INTEGRATION OF FIBER OPTIC SENSORS INTO CFRP FOR STRUCTURAL HEALTH MONITORING OF A MARINE COMPOSITE PROPELLER

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Abstract
The purpose of this study is to investigate several aspects of implementing a fiber optic distributed sensing system into a composite laminate. The integration of sensors and their effect on the mechanical properties of the host composite material were examined. The analysis of the measurements was focused on evaluating the strain acquired measurements from the sensors. To evaluate the impact of the optical fiber (OF) on the mechanical properties of the host composite material, specimens with and without integrated OF were subjected to mechanical testing. Furthermore, the fiber optic system was utilized to monitor strain under 3-Point bending loading and the acquired data were correlated with the loading condition. The integration tests manifested that the protection of the optical fiber at the ingress and egress points of the fabric is critical for the survivability of the sensor. The mechanical tests validated that the optical fiber does not degrade the mechanical properties of the composite material. The results of the measurements indicated that the system is suitable to monitor the structural integrity of the material as the obtained strain values were equivalent to the applied loading condition.

1. Introduction

The application of composite materials is wide to many industrial sectors due to their many advantages such as low weight, high mechanical strength, high stiffness, and vibration damping ability. However, their main drawback is the existence of imperfections inside the material which can reduce their mechanical properties and lead to unpredictable failure. For several years, Non-Destructive Testing (NDT) was applied on composites for early damage detection and determination. Later, scientists focused on the development of Structural Health Monitoring (SHM) systems and methods. SHM systems provide continuous information for the integrity of a structure during operation. Detection of measures that indicate damage at an early stage enables better exploitation of the materials. Damage can be detected by comparing the responses of the structure, acquired by sensors, before and after it occurs. Consequently, the only way to acquire information related to damage is by processing and comparing the raw signals received from the sensors before and after damage. Signal processing provides the feasibility to identify the "features", or parameters, which are sensitive to minor damage and can be distinguished from the response to natural and environmental disturbances [1]. Several types of sensors can be used for this purpose. However, only those based on fiber optic technology offer the capability to perform quasi-distributed, and distributed measurements and can be embedded within the structure.

The optical fiber consists of 3 parts: a glass core, a glass cladding and a polymer coating. The cladding has a lower refractive index than the core so that light can travel inside the core of the optical fiber due to the total internal reflection effect [2]. There are 3 main categories of fiber optic sensors: Grating based sensors, Interferometric sensors, and Distributed sensors. Distributed fiber-optic sensors provide a continuous profile of measurements over the length of the optical fiber and thus are most suitable for large structural applications. Three main physical effects are used for distributed sensing: Brillouin scattering, Rayleigh scattering, and Raman scattering [3]. The Rayleigh scattering is significantly larger than the Raman and Brillouin and thus provides distributed sensing with measurements of a spatial resolution in the mm range.

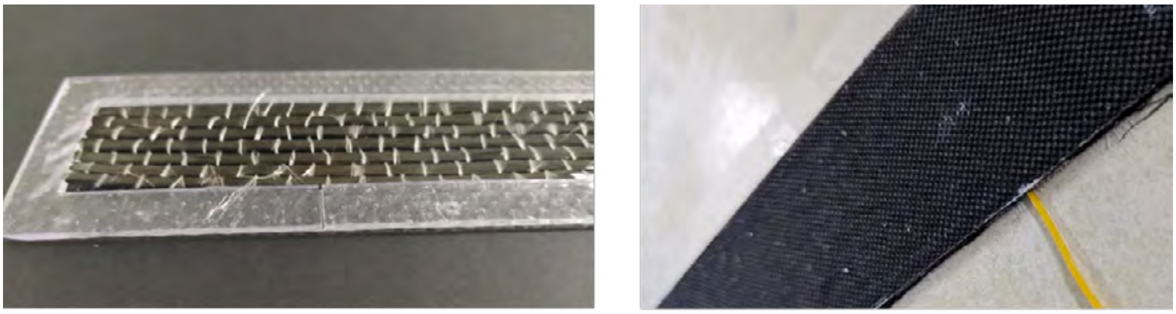
Fiber optic distributed sensing measures strain and temperature by processing spectral shift in the Rayleigh backscatter of optical fibers integrated in a structure. When the strain in the fiber changes, the spectrum of back-scattering signals will drift in terms of frequency. The amount of drift is proportional to the strain generated by the optical fiber. Through relevant calculation of the measured and initial signals, the drift value can be obtained. The distributed strain information of the entire optical fiber can be obtained by scanning [4]. The method described above is known as Optical Frequency Domain Reflectometry (OFDR).

