Integration and evaluation of a meander-shaped fibre-optical sensor in GFRP coupons

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Abstract. Fibre-reinforced plastics are attracting more and more attention also in non-aviation sectors. The possible formation of internal damage and its difficult detection thus simultaneously increases the need for structural health monitoring. In this case especially fibre-optical sensors possess an enormous potential. In the previous work the use of a meander-shaped sensor layout was proposed, utilizing strain in longitudinal direction for loads monitoring and distinct measuring sections in zero-strain direction for structural health monitoring. In the present work, the proposed meander-shaped sensor layout is integrated inside unidirectional coupons using tailored fibre placement. Further samples without a sensor and samples with a straight sensor-fibre were also manufactured as a reference. The influence of the sensor on the static strength and stiffness is then examined in a test campaign using a three-point bending setup. In addition, the functionality of the meander-shaped sensor layout is validated.

1. Introduction

Due to their good strength-to-weight and stiffness-to-weight ratio, structures made of fibre-reinforced plastics (FRP) are attracting more and more attention also in non-aviation sectors. However, predicting component fatigue and fatigue life is a serious challenge. Despite controlled manufacturing processes, it is subject to a wide scatter. The exact time at which the damage is initiated and the exact progress of the damage can only be estimated despite extensive testing. Particularly difficult in this context is the fact that fatigue damage is not easily visible from the outside. They are, especially in the case of purely unidirectional laminates under bending, mainly characterized by matrix cracks and delamination. High, conservative safety factors are therefore required to ensure structural integrity in service, especially in case of long service lives.

Structural health monitoring (SHM) describes the online monitoring of the integrity of a structure in service. Thus, SHM ensures safety of a structure despite current uncertainties concerning fatigue.
Rytter [1] introduced four different levels of complexity in order to classify different SHM approaches:

- Level 1 (detection) refers to a system which detects the mere presence of damage.
- Level 2 (localisation) is capable of determining the rough location of damage.
- Level 3 (assessment) is also able to measure the size and severity of the damage.
- Level 4 (consequence) evaluates the significance of the damage on the structural integrity.

The required complexity of the corresponding monitoring system increases with increasing level of complexity. While a level 1 system can be a relatively simple system that derives a damage from a deviation from the expected measured value, a level 4 system must provide enough information to determine the residual strength due to the damage. This is exactly where the potential of physics-based methods [2] for damage monitoring lies. Based on physical methods and the corresponding analytical and numerical models, a correlation between the damage size, its influence on the selected measurand, the damage indicator, and the resulting residual strength can be determined. This correlation is the basis for an efficient damage assessment.

In combination with physics-based methods, fibre-optical sensors (FOS) offer an enormous potential. They allow the measurement of strain along the fibre at several measuring points (up to a quasi-continuous measurement). Due to their fibre-like shape, FOS can be easily integrated into FRP. For example, an automated sensor integration into a shaft made of glass-fibre reinforced plastic (GFRP) has already been implemented using the braiding process [2].

However, common FOS have a larger diameter than structural fibres. They therefore represent a possible disturbance in the laminate, which can lead to fibre undulations and matrix pockets. The influence of FOS on the strength of a laminate has already been the subject of several studies [3-6]. Still, the results do not allow a general conclusion to be drawn. Many parameters, such as laminate thickness and fibre orientation, have an influence. The influence of a meander-shaped pattern of the FOS has not yet been considered, although preliminary studies [2,7] have shown that this layout is particularly suitable for the simultaneous measurement of possible damage and external loads.

In the present work a series of coupon tests was carried out using the meander-shaped design of the FOS. The aim was on the one hand to ensure the functionality of the FOS inside the laminate and on the other hand to investigate the influence of the sensor on the properties of the host material, starting with the static strength and stiffness.

2. Monitoring concept

This contribution is based on the so-called structural damage indicators [2,7-9]. They are derived by simulating both the undamaged and the damaged component. In direct comparison, structural effects are identified that are directly related to the presence of damage. From this, indicators can be derived that react with high sensitivity to the presence of damage, but are preferably independent of other effects. This ideally results in a zero-baseline, where the deviation can be directly assigned to the damage. The subsequent damage assessment is also simplified, as less filtering/modification of the signal is required.

