INVESTIGATION OF THE ELECTRICAL RESISTIVITY OF DAMAGED CARBON FIBERS SENSORS WITH REGARD TO SHM

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Abstract

This paper reports on a detailed investigation of the sensing potential of carbon fiber sensors (CFSs). Four different types of carbon fibers were examined. CFSs were embedded in flat specimens made of a glass fiber reinforced polymer composite. Changes in the electrical resistance of the CFSs were measured during cyclic flexural loading. An evaluation was made of the influence of damage to the measured signal due to impact and due to incision of the sensor. It was found that cyclic flexural loading affects the possibility of detecting damage in contrasting ways for different types of carbon fibers. It is revealed that the pitch carbon fibers investigated here have great potential for impact damage detection.

1. Introduction

Fiber-Reinforced Polymer (FRP) composites can be used to produce tailor-made materials. This adds value to products in many industries by providing a better strength/weight ratio, better impact resistance, more functionality and a longer service lifetime. The only remaining problem with the use of fiber-reinforced polymers is damage tracking and repair monitoring. Structural Health Monitoring (SHM) of composites has attracted considerable attention not only in the aerospace industry [1] but also in the construction industry [2] and in the automotive industry. The aerospace industry has in addition been working intensively on integrated sensors for production process monitoring and lifetime monitoring [3].

Within this context, approaches based on measurements of the electrical resistivity of carbon fibres, CNT fibres and matrix with and without carbon nanotubes have great potential, and are under intensive investigation [4]. Previous investigations have shown that carbon fibers themselves can be used as sensors for detecting structural damage such as microcracks and delamination [5, 6]. Structural damage can be detected by changes in the electrical resistance of the Carbon Fiber Sensor (CFS) network embedded in a glass fiber polymer composite. The influence of damage, e.g. breakage of a single filament, on the electrical properties of carbon fiber sensors is therefore of great interest. The study presented here deals with the possibility of damage detection and impact monitoring with the use of carbon fibers that function as CFS. This study investigates:

- the possibility of using embedded carbon fibers to detect impact damage,
- the influence of cyclic flexural loading on the possibility of damage detection,
- the influence of damages to embedded carbon fibers on measured signals.

Flat specimens made of glass fiber reinforced polymer with embedded CFSs were prepared for our experiments. To provide comprehensive information about the influence of damage to CFSs on measured signals, some of the specimens were embedded in undamaged condition, and others were embedded with incised CFCs. After the first series of loading cycles, the specimens with undamaged CFSs were impacted, and were exposed to cyclic loading again. Electric resistance measurements were made during the loading. For comparison, four different types of carbon-fibre tows (two types of ex-PAN, ex-Pitch, nickel coated) were investigated to assess their potential as sensors for the purposes of SHM. The investigated carbon fiber types produced great differences in their sensing potential.

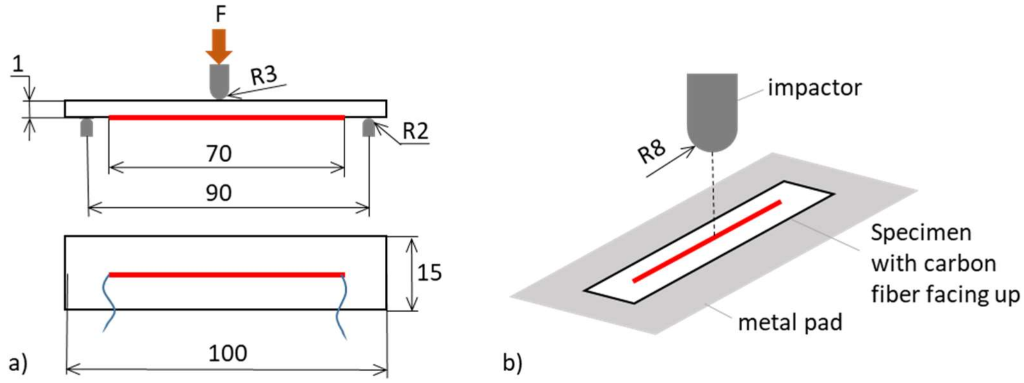


Figure 1. Specimen and loading description (a), Configuration during impact loading (b)

2. Experiments and evaluation methods

2.1. Specimen preparation

Flat specimens according to Fig. 1 were prepared for the experimental procedure. The specimens were made of two layers $[0]_2$ of unidirectional glass non crimp fabric 600 g/m², delivered by R&D Faserverbundwerkstoffe GmbH. L20 epoxy resin and EPH 161 hardener were used during the manufacturing process. The specimens were cured for 15 hours at a temperature of 60°C. CFSs were placed on one side of the fabric before curing. All specimens were cut from a single plate after curing.