2. Experimental Procedure

2.1. Integration of optical fiber

Integration tests have been performed to investigate the functionality of embedded fiber optic sensors. The fiber optic sensor was embedded into the composite by integrating the optical fiber to the fabric before the manufacturing process. The integration of the sensor using different methods has been tested and several parameters of the manufacturing process that affect the survivability of the integrated sensor have been identified. Composite plates with integrated optical fibers were fabricated with several modifications on the process to ensure the functionality of the optical fiber after the manufacturing process. Regarding the integration of the optical fiber (OF) on the fabric the following protocols were tested: 1) interwoven optical fiber to the fabric, 2) OF placement through the stitching of the fabric, 3) OF positioning at a certain location and fixing in place with loops of carbon fibers and 4) sewing the entire length of the OF with carbon fibers. The examined means for protecting the optical fiber were a) plastic tubes at the ingress and egress points, b) grooves on the metallic spacers, c) silicon application, and d) wax application. The integrity of the embedded optical fiber was checked after fabrication using a visual fault locator.

After identifying the parameters that lead to breakage of the optical fiber during the manufacturing process a specialized method was developed. The key feature of this method was a resin 3D-printed spacer with dimensions of the specimen of interest and a groove to accommodate the optical fiber at the ingress and egress points. Additionally, wax was applied on the plastic tube in the groove area to secure that no resin leakage would occur. The purpose of the above-described method was to manufacture specimens with good quality at the edges and ensure the functionality and survivability of the embedded sensor (Figure 1).



(a) (b)

Figure 1. Manufacturing process of specimens with integrated OF a) Resin 3D printed spacer with grooves to extract the OF, b) specimen with an integrated fiber optic sensor.

2.2. Mechanical characterization

3 Point bending tests based on ISO 14125 and NR 546 BV guidelines and tensile experiments based on ISO 527 were conducted to validate the minimum effect of the optical fiber to the mechanical properties of the host material. Regarding the 3 Point bending tests, quasi-isotropic specimens were manufactured to check the effect of integrating the optical fiber in parallel and perpendicularly to the reinforcement. As for the tensile tests, the optical fiber was positioned in parallel to the reinforcement. In the 3-point bending specimens 4 OF were integrated in different offsets from the midplane and symmetrically positioned to monitor tensile and compressive developed strains. The layout of the specimens is presented in Figure 2.

The LUNA ODiSI fiber optic system was used to monitor the developed strain during the mechanical tests. The ODiSI system is based on the Rayleigh fiber optic sensing technology combined with optical frequency domain reflectometry. The interrogator of the system transmits the optical signal to the fiber and the signal travels in the core of the optical fiber based on the total reflection effect. The properties of the backscattered Rayleigh profile change with strain application as the optical fiber is stretched or compressed. The ODiSI system correlates the changes in the optical properties of the fiber with strain and provides the strain values to the user.

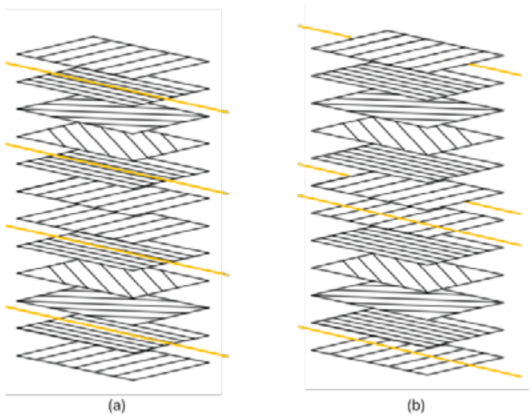


Figure 2. OF layout in the 3-point bending composite plates (a) OF placed in parallel with the reinforcement, (b) OF placed perpendicularly to the reinforcement.

3. Results and discussion

3.1. Tensile test results

The results of examining the impact of the embedded optical fiber on the mechanical properties of the host material under tensile loading are presented on Table 1. The failure stress of specimens without and with an integrated optical fiber was compared. The integrated optical fiber caused 2.6 % strength reduction to the material.

Table 1. Tensile results.

	Specimens without OF	*Specimens with 1 OF*
Number of samples	5	6
Average failure stress (MPa)	1389	1353
STDV	166	129

3.2. 3 Point bending test results

The effect of the embedded optical fiber on the mechanical properties of the composite material under 3 Point bending load are presented on Table 2 and Table 3. The failure stress of specimens without and with four integrated optical fibers was compared. The optical fiber caused 0.7 % strength reduction to the material when it was embedded in parallel to the reinforcing fibers and 0.9 % strength reduction when embedded perpendicularly to the reinforcement.

Table 2. 3 Point bending loading with OF embedded in parallel to the reinforcement.

