Fiber Optic Sensing

vs.

Strain Gauges

-

Cost Analysis Study

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Nomenclature

BSSM = British Society of Strain Measurement

CTA8.1 = Cylinder Composite Test Article 8-foot-diameter design

DAQ = data acquisition

DIC = digital image correlation

DTG = draw tower grating

FBG = Fiber Bragg Grating

FOS = fiber optic sensing

IML = inner mold line

NASA AFRC = NASA Armstrong Flight Research Center

OML = outer mold line

P_{cr} = critical buckling load

SBKF = Shell Buckling Knockdown Factor

ϵ_b = bending strain

1 Introduction

The medium used for strain gauges is typically a metal alloy connected to a few copper wires. The same type of technology enabled the telephone network to interconnect the world starting in the second half of the 19th century. At the advent of the internet, copper became a bottleneck to transmit data (as those of you who are familiar with dial up internet will remember). Fiber optics made it possible to start streaming information across significantly longer distances at bandwidth levels orders of magnitude higher than any copper transmission line. Because of the sheer amount of data that can be sent using fiber optics, an entire new set of applications and services became available to users, such as high speed video streaming.

Similarly, Sensuron's fiber optics sensing technology enables a paradigm shift to take place in the area of structural testing, specifically for strain and temperature sensing. Spatially continuous measurements along the length of thin, flexible, and virtually weightless optical fiber make it possible to develop a new set of tools that provide deeper insights into how materials react to both strain and temperature. One great example of this is the structural testing of full-scale aerospace structures. Thousands of fiber optic strain gauges can be installed on an aircraft in a fraction of the time required to install traditional strain gauges, making it economically feasible to collect strain measurements at thousands of sensing points. Another one is the structural health monitoring of weight sensitive structures, such as a lightweight UAV, due to the remarkable reduction in cabling required for FOS sensors. The contrast in cabling requirements is illustrated in Figure 1.

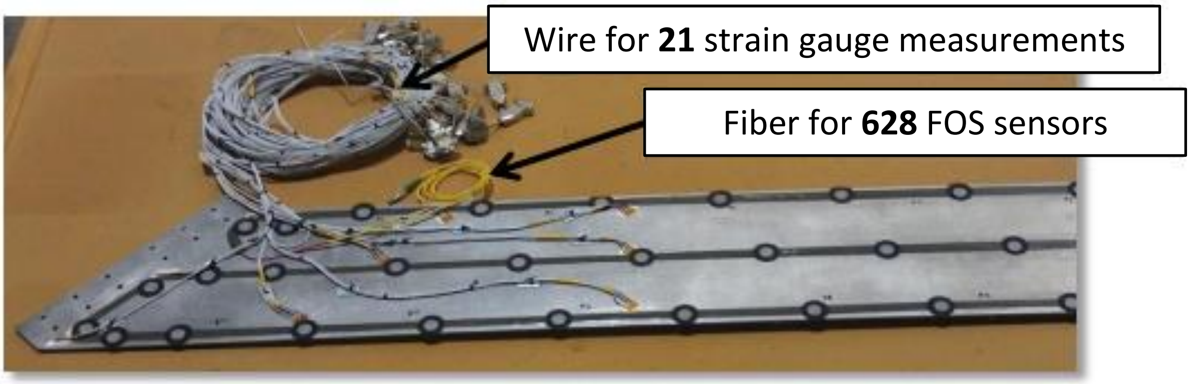

Figure 1: Instrumentation comparison of strain gauge and fiber optic sensing technology [1].

Trade studies performed at NASA Armstrong Flight Research Center (NASA AFRC) show that a typical FOS installation is 0.1% to 1% the weight of a traditional foil strain gauge installation [2]. While FOS sensors have created a paradigm shift in the structural testing arena, their operation is still analogous to that of an electric strain gauge. Instead of monitoring changes in electrical resistance (R), changes in reflected optical wavelength (λ) are monitored and correlated to mechanical strain (ϵ) via a gauge factor (κ):

$$\frac{\Delta R}{R} = \kappa\epsilon \rightarrow \frac{\Delta\lambda}{\lambda} = \kappa\epsilon$$

Strain gauge technology was developed nearly a century ago and has been considered the gold standard for performing experimental strain measurements for the past several decades. However, the use of FOS technology continues to become more prevalent as engineers increasingly take advantage of the advanced testing technologies available in the 21st century. The primary advantages of FOS technology will be discussed in the follow sections.

