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DOCTORAL THESIS STATEMENT

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DOCTORAL THESIS STATEMENT

ELECTRICAL RESISTANCE MEASUREMENT FOR STRUCTURAL HEALTH MONITORING OF COMPOSITE MATERIALS

by

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Doctoral Study Programme: Mechanical Engineering

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Teze byly rozeslány dne: ....

Obhajoba disertace se koná dne .... v ……… hod.

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S disertací je možno se seznámit na oddělení vědy a výzkumu Fakulty strojní ČVUT v Praze, Technická 4, Praha 6.

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Annotation

The dissertation deals with the topic of monitoring of long-fiber composite material structures using the method of measuring changes in electrical resistance. It deals with two approaches. The first approach is based on measuring of the electrical resistance change directly on long-fiber carbon composites. These measurements allow the detection of deformation and damage within the material. The second approach employs the use of sensors made of carbon fiber tows that exhibit piezoresistive behavior.

Novel findings on the use of carbon fiber sensors for detecting barely visible impact damage (BVID) are presented. Additionally, thermography has been validated for visualizing sensor damage and localization of damage along the sensor length.

This work includes a comparative analysis of existing methods for determining the electrical resistivity of composites. It also assesses the impact of these methods on predicting delamination size through finite element (FE) simulations. The influence of temperature and the positioning of electrical contacts on delamination detection are quantified using FE simulations. Finally, the dissertation introduces a new technique for fabricating electrical contacts on the inner surface of composite profiles and the results of damage detection of both approaches on components fabricated by the winding technology are also presented.

Keywords: SHM; piezo-resistive sensor; carbon fiber sensor; impact damage; BVID; polymer composites; sensor embedment; NDT; active thermography; electrical resistance; Structural Health Monitoring; damage detection; Composites.

Anotace

Disertační práce Monitorování a lokalizace poškození kompozitních materiálů pomocí měření změny elektrického odporu se zabývá tématem monitorování konstrukcí z dlouhovláknových kompozitních materiálů pomocí metody měření změny elektrického odporu. Konktrétně se zabývá dvěma přístupy. První přístup spočívá v měření změny elektrického odporu přímo na dlouhovláknových uhlíkových kompozitech. Z naměřených hodnot elektrického odporu lze detekovat deformaci i poškození materiálu. Druhá metoda spočívá v použití senzorů vyrobených ze svazků uhlíkových vláken, které vykazují piezorezistivní chování.

V práci jsou prezentovány nové výsledky ohledně možnosti využití senzorů z uhlíkových vláken pro detekci BVID impaktu. Byla validována termografická metoda pro vizualizaci poškození senzoru a lokalizaci poškození po délce senzoru.

Jsou prezentovány výsledky porovnání několika používaných metod pro stanovení rezistivity kompozitu. V práci byl dále stanoven vliv použití konkrétních metod na predikci velikosti delaminace pomocí numerické simulace metodou konečných prvků. Pomocí konečně prvkových simulací je kvantifikován vliv teploty a vzdálenosti el. kontaktů na detekci delaminace. V práci jsou uvedeny také výsledky použití nové metody výroby el. kontaktů na vnitřním povrchu kompozitního profilu a výsledky detekce poškození obou metod na komponentách vyrobených technologií navíjení.

Klíčová slova: SHM; piezorezistivní senzor; senzor z uhlíkových vláken; impaktní poškození; BVID; polymerní kompozity; integrace senzoru; NDT; aktivní termografie; elektrický odpor; monitorování zdraví konstrukce; detekce poškození; kompozity.

Contents

Nomenclature

Abbreviation	Description
3PB	Three-point bending test
4PB	Four-point bending
2T	Two-terminal (measurement method)
4T	Four-terminal (measurement method)
4W	Four-wire (electrical resistance measurement method)
BVID	Barely visible impact damage
CF	Carbon fiber
CFR	Carbon fiber reinforced
CFRP	Carbon fiber reinforced polymer
CF-PPS	Carbon fiber, polypropylene sulphide matrix
CNT	Carbon nanotube
DCB	Double-cantilever beam
DFOS	Distributed fiber optics sensing
ER	Electrical resistance
ERCM	Electrical resistance change measurement
FE	Finite element
NDT	Non-destructive testing
SHM	Structure health monitoring

Symbol	Description	Units
R	resistivity	[Ω]
r	radius	[m]
ρ_x	resistivity (the index indicates the respective measurement direction)	[Ωm]
l	length	[m]
A	cross-section	[m^2]
ε	strain	[-]
ν	Poisson's ratio	[-]
k	strain sensitivity	[-]
U	voltage	[V]
w	width	[m]
t	thickness	[m]

1 Introduction

Carbon Fiber Reinforced Polymer (CFRP) composites are nowadays widely used for structural components across the aircraft, automotive, and manufacturing industries. These materials are also employed in civil infrastructure for the construction and reinforcement of bridges and roofs. In all these applications, a high level of safety has to be ensured. CFRP composites excel by their high strength, rigidity, low density, damping properties, and fatigue resistance. However, a notable drawback is their tendency to exhibit minimal signs of damage before failure, unlike conventional materials such as steel, aluminum alloys, or concrete.

Traditionally, parts are controlled by naked eye during scheduled maintenance checks. However, during these inspections, damage to composite parts can be easily overlooked. Therefore, efficient in-situ assessment of a components damage state and accurate prediction of its remaining service life are necessary.

Greater use of NDT techniques to monitoring damage state of CFRP components can be suggested. However, conventional NDT techniques like C-scan, X-ray, thermography, and eddy current testing are time-consuming and typically require taking the component out of service. Additionally, with increasing pressure for cost savings, the aircraft industry is shifting towards Structural Health Monitoring (SHM) and Condition-Based Maintenance. Several SHM techniques are already under investigation. The SHM approaches are spreading in other industries as well.

One of the potential SHM methods for composite structures is the Electric Resistance (ER) measuring method. There is a wide range of approaches, which utilize measurement of electrical resistance. These can be broadly categorized into two groups.

The first group exploits the electrical properties of the material of the primary structure itself. This includes composite materials with carbon fibers or carbon particles, and non-conductive fiber composites with conductive particles in the resin, such as Carbon Nanotubes (CNTs) or carbon black.

The second group involves integrating sensors into the composites. The measurement of electrical resistance of these sensors are used for strain and damage sensing. Among these sensors we can include sensors made from carbon fibers and tows, CNTs, buckypaper, and other novel materials.

This research focuses on the **self-sensing capabilities of carbon fiber composites** without the addition of conductive particles because the usage of nanoparticles requires extra demands on save handling, which is not easy to withstand during manufacturing. The second area of interest is the **use of carbon fiber tows as sensors**. Their robustness makes them suitable for standard composite manufacturing processes. Additionally, Carbon Fiber Sensors (CF Sensors) made from carbon fiber tows can be easily tailored for specific sensing applications.

Both approaches under investigation are relatively cost-effective in terms of preparation, and the sensing equipment required is more accessible compared to measurement units used for optical fibers or acoustic emission. Crucially, both approaches utilize the structural material itself for sensing.

The sensing ability of carbon fibers have been documented in the literature. In this work are presented experiments dealing with new possible utilization of sensors made of carbon fiber tow. The investigated area is impact damage. Influence of the material type, cyclic loading, temperature, and size of impact energy on impact damage detection using carbon fiber tow as a sensor is discussed.

Previous experimental studies have proved that coupling between the damage and loading state of CFRP composites and their electrical resistance exists. This phenomenon is attributed to the unique composition of CFRPs, which consist of electrically conductive and piezoresistive carbon fiber tows, and an insulating polymer matrix, typically epoxy. The possibility of damage monitoring in these composites has been demonstrated through numerous experiments. Although a lot of work have been done on describing coupling between the measured electrical resistance and the material state, a lot of information is missing to be able to perform electrical resistance method in industrial applications.

