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MONITORING OF STRUCTURAL INTEGRITY OF COMPOSITE STRUCTURES BY EMBEDDED OPTICAL FIBER SENSORS

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Abstract
In-service structural health monitoring of engineering structures has assumed a significant role in assessing their safety and integrity. Fiber Bragg grating (FBG) sensors have emerged as a reliable, in-situ, non-destructive tool for monitoring, diagnostics and control in civil and aerospace structures. They can be used to measure a multitude of parameters like strain, temperature, pressure and chemical and biological effects of the environment. The versatility of Fiber Bragg grating sensors represents a key advantage over other technologies in the structural sensing field. In this study, Bragg gratings written into a Germanium doped optical fiber are embedded in carbon-epoxy laminates to measure the tensile strain in the composite material. Strain measurements from a more conventional electro-mechanical instrumentation are compared to those from the Bragg sensors and an excellent agreement between the two measurements has been verified. The experimental results of this study indicate that fiber optic Bragg grating sensors, integrated with composites, have potential applications for monitoring the structural integrity of composite structures. .

Keywords: composite, Bragg sensors, embedded FBG, carbon-epoxy, tensile strain

INTRODCUTION

Real time monitoring of the mechanical integrity and stresses on key aerospace composite structures like aircraft wings, walls of pressure vessels and fuel tanks or any other structurally extended components and panels as in space telescopes is very important to many private and governmental agencies. Future military and commercial aircraft will incorporate a monitoring system to sense any degradation to the structure. In the extreme flight conditions of an aerospace vehicle it might be desirable to measure the strain every ten centimeters and thus fully map out the strain field of a composite component. A series of missions and vehicle health management requirements call for these measurements. At the moment thousands of people support a few vehicle launches per year. This number can be significantly reduced by implementing intelligent vehicles with integral nervous systems (smart structures). This would require maintenance to be performed only as needed. Military and commercial aircrafts have an equally compelling case. Annual maintenance costs are currently reaching astronomical heights. Monitoring techniques are therefore required that allow for maintenance to be performed only when needed. This would allow improved safety by insuring that necessary tasks are performed while reducing costs by eliminating procedures that are costly and not needed.

In-situ monitoring techniques are also needed for other civil structures especially in the construction industry. Today's civil structures in most developed nations depend tremendously on the use of sensing technology for real time structural health monitoring that could detect a decrease in performance or imminent failure , for example variation in strain, temperature , corrosion or crack formation. However, in third world nations, infrastructure lacks a rigorous mechanism for structural health monitoring. It is mostly done through visual inspections of the structure which are extensive and quite expensive. As future structures are built which have to work safely under extreme weather conditions, it becomes imperative that these structures are inherently smart and sense their own structural health so that their safety is never compromised. The structural health monitoring is very important and definitely needed for assessing the safety and integrity of engineering structures such as concrete structures. It is an emerging trend for sustainable development in the third world nations.

The advantages fiber optical sensors have over conventional electro-mechanical systems like strain gauges have been widely extolled in the research literature (LeBlanc et. al., 1996). These advantages include their small size, low weight, immunity to electromagnetic fields, high voltage, corrosion resistance, compatibility with composite materials and process conditions, and multiplexing capabilities. One fiber optic device which is suitable for distributed sensing is the fiber Bragg grating (FBG).

Recent research and development activities in structural health monitoring using FBGs have been reported in the literature. A major application of FBG strain sensors is in the field of real-time health monitoring of bridges and civil structures (Lin et al., 2006; Ansari et al., 1997; Tennyson et al., 200). Twenty–six FBG strain sensors were reported to have monitored the Horsetail Falls Bridge in Oregon successfully for two years (Schulz et al., 2000). FBG sensors have been used on aluminum as well as concrete specimens to monitor the strain and the results against electrical strain gauges have been validated (Saouma et al., 19998). Monitoring of the prestressing tendons of the Beddington Trail Bridge, Canada using Bragg grating strain sensor array has been reported (Maaskant et al., 1997). Three types of prestressing tendons were used in this bridge, namely steel brand, carbon fiber composite cable and leadline rod. The main objective behind this work was to study the long-term losses in the tendons due to stress relaxation and creep. The use of forty FBG sensors to remotely monitor the real-time strain in Europe's first all-fiber reinforced composite bridge , The West Mill Bridge has been reported (Gebremichael et al., 2005). The main objective behind this study was to collect real-time, in situ strain data from the bridge and to analyze this data for assessment of its structural integrity, maintenance scheduling and validation of design code.

