Cyclic testing of novel carbon fiber based strain sensor with spatial resolution

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Abstract

Strain measurement plays a crucial role in the development of innovative products with increased efficiency and optimized utilization of the material resources. The trend towards smart structures with the capability of *in operando* measurements, e.g. for the realization of Strucutral Health Monitoring is challenging in terms of the availability of a practicable strain measurement system that fullfils the application requirements. The contribution deals with a novel continuous strain sensors with spatial resolution that could significantly improve the applicability of current strain measurement systems. The measurement principle of the innovative carbon fiber strain sensor is based on a reversibly opening and closing of filament fragments.
In this work, the cyclic behavior of the sensor is investigated for the first time in order to identify current limitations. The sensor was loaded with up to 10^6 cycles and the resistance of the carbon fiber roving was measured continuously. Combined microscopy and resistance analysis show that the sensor behavior changes over the number of cycles resulting from different damage types on the microscale.

1. Introduction

Strain measurement realised in various long-established scenarios provides fundamental data for the development of materials and mechanically loaded structures. It is also a prerequisite for the realization of some important classes of intelligent function-integrative structures e.g. with health monitoring or active-damping functionalities. Affordable, material- and application compatible sensors as well as electronic peripherals enabling a high spatial resolution of strain field sampling are particularly important for the latter applications. In this context, current strain measurement systems like strain gauges or fiber optic sensors have some deficits regarding the complexity (multi-channel installation and processing), cost and design (weight and installation space). The challenge is to make a strain measurement system available that combines a high spatial resolution with manageable complexity, low weight and low costs.

Based on preliminary work, an innovative strain sensor based on carbon fibers (CF) is proposed. The unique characteristic of the sensor is its measurement principle. Conventional CF based strain sensors use primarily the piezoresistive effect [1-3]. Their gauge factors (GF) are therefore limited to approx. 1.7 [3]. Such relative small sensitivity implies the application of bridge circuits and the capture of averaged strains along the whole sensor fiber. In contrast to the state of the art, the novel strain sensing principle is based on deliberately introduced CF breaks in interaction with residual stresses of the composite sensor carrier material that enable much higher GFs. Instead of the bridge circuit, a reflectometry based technique can be applied for the evaluation of the strain-dependent resistance distribution of the sensor.

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The reflectometry method enables both a spatially resolved strain measurement and damage detection using a compact (e.g. hand-held device), low-power consuming and cost-effective measurement device. A variety of the mentioned charecteristics make the sensor interesting for the application as on-board measurement system, especially in the transportation sector such as the automotive and aerospace industry. Possible measurement tasks include the *in operando* monitoring of safety-relevant parts such as the fan blades or the deformation of chassis parts at crashes.

1.2 Measurement principle of the proposed strain sensor

The proposed strain sensor is based on a fiber-break resistive measurement principle. In preliminary work the phenomena of the measurement principle was investigated by means of a combined analysis of sensor patch strain, CF-roving resistance and microscopy images in a specific tensile testing device [4]. The focused sensor patch basically consists of a brittle carbon fiber (HM-CF) roving which is embedded in a glass-fiber epoxy (GF-EP) carrier material (Fig. 1). The resistive measurement principle is based on the reversible opening and closure of single fragmented filaments of the CF-roving.

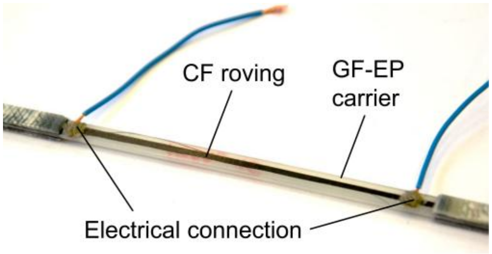

Figure 1. Basic configuration of carbon fiber sensor patch.

For the realisation of the measurement principle, a functionalisation of the sensor is necessary in order to initiate filament breaks of the roving (Fig. 2). This was done by applying a static tensile load on the sensor patch which is uncritical for the carrier material, but introduces an initial pattern of sensing fiber breaks. A first-time tensile loading of the sensor patch (“functionalisation cycle”) results in a relatively high density of CF-roving breaks and in a resistance increase. An important aspect for the strain dependent resistance change is the breaking pattern of the roving in form of a zig-zag. This enables the establishment of alternative conductive paths along the roving by means of overlapping filament fragments. The breaks close with decreasing loading and the roving resistance drops back to the initial value. After the functionalization cycle, the sensing function of the sensor can be realized. The basic characterisation of the electrical behavior of the novel strain sensor under tensile load has shown a reproducible, nonlinear behavior with strain sensitivity up to two orders of magnitude higher than that of commercial semiconductor strain gauges and even four orders of magnitude higher than that of current carbon fiber sensors.

