On the mechanical behavior of a composite stiffener with inkjet-printed electronics

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Abstract

Multifunctional composites combine the advantages of modern fiber reinforced composites and of printable electronics. Compared to conventional materials and sensors, multifunctional composites offer the possibility to reduce weight with respect to both, structure and employed sensors and wires. For that reason, first investigations have already been performed in the past: Structural abilities of plate-shaped fiber reinforced composites equipped with printed electronics for SHM purposes were considered. To extend past investigations, a multifunctional composite is tested under near-reality conditions. For this purpose, a 3D fiber reinforced structural component in the shape of an aeronautical stiffener is examined. An additive manufacturing process is used to apply a conductive silver nanoparticle ink and to deploy printed electronics on the surface of the stiffener in different shapes and at different locations. The production of the ink is described and quantitative process parameters are explained. The structural abilities of the multifunctional stiffener are investigated in a customized three-point bending experiment. In particular, the behavior of the printed electronics is observed. Also, their ability to detect damages is considered. Based on these results, the applicability of this type of multifunctional composites to SHM is discussed, especially with respect to structural integrity.

Keywords: structural health monitoring, printed electronics, multifunctional composites, composite stiffener, resistance measurement

1. Introduction

Non-destructive instrumentation-based monitoring is becoming more accepted for estimating the structural health of carbon fiber reinforced polymers (CFRP) [1–3]. The literature shows a variety of approaches on this issue [4]. Several authors have proposed to embed wafer or sensor networks, e.g. with piezoelectric sensors, in a composite laminate during the manufacturing process. With this approach, monitoring and detection of damages in CFRP structures could be enhanced [5–7]. Another approach is to use the carbon fibers that already exist in CFRPs as embedded self-sensors [8]. Due to their high electrical conductivity, any physical interrupt or mechanical damage of their structural continuity causes a change in the electrical conductivity of the entire CFRP structure [9]. Consequently, instrumentation-based structural health monitoring (SHM) of CFRP could be performed through the observation of the electrical resistance changes of CFRP before, during and after the initiation of the damage [10–12]. Accordingly, electrical measurements require electrodes that are deposited at various locations on the CFRP structure in
order to achieve an adequate contact with the carbon fibers [13–15]. Due to its highest
electrical conductivity in comparison to any other metal [16], high resistance against
corrosion and oxidation [17], and its availability in form of nanoparticle inks with low
curing temperature [18–20], silver is widely used to create electrical contacts for the testing
of CFRP [21–26]. To deposit the electrodes on the CRFP surface, several techniques such
as electroplating [9], painting [27], aerodynamically focused nanoparticle printing [28],
Compared to other techniques, the inkjet technology for printing contacting electrodes
has many advantages. In particular, physical pre-manufactured master printing plates or
sieves are not required, hence flexible and non-contact processes with any printing size or
positioning form can be realized. Through fine printing heads, various thicknesses, widths
and thin films can be realized in a drop-by-drop manner. A wide range of materials can be
selectively deposited onto a wide range of substrates with minimal ink consumption and
material wastage. In this way, digitally designed contacts, electrodes, or specific electronic
components can be constructed in a stepwise manner directly on the substrate [30, 31].

In this work, an online instrumentation-based SHM of a multifunctional composite is
presented under near-reality conditions. A fiber reinforced structural component in the
shape of an aeronautical stiffener is equipped with silver nanoparticle inkjet-printed
electronics and is simultaneously examined with respect to its mechanical and electrical
properties. For that purpose, a detailed observation of the electrical resistance changes in a
stiffener under mechanical load is performed with regard to damage initiation. Ultimately,
the applicability of this type of multifunctional composites to SHM is evaluated, taking
into consideration related past investigations [11, 15, 32, 33].