A number of strain studies of reinforced concrete beams instrumented with FBG sensors have been undertaken by many researchers. A comparison of the response of FBG strain sensors and conventional resistive strain gauges on reinforcing bars has been reported (Maher et al., 1993). The use of embedded wavelength division multiplexed FBG sensors in monitoring the strain on reinforced concrete beams and decks till their failure has also been reported (Davis et al., 1997). Laboratory trials of measuring the internal strain generated inside concrete structural components has been undertaken (Saouma et al., 1998). The fiber was embedded inside a prismatic specimen while a strain gauge was mounted on the surface. Strain readings obtained from the two sensors show close agreement with each other.

Sandwich composite materials like glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) have emerged as a promising load-bearing material in the civil and aerospace industries because of their high strength, high fitness and low weight. The creep and brittle nature of the FRP materials have made it necessary to study their internal failure at an early stage by embedding suitable strain sensors like FBGs in them. Health monitoring of smart fiber reinforced polymers embedded with FBGs have been reported by many investigators (Kalamkarov et al., 1999; Aoyama et al., 2001; Lu et al., 2007; Panopoulou et al., 2011; Antunes et al., 2011; Ramly et al., 2012).

As will be evident from above, there have been a lot of research and development activities in structural health monitoring using FBGs. Structural health monitoring is very important for assessing the safety of engineering structures and structural materials. The purpose of this work is to contribute to the ongoing efforts in developing techniques for using FBGs for monitoring the integrity of advanced structural materials expected to become the mainstay of the current and future generation space structures. Since carbon-epoxy composites are the materials of choice for the current space structures, the initial study is concentrated on this type of composite. This paper describes an experiment to demonstrate the use of an embedded FBG for measuring strain in a carbon-epoxy composite material. The performance of the fiber optic sensor is determined by direct comparison with results from more conventional instrumentation. The technique described in this paper can also be applied to the health monitoring of other engineering structures and can be very useful in monitoring the structural health of infrastructure in the third world nations.

FIBER BRAGG GRATING SENSORS

Bragg gratings can be written into Germaniun doped optical fiber by exposing the fiber to an UV interference signal generated either holographically via two beam interferometry (Meltz et al. 1989) or by using a diffraction mask (Hill et al. 1993). The absorption of the UV light in the fiber changes the chemical bonds in the glass (producing defect centers) thus giving rise to a change in the complex refractive index of the glass. The resulting spatial modulation in the index of the fiber produces the Bragg grating. This structure is permanent for temperatures up to 350 degrees Celsius, and acts as a very narrow- band in-line filter. In reflection, the grating reflects strongly at the wavelength, λ_B for which the Bragg resonance given by equation (1) is satisfied,

$$\lambda_B = 2n\Lambda \qquad (1)$$

where Λ is the grating pitch and n is the effective index of the core. With such a device, injecting spectrally broadband source of light into the fiber, a narrowband spectral component at the Bragg wavelength is reflected by the grating. In the transmitted light, this spectral component is missing, as depicted in Fig. 1. The bandwidth of the reflected signal depends on several parameters, particularly the grating length, but typically is ~ 0.05 to 0.3 nm in most sensor applications. A strain applied to the grating results in a shift in the Bragg wavelength of the device which can be detected in either the reflected or transmitted spectrum as shown. By measuring the shift in Bragg wavelength, one can easily determine the applied strain according to equation (2):