Until now, the behavior of the sensor at only a few loading cycles has been investigated. It is an open questions, how the reversible resistance characteristic, respectively the sensor function, behaves with higher number of loading cycles.

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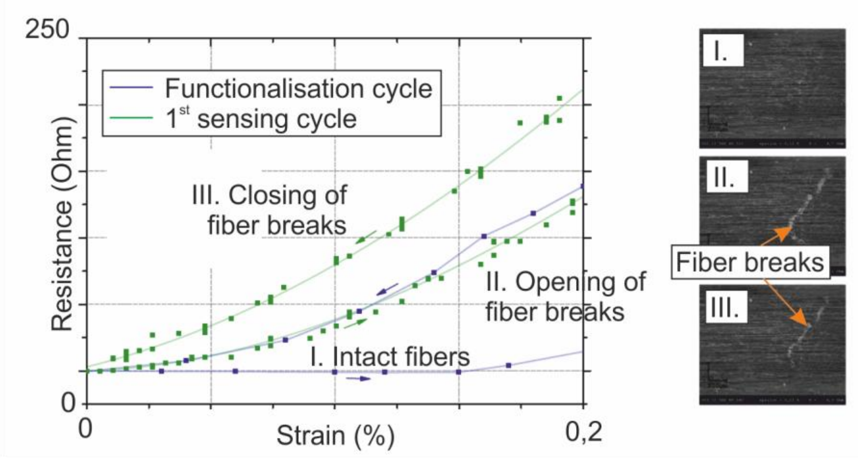

Figure 2. Phenomenological effects at the initial functionalisation of the sensor (based on [4])

2. Materials and method

2.1. Sensor patch configuration

Sensor patches with a length of 250 mm and cross-section of 25 mm x 2.7 mm were manufactured in autoclave process. GF-EP cap strips were adhesively bonded to the sensor patches for a reliable application of tensile loads. A sensor patch consists of a CF-roving (2K Dialead K13C2U) and a copper strip (70 µm thick and 6 mm width) which were embedded in a GF-EP carrier (HexPly® M9.6G, Hexcel Composites GmbH) (Fig. 3a) in order to realise a sensor suitable for reflectometry method. A more detailled description of the connection of the reflectometry sensor is not presented since in this investigation only resistance measurement was performed. The CF-roving was lead through the sensor patch to the front surface. A short copper strip was added at the end of the roving in order to contact a cable using soldering (Fig. 3b). Drops of conductive epoxy were applied at the ends of the roving to ensure electrical contacting to all the filaments.

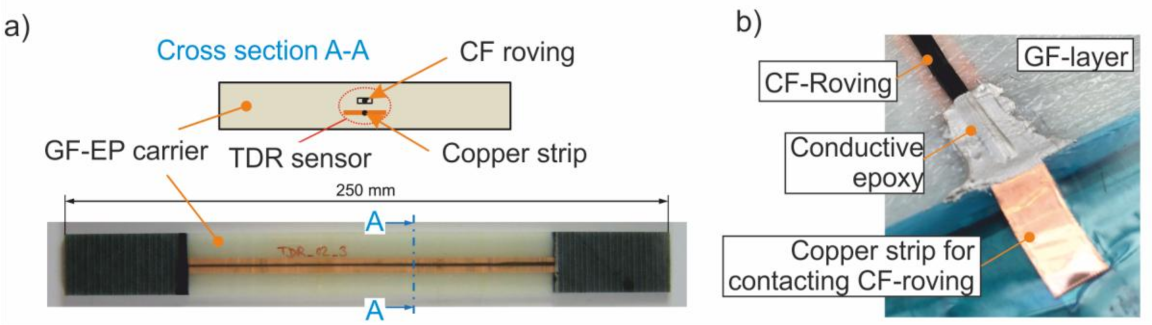

Figure 3. Schematic cross-section and exemplary sensor patch (a) and preparation of the CF roving for electrical contacting (b).

2.2. Measurement setup and testing

For the cyclic test one sensor patch was tested using a servohydraulic testing machine (Schenck PC63M-50, Fig. 4). In the first step, the nominal strain to rupture of the sensor patch was determined in static tests. An average strain to rupture of 2.8 % for three identical configured and manufactured

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sensor patches was determined. Based on this, a maximum strain level of 0.8 %, corresponding to a stress of approx. 190 MPa for the undamaged patch, was defined for the cyclic tests. At this load level no fatigue fracture of the sensor patch was expected. The stress ratio was set to 0.1 and the testing frequency was set to 7.5 Hz. The strain level was set constant over the entire testing by using a strain-based trimodal control. The resistance of the CF-roving was measured during cyclic tests over the entire roving length with a sampling frequency of 200 Hz. Besides the resistance measurement, the strain of the sensor patch was logged by means of an extensometer for control purposes. The sensor patch was functionalized (creation of fiber breaks) by means of statically loading the patch at a strain level of 1.1 % once, before starting the cyclic tests.