2 Installation Effort/Complexity

Any experienced experimental stress analysis engineer would agree that the quality of a strain gauge installation greatly influences the accuracy of the measurement. Simply put, a strain gauge can only function as intended if the substrate strain is transferred to the gauge properly, which requires comprehensive expertise from the installer. As a matter of fact, the British Society of Strain Measurement (BSSM) has offered a formal strain gauge certification program since 1964 to formally qualify individuals who demonstrate the ability to competently install strain gauges. The most basic qualification (Level 1) offered for technicians or engineers requires 2 full days of training and typically 2 months of practical installation experience [3, p. 1]. In other words, proper strain gauge installations are not easy and precision is required during every step of the installation. Large aerospace organizations often provide technicians with lengthy self-inspection checklists to ensure each step of the process is correctly followed. A typical strain gauge and FOS installations are shown in Figure 2.

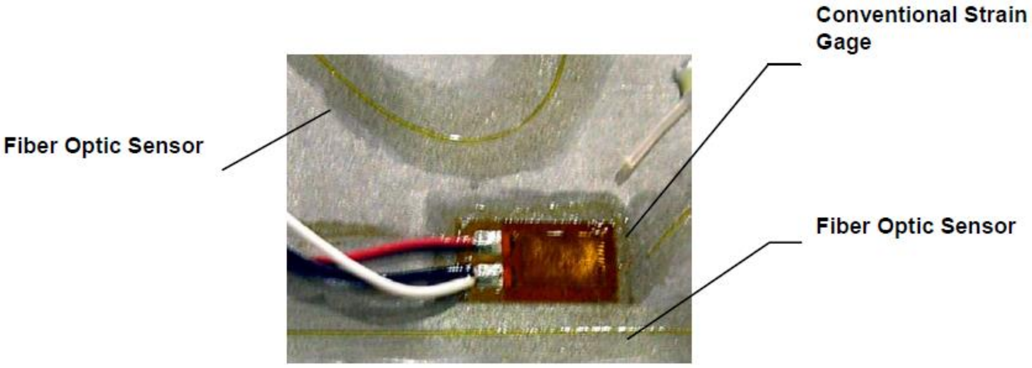

Figure 2: Typical strain gauge and FOS installations [2].

Due to the laborious nature of the installation process [3], strain gauges are often deployed in limited numbers at probable critical points throughout a structure. FOS sensors are installed using similar methods, but at a significantly faster pace. The reduced installation effort is an enormous advantage for large structures where hundreds or thousands of strain sensors are required. In the following subsections, a comparison of installation time and cost for both traditional strain gauges and fiber optic strain sensors is provided.

2.1 Traditional Strain Gauges

2.1.1 Required Installation Time

Install time for a single gauge varies greatly depending on the application (bridge configuration used, substrate material, difficulty of access, routing requirements, etc.). As a baseline reference, the time allotted (180 minutes) during the BSSM Level 1 certification assessment to install a general-purpose quarter-bridge strain gauge is used [4]. The following assumption is made to determine the per sensor installation time:

- An experienced strain gauge installer only requires 15% of the 180 minutes allotted during the BSSM Level 1 certification assessment. Thus, **27 minutes** of installation time is required per strain gauge.

2.1.2 Required Installation Material Cost

Strain gauges are procured in hundreds of different configurations depending on the application (backing material, gage length, pattern type, resistance value, etc.). The price per strain gauge varies depending on the rarity of gauge and the ordered quantity. As a baseline reference, the price of a common general purpose axial strain gauge (CEA – XX – W250A-350) is used. This commercially available strain gauge is available for **$13** [5] when ordered in quantity (>250). The following assumptions are made to determine the material costs required to install a traditional strain gauge:

- The costs associated with electrical wiring varies based off the length of wire required and the strain gauge configuration (i.e. 2 wire vs. 3 wire vs. 4 wire). Commercial strain gauge wire can be procured for $1.50 per meter [6]. It is assumed that required electrical wiring costs **$10** per strain gauge.
- The costs of surface preparation materials and adhesives are omitted.

2.1.3 Cost Summary

Using the assumption that the labor rate for a skilled technician is $50/hour, the per sensor cost breakdown for traditional strain gauges is summarized in Table 1.

