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METHODS FOR FBG SENSOR INTEGRATION FOR RTM PROCESS MONITORING AND SHM OF THE FINAL CFRP COMPONENT

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Abstract.
Structure integrity or stress monitoring of fiber-reinforced plastic (FRP) components are popular applications of Fiber-Bragg-Grating (FBG) sensor technology in the field of Structural Health Monitoring (SHM). In aerospace industry, health monitoring of safety-critical structures is of particular interest. The use of SHM is one of the key factors to increase flight safety and reduce maintenance and repair costs. Integrated FBGs for monitoring the condition of aircraft components can significantly reduce or even replace costly maintenance by implementing on-demand maintenance, since remote access and real-time data processing are provided.
The research presented in this paper is part of the MORPHO ("Manufacturing, Overhaul, Repair for Prognosis Health Overreach") project. MORPHO is a publicly funded HORIZON 2020 research project aimed at supporting the development of smart aerospace parts equipped with cognitive capabilities and optimizing their manufacturing and lifecycle management. This study provides an insight of the recent research activities regarding the use of FBG sensor technology for smart aerospace structures. The embedded FBG sensor network should serve both the monitoring of the Resin Transfer Molding (RTM) production process as well as the SHM of the final high-end CFRP structures. Since the integration of sensor technology into the RTM (closed mold) manufacturing process includes some unresolved challenges, a hybrid approach is developed to realize a successful implementation.

Key words: FBG, fiber optics, sensors, composite, CFRP, smart structures, SHM, RTM, process monitoring, MORPHO H2020,

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1 INTRODUCTION

The Aerospace industry relies heavily on composites due to their high strength-to-weight ratio, making them ideal for use in aeronautic applications. However, composites are susceptible to damage from environmental factors, such as large temperature changes and high mechanical stresses, which can lead to material degradation, resulting in reduced structural integrity up to structural failure [1]. Accordingly, there is a strong need for a suitable technology for Structural Health Monitoring (SHM), which includes Fiber Bragg Grating (FBG) sensor technology in particular. As a result, FBG sensors have become increasingly popular for SHM of aerospace composite parts applicable in harsh environments [2], [3]. In the aviation industry, FBG sensors are used to monitor critical components such as wings, fuselages, landing gears, and engines [4], [5], [6]. By detecting changes in strain or deformations, FBG sensors can identify potential structural issues before they become serious problems, allowing for early intervention and maintenance. FBG sensors can also be used for monitoring engine components such as turbine blades, compressor blades, and fuel lines [7], [8]. These sensors can detect changes in temperature and strain, allowing for early detection of potential engine failures. Moreover, FBG sensors can be used in flight testing to measure parameters such as wing deformation, engine vibrations, and other structural responses [9]. This data can help engineers improve the design and performance of aircraft.

Due to its simplicity of construction FBG sensors are strongly resistant to corrosion, fatigue, and wear and tear. They can withstand the stress of continuous use and harsh conditions such as high temperatures or even under high radiation environments without breaking down [2], [10]. Furthermore, FBG sensors are extremely small in radial size (< 0.3 mm) and thus lightweight, allowing them to be integrated into the structure of FRP materials without affecting the integrity of the structure [11]. FBG sensors can be multiplexed, meaning that multiple FBG sensors can be implemented along a single optical fiber, allowing for multiple parameters to be measured simultaneously. Since FBG sensors are addressed by optical fibers, they are immune to electromagnetic interference (EMI) and can be used under critical conditions in potentially explosive atmospheres, as no electrical connections are required [12]. Overall, FBG sensor technology provides a reliable and accurate way to monitor and measure various parameters in aviation applications and provides essential data to improve aircraft design, performance, and safety.