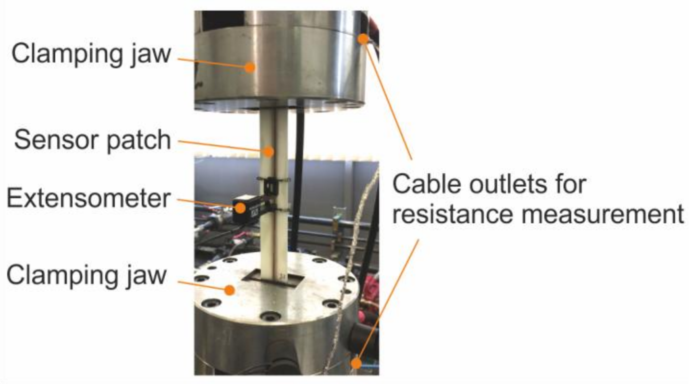

Figure 4. Sensor patch fixed in servohydraulic testing machine.

3. Results and discussion

3.1 Investigation of introduced damages

After the cyclic testing, the sensor patch was inspected by means of visual inspection and microscopic observation. On the macroscopic scale the development of longitudinal and periclinal matrix cracks on the sensor patch surface as wells as inside the material is obvious (Fig. 5a). Furthermore, large-scale delaminations at the edges can be identified. It can be assumed that the origin of these damages in the carrier material occured due to typical material fatigue reasons and were not influenced by the embedded sensing elements. The sensor patch was cutted and microsections of several cross-sections were prepared for the microscopic observation (Fig. 5b-d). They reveal interface failures (shown in red) between single CF and the epoxy resin as well as immense inter fiber failures throughout the CF roving. The origins of the damage modes visible at the microscale (interface failure and inter fiber failure) are probably due to the stiffness gradient from CF to the surrounding epoxy resin causing local stress peaks in the interface region occur.

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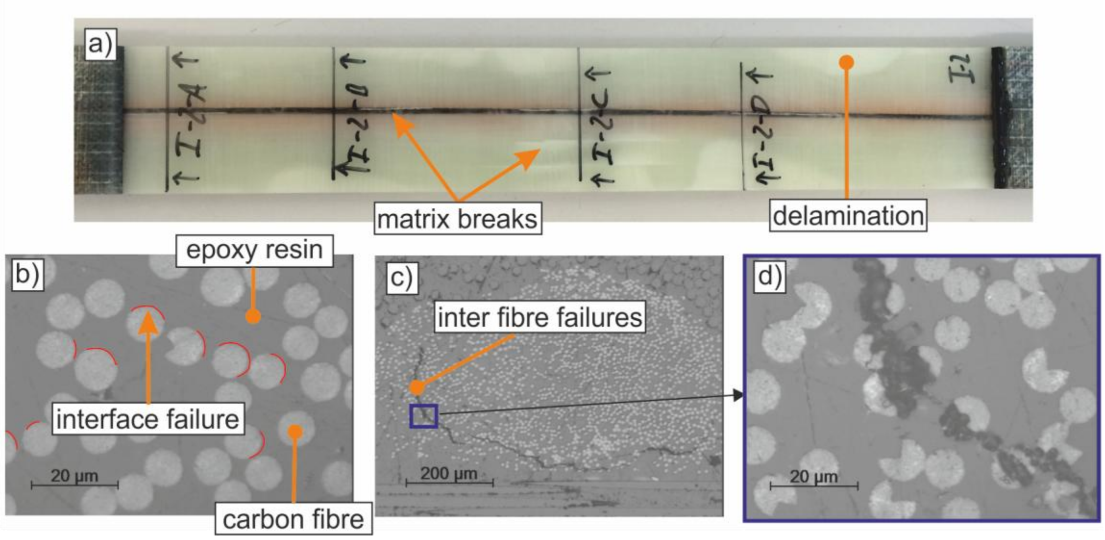

Figure 5. Macroscopic damages of the sensor patch after 10^6 cycles (a) and microscopic damages in the CF roving (b-d).

3.2 Analysis of the resistance change

Several sections of the continuously recorded signal were analysed for a first description of the sensor behavior over the number of cycles (Fig. 6). At each order of magnitude (10^1 up to 10^6 cycles) signal sections of 2 s length (corresponding to approx. 15 cycles) were separated. For the analyses of the signal sections, the histogram method described in [5] was used. This method estimates the low- and high-state levels in a bilevel waveform. The advantage of this method is that all the information in the signal section are analysed at once in order to estimate the state levels.

