Distributed Fiber Optic Strain Sensing: Applications in Composites Test and Measurement

Introduction

As the push for stronger and lighter materials permeates through industry, the necessity to fully understand the structural properties of materials being used grows ever more important. Analyzing the strain response of a material or structure under various loading conditions provides invaluable information relating to the strength and robustness of a given material or design. Given the non-homogenous nature of composite materials, the concept that there is a uniformly distributed strain across a test article is not a valid assumption. The vast majority of strain sensing done today employs foil gauges to acquire data. However, point sensors such as these can easily miss details in the strain profile of an article under test. The nature of Luna's distributed fiber optic sensing (DFS) technology provides high spatial resolution strain measurements. This high resolution data allows one to obtain a distributed strain response over the length of a fiber sensor in a single measurement. With gauge lengths as small as 2-5mm, a single 1m sensor made of unaltered telecom-grade optical fiber provides hundreds of effective independent sensors. It is this spatial resolution that makes our DFS technology ideal for measuring the complex strain responses possible when testing composite materials and structures. Below examples of applications illustrate how a high spatial resolution measurement provides insight that cannot be practically achieved using single point sensors such as conventional foil strain gauges.

Case Studies

Coupon Testing:

To illustrate the benefit of high spatial resolution distributed strain measurements, a study was performed using a standard, epoxy-based carbon fiber coupon, with three holes drilled in it to act as stress concentrations [1]. As seen in the Figure 1, the coupon was instrumented with an industry standard foil strain gauge, as well as a fiber optic strain sensor. Note the clean installation of the fiber sensor; the technician was able to make four complete passes along the length of the coupon, around the holes, using the same bonding techniques and agents as with the foil gauge, but with only a single optical connection as opposed to soldering 2-3 connection wires. With four passes made by the fiber sensor and data taken with a 2.5mm gauge length, this is the equivalent of placing 192 foil gauges [1].

Once instrumented, the coupon was clamped at its base and loaded at the tip in a cantilever beam configuration. Strain data were acquired on the foil gauge and the fiber sensor for various loads.

Distributed strain measurements were taken on the fiber sensor using an Optical Backscatter Reflectometer (OBR), a commercially available Optical Frequency Domain Reflectometer system [1].

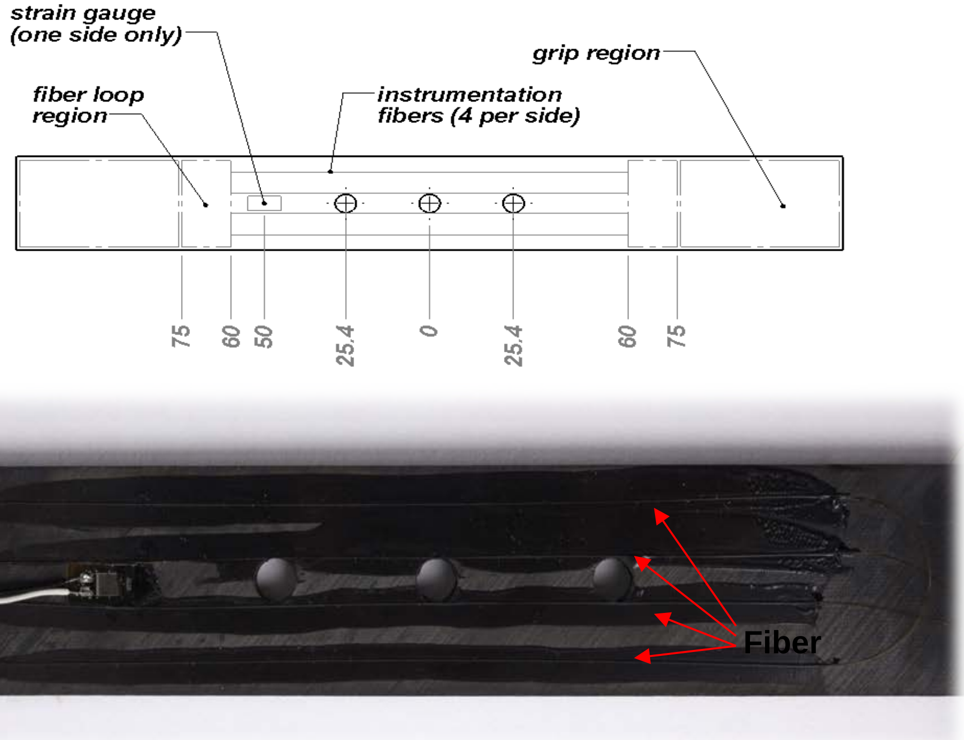

Figure 1: Depiction of a sample coupon cut from the composite panel. It features three open holes, an electrical foil strain gauge, and a surface bonded optical fiber. Measurements are in millimeters (top) [1]. A picture of the actual coupon (bottom).

