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Reliability of strain monitoring of composite structures via the use of optical fiber ribbon tapes for structural health monitoring purposes

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ABSTRACT

In aerospace industry, a lot of effort has been focused on the practical implementation of optical fibers on composite subcomponents for health monitoring purposes during the service life of an aircraft. To this direction the fiber optic ribbon tapes (FORTs) concept was developed in order to ease the handling, the surface placement and the maintenance of such sensitive sensors. In this paper, we investigate the structural durability of this concept comparing two ways of mounting the FORT (co-bonding and secondary bonding) under fatigue loading conditions. Through long term fatigue tests and utilizing additional experimental (electrical strain gauges (ESG)), theoretical as well as numerical tools, it is concluded that the deviation of the experimentally measured strains using the FORT approach versus conventional ESG values are well within an error of maximum 6%. Moreover, they remain in this error bound for as much as 10^6 loading cycles, rendering FORTs a reliable solution for aerospace SHM. In the final part of the study, the effect of the FORTs placement on the stiffness of a structure is assessed through numerical analysis of the changes of the dynamic characteristics as well as the modal response of an aeronautical subcomponent representative of a wing front spar.

1. Introduction

The continuously growing composites industry combined with the global effort to reduce maintenance costs across industrial applications and also the need for better utilization of resources and materials create the ground for novel structural health monitoring systems (SHM) to be developed. The need for reliable use of high performance composite materials to aerospace structures is a characteristic example [1], hence the implementation of health monitoring techniques that enhance the safe operation of a structure is of top priority. Researchers across the world are working to this direction. Examples of lab-scale and relatively low to medium Technology Readiness Level (TRL) systems with the ability to monitor physical and/or mechanical properties (i.e. temperature, strain, displacement, acceleration) of structures during pre-defined operating conditions are abundant in the relevant literature [1–5].

From the variety of SHM techniques, a lot of attention has been devoted the last 20 years on strain sensing with optical fibers with inscribed FBG sensors. FBGs are a state-of-the-art class of sensors that have been recognized to suit this purpose for various structural applications [6–8]. They are used for sensing applications, for measuring temperature, strain, pressure, refractive index etc. They offer many advantages over classic electrical sensing devices. Among the most important ones is their advantage of multiplexing by using different wavelength of light for each sensor. Hence, a large number of optical sensors can be inscribed in a single fiber optic cable utilizing only one channel in the interrogation unit. Worth mentioning in the case of composite structures, is their flexibility to be placed either on the surface of the composite component of interest, or embedded inside the composite structure [9]. The integration of optical fiber sensors into the composite material could allow potentially in situ curing monitoring during the manufacturing process, and further on, the same sensors can be utilized for the component qualification/approval, as well as for the monitoring of the structural integrity during its service life [10]. The concept of embedment, despite its advantages, is under certain criticism since it is argued that the mechanical properties of the host structure degrade [11], since the region of material around the embedded FBG is a potential site of damage initiation and additionally the maintainability of the sensor network in case of sensor/optical fiber failure becomes questionable. Other studies [12–15] support that the influence of the optical fiber is negligible

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if deployed in the direction of the reinforcement fibers. No decreased properties have been reported on specimens with optical fibers when subjected to tensile, bending or even interlaminar shear stress tests. Especially for the aeronautics industry, an otherwise certified-to-fly material with an embedded sensor network is regarded as a new material that requires the long and costly process of full certification.

A number of studies have focused on their metrological characteristics trying to assess their performance as compared to the "conventional" electrical strain gauges (ESGs). In [16], Baere et al. study the reliability of FBG sensors embedded and surface attached in thermoplastic composites for half a million cycles. The FBG readings from the embedded sensor are compared with the extensometer measurements showing excellent correlation of the measured strains despite the fact that the two measuring devices actually measure strain at different locations. Excellent operation of the FBG sensor is reported throughout the whole duration of the fatigue test. In an earlier study in [17] De Waele et al. conducted a similar study during quasi-static loading of composite pressure vessels with main focus on assessing the reliability and accuracy of FBG versus ESG sensors. They conclude on the clear superiority and stability of FBG sensors reporting a difference of 5–10% with the measurements acquired via ESGs. Groves et al. [18] compare surface strain measurements from a hydrostatically loaded ABS pipe with three techniques: speckle shearography, FBG sensors and ESG sensors to find reasonable agreement between experimental and theoretically calculated axial and hoop strains. They report variations of FBG versus ESG values of maximum 10% for axial strains and only 0.1% for hoop strains attributing high variations to slight misalignment of the respective sensors as well as local inhomogeneities (defects, non-uniform thickness) of the structure. FBG values from theoretically obtained ones deviate as much as 4% and 7%.

