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Assessment of the strain monitoring reliability of fiber Bragg grating sensor (FBGs) in advanced composite structures

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ABSTRACT

Fiberoptic Bragg grating sensors were embedded in composite structures in order to be used as the detection system for structural health monitoring purposes. Firstly, optical fibers had been embedded in several locations in between the layers of composite material and for the typical tensile testing coupon configuration. It has been shown experimentally and with finite element analysis that embedding the optical fiber out of the neutral axis of the coupon, downgrades significantly the composite's ultimate tensile strength. Secondly, a composite patch with embedded FBG has been used to restore a typical damage case on aluminum structure currently applied on advanced 'aging' vehicles. Data values taken from the FBG system during the experimental tension tests of the composite structures were calculated to axial strain values with the aid of an interrogator. Theoretical axial strain values of the composite patch had been calculated by exploiting a newly-developed finite element model. Discussion has been made on the correlation between experimental and theoretical results for the verification of sensing sensitivity and accuracy.

1. Introduction

In recent years, serious consideration has been given to the use of composite materials in the structures of advanced vehicles and the need of real time monitoring their structural integrity for increasing safety and decreasing cost service and maintenance purposes. However, their structural health monitoring is not a straight-forward procedure and represents a major concern to the engineering community. This need is even more intense in the case of aircraft aging structures, many of which are operating well beyond their initial design lives. The current damage tolerance design philosophy mostly used in cases of composite structures requires that a structure should be capable of sustaining small damage without failure, and that an inspection program can be instituted to detect such flaws before they grow to a critical size. This damage tolerance approach recognizes the impossibility of establishing complete structural redundancy – the fail safe design premise – and places greater emphasis on inspection to ensure safety and reliability [1].

Recently, a strong demand on developing high performance structures, which are able to monitor the physical and mechanical properties such as temperature and strain during operation condition, is appreciated as a "Smart structural health monitoring system". Fiberoptic Bragg grating (FBG) sensor has been recognized as a new non-destructive evaluation (NDE) technique to suit this purpose for all structural applications [2,3]. The specialty of using FBG sensor for strain sensing application enables the fiber to measure axial strains in specific locations with high resolution and accuracy, Fig. 1, e.g. [4–6]. As the physical size of an optical fiber is extremely small compared with other strain measuring components, and the size of the hosting material/layers of the laminate is too large when compared to the size of the diameter of the FBG, it enables to be embedded into structures for determining the strain distribution without significantly influencing the mechanical properties of the host materials [1–3].

Fiber optic sensor technology has grown rapidly to the level where it is being used in a wide variety of materials, e.g. [7–11] as well as structural monitoring applications as bonded joints, repairs and structures e.g. [12–16]. Fiber optic sensors have the advantages of geometric versatility of the sensing element, sensor multiplexing capabilities, wide dynamic range and high sensitivity. Such a sensor uses a Bragg grating which is a periodic variation of the index of refraction of the core of the optical fiber along the length of the fiber. The variation of the index of refraction is formed by exposure the fiber core to an intense optical interference pattern of ultraviolet light e.g. [9,17]. Damage detection can be

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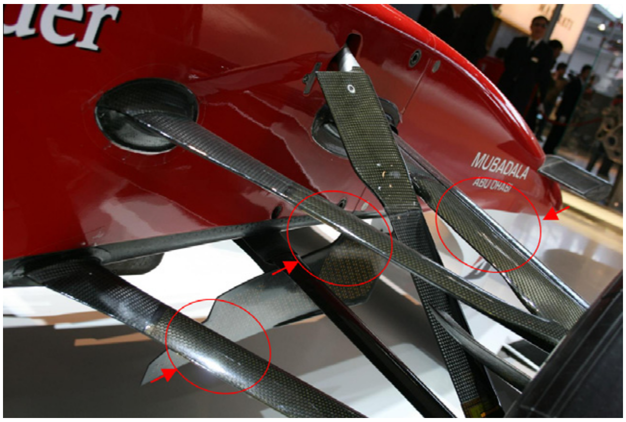

Fig. 1. Use of fiber Bragg gratings as embedded sensors in composites to engineering applications that real time monitoring of the composite is demanded.

realized by a breakage of the optical fiber, resulting in a loss of a transmitted light signal [18] or by mechanical coupling, where a change in local strain leads to a change in the coefficient of refraction [19]. The detection of these changes can be used for SHM in composite structures by an interferometric system or by small embedded Bragg grating sensors, e.g. [20–24].