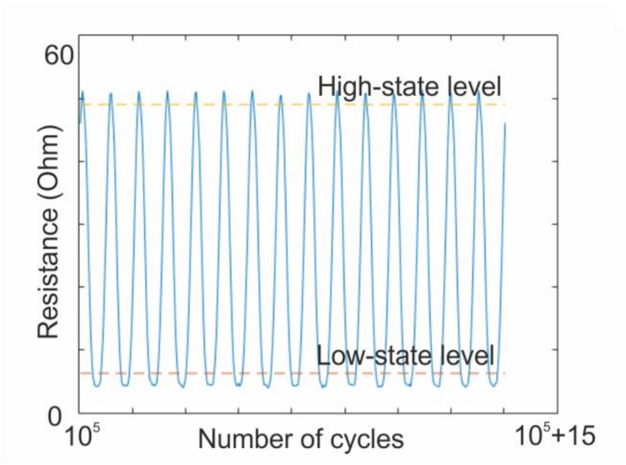

Figure 6. Exemplary signal section with a length of 2 sec recorded at 10^5 cycles together with estimated state levels using the histogram method.

A separate analysis of the low- and high-state levels in the resisitance change is necessary due to the different influencing effects. On the one hand, the high-state level occurs when the CF breaks are opened. Thus, this measurand ist predominantly influenced by the interactions in between the single filament fragments and the actual breaking pattern. The high-state level is directly correlated to the sensitivity of the sensor. On the other hand, the low-state level is predominantly influenced by the elastic behavior of the matrix material and the condition of the fiber fragment interfaces responsible for closing the CF breaks. The low-state level can be taken as a measure for the intactness of the sensing elements. The results of the analysis for each order of magnitude and the change of the state levels over the number of cycles in semilogarithmic format are given (Table 1 and Fig. 7).

Table 1. Analysis of signal characteristics over the number of cycles

Signal characteristic	Number of cycles at which signal extract is analysed						
	10^0	10^1	10^2	10^3	10^4	10^5	10^6
Low-state level (Ohm)	4.96	4.77	4.53	4.50	4.17	4.72	7.59
High-state level (Ohm)	10.27	14.25	21.87	33.21	51.16	78.25	200.55

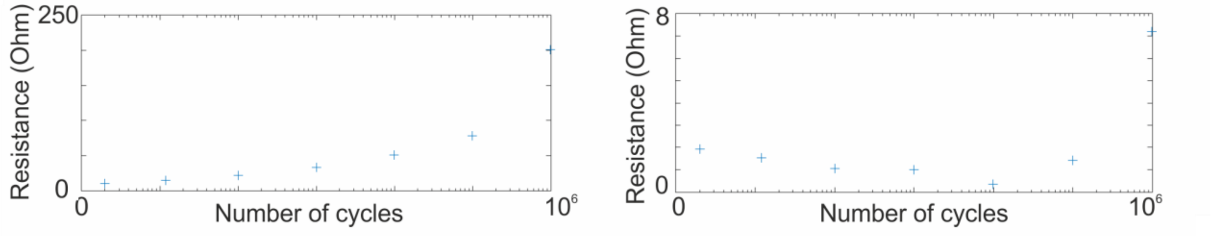

Figure 7. Change of the low-state (a) and high-state level (b) of the resistance over the number of cycles.

The conclusion can be made, that the state levels of the resistance increases over the number of cycles. The high-state level changes by a factor about 19 and thus the sensor sensitivity, whereas the low-state level changes by only 1.5. Further differences in the change of the state levels over the number of cycles can be identified. A steady relation can be fitted between load cycles in logarithmic format and the resistance change for the high-state level. In contrast, the low-state level decreases at the first 10^3 cycles before the resistance rapidly increases up to 10^6 cycles. At the same time, the funcamental sensor function remains preserved.

4. Summary

The identification of an appropriate sensor configuration in order to realise a robust and reliable sensing function is of high importance for the establishment of a new measurement principle with high potential for a continous strain measurement with miniatuized and cheap electronic units. Therefore, the central objective of this contribution was the analysis of the cyclic behavior of a new kind of carbon fiber sensor. In contrary to common carbon fiber sensors, a fiber-break resistive measurement principle is used. In a first step, sensor patches that operate on the innovative measurement principle were manufactured. For this purpose, brittle carbon fiber rovings were embedded in a glass fiber epoxy composite and electrically contacted enabling resistance measurements. Cyclic tests up to 10^6 cycles were performed at 7.5 Hz with a strain ratio of 0.1. Subsequently, the sensor patch was analysed by means of visual inspection and microscopic analysis in terms of occurred damages. At the microscale, inter fiber failures and matrix cracks in the area of the sensing roving were observed. Furthermore, the bilevel resistance change over the number of cycles was analysed using the histogram method. A monotonic increase of the sensor sensitivity was identified, whereas the state levels change with different extents. The investigation of the sensor behavior at cyclic loads raised a

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number of open questions that needs to be focused in further studies. Especially the relation between the observed damages modes and the resistance change is a major task for ongoing works.

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