Chapter 4 – SENSOR CHARACTERIZATION AND ATTACHMENT

Prior to the collection of any practical strain measurement, an investigation must be undertaken to develop and evaluate the attachment techniques used to bond the sensor to the requisite substrate. Early attempts at bonding surface-mounted fiber optics sensors to structural surfaces began with a logical extension of strain gage attachment methods developed over the past four or five decades. Past experience at Dryden with strain gage attachment up to 2000°F was used as a general guide for the accurate characterization and reliable attachment of FBG sensors. For high temperature applications, such as for aerodynamic and combustion heated structures, initial attachment studies were conducted on monolithic titanium to minimize the measurement uncertainty associated with an uncharacterized sensor with a complex material substrate. Several different combinations of strain gage epoxy adhesives have been tested and evaluated with fiber optic strain sensors. After several iterations, good agreement with conventional strain gages was obtained at room temperature, 350°F, and 550°F. Additional studies on surface attachment and characterization of fiber optic sensors are referenced. [14-18]

4.1 FBG TRANSVERSE SENSITIVITY

Similar to conventional strain gages, FBGs are considered to be intrinsic sensors, that is, the physical transduction takes place within the medium itself. Conversely with extrinsic sensors, the measurement takes place outside the sensing medium, most commonly in air (e.g. the Extrinsic Fabry Perot Interferometer, or EFPI). For foil strain gages, the strain gage resistive element experiences a change in resistance due to the strains produced in the structure to which the element is attached. Similarly, the Bragg grating sensor experiences a change in wavelength due to strains that are transferred from the straining structure to the FBG sensor. The implication of intrinsic measurements is that they possess an undesirable sensitivity to transverse strains and temperature effects.

Ideally a strain sensor is only sensitive to strains along its primary axis and completely insensitive to strains in all other directions. For this reason, the resistive strain gage has been designed to maximize sensitivity to axial strains while minimizing sensitivity to transverse strains by geometrically increasing the area of the end loops in its resistive grid, as described by a strain gage manufacturer. [15] Even with these attempts at minimizing the error, the strain gage sensitivity to transverse strains is usually not zero. However, the transverse sensitivity for both strain gages and FBGs is a systematic error and can be successfully eliminated.

4.2 FBG TEMPERATURE SENSITIVITY

For conventional strain gages, temperature sensitivity is a non-trivial problem resulting in the publishing of literally volumes of studies over the last 50 years to help cope with this phenomenon. These studies are well beyond the scope of this present work – some are referenced, see [16]-18]. Although the methods developed for conventional strain gages are by now well established and tractable, the temperature sensitivity issue nevertheless represents an added complexity that must be dealt with to ensure that accurate strain data are acquired.

Mechanical strain measured in a varying temperature environment can be corrected for temperature by accounting for apparent strain, similarly as to what is done when using a single active foil strain gage. Apparent strain is the strain component contributed to the expansion of the substrate material and the thermal output of the FBG sensor itself (eq. (1)). The apparent strain correction curve is generated by bonding the FBG strain sensors to an exact substrate material sample and heating slowly to the maximum

test temperature (avoiding thermal stresses). The generated curve is then subtracted from indicated strains as a function of temperature to derive applied true strain or thermal strains for stress analysis (eq. (2)).

$$\varepsilon_{\text{app}} = (\alpha_{\text{sub}} + \xi)\delta\text{T} \tag{1}$$

$$\varepsilon_{\text{true}} = \varepsilon_{\text{ind}} - \varepsilon_{\text{app}} \tag{2}$$

In general, FBGs are sensitive to both temperature and strain effects simultaneously. Therefore to make accurate temperature measurements with FBGs, the strain response from the structure must be separated from the temperature response. FBG strain sensitivity is eliminated from the FBG measurement by encasing the grating in a small tube and bonding the tube, usually made from polyimide, to the structure. The tube effectively decouples the FBG from the structural strain and is therefore only sensitive to the temperature environment. If the FBG tube is small and the thermal environment is sufficiently uniform, the temperature difference between the bonded tube encasing the FBG and the substrate is usually negligible. The resulting indicated output from the encapsulated FBG that is produced by thermal loading is converted to engineering units of temperature using strain/temperature calibrated curves that are generated in the laboratory.

