DEVELOPMENT AND IMPLEMENTATION OF AN AUTOMATIC INTEGRATION SYSTEM FOR FIBRE OPTIC SENSORS IN THE BRAIDING PROCESS – WITH THE OBJECTIVE OF ON-LINE-MONITORING OF COMPOSITE STRUCTURES

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ABSTRACT

Increasing economic, political and ecological pressure leads to steadily rising percentage of modern processing and manufacturing processes for fibre reinforced polymers in industrial batch production. Component weights beneath a level achievable by classic construction materials, which lead to a reduced energy and cost balance during product lifetime, justify the higher fabrication costs. However, complex quality control and failure prediction slow down the substitution by composite materials. High-resolution fibre-optic sensors (FOS), due their low diameter, high measuring point density and simple handling, show a high applicability potential for an automated sensor-integration in manufacturing processes, and therefore the online monitoring of composite products manufactured in industrial scale. Integrated sensors can be used to monitor manufacturing processes, part tests as well as the component structure during product life cycle, which simplifies allows quality control during production and the optimization of single manufacturing processes.[1;2]

Furthermore, detailed failure analyses lead to a enhanced understanding of failure processes appearing in composite materials. This leads to a lower wastrel number and products of a higher value and longer product life cycle, whereby costs, material and energy are saved.

This work shows an automation approach for FOS-integration in the braiding process. For that purpose a braiding wheel has been supplemented with an appliance for automatic sensor application, which has been used to manufacture preforms of high-pressure composite vessels with FOS-networks integrated between the fibre layers. All following manufacturing processes (vacuum infiltration, curing) and component tests (quasi-static pressure test, programmed delamination) were monitored with the help of the integrated sensor networks.

Keywords: SHM, high-pressure composite vessel, braiding, automated sensor integration, pressure test, quality control, optic-fibre sensors, Rayleigh signals, Luna Technologies

1 MOTIVATION

Braids are two- or three-dimensional fabrics with a closed profile, which show a uniform yarn density. The braids structure is comparable to weaved fabrics, with the difference, that the fibre angle can be varied between 5° and 86°. [3]

The braiding method derives from the hand braiding technique, in which three yarns cross each other alternately from right to left, which results in a plait. Thereby every single yarn passes an 8-shaped way. Modern braiding machines can handle several hundreds of yarns simultaneously.

The Institute of Lightweight Engineering and Polymer Technology (ILK) of the Technical University Dresden (TUD) possesses a circular braiding machine with a maximum number of 288 bobbins. By the help of a manipulator, a braiding core can be moved in any desired angle in the middle of the horizontally mounted braiding frame, in order to apply technical fibre braid on its surface (Fig. 1). This process allows perform production for any kind of composite structures with a closed profile.

Measuring systems enabling quasi-continuous distributed sensing are based on the analysis of light fractions scattered back from the optical fibres material itself, whose properties depend on the strain and temperature state of the sensor fibre. By means of a Optical Time Domain Reflectometer (OTDR) or Coherent Optical Frequency Domain Reflectometer (c-OFDR) the runtime of light fractions, and therefore reflections distance to the reflectometer, can be determined. Therefore through analysis of the reflected light fragments properties in dependence on the distance of the reflection point a continuous temperature or strain profile is obtained. As sensor fibre, any commercially available single-mode fibre can be applied, although the coating material constrains the practicable temperature range (polyimid coating: up to 350°C; gold coating: up to 700°C) and the accuracy, with which strain is transmitted from the material to the fibre core. [8]

This measurement method has following advantages, which lead to a high exploitation potential for their integration in composite materials:

- Continuous measurement technology:
  - → Strain and temperature gradients are measurable
  - → Strain and temperature are precisely capturable
  - → Monitoring of crack propagation
- Measurement resolution: 1 mm
- Sensor diameter: 155 µm
  - → Low influence of sensor geometry on monitored structure
- High mechanical pliability of sensor fibres:
  - → facilitated integrability
  - → lower damage probability during handling
- Measuring sensitivity: ± 0,1 °C; 1 µm/m
- Measuring dynamics: depending on density of measururing point up to 250 Hz

Integrated sensors allow full monitoring of manufacturing processes, which simplifies and accelaretes quality management. Furthermore the same sensors can be used for online monitoring of manufactured parts during component or structure testing under laboratory and working conditions, as well as during the whole product life cycle.