The present study gives an inside of using the FBG sensor technology for SHM of a hybrid-material specimen, referred to as Foreign Object Damage FOD-panel in the following. This FOD-panel represents an engine fan blade and consists of a 3D woven CFRP body and a metallic leading edge protection. The embedded FBG sensors are intended to be used in two phases: (1) during the Resin Transfer Molding (RTM) manufacturing process of the FOD-panel and (2) for SHM after its production. This approach offers the potential, in addition to the capabilities for SHM of the composite part, to improve the RTM process through gaining extended process control using the sensors for process monitoring. Integrated FBG sensors in the preform can be used to monitor the temperature and flow front of the resin during the manufacturing process [13]. A main challenge for the use of FBG sensors for RTM process monitoring is the sensors integration in a way that they could be used for RTM process monitoring and also for SHM of the composite part. To meet these challenges, a hybrid approach is developed within MORPHO project and addressed in this study. This study presents various approaches for integrating fiber optic sensors into the RTM preform. In addition, the paper provides insight into the different approaches for connectiong the embedded optical fibers during and after the RTM process. Furthermore, the results of experiments demonstrating an approach to using FBG data for monitoring the manufacturing process of composites and monitoring loading with respect to SHM are presented.

2 FBG SENSOR TECHNOLOGY

Fiber Bragg Grating is a periodic refractive index modulation inscribed conventionally into the core of an optical fiber with a regular grating period Λ (See **Figure 1**).

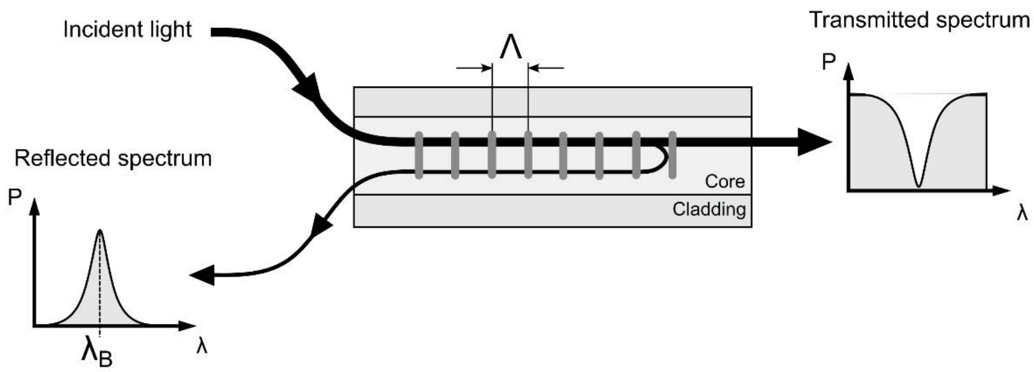

Figure 1: The schematic of fiber Bragg grating inscribed into the core of an optical fiber.

This periodic modulation leads to the reflection of a particular wavelength by coupling the spectral broadband light into the optic fiber. The reflected wavelength is known as the Bragg wavelength λ_B [14] and given by

$$\lambda_B = 2n_{eff}\Lambda,$$

where n_{eff} is the effective refraction index. The reflected Bragg wavelength depends on changes in fiber properties caused, for example, by temperature variation and external strain, resulting in a wavelength shift $\Delta\lambda_B$ of the Bragg wavelength. The shift due to strain and temperature influence is given by:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_e)\Delta\varepsilon_z + (\alpha+\xi)\Delta T,$$

where $\Delta\lambda_B/\lambda_B$ is the Bragg wavelength variation, ρ_e is an effective photoelastic constant, $\Delta\varepsilon_z$ is the applied longitudinal strain in the fiber, α is the thermal expansion coefficient of the glass fiber, ξ is the thermo-optic coefficient of the glass fiber and ΔT is the temperature variation. Measuring this shift is the basic operating principle of many FBG-based sensor systems. One of the main benefits of Fiber Bragg Grating is its ability to be multiplexed in one optical fiber. This is possible because each grating can be tuned to reflect a different wavelength. Many gratings can be written in only one optical fiber with different grating periods at specified locations along an optical fiber.