Table 1: Per sensor cost breakdown of traditional strain gauges

	Material Cost	Labor Cost
Per individual sensor	$23[1]	$22.5[2]

Traditional strain gauges are discrete point sensors that are installed on a per sensor basis. Multiplexing multiple sensors together is not possible, therefore, there is no cost break when using multiple sensors.

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[1] (cost of strain gauge + cost of electrical wiring)

[2] $\left(\frac{\$50}{\text{hour}}\right) * \left[(27\text{ min}) * \left(\frac{1\text{ hour}}{60\text{ min}}\right)\right]$

2.2 FOS

2.2.1 Required Installation Time

A representative FOS installation is shown in Figure 3. The installation consists of 4’ of fiber bonded to the surface of a uniaxial carbon fiber beam. With the operational gauge length set to 0.0625”, the installation comprised of 798 individual strain sensors spaced uniformly along the length of the fiber.

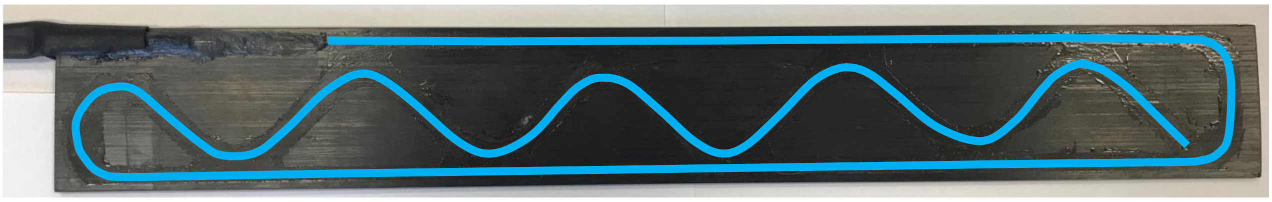

Figure 3: Representative fiber installation using similar procedures to a strain gauge installation. Fiber is installed at the locations and directions where a strain measurement is desired. 72 minutes were required to install the 798 individual strain sensors.

72 minutes were required to complete the installation including fiber connectorization, material surface prep, fiber routing, and application of the adhesive. The following observations and assumptions are used to determine the per sensor installation time:

- Although the installation included 798 individual strain sensors, some of the sensors are not at locations/orientations of interest. It is conservatively assumed that 80% of the sensors are useful (**638 sensors**).
- The 72 minutes required to complete the installation breaks down as follows:
    - Install prep: 22 minutes
        - Fiber connectorization: 7 minutes
        - Substrate surface prep: 15 minutes
    - Fiber routing: 40 minutes
    - Adhesive application: 10 minutes

Based off these observations and assumptions, each individual fiber optic strain sensor within this installation required approximately **7 seconds**[1] of installation time.

2.2.2 Required Installation Material Cost

In contrast to strain gauges, FOS sensors are procured in only a few different varieties because the sensor gauge length is software selectable and not physically inherent to the fiber. Sensors are available in a few different diameters and coating options. As a baseline reference, 195 μm ORMOCER coated fiber is used which is procured at **$30/ft**. The following observations and assumptions are made to determine material costs required to install a fiber optic strain sensor:

- If only a single fiber strain gauge is desired, a minimum 6” length of sensing fiber (**$15)** is required to practically connectorize the fiber and perform the installation. Additionally, a **$5** fiber optic pigtail is required to connectorize the fiber.
- The costs of surface preparation materials and adhesives are omitted.

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[1] $\left[(72\text{ min})*\left(\frac{60\text{ sec}}{1\text{ min}}\right)\right]/(638\text{ sensors})$

2.2.3 Cost Summary

FOS technology allows over 2000 individual strain sensors to be multiplexed onto the same fiber, thus providing some significant savings. The costs for individual sensors and multiplexed sensors are summarized in Table 2 using the following assumptions and observations:

- The labor rate for a skilled technician is assumed to cost $50/hour.
- If only a single fiber optic strain gauge is desired, the full **22 minutes** of install prep is still required (conservative) as well as **5 minutes** (conservative) to bond the sensor.
- When several sensors are multiplexed on the same fiber, each additional sensor requires an additional 0.0625” of sensing fiber (**$30/ft**) and an extra 30 seconds of installation time (conservative).

Table 2: Per sensor cost breakdown of FOS strain sensors

	Material Cost	Labor Cost
First sensor	$20[1]	$22.5[2]
Per additional multiplexed sensor	$0.16[3]	$0.42[4]

2.3 Cost Comparison

As shown in the Figure 4, the per sensor cost for traditional and fiber optic strain gauges are comparable for a single sensor.

