Fiber-optically sensorized composite wing

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ABSTRACT

Electromagnetic interference (EMI) immune and light-weight, fiber-optic sensor based Structural Health Monitoring (SHM) will find increasing application in aerospace structures ranging from aircraft wings to jet engine vanes. Intelligent Fiber Optic Systems Corporation (IFOS) has been developing multi-functional fiber Bragg grating (FBG) sensor systems including parallel processing FBG interrogators combined with advanced signal processing for SHM, structural state sensing and load monitoring applications. This paper reports work with Auburn University on embedding and testing FBG sensor arrays in a quarter scale model of a T38 composite wing. The wing was designed and manufactured using fabric reinforced polymer matrix composites. FBG sensors were embedded under the top layer of the composite. Their positions were chosen based on strain maps determined by finite element analysis. Static and dynamic testing confirmed expected response from the FBGs. The demonstrated technology has the potential to be further developed into an autonomous onboard system to perform load monitoring, SHM and Non-Destructive Evaluation (NDE) of composite aerospace structures (wings and rotorcraft blades). This platform technology could also be applied to flight testing of morphing and aero-elastic control surfaces.

Keywords: Composite Wings, Load Monitoring, Fiber Bragg Gratings (FBGs), Fiber Optic Sensors, Structural Health Monitoring (SHM), Structural State Sensing

1. INTRODUCTION

FBG arrays provide multiple electromagnetic-interference-immune harsh-environment-tolerant systems[1-3] along small diameter optical "nerves" and a basis for multi-point dynamic strain input for SHM. Key to their use as sensors is the interrogation instrumentation discussed in the Section 2, following which, in subsequent sections, we discuss (3) the model wing, (4) composite coupon testing and (5) composite wing testing.

2. SENSOR INSTRUMENTATION

IFOS has developed a parallel processing interrogator that allows massive multiplexing of FBG sensors sampled at high rates. Groups of up to 16 sensors can be sampled simultaneously on a single fiber from DC up to 1 MHz with the capability of switching between multiple fibers at kHz. This broadband capability allows for smart composite sensing applications[2, 4] ranging from low-frequency load monitoring applications[2] to ultra-high frequency acoustic emission (AE) monitoring[3] and Lamb-wave based damage detection[5]. In this paper, our focus is on capturing loading and relatively low frequency vibration phenomena. We provide results at the coupon level for 50 kHz sampling and, in a wing obtain results for sampling of 4 sensors at 6 kHz. A functional schematic of the IFOS system is given in Figure 1.

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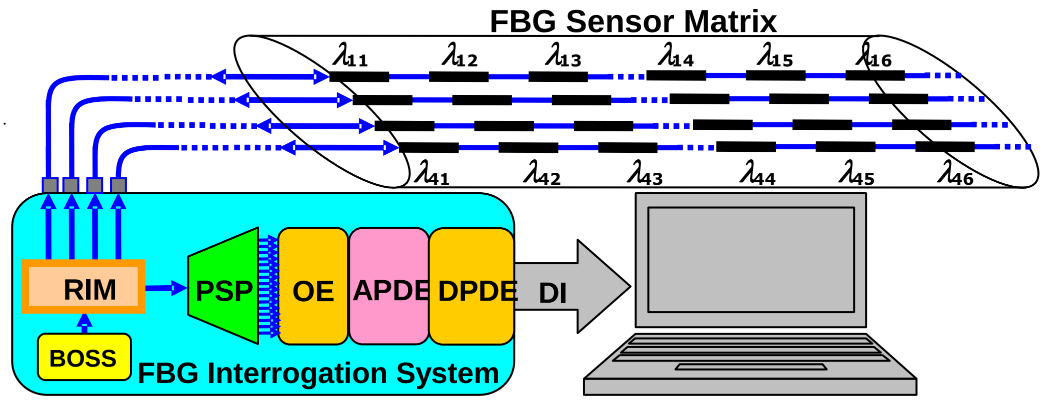

Figure 1. Enabling interrogation instrumentation: The interrogation system comprises a Broadband Optical Source Subsystem (BOSS), Routing and Interface Module (RIM), Photonic Signal Processing (PSP) subsystem, Opto-Electronic (OE) interface, Analog Post-Detection Electronics (APDE) subsystem, Digital Post-Detection Electronics (DPDE) subsystem and Data Interface (DI).