3 POSITIONING OF FBG SENSORS

The FBG sensors embedded in the FOD panel have multiple purposes: Monitoring the resin front flow during the RTM process and measuring the load conditions during mechanical tests. In the MORPHO project, a symmetrical arrangement of the sensors has been chosen to meet the requirements of both application scenarios simultaneously. The lead-in of each optical fiber can be placed in such way that the fibers are led to one of two fiber-optical-feedthroughs. This implies that the sensor network is designed to always have some fail-safe redundancy and will still be operational if one feedthrough is damaged during the RTM process. The positions of the sensors are shown in **Figure 2**. In total, 40 horizontal sensors are distributed equally on 5 fibers with 8 sensors. Two fibers are integrated during the weaving process, which are not shown in the figure. The 12 additional, redundant FBG sensors are distributed on a similar sensing area in vertical orientation using only one fiber and 12 FBG sensors.

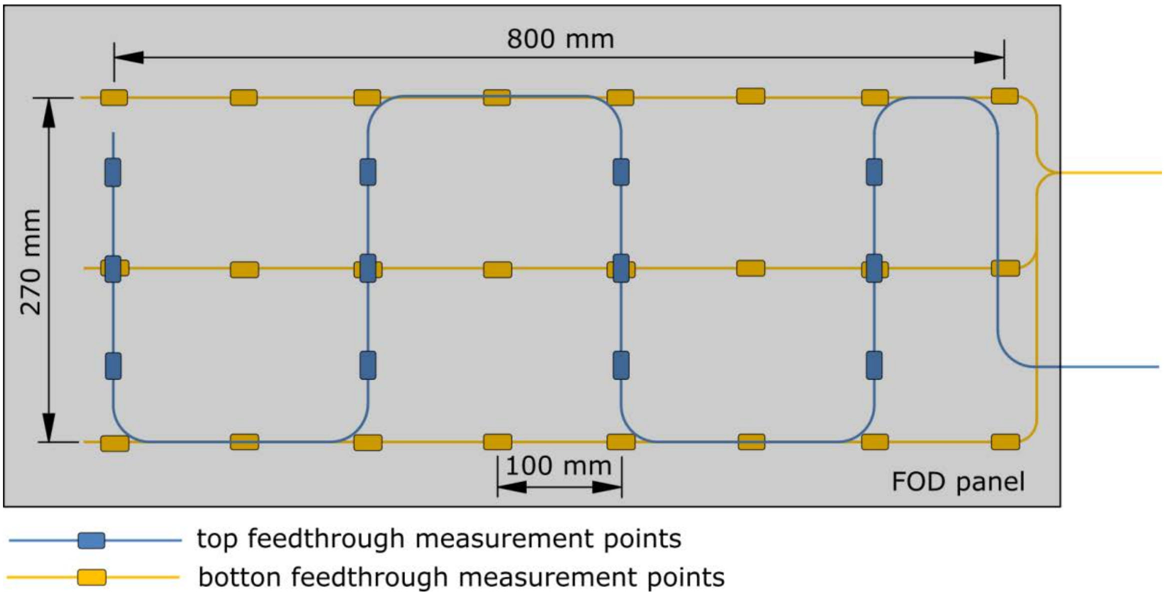

Figure 2: FBG positions for monitoring the RTM process: (orange) available via the top feedthrough, (blue) available via the bottom feedthrough.

4 FBG INTEGRATION METHODOLOGY

Basically, there are two possibilities for inserting the optical fibers into the component part manufactured with the RTM process. The first possibility already comes up during the weaving of the preform. This has explicit advantages, such as the possibility of placing the FBG sensors in deeper component layers and the advantage that the optical fibers are inserted together with the carbon fiber bundles and thus, they are well connected into the force path of the fiber bundles. The second option is the subsequent insertion of the optical fiber after the preform has been manufactured by the weaving process. Here, optical fibers can only be integrated in the outer surface of the preform. The manual integration offers the important advantage that it can be carried out flexibly and independently of the carbon fiber bundle path. This also offers the possibility to lay transverse sensor fiber sections. The details of the developed integration methodology using an insertion capillary are presented below.