The plot below displays the strain data from both the fiber sensor and the foil gauge at four different load levels. First, we note the agreement on the strain level between the fiber sensor and the foil gauges at the location of the foil gauge. The strain data from the foil gauges agrees with the strain gathered from the fiber sensor. In addition, the fiber sensor provides a wealth of detailed information about the article under test, most notably the locations of the stress concentrations in the coupon, identified as the significant peaks in the strain response. If one were running this test with only the foil gauge, these regions of higher strain would be missed unless the foil gauges were placed at the precise locations of the features. Further, we can see structure in the signals between the peaks, which could be mistaken as noise in the signal, but in fact is the high resolution strain profile for the carbon composite [1]. This level of detail allows the user to accurately interpret the location and strain response along the entire length of the test artifact in a single measurement. One could use a similar test to determine the location and the effect of a ply drop or verify the distribution of resin after injection and the residual strain after curing [4-5].

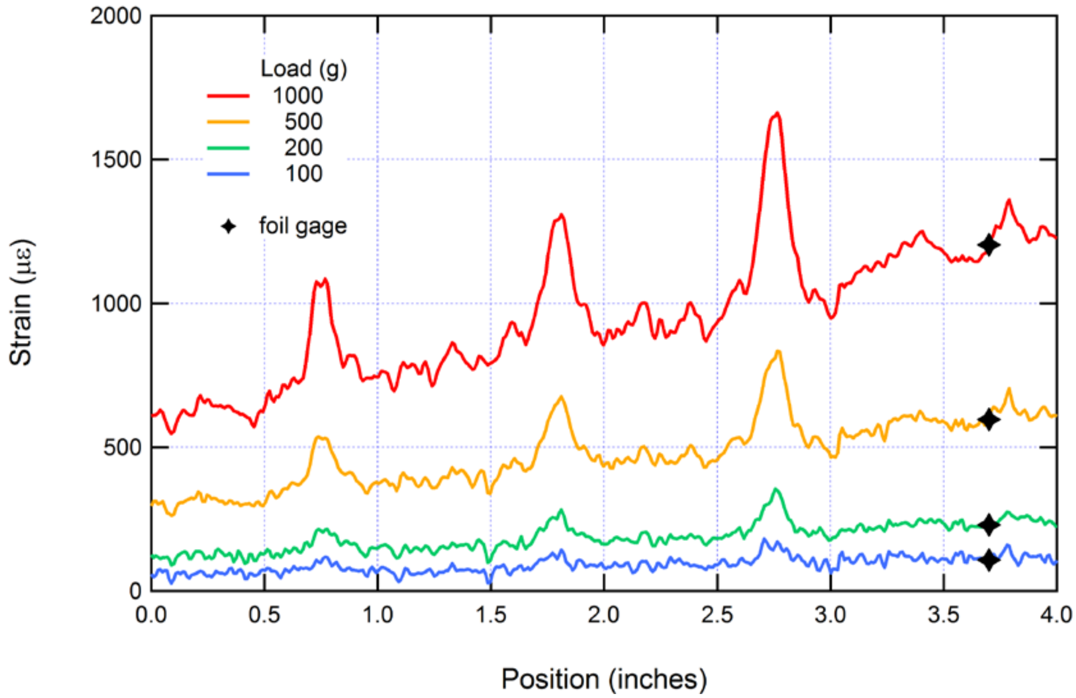

Figure 2: Strains measured by the optical fiber bonded to the front-side surface of the composite for various loading conditions. Strains reported by the foil strain gage are also plotted at each load (diamonds) [1].

