Distributed strain sensing with sub-centimetre resolution for the characterisation of structural inhomogeneities and material degradation of industrial high-pressure composite cylinders

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Abstract

Fibre-reinforced plastics (FRP) especially carbon-fibre-reinforced polymer (CFRP) and glass-fibre-reinforced polymer (GFRP) are commonly used materials in high pressure vessels and storage units for automotive and aerospace purposes. Optical fibres are suitable to be integrated or directly applied to the surface of FRP components. Using optical fibres it is possible to monitor the distributed strain profiles and changes within the fatigue life of a pressure vessel to ensure the operational safety. Within artificial age experiments we used swept wavelength interferometry (SWI) based distributed strain sensing for the monitoring of commercial high-pressure composite cylinder. This artificial ageing was performed using test conditions of 503bar pressure load (service pressure 300 bar) and 89 °C for 100 h. The polyimide coated optical fibres were glued to the surface externally in circumferential and axial direction. Using distributed strain sensing (DSS) material expansion of over 0.5% were monitored with sub-centimetre spatial resolution. Within the circumferential direction we observed up to 10% local fluctuation compared to the median strain caused by inhomogeneous material expansion, which could cause local material fatigue. In addition, we determined material degradation manifested itself as localized remaining material expansion and/or contraction. Results have been validated by other non-destructive methods like digital strip projection.

1. Introduction

Composite materials offer high specific strength, corrosion resistance and an excellent fatigue lifetime. FRP combine high tensile strength and a great strength-to-weight ratio. This offers the possibility of lightweight construction and takes on specific interest for automotive or aerospace industries. Another important application of FRP are pressure vessels or natural gas storages. Modern high-pressure vessels consist of an aluminium (type 3) or polymer liner (type 4) fully wrapped with CFRP or hybrid CFRP and GFRP layers. Since this material combination has quite complex degradation mechanisms (1), an accurate lifetime prediction is a demanding challenge (2-3). Monitoring the strain of these composite structures is one opportunity to ensure the operational safety during the lifetime and allows an early detection of material degradation. Using strain gauges is a well-established and most common method for these strain measurements, but only delivers strain information of a single point. Due to handling (cabling) multiplexing is a challenging task. Optical fibre sensors offer the possibilities of a minimal invasive integration to composite structures together with an excellent fatigue lifetime. Swept
wavelength interferometry (SWI) can determine truly distributed strain profiles for structural health monitoring of GFRP (4). This paper stands in context of the current research project COD-AGE at the Federal Institute for Materials Research and Testing (BAM), which studies the aging behaviour of composite pressure vessels (CPV). The aim of this work is to show the capability of distributed strain sensing for structural health monitoring of composite pressure vessels.

2. Method and Experiment

2.1 Preparation and sensor fibre installation of the type 3 pressure vessel

We used type 3 pressure vessels from MSA GmbH for our investigations. This specific CPV have a volume of 6.9 l with a service pressure of 300 bar and are commonly used by firefighters. The CPV have a circumference of 49 cm, a length of 60.5 cm (~35 cm cylindrical section) and a typical lifespan of up to 30 years. We determined the thicknesses of the individual layers of the CPV using optical microscopy (Tab. 1.).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Aluminium</th>
<th>CFRP</th>
<th>GFRP</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (µm)</td>
<td>2000</td>
<td>3700</td>
<td>360</td>
<td>330</td>
</tr>
</tbody>
</table>

The aluminium liner has a thickness of 2 mm and is overwrapped with approximately 3.7 mm CFRP in different layers and with varying fibre orientation. Under operating pressure and temperature both materials together ensure the mechanical stability of the CPV. To protect these layers from mechanical damage (impacts) a 0.36 mm GFRP layer with 87° fibre orientation together with sealing, primer and lacquer is placed on top. Preliminary tests soon revealed that the determined strain at the lacquer could be influenced by local surface damages. For this reason, we mechanically removed the outer layers up to the GFRP (see Fig. 1a.) at 1 cm wide strips in circumferential direction and on the front side in axial direction. A polyimide coated standard single-mode optical fibre was wrapped around the vessel in these sections and glued to the surface using the epoxy resin-based X280 adhesive from HBM. A thin layer of the hybrid polymer Soudal High Track was used to cover the monitoring sections and protect them from mechanical damage (see Fig. 1b.).

