In-situ structural monitoring of fibre-reinforced plastic composites under compressive loading

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At the ITM, the simulation-based design and realisation of pressure sensitive textile-based sensors and their textile-technical integration into functionalised textile reinforcements for the use in fibre-reinforced plastic (FRP) composites was carried out in the IGF project 21169 BR (Comp-i-TenS).

Introduction

Fibre-reinforced composite structures are currently used in the fields of mechanical engineering, aircraft construction and automotive engineering, among others, due to their excellent mechanical properties combined with a high lightweight construction potential [1]. In the construction sector, high-performance textiles are increasingly being used as a substitute for steel reinforcement in textile reinforced concrete [2], due to their mechanical and chemical properties and the resulting resource-saving, filigree, lightweight construction potential. The long-term stable functionality and safety of fibre-reinforced composite structures is urgently required due to their frequent use in safety-critical components and structures. A promising practice-oriented approach is the continuous structural monitoring in order to quantify the (residual) load-bearing capacity and to initiate any necessary measures to ensure functional capability. A particularly economical and structurally compatible solution are textile-based sensors that are integrated during the manufacture of the textile reinforcement and used to detect complex load scenarios as well as cracking and delamination processes at the composite scale. [3 – 6]

Due to their operating principle, textile-based strain sensors are mainly used for monitoring composite structures subjected to tensile stress. In order to be able to derive reliable statements about structural changes and critical overload conditions even in complex overlapping stress scenarios (e.g. tensile and compressive stresses), textile-based pressure sensitive sensor systems for continuous in-situ structural monitoring for FRP were developed in IGF project 21169 BR.

Objective and solution

The aim of the IGF research project was the development, characterisation and testing of textile-based pressure sensitive sensor systems and their textile-technical integration in multi-axial warp knitting for the production of sensor-functionalised textile reinforcements for use in FRP. The requirements for the textile sensors were derived simulation-based by analysing a functional demonstrator. The textile sensors were specifically designed to detect structural deformations induced by tensile, bending and especially compressive stresses. Therefore, the approach of increasing the pressure sensitivity of textile sensors by pre-tension was investigated. The sensor behaviour was extensively analysed in electromechanical investigations at fibre and composite scale and tested on the functional demonstrator.

Results

Simulation-based design

A generalised FEM model was developed and adapted in order to define the sensor positioning and to be able to estimate the required pre-tension (or pre-strain) for pressure measurement capability. A square profile made of carbon fibre reinforced plastic (CFRP) was chosen as the functional demonstrator and simulated in a three-point bending scenario. In Figure 1, it can be seen that due to the bending stress, the expected compressive stress occurs on the upper side and tensile stress on the lower side. In contrast, the stresses are lowest in the neutral fibre. Consequently, the sensor yarns are positioned on the tension and compression side to detect the corresponding resulting strains or compressions.

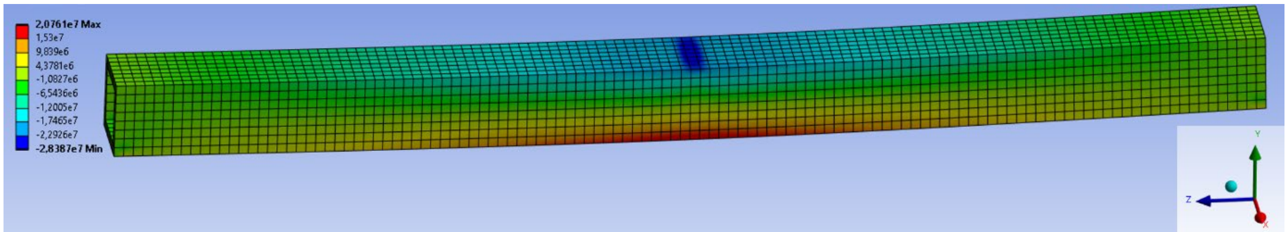
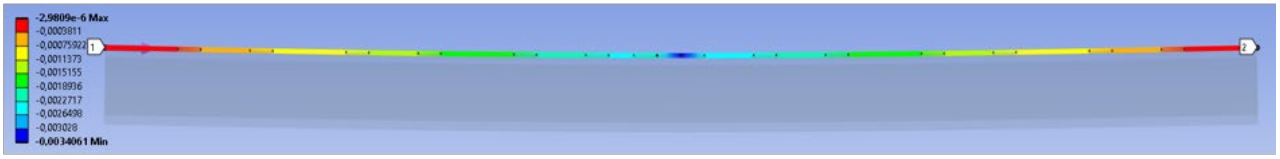