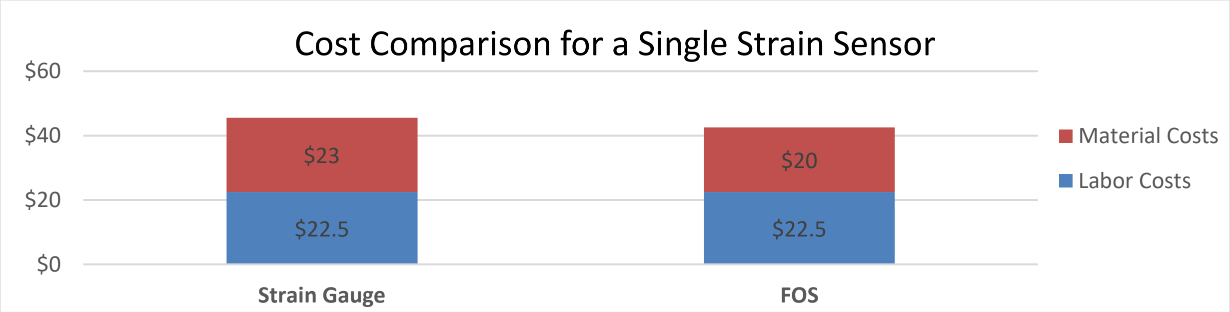

Figure 4: Installation costs associated with a single traditional strain gauge compared to a single fiber optic strain sensor.

However, significant savings are realized when using multiple sensors due to the cost benefits associated with multiplexing several FOS sensors. For the same amount of money required to install two quarter bridge strain gauges, approximately 85 FOS strain gauges can be installed (11.25” of fiber discretized at 0.0625” gauge length). As illustrated in Figure 5, significantly more spatial coverage is accomplished via FOS as a result.

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[1] (cost of sensing fiber (6”) + cost of fiber optic pigtail)

[2] $\left(\frac{\$50}{\text{hour}}\right) * \left[(27\text{ min}) * \left(\frac{1\text{ hour}}{60\text{ min}}\right)\right]$

[3] $(0.0625\text{ inches}) * \left[\left(\frac{1\text{ foot}}{12\text{ inches}}\right) * \left(\frac{\$30}{\text{foot}}\right)\right]$

[4] $\left(\frac{\$50}{\text{hour}}\right) * \left[(0.5\text{ min}) * \left(\frac{1\text{ hour}}{60\text{ min}}\right)\right]$

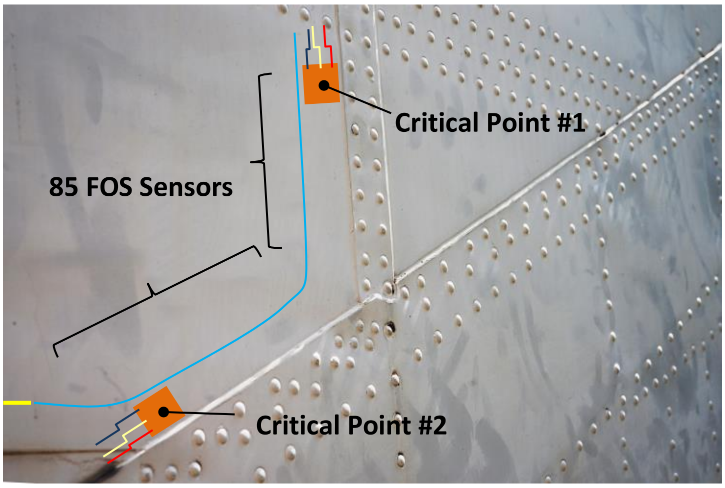


Figure 5: 85 FOS sensors can be installed for the same costs associated with 2 quarter bridge strain gauges, providing increased spatial coverage and significantly more insight into the behavior of the test article.

The increased spatial coverage is invaluable for complex structures, especially in areas where high strain gradients exist. Thom Rollins, Sr. Principal Engineer at Northrop Grumman said it best: "A single fiber allows us to replace thousands of strain gauges, saving us significant man-hours of effort on a single project and providing us with new insight we would not have gotten by using legacy sensing technology.”

For applications that require or can benefit from the use of several strain sensors, FOS technology is clearly attractive due to cost effectiveness, shown graphically in Figure 6. However, the reduced installation time is also advantageous for keeping projects on schedule.