Fig. 1a. Pressure vessel after mechanical surface preparation

Fig. 1b. Specimen with surface applied fibre (with cover) and reference marker

2.2 Hydraulic test bench for the creep experiments

Fig. 2 shows the schematic overview of the test bench which consists of I. Water degasification unit, II. Machine housing with control unit, III. Two pressure intensifiers,
IV. Hydraulic pressure unit, V. Pneumatic high-pressure pump, VI. Water heated protection containment. The main module (IV.) with drive hydraulic is placed in a machine housing (II) together with two pressure intensifiers (III.) and the corresponding valve technology. The pressure intensifiers operate in tandem and are driven primarily by hydraulic oil. Water mixed with Pekasol is used as the test medium on the secondary side. A degassing system (I.) ensures the gas-free hydraulic pressurising of the vessels. Up to 3500 bar could be realised on the secondary pressure side. The main unit is directly connected to the probe chamber until the holding pressure for the creep test is reached. For this holding time interval, the pressure intensifiers were switched to a long-term test cabinet (V.) which is used for the automatic pressure holding. Heating of the test chamber (VI.) shown in Fig. 2c. is realized by an integrated water jacket. Without additional external heating a maximum test chamber temperature of 85 °C could be realized.

![Fig. 2a. Schematic overview of the test bench](image)

![Fig. 2b. Main module of the hydraulic test bench](image)

![Fig. 2c. Vertical probe chamber with vessel specimens](image)

### 2.3 Swept wavelength based distributed strain / temperature sensing (DSS / DTS)

The DSS measurements were performed with an SWI (OBR 4600) from Luna Inc. Fig. 3 shows the working principle of this method. A tunable laser source (TLS) is swept within a defined wavelength range, in our case 88 nm around the centre wavelength of 1550 nm. Light is split into a measurement path (meas.) which includes the fibre under test (FUT) and reference path (ref.) with a polarisation controller (PC). Both paths are recombined and detected polarisation dependent using two detectors (P & S) and a polarising beam splitter (PBS). A Fourier transform (FFT) is performed to recover the Rayleigh backscatter signal of the FUT from the determined spectrum. Subsequently, the backscatter profile is divided into local sections (sensor length) with a defined step size (overlapping sensors are possible). Local frequency shifts are calculated by performing a cyclic cross correlation of two measurements in the frequency domain. Using calibration coefficients this frequency shift can be converted to strain or temperature (5).

![Fig. 3. Measurement principle of a swept wavelength interferometer](image)
2.4 Digital strip projection

Additional to the DSS the remaining deformation (residual strain) at room temperature is measured with the ATOS 2 Triple Scan from GOM GmbH. This system consists of a stereo camera and a centrally arranged projector. Stripe patterns of different space-frequencies are projected onto the vessel surface in a time sequence. The 3D coordinates of the surface point cloud are determined by means of photogrammetric triangulation with lateral spacing of approximately 350 µm. Using additional reference points, finally, the single sensor views are transformed into the 3D vessel coordinate system. Vessel surface deformation is determined by comparing two full 3D vessel shapes.

3. Results and Discussion

3.1 Evaluation of the temperature and pressure related strain

At the beginning of the creep test the specimen was heated up from approximately 21 °C or room temperature (RT) to the test temperature of 89 °C. Using the non-attached fibre segments of the FUT we determined the temperature before installation of the pressure vessels into the probe chamber and during the temperature increase. After installation of the pressure vessels the temperature was monitored additionally with a surface applied Pt100 temperature sensor (see Fig. 4a.). For the thermal conditioning comparable results could be observed from Pt100 and DTS. Using the surface applied fibre section, we further monitored the pressure-free strain change (see Fig. 4b.). According to the 69 °C increase in temperature a median strain of 1350 µε (µm/m) in axial and 1140 µε in circumferential direction could be determined (see marked sections in Fig. 4.b). Based on this result the coefficient of thermal expansion (CTE) of the vessel is 20 x 10⁻⁶/K in axial direction and 17 x 10⁻⁶/K in circumferential direction. As assumed the CTE is close to aluminium (23 x 10⁻⁶/K) caused by the thick liner material. Combined thermal expansion of the GFRP and CFRP layers cause a reduction of the thermal expansion depending on the fibre orientation.

![Fig. 4a. Pressure and temperature over the different stages of the creep test: thermal conditioning, pressure steps and 100 h creep test](image)

![Fig. 4b. Determined temperature and strain profiles for the surface applied optical fibre and the connection fibre inside the probe chamber](image)
This thermal conditioning was followed by a stepwise 100 bar pressure increase till 503 bar as shown in Fig. 4a. The resulting strain for the individual steps are shown in Fig. 5a. for the full specimen. Bold marked sections are used for the linear regression shown in Fig. 5.b and shown in detail in for the axial (Fig. 6a) and circumferential (Fig. 6b.) direction, respectively. The distributed strain profiles for each pressure step have been corrected by the small temperature change (<1°C) during this test interval using the previously determined CTE. For the total pressure change of 503 bar a related strain change of 5104 με ± 625 με (circumferential) and 2810 με ± 118 με (axial) could be observed. The strain fluctuation along these profiles are related to local changes of the mechanical material properties. With higher load these local inhomogeneous are increasing (see Fig. 6a-b.). Nevertheless, does both strain-directions show an almost perfect (R² = 0.99) linear-elastic increase of strain due to the higher inner pressure load (see Fig. 5b.). Using a linear regression, the pressure dependent strain changes could be determined to be 5.6 με/bar (axial) and 10.0 με/bar (circumferential). Therefore, the expansion of the vessel in circumferential direction is roughly doubled compared to the axial. From the mechanical point of view an equal expansion would be the optimum for the lifetime of the vessels. To adjust these properties additional layers in circumferential direction would be necessary. From a commercial point of view this potential lifetime improvement generates disproportional higher manufacturing costs. It is worth to mention that this strain relation between circumferential and axial is very common for this kind of pressure vessels.