2. Ink formulation for inkjet-printing

A silver nanoparticle-based ink is formulated in order to deposit contacting electrodes on
the 3D aeronautical-shaped CFRP stiffener by inkjet printing. As stated in [11], the ink
consists of three components: A silver nanoparticle paste (Ames Advanced Material Corp.,
R & DS7000-95 Nano Ag Powder in Butyl Carbitol, d90 ≈ 60 nm), the stabilizing polymer
ethyl cellulose (Dow Chemical, ETHOCEL™ Standard 7), and the dispersion medium
diethylene glycol monobutyl ether (Bernd Kraft GmbH, purity ≥ 98%). For synthesis of 10
g of ink, the starting materials are introduced to each other in a three-step procedure. First,
0.05 g of ethyl cellulose are fully diluted in 5.65 g of diethylene glycol monobutyl ether.
Second, 4.3 g of silver nanoparticle paste is added to the above vigorously stirred solution.
Third, the mixture is ultrasonicated using an ultrasonic probe MS 73 (Sonopuls HD 2070;
Bandelin Electronics, Germany) for 7.5 minutes (75% power) to form a well-dispersed
suspension. The formulated ink is then kept on stirrer plates until used.

3. Inkjet-printing of electrodes

The printed electrodes are fabricated on the surface of the CFRP specimen using a piezo-
driven inkjet printhead MD-K-140-030 (Microdrop Technologies GmbH, Germany) with
an inner nozzle diameter of 100 µm. The CFRP stiffener surfaces are pre-cleaned before
printing with a lint-free paper towel, wetted with isopropyl alcohol. The surface of the
stiffener is subjected to a BOUSSEY CONTROL corona pre-treatment. The ink is
ultrasonicated for 2.5 min, filtered in a double filter of woven wire mesh #325 with a 34 µm aperture (The Mesh Company Ltd, United Kingdom), and is then filled in the printing reservoir for direct printing. Square-shaped electrodes of 10 mm × 10 mm are printed at room temperature with a drop spacing of 100 µm in three layers on different locations of the CFRP stiffener as shown in figures 1 and 2. The fresh printed silver nanoparticle-based ink is dried on a hot plate at 60 °C and is then transferred to a sintering oven at 170 °C for 4 h.

4. Contacting of the electrodes

After the sintering process is completed, the CFRP stiffener exhibits five printed silver electrodes as shown in figure 1 and in figure 2: Two rectangular electrodes are located on the top side of one flange as shown in figure 1. Two further rectangular electrodes are located on the bottom side of the other flange as shown in figure 2. A fifth electrode is printed in the shape of four connected electrode patches in the middle of the top side of the stiffener as shown in figure 1. Although this forms one single electrode, the different patches are printed to better connect external wiring. In the present work, the printing design is not yet optimized. However, locations of the electrodes are chosen so that a large part of the stiffener can be covered by electrical resistance measurements. These resistance measurements shall be taken along four different paths through the CFRP material while the bending experiment is carried out. To connect the printed electrodes with an external measuring device, a copper wire is glued to each electrode patch. For this purpose, a cw2400 conductive epoxy resin is used, as soldering could damage the CFRP material. The wiring is shown in figures 3 and 4 and includes the numbering of each electrode. Each electrode on the flanges is then assigned to a patch of the upper electrode in the middle of the specimen. In that way, the electrical resistance can be measured diagonally through the CFRP between every electrode on the flanges and the middle top electrode. These four paths are referred to as the four measuring channels C1 to C4 in the following. The two wires of each channel are then connected to a KEITHLEY 2700 digital multimeter with a KEITHLEY 7700 20 channel multiplex adapter. Here, conventional wires are only needed to connect the electrodes to the digital multimeter. In a practical application, conductive paths could be printed to cover large distances.
5. Bending experiment

The prepared stiffener is placed on a bending device as shown in figure 5. The test setup resembles a three point bending experiment while a two-part mandrel is used so that the front and the back flange of the stiffener are equally loaded. Although stiffeners are structural elements that are used to prevent plate-like structures from buckling, a bending test is carried out instead of a stability test as the load-deformation behavior can be better observed. All supports and mandrels are equipped with isolating tape to electrically decouple the stiffener from the bending device. A displacement boundary condition is prescribed so that the mandrels are lowered at a constant displacement of 0.25 mm/min. Simultaneously, the digital multimeter is set to constantly measure the resistance values for each of the four channels C1 to C4. The multimeter records a resistance value for each of the channels approximately every 0.3 s. The slow displacement boundary condition is thus used to ensure that occurring cracks can be resolved in the electrical signal.