Especially interesting is the so-called zero-strain direction, which was derived by Schagerl et al. for thin-walled structures [10]. The zero-strain direction describes the direction in the material where there is no longitudinal strain in the reference state despite the applied load. The simplest example to illustrate the zero-strain direction is the consideration of a plate under uniaxial tensile loading as shown in Figure 1. Due to the applied tensile load, a relatively high positive elongation occurs in the longitudinal direction. Transverse to the load, there is a smaller compressive strain as a result of the transverse contraction. If now the strain is measured in a direction rotated by the angle β from the longitudinal direction, a measured value is obtained that is between these two values. The zero-strain direction is the angle β where both effects cancel each other out exactly and thus zero-strain is obtained. In the considered case of uniaxial loading of a plate stripe, it is easily possible to derive the zero-strain direction analytically. The longitudinal strain $\varepsilon_{11}$ in an arbitrary direction $\beta$ is dependent on the strain-state of the corresponding $x_1$-$x_2$ plane.
Figure 1. Illustration of the zero-strain direction for a plate under uniaxial tensile load [7].

\[ \tilde{\varepsilon}_{11} = \frac{\varepsilon_{11} + \varepsilon_{22}}{2} + \frac{\varepsilon_{11} - \varepsilon_{22}}{2} \cos(2\beta) + \varepsilon_{12} \sin(2\beta) \]  

(1)

For the considered load case, there is no shear strain \( \varepsilon_{12} \). Thus, the equation can be simplified and rearranged to:

\[ \cos(2\beta) = \frac{\varepsilon_{11} + \varepsilon_{22}}{\varepsilon_{22} - \varepsilon_{11}} \]  

(2)

Using the definition of the Poisson's ratio \( \varepsilon_{22} = -v_{12}\varepsilon_{11} \) the zero-strain direction is derived as:

\[ \beta_{1,2} = \pm \frac{1}{2} \arccos \left( \frac{v_{12}-1}{v_{12}+1} \right) \]  

(3)

As it can be seen in Equation (3), the zero-strain direction for the considered load case is only dependent on the Poisson's ratio \( v_{12} \) and can thus be considered as material parameter. The height of the applied load has no influence on the zero-strain direction. If a strain sensor such as a strain gage or a FOS is applied in this direction, then no strain is measured in the reference state. If, however, damage does occur, parts of the load will be diverted around the damage due to the local stiffness change (see Figure 2). As a consequence, significant shear strains \( \varepsilon_{12} \) now occur and the assumptions for the derivation of Equation (3) are violated. Thus, there is a measurable strain \( \tilde{\varepsilon}_{11} \) in the former zero-strain direction. This considered case can be directly transferred to simple bending loads such as three-point or four-point bending. In this case, the uniaxial stress state as shown in Figure 1 is present in the plane normal to the applied shear force.

Figure 2. Representation of the changed principal stress direction if damage occurs (grey ellipse) [7].

In order to enable an easy integration of the FOS, it should be located in the interface between two sheets of the host material. Logically, the sensor cannot solely lie in the zero-strain direction. The resulting sensor layout therefore takes on a meandering shape as shown in Figure 3. In the longer, red marked passages, the strain in the zero-strain direction can be measured to allow damage monitoring. In the radii, the strain is measured in longitudinal direction (blue dots). This measurement is relatively insensitive to the damage, but very sensitive to the external load. Thus, the meander-shaped sensor layout enables an SHM alongside loads monitoring. A more detailed presentation of the sensor layout was already done in a previous work [2,7]. This work also includes the simulation of a virtual sensor in a GFRP leaf spring.
3. Test setup
GFRP Coupon tests were performed to test the presented measurement concept. Furthermore, the influence of the FOS on the strength and stiffness of the host material should be investigated. Based on the planned application in a GFRP leaf spring, the coupons were subjected to three-point bending. In total four different configurations were considered: (1) Reference configuration without a sensor, (2) FOS in longitudinal direction, (3) FOS in zero-strain direction and (4) FOS in meander-shape. It should be noted that Configuration 2 and 3 do not include an active sensor. Here the sensor was only integrated into the interface, but not contacted. An active sensor was only used in Configuration 4. In all three cases, the FOS is located at 75% of the height. The FOS is therefore not located on the neutral axis and is thus exposed to part of the applied bending. Figures 4-7 sketch the four different configuration.

Figure 4. Sketch of configuration 1: reference configuration without a sensor.

Figure 5. Sketch of configuration 2: FOS in longitudinal direction (inactive).

Figure 6. Sketch of configuration 3: FOS in zero-strain direction (inactive).
As FOS, a polyimide coated glass fibre with 125 μm cladding diameter and 9 μm core diameter was used. The FOS was evaluated using optical frequency domain reflectometry (OFDR). This method utilizes Rayleigh backscatter to measure a quasi-continuous strain distribution [11] and is therefore very useful especially in the field of research applications. To enable simple sensor integration, the sensor fibre was stitched via tailored fibre placement (TFP) onto a carrier fleece (see Figure 8) which then was inserted at the desired position between the layers of the hosting prepreg material (see Figure 9). The sensor fibre was contacted after successful pressing using an LC/APC connector.