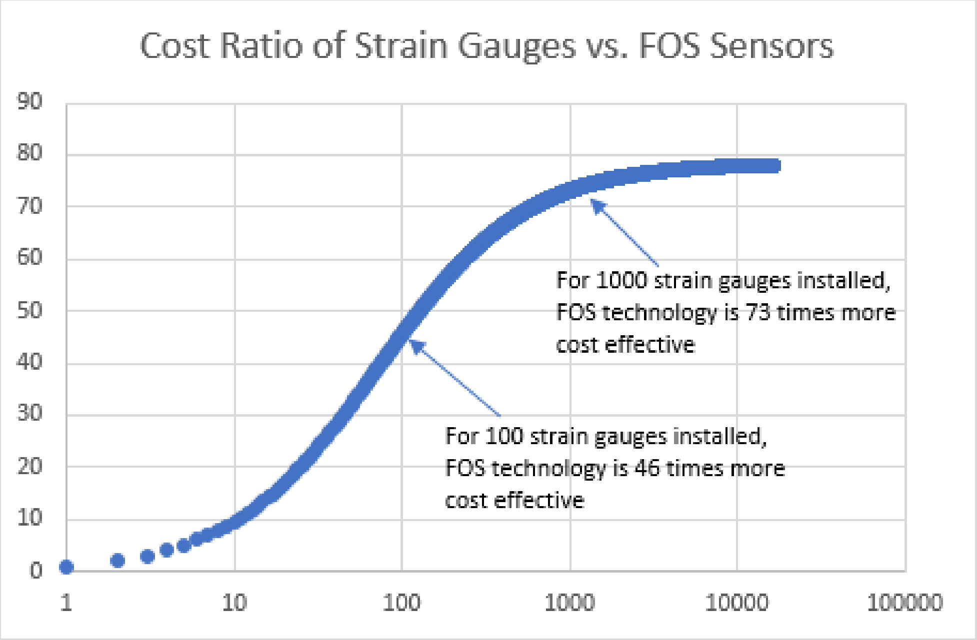
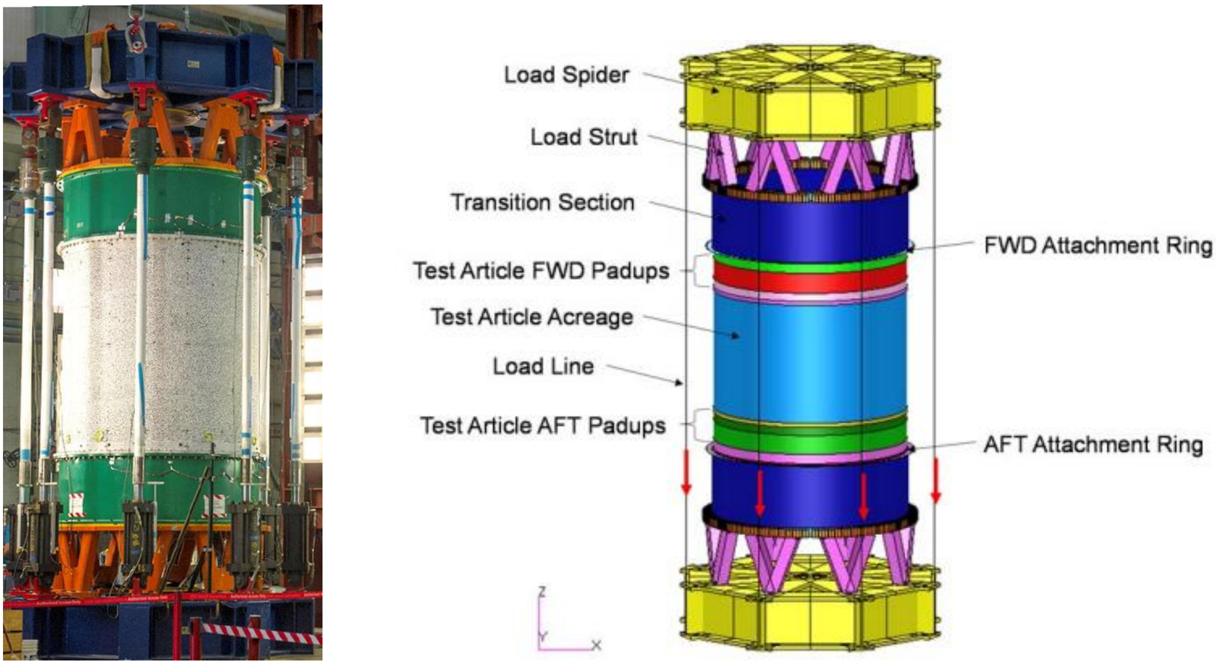


Figure 6: Cost effectiveness of FOS strain sensors.

