IN-SITU LOAD-MONITORING OF CFRP COMPONENTS USING INTEGRATED CARBON ROVINGS AS STRAIN SENSORS

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Keywords: fibre-based strain sensor, in-situ load monitoring, CFRP, integrated sensors, strain sensing

Abstract

For the purpose of structural health (SHM) and even load monitoring, the conceptual design and approaches for structural integration techniques of suitable fibre-based sensor components for composite components are still a challenge for both engineering and materials science. In this contribution, the characteristic of yarns that have intrinsically conductivity, e.g. carbon fibre (CF), and their suitability to act as in-situ strain sensors are described. The objective of the based research project is the real-time in-situ sensing of global stresses and the detection of resulted local microscopic damages due micro-cracks and delamination in the load bearing layers of carbon fibre reinforced plastic (CFRP) components. Sensor material similar to the particular CFRP and its mechanical behaviour has been chosen, in this case a CF roving with total titer of 67 tex. The measurement principle bases on usage of the piezo-resistive effect for the usage as in-situ strain sensors, means that every mechanical straining of the roving's filaments causes a correlative change of the measureable resistance. In the next step, suitable fibre-based dielectric jackets have been preferably applied by brasiding technology, granting sufficient isolation to avoid short-circuits between the conductive sensor itself or between the sensor and intrinsically conductive CFRP respectively. Performing load test of CFRP specimens with suchlike functionalised integrated sensor yarns, the sensor's performance to detect global strain, means the accumulated strain along the integration length of the sensor yarn, has been evaluated.

1. Introduction

Carbon fibre reinforced plastics (CFRP) have sparked the interest of mass markets, e.g. in the automobile, aerospace or in the sports sector. Due to its adjustable material behaviour and its outstanding processing properties – e.g. high tenacity, high stiffness, low creep behaviour and high corrosion resistance at a five times smaller density than those of steel – in comparison to conventional construction metals, CFRP are attracting growing interest and therefore demands from both the scientific community and the industry. With the increased application of CFRP in diverse application fields, the monitoring of structural damages and serious material degradations that occur due to service loading during is getting more importance.

However, for the purpose of structural health monitoring (SHM) and even load monitoring, the conceptual design and approaches for the structural integration of suitable fibre-based in-situ sensors in CFRP is still a challenge. Although, the embedding of conventional sensor devices, like strain gages or acoustic emission transducers, into/onto CFRP is possible, they are usually expensive and normally

not suitable for a direct integration into CFRP components due to their low resistance against physical or chemical process stresses (e.g. pressure, corrosion, cross linking temperature) during composite manufacturing. For the purpose of both, the operational load monitoring and the SHM of CFRP components, the literatures reports two approaches using the principle of electrical resistance measurements. The first approach includes the use of CNTs distributed throughout the bulk matrix for sensing mechanical strains [1-6]. The second approach involves the insertion of either inherently conductive fibres, e.g. CF [7-9] or GF coated with CNTs [10].
In earlier researches, the fundamental suitability of integrally measuring CF-based strain sensors has been successfully demonstrated in glass fibre reinforced plastics (GFRP), but reproducible linear transfer behaviour is observed to be limited to maximum of 1.0 % strain [8]. Furthermore, fine correlations between the transfer behaviour depending on the level of structural integration regarding the force and form closure with the textile reinforcement semi-finished products has been reported [9].
Since CFRP is intrinsically conductive, the first approach using percolated networks of conductive particles or even fibres is not suitable, because of the parallel connection of sensor and CFRP. Furthermore the measureable strain of CNT-based strain sensors is obviously limited to 0.5% tensile strain due to the percolation threshold [10].
Therefore, the necessity for a fibre-based sensor able to detect strain depending on the global load case of the measuring object and simultaneously able to monitor stress-induced micro cracks until complete integrity loss of the monitored CFRP component is very high.