Figure 4-1 illustrates the typical installation for measuring strain and temperature with both conventional and fiber optic sensors. The figure shows a standard installation of a conventional strain gage, a conventional spot-welded thermocouple, an FBG strain sensor, and an FBG temperature sensor (in a polyimide tube).

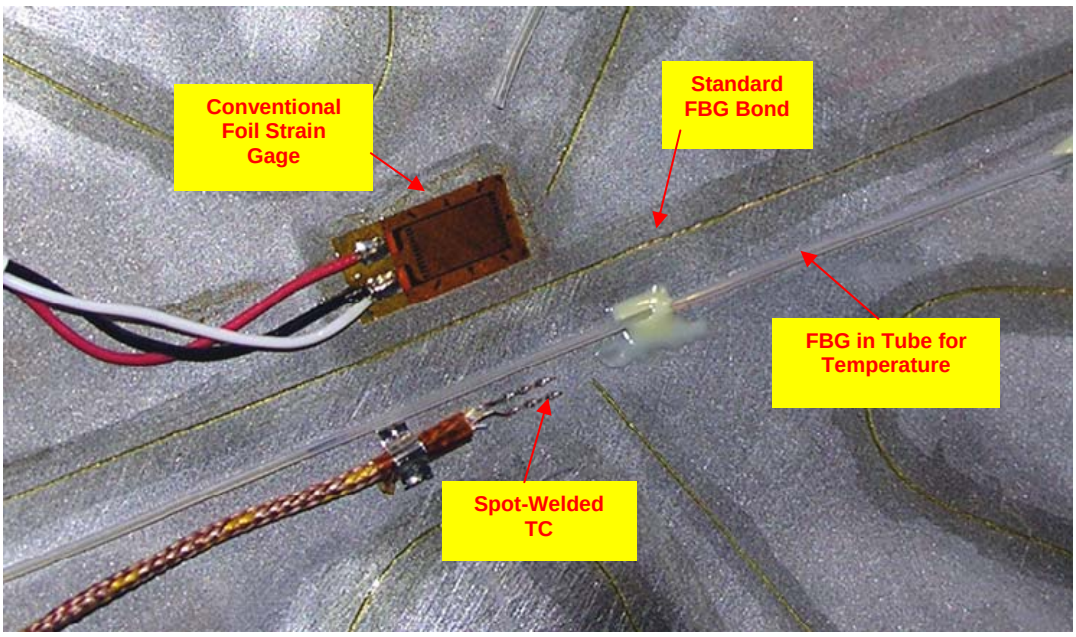
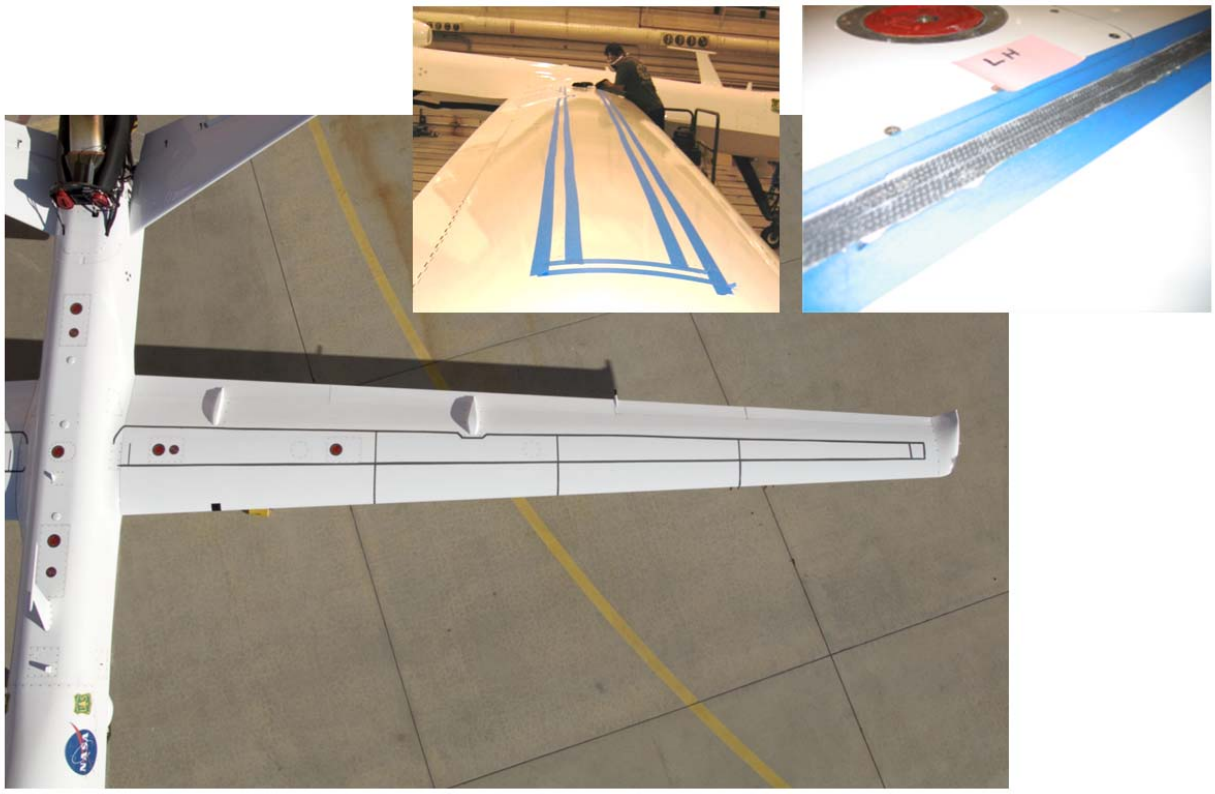