2.2. Carbon fiber sensors (CFSs)

CFSs were prepared in the length of 70 mm from each of the tested carbon-fiber tows. The preparation of CFS has been described in [5], and the same procedure was used here. A nickel electrolyte coating was applied to the ends of each roving. Then electrical contacts made of thin copper wire were soldered to the ends, see Fig. 2 and 3.

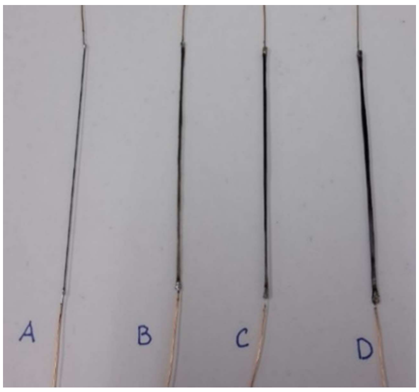


Figure 2. CF sensors prepared for installation into the specimens

Figure 3. Specimens with integrated CF sensors

Table 1 presents the properties of the carbon fibers used as CFSs in this study. The first type is Toray T300 (label A), which has already been used successfully for strain and damage monitoring [5], [6]. The second type is also a PAN fiber, but with nickel metallization (label B), produced by Toho Tenax. This material was used to investigate the influence of the nickel layer. The original nickel-coated PAN fiber was made of 12000 filaments. For the investigation we wanted to use a thinner tow, so the carbon fiber tow was divided. The part of the tow that was used consisted of 7720 filaments. To ensure a relevant comparison, with no influence of the production process of the nickel coating, the same PAN fiber manufactured by Toho Tenax, without a nickel layer (label C), was included in the test matrix. The tow was also divided into two parts, and the part for preparing CFS contained 6000 filaments. The fourth investigated fiber was PITCH-fiber, manufactured by Nippon Graphite Fibre Corporation (label D).

Table 1. An overview of the examined carbon fibre tows.

Label of the fiber		**A**	**B**	**C**	**D**
	[-]	T300 1000-50A	HTS40 A23 12K 1420TEX MC	HTS 40 MC	CN-80-30S
Type	[-]	PAN	PAN	PAN	PITCH
Producer		Toray	Toho Tenax	Toho Tenax	Nippon Graphite Fibre Corporation
Number of Filaments	[-]	1000	12000	12000	3000
Number of Filaments Used	[-]	1000	7720	6000	3000
TEX-number	[-]	66	1437	1430	-
Metalization	[-]	-	Nickel	-	-
E	[GPa]	230	215	230	780
Rm	[MPa]	3530	2760	2900	3430
Elongation	[%]	1.5	1.28	1.3	0.5
Thermal conductivity	[W/mK]	10.46	-	10	320
Volume resistivity	[μΩm]	17	-	16	5

2.3. Loading and damage preparation

Two types of damage to CFSs were investigated. Two groups of specimens were prepared from each type of CFS. The specimens in the first group were prepared with undamaged CFSs. The second group were equipped with CFSs that were incised using a scalpel. The incisions resulted in breakage of about 30 to 50 % of the filaments in the roving. The cutting of the carbon fibres was observed using a Tescan LYRA 3 electron scanning microscope. Images of the cuts of the carbon fibers A and D are depicted in Figs. 4 - 5. The brittle behavior of the ex-pitch fibre is indicated by the morphology of the filament breakage. The morphology of the filament breakage for all ex-PAN fibers (A, B and C) look the same.

All specimens were exposed to cyclic flexural loading. A three-point bending test was chosen in order to prevent possible damages in the area where the electrical contacts had been soldered. The test was configured in such a way that the tension stress in the area of the electrical contacts of the CFS was negligible. The loading was performed using a Zwick Roell Retroline 1145 universal testing machine, under the following configuration: support distance 90 mm, maximal loading force 12 N, preload 1.1 N, loading velocity 50 mm/min. Strain gauges were applied to determine the cyclic load in such a way that the strain level was 3000 μm/m for the outer layer of the bending specimens. In order to investigate the changes in electrical resistivity, 300 load cycles were applied to each specimen (with undamaged CFSs, and with incised CFSs).