2. Material and methods

2.1. Manufacturing of isolated carbon fibre-based sensors

The measurement method focuses on the usage of intrinsically conductive CF rovings Tenax HTA40 H15 (Toho Tenax Europe) with a yarn count of 67 tex and 1,000 filaments. The costs are quantified to 0.02 €/m. Each mechanical straining of these filaments due to applied mechanical and or thermal induced stresses on the sensor carrying CFRP causes a strain-correlative change in resistance. For the forming of filament-based jackets, different textile-technological application methods has been investigated, in particular friction spinning technology (Fig. 1) using a DREF 2000 spinning system (Dr. Ernst Fehrer AG) and a circular braiding technology (Fig. 2) by use of a RU2/12-80 braider (Herzog GmbH).

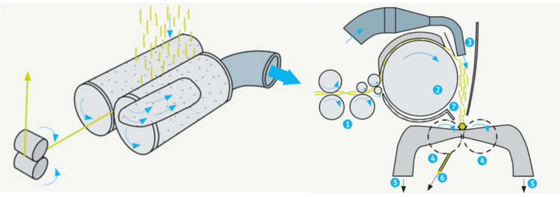


Figure 1. Friction spinning technology using a DREF 2000 spinning system (Dr. Ernst Fehrer AG; © 2018, Rieter Holding AG)

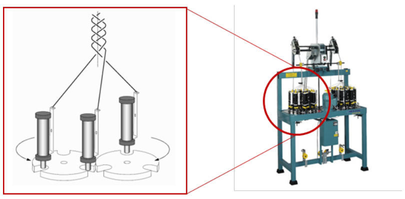


Figure 2. Braiding technology using Herzog RU2/12-80 circular braider

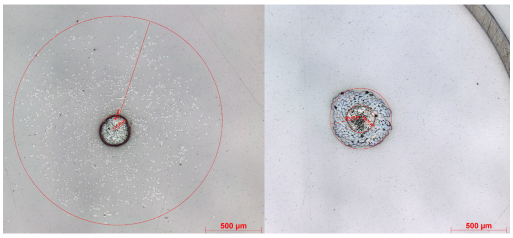


Figure 3. Photomicrographs of friction spun (left) and braided (right) isolation jackets of CF-based strain sensors for integration in CFRP components

Different types of staple fibres or filament yarns have been housed around the CF sensor (CFS) core respectively to form isolating jackets (cf. Table 1). This suchlike isolated CF-based sensor yarns (cf. Fig. 3) reach a leakage resistance of at least 2.0x10^3 Ω up to 10x10^9 Ω depending on the realised jacket diameter and the applied type of fibre. Braiding is identified as preferred solution due to the flexibility and consistency of the braided jacket against subsequent manufacturing steps. The jacket with a total titer of approx. 200 tex and 150µm thickness is formed rope-like by 12 PES filament yarns with a braid density (pitch) of 37 cm^{-1}. Anyway, account should be taken, although the production speeds of DREF 2000 with 3,000…15,000 m/h are outstanding compared with those of conventional braiders and speeds up to 10 /h, braiding is much more gentle to the sensing core fibres of the CFS, means less filament breakage and less induced twists and therefore a homogenous aligned orientation of the CF roving filaments in the subsequent major load directions and thus a more linear transfer behaviour of the sensor.

Table 1. Fibre-based jackets and resulting isolating capacities

type N°	jacket fibre type	application method	fibre length (mm)	jacket yarn count (tex)	jacket diameter (µm)	leakage resistance (Ω) 20°C 60% r.H.
1	PES			12x16.7	150	> 2.0x10^9
2	EC6-34-Z40 E35			8x34	190	< 3.0x10^3
3	EC9-136-S20 B3/4J	circular braiding	filament (∞)	6x136	470	> 10x10^9
4	TWARON® T2040			6x42	370	> 35x10^6
5	PA6.6			8x32	290	> 1.0x10^9
6	Kynol® KF-0251HC	friction spinning	51	300	800	1.8x10^3… 20x10^6

For better processability and to avoid short circuits due to stick out filaments of the CF roving core, a 5.0 wt.-% starch size F9086 EMGLASS K150 (Emsland Food GmbH) is applied by padding and subsequent drying at 160 °C for 150 sec on BaseCoater BC32 (COATEMA Coating Machinery GmbH) before. The reachable leakage resistance is higher than 2.0x10^9 Ω at 1,051 V_{DC} test voltage applied with a FLUKE 1507 insulation tester (Fluke Deutschland GmbH). For this purpose, a 300 mm long piece of insulated sensor yarn is clamped between two copper plates same length acting as outer electrode. The test voltage is then applied between this outer and the conductive core acting as inner electrode and the leakage resistance is then calculated by the test device.