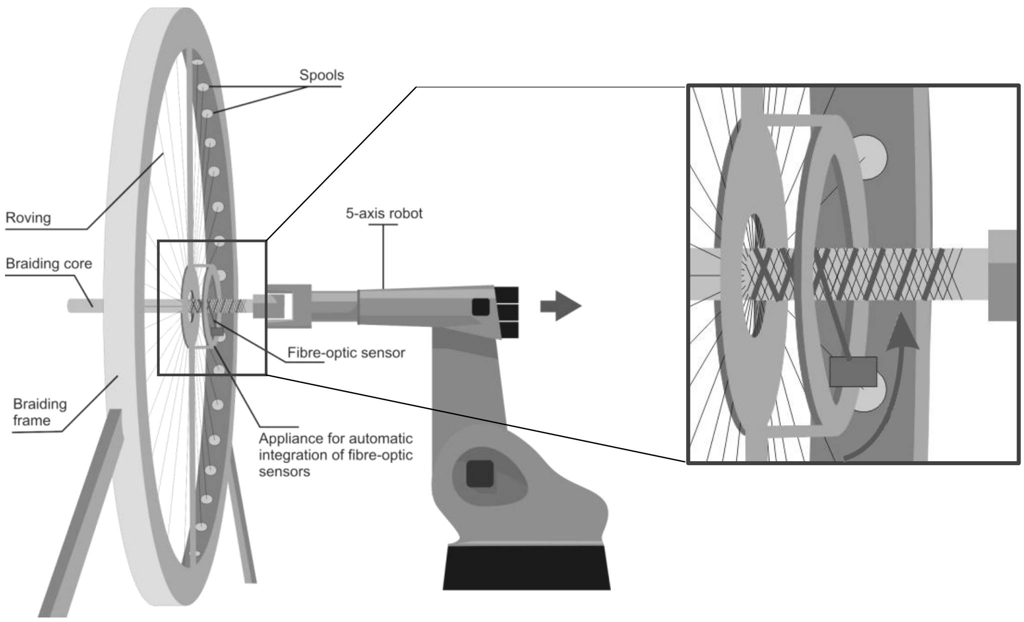


Fig. 1 Schematic construction of the braiding machine at the ILK of TUD with the appliance for automated FOS-integration

2 AUTOMATIC INTEGRATION OF FIBRE-OPTIC SENSORS DURING THE BRAIDING PROCESS

Due to its high degree of automation and suitability for continuous processes the braiding process is predestined to be complemented by an automated sensor integration. However, because of their vulnerability to low bending radiuses and high pulling forces, FOS cannot easily braided together with reinforcement fibres. Besides, simultaneous braiding of sensor fibres would restrict their possible angle to the actual braiding angle. Therefore an additional appliance is needed to lay optic fibres damage free on the braid or the braiding core, while the applied sensor-angle and sensor-prestressing must be adjustable. In order to fulfil these requirements the appliance needs to comprise a sensor spool and a prestressing unit which it moves perpendicularly to the braiding direction around the braiding core (Fig. 1).

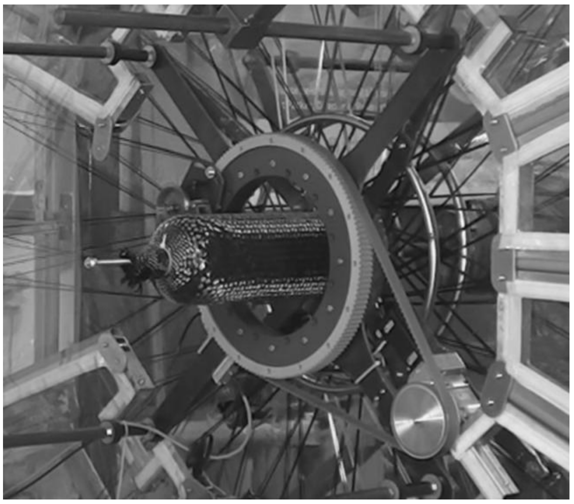
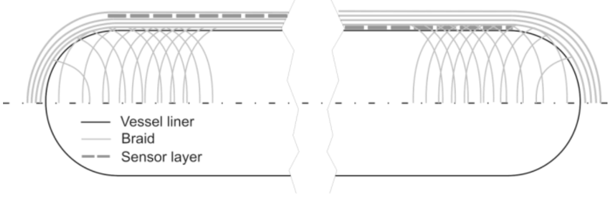


Fig. 2 Appliance for automated FOS-integration during braiding process; mounted on the braiding machine at ILK (TUD)

Figure 2 shows the implemented appliance mounted on the braiding machine at ILK (TUD) during a production process for ultra-high pressure vessels with integrated FOS.

With the aid of the appliance for automated sensor integration during braiding process, it is possible to incorporate a sensor fibre directly on the braiding core or on any previously braided technical fibre layer, with an adjustable sensor angle (Fig. 3).



a) b)

Fig. 3 Sensor positioning inside the braided composite structure: a) between two braided layers; b) directly on the braiding core

The sensor-alignment on a cylindrical geometry and geometrical dimensions, which are relevant for sensor-application and subsequent analyses of gathered measurement data, is illustrated in figure 4.