3 Sensor Density

Due to the time and resource intensive installation process, traditional electrical strain gauges are often deployed in limited numbers. Because of budgetary or schedule constraints, engineers are often forced to determine critical points throughout the structure where individual strain gauges will be installed. This lack of comprehensive coverage creates unforeseen risks that can translate into catastrophic failure. Ignorance is not bliss when it comes to testing. FOS technology enables engineers to capture significantly more data than they can practically with strain gauges and ensure that potential problematic areas on a structure are not missed.

One application amongst many where FOS has demonstrated its usefulness is in the structural testing of a large-scale sandwich composite cylinder (CTA8.1) at NASA Marshall Space Flight Center, shown below in Figure 7.

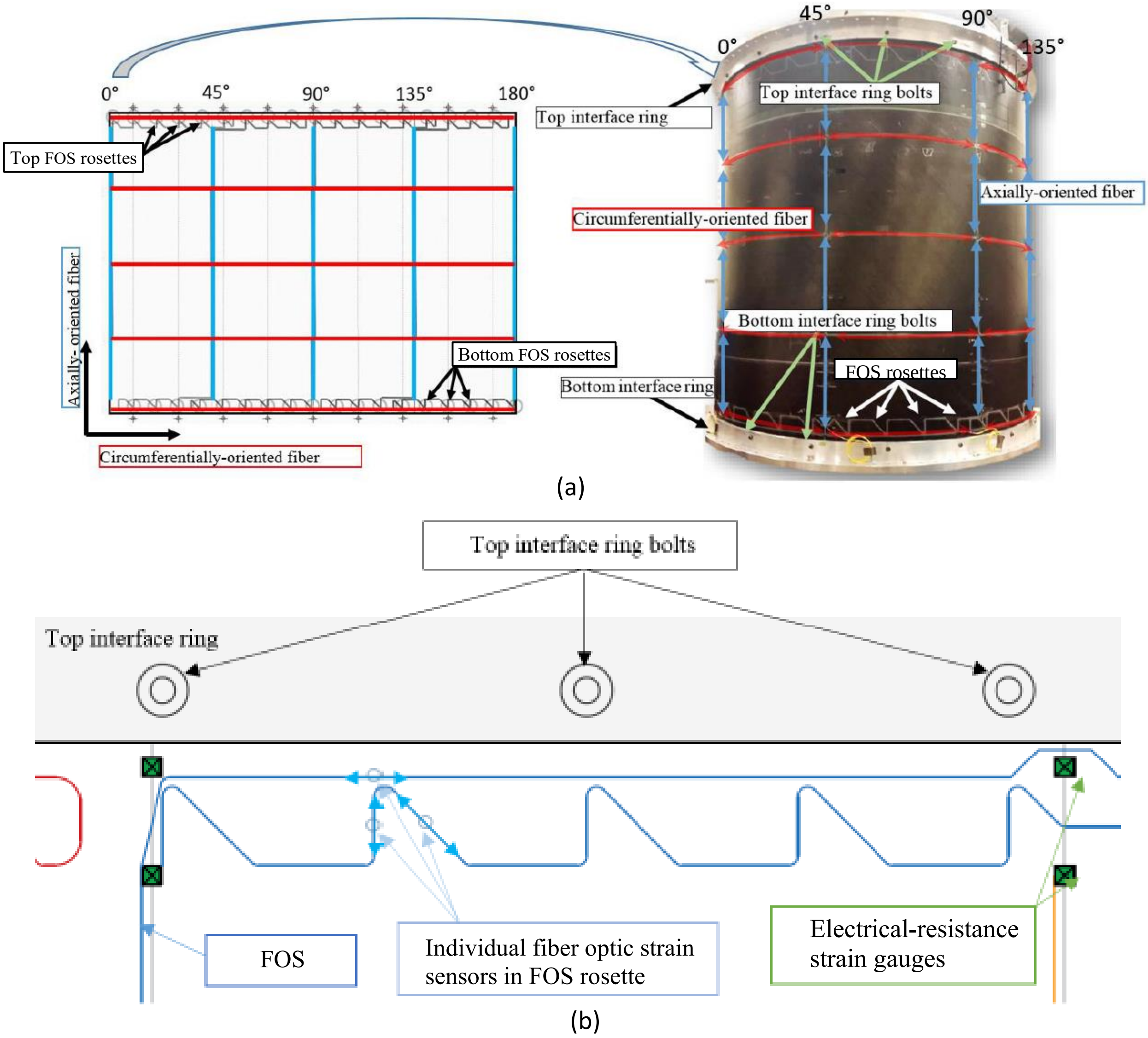


(a) (b)