Friebele et al. [19,20] performed cyclic tests (100 cycles) on a composite C-channel instrumented with an array of FBG sensors to assess the survivability and reliability of the embedded sensors. Good agreement with surface bonded strain gauges was observed. Kalamkarov et al. [21] conducted a wide range of experimental tests focusing on the long-term performance of FBG sensors embedded in composite materials. Specimens with embedded FBG sensors were subjected to multiple loading cycles and it was shown that the sensor output offered excellent agreement with the results of a surface mounted extensometer. In addition, dynamic tests were conducted in which the FBG sensors were subjected to trapezoidal and sinusoidal waveform loadings. The authors reported that the strain output of the sensors again agreed very well with that of the extensometer. In another study, Mrad et al. [22] conducted cyclic load tests to evaluate the reliability, durability, and fatigue life performance of bonded FBG sensors. It was shown that bonded FBGs exhibit longer fatigue lives than electrical strain gauges.

The present work aims to prove the reliability of the concept of a fiber optic ribbon tape (FORT) to provide accurate and repeatable strain measurements under prolonged cyclic loading of one million cycles at high strain levels (up to 4,000 $\mu\varepsilon$). FORTs are actually precured ribbon tapes that are separately produced by embedding the optical fiber(s) between two compliant laminas of glass/epoxy woven fabric prepreg. This concept eases the handling, mounting and replacement of the optical fibers on a structure and protects them during service conditions. Two different technological approaches were examined regarding the mounting of the FORT on a composite structure i.e. via secondary adhesive bonding or via co-bonding during the manufacturing autoclave process. A direct comparison of the experimentally acquired measurements with the FORT versus experimental measurements from ESGs as well as theoretical and numerical ones is realized, providing with interesting correlations and conclusions on the whole strain sensing approach. Additionally, the effect of the FORTs placement on the stiffness of a structure is assessed through an analysis of the changes in the dynamic characteristics and the modal response of an aeronautical subcomponent representative of a wing front spar.

2. Basic principles of FBG sensors

Fiber Bragg grating sensors are actually spectral filters, which utilize the principle of Bragg reflection. The gratings are a series of parallel lines close together, inscribed in the core of an optical fiber. Optical fibers are exposed to a periodic pattern of ultraviolet light and, as a result, the gratings consist of alternating regions of high and low refractive indices. The periodic grating acts as a filter, reflecting a narrow wavelength range, centered about a peak wavelength. This wavelength is known as the Bragg wavelength, λ_B, and is given by:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the average refractive index and Λ is the grating period. When a mechanical or thermal load is applied to the structure, the grating is strained and thus, there is a change of the peak reflected wavelength [1]. This way, the grating works as a strain sensor. Assuming that there is no change in the pressure, the change of the reflected wavelength is given by:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left[1 - \left(\frac{n_{eff}^2}{2}(p_{12} - v(p_{11} + p_{12}))\right)\right]\varepsilon + (a+\xi)\Delta T = F_G\varepsilon + (a+\xi)\Delta T \tag{2}$$

where $\Delta\lambda_B$ is the wavelength shift, λ_B is the initial reference wavelength, v is the Poisson's ratio of the fiber, p_{11} and p_{12} are the elasto-optic coefficients of the elasto-optic tensor constants of the strain optic tensor and F_G represents in total the gauge factor of the fiber. α is the coefficient of thermal expansion of the glass fiber, ξ is the fiber thermo-optic coefficient, and ΔT is the temperature change. For typical germanosilicate fibers, the gauge factor F_G equals to 0.773 and the wavelength–temperature sensitivity $(\alpha + \xi)$ of a 1550 nm FBG is in the region of 10 pm °C^{-1}.

3. Experimental procedure

3.1. Specimen manufacturing and sensorization

Three point bending fatigue tests were scheduled in order to test the reliable long-term operation of the FORTs. The specimens were manufactured according to the ASTM D7264/D7264M-07 standard Test Method for Flexural Properties of Polymer Matrix Composite Materials. Carbon fiber reinforced plates with dimensions of $300 \times 300\ \text{mm}^2$ were manufactured in-house via the autoclave technique, at a stacking sequence $[+45/-45/0_2/90/0_2/90/0/90/0]_s$ using uni-directional M21/34%/UD194/IM7-12k carbon fabric prepreg by Hexcel. Two plates were fabricated with a final average thickness of 4.09 mm.

Two groups of coupons were cut at dimensions $400 \times 20\ \text{mm}^2$, the first group was sensorized with FORTs via co-bonding and the other via the secondary bonding approach.

The FORTs were manufactured by KVE Composites Group (Netherlands) via a simple autoclave process utilizing a specially designed mould. The optical fiber is protected from possible damage during the manufacturing by a low modulus Teflon tubing, except the region of the FBG sensor. Their dimensions for this application were 20 (width) $\times$ 160 (length) mm^2. Apparently, the size of the FORTs can be customized to the structure under SHM.