$$\frac{\Delta \lambda_B}{\lambda} = (1 - P)\frac{\Delta L}{L} \qquad (2)$$

Where L is the length of the sensor and P is the optical strain coefficient which has a typical value of 0.22 for axial strain (Davis et al. 1997). The nature of the output of Bragg gratings provides these sensors with built-in self-referencing capability. As the sensed information is encoded directly into wavelength, which is an absolute parameter, the output does not depend directly on the total light levels, loses in the connecting fibers and couplers, or source power. This is widely acknowledged as one of the most important advantages of these sensors. The wavelength encoded nature of the output, however, also facilitates wavelength division multiplexing (Kersey et al. 1997) by allowing each sensor to be assigned to a different portion of the available source spectrum. The upper limit to the number of gratings which can be addressed in this way is a function of the source profile width and the operational wavelength bandwidth required for each grating element.

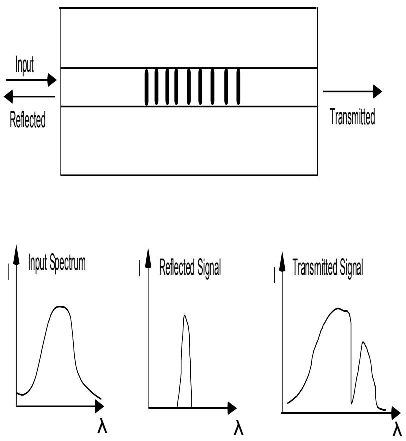

Figure 1: Reflected and transmitted Bragg grating signal with a broadband source

FABRICATION OF BRAGG GRATINGS

High reflectivity Bragg gratings were produced into the core of single mode, Germanium doped optical fibers using the phase mask method described earlier. The optical fibers were hydrogen loaded (Lemaire et al., 1993) under high pressure to increase photosensitivity prior to writing the grating. A continuous wave argon ion laser operating at 244 nm (second harmonic of the blue line) was used as the source for writing the gratings at Bragg wavelengths around 1300 nm. Real-time monitoring of grating growth was carried out during the writing process by illuminating the grating with broadband source (a laser diode) covering the grating reflection spectrum. Transmission and reflection spectra were measured with the aid of a monochromator and a recorder.

EMBEDDED OPTICAL FIBERS

Carbon /epoxy composite panels, with embedded optical fiber sensors were fabricated using the NASA-MSFC composite fabrication facilities. The carbon/epoxy prepreg used for the panel fabrication was provided by NASA. The fabrication technique focused on the hand lay-up and autoclave cure. The optical fiber was arranged to lie parallel with adjacent structural carbon fibers during fabrication. The study concentrated on fabric based composites.

EXPERIMENTAL SET—UP

Shown in Figure 2 is a schematic of the set-up used for performing physical tests on the composite panels fabricated with the embedded optical sensor. The composite was tested under axial tension. It was gripped on either end in a special hydraulic wedge grips. Approximately one inch of the composite was gripped by each of the two wedge grips. A compact tunable diode laser was used to couple light into the optical fiber. The transmission spectrum of the grating was recorded with the aid of a detector and a lock-in amplifier. The composite was loaded to approximately 20,000 psi and unloaded. At each load level the shift in Bragg wavelength was obtained from the transmission spectrum. The unstrained Bragg wavelength was 1292.1 nm. The corresponding strain, defined as the change in length divided by the original length, was also recorded at each load level.