The manual FBG sensor embedding process is based on the manual integration of individual optical fibers into the surface of the CFRP preform. The optical fibers containing the FBG sensor arrays are inserted using a 1 mm thick steel capillary, which is inserted under the top layer of the preform fiber bundle in the first step. To assist insertion of the steel capillary, an additional steel capillary can be used to slightly lift the transverse fiber bundles (see **Figure 3**). After the steel capillary is fully inserted, the optical fiber with the FBG sensor array can be inserted into it. Subsequently, the steel capillary can be pulled out to the back so that the optical fiber takes its place in the preform. Placing the FBGs at the right position in the component completes the integration process.

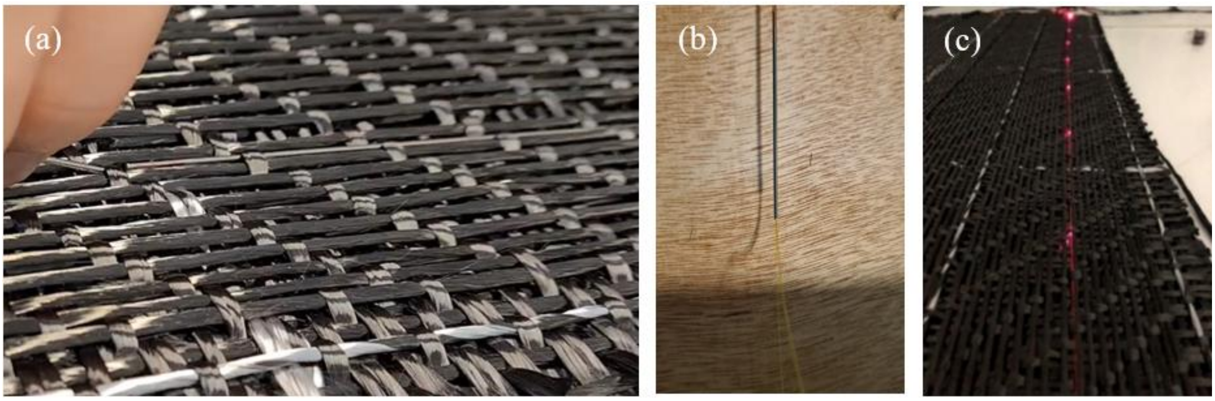

Figure 3: (a) Manual embedding of a steel capillary for integration of a optical fiber into the preform; (b) Steel capillary with inserted glass fibers; (c) Preform with integrated FBG sensor array (visualized by lighting the optical fiber).

5 FBG CONNECTING SOLUTIONS FOR RTM PROCESS

Two approaches for connecting the FBG sensors have been developed. The first approach, using a vacuum feedthrough in combination with a steel tube, aims at using the FBG sensors for both, the RTM process controll and the SHM of the FOD-panel. The second approach is to securely embed protected connector sockets or the optical fibers themselves into the CFRP part in order to use the embedded FBG sensors only for SHM of the FOD-panel.

5.1 Feedthrough Solution for RTM process monitoring

The fiber optic feedthrough solution allows multiple optical fibers to be fed out of the RTM mold at two separate locations next to the resin outlet. The feedthrough must ensure two things: First, the optical fiber must survive the RTM process, and second, the mold must be sealed so that the vacuum is contained and no resin is leaking even at high resin pressures. The general concept of RTM mold fiber-optic feedthrough is represented in **Figure 4**.

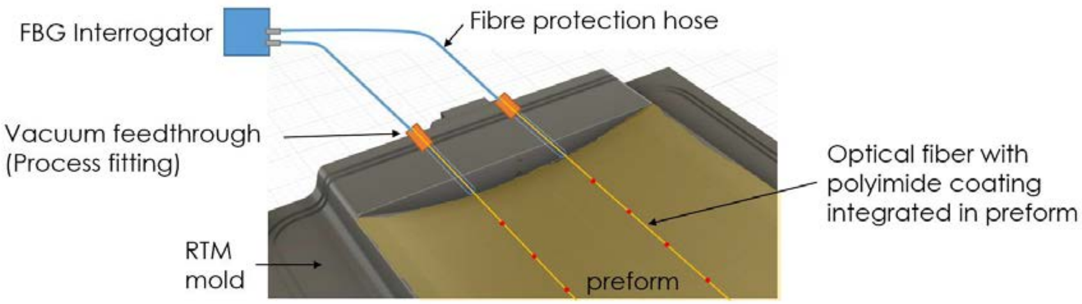

Figure 4: General concept of RTM mold fiber optic feedthrough represented by two optical fibers integraded into a preform.

