Structural Health Monitoring of Composite Structures by Distributed Fibre Optic Sensors

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Abstract

Structural Health Monitoring of composite materials gains in importance with the increasing use of composite structures for safety-related applications, e.g. in aerospace. Because of the material properties of composites, defects often occur inside the structures and raise the demand for integrated sensors. The advantages of optical fibres predestine them not only for the surface-application on composite structures but also for the integration into composite structures. Even without quasi-distributed sensors such as FBGs or LPGs, the optical fibre itself can be used to measure the structure and occurring events over the entire fibre length by distributed sensing techniques. This paper presents the surface-application of polyimide coated silica optical fibres onto PEEK specimens and the integration of copper and polyimide coated silica optical fibres into an AS-4/PEEK composite to be used as distributed fibre optic sensors for SHM. Results from distributed measurements by optical backscatter reflectometry based on Rayleigh backscattering are shown.

Keywords: Structural health monitoring (SHM), composite structures, optical fibre, distributed fibre optic sensors, optical backscatter reflectometry

1. Introduction

Since the demand for light weight structures increases, composite structures are progressively replacing steel or aluminium structures. This also includes safety-related applications, at which aerospace applications are a major driving force. Because of the material properties and the laminar structure of composites, defects such as cracks, delamination or fractures often occur inside of the composite structures and therefore, complicate the commonly used maintenance and monitoring procedures. In order to verify the functionality and to ensure the safety of the composite structure at all times, it is necessary to monitor the structural health of the structure itself continuously.

The well-known advantages of optical fibres e.g. small size, low weight and insensitivity to electromagnetic fields predestine them for the surface-application on composite structures as well as the integration into composite structures for structural health monitoring (SHM). Fibre optic sensors based on fibre Bragg gratings (FBGs) [1, 2, 3] and long period gratings (LPGs) [4] have been developed during the last decades and allow quasi-distributed sensing of the monitored structure. But for most safety-related applications a spatially continuous sensing is desired which led to the development of several fully distributed sensing techniques. The technique most commonly used for the measurement of several tens of meters with the resolution of millimetres is optical backscatter reflectometry (OBR) based on Rayleigh backscattering [5, 6].

Rayleigh backscattering is a result of slight fluctuations in the refractive index caused by imperfections along the fibre which reflect back light. The Rayleigh backscatter pattern of each fibre is unique and by applying strain or temperature to the fibre, the reflected spectrum will change at the location of the impact. By comparing the measured backscatter profile to a reference profile, the local frequency shift of the pattern and the applied strain or temperature can be derived.

As part of the EU-project “Multiscale reinforcement of semi-crystalline thermoplastic sheets and honeycombs” (M-RECT) BAM demonstrates SHM sensors for fully distributed
measurements of composite structures based on optical frequency domain reflectometry (OFDR). The investigations involve distributed fibre optic sensors (DFOS) with silica optical fibres for surface-application on composite structures as well as DFOS for integration into composite structures which will be presented in this paper along with results from distributed measurements.

2. Structural health monitoring by distributed fibre optic sensors applied on the surface of composite structures

DFOS based on OFDR using polyimide coated silica fibres for surface-application on composite structures have been demonstrated and investigated at BAM. As a first result, the adhesive X280 from HBM has been selected as an adhesive suitable for fatigue loading of up to 1.0% strain and static loading of up to 1.5% strain.

In order to evaluate the operation stability and the reliability of the strain sensors, the dogbone samples shown in figure 1 (a) were made by injection moulding of VICTREX® PEEK™ 450G according to the ASTM D368 standard. The test procedure consists of 10 million loading cycles at 10 Hz, which are interrupted every 100000 cycles for the static loading cycle shown in figure 1 (b). This static loading cycle consists of three preloading cycles and two stepped loading cycles up to 0.5% strain as well as three preloading cycles and one stepped loading cycle up to 1.0% and 1.5% strain. The test procedure was applied to three dogbone samples at the tensile testing machine shown in figure 2 (a). The tensile testing machine was operated strain-controlled by mechanical extensometers which can be seen in figure 2 (b).