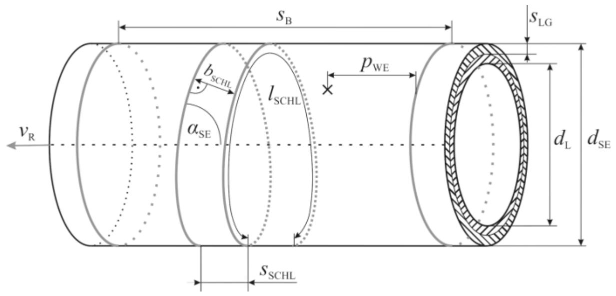


Fig. 4 Sensor alignment on a cylindrical braid: v_R - feeding speed of robot/braiding core, s_B - length of cylindrical braid-section applied by sensor-fibre, s_{LG} - layer thickness, d_L - external diameter of liner, d_{SE} - diameter in sensor layer, p_{WE} - distance of discrete point to turning plane, l_{SCHL} - lentgh of complete sensor loop, s_{SCHL} - loop distance in feeding direction, α_{SE} - sensor angle in relation to feeding direction, b_{SCHL} - loop distance

2.1 Process conduction

The manufactured high-pressure composite vessels were composed of a polymer liner, on which 5 layers of carbon fibre were applied by the help of the braiding process conducted by the braiding machine at ILK. During the braiding process, in every vessel an FOS was automatically incorporated on the cylindrical vessel section between the 3rd and 5th braiding layer in angles of ± 54,7° and ± 85° (Fig. 5).

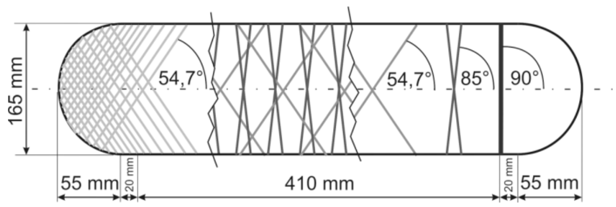


Fig. 5 Braiding angle; application scheme of fibre-oftic sensor; sensor angles

In total 25 m of FOS were incorporated. A part of the fibre had to be applied in a 90° angle in the turning plane, in order to ensure a clean start for sensor application in opposite direction. The distribution of sections applied in different angles along the fibre length is demonstrated in figure 6.

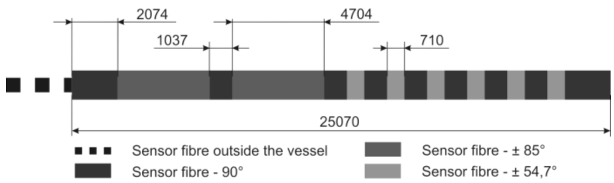
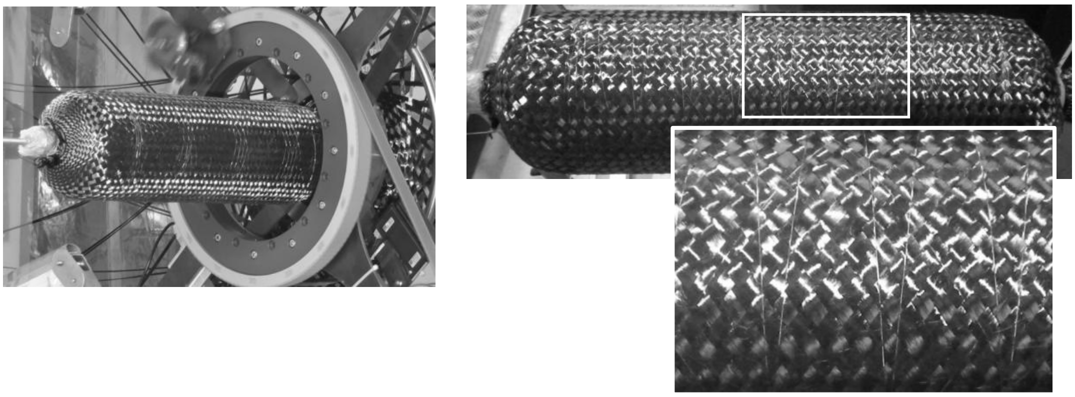


Fig. 6 Schema of sensor angle distribution along the whole sensor fibre

Figure 7 a) shows the process of sensor application during the braiding process, while the resulting sensor network is presented in Figure 7 b).



a b

Fig. 7 Manufactioring of high pressure composite vessel with integrated optic-fibre sensors: a) automated application of fibre-optic sensors during braiding process; b) optic-fibre network, applied on third carbon-fibre layer

Directly after its integration the sensor fibres damping was measured by a reflectometer (Fig. 8). On the resulting reflectogram defects and connectors can be detected. The first two peaks show reflections originating from two optic cable connectors, while the big peak at around 30 m is caused by the fibre end. Between the second and the third peak no fibre damages can be detected.