Figure 1: Analysis of the local normal stresses (Z-axis) of the CFRP square profile under bending load

Compression of the textile sensor on the pressure side



Strain of the textile sensor on the tensile side

Figure 2: Simulated compression/strain behavior of the textile sensors on the pressure and tensile side of the CFRP square profile

For the simulative estimation of the required pre-tension of the sensor yarn to realise the desired pressure measurement capability, the sensor was discretised with beam elements and coupled to the 0° fibre layer of the component. The developed simulation model enabled a layer-specific evaluation of the loads and the determination of local strain or stress peaks.

With a bending load of 1000 N and a wall thickness of 5 mm, a maximum bending deformation of 4.15 mm was determined. The resulting sensor compression or strain is < 0.4 % (Figure 2). From the simulation results, it could be derived that a pre-tension of the sensors with 0.5 % strain is sufficient to resolve the occurring compressive loads. At the same time, the simulation showed that a localised measurement of the compressive stress is beneficial in order to avoid a reduction in sensitivity due to large low-stress areas.

Electromechanical characterisation on yarn scale

Fundamentally, four different sensor materials (carbon fibre-based, metallic, and silver-coated polyamide, see Figure 3) were systematically characterized electromechanically at yarn and composite scale in various test scenarios and compared with each other. For this purpose, the sensor materials were tested in uniaxial tensile tests with simultaneous electrical four-wire resistance measurement in order to investigate the sensor behavior. The sensor characteristic is approximated by a linear or polynomial fit, respectively (Figure 4).

Figure 3: Materials for the sensor yarns and microscopic view; modified carbon fibre yarn (Sigrafil) (a); carbon fibre roving (CF1K) (b); Isaohm metallic wire (Isaohm) (c); Silver tech 120 (ST120) (d).

The following conclusions can be derived from the electromechanical characterisations of the sensor materials at yarn scale:

- The sensor behaviour of Sigrafil at yarn scale correlates insufficiently with increasing strain.
- CF1K shows a very good linear sensor behaviour up to 0.8 % strain with a gauge factor (GF) of 1.10, at higher strains the exponential resistance changes can be used for crack detection.
- Isaohm (GF = 1.85) and ST120 can cover a high measuring range due to their high strain capacity, but crack detection is limited with these materials, especially for use in CFRP. The sensor behaviour of ST120 can be approximated with the shown polynomial function.