Figure 7: (a) CTA8.1 Test Assembly [7] (b) Finite element model of CTA8.1 Test Assembly [8].

The testing was completed in 2016 under NASA's Shell Buckling Knockdown Factor (SBKF) Project. The goal of the project was to improve thin-walled shell buckling design guidelines widely used throughout the aerospace community that have not been updated since the 1960s. For modern launch vehicles, buckling is often the critical failure mode and the current guidelines have proven to be overly conservative in most cases. Under improved design guidelines, structural margins can be confidently reduced while maintaining safety of the structure, yielding significant weight savings. For modern launch vehicles, significant costs savings per launch are realized due to reduced material costs and increased payload capacity.

The composite cylinder (CTA8.1) was instrumented with 16 optic cables (40-foot long), each containing over 1,000 individual fiber optic strain sensors (0.50” gauge length). The 16 fibers were directly connected to a modified version of the Sensuron RTS125+ FOS system. The installation layout, shown in Figure 8 (a), included eight axial (vertical) runs and five circumferential (horizontal) runs. Additionally, 144 individual fiber optic strain rosettes were implemented near the top and bottom interface rings (Figure 8 (b)). Note that the installation is mirrored on both the outer mold line (OML) and inner mold line (IML) surfaces (not obvious in the Figure).



(a)

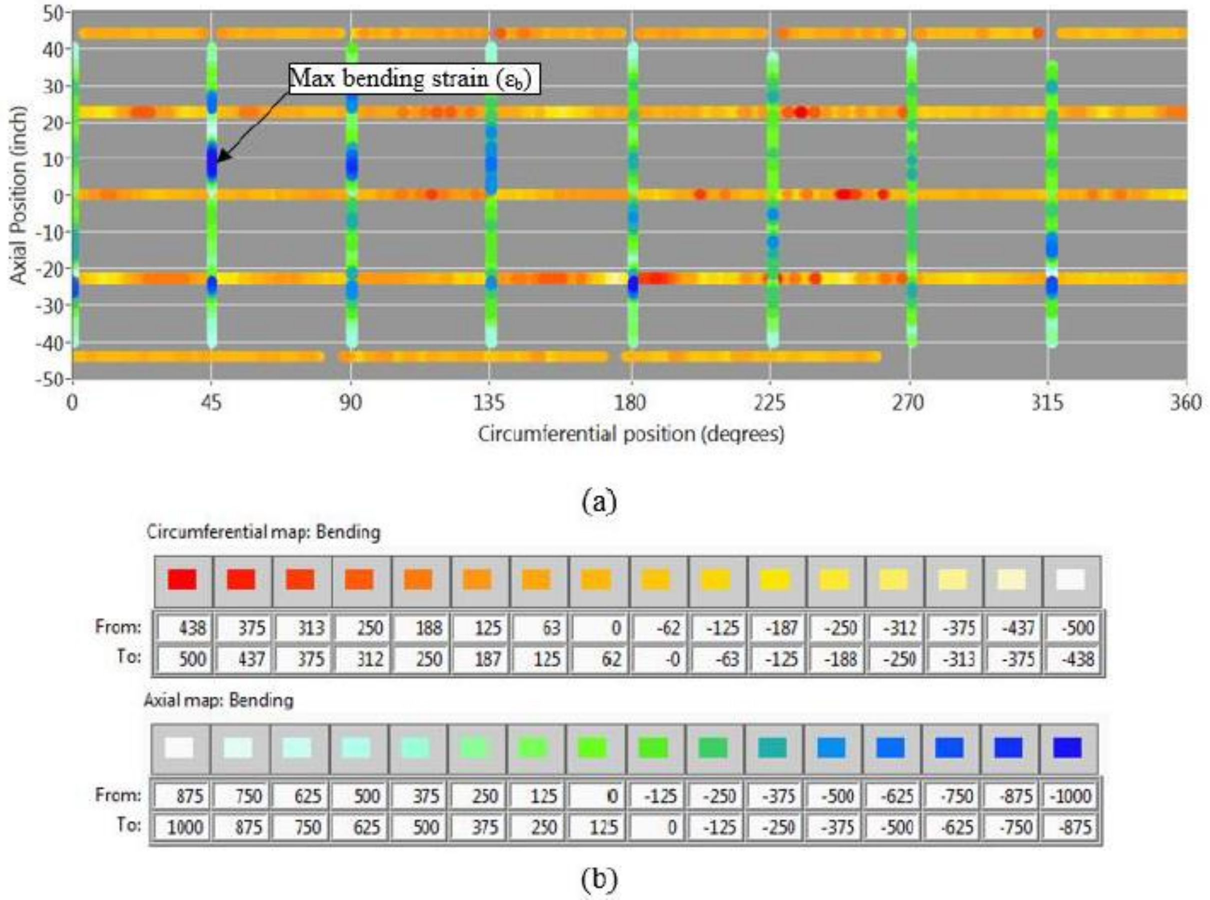
(b)