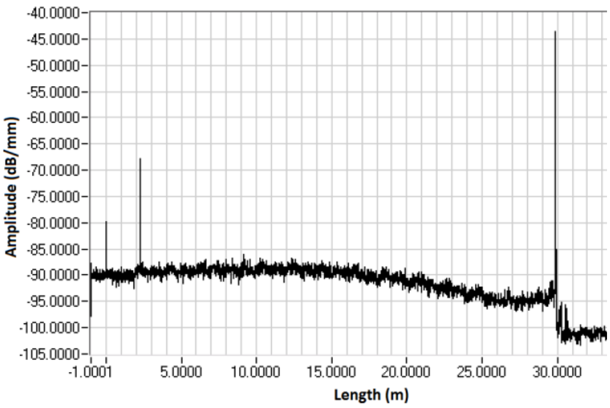


Fig. 8 Reflectogram of sensor fibre after integration

2.2 Monitoring of vacuum infiltration

A braided carbon fibre high-pressure vessel with a polymer liner was infiltrated by epoxy resin through a VARI-process (vacuum assisted resin infusion), as shown in Figure 9, which was completed after 29 min.

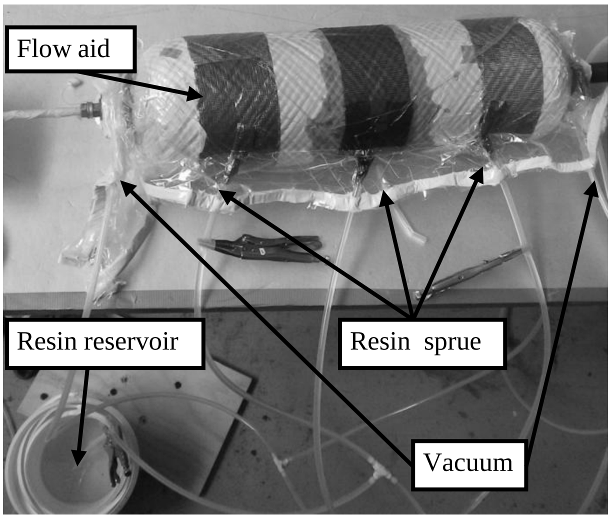
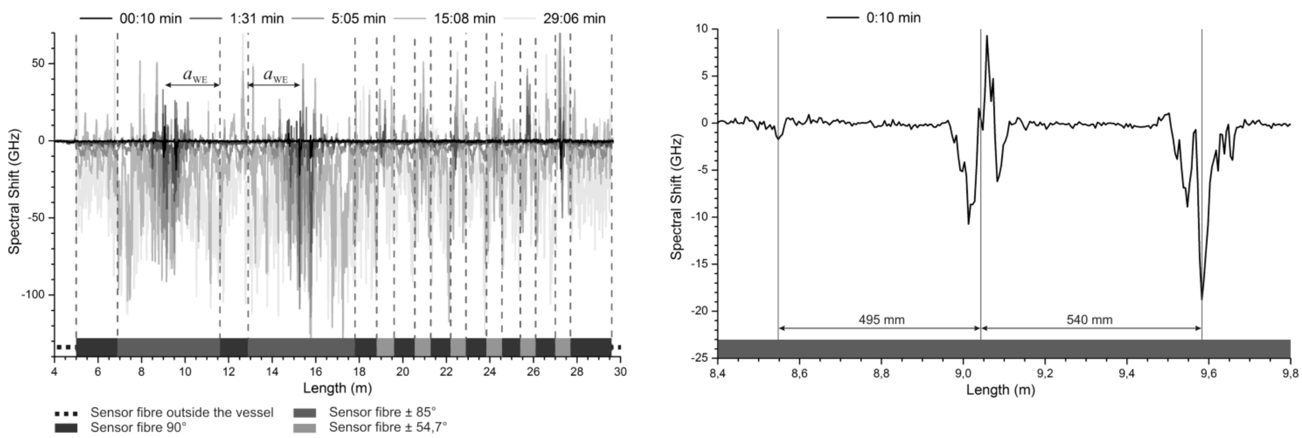


Fig. 9 VARI-infiltration of the high-pressure composite vessel

The structure has been monitored during the whole infiltration process by the help of the integrated sensor network. At the beginning of the infiltration only the central resin sprue was opened, while the outer ones where unblocked as soon as the resin flow in the structure reached their position. Due to fact, that strain and temperature are always measured by observing the same physical phenomenon, it is impossible to obtain information about their propagation in the overlayed signal. Therefore the raw data is shown.

Figure 10 a) shows the spectral shift of the Rayleigh-signal, which is backscattered inside the optic-fibre, in dependence on the sensor length for different times of the infiltration process. The spreading resin propagation along the sensor fibre, and therefore in the area of the sensor network is clearly recognizable, due to the starting polymerisation which causes the resin to be warmer then the infiltrated structure. Furthermore a clear symmetry exists between the two 85°-sensor-sections, while the distance between the single fibre-loops in the 54,7°-sensor-section comes with a high detection unsharpness for events, which cover only a discrete are. This explains why after 10 s, not all them show a sensor reaction.



a b

Fig. 10 Spectral shift of Rayleigh scattering; a) whole sensor fibre for different infiltration times; b) 85°-sensor-section in resin sprue area after 10 s infiltration time

Figure 10 b) shows a 85°-graph-section after 10 s infiltration time. The calculated sensor loop length of 520,3 mm should theoretically equal the distance of peaks in the diagram, however shown peak distances differ from the theoretical value, due to irregularities of the infiltration process. Thus, through recognition of peak distances, peak growth as well as time intervals between occurring new peaks the infiltration process is monitorable. This helps detecting deviations from the desired process flow and therefore ensuring the process reproducibility.