![Figure 1](image1.png)

Figure 1. VICTREX® PEEK™ 450G dogbone sample with surface-applied DFOS for SHM (a) and static loading cycle of the test procedure for fatigue loading (b).

![Figure 2](image2.png)

Figure 2. Tensile testing machine with measurement equipment (a) and close-up view of the dogbone sample with mechanical extensometers (b).
The strain profiles of the three dogbone samples for 0.5% strain before and after 10 million strain cycles are shown in figure 3 (a). The change in the width of the strain profiles is caused by a minor detachment at the ends of the adhesive track. A crack in the adhesive of sample 2 occurred during the tests, which can be seen clearly in the centre of figure 3 (a), but the remaining strain profile beside the location of the crack can still be used for distributed strain measurements.

Figure 3 (b) shows the strain behaviours of the sensors during the 10 million strain cycles for all three dogbone samples. The drifts in the signal of sample 1 are most likely caused by a variation in the ambient temperature which could be improved for sample 2 and 3. The gaps in the signal of sample 3 are caused by a discontinuous data acquisition which unfortunately resulted in the loss of the measurement data. But beside this, the signal of sample 3 during the last 2 million loading cycles is still similar to the signal of the first loading cycles. Therefore, all samples and sensors withstood the 10 million strain cycles and provided reliable and stable sensor signals during the test.

Concerning cracks and detachments, the surface-applied strain sensors clearly show the ability to detect such defects in the adhesive.

In case of a crack, a local increase in strain could be observed at the position of the crack. Figure 4 (a) shows several minor cracks which lead to slight increases in strain in the corresponding strain profile in figure 4 (d). For a major crack as shown in figure 4 (b), the local increase in strain is considerably higher, as can be seen in figure 4 (e). Beside the local disturbance of the strain profile, the strain sensor remains fully functional in front of and after the crack, which is confirmed by the stable strain values during the 10 million strain cycles in figure 3 (b).

Detachments will lead to a decreasing width of the strain profiles shown in figure 3 (a). In rare cases of debonding as in figure 4 (c), an additional valley in the strain profile could be observed as in figure 4 (f). Although the width of the strain profile decreases, the strain sensor still shows a reliable strain behaviour, which is confirmed by the stable strain values during the 10 million strain cycles in figure 3 (b).
The surface-applied strain sensors could clearly detect cracks and detachments in the adhesive while keeping their functionality and reliability. The local disturbances of the strain profile caused by cracks and the decreasing width of the strain profile due to detachments at the edges of the adhesive did not influence the sensor behaviour. It was not possible to detect cracks in the samples itself yet, because no cracks arose at the surface of the samples during the conducted tests. Since surface applied sensors in general are only able to detect cracks which propagate up to the surface, no information can be gained about cracks inside of the samples. In order to overcome this disadvantage, distributed fibre optics sensors integrated into composite structures have been investigated.

3. Structural health monitoring by distributed fibre optic sensors integrated into composite structures

DFOS based on OFDR using copper and polyimide coated silica fibres for integration into composite structures have been demonstrated and investigated at BAM. One of the major challenges of integrated DFOS concerns the ability of the optical fibre to withstand the partially harsh process conditions during the fabrication of the composite structure. In case of the AS-4/PEEK laminate the composite structure is fabricated in a press by a heating period up to 380 °C for approximately 1.5 hours, a hold period at 380 °C for approximately 30 minutes, an additional applied pressure of 10 bars by the press and a cooling period down to 80 °C at 10 bars pressure for approximately 1.5 hours.

