with a three-point bending-like impact test: we modified the specimen support and the tup of a falling-weight impact tester (Ceast Fractovis 9350, Ceast, Italy) to form an arrangement similar to the Charpy impact test, but with a falling weight moving vertically instead of the pendulum. The carbon fibers were on the drawn side of the specimen. Falling height was 638 mm, the speed of impact was 4.43 m/s, and impact energy was 15 J.

Fig. 2. Side and top view of a specimen.

In order to apply current to the carbon fibers, we used copper blocks clamped onto the dry carbon fibers sticking out of the specimen. The copper block had to be fixed to the machine, so we adjusted the support with two custom parts made by fused deposition modelling (Fig. 3).

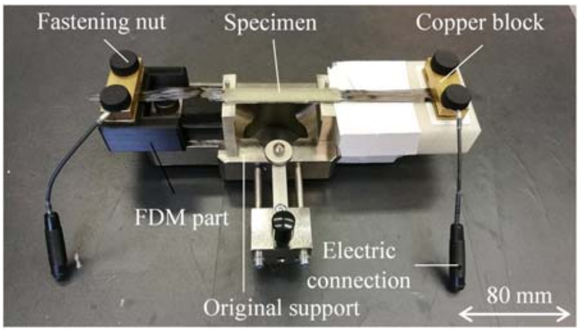

Fig. 3. Custom designed support for dynamic testing and copper block positioning.

We applied different currents (0.5; 1; 1.5; 1.75; 2; 2.25 A) to the carbon fibers reinforcing the composite through the copper blocks with a power supply (GW Instek GPD-3303S, GW Instek, Taiwan). We varied the connection time (2; 10; 30; 60; 90 s) of the flow of electric current before the impact and switched the power supply off immediately after the impact test. We prepared 12 specimens in one batch, from each batch, and tested 3 pieces as references without current.

We measured the temperature of the specimens and how it changed due to the electric current. We used a thermal imaging camera (A325SC, FLIR Systems, USA) to monitor the temperature change under the aforementioned current values for 90 s (the longest connection time).

3. Results and Discussion

To determine which is the highest current and longest connection time to apply to the specimen we started with temperature measurement. We calculated the surface average of the maximal temperature after 90 s connection time (Table 1).

The measured data show that even the lowest inspected current heated up the specimen from room temperature in 90 s. However, at the lowest current, the temperature stabilized after the electric power was connected (Fig. 4). Based on our previous research [12], this increment doesn't affect the feasibility of the carbon fiber as sensor, but Joule heating should be taken into account when an electric current is used. As expected, with increasing current, the maximum temperature increased. With increasing current, the temperature did not stabilize in 90 s – it would have warmed up further (Fig. 4). At a longer connection time and higher current (see Fig. 4 2.5 A), the specimen become so hot that it degraded the epoxy resin and the support, therefore we maximized the current and connection time.

Table 1. Average maximum temperature on the surface of the specimen after 90 s connection time.

Current [A]	**Average maximum temperature [°C]**
0.50	31
1.00	49
1.50	75
1.75	83
2.00	95
2.25	127

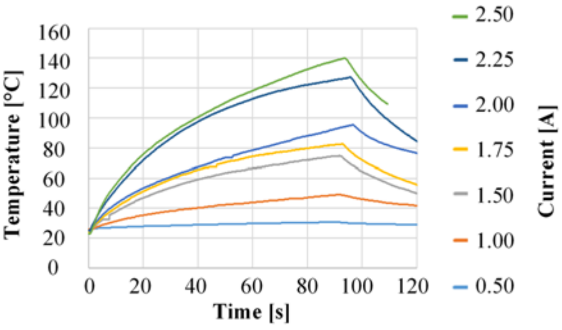

Fig. 4. Surface temperatures reached at various amperages in 90s.