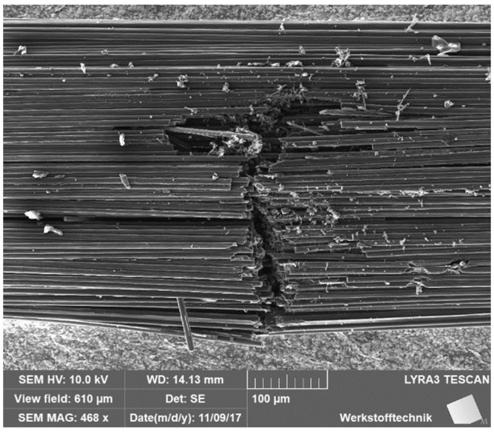


Figure 4. Detail of the cut of the Toray T300 carbon fiber (A)

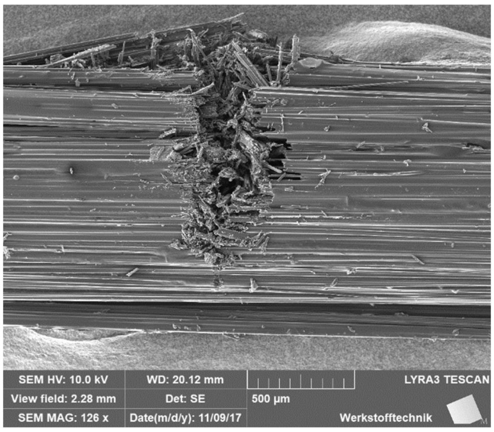


Figure 5. Detail of the cut of the Nipon CN-80-30S carbon fiber (D)

The specimens with undamaged CFSs were exposed to impact loading after the first loading series. Impact loading was performed using an impactor 16 mm in diameter. During impacting, the specimen was placed on a metal pad with the CFS facing upwards, see Fig. 1. The impact energy was 2 J and 3 J, according to Table 2. After impacting, the specimens were exposed to the second loading series of 300 cycles. The influence of the damage in combination with cyclic loading was characterized, and was compared with the behavior of the specimens with undamaged carbon fiber sensors.

2.4. Electrical resistance measurements

Measurements of the changes in electrical resistance change were performed using a Quantumx MX 1615 strain gauge amplifier, manufactured by Hottinger Baldwin Messtechnik GmbH. The output of the Wheatstone bridge was used to determine the changes in the electrical resistance of the measured carbon fiber sensor embedded in the specimens. A half bridge connection was used in order to eliminate changes in the electrical resistance change due to changes in temperature during the measurements. In each branch, one specimen with the same type of carbon fiber sensor was connected with an additional resistance (R_{ad}), because the minimum electrical resistance in each branch has to be 80 Ω. The changes in electrical resistance were calculated using the following equations, where U_O is output voltage and U_I is input voltage.

$$\frac{U_O}{U_I} = \frac{1}{4} \cdot \frac{\Delta R}{R} \quad \left[\frac{mV}{V}\right] \rightarrow \left[\frac{m\Omega}{\Omega}\right] \tag{1}$$

$$\Delta R = 4 \cdot \frac{U_O}{U_I} \cdot R_0 \; [m\Omega] \tag{2}$$

$$R_0 = R_{CFS} + R_{ad} \tag{3}$$

$$Relative\ change\ in\ electrical\ resistance\ = \frac{\Delta R}{R} = \frac{\Delta R}{R_{CFS}} \tag{4}$$

The relative change in the electrical resistance of each specimen was determined according to equation (4). The value was used in the subsequent evaluation, and is marked $\frac{\Delta R}{R}$. An overview of the measured electrical resistivity for all specimens is given in Table 2.

3. Results and Discusion

For the purposes of SHM, the following two factors are of great interest:

- the change in the electrical resistivity of the CFS due to the damage,
- the change in the electrical resistivity of the damaged CFS due to cyclic loading.

Smooth, almost linear dependence of the measured relative resistance of the fiber on the loading was measured for all types of carbon fibers in the pristine state, see Fig. 6, 8 and 9. The incision of the fibers was the first type of damage investigated. Incision simulates the interruption of filaments that can occur during tension or compression loading, and also after an impact. It was assumed that incising the fibers before embedding can have a significant influence on the measured signal during the subsequent three-point bending test. A significant change in the signal was also observed for some specimens with CFS made of type B and C fibers, see Fig. 8 and Fig. 9. Small changes in the shape and size of the signal were also observed for specimens A4 and A8 (Fig. 7). No change in measured signal compared to undamaged specimens was observes for specimens equipped with CFS type D – pitch fibers.