The Effects of Defects:

One can further illustrate the benefit of a spatially dense strain measurement by considering a more advanced structure, a wind turbine blade. In a collaborative testing effort with UMass Lowell ("Effects of Defects" program, funded by the DOE) to analyze the effects of defects, we instrumented a wind turbine blade with telecom-grade off-the-shelf optical fiber. Flaws were intentionally placed in the carbon spar cap during manufacturing at the 3.5m, 5m, and 6m blade station locations [2]. The 9m CX-100 wind turbine blade was designed by Sandia National Labs and manufactured at TPI Composites. Using a VARTM resin infusion process, the blade was manufactured in two halves, a high pressure (HP) side and a low pressure (LP) side [2]. Fibers were embedded in the blade during manufacturing as well as surface mounted after the blade was assembled.

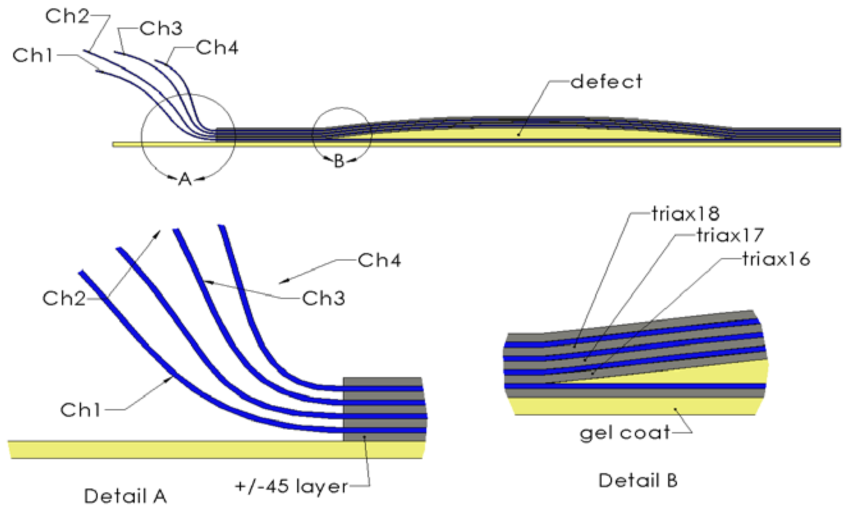

Figure 3: Sectional view of defect with optical fibers embedded between four layers of the spar cap [2].

Both the embedded fibers as well as the surface mounted fibers were immediately able to sense the defects, reading significantly higher strain levels at those locations as observed in Figure 4 [2].

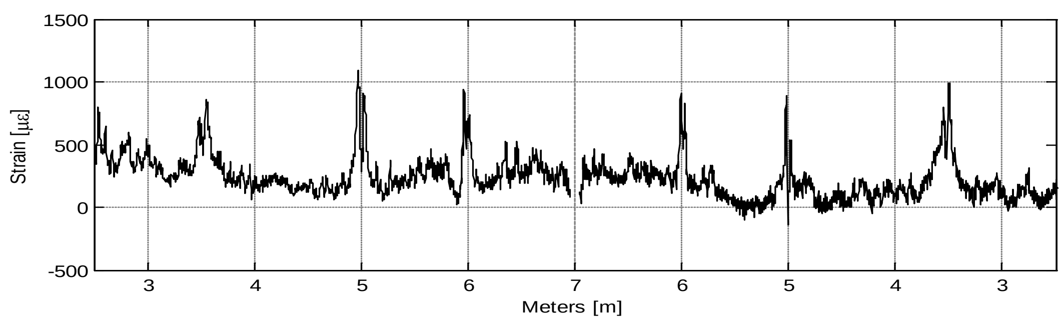

Figure 4: Residual strain measured by the embedded fiber in the HP side of the blade. Note that the 7m mark on the blade is where the fiber turns around to go under to another ply, hence the symmetry about that point [3].

The blade was then loaded and cycled to failure. Static, distributed strain measurements were taken throughout the test using the same acquisition system as our previous example, a Luna OBR. The eventual failure point in the blade occurred at the middle defect, located at the 5m mark along the blade, at approximately the 2 millionth cycle [3]. As is easily observed in the following figures, the fiber sensors were clearly able to identify the locations of the defects in the turbine, and allowed one to predict where the failure would eventually occur. Throughout the testing of the blade, the fiber sensor measured significantly higher strain responses at the locations of the defects in the resin, the highest strain levels occurring at the middle defect where the blade ultimately failed. In Figure 5 below, it is evident that the fiber optic sensor clearly identifies the point of failure after only 716k cycles, well before any visible cracks and less than half the number of cycles required for failure [3].