The tests were performed on the universal testing machine Instron 5567 using a displacement rate of 10 mm/min. All tests were run up to an abrupt loss of stiffness after reaching the maximum load. The predicted failure load is 16.7 kN (referring to a maximum bending stress of 1000 MPa) with a deflection of 34.2 mm. In order to obtain the most accurate measurement of deflection, the deformation of the sample was measured using Digital Image Correlation (DIC). The GOM system from Aramis was used for this purpose. The whole test setup is shown in Figure 10.
4. Test results and discussion

4.1. Influence of the sensor fibre on static strength and stiffness

The aim of the test series was to evaluate the influence of the sensor fibre on the static strength and stiffness. For this purpose the samples were loaded quasi-statically until failure and the load displacement curve was recorded. The static strength results from the maximum of the force before abrupt loss of stiffness. The stiffness of the samples is evaluated as averaged stiffness until a load of 6 kN is reached. In this range the load displacement curve can still be considered approximately linear. All load-displacement curves are shown in Figure 11. The different configurations are indicated by corresponding coloured markings. Even though this figure does not allow a detailed evaluation, it can easily be seen that the individual configurations provide very similar results.

The evaluation of the static strength and stiffness is shown in Table 1. The standard deviation s and the difference Δ to the reference configuration are also given here. The strength of all configurations is about 17.9 kN. The deviation of the configurations to each other is minimal and negligible. The average stiffness of the samples is 42.7 GPa. Here the deviations of the individual samples are more significant; however, they are still small compared to the standard deviation. Likewise, no clear trend (increase or decrease) can be deduced. Therefore, it is assumed that the deviations occur within the scope of the sample scatter and are also negligible.

Table 1. Evaluation of the static strength and bending stiffness of the different configurations

| Configuration | Static strength | Bending stiffness |
|---------------|----------------|------------------|
|               | Average        | s    | Δ   | Average       | s     | Δ   |
| (reference)   | 17932 N        | 585 N | (3.3%) | 42742 MPa     | 1826 MPa | (4.2%) |
| (longitudinal)| 17926 N        | 587 N | (3.3%) | 43063 MPa     | 1100 MPa | (2.6%) | + 321 MPa
| (zero-strain) | 17889 N        | 442 N | (2.5%) | 43321 MPa     | 675 MPa | (1.6%) | + 579 MPa
| (meander-shape)| 17889 N      | 331 N | (1.9%) | 42028 MPa     | 796 MPa | (1.9%) | - 714 MPa

Figure 11. Load-displacement curves of all specimens and all configurations.
4.2. Evaluation of the integrated FOS
The measured strain in the FOS is shown exemplarily in Figure 12 for a single specimen. Here the characteristic behaviour can be seen. Outside the sample as well as at the edge of the sample there is no strain. Only when the FOS runs under the first cylinder (at about 400 mm) the measured strain increases linearly. This observation corresponds very well with the expectation: due to the three-point bending, there is a linear bending moment and thus a linear bending stress with a maximum at the middle cylinder. At about 450 mm the measured value breaks down and approaches zero. Here the first meander runs in the direction of zero-strain. This is followed by a single large measured value at 510 mm. Here is the first complete deflection radius with a measurement in longitudinal direction. Afterwards the measured value returns to zero as expected. Only in the middle of the sample there are significant deviations from zero. This can be explained by the disturbance of the stress state due to the load introduction via the cylinder.

Figure 11. Strain measured by the integrated FOS at 15 kN.

Four of six samples show the expected course above described. Two samples could not reproduce a useful signal. Here the sensor fibre was damaged by external influences. It is particularly vulnerable at the point where the FOS is introduced into the sample. Due to the stiffness jump, this area functions as a weak spot. The handling of this problem will be important for further investigations.

5. Conclusion
This paper describes the use of a meander-shaped layout for FOS under uniaxial loading as it occurs under a simple tensile or bending loads (such as three-point or four-point bending). The presented layout measures strain in the zero-strain direction over several passages for damage detection, while strain in the longitudinal direction is used for loads monitoring. The functionality of this concept has been numerically proven in preliminary work for a GFRP leaf spring [2,7]. In the presented test series the meander-shaped FOS was integrated by TFP between the layers of GFRP coupon. Samples without sensor and with straight sensor sections were also examined in order to investigate the influence on the static strength and stiffness.

The results of the test series show that the integrated FOS has no significant influence on static strength and stiffness. The measured deviations were significantly smaller than the standard deviation of the individual configurations, especially with regard to strength. The measurement of the integrated FOS led to the expected result. The linear increase in bending strain due to the three-point bend is clearly visible. The measurement in the zero-strain direction was also carried out successfully. Only in the range of the centre load application there were deviations from zero. It shall be noted that two of
the six samples had a damaged sensor. The point where the FOS is introduced into the sample is particularly problematic. Here, the FOS breaks quickly occur due to the stiffness jump.

Based on the successful test results, the authors will conduct a new test series at the demonstrator level. Here the FOS will be integrated in a GFRP leaf spring. Healthy and artificially damaged specimens are planned to verify the functionality of the measurement concept for the SHM.

The concept of the zero-strain directions can be applied to a wide range of geometries and load cases as long as no hydrostatic stress is predominant (e.g. in the case of pressure vessels). The concrete zero-strain direction is of course dependent on the actual load case. The sensor layout must be adapted accordingly.

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