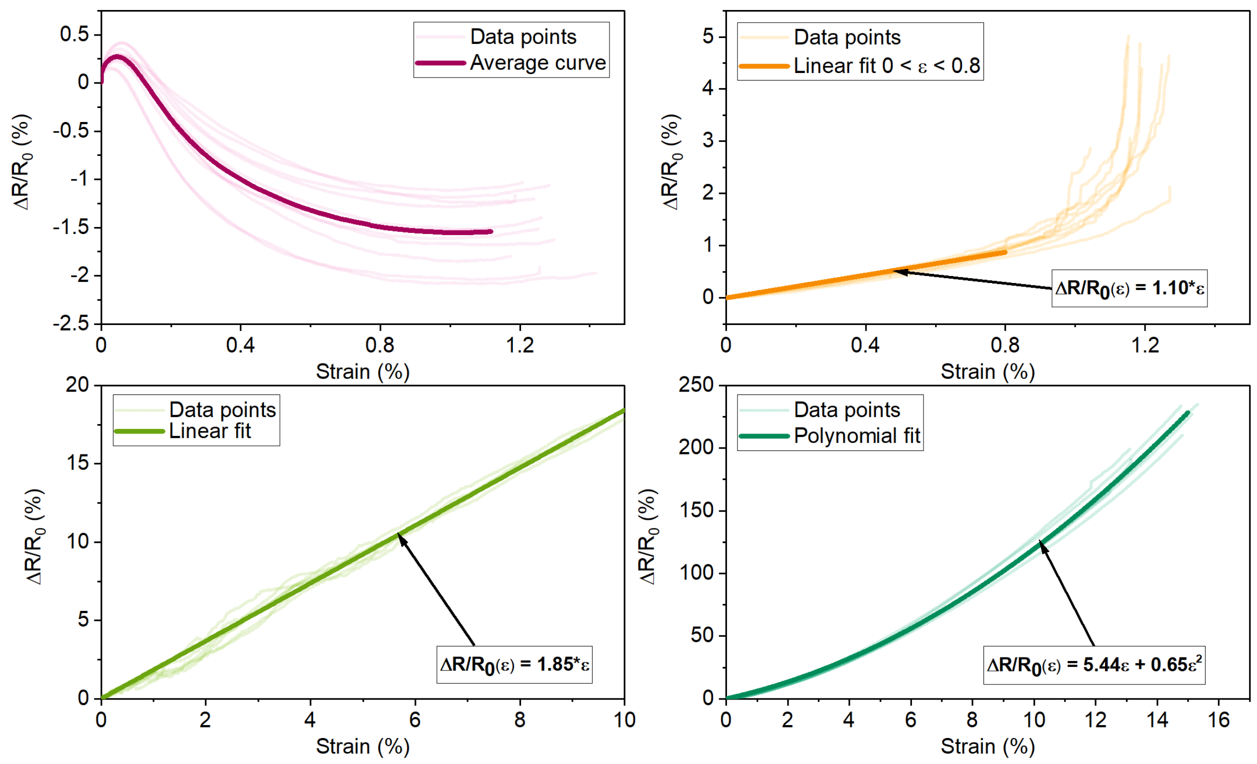


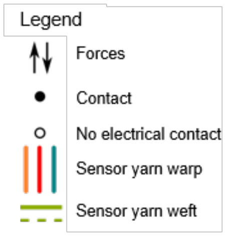
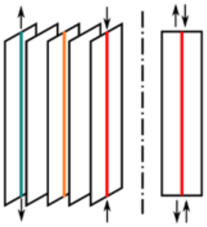
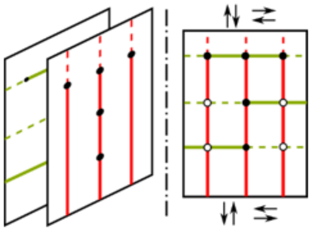
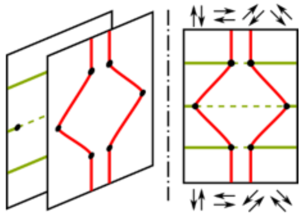
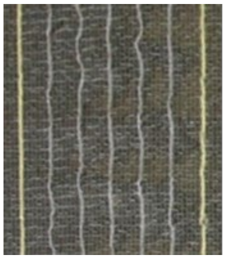
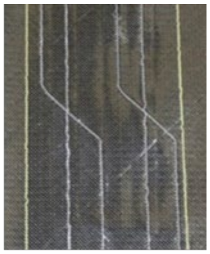
Figure 4: Relative change in electrical resistance ($\Delta R/R_0$) as a function of strain for the four sensor materials at quasi-static tensile testing speed (0.1 mm/s)

Pre-tension of the textile sensors and textile manufacturing

In total, three solution approaches (SA) for applying and maintaining the pre-tension of the sensors in three functional patterns (FM) were extensively investigated in terms of feasibility and functionality (cf. Table 1). The pre-tensioning of the sensor yarns was realised for SA I (pre-tensioning at yarn scale) and III (pre-tensioning during consolidation) by applying mass pieces. This shows that the pre-tensioning by partial consolidation (SA I) allows a permanent pre-tension of the sensor yarns. However, the increased stiffness of the rod-like sensor yarns complicates further processing and textile-technical integration during the fabrication of the warp-knitted fabrics. Furthermore, SA I can only be realised for planar FRP geometries, as no forming or draping processes are possible due to the structural stiffness of the sensors.