![Fig. 5a. Distributed strain profiles of the different pressure step](image1)

![Fig. 5b. Linear regression (lin. reg.) of the mean strain in axial and circumferential direction](image2)
3.2 Results of the 100 h creep test with 503 bar and 89 °C

In the following, the material degradation within a creep test was investigated. Therefore, the previously determined CTE and pressure dependent strain changes have been used to compensate the small temperature (± 2 °C) and pressure drifts (± 1 bar) during the 100h creep test (see Fig. 4a.). Another creep test within the adjoining probe chamber was responsible for the ongoing temperature increase within the probe chamber. Fig. 7. shows the drift compensated determined strain profiles for the axial (7a.) and the circumferential (7b.) direction. A strong dependent between the individual position along the fibre and the related determined strain could be observed. This behaviour is caused by local material mechanical changes. Comparing to the median strain these local changes are approximately 10%. Further an increase in median strain during the 100h creep test in axial and circumferential direction could be observed. It can be assumed that due to material degradation the stiffness is decreasing which causes an increase in elongation.
For an evaluation of the local material changes, we calculated the strain changes during the creep test at 503 bar relative to the initial strain at the beginning (0 h). In addition, the pressure-less residual strain profiles were determined at creep test temperature (HT) and room temperature (RT). These strain changes are shown in Fig. 8 and summarized in Tab. 2. In this context does the standard deviation of the determined strain profiles show local structural mechanical differences of the pressure vessel. It could be observed that this inhomogeneities increase during the creep test resulting caused by local differences in material degradation. Further an increase in median strain could be observed, which remains for the pressure-free conditions (HT & RT). This residual strain is caused by a remaining deformation of the pressure vessel, which was further qualitatively evaluated using 3D strip projection shown in Fig. 9. Due to uncertainties caused by the elastic polymer protection cover the section of the surface applied fibre are not considered for the 3D image. The strain peak at the fibre position of 10.68 m is also present in the 3D image. This position is the border between wrapped vessel label and lacquer (shown in Fig. 1), which could explain the local strain peak.

![Fig. 8. Distributed strain profile changes during the creep test together with the residual strain in axial direction (left) and circumferential direction (right)](image)

**Tab. 2. Median strain related standard deviation ($1 \sigma$) of the distributed strain profiles for axial and circumferential direction (shown in Fig. 8)**

<table>
<thead>
<tr>
<th>Time interval (h)</th>
<th>Median strain in axial direction ($\mu$m/m)</th>
<th>Median strain in circumferential direction ($\mu$m/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10</td>
<td>64.3 ± 34.5</td>
<td>60.9 ± 31.8</td>
</tr>
<tr>
<td>0 - 20</td>
<td>92.9 ± 40.8</td>
<td>84.8 ± 38.7</td>
</tr>
<tr>
<td>0 - 50</td>
<td>119.8 ± 51.8</td>
<td>93.6 ± 49.5</td>
</tr>
<tr>
<td>0 - 100</td>
<td>132.3 ± 64.2</td>
<td>102.1 ± 58.3</td>
</tr>
<tr>
<td>residual (HT)</td>
<td>133.5 ± 100.6</td>
<td>119.0 ± 78.4</td>
</tr>
<tr>
<td>residual (RT)</td>
<td>142.4 ± 85.1</td>
<td>33.3 ± 70.4</td>
</tr>
</tbody>
</table>
Fig. 9. Picture of the 3D surface deformation determined by fringe projection

4. Conclusion

In this article a surface applied optical fibre was used for the structural health monitoring of commercial high-pressure composite cylinder. Distributed strain profiles were determined in circumferential and axial direction for different pressure loads as well as during and after a 100h creep test. Inhomogeneous material expansion of up to 10% could be determined in circumferential direction for a 503 bar pressure load. Monitoring the strain changes during the 100h creep test an increase of this local changes due to material degradation could be observed. Local material deformation changes and critical deformation peaks could be further determined by distributed strain sensing and confirmed by digital strip projection.

Acknowledgements

The author thanks the Federal Institute for Materials Research and Testing (BAM) for the funding of the research project COD-AGE.

References