Figure 4-1: Typical Installation for Measuring Strain and Temperature.

Past work at NASA Dryden has included the installation of approximately 3,000 FBG strain sensors located on six 20-ft optical fibers bonded to the upper wing surfaces of an existing Predator-B, named Ikhana (Figure 4-2). These fibers were installed using conventional foil strain gage installation techniques. Such conventional installation methods involved the masking of approximately 120-ft-long by 3/4 in-wide runs on the upper wing surfaces, hand grinding the paint and filler down to the composite wing surface along these runs, adhering the optical fibers to the surfaces using conventional foil strain gage adhesives and procedures, sealing/aero-fare with class B-1/2 polysulfide polymer compound over the installation,

and re-painting. Though this method was successful for the entire flight test program, it was obvious more efficient installation methods would greatly enhance the practicality of covering large fuselage acreage or long wing spans.



NASA Photo ED07-0287-08

Figure 4-2: Installation of FBG Fiber on Wing Upper Surface of Dryden's Predator-B UAV.

To support future requirements for installing copious numbers of sensors in geometrically challenging sensor arrays, new paradigms for sensor characterization and attachment are required. NASA Dryden has been pursuing more efficient techniques for large-scale application of large number of sensors on the aircraft surfaces. One promising technique involves combining these FBG networks into an integrated structural health-monitoring package for installations on large-scale aerospace vehicle structures. As a first step in achieving this overall goal, an integrated demonstration was initiated in which FBG strain sensors for usage monitoring was integrated into a single package that significantly simplified current attachment techniques for large-scale application. These first steps have been directed at measurement validation and addressing a deficiency in bonding enormous number of fiber optic sensors to the surfaces of realistic structures using conventional methods. Highlighted here are past methods used to apply fiber, and the work being done to make the method of installing dense forms of instrumentation on aircraft more efficient.