3. MODEL T38 WING

As we described recently in Reference 6, a ¼-scale model of a T38 airplane wing was designed and manufactured using fabric reinforced polymer matrix composites. FBG sensors were embedded under the top layer of the composite. The sensor layout is shown in Figure 2.

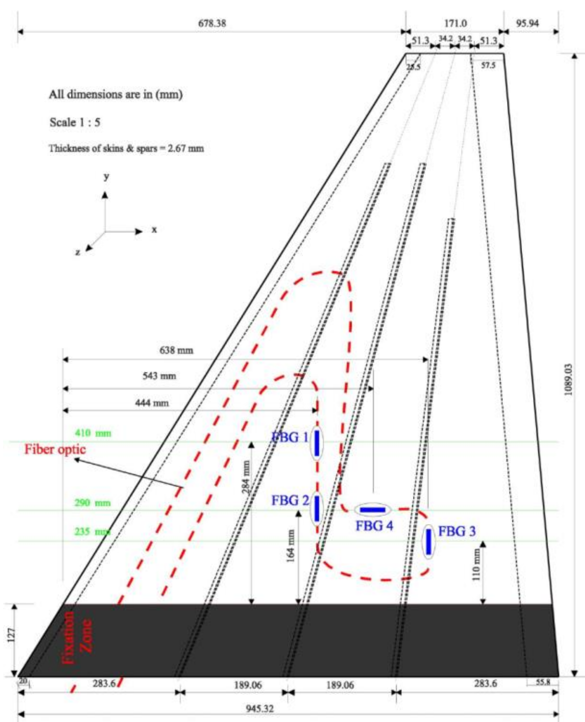

Figure 2. Dimensions of the T38 wing model.

The model wing contains two mirror-image airfoils of chord lengths 855 mm and 171 mm at the root and tip, respectively. The two airfoils are connected to each other with three longitudinal spars at distance ratios of 30%, 50%, and 70% of the chord length, as shown. A fixation zone of 127 mm in length was added on the root side to allow for clamping the wing during testing.

Prior to the manufacture, in order to identify optimum locations on the T38 wing surface to place the FBG sensors, maps for the distribution of the strain components were plotted based on finite element modeling[6] (using ANSYS with experiment and the micromechanics algorithm pcGINA© providing the elastic properties[7]). These components were chosen as the axial strain in the longitudinal directions, ε_y, and the interfacial shear strain, ε_{xy}. These plots are shown in Figure 3**,** where preferable zones were marked with an oval and also zones of local high strain concentration were marked as possible locations for FBG sensors. These zones were selected as those zones with the highest strain values combined with a minimum rate of change of strain with distance. These locations would allow evaluation of critical strain values with a low chance of errors in sensor placement.