	Specimens without OF	*Specimens with 4 OF*
Number of samples	4	4
Average failure stress (MPa)	503	500
STDV	42	9

Table 3. 3 Point bending loading with OF embedded perpendicularly to the reinforcement.

	Specimens without OF	*Specimens with 4 OF*
Number of samples	4	4
Average failure stress (MPa)	503	499
STDV	42	37

The results of strain measurements over the length of 2 specimens, Specimen A and Specimen B under the same applied 3 Point bending load are presented in Figure 3. The embedded optical fibers were symmetrically placed in relation to the midplane of the specimen (bending neutral axis) to acquire strain under tension (OF1) and compression (OF2). In Specimen A, 2 optical fibers were placed near the external surfaces of the specimen, where the maximum strain values were expected. In Specimen B the optical fibers were placed near the midplane of the specimen, where the minimum strain values were expected.

The structural health monitoring system captured the bending deformation of the specimen. The acquired strain was minimum near the edges of the specimen and maximum at the middle of the specimen's length. Strain values measured over the length of Specimen B were lower compared to the

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one's measured over the length of Specimen A as it was expected from the theoretical profile of stress distribution on a beam's section under bending load.

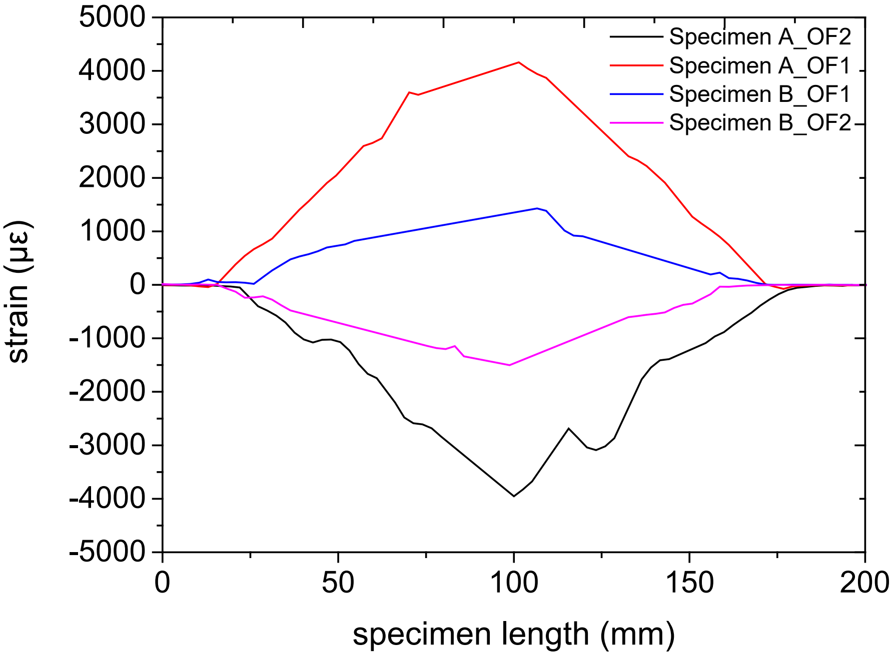

Figure 3. Strain measurements over the specimen length under 3 Point bending with 2 OF symmetrically placed near the external surfaces of the specimen (Specimen A) and near the midplane of the specimen (Specimen B).

4. Conclusions

The mechanical test results of this study proved that the integration of the optical fibers does not degrade the mechanical properties of the host fiber reinforced composite material while offering to the composite the capability of structural integrity monitoring. This capability was manifested by the acquired strain values under loading conditions which were equivalent to the loading scenario of the utilized three point bending test. However, the manufacturing process of the composite plates requires elaborate design and careful handling for the sensor to survive integration into the composite structure after the curing process. On these lines, this study indicated that the most efficient protection method of the optical fiber at the ingress and egress points of the specimen during the manufacturing process is presented in Figure 1 which is a configuration developed after examining different protective measures.

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References

[1] A. Güemes, A. Fernández-López, and B. Soller, Optical fiber distributed sensing - physical principles and applications. *Structural Health Monitoring*, volume(9):233–245, 2010.
[2] J. M. López-Higuera, Fiber optics in structural health monitoring. *Collocated National Fiber Optic Engineers Conference*, 2010.
[3] G. Rajan and B. G. Prusty, *Structural health monitoring of composite structures using fiber optic methods*. Taylor & Francis Group, Florida, 2017.

[4] L. Gao, Y. Cao, H. L. Liu, G. Q. Kong, X. Cheng, and X. L. Zhang, Distributed monitoring of deformation of PCC pile under horizontal load using OFDR technology. *IOP Conference Series: Earth and Environmental Science*, 2020.