The fiber optic feedthrough consists of two main components: A commercially available vacuum process fitting and a steel tube. The vacuum process fitting is screwed into the outside of the RTM mold, guiding the steel tube through the RTM wall to the CFRP preform. An essential aspect of the fiber optic feedthrough concept is the internal sealing of the glass fibers inside the steel tube. For this purpose, a low viscosity epoxy adhesive (Polytec EP 641) with a temperature stability of 180°C (230°C short-term) is used. At the end of the steel tube an optional protection hose is used to protect the bare fibers. The steel tube is equipped with a sealing ring and with two insertion bars to improve the adhesion to the CFRP part. Accordingly, it will remain attached to the FOD panel after the RTM process. Schematically, the cross-section of the RTM mold with fiber-optic feedthrough and the concept for improved attachment of the steel tube to the FOD panel are shown in **Figure 5**.

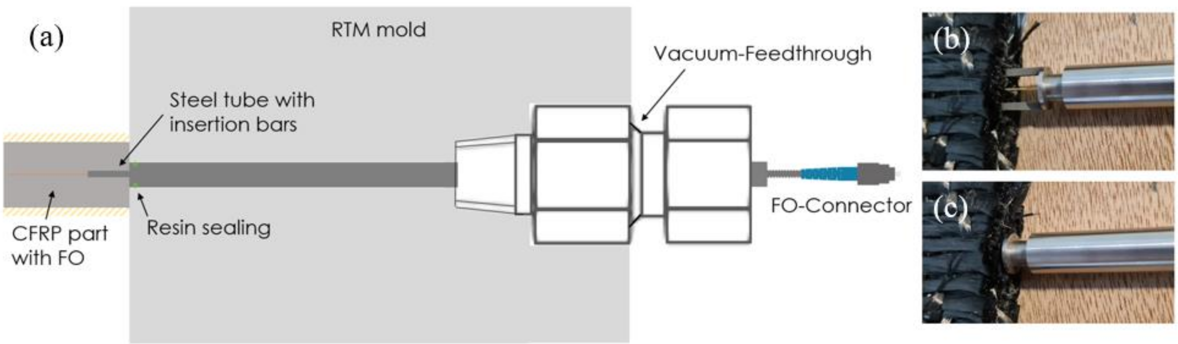

Figure 5: (a) Schematic cross-sectional view of the RTM mold wall showing fiber optic feed-through concept; (b) Steel tube with insertion bars in front of the CFRP part; (c) Steel tube inserted into the edge of the CFRP part.

5.2 Embedded connectors

In addition to the fiber optic feedthrough approach, three concepts of embedded FBG connecting solutions for the RTM process have been developed and tested: (a) fiber optic connector solution; (b) fiber optic ferrule solution; (c) bare fiber solution protected by a glass bulb. The concepts are shown schematically in **Figure 6** (a, b, c). A fiber optic connector solution is based on using the commercial standard DIN/APC connector directly attached to the preform. It is protected by silicone rubber potting, which can withstand high temperatures and pressure during the RTM process and can be removed without residue from the connector after the process is finished. The silicone rubber is vacuum-compatible and can operate in the temperate range of -55 °C to 260 °C. In laboratory tests **Figure 6**(d), it was verified that the potting fully encapsulates the connector and fills minimal gaps.