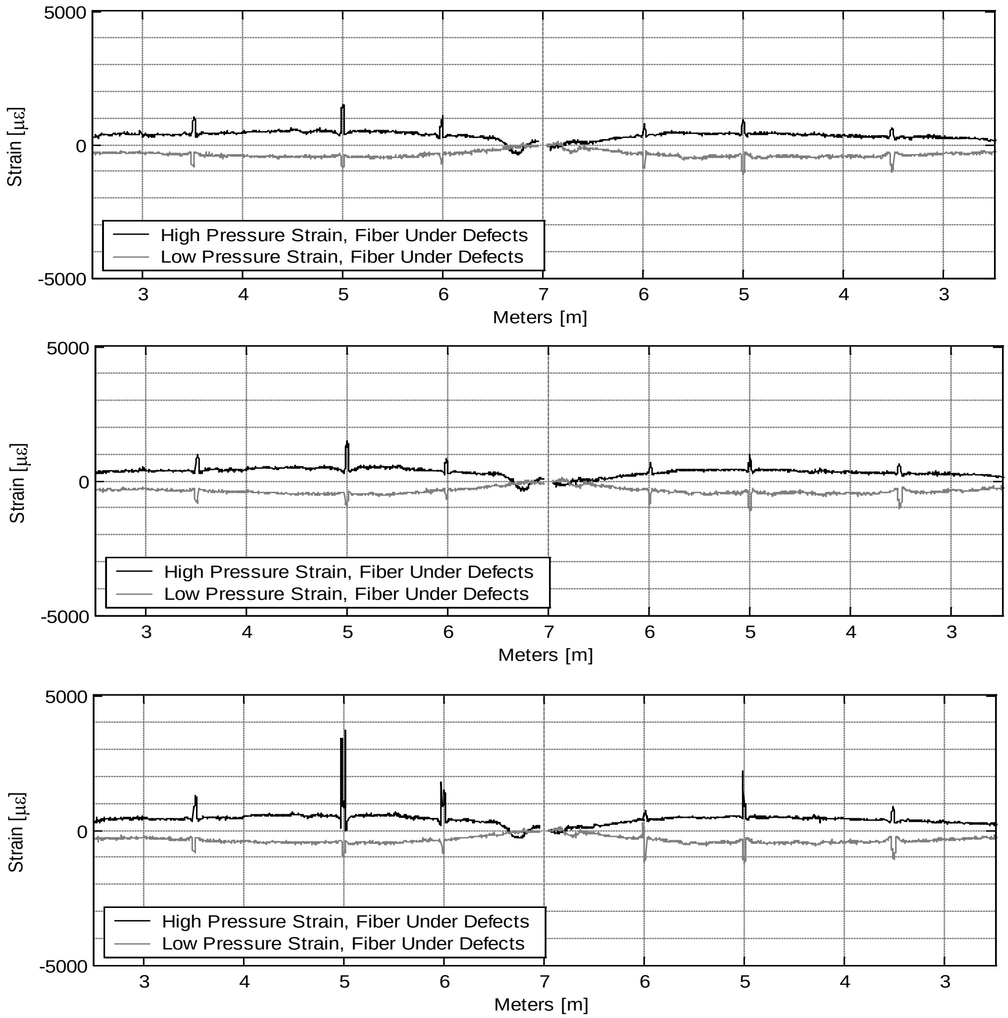

Figure 5: DFS embedded fibers located in +/- 45 layer under defects at 0 cycles (top), 204k cycles (middle), and 716k cycles (bottom). Note that the OBR identifies the failure point at less than half the cycles if took to actually achieve failure [3].

Summary and Conclusion

Inherent in materials testing for failure and fatigue is some amount of waste. One must have enough information on hand before they can be confident in the properties of a new material or design, however this can lead to considerable numbers of repetitions and consumption of materials. With fiber optic sensing, the resolution and distributed nature of the measurements provides sufficient information to completely map out strain profiles, which are of particular interest with nonhomogeneous materials, thereby drastically increasing the efficiency of testing. Distributed fiber optic sensing provides a perspective to the entire strain response of a structure in a single measurement. As conventional materials are replaced with advanced composites, the availability of detailed structural analysis for these materials becomes increasingly important. Distributed fiber optic sensing provides the detailed, high resolution data required to greatly increase the ability of the user to test, analyze, evaluate, and model composite structures.

References:

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