After temperature measurement, we carried out the mechanical test in order to determine the dynamic bending behavior. Based on the maximal impact force (F) and specimen geometry, we calculated the dynamic bending strength (σ_{db}) of the specimen (1).

$$\sigma_{db} = \frac{3FL}{2bh^2}, \tag{1}$$

where L is the support span, b is the width of specimen and h is the thickness of the specimen. The dynamic bending strength was plotted as a function of the current (Fig. 5), so that the effect of the magnitude and the time of the current on bending strength became visible. The diagram clearly shows that bending strength decreases with increasing current and connection time. At higher currents or longer connection times, the Joule heat heats up the specimen and this can lead to softening.

The dynamic bending modulus (E_{db}) was calculated based on the same specimen geometry and the slope of the force-deflection diagram (2).

$$E_{db} = \frac{1}{4}\frac{L^3}{bh^3}\frac{F}{f}, \tag{2}$$

where f is the deflection at maximum force. The calculated dynamic bending modulus values are in Table 2, the reference value (without current) was 3630±205 MPa. It can be seen from the table that increasing the current and connection time decreases modulus. Therefore, if carbon fibers are used as a sensor, it is advisable to use a current of less than 0.5 A so that the mechanical properties of the structure are not affected. In practice, this can be solved by, for example, sampling every half minute with the current switched on for a short time only.

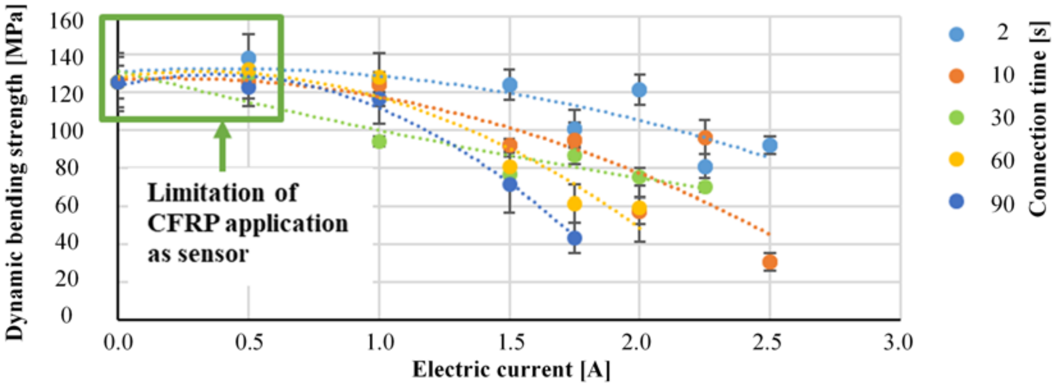

Fig. 5. The effect of electric current and connection time on the dynamic bending strength of carbon-glass hybrid reinforced composite.

4. Conclusion

Reinforcing carbon fibers nowadays are used for additional functions as well, such as sensors. In these applications, a current flows through the composite, which can alter the mechanical properties of the material. In our research, we investigated the effect of the magnitude of the current and connection time on the dynamic bending properties of composite specimens. The results indicate that CFRP is well suited for multifunctional purposes, but particular attention needs to be paid to the change in mechanical properties due to the heating effect of the current. Either a low current electric circuit should be used (I<0.5 A), or the electric current should only be switched on for a short period of time (less than 2 s in the case of a higher current).

Table 2. Dynamic bending modulus in the case of different currents and connection times in MPa. X – the specimen become too hot to handle safely, n.a. means that appropriate data was not available.

Time [s] **Current [A]**	2	10	30	60	90
0.50	3687±125	3626±327	3426±204	3659±205	3689±242
1.00	3393±412	2879±258	2617±269	3586±573	3217±412
1.50	2297±782	1842±636	2014±263	2036±284	1634±568
1.75	1687±126	1909±918	1924±234	1212±396	1387±258
2.00	3473±240	n.a.	1874±294	981±202	1279±256
2.25	n.a.	2752±228	1589±140	×	×

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