Table 2. An overview of the specimens with measured electrical resistance.

A	Toray T300					
Undamaged	[Ω]	Impacted	Impact energy [J]	[Ω]	Incised	[Ω]
A1	29.2	A1	3	45.5	A3	32.2
A2	31.3	A2	3	31.3	A4	33.5
A5	29.7	A5	2	29.9	A7	32.4
A6	29.5	A6	3	30.9	A8	30.8
					A9	31.3
					A10	-
B	Tenax Ni-coated					
Undamaged	[Ω]	Impacted	Impact energy [J]	[Ω]	Incised	[Ω]
B1	0.40	B1	3 (2x)	0.46	B3	0.45
B2	0.41	B2	3 (2x)	0.48	B4	0.43
B5	0.60	B5	3	0.60	B7	0.56
B6	0.60	B6	2	0.60	B8	0.63
					B9	0.58
					B10	0.60
C	Tenax HTS 40 MC					
Undamaged	[Ω]	Impacted	Impact energy [J]	[Ω]	Incised	[Ω]
C1	4.83	C1	3 (2x)	4.97	C5	4.96
C2	4.82	C2	3	4.86	C6	5.38
C3	4.79	C3	3	4.82	C7	5.45
C4	4.74	C4	2	4.76	C8	5.14
D	Nippon CN-80-30S					
Undamaged	[Ω]	Impacted	Impact energy [J]	[Ω]	Incised	[Ω]
D1	1.63	D1	3	2.02	D5	2.40
D2	1.75	D2	3	2.36	D6	2.16
D3	1.82	D3	3	2.13	D7	2.77
D4	2.04	D4	2	2.28	D8	2.51

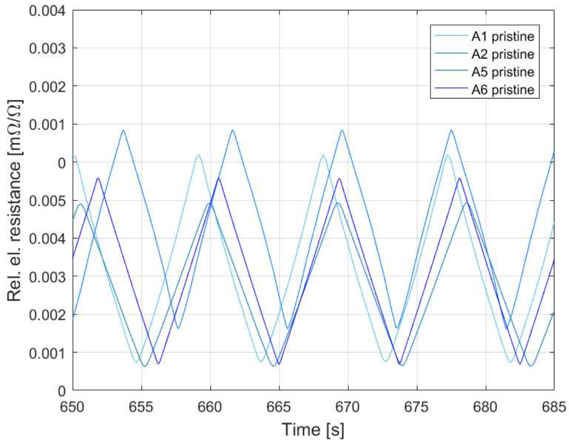


Figure 6. Electrical resistivity of type A embedded CFS - pristine during cyclic loading

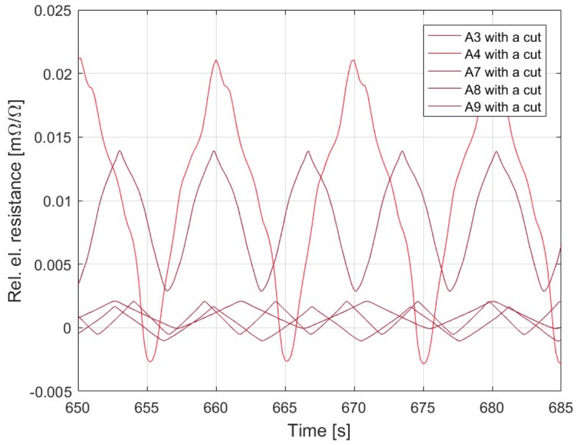


Figure 7. Electrical resistivity of type A embedded CFS - incised during cyclic loading

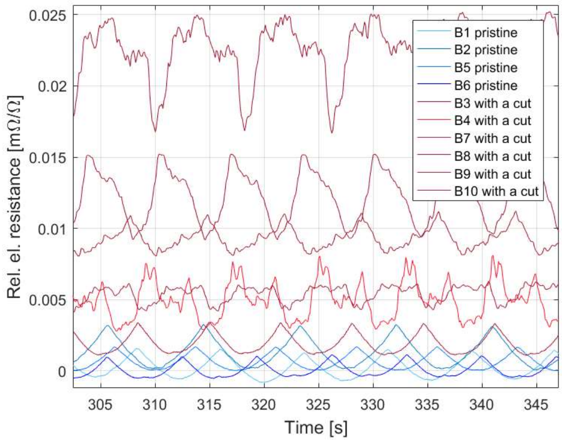


Figure 8. Electrical resistivity of type B embedded CFS - pristine and incised during cyclic loading