2.3 Monitoring of hardening process

The infiltrated composite vessel structure has been monitored during the hardening process under room temperature, as illustrated in Figure 11. The recognizable inhomogeneous changes of frequency shift lead to the conclusion, that during the curing process, not only temperature has changed, but also strains were induced, due to shrinking processes caused by polymerisation of the resin components. Therefore an overlaid measuring result is obtained.

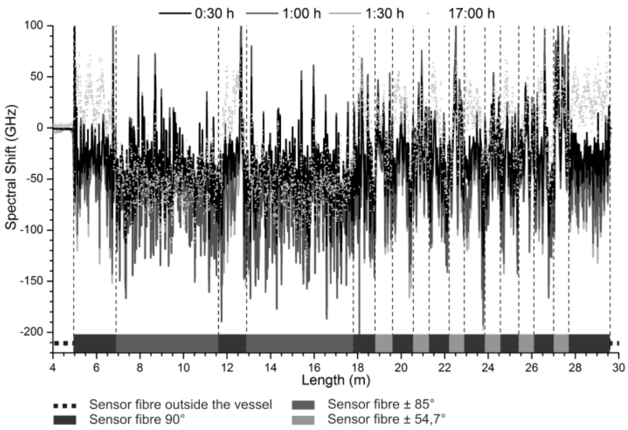


Fig. 11 Frequency shift over the length of the Rayleigh-sensor during curing process under room temperature

2.4 Verification of sensor positioning

On the vessel surface a pattern of 16 spots was marked (Fig. 12). Every single of them was cooled down by ice spray, while pausing 5 min between all of them to allow them warming up again.

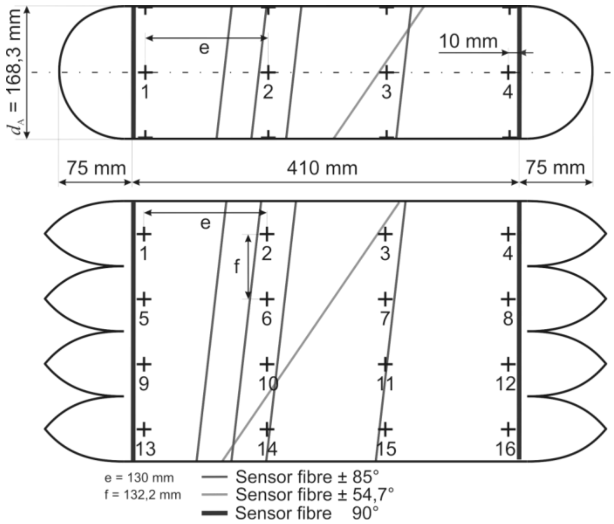


Fig. 12 Schematic illustration of cooled spots on the vessel surface

During this experiment the reproducibility of the single cooling events was not ensured, yet it is possible to qualitatively evaluate the measurement results.

The resulting spectral shift for the measurement spots 1 to 4 is shown in figure 13. It is recognisable that cooling of spot 1 and 4 results in a peak in a sensor-section wound around the turning point at the vessel ends, while cooling of spot 2 and 3 clearly causes sensor peaks in the middle of the 85°- and 54,7°-sensor sections. Furthermore the previously recognized symmetry in the 85°-section is observable, represented by the distances a_{WE2} and a_{WE3}). Though it is disturbed by an unsharpness, which amounts one sensor-loop length.

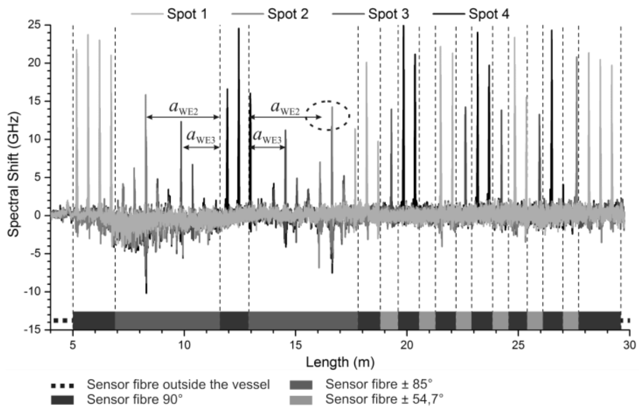


Fig. 13 Measurement of cooled Spots 1 to 4; distances a_{WE2} and a_{WE3} marking the theoretically symmetric identical peak distances from the turning point (unsharpness of a_{WE2} marked by ellipse)

The geometrical constellation explaining the sensor-angle dependent detection unsharpness, as well as the detection probability, is sketched in figure 14. Lower sensor-angles come with a lower accuracy and lower event detection probability, depending on the event shape and size.