The method based on electrical resistance measurement has wide range of potential applicability. On the other hand, there are many influences which can affect the method, such as temperature, fiber orientation, stacking sequence, and electrical contact configuration. It is essential to identify and quantify the influences on the measured electrical resistance of CFRP composites more precisely. Understanding these limitations will help further development and application of this method. In this work, we specifically explore how electrical contact configuration, temperature, and material resistivity impact delamination detection using the electrical resistance method.

The findings, based on experimental verification at the component level, along with recommendations for future research, are summarized at the conclusion of the thesis.

2 State of the art

There are many approaches being investigated for the goal of Structural Health Monitoring (SHM) of composite materials. In this work we focus on two specific approaches: carbon fiber roving for damage detection and the measurement of the electrical resistance response of the whole CFRP composite. It is believed that a better understanding of both phenomena is beneficial, and both approaches can enrich each other.

2.1 Sensing properties of carbon fiber rovings

Carbon fibers are electrically conductive and also show piezoresistivity [1], [2], [3], [4]. In [4], a broad range of carbon fibers (PAN-fibers, graphite fibers, low modulus, high modulus) was investigated, and their piezoresistive behavior was determined. It is important to note, that each type of carbon fiber shows different piezoresistive behavior, as shown in Fig. 1. The carbon fibers vary also in resistivity.

For practical applications it is difficult to manipulate with individual carbon fibers (diameter 7-8 μm). In literature we can find many applications when carbon fiber rovings (tows) are used for strain sensing. Carbon fiber roving can contain varying amounts of carbon fibers (1K=1.000 filaments, 3K=3.000 filaments, 12K=12.000 filaments). The conduction of such a bundle of carbon fibers is more complex and so can be the stress distribution in the carbon fiber roving [5], [6].

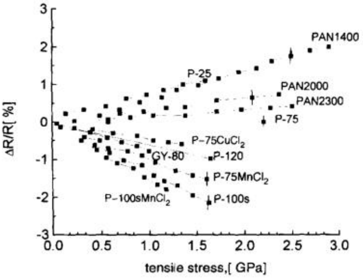


Fig. 1 Changes in relative resistance of carbon and graphite fibers as a function of stress (figure was published in [4])

There is a question about techniques for contacting carbon fiber rovings. Ideally, all filaments of the roving should be electrically connected to lead wires. Otherwise through thickness/transversal conduction pattern will have influence on the contact resistivity of the sensor (see Fig. 2). This is especially important for thicker rovings. The sensing ability of the sensors can be influenced by pre-stress applied during manufacturing, due to increased straightening of the filaments and an increase in the number of fiber-fiber contacts. This influence was investigated in [7].

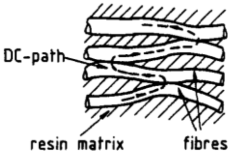


Fig. 2 Schematic related to transverse resistivity from [8].

Various techniques can be used for preparing electrical contacts, including the use of clips, metal splices, conductive paints, conductive adhesives or deposition of nickel (electroplated coating) [9]. Conductive carbon cement was also used for electric contact preparation [10]. The process for depositing nickel is described in [11].

Individual carbon fiber sensors can be arranged in mesches [1] or denser in grids [12], [13], as shown in Fig. 3 and Fig. 4. The crosssections of the fibers or the sensors in the grid can be separated by insulating fibers or sheets. When the network becomes denser, it transitions to sheets of carbon fiber fabric. Measuremnents are no longer conducted on individual fiber tows, but on the number of tows.

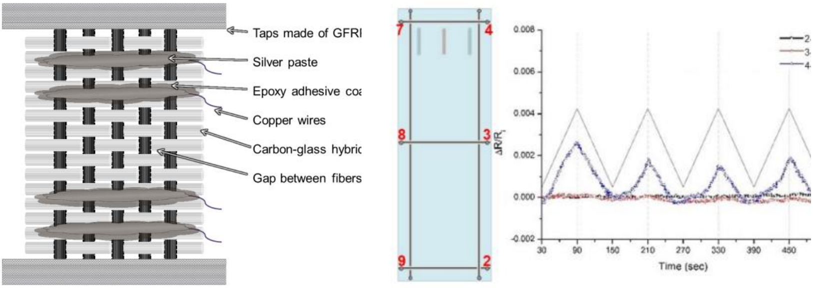


Fig. 3 A schematic of specimen made of multiple carbon fiber tows and glass fibers [12] (left), Specimen description of a specimen with carbon fiber grid sensor and its electromechanical response of multiple electrical channels [12] (right).

Fig. 4 Sensor network modules and carbon filament yarn strain sensors on knitted fabric before stacking and curing (left), demonstrator setup: composite component with embedded sensor network and laptop with hand reader for the read-out of the stored data (right). [13]

The advantages and disadvantages of the method based on usage of sensors made of carbon fiber tows are summarized in Table 1.

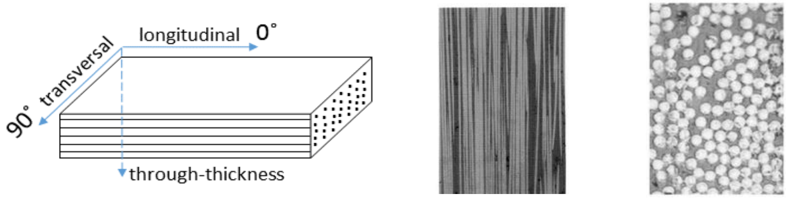
Table 1 Carbon Fiber Sensor (CF sensor) - overview

	advantages	disadvantages
Carbon Fiber Sensor (CF sensors)	- in-situ monitoring	- electric current has to be supplied to the sensor - possible problem with electromagnetic coupling
	- CF sensor can be manufactured in defined length and shape	- signal is integrated along the fiber length – configuration of the measurement has to be adjusted to the specific application
	- small diameter of the sensor	- CF sensor must be integrated during manufacturing or installed to the surface
	- measurement device is not too expensive	- resistance is temperature dependent - temp. compensation needed (additional temperature measurement or unloaded sensor measurement at the same temperature – “dummy sensor”)
		- reliable electrical contacts must be prepared
		- calibration of each sensor should be performed
	- electrical resistance of CF sensor is loading state dependent	
	- is electrical resistance fatigue dependent? – not described	
	- electrical resistance is damage dependent	

2.2 Electrical properties of CFRP composites

CFRP composite plates are usually prepared by laminating individual layers of lamina at different angles of the fibers to the longitudinal axis. The electrical resistivity ρ of CFR composite of each lamina depends on the direction of measurement and the direction of the carbon fibers.

In unidirectional CFR composite plates, we can distinguish three perpendicular measurement directions and three distinct resistivities (ρ_x, ρ_y, ρ_z).



(a) (b) (c)

Fig. 5 Measurement direction for electrical resistivity of unidirectional CFR composite plate in section a), contact of align carbon fibers in transversal direction (b) [14], fiber-fiber contact in through-thickness direction (c) [15]

The electrical resistivity of the material can be determined by two measurement configurations (two-probe method and four probe method). Pitfalls of these two methods are summarized also in [16]. In Fig. 6 is depicted contour plot of electrical potential in the unidirectional CFRP laminate.

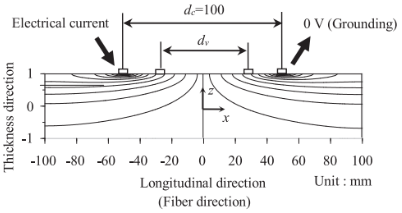


Fig. 6 Contour plot of electrical potential in the unidirectional CFRP laminate. The Figure is copied from [17].