The crosshead is moved until a first major force drop is detected and the machine is stopped at 7.39 mm. The stiffener is then released and visually inspected without changing its position on the bending device. As no severe damage can be found besides minor pressure marks where the mandrels were in contact with the flanges, the experiment is further carried out in a second test run. To do so, the isolation tape at the mandrels is renewed and the crosshead is lowered again to a vertical displacement of 7.39 mm without measuring the force-displacement diagram. A force of 2670 N is measured at this starting point of the second test run. The second test run is then carried out similarly to the first one: The crosshead is lowered at a constant velocity of 0.25 mm while the force-displacement diagram is recorded and electrical resistance values are again measured for each of the four channels at approximately every 0.3 s. The force rises with increasing displacement so that the stiffener is still load-bearing after the force drop of the first test run. A second sharp force drop is then detected at a vertical displacement of 9.88 mm. This second force drop is accompanied by a severe delamination that can be visually observed on the front and on the back of the stiffener. The delamination on the front side of the stiffener is shown in figure 6. After the major delamination has taken place, the experiment is further carried out. The stiffener has now lost its structural stability, so the force does no longer
rise significantly for increasing displacements. The structure is thus not able take higher loads anymore and deforms severely. During the sudden delamination at the second force drop, two electrodes separate from the CFRP. One of them is shown at the right side of figure 6 in the foreground.

6. Results

The measured force-displacement values for test run one and test run two are plotted together with the electrical resistance values of each channel as a function of the applied displacement. In figure 7, the force-displacement diagrams are plotted together with the resistance-displacement diagram of the representative channel C3. In the force-displacement diagram of test run one, minor force drops can be found that were audible as light clicking sounds during the experiment. After a vertical displacement of 7.39 mm is reached, the diagram shows the first force drop. The force-displacement data of test run two is then corrected by the measured offset of 7.39 mm and 2670 N and is plotted after the data of test run one. The data shows a load-bearing behavior where the force rises with increasing vertical displacement of the crosshead. As noticed during the experiment, the major delamination at 9.88 mm results in a second sharp force drop. Structural stability is severely decreased, so that the forces after the second force drop do not reach the force-level prior to the second force drop anymore. Experimental data is thus shown until a vertical displacement of 12 mm where the structure has already undergone finale failure.

The corresponding resistance measurements of channel C3 show an approximately constant value of $R_{33} = 1.2 \, \Omega$ after the initial non-linearity of the force-displacement diagram is overcome. Although smaller force drops at displacements between 2.25 mm and 7.36 mm cannot be easily identified through the unfiltered resistance signal, the first significant force drop at a displacement of 7.36 mm is clearly captured by a 1.3 % jump in resistance from 1.2 $\, \Omega$ to 1.215 $\, \Omega$. This jump shifts the baseline of the electrical signal so that the damage can be identified from the signal even after the jump in resistance has occurred.
Figure 7: Experimental bending test data. Two consecutive measurements are shown where the force is plotted over the displacement. In addition, the measured resistance values of channel C3 are displayed. Resistance values are plotted until a displacement of 9.88 mm where final failure occurred. Last data point capped at 1.25 $\Omega$ to allow for better scaling.

The second significant force drop at a displacement of 9.88 mm that is related to the severe delamination and thus to final failure is also clearly captured by a jump in the resistance value of channel C3. This jump is shown in figure 7 as a single spike in the resistance data. In the raw data, a constant resistance value of $1 \times 10^3 \Omega$ was measured after this jump, which denotes an open circuit of channel C3 when the electrode is separated from the stiffener as it was shown in figure 6. The open circuit resistance values are thus not shown between 9.88 mm and 12 mm and the spike at 9.88 mm is capped at 1.25 $\Omega$ to allow for a better scaling of the diagram.

7. Conclusion

In this work, a CFRP stiffener element is equipped with inkjet-printed silver electrodes and investigated in a three point bending experiment. Electrical resistance values between different electrodes are measured and partial damage is detected through the electrical measurements before final failure occurs. Possible next steps include the optimization of the sensor layout with respect to the expected damages and the substitution of the employed silver nanoparticle inks with other inks that allow for a better structural integrity, such as dispersed carbon nanotubes in an epoxy matrix.
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References