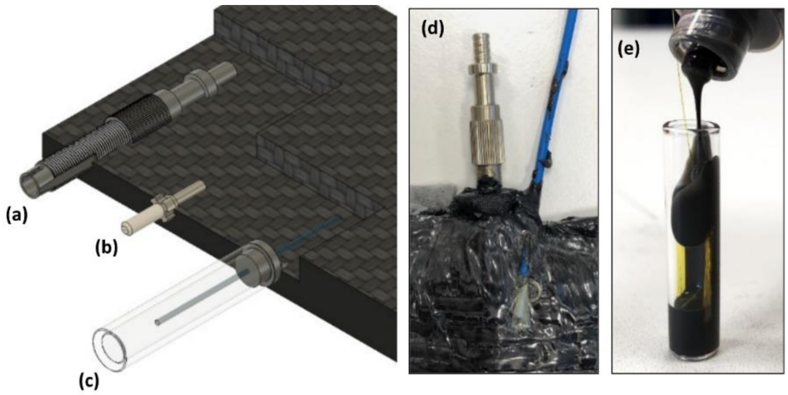

Figure 6: Schematic overview of FBG embedded connecting solutions for RTM process: (a, d) fiber optic connector solution; (b) fiber optic ferrule solution; (c) bare fiber solution protected by a glass bulb and (e) its manufacturing process.

The second connecting solution is the use of a fiber-optical ferrule, which is the inner part of a standard fiber optic connector and is responsible for the alignment of the cores of both connecting fibers to each other, establishing the fiber optic connection. Tests showed that it is more compact than an entire connector but has more losses in signal and is more sensitive to external influences. An additional mechanism to secure the optical connection must be applied for field applications. The third solution involves employing the bare fiber to decrease the cross section needed to store the connection. Inside the blind hole (containing the connector or ferrule), a small fiber spool protected by a glass bulb could be placed. Internal tests showed that the fibers would not be destroyed when they are forced to hold these critical bending radiuses, even for several weeks, and that they would regain their optical conduction after returning to normal operating conditions. When embedding the fiber spool, it must be protected from resin. This can be done by coiling it up and placing it in a flat bottom tube sealed with silicone so that no resin can reach the coiled fiber, see **Figure 6**(e).

5.3 Comparison of different solutions

Comparison of different solutions to access the FBG sensors with an external measurement system after embedding them into the FOD-panel is shown in **Table 1**.

Table 1: Comparison of different solutions to access the FBG sensors with an external measurement system after embedding them into the FOD panel.

Solution	Advantages	Disadvantages
Fiber-optic feedthrough connection	- The front flow parameters can be monitored during the RTM process.	- Sensors can easily be destroyed during the de-molding process.
Fiber-optic connection using embedded connectors	- There is no need for sealing the mold, thereby reducing the risk of damaging the connector during the de-molding. - It is robust when handling and removing the FOD panel from the mold.	- The FBG sensors are not available during the RTM process; thus, the front flow parameters cannot be monitored during the RTM process. - The preparatory work is relatively time intensive.
Fiber-optic connection using embedded ferrules	- There is no need for sealing the mold, thereby reducing the risk of damaging the connector during the de-molding. - Reduction of cross section needed inside the part.	- The FBG sensors are not available during the RTM process; thus, the front flow parameters cannot be monitored during the RTM process. - It has more losses (In contrast to connector) and is more sensitive to external influences.
Fiber-optic connection using bare fiber	- There is no need for sealing the mold, thereby reducing the risk of damaging the connector during the de-molding. - Reduction of cross section needed inside the part.	- The FBG sensors are not available during the RTM process; thus, the front flow parameters cannot be monitored during the RTM process.

6 EXPERIMENTAL RESULTS

Since no tests with sensorized FOD panels can be performed at the present project stage, laboratory-scaled experiments are presented. These laboratory-scale experiments were carried out using a specimen of a section of the 3D-woven preform with embedded FBG sensors. The FBG sensors were manually inserted into the outer layer of the preform. Results of an experiment on process monitoring and the results on load monitoring of this preform section specimen are presented. The specimen positioning of the respective experiment setups are shown in Figure 7.