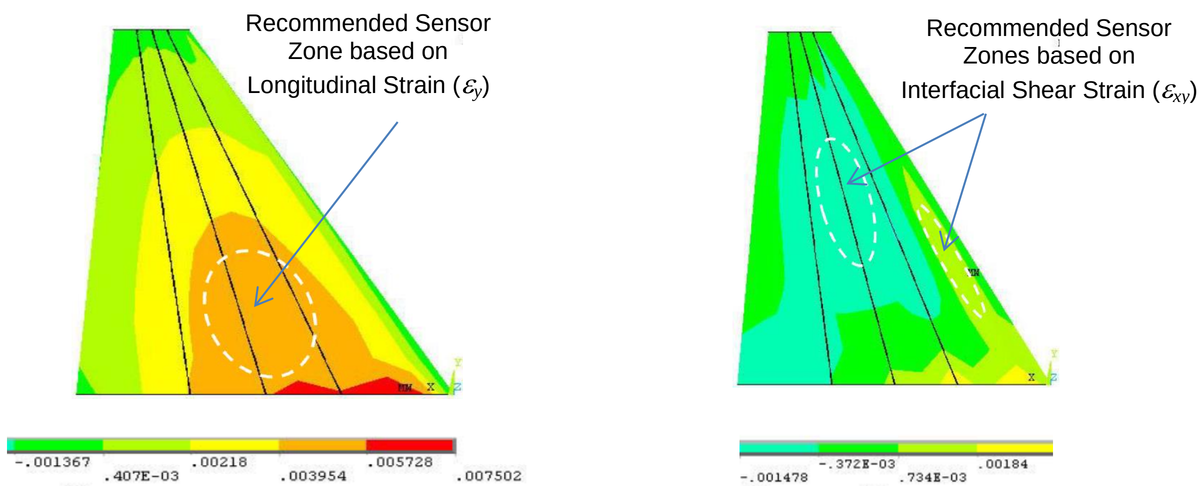

Figure 3. Recommended locations for FBG sensors in bottom skin of the wing based on distribution of (a) longitudinal strain component ε_y, and (b) interfacial shear strain component ε_{xy} given the maximum loading condition for 15° angle of attack[6].

4. EXAMPLE COMPOSITE COUPON TESTING

The accuracy and durability of the sensors were first evaluated at the coupon level utilizing static and dynamic testing. Strain measurements using embedded FBGs with an optical interrogator were found to be in agreement with values measured using other strain measuring devices and with results obtained using finite element analysis (ANSYS®). Figure 4(a) and (b) show example static and dynamic tests respectively.

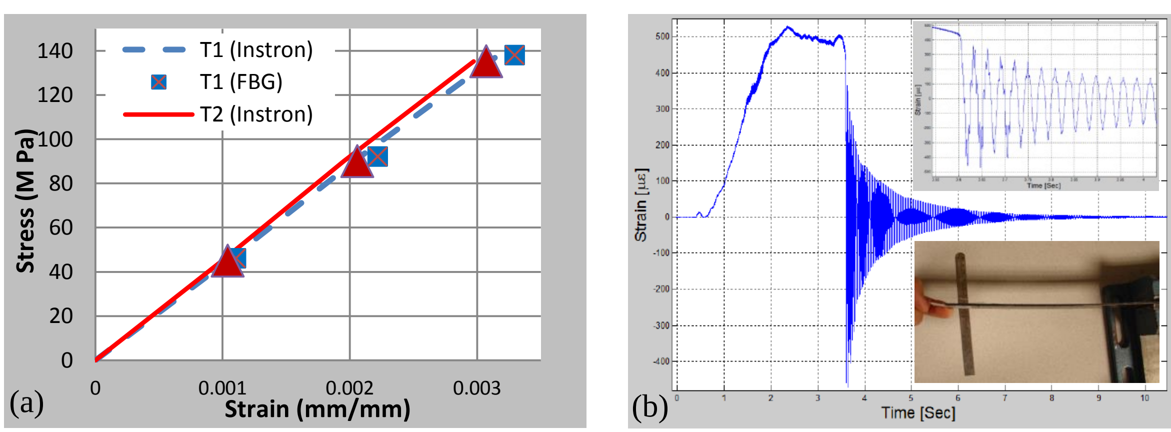

Figure 4. Coupon testing: (a) Static stress-strain test with results from FBG sensors compared with results from an Instron 5565 video extensometer. (b) Dynamic end displacement test showing transient response of an example coupon following end displacement using an embedded FBG sensor with output sampled at 50 kS/s.

5. EXAMPLE COMPOSITE WING TESTING

Following the coupon tests, testing was performed on the assembled wing.

5.1 Quasi-Static Tests

The wing was loaded with weights as shown in Figure 5(a). An example sensor response is shown in Figure 5(b), where we see that doubling the weight doubles the strain. As expected the three sensors in the longitudinal direction (FBG1, 2, and 3) along the wing in the top skin registered tensile strain when the wing tip was loaded. By contrast the sensor in the transverse direction (FBG4) across the wing registered compressive strain as seen in Figure 6.

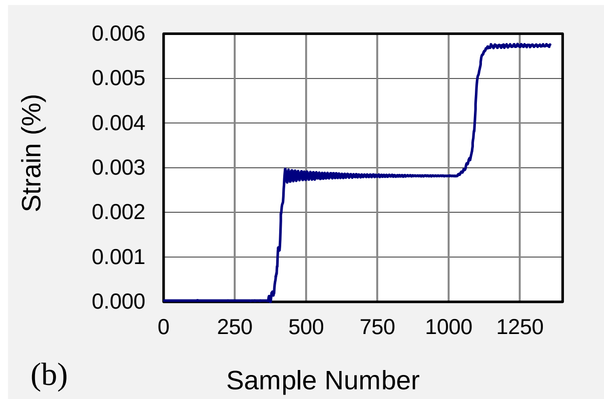

Figure 5. Wing testing: (a) Loaded wing. (b) FBG2 response to 50 and 100 lb loading.