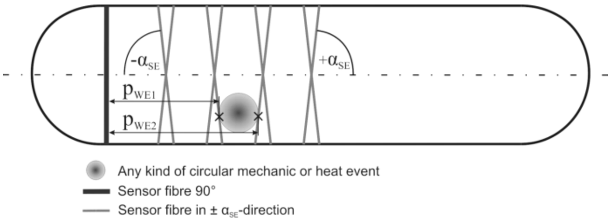


Fig. 14 Cause of unsharpness and detection probability in dependence on event size; p_{WE1} and p_{WE2} symbolise the different detected distances of one and the same event to the turning point, while being recognised by two neighbouring sensor-sections of the same absolute angle

2.5 Verification of sensor sensitivity to strain and compression

For the strain and compression validation the composite vessel has been constrained horizontally while laterally loaded by a 30 kg weight, separately on the edge of the cylindrical vessel section and a central position, as shown in Figure 15.

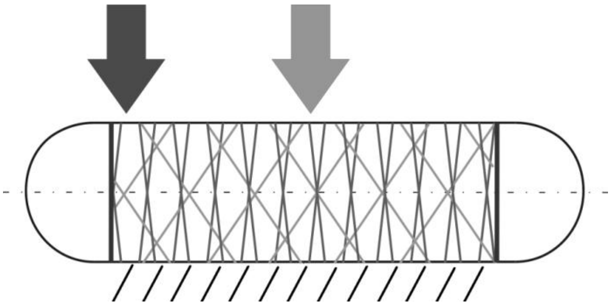
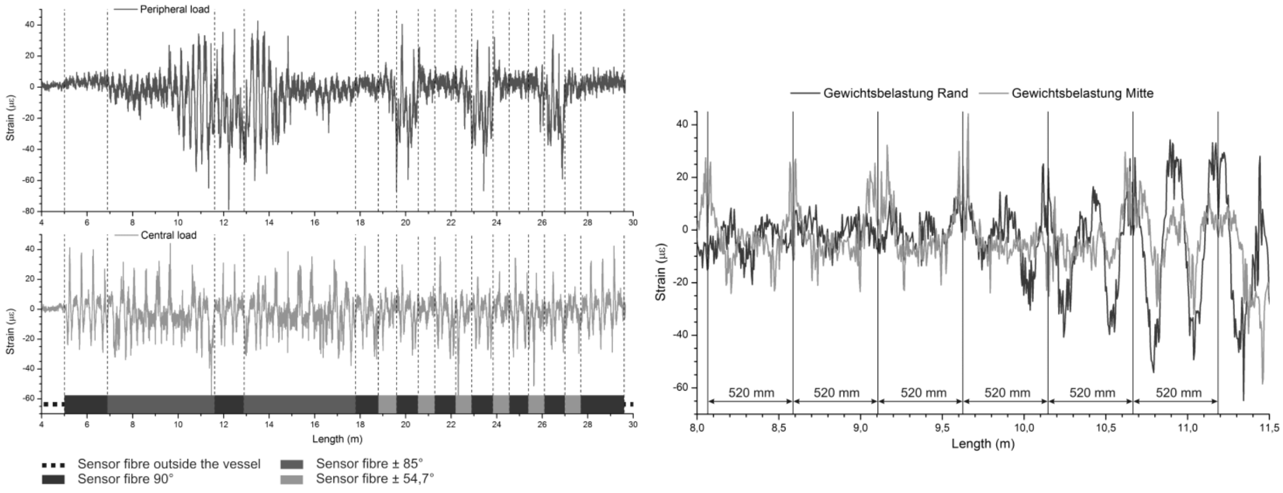


Fig. 15 Lateral load by 30 kg weight

Figure 16 a) shows strain over sensor length for both load cases. A global axial symmetry regarding $y = 0\ \mu\varepsilon$ is observable in figure 16 a) and b). It is only disturbed by some negative peaks in the area of the hard constraint surface, which causes locally higher tensions in the contact area. Moreover it is clearly recognizable, that the load on the edge causes significantly higher strain and compression peaks close to one of the two turning points (around 12 m sensor length). While the central load condition leads to more homogeneous strain propagation along the vessel length.

As demonstrated in Figure 16 b) the peak distances equal the theoretical sensor-fibre loop length of 520 mm.



a b

Fig. 16 a) Strain propagation along the whole sensor length according to load cases shown in Fig. 15; b) Strain over sensor length for 85°-sensor-section during lateral load

2.6 Quasi-static pressure test

All quasi-static pressure test were carried out in the High Pressure Composite Vessel Laboratory (Fig. 17) at the Institute of Material Science and Mechanics of the Wrocław University of Technology (Poland), while using optical-fibre measurement equipment from the ILK of TU Dresden (Germany).