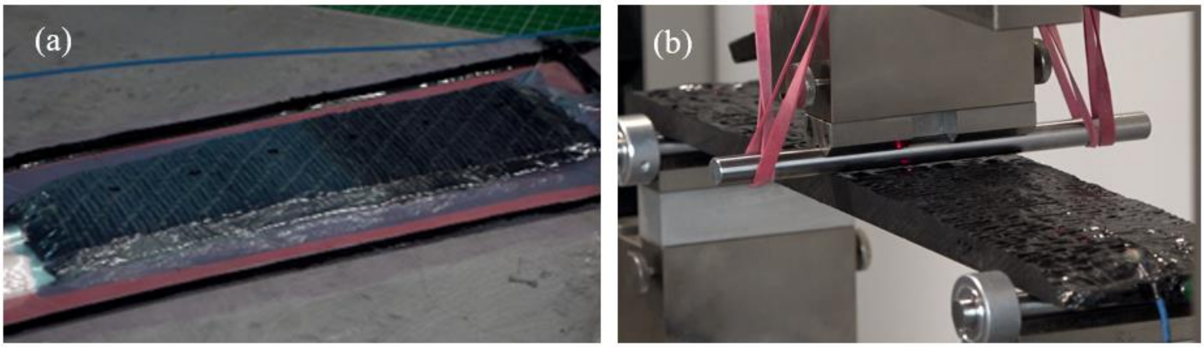

Figure 7: (a) Vacuum infusion process of a preform section specimen with integrated FBG sensors, (b) Sensorized CFRP specimen in 3-point-bending test bench.

6.1 Process monitoring

For initial evaluation of the suitability of the embedded FBG sensors for process monitoring, a sensorized preform section specimen was infused with resin by vacuum infusion process. The aim was to evaluate whether the passage of the resin flow front can be represented in the FBG signal. A graph of the recorded wavelength of 5 FBG sensors versus time is shown in **Figure 8**: Wavelength-shift of 5 integrated FBG sensors in prefrom section specimen duing vacuum infusion process with marked visual detected resin arrival at each FBG position.

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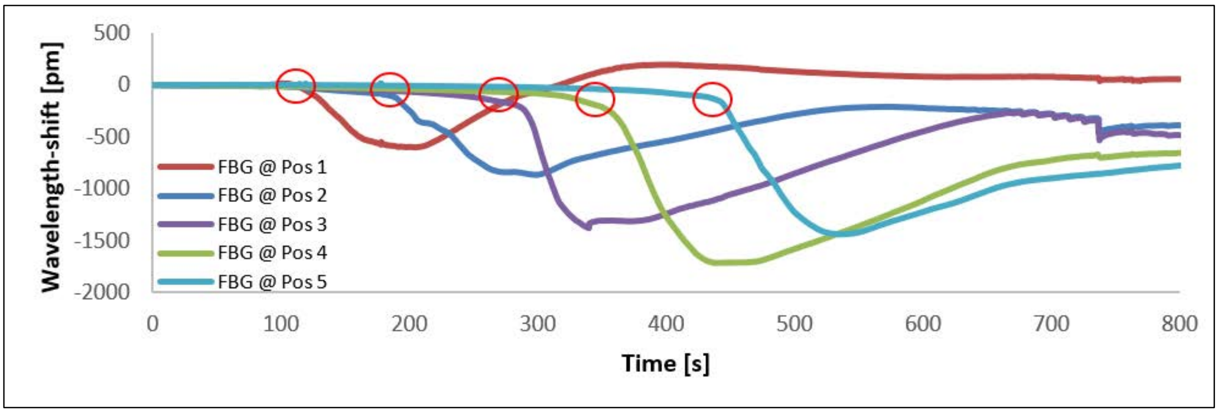

Figure 8: Wavelength-shift of 5 integrated FBG sensors in prefrom section specimen duing vacuum infusion process with marked visual detected resin arrival at each FBG position.