2.2. Technological integration of CF-based sensors into semi-finished reinforcement fabrics for CFRP applications

The integration of the above described CFS into CF-based reinforcement structures during its manufacturing process, can be carried out using different textile technological fabric formation processes, e.g. open reed weave ORW or multiaxial warp knitting technology. For the research presented in this contribution, CFS with the above mentioned types of isolation jackets (cf. Table 1) are integrated simultaneously into single-layer woven CF-based fabrics using a rapier weaving machine PTS4/S (Lindauer Dornier GmbH). The one-dimensional alignment of the CFS is in warp direction (Fig. 4). The weft and warp density of the woven fabric is 2.5cm^{-1} and it is designed in twill weave. SIGRAFIL® CF rovings of type CT24-4.8/280-E100 (SGL Carbon SE) with 24 k filaments and a yarn count of 1,600 tex are applied in both weave orientations, in warp and weft. The length of the weave pattern is adapted operationally to the standardised sizes of generic CFRP specimen (cf. subsection 2.4).

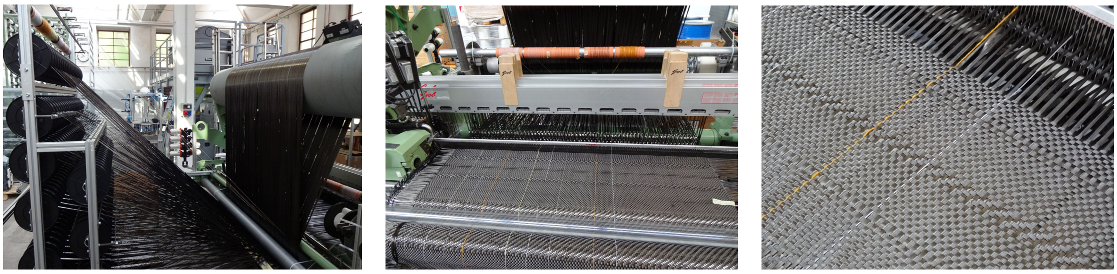


Figure 4. Rapier weaving machine PTS4/S with CF roving twill weave fabric (left, centre) and CF-based sensors with diverse isolating jackets integrated in warp direction (right)

2.3. Electrical contacting of the CF-based sensors

After the textile-technological manufacturing process but before the CFRP consolidation to composite, the CF-based sensor ends have to be electrical contacted manually (Fig. 5) by clamping each of the sensor yarn ends between approx. 2.5 mm² small and 35µm thin copper sheets with attached piece of a 400 µm flex for the interconnection with conventional measurement equipment, e.g. ohmmeter or amplifier. The force closure of the CFS ends results due to the solidification of the solder which is inserted between the copper plates. For isolation, the suchlike prepared electrical contacting zones are in a final step encircled by conventional heat shrink tubes. For reasons of ensuring integrity of the subsequent CFRP component, the electrical contacting has to be placed in the near of the component's geometrical boundary areas or lateral edges respectively as well as in oversizing regions with higher wall thickness. With regard to subsequent application scenarios, this positioning allows a comfortable accessibility or even the embedding of established (serial) interfaces, e.g. printed-board connectors, in the CFRP body.

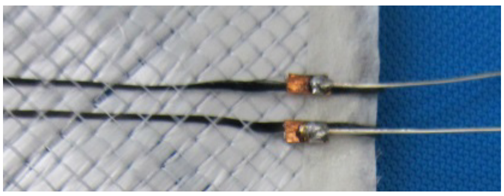


Figure 5. Exemplary electrical contacting of CFS onto textile reinforcement structure for further FRP applications before encircling isolation by heat shrink tubes