Pros and cons of ER measurement method on composite materials are summarized in Table 2.

Table 2 Electrical resistance (ER) measurement method - overview

	advantages	disadvantages
Electrical resistance measurement method	- in-situ monitoring	- electric current has to be supplied to the material - possible problem with electromagnetic coupling
	- no additional sensors needed - information direct from the structure	- signal is structure dependent (dependent on stacking sequence and type of material, manufacturing)
	- measurement device is not too expensive	- signal is dependent on configuration of electrical contacts
		- signal is dependent on orientation of the material (electrical anisotropy of the CFRP composite)
		- resistance is temperature dependent - temp. compensation needed (additional temperature measurement or measurement always at the same temperature) - resistance is dependent also on humidity
		- reliable electrical contacts must be prepared
	- electrical resistance is loading state dependent	
	- electrical resistance is fatigue dependent	
	- electrical resistance is damage dependent	

Evaluation of measured data must be adjusted for each case.

Repeatability of the measurement? Reliability of the measurement?

2.3 Conclusions of chapter 2 and potential areas for further creative research

2.3.1 Conclusions on the carbon fiber sensors section

- Number of experimental campaigns have proven possibility of utilization of CF sensors for strain sensing.
- The sensing properties of CF sensors depends on the carbon fiber tows used for the fabrication of the sensor and on the manufacturing process itself.
- Influence of temperature and humidity on sensing using CF sensors made of several carbon fiber tows were published. **It is necessary to quantify this influence for new carbon fiber tows used for sensing.**
- One campaign showed that microcrack detection using CF sensors is possible on GFRP composite. Idea of impact damage detection using CF sensors was shown, nevertheless no detailed information regarding this approach were given. **The author believes that impact damage detection by the mean of integrated CF tow could be an efficient way for impact damage detection on larger structures rather than ERCM method itself.**
- When speaking about SHM systems and sensors, there is also question, how to distinguish between sensor damage and damage of the structure itself. **A method for checking of the CF sensors would be beneficial.**
- CF sensors were used so far only for component made of GFRP composites or concrete structures. CF sensors were integrated in non-conductive materials. **It would be beneficial to verify the feasibility of integrating CF sensors directly into wound composite parts made of carbon fibers.**

2.3.2 Conclusions regarding electric resistance change measurement (ERCM) method on CFR composites

- The number of influences, which can affect results of ERCM method were described (mechanical loading, environmental effects, fatigue loading, material parameters, configuration of electrical contacts, type of damage).

- Several configurations for determination of electrical resistivity and piezoresitivity of the CFRP material are used.
- Although the ERCM method is investigated for several decades the contact configurations for determination of the electrical resistivity has not been compared so far. **The influence of measurement configuration on the accuracy of the determined electrical resistivity and further predictions of FE analysis is not given and should be investigated**.
- Best results for impact and delamination detection show experimental campaigns when trough-thickness and oblique resistance was measured.
- For practical use of electrical resistance measurement method, **adjusting of the method will be necessary according to loading of examined component.**
- Although a lot of researchers work on algorithms for impact damage detection, the detection is possible only on plate specimens with limited dimension so far. **The author sees a greater potential in practical application of the method for the delamination detection.**
- Only a few papers deal with the delamination or debonding monitoring. **It is desirable to broaden the portfolio of similar own experiments.**
- No mention of the use of the method on thermoplastics and filament wound composites has yet been found. **Therefore, it would be beneficial to expand the base of experimental data and the development of measurement methods here as well.**
- The quantification of the influences on the delamination detection using ERCM is limited so far. **This area will be investigated as well.**
- In the review of current state, several contacting methods for ERCM were described. Most of them are not possible to use for preparation of electrical contacts on the internal surface of the component during manufacturing. **It would therefore be appropriate to find and validate a contacting methodology for these cases.**

3 Aims of the thesis

In the first part of the work the possibility of usage of CF sensors for impact damage detection will be investigated. This new approach for impact damage detection has to be verified and possible influences on the sensor's response arising from the operational loads should be analyzed. Other aspects that could influence the successful use of this method are also investigated.

The first objective of attention was established:

A. Development of impact detection method using CF sensors.

The main goals in the frame of this aims were established as follows:

1. Verify possibility of impact damage detection using CF sensors – find appropriate CF tow.
2. Determine the influence of cyclic mechanical loading of the structure to damage detection.
3. Determine the influence of temperature to damage detection.
4. Determine the influence of positioning of the sensor in the stacking sequence of the composite to damage detection.
5. Propose inspection of CF sensors and verify the proposal.
6. Quantify the influence of the length of the sensor to change of electrical resistance after impact.
7. Describe the relationship between electrical resistance change measured on integrated CF sensor after impact and mechanical response of the structure to the impact.

Detection of delamination using the Electrical Resistance Change Measurement (ERCM) method will be examined, and practical aspects of its application will be discussed in the second part of this work. There are a lot of construction where delamination can occur, and which are difficult to monitor by other methods because of their complex shape (for instance corners). The ERCM method should not be limited by the complexity of the shape of investigated part. For this reason, the author focused on the delamination detection using ERCM method.

In literature, there are published several contact configurations for determining electrical resistivity of CFRP composites. Influence of such configurations on the electrical resistivity determination need to be quantified. The following possibility of prediction of delamination detection by the means of FE analysis should be evaluated. The influence of distance of electrical contacts on the detectability of delamination needs to be evaluated and the influence of temperature changes also needs to be evaluated.

The second objective of attention was established:

B. Methodology of delamination detection using electrical resistance measurement on the CFRP composite.

The main goals in the frame of delamination detection were established as follows:

1. Based on experimental investigation and numerical simulation determine the appropriate procedure for electrical resistivity determination in longitudinal and through-thickness direction.
2. Determine the electrical resistivity of CF composite with thermoplastic matrices and compare it to the electrical resistivity of the CFRP composite.
3. Specify the influence of temperature change, electrical resistivities of the material and electrical contact configuration.

It is necessary to gather knowledge and experience for the practical utilization of CF sensors and ERCM method on real components. The objective of the third section is to deal with the requirements on the utilization of the approaches on the carbon fiber filament wound component.

The third area of investigation was defined as:

C. Experimental verification on component level.

Key objectives within this framework have been identified as follows:

1. Propose and verify the method of electrical insulation of CF sensors incorporated into a carbon fiber composite structure.
2. Propose and verify a methodology for electrical contact preparation for ERCM method on the filament wound components.

4 Impact damage detection of GFRP using of CF sensors

The potential use of CF sensors for impact damage detection is investigated in this chapter. The possible use of sensors for impact damage detection is shown schematically in Fig. 7. Seven different types of carbon fiber tows were used for sensing purposes. The response of the prepared sensors to mechanical strain, damage and temperature was described. Prepared CF sensors and specimens with integrated CF sensors are shown in Fig. 8 and Fig. 9. Impact damage was quantified by electrical resistance measurement of the CF sensor before and after loading. The change in electro-mechanical response to cyclic loading with regard to impact damage was also evaluated. A sensitivity test on the influence of the sensor's position in the material for impact damage detection was also conducted. The findings gathered in this section were presented in several publications by the author [A6],[A1].

The influence of the length of the CF sensor was also investigated, as well as the size of the impact on the sensor's response. A correlation between impact damage size, response of the CF sensor and mechanical response of the specimens was found. These findings were published in [A18].

Three experimental campaigns were conducted. During all campaigns specimens were first loaded by cyclic mechanic loading, see Fig. 10 and Fig. 14.

Fig. 7 Possible impact damage scenarios during flight [18]

Afterwards impact loading was applied to the specimens, see Fig. 11. Finally impacted specimens were loaded by cyclic mechanic loading again. The loading was set such that the maximal deformation was 3000 µm/m.