Applying the pre-tension to the sensors during textile production is the most effective method to manufacture functionalized textiles with pre-tensioned sensor yarns. However, maintaining the pre-tension by force-fit fixation during textile production (SA II) is particularly challenging, as "spring-back" of the sensors was observed after removal of the warp-knitted fabric. It was not possible to achieve sufficient fixation of the pre-tensioned sensor yarns by the thread yarn. SA III offers the great advantage of a subsequent application of the pre-tension during the composite production, so that a stretched as well as pre-tensioned sensor position is guaranteed. Furthermore, individual sensor yarns can be individually pre-tensioned. For this reason, the SA III approach was chosen as the preferred solution and implemented in the ongoing experiments.

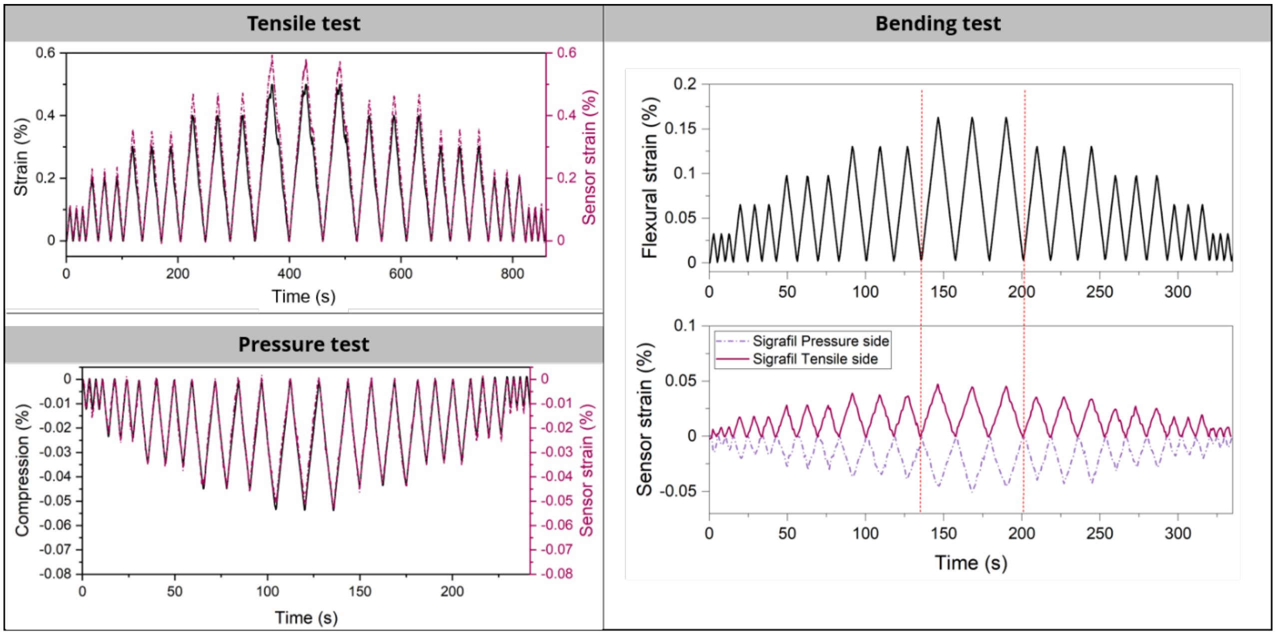
Table 1: Approaches to maintain the pre-tension of sensor yarns and functional samples (FM) with integrated sensors using multiaxial warp knitting