2.4. Manufacture of CFRP composite material and generic specimens for testing

After weaving and electrical contacting, three layers of semifinished fabrics are tailored according to the standards and stacked in [90°,0°,90°,0°$_{CFS}$,90°,0°] for fabrication of CFRP specimen using vacuum-assisted-processing (VARI). According to the standards, the specimen has been detached from the obtained 2.00 mm thick CFRP plates by water cutting. Using a conventional universal testing machine Zwick Z100, destructive tests based on three major loading situations are performed and investigated: tensile straining (DIN EN ISO 527-4) and compression loading (DIN EN ISO 14126). The resistance measurement is simultaneously done to the load tests using a FLUKE 8846A precision multimeter (Fluke Deutschland GmbH) operating in two-electrodes-four-wire-measurement mode according to standard DIN EN 16812. For DAQ purposes, an executable runtime-script has been realised in the LabView® development environment (National Instruments Deutschland). Apart from the specimen for 4P-bending tests [0°$_{CFS}$,90°,0°,90°,0°,90°], the CFS is positioned within the neutral reinforcement layer [90°,0°,90°,0°$_{CFS}$,90°,0°] for both, tensile and compression tests.

3. Results and Discussion

First test series of CFS with friction-spun jacket show sporadically inhomogeneous consistency of the fibre jacket. Due to filaments stuck out of the jacket, short circuits between CFS and the electro conductive CFRP structure occur in statistically undefined intervals along the CFS integration length. For a qualitative evalutation of the integration quality of the CFS in the surrounding CFRP, x-ray radiography shots has been made in cooperation with nanoeva (Center for NDT nano Evalution at TU Dresden) using a GeneralElectric phoenix NANOTOM®M high resolution computed tomography system. In Fig. 6 it is obviously, that the structural embedding of CFS can be crucial with regard to the inclusion of air pockets (mould cavities) or shrinking. In this regions, the applied mechanical load of the CFRP component cannot be transferred on the strain sensitive CFS. Inhomogenous strain fields along the longitudinal axis and thereby a decrease of the CFS's sensitivity can be caused.

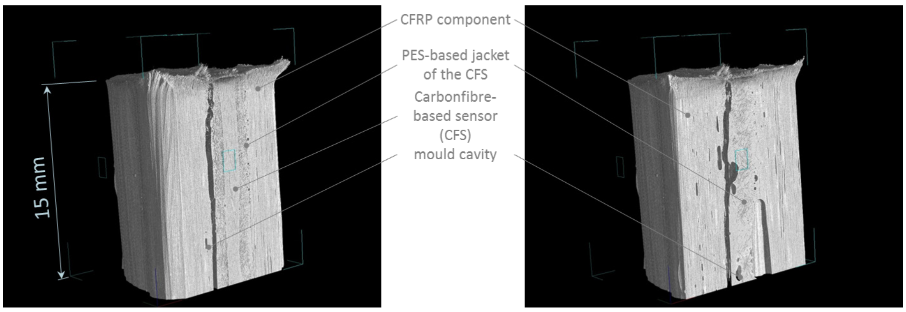


Figure 6. Detail of x-ray radiography shot (60 kV, 120 µA, 5.0 µm voxel size) of a CF-based sensor with preferred isolation solution with braided PES-filament jacket embedded in generic CFRP

These imperfections can have direct influence on the transfer behaviour and even more drastic, on the stability of the CFRP component itself. Such air pockets can act as induced break point for fibre fracture or delamination. It can be assumed, that smaller the resulting diameter of isolated CFS that lower the risk of suchlike inclusions.

First tests with CFS with friction spun jacket consisting of staple fibres show that the thickness of the fibre jacket is insufficient. It is has been showed, that short circuits between single filaments of the CFS and the electro conductive CFRP structure occur in statistically undefined intervals along the CFS integration length due to the rough spinning process itself. Dependant on the number of CF filaments that are directly in contact with the CF fabric, the leakage resistance can vary in a range of 10^{-3} to

10^4 Ω. Therefore, it becomes apparent, that CFS with braided jacket and in particular with starch size provides better protection against short circuits due to stick out CF filaments.
With regard to the measured stress-depending change in resistance of the CFS integrated in CFRP during tensile load test until full rupture, good and approximatively linear transfer behaviour up to 0.6 % stress with the characteristic linear transfer function can be observed. In Eq. 1, *ΔR/R* represents the measured relative change in resistance of the CFS during the application of mechanical strain *ε*. The transfer linear transfer factor *k* aka k-factor like conventional strain gages, represents the gain of the measured mechanical stress mapped on measured change in resistance.