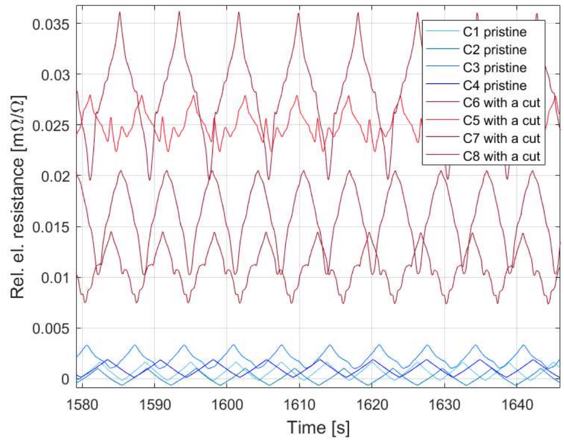
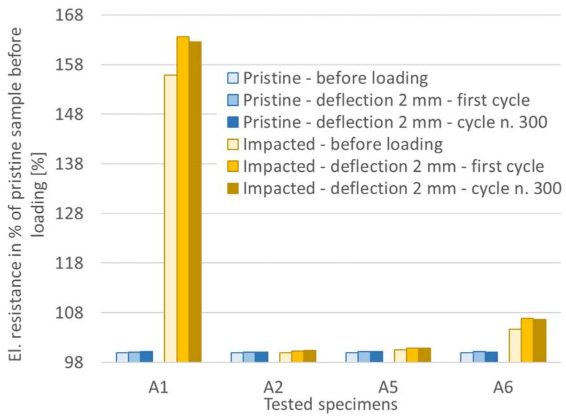


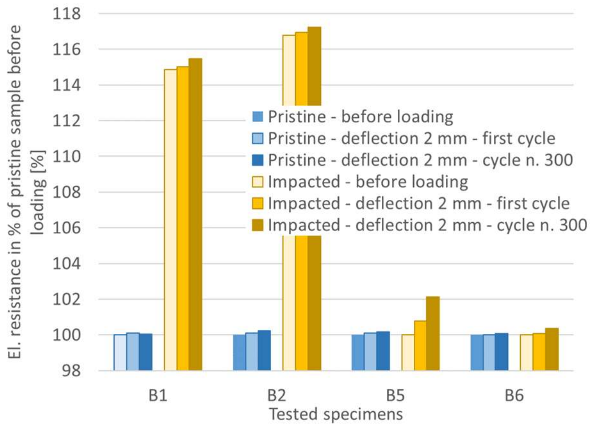
Figure 9. Electrical resistivity of type C embedded CFS - pristine and incised during cyclic loading

Differences in change of measured signal may have been caused by the way in which the incised specimens were prepared and in the way in which the incised CFS was embedded in the specimens. For further experiments, it is suggested that the CFS should be interrupted after the specimens have been prepared. Nevertheless, the experiments as they were conducted provided information about the behavior of partly interrupted CFS.

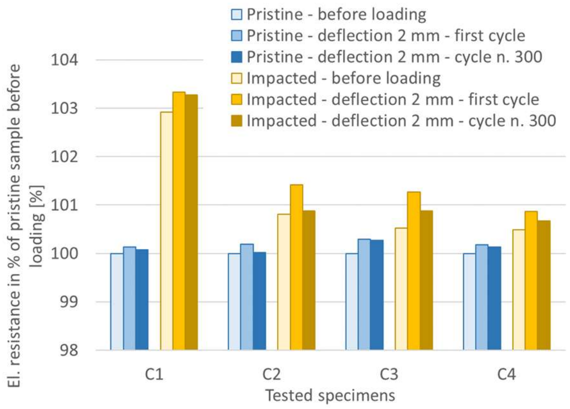
Impact was the second investigated damage mechanism. Specimens with embedded CFS according to Table 2 were loaded before and after impact. The electrical resistivity of the embedded carbon fibers was measured before flexural loading and during 300 subsequent cycles. After the impact on the specimens, the resistivity of the embedded CFS was measured again, and it was also measured during the subsequent 300 cycles of flexural loading. The graphs in Fig. 10 summarize the results of these measurements. For each specimen, the measured resistance for three states of an undamaged (pristine) specimen is given for each specimen. The following states are compared: before loading, during the first cycle of flexural loading at a deflection of the specimen of 2 mm (corresponds to a strain of 900 μm/m), and during cycle number 300 at a deflection of 2 mm. The same data are given for all specimens for the state after impact. Fig 10 (A) presents data for type A CFSs. It can be seen that there are great differences among the tested specimens, and no clear conclusions can be drawn. The situation is similar for nickel-coated carbon fiber (Fig 10 (B)). The data obtained for type C CFS (Fig. 10 (C)) shows that the change in electrical resistivity after impact is only from 0.5 % to almost 3 % in the unloaded state.