Since the highest sensitivity to impact was observed for the ex-PITCH fiber tow during the first experimental campaign, it was hypothesized that this could be related to its low limit of maximal elongation. For the second experimental campaign, two types of pitch carbon fiber tows with low maximal elongation were chosen.

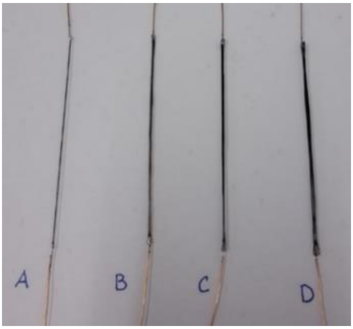


Fig. 8 CF sensors prepared for installation into the specimens (first experimental campaign).

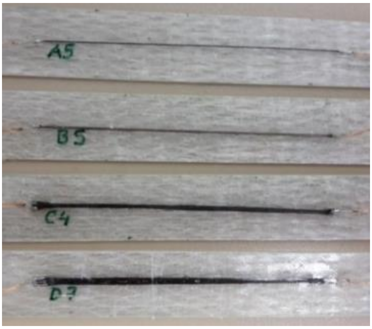
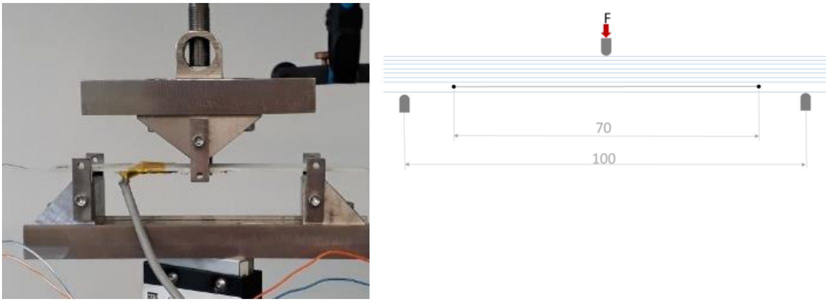


Fig. 9 Specimens with integrated CF sensors (first experimental campaign).

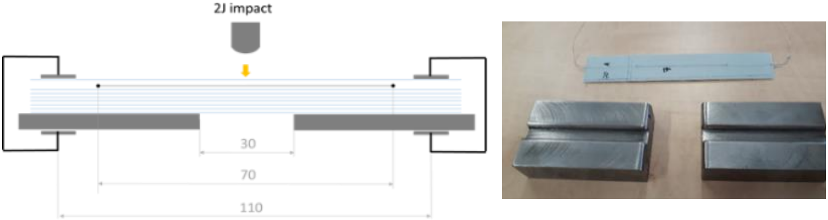
The ex-PAN carbon fiber Toray T300 was chosen as a reference fiber tow, because it has shown stable and repeatable behavior in other sensing applications, such as those reported in [19] and [20]. In the second experimental campaign an autoclave curing technique was used, contrary to the first experimental campaign, during which hand lamination was used, see Fig. 9. An overview of the carbon fiber tows examined in second experimental campaign is given in Table 3.

Three different integration arrangements were applied for the carbon fiber sensors. They were placed between the first and second layer, in the middle of the specimen 's thickness (between the fourth and fifth layer), and between the seventh and eighth layer.



(a) (b)

Fig. 10 Configuration of the 3-point-bending test: (a) specimen during cyclic flexural loading; (b) configuration of the composite lay-up during cyclic flexural loading.



(a) (b)

Fig. 11 Configuration of the drop weight impact test: (a) schema of the impact test; (b) supports for the impact test (second experimental campaign).

The purpose of the mechanical testing during second experimental campaign was to describe the response of the measured signal of the investigated sensors with regard to the number of cycles, the positioning of the CF sensor in the composite lay-up and the influence of different materials on the CF sensor signal.

In practical applications, it is not always feasible to conduct simultaneous temperature measurements at the location where impact detection is needed. The schematic representation on Fig. 12 illustrates the evaluation procedure applied for different experimental steps. Using this procedure, temperature measurements become unnecessary.

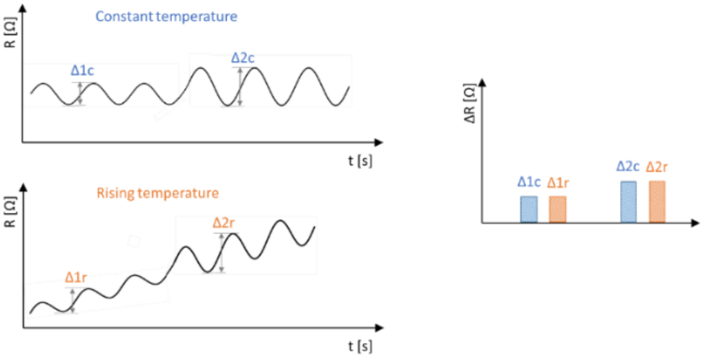


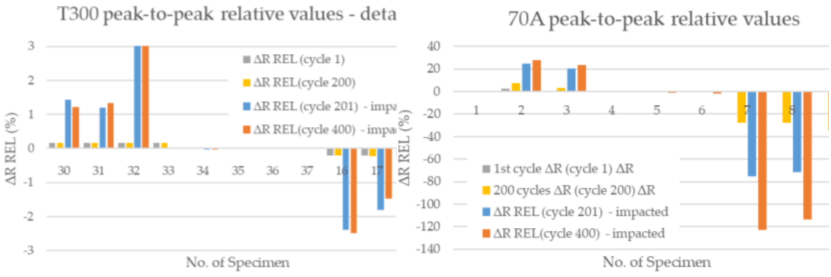
Fig. 12 Evaluating the peak-to peak data [A1].

According to our investigation, it is better to position CF sensors on the side opposite the impact, rather than on the impacted side. Placing a CF sensor on the opposite side increases the probability of detecting an impact, see Fig. 13. This is probably caused by the nature of impact damage in composite layups, where greater damage tends to occur closer to the surface opposite the impacted side.

The PAN type of fiber tow used for integrated CF sensor showed stable behavior under cyclic loading.

Table 3 An overview of the carbon fiber tows examined here.

Label of the fiber tow		**T300** **T300 1000-50A**	**95A** **YS-95A-30S**	**70A** **YSH-70A-30A**
Type		PAN	PITCH	PITCH
Producer		Toray	Nippon Graphite Fiber Corporation	
Number of filaments	[-]	1000	3000	3000
Tensile modulus E	[GPa]	230	893	714
Tensile strength R_m	[MPa]	3530	3600	3600
Ultimate elongation	[%]	1.5	0.3	0.5
Thermal conductivity	[W/mK]	10.46	600	250
Volume resistivity	[μΩm]	17	2.2	5



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

Fig. 13 Peak-to-peak relative values of the measured signal from CF sensors integrated into the specimens before and after impact loading: (a) results for specimens T300 – detail; (b) results for specimens 70A.

Manufacturing CF sensors using extremely brittle pitch carbon fiber tows (Pitch 95A) is not recommended. Ensuring contact quality is challenging, and difficulties arise in sensor manufacturing and handling, especially during integration into structures.