SA pre-tensioned sensors	**SA I (yarn scale)**	**SA II (textile scale)**	**SA III (composite scale)**
Description	Fixation in the pre-tensioned state at yarn level by means of partial consolidation	Binding variation for specific pretensioning during textile-technical integration	Adjusted pretensioning during the consolidation process
Functional sample	**FM1**	**FM2**	**FM3**
Description	Sensor in warp or weft direction (material)	Sensor network of sensor warp and sensor weft yarns (contacting)	Sensor network of load-path-appropriate sensor warp and sensor weft yarns (warp yarn offset)
			
Exemplary representation			

For the systematic characterisation of the functionalised warp-knitted fabrics, the functional samples 1-3 were successfully produced on a technologically modified multiaxial warp-knitting machine (cf. Table 1). In the case of FM 2 and 3, sensor networks were realised by selective electrical contacting the sensors with each other or to lead wires. It should be noted that the contact points require a comparatively high manual effort (stripping, crimping, insulating) and represent potential sources of error. For the basic electromechanical characterisations and functional testing of the pressure measurement capability at the composite scale, FM 1 was predominantly used.

Electromechanical characterisation on composite scale

The functionalised multiaxial warp-knitted fabrics were further processed in the "vacuum assisted resin infusion" (VARI) process to specimens for tensile, compression and flexure tests according to the standards DIN EN ISO 527-4, 14126 or 14125. Quasi-static and cyclic test series were carried out with simultaneous resistance measurement. The respective sensor behaviour of the four sensor materials investigated generally showed excellent correlation with the tensile, compressive and bending stresses induced in the CFRP specimen. Figure 5 shows exemplary results of the cyclic electromechanical investigation for the sensor material Sigrafil.



Tensile test

Pressure test

Bending test

Figure 5: Exemplary results of the acquired sensor strain of the pre-tensioned Sigrafil sensors in FRP under cyclic tensile, compressive and bending stresses

The sensor strains correspond qualitatively and quantitatively with the induced strain (tensile test) and compression (compression test). The induced strain causes a positive change in electrical resistance and thus sensor strain, whereas the compression generates a negative sensor signal. Also in the bending test, (two integrated sensors, each on the tensile and pressure side), depending on the sensor position, a positive sensor signal is observed on the tensile side and a negative one on the pressure side. The Sigrafil sensor material was identified as the preferred solution for monitoring the structure, cracks and delamination of CFRP based on the following parameters and findings:

- Same type of sensor, thus similar or higher strain range and material behaviour
- Sensor sensitive to tensile, compressive and bending stresses
- Very good textile processability and manageability
- Suitable for the detection of cracks and delamination processes

Functional demonstrator

The selected functional demonstrator was used to exemplify the technological feasibility and realisation, from the production of the sensor yarns and functionalised multiaxial fabrics to the production of a CFRP profile with pressure-measurable, textile-based sensors. To illustrate the sensor measurement capability, the interactive test stand shown in Figure 6 a was designed and realised.