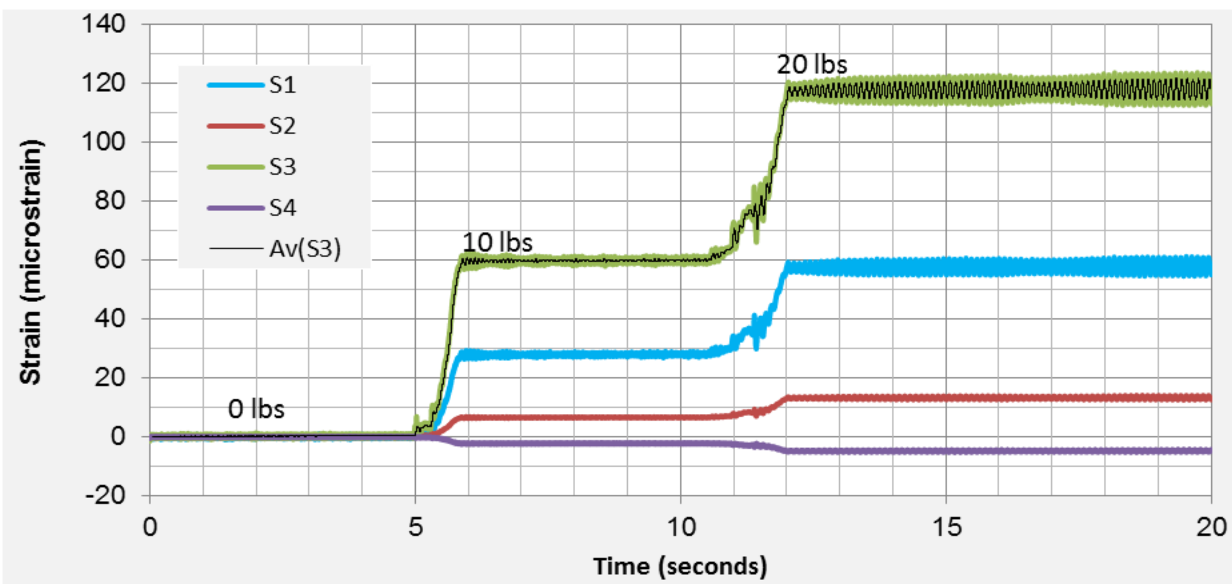

Figure 6. Response to 10 and 20 lb loading. Note the placement of each weight led to vibration of the wing.

5.2 Dynamic Tests

The following plot (Figure 7) shows the response to a metal hammer impact. The oscillations last approximately 2 seconds and after 0.4 seconds take the form of a damped sinusoid with a frequency of approximately 29 Hz. As shown in the time zoom of Figure 8, however, higher frequency components are seen having significant amplitude for the first 0.2

seconds. We also note that sensor S4 is π out of phase with respect to the other three sensors, i.e., as in the quasi-static case, sees compression when the other sensors see tension and vice-versa.