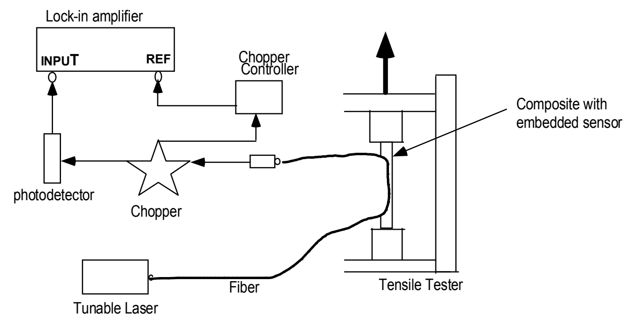

Figure 2: The Experimental Set-Up

RESULTS AND DISCUSSION

The results of the tests are presented in Figures 3 and 4. Shown in Figure 3 is a plot of the fiber optic measured strain (change in wavelength divided by original wavelength) as a function of the actual strain. Linear regression analysis performed on the data gives an indication that there is an overall excellent linear relationship between the actual strain and the fiber optic strain. Equation to this regression is shown in the figure. The fiber optic measured strain is seen to be 78.7% of the actual strain. This gives a fiber optic strain calibration factor here, whereby, actual strain values are closely approximated by dividing the fiber optic strain measurement by 0.79. This value is very close to what has been reported in the literature

A plot of stress versus strain is shown in Figure 4. The actual strain values were obtained from the fiber optic strain by dividing fiber optic strain measurements by 0.79. Excellent agreement between the machine measured strain and the fiber optic strain sensors is evident. A linear regression of the fiber optic data was performed and the equation is displayed in the figure.

Three sets of data were taken and the plots described above were done for each set. Plots of only one data set are shown for convenience. Results show a good repeatability for the experiment.

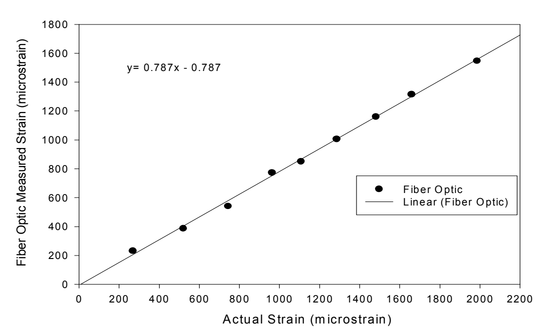

Figure 3. Fiber Optic Measured Strain versus Actual Strain

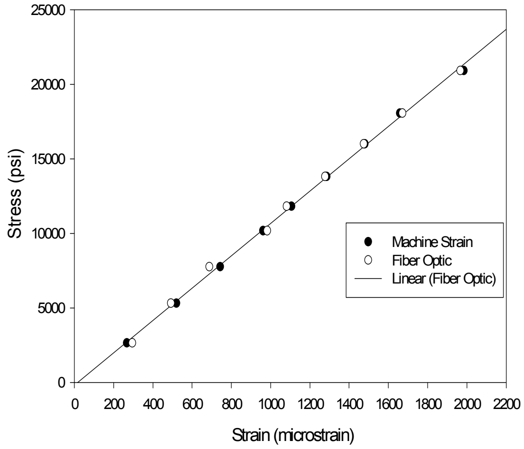

Figure 4. Stress versus Strain

CONCLUSION and FUTURE PERSPECTIVES

Optical fibers with Bragg sensors have been embedded into carbon-epoxy composite to measure the tensile strain in the composite material. Excellent agreement between strain measurements from a more conventional instrumentation and the Bragg sensors has been verified. The experimental results of this preliminary study indicate that fiber optic Bragg grating sensors, integrated with composites, have potential applications for monitoring the structural integrity of composite structures.

The work reported in this paper can be extended in many directions. Further study is required to discriminate between mechanical and thermal strain. The potential of multiplexing to provide a multi-point sensing capability with a single fiber could be verified. The work could also be extended to measurement of transverse strain. Finally, a research effort could focus on the study of efficient integration of the arrays of sensors in complex composite shapes.

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BIOGRAPHICAL SKETCH

Dr. Albert J. Osei is a Professor of Physics in the Department of Mathematics, Physics and Computer Science at Oakwood University in Huntsville, Alabama. He obtained his PhD in Applied Physics from Alabama A&M University. His research interests include, but are not limited to, (1) Evolutionary Algorithms (2) Modeling and Simulation of the Radiated Fields of Ultrasonic Transducers (3) Optical sensors and (4) Use of Remote Sensing and GIS technology in monitoring the Environment .Dr. Osei is a member of the Optical Society of America, Biophysical Society, American Association of Physics Teachers and the Alabama Academy of Science.

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