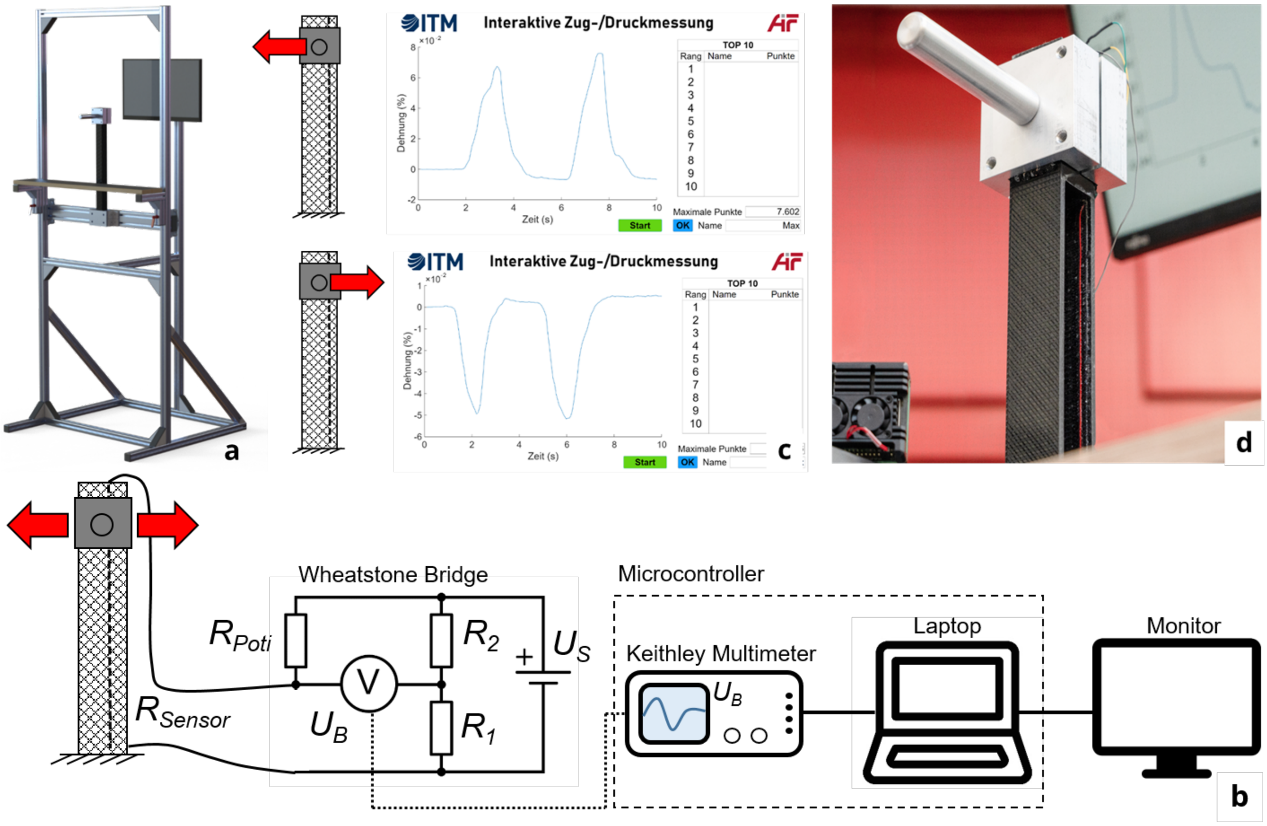


Figure 6: *Test stand for interactive tension and compression measurement with real-time visualisation of the sensor strain (a, c, d), schematic representation of the measurement chain for real-time acquisition of the sensor strain through interactive application of force (b)*

For strain measurement, the Sigrafil sensors were wired in Wheatstone quarter bridges. The high-precision multimeter and measuring computer used for functional validation was then replaced by a microcontroller (Raspberry Pi 4) (Figure 6 b). The generated sensor strains, caused by the interactive force application, were graphically displayed on a monitor in real-time using a developed Matlab user interface (Figure 6 c). Depending on the direction of the force application, positive and negative sensor signals (tension or compression) were recorded, similar to the electromechanical tests on composite scale. A detailed image of the CFRP profile with force application is shown in Figure 6 d.

Summary and outlook

Continuous structural monitoring of FRP components, especially in complex, changing load scenarios, represents an efficient solution approach to detect potentially occurring fatigue or damage at an early stage. Especially in FRP components, textile-based sensors are an economical solution for continuous in-situ structure monitoring, due to their high structural compatibility and direct textile integration during textile production.

The textile-based sensor concept developed in this research project was electromechanically characterised at the yarn and composite scale and was further processed in multiaxial warp-knitting to manufacture functionalised fabrics. The sensor functionality in CFRP specimen was tested in tensile, pressure and bending tests. Finally, a CFRP profile demonstrator was used to test and prove the practical feasibility and functionality. These "smart composites" not only enable continuous in-situ structural monitoring of FRP components under tensile, bending and, especially, compressive stress, but can also be used to detect cracking and delamination processes. This allows both the understanding of the material behaviour to be improved and taken into account for future designs, as well as necessary measures to be initiated to ensure the functionality of the overall system.

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