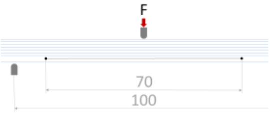
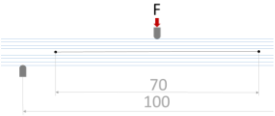
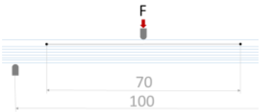
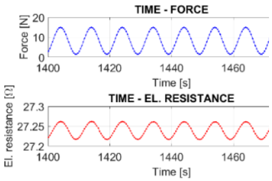
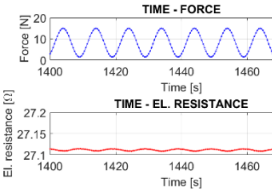
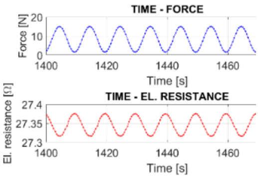
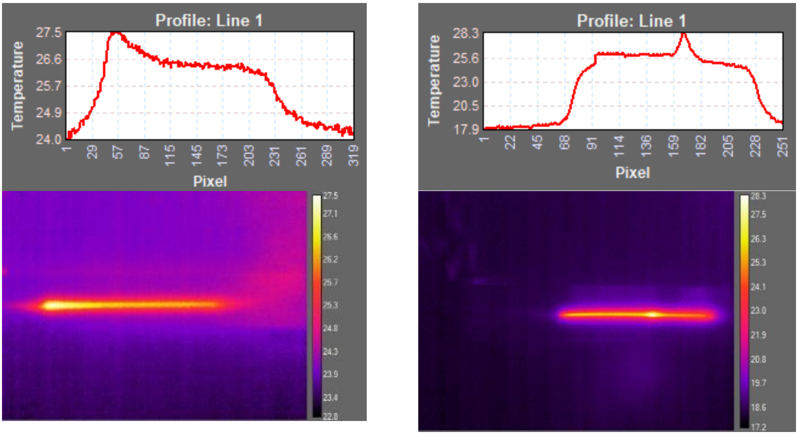
Specimen with CF sensor between the 1st and 2nd layer during 3PB	Specimen with CF sensor between the 4th and 5th layer during 3PB	Specimen with CF sensor between the 7th and 8th layer during 3PB
		
Specimen T300-30	Specimen T300-37	Specimen T300-16
		

Fig. 14 Configuration of the 3PB test and the measured signal from the integrated CF sensor.

During the second experimental campaign, a FLIR A325sc infrared camera was used to perform an active thermographic inspection of all specimens for impact detection using the CF sensor. The CF sensor is supplied with electric current, and the thermographic camera displays a temperature field that indicates where local heating is occurring. All specimens were inspected after manufacturing and again following drop-weight impact testing. The inspections focused on the mold side of the specimen, which is both the impacted side and the outer surface during the cyclic flexural test.



(a) **(b)**

Fig. 15 Active thermographic inspection: (a) 95A-11 before loading, (b) T300-30 after impact.

Active thermography proves to be a successful method for inspection of CF sensors after manufacturing. It can reveal damage in the area of electrical contacts, see Fig. 15.

It was demonstrated that active thermography, in combination with a CF sensor, can effectively visualize barely visible impact damage (BVID) in components.

The temperature coefficients for CF sensors made of T300 and 70A materials were determined through experiments on sensors integrated into GFRP composites, see Fig. 16.

The third experimental campaign was designed to investigate the potential influence of sensor length on the ability of a CF sensor to detect impact damage, the impact of a higher number of cycles on the response of the CF sensor, the possibility of establishing a correlation between measured signal from CF sensor after impact and mechanical response of the structure to the damage.

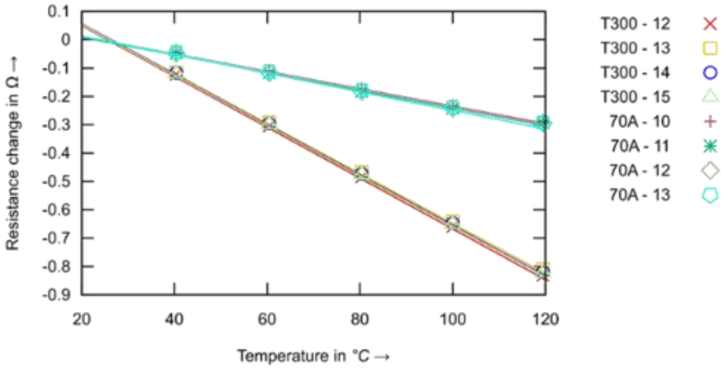


Fig. 16 A linear fit function for the measured mean values of the CF sensor

The results for two sensor groups with lengths of 70 mm and 140 mm, are presented in Fig. 17 and Fig. 18. The absolute values of electrical resistance change were found to be the same, indicating that the relative resistive change is smaller for the longer sensors.

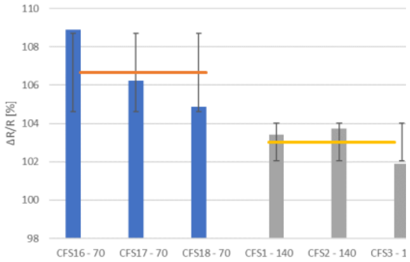


Fig. 17 Relative electrical resistance change after BVID impact of 2J of sensors with length of 70 mm and 140 mm

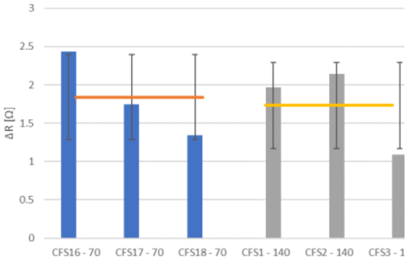
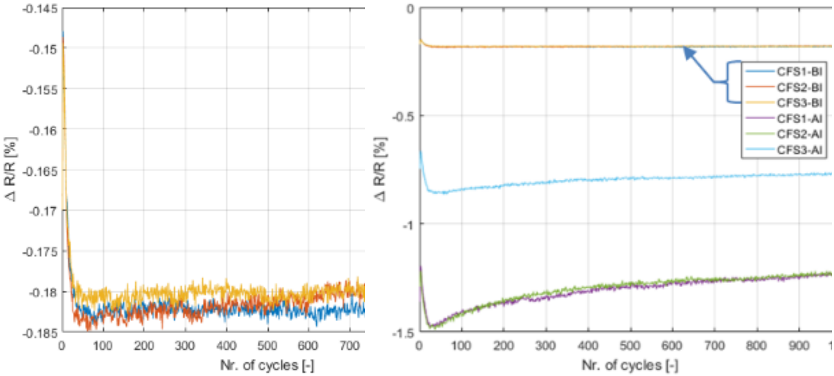


Fig. 18 Absolute values of electrical resistance change of integrated CF sensor after BVID impact of 2J

The influence of cyclic loading to the sensor's behavior was evaluated in the same manner as in the second experimental campaign, but the amount of loading cycles was extended from 200 to 1,000 cycles, see Fig. 19. Switching the loading configuration from 3PB to 4PB resulted in a larger area of constant deformation under maximal loading. The loading was set such that the maximal deformation matched that of the previous 3PB test, which was 3000 µm/m.



(a) (b)

Fig. 19 (a) Relative electrical resistance of the CF sensors during cyclic test before impact for specimens CFS1, CFS2 and CFS3; (b) Relative electrical resistance of the CF sensors during cyclic test before impact (BI) loading and after impact loading (AI).

Given that CF sensors can be used to detect impact damage to structures, it was investigated whether it is possible, based on the measured change in electrical resistance of the integrated CF sensor, to predict the amount of damage after impact and the resulting structure's response to mechanical loading.

Let us consider a beam of a manipulator with a working head drive. Different working heads with different masses are moving within the beam. We must consider the variable loading of the beam. During the operation of the manipulator, a collision may occur. We can assume decrease of the maximum loading capacity of the beam due to damage. Detecting such collisions and predicting the residual strength of the structure would be useful. We have established our specimen to be such a beam. We wanted to show a correlation between damage size and the measured response of the CF sensor. Moreover, we aimed to measure the changes in the response of the sensor to the loading at different levels of impact.