$$f(\varepsilon) = \Delta R/R\ (\varepsilon) = k\cdot\varepsilon \ldots \textit{linear transfer function} \quad (1)$$

$$f(\varepsilon) = \Delta R/R\ (\varepsilon) = a + k\cdot\varepsilon^b \ldots \textit{non-linear transfer function} \quad (2)$$

In Table 2 the *k*-factors (linear gain factors) of CFS integrated in CFRP specimen by tensile straining (cf. Fig. 5a) until full rupture of the composite are summarised. R^2 represents the coefficient of determination and *StE* the standard error of performing a linear approximation. R_M is the calculated tenacity and E_t the tensile modulus.

Table 2. *k*-factor and mechanical behaviour of diverse jacketed CFS into CFRP performing tensile loading according DIN EN ISO 527-4

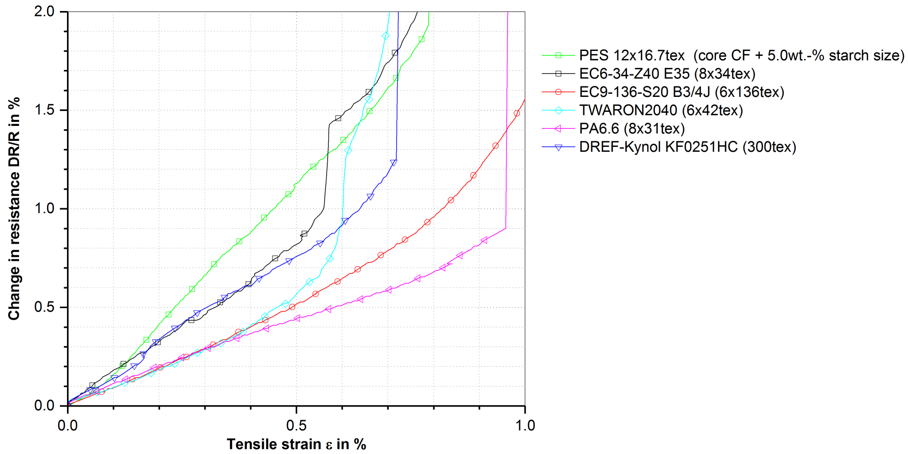
type N°	fibre/filament jacket	$f(\varepsilon)=\Delta R/R(\varepsilon)=k*\varepsilon$ k (ε < 0.6%)	R^2	R_M (MPa)	E_t (GPa)
1	PES 12x16.7tex (core CF + 5.0wt.-% starch size)	1.893	0.973	346	26.2
2	EC6-34-Z40 E35 (8x34tex)	1.759	0.974	333	27.3
3	EC9-136-S20 B3/4J (6x136tex)	1.049	0.998	304	25.9
4	TWARON2040 (6x42tex)	1.108	0.975	264	25.8
5	PA6.6 (8x31tex)	0.867	0.986	294	23.5
6	DREF-Kynol KF0251HC (300tex)	1.487	0.978	259	29.3

In Table 3 the coefficients of a non-linear transfer function of CFS integrated in CFRP specimen by compression loading are summarised. The approximated transfer function has linear gain factor (*k*-factor), an offset *a* and an exponential share *b*. Comparing the specific values of the transfer functions for the two different loading scenarios, isolation type depending differences become obviously. In case of tensile loading, CFS type N° 1 with braided jacket consisting of 12 PES-filaments shows highest gain (k = 1.893) and predominant linear transfer behaviour up to 0.6% strain. This specific value is competitive with this of conventional and usually superficial applicable foil strain gauges, which have normally *k* factors in a range of 1.9 to 2.1.
In case of compression loading, all sensors show predominate non-linear behaviour with a negative change in resistance. The CFS types N° 3 and N° 6 show the highest sensitivities, with linear shares of k_3 = 12.44 or k_6 = 9.53 respectively and appropriate exponential shares of b_3 = 2.19 or b_6 = 2.51 respectively.
In Fig. 5 the observed signal sequences of the investigated CFS types are depicted exemplary. For the two investigated loading cases, mostly stress-correlating signal sequences can be measured. The higher the slope of the sensor signal pattern, the higher the sensitivity of the particular CFS. The raw signals of the CFS during compression loading are originally negative. In Fig. 5 (b) the absolute signal