In the present work, optical fiber Bragg sensors will be used to monitor the health of a composite structure bonded on metallic substrate. Series of specimens simulating typical smart boron composite patches bonded on a cracked aircraft skin were manufactured and tested. A specific manufacturing process was developed for embedding Bragg grating sensors into the composite structure. Fiber Bragg grating sensor was embedded in different locations between the plies of the composite patch and was placed above the crack tip of the metallic structure. The objective of this investigation is to establish a warning method for recording a pre-critical integrity condition of a composite structure taking into consideration the critical substrate stress intensity factor and the relevant strain measurements during the damage evolution. Experimental and theoretical analysis will be exploited in order to facilitate and develop this warning methodology for structural health monitoring purposes.

2. The fiber Bragg grating (FBG) sensing and interrogation

FBGs are optical fibers currently used for sensing techniques in many engineering applications. For the convenience of the reader, a small paragraph with the necessary background of FBGs will follow. Bragg gratings are made by illuminating the core of a suitable optical fiber with a spatially-varying pattern of intense UV laser light. Short-wavelength (<300 nm) UV photons have sufficient energy to break the highly stable silicon–oxygen bonds, damaging the structure of the fiber and increasing its refractive index slightly. A periodic spatial variation in the intensity of UV light, caused by the interference of two coherent beams or a mask placed over the fiber, gives rise to a corresponding periodic variation in the refractive index of the fiber.

This modified fiber serves as a wavelength selective mirror: light traveling down the fiber is partially reflected at each of the tiny index variations, but these reflections interfere destructively at most wavelengths and the light continues to propagate down the fiber uninterrupted. However, at one particular narrow range of wavelengths, constructive interference occurs and light is returned down the fiber. Maximum reflectivity occurs at the so-called Bragg wavelength λ_B, given by:

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

where n_{eff} is the effective refractive index of the mode propagating in the fiber and Λ is the FBG period. Eq. (1) implies that the reflected wavelength λ_B is affected by any variation in the physical or mechanical properties of the grating region. For example, strain on the fiber alters Λ and n_{eff}, via the stress-optic effect. Similarly, changes in temperature lead to changes in n_{eff} via the thermo-optic effect and in an unconstrained fiber, Λ is influenced by thermal expansion or contraction. This situation is expressed in Eq. (2), where for an non embedded FBG the first term on the RHS gives the effect of mechanical strain on λ_B and the second describes the effect of temperature:

$$\Delta\lambda_B = \lambda_B \cdot (1 - \rho_a) \cdot \Delta\varepsilon + \lambda_B \cdot (\alpha + \xi) \cdot \Delta T, \tag{2}$$

where $\Delta\lambda_B$ is the change in Bragg wavelength, ρ_α, α and ξ are respectively the photoelastic, thermal expansion and thermo-optic coefficients of the fiber, $\Delta\varepsilon$ is the change of strain and ΔT is the temperature change, respectively. For a typical grating written in a silica fiber and with $\lambda_B \approx 1550$ nm, sensitivities to strain and temperature are approximately 1.2 pm/με and 10 pm/°C respectively.

To use an FBG as a sensor, it is illuminated by a light source with a broad spectrum and the reflected wavelength is measured and related to the local measurands of interest. Shifts in the Bragg wavelength can be monitored by any of the following techniques:

(i) An interferometer may be used to convert wavelength shifts into phase shifts, which can be detected by measuring variations in the light intensity as the path difference in the interferometer is varied. This technique potentially allows for very high sensitivity, but the equipment to do it is expensive and prone to environmental interference. No commercial equipment employs interferometry.

(ii) A sloped optical filter, which may be another Bragg grating, can be used to convert wavelength shifts directly into intensity changes. If the filter is designed to have a known pass/reject ratio which varies with wavelength, then the wavelength of a narrowband reflection from a single grating can be determined simply by measuring and comparing the passed and rejected intensities. For the filter with a transmission spectrum shown on the left in the figure below, as the Bragg wavelength.

When FBGs are being strained the wavelength of the reflection peaks will be shifted. For measuring strain with FBGs it is necessary to measure these shifts very precisely. Resolution and short-term stability of +1 pm is required, if strain values of 1 μm/m are to be measured. 1 pm resolution of peak wavelength of 1550 nm means a relationship of >106. There exist many different principles to analyze such optical spectrums. For laboratory investigations, interferometers are often used, but they are not so well suited to robust industrial applications; in industrial environments other principles dominate.

3. Material manufacturing

Composite materials had been manufactured in the Advanced Composites Laboratory in the Research and Development Department of Hellenic Aerospace Industry. Two different types of specimens were manufactured: (a) type I specimens aimed to assess the effect of the embedded fiber on the mechanical behavior of the composite, while (b) type II specimens aimed to calibrate the validity of the readings of the embedded FBG sensors and thus, establish a warning methodology for SHM of repaired metallic structures.

Type I specimens were composite specimens manufactured in the autoclave by boron–epoxy prepregs (Textron 5521,