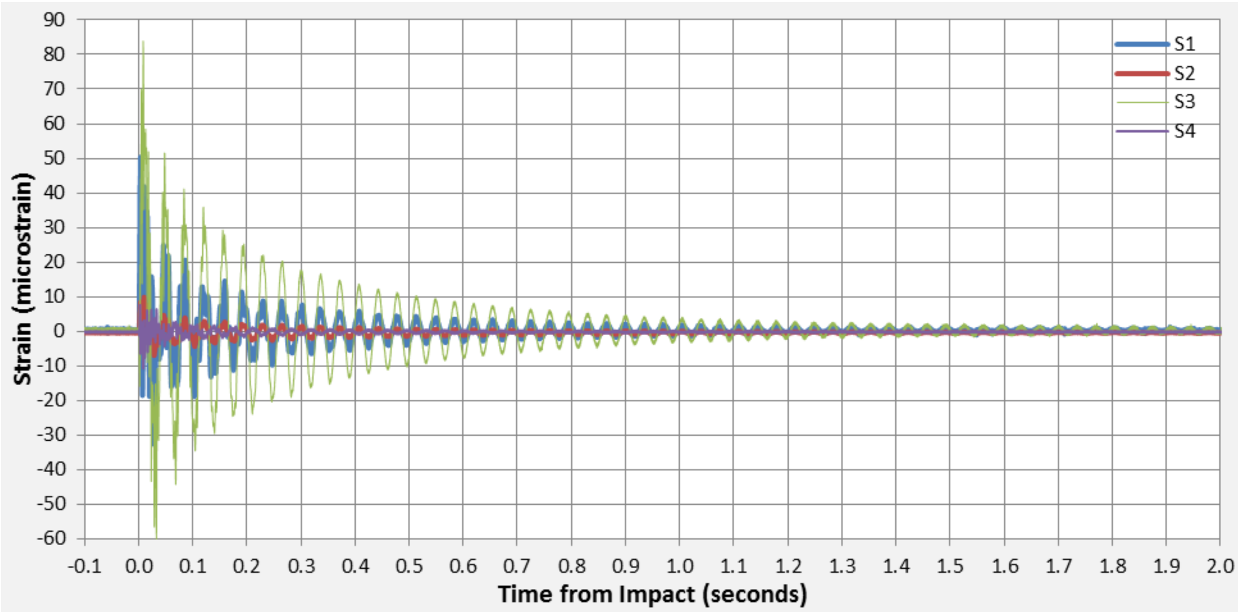

Figure 7: Response to metal hammer impact.

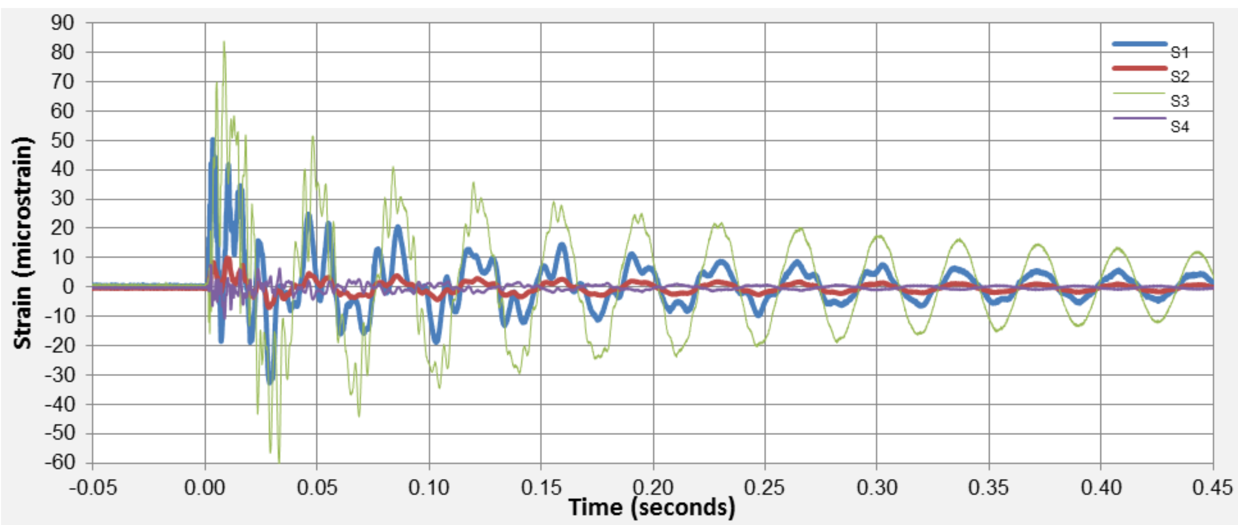

Figure 8: Time zoom of previous figure for the metal hammer impact.

6. CONCLUSIONS

The FBG sensor arrays together with IFOS' broadband (DC to MHz) interrogation provide precision measurement of static and dynamic strains. The sensors are light-weight, EMI-immune, unobtrusive and highly multiplexable with many sensors supportable on a single optical fiber. They offer considerable promise for composite wing load monitoring and SHM. Furthermore, the use of FBG sensor arrays in composite wings also provides a stepping stone toward their use in composite vane surfaces for jet engine monitoring.

ACKNOWLEDGEMENTS

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