According to the 3D graph of dependency of ΔR, deflection, and force in Fig. 21, the greater is the deflection, the more pronounced is the effect of stiffness loss caused by impact damage.

A correlation was found between the measured change in electrical resistance of the integrated CF sensors and the decrease in stiffness of the specimens caused by impact loading.

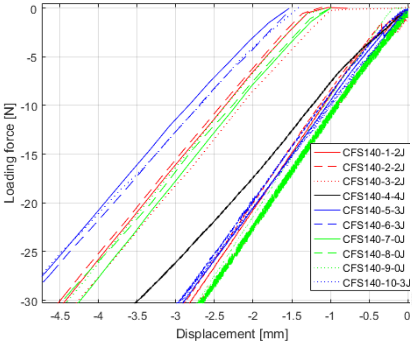


Fig. 20 Detail of force displacement dependency during 4PB of pristine and impacted specimens

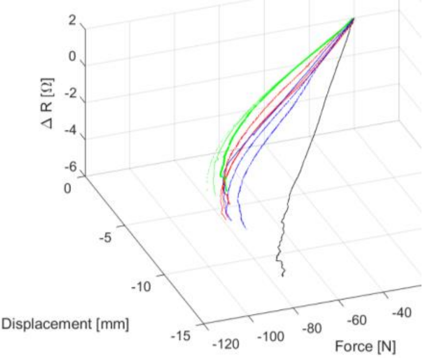


Fig. 21 3D Force-displacement-ΔR from integrated CF sensor during 4PB test

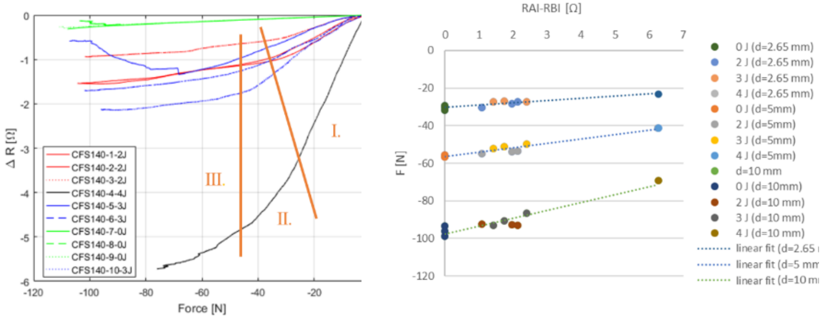


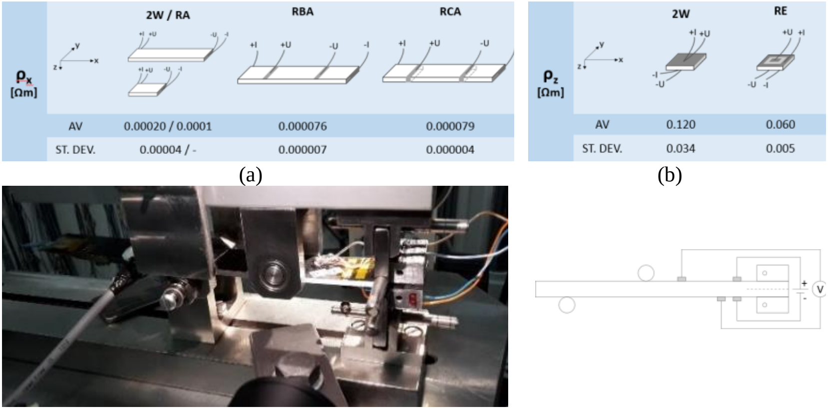
Fig. 22 Change of electrical resistance of the integrated CF sensor depending on applied force during 4PB (on the left), graph of force – change of measured electrical resistance AI (after impact) and BI (before impact) (for different impact energies and displacements) (on the right).

In Fig. 22 it is evident that the relationship between the depicted quantities is not consistent across the entire load range. We can distinguish areas of two different slopes in the loading curve, sections I and III. The section II can be called a transition area.

The decrease in stiffness of the specimen due to impact can be predicted from the measured change in electrical resistance of the integrated sensors during loading as well as from the electrical resistance change measured before and after impact on the unloaded structure.

5 Damage detection – delamination

Three contact configurations were tested for the determination of in-plane resistivity of CFRP composite material (Fig. 23 (a)). The resistance in the through-thickness direction was determined using two contact configurations (Fig. 23 (b)). The obtained values were then compared to experimental data from cyclic MMB tests (Fig. 23 (c,d)) and subsequently used for the numerical simulation of delamination specimen tests and for sensitivity analysis regarding electrical contact distance, temperature change and electrical resistivity of the used carbon composite.



ρ_x [Ωm]	2W / RA	RBA	RCA
AV	0.00020 / 0.0001	0.000076	0.000079
ST. DEV.	0.00004 / -	0.000007	0.000004

(a)

ρ_z [Ωm]	2W	RE
AV	0.120	0.060
ST. DEV.	0.034	0.005

(b)

(c) (d)

Fig. 23 (a), (b)Configurations of electrical contacts for determination of in-plane and through-thickness resistivity, (c), (d) Configuration of experimental measurement during cyclic MMB test

The procedure of electrical resistivity measurement affects the accuracy of delamination growth prediction using the FE model, see Fig. 24. It is not recommended to use 2 terminal measurement method for electrical resistivity determination.

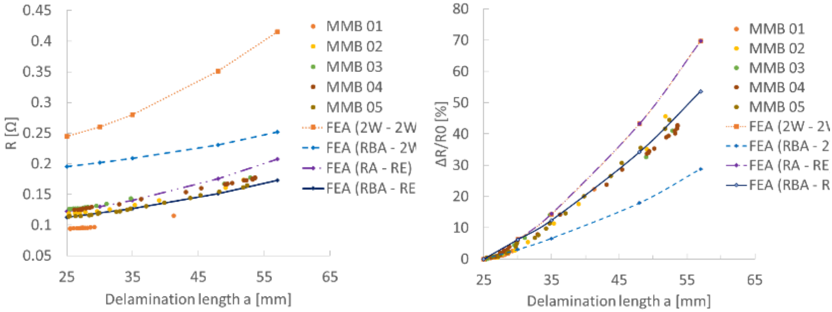


Fig. 24 Results of finite element analysis and measured experimental data.

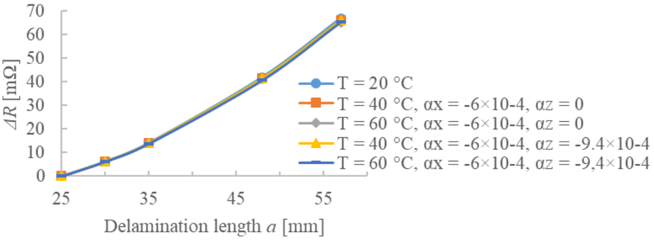


Fig. 25 Influence of the temperature coefficients of the resistivity on the electrical resistance change (FEM simulation).

Based on performed simulations, it can be stated that the influence of temperature change on measured change of electrical resistance is relatively small compared to the influence of the delamination growth, see Fig. 25.