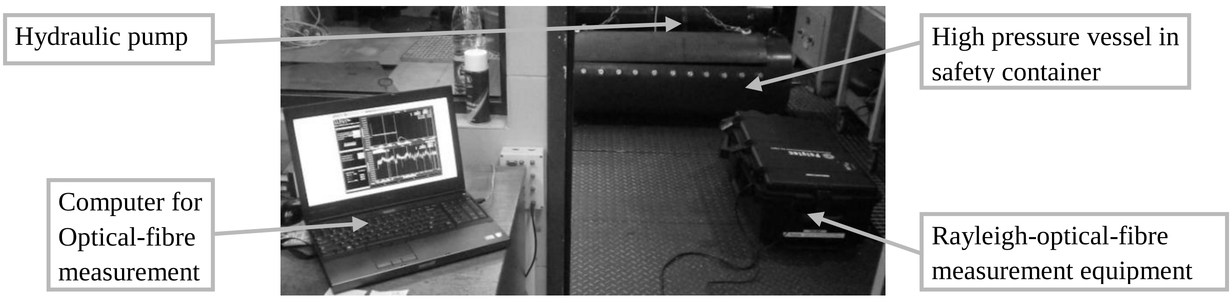


Fig. 17 High Pressure Composite Vessel Laboratory at the Institute of Material Science and Mechanics of the Wrocław University of Technology (Poland)

On the high-pressure composite vessel pressure was applied in 5 steps, each 10 bar pressure difference.

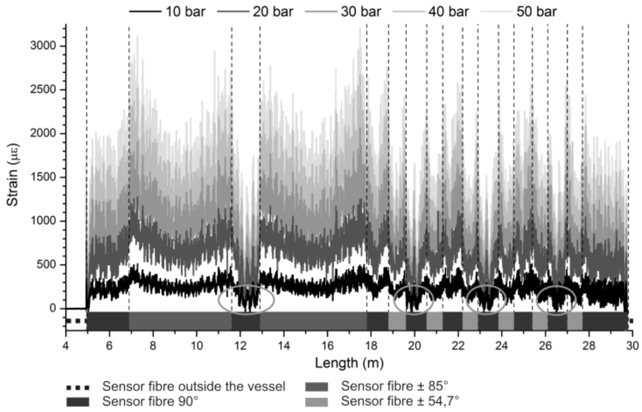


Fig. 18 Strain values over sensor length during for different pressure loads during quasi-static pressure test of composite vessel

As expected, also during pressure test the earlier discussed symmetry around the turning points is observable. Additionally it can be seen, that strain values close to the turning points, hence the vessel ends, are significantly higher than in the middle vessel section. According to Barlow's formula, under inner pressure on a cylindrical structure, strain should be constant under a certain angle. This could be explained with sensor fibre crossings, which have a negative influence on its performance. As well unwanted variations of sensor-pretension could have an influence, which is also a reason for the low measured strains on one turning point (Fig. 18, marked by grey ellipses). Moreover the vessel cap geometry leads to a complex stress state, which leads to higher strains close to the turning points. Still, as shown in figure 19, the theoretic strain growth close to the vessel caps is much lower than the measured one.

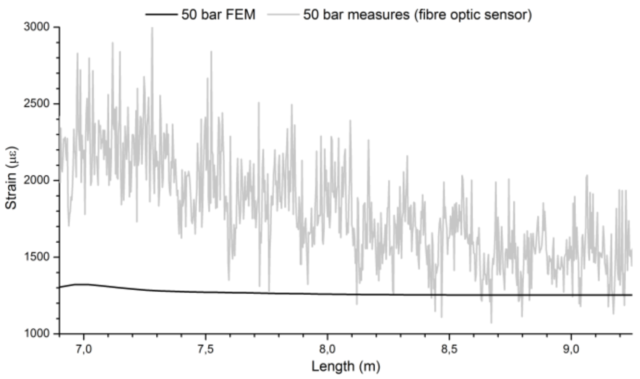


Fig. 19 Measured strain from the turning point/vessel cap (left side of graph) to the vessel centre plane (right side of graph); comparison between FE-results and measured values

Furthermore, single strain peaks are observable (fig. 20), which result from abnormalities in the composite structure, caused by fabrication and/or material errors. Due to their expansion (Fig. 20 a) and repetitive pattern (Fig. 20 b) it is possible to localise and identify existing defects.