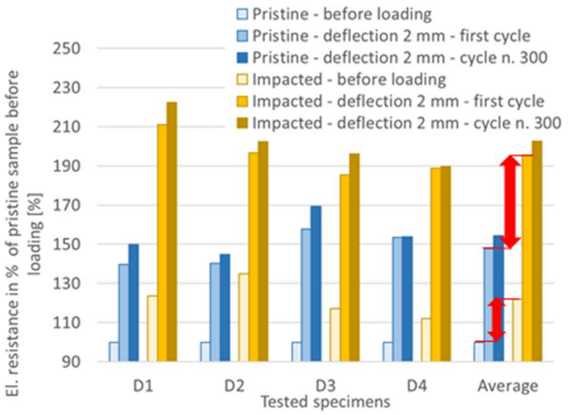
Toray T300 carbon fiber (A)



Tenax Ni-coated carbon fiber (B)



Tenax HTS 40 MC carbon fiber (C)



Nipon CN-80-30S carbon fiber (D)

Figure 10. Measured data for the pristine state and for the impacted state of the specimens

The change is slightly higher for the loaded state, but it decreases as the number of cycles increases. A significant change in measured electrical resistivity was observed for the pitch carbon fiber (Fig. 10 (D)). The change in the measured electrical resistivity values for all specimens was similar, and was one order of magnitude higher than for the other tested types of carbon fibers. The average change in electrical resistance after impact for an unloaded specimen is greater than 20%, and for loaded specimens the change is even much greater. The electrical resistivity of pitch carbon fibers increases due to cyclic loading.

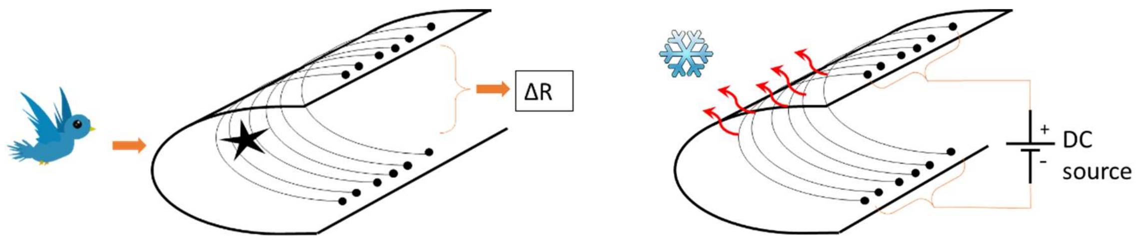


Figure 11

Fig. 1 Possible applications of CFS-network during impact detection, and as a heating element in a leading edge

4. Conclusion

An experimental study has been carried out on the electrical resistivity response of carbon fiber sensors embedded in glass fiber composite specimens. Changes in the electrical resistivity of four different types of carbon fibers were measured during cyclic flexural loading. Two types of damage have been investigated: incision of the carbon fiber tow, and impact. The following conclusions can be drawn from the investigation:

- The changes in measured electrical resistivity due to impact with the specimens are most significant for the tested ex-PITCH fiber. The changes are higher by an order of magnitude than for the tested ex-PAN fibers.
- Cyclic loading has a greater influence on changes in the electrical resistivity of damaged ex-pitch fibers than on changes in the electrical resistivity of the ex-PAN fibers.
- The changes in electrical resistance are more pronounced in the loaded state for tested type C and type D fibers, while no decisive conclusions can be drawn in this area for other types of fibers.
- Changes in the measured dependency between the electrical resistivity and the flexural loading of incised CFSs are most likely to occur in specimens with type B and type C embedded fibers.

The different characteristics for ex-PITCH fibers and for ex-PAN fibers can be attributed to the brittle behavior of the carbon structure of pitch fibers. The characteristics investigated here are of strong interest, because they can help in the development of a complex CFS network for use in various aspects of Structural Health Management.

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