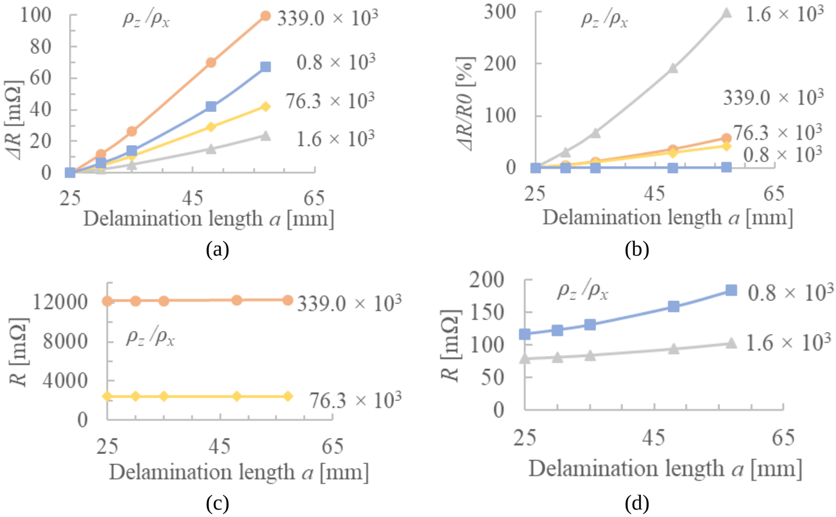
The conducted numerical experiment showed that the magnitude of electrical resistance change caused by the delamination growth depends not only on resistivity ratios (ρ_z/ρ_x), but also on the magnitude of resistivity in longitudinal and through thickness direction.

In scientific papers, the results of simulations are often given only as percentages of the relative resistance change ($\Delta R/R_0$). The results presented in Fig. 26 demonstrate the need to present results also in absolute values for a better understanding of the problem.

The numerical investigation of the influence of the electrical contact distance shows that the increase of measured electrical resistance may increase by 21 %

for the delamination length of 30 mm when we decrease the distance between the positive and negative voltage electrodes from 40 mm to 20 mm.

This is because the change in measured electrical resistance caused by the delamination growth is relatively small. The resolution of the resistance measurement device could be a limitation for the method. Based on the numerical simulation, it is possible to define the distance between the voltage electrodes in such a way that the appropriate resolution of the delamination growth can be detect.



(a) (b)

(c) (d)

Fig. 26 Influence of the nominal resistivity on the electrical resistance change.

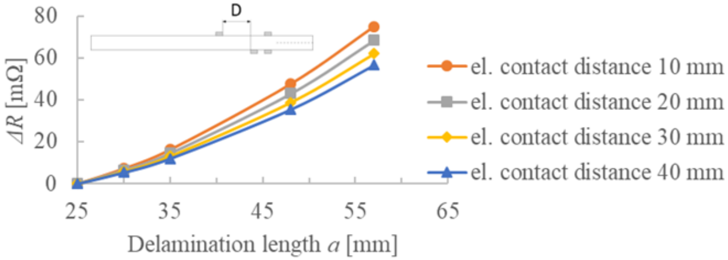
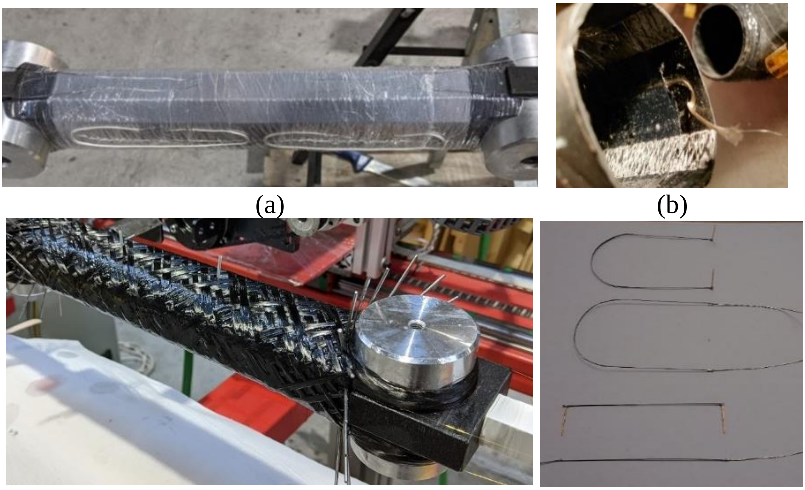


Fig. 27 Comparison of numerical simulation of delamination growth on the CF-epoxy specimen with different distance between positive and negative voltage electrodes.

6 Experimental verification on component level

Several types of damage detection scenarios were investigated as part of a research project regarding investigation of Integrated Loop Technology Joints. There were three areas investigated:

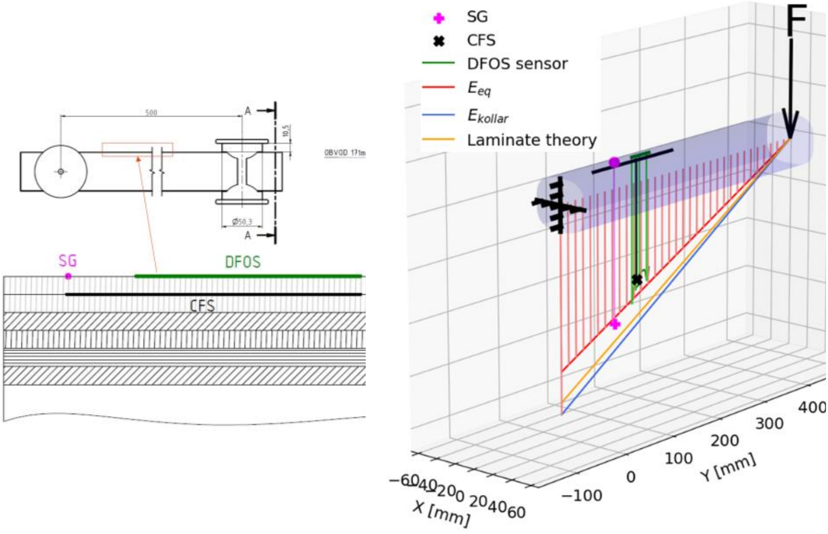
- Crack detection using a CF sensor (Results were published in [A13].)
- Strain monitoring using the CF sensor integrated within the filament wound layup (Results were published in [A15] and [A16].)
- Electrical resistance measurement on the filament wound profiles (Results were published in [A14].)


(a) (b)

(c) (d)

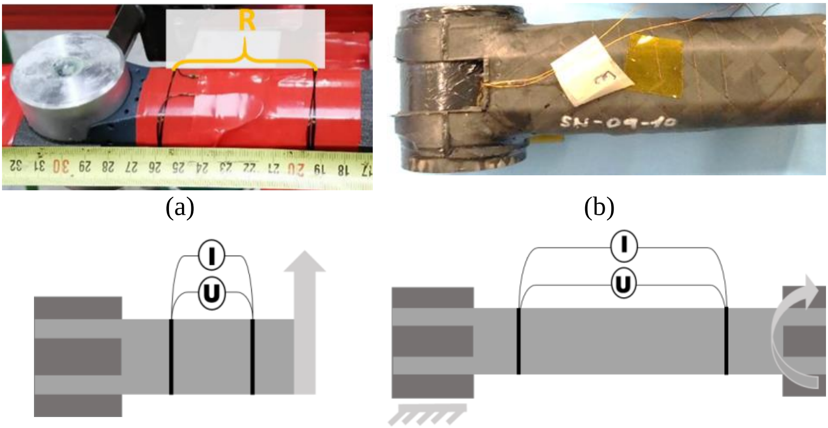
Fig. 28 CF sensors with braided sleeve during integrating (a), detail of connecting wire of CF sensors with braided sleeve after manufacturing (b), electrically isolated connecting pins of integrated CF sensor during manufacturing (c), CF sensors of different shapes before integration (d).

The technology for manufacturing CF sensors in a specific shape was developed, see Fig. 28. Two methods for the effective electrical insulation of CF sensors from the rest of the CF filament wound profile were developed (the epoxy adhesives used for bonding CF sensors to the surface of the carbon composite profile can serve as electric insulation, glass fiber layer is a sufficient electrical insulator between the CF sensor and CF filament wound layers). The values of strain determined by the integrated CF sensor during loading are comparable with the results obtained from an optical fiber using the DFOS method and a strain gauge, see details regarding the experiment in Fig. 29.