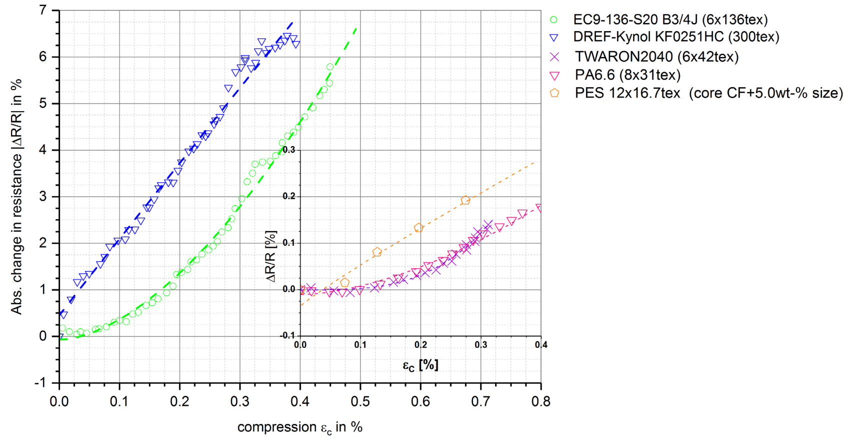
sequence is depicted. It becomes obviously that the CFS type N° 6 which is produced by friction spinning shows the highest sensitivity due to an undefined process-related pre-damage of the CF filaments.

Table 3. Coefficients of transfer function and mechanical behaviour of diverse jacketed CFS into CFRP performing compression loading (cf. Fig. 5b) according DIN EN ISO 14126

type N°	fibre/filament jacket	$f(\varepsilon)=\Delta R/R(\varepsilon)=a+k*\varepsilon^b$ a	k	b	R^2	E_C (GPa)	σ_{max} (MPa)	ε_{max} (%)	σ_B (MPa)	ε_B (%)
1	PES 12x16.7tex (core CF+5wt.% starch size)	-0.03	0.74	0.92	0.986	50.7	193.9	0.57	192.1	0.56
2	EC6-34-Z40 E35 (8x34tex)	--	--	--	--	28.4	181.8	0.71	179.4	0.69
3	EC9-136-S20 B3/4J (6x136tex)	-0.04	12.44	2.19	0.991	31.8	180.7	0.69	172.0	0.69
4	TWARON2040 (6x42tex)	-0.001	6.36	3.27	0.984	49.0	175.6	0.29	171.8	0.23
5	PA6.6 (8x31tex)	-0.02	2.74	2.51	0.955	40.5	170.6	0.37	169.7	0.36
6	DREF-Kynol KF0251HC (300tex)	-0.18	9.53	0.61	0.919	57.9	182.7	0.33	181.8	0.31



(a)



(b)

Figure 5: Transfer behaviour of carbon fibre sensors (CFS) under tensile (a) and compression loading (b) of the sensor carrying CFRP structure

3. Conclusions

First studies on carbon fibre based sensors (CFS) with dielectric fibre jackets for their usage as in situ strain sensors in intrinsic electro-conductive carbon fibre reinforced plastics (CFRP) have shown that a predominantly stress-correlative monitoring by online-measurement of the CFS' change in resistance is possible for both, tensile and compression loading of CFRP components. Anyway, short-circuits have been detected due to filaments stuck out of the jacket and it can be assumed, that the observed nonlinear transfer behaviour of suchlike CFS is caused consequently. Further research efforts will be spent to reach homogenous and fully sealed jacket and to verify the long-term stability as well as reliability for suchlike *in-situ* sensors.

Acknowledgments

The authors gratefully acknowledge the receipt of funds for the research and publication of this article. The DFG project DFG CH174/40-1 is funded by the German Research Foundation.
The IGF research project 18901BR/1 of the research association "Forschungskuratorium Textil (FKT) e. V." is funded through the AiF within the program for supporting the industrial collective research („Industrielle Gemeinschaftsforschung", IGF) from funds of the Federal Ministry of Economics and Energy (BMWi) by a resolution of the German Bundestag.

DFG

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

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