4.3 ADVANCED SURFACE-MOUNTED INSTALLATION METHODS

As the next step towards the high-level goal of more efficient integrated installations, NASA Dryden partnered with Acellent Technologies, Inc. (Sunnyvale, California) to develop innovative concepts and approaches for the attachment of thousands of fiber optic sensors. These sensors were multiplexed along dozens of optical fibers, arrayed in complex patterns (to accommodate rosette measurements) and bonded to the surface of complex aerospace vehicle structures (e.g. lifting surfaces, fuselage, bulkheads). Initial work

involved incorporating Acellent's patented SMART Layer technology with FBG strain sensors and validating strain and temperature measurements embedded in the polyimide layer or sheet. Side-by-side fibers bonded using conventional methods, as on the Ikhana experiment, and fiber embedded in the SMART Layer were compared (Figure 4-3). Combined thermal/mechanical cantilever bending tests confirmed no undesired effects were induced by the polyimide layer and no effect to sensitivity, or gage factor, of the gratings were detected in both tension and compression, and at room temperature or elevated temperatures of 300°F. [19] These SMART Layer sheets could now be upsized and attempts to co-bond the layer during manufacture processes were initiated for larger scale test articles and aircraft wing or panel applications.

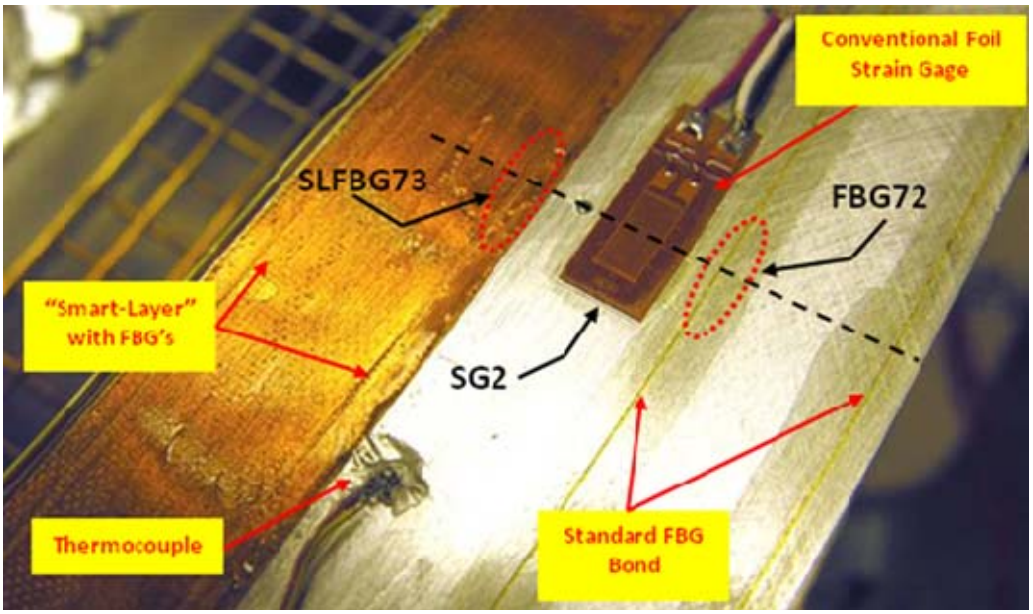


Figure 4-3: Typical Collocated Cross-Section with Conventionally Bonded FBG, Conventional Foil Strain Gage, and FBG Incorporated into the SMART Layer.

Given that the SMART Layer had negligible effect on the measurement compared to conventional direct bonds on the coupon level, the next goal was to address the applicability of the SMART layer for large-scale realistic aircraft structures. Such structures have added complexity due to complicated geometries, numerous egress ports for umbilical attachments, communications and power connections, fuel tank ports, actuator housings, and structurally complex features such as stiffeners, flanges, gaps, and wing folds. These geometric complexities make the extension of conventional approaches, such as those used on the Ikhana flight experiment, for realistic aerospace structures especially difficult.

4.4 ADVANCED EMBEDDED INSTALLATION METHODS

Work has begun with composite manufacturers in co-bonding the SMART Layer during the fabrication process. It is believed this method of a co-bonded surface installation will avoid typical problems encountered when embedding the fiber at depth into the composite material itself. As mentioned earlier, embedded FBG strain sensors are sensitive to transverse strain, which occur during tensile or compressive loading. In addition, if the fiber is embedded, bending strain outputs would be reduced as a function of distance from the neutral axis. Bonding on or near the surface of the structure not only eliminates these undesired traits, but the polyimide SMART Layer will also provide added protection from incidental damage.

Overall, the SMART Layer has potential to help transform installation methods for future aircraft sensor installations.