(a) (b)

Fig. 29 Configuration of the specimen with integrated CF sensor (a), Graph of measured mechanical strain compared to calculated values of strain [A16] (b)



(a) (b)

(c) (d)

Fig. 30 (a) Integration of the carbon fiber tow as electrical contact before filament winding procedure; (b) Specimen for flexural loading after manufacturing; (c) Configuration of electrical resistance measurement during flexural test; (d) Configuration of electrical resistance measurement during torsional test. [A14]

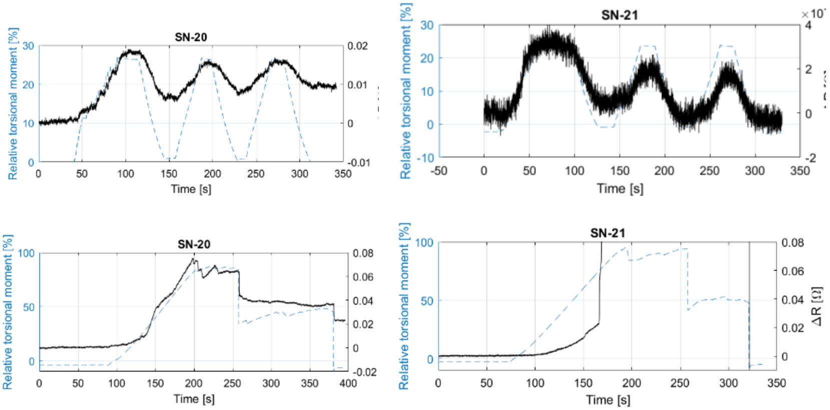


Fig. 31 Measured electrical resistance changes and relative resistance moment of cyclic and static torsional tests.

The ER measurement method was used for fracture monitoring of CFRP composite wound specimens with Integrated Loop Technology (ILT) joints. In Fig. 31 are presented results for specimens loaded by torsional moment. The novel approach to electrical contact preparation was tested. Further conclusions and suggestions can be drawn:

- Preparation of electrical contact on the inner surface of the profile manufactured using filament winding is feasible by the usage of carbon fiber tow with nickel coating at the ends, nevertheless improvement of the production technology is needed.
- It was shown that 2-terminal continuous electrical resistance measurement can reveal fracture during flexural and torsional loading, but for further experimental campaigns 4-terminal measurement is suggested.
- When comparing the investigated types of loading, the presented measurement configuration appears to be more suitable for monitoring operational loading during torsional loading than during flexural loading.

7 Conclusions and future work

The aims of the thesis were accomplished with the following comments:

7.1 Objective A: Impact detection using CF sensors

The possibility of impact damage detection was verified. It was found that CF sensors made of different carbon fiber tow show different sensitivity to impact damage. During two experimental campaigns, the response of CF sensors made of different material was investigated. The temperature coefficients for CF sensors made of T300 and 70A materials were determined through experiments on sensors integrated into GFRP composites. The PAN type of fiber tow used for integrated CF sensor showed stable behavior under short-term cycling, in contrast to sensors made of pitch carbon fiber tows. The carbon fiber tow which exhibits best properties was Toray T300 1000-50A carbon fiber tow. It was shown that there is no evidence of damage to the CF sensor made of this carbon fiber tow after 1000 cycles of mechanical loading. The behavior of CF sensor after BVID impact changed significantly. The measured ΔRREL is four to seven times larger than the sensor's response prior to impact loading.

The influence of stacking sequence on the sensitivity of the sensor to the impact damage was quantified. It was revealed, that under the tested configuration the position of the sensor close to the opposite side of the specimen to the impact is the most convenient for the impact damage. The inspection of the CF sensor using thermal camera was suggested and tested. It was found that damage of the sensor during manufacturing of the GFRP composite can be revealed. The thermal camera imaging can be also used for localization of the impact along the CF sensor. It was shown that the length of the sensor has negligibly influence on the possibility of impact detection. The relationship between electrical resistance change measured via CF sensor after impact and mechanical response of the structure to the impact was described. The relationship, which was found could be used for adjusting the loading of the structure after impact damage, so that the structure would not be overloaded.

The author's findings in this area are published in [A1], [A5], [A6], [A18].

7.2 Objective B: Delamination detection using electrical resistance change method on CFRP composite

The appropriate procedure for electrical resistivity measurement was determined. The results of several measurement configurations were compared, and results were used for FE analysis of delamination detection. It was shown that the results of FE analysis correspond to the experimental data when proper resistivity in the simulation is used. It was found that reporting of results of FE simulations in relative values of resistance is potentially misleading and can hide the error in electrical resistivity determination. It was found that electrical resistivity values of the CF composite with PPS matrices show comparable values of electrical resistivities as was determined for CFRP composite. The influence of the temperature change, electrical resistivities and contact configuration on the delamination detection was determined.

The author's findings in this area are published in [A2], [A3], [A4], [A7], [A10], [A11], [A12].

7.3 Objective C: Experimental verification on experimental level

The CF sensors were used for monitoring of a CF filament wound profile, within this research objective. First CF sensors were attached to the surface. It was confirmed that thin layer of adhesive used for installing of strain gauge is a sufficient electrical insulation. Then CF fibers were integrated during manufacturing of the component. It was found that Glass fiber layer is a sufficient electrical insulator between the CF sensor and CF filament wound layers. The strain measurement of such integrated CF sensor gives comparable results with integrated optical fiber for distributed fiber optic sensing.

A novel approach for electrical contact manufacturing on the inner side of carbon fiber filament wound profile was suggested and tested. Although several technological modifications need to be done. The proposed method enables to monitor electrical resistance change of the profile during loading. According to gathered data, it is possible to distinguish fatal fracture of the profile when compared to operational loading.

The author's findings in this area are published in [A8], [A9], [A13] to [A24].

8 References

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9 Publications related to the topic

9.1 Reviewed papers

[A1] N. Schmidová, et al. "Impact Damage Detection of a Glass Fabric Composite Using Carbon Fiber Sensors with Regard to Mechanical Loading", *Applied Sciences*, 2022, 2022(12), ISSN 2076-3417. DOI 10.3390/app12031112

9.2 Conference contributions

[A2] N. Schmidová, M. Dvořák, and M. Růžička, "Structural Health Monitoring of CFRP Using Electrical Resistance Measurement", In: *21st Workshop of Applied Mechanics - Proceedings*, Praha, 2016-12-21. Praha: České vysoké učení technické v Praze, Fakulta strojní, 2016. p. 37-40. ISBN 978-80-01-06085-8.

[A3] N. Schmidová, and R. Fajtl, "Modeling of Electrical Resistance Measuring Method for Sensing Damage and Deformation in CFRP Composites", In: *Sborník konference TECHSOFT ENGINEERING ANSYS 2017 Setkání uživatelů a konference*. TECHSOFT

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[A4] N. Schmidová, M. Dvořák, and M. Růžička, "Sensing Damage in CFRP Composite Beam by Electrical Resistance Measurement", In: *Experimental Stress Analysis 2017. 55th International Scientific Conference Experimental Stress Analysis 2017*, Nový Smokovec, 2017-05-30/2017-06-01. Košice: Technical University of Kosice, 2017. p. 13-14. ISBN 978-80-553-3167-6.

[A5] N. Schmidová. and M. Růžička, "Carbon Fibers for Sensing and Damage Detection of Composite Materials", In: *Proceedings. 25th Workshop of Applied Mechanics,* Praha, 2018-12-07. Praha: České vysoké učení technické v Praze, Fakulta strojní, 2018. p. 46-49. ISBN 978-80-01-06536-5.

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