Concerning the ability of the optical fibres to withstand the given process conditions two types of fibres were investigated: a copper (Cu) coated silica fibre and a polyimide (PI) coated silica fibre with a special high temperature PI-coating. Therefore, six PI-coated silica fibres (DFOS 1 – 6) and four Cu-coated silica fibres (DFOS 7 – 10) were integrated into the AS-4/PEEK laminate.
In order to reduce the losses caused by residual strain during the shrinking of the laminate the fibres were pre-strained during the fabrication process, which also minimises the misalignment of the fibres inside the laminate. For further reduction of fibre misalignments the capillaries guiding the optical fibres were fixed to a steel plate below the laminate shown in figure 5 (a).

After the fabrication of the laminate, the x-ray image shown in figure 5 (b) was taken. Because of the small x-ray optical contrast between AS-4/PEEK and the PI-coated fibre, the PI-coated fibres (DFOS 1 – 6) could not be visualised as well as the Cu-coated fibres (DFOS 7 – 10). The fibres show a good alignment except for DFOS 5. Because of the fibre breakage between DFOS 5 and 6 during the fabrication the pre-straining of DFOS 5 was lost and therefore, a misalignment of the fibre occurred.

For the distributed loss measurements of the integrated DFOS, the fibres of each DFOS were spliced together as one continuous fibre. This results in alternating fibre sections of integrated and connecting fibres. As a result, the sections without losses represent the connecting fibres while the sections with losses represent the integrated DFOS in figure 6. Two measurements from both sides of the fibre were necessary because of the fibre breakage between DFOS 5 and 6. The losses of the DFOS are assumed to be caused by lateral forces affecting the fibre. These lateral forces would arise from residual stresses during the shrinking of the laminate and from the pressure applied by the press during fabrication. The differing loss of DFOS 5 compared to the other DFOSs is a result of the fibre breakage and the consequential loss of the pre-straining of the fibre.
3. Conclusions and Outlook

Distributed fibre optic sensors (DFOS) based on silica optical fibres for surface-application on composite structures as well as for integration into composite structures have been successfully demonstrated and investigated for SHM at BAM.

The surface-applied structural health monitoring sensors based on polyimide coated optical silica fibres were able to withstand 10 million strain cycles of 1.0% strain and provided reliable and stable sensor signals and distributed measurements by OFDR during this test. Additionally, the surface-applied strain sensors could clearly detect cracks and detachments in the adhesive. The resulting local disturbances of the strain profile did not influence the sensors’ behaviour, instead the sensors kept their functionality and reliability. It was not possible to detect cracks in the samples itself yet, because no cracks arose at the surface of the samples during the conducted tests. As a result, the distributed surface-applied fibre optic sensors not only proved to be an alternative for structural health monitoring of composite structures compared to quasi-distributed sensors such as fibre Bragg gratings and long period gratings, but also clearly demonstrated their major advantage of reliable continuous distributed measurements along the entire composite structure.

The integrated DFOS based on copper (Cu) as well as polyimide (PI) coated optical silica fibres were successfully integrated into AS-4/PEEK laminates for SHM. Significant improvements could be reached concerning the alignment of the optical fibres inside the laminate. Because of the advantages of integrated DFOS to detect cracks inside of the samples compared to surface-applied DFOS, which are only able to detect cracks on the surface, further investigations are planned.

In order to verify that the polyimide coated optical fibre did not oxidise during manufacturing and that both Cu- as well as PI-coated optical fibres are well-integrated into the matrix, cross sections will be taken and evaluated. Additionally, these cross sections will be used for pull-out or indentation tests to determine the adhesion between the laminate matrix, the Cu-respectively PI-coating and the optical fibre.

For the evaluation of the operation stability and the reliability of the integrated strain sensors, fatigue tests similar to the surface-applied sensors with 10 million strain cycles are planned. It is assumed, that the sensors will be able to detect cracks inside the laminate, which will be evaluated either if cracks occur during fatigue testing or by induced cracks after the fatigue testing is completed.

![Figure 6: Loss measurement along the integrated fibre.](image)
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