The infusion process was performed at room temperature (20°C), resin and component were not heated during the infusion. The diagram shows the signal curves of 5 integrated FBG sensors placed serially along the specimen. The first FBG was placed on the sample surface at the resin inlet side and the last one towards the vacuum port, while the second, third and fourth FBG were evenly distributed along the specimen length. As can be seen, the arrival of the resin resulted in a significant decrease in wavelength at each FBG. This initial wavelength shift was between 500 pm and 1700 pm. Following this significant decrease in wavelength, there was an increase in each FBG signal. Combined effects of temperature, tension and compression on the optical fiber and varying pressure influences can lead to these effects. Furthermore, even small mechanical influences can affect the FBG signal. For example, moving air bubbles at the flow front can lead to an influence on the sensitive FBG signal. This laboratory-scaled experiment shows that FBG sensors are clearly evident for monitoring the resin flow front during the vacuum infusion process. The transfer of these results to the RTM process and the analysis including data interpretation of FBG signals during the RTM process are important aspects for evaluating FBG sensors for their intended use as sensor technology for RTM process monitoring.

6.2 Load monitoring

To investigate the SHM capabilities of the embedded FBG sensors the specimen of a preform section was loaded in a 3-point bending test. The graphic in figure X shows the force curve of the 3-point bending machine with an exemplary FBG signal of the integrated optical fiber. For this experiment, the bending force was increased steadily up to 500 N, and was then immediately relieved to 0 N. The strain measured in the component corresponds very closely to the bending force curve. This test demonstrates the capability of the embedded FBG sensors to detect bending loads in the component.

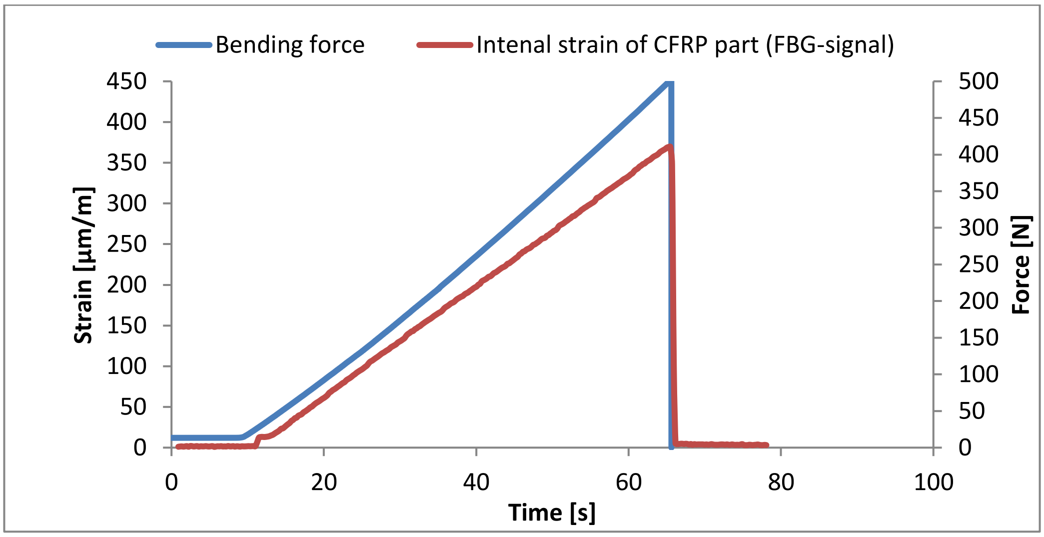

Figure 9: Internal strain of CFRP specimen (FBG Signal) and bending force during 3 point bending test.

7 CONCLUSION

FBG sensors are an effective tool for monitoring composite structures. Several capabilities, such as, high accuracy, durability,multiplexing capabilites and the possibility to integrate FBG sensors into composite structures due to their small size, make them ideal for SHM application especially in the aviation industry. In addition, this study demonstrates that FBG sensors have the potential to be used to monitor the RTM manufacturing process of the composites.

The hurdles of integrating the sensor technology, as well as connecting the fiber optics to the readout during the RTM process, present some challenges for which this paper provides potential solutions. Furthermore, different approaches for the protected integration of the connectors and fiber ends into the RTM are shown, which will be tested and evaluated regarding their suitability in further investigations. The experiments in this study demonstrate the capabilities of FBG sensors for process monitoring and for use in SHM. Verification of the results using the RTM process and fatigue experiments of the fabricated FOD panels will be addressed in future work.

8 ACKNOWLEDGEMENTS

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