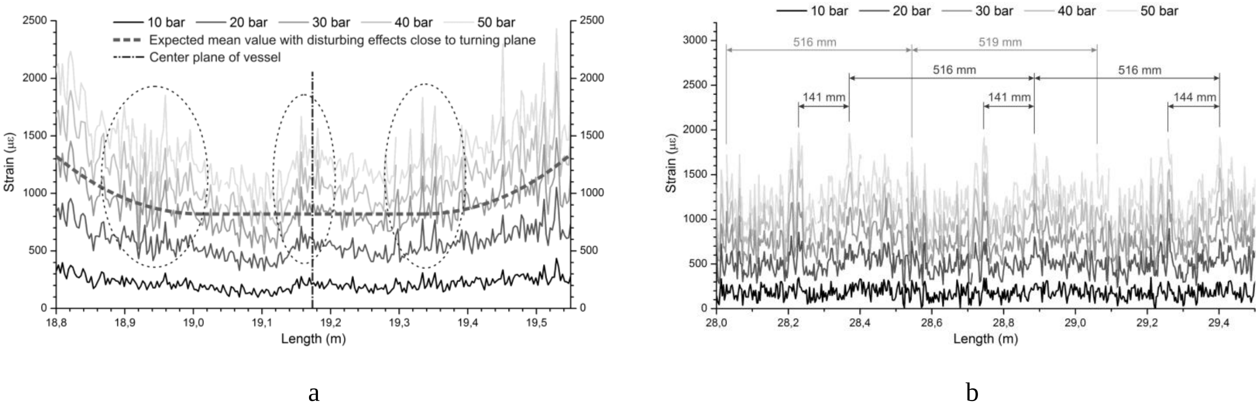


Fig. 20 Strains during quasi-static pressure test; a) 54,7° sensor angle; b) 90° sensor angle

2.7 Quasi-static pressure test with programmed delamination

Initially a spot was marked on the vessel surface, which marked the later area of programmed delamination. In order to locate the point along the sensor length, before application of delamination, the marked spot was cooled by ice spray, which caused a sensor reaction as observable in Figure 22. Afterwards, by the stroke of a hammer, a programmed delamination was applied at exactly the same point, which caused a remaining sensor reaction in the impact area. After applying a pressure of 50 bar the visible have been grown.

Even though the symmetry is clearly observable, it comes also with the earlier discussed unsharpness (marked by ellipses in Fig. 21), which affects not only the position of the peaks along the sensor length, but also the dimension of the peaks itself.

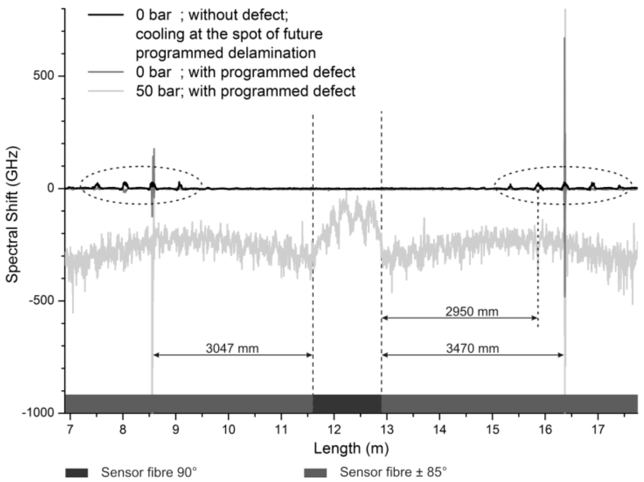


Fig. 21 Frequency shift during experiment with programmed delamination; clear symmetry with observable unsharpness (drift of defect peaks about 1 sensor-loop length, l_{SCHL} = 520 mm)

The experiment has confirmed the thesis, that it is possible to detect and localise delaminations with the help of optic-fibre Rayleigh-sensors. This is possible in real time during defect propagation, as well as through analysis of baseline data from before and after the event after any time interval. Still the detection probability and localisation accuracy is dependent on the damage size and sensor network density.

3 SUMMARY AND OUTLOOK

Structural health monitoring of composite structures by means of integrated sensor networks, due to the given potential for process optimisation during manufacturing, increasing quality control effectiveness and rising light-weight coefficients, is gaining rising popularity. High resolution optic-fibre sensor systems for strain and temperature measurement, because of the low costs for sensor fibre, can be applied effectively in manufacturing processes for composite structures, which enables the exploitation of named potentials for a wider product range.

Within this work, a novel system for automated fibre-optic sensor integration during a composite manufacturing process could be developed and implemented in order to complement the braiding machine at the ILK of TU Dresden.

Utilizing the braiding machine in combination with the compliance for automatic sensor integration high pressure composite vessels with integrated optic-fibre networks were produced, as well as tested during working conditions and failure event.

The data, collected during the carried out experiments, have shown, that automatically integrated fibre-optic Rayleigh-sensors are suitable to ensure a holistic structure monitoring during manufacturing process (braiding, infiltration, curing). This enables the comprehension and analysis of all manufacturing steps, which after part tests allows a conclusion to be drawn about the process quality.

A high sensor network density in combination with a sensor length of 60 m and a realisable measurement resolution of 3 mm allows an accurate sensor mapping for all sensor points. Hence it is possible to quantify and localise thermal and mechanical load events as well as failure processes during product lifetime – even if from the outside no effect is observable.

The realised system for automated sensor integration within the industrial braiding process allows elastic deformation analysis between all reinforcement layers, which perspectively leads to a better understanding of both failure mechanisms and influence of manufacturing parameters on mechanical properties of braided composite structures. Such findings will have direct influence on the realisable light-weight-ratio.

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