Figure 8: (a) FOS Instrumentation layout on the outer mold line [7] (b) FOS rosette layout [7].

The axial and circumferential fiber optic cables (Figure 8 (a)) are installed in order to capture the global strain distribution throughout the cylinder for the subcritical load cases as well as to identify the failure location for the critical load case. The FOS strain gauge rosettes are installed near the top and bottom attachment rings (Figure 8 (b)) to monitor the uniformity of the load introduction onto the composite cylinder. In addition to the 16,000 fiber optic strain sensors, traditional measurements were collected from 256 electric strain gauges, 28 displacement transducers, and 14 digital image correlation (DIC) photogrammetry systems. All 3 technologies used as part of this experiment were complementing one another.

The test article was initially subjected to a series of subcritical axial compression load cases (ranging from 20% to 50% P_{cr}). At these subcritical load steps, the axial fiber runs confirmed that the axial strains were being distributed essentially uniformly. During the final load case, uniform axial compression was incrementally applied until buckling failure occurred. As the applied load approached P_{cr}, deformations throughout the structure began to produce a non-uniform internal load distribution due to stiffness changes.

As thin-walled shells are loaded critically in compression, the amount of bending present is a useful parameter to monitor as it is indicative of the amount of radial deformation occurring in each panel, leading to buckling. The FOS sensors were purposely installed on the OML and IML surfaces to characterize the bending strain in each panel. In the Figure below, the bending strain distribution throughout the cylinder is shown just prior to the failure.



(a)

Circumferential map: Bending

	🟥	🟥	🟥	🟧	🟧	🟧	🟧	🟧	🟨	🟨	🟨	🟨	🟨	🟨	🟨	⬜
From:	438	375	313	250	188	125	63	0	-62	-125	-187	-250	-312	-375	-437	-500
To:	500	437	375	312	250	187	125	62	-0	-63	-125	-188	-250	-313	-375	-438

Axial map: Bending

	⬜	⬜	⬜	⬜	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
From:	875	750	625	500	375	250	125	0	-125	-250	-375	-500	-625	-750	-875	-1000
To:	1000	875	750	625	500	375	250	125	0	-125	-250	-375	-500	-625	-750	-875

(b)

Figure 9: (a) Distributed bending-strain measurements just prior to failure [7] (b) Bending-strain intensity color scale [7].

The bending strains shown in Figure 9 are calculated as one-half the difference between the IML and OML strain measurements. Since the FOS system was operated at a 0.50” spatial discretization, the IML and OML strain measurements were aligned within 0.50”. As shown in the Figure, the maximum bending strain occurred at approximately 10 inches above the mid-height of the cylinder at the 45° circumferential position. Pre-test buckling predictions often deviate from actual buckling, making it difficult to identify critical points for traditional strain gauges to be installed. The large spatial coverage provided by the 16,000 FOS sensors greatly increased the probability of capturing bending strain from the critical panel and location.

The distributed data from the FOS measurements provided a high resolution strain map of the axial and circumferential strain occurring throughout the structure. Additionally, the mirrored FOS installation made it possible to monitor the bending strain occurring throughout each panel as the applied load approached P_{cr}.

4 Fatigue

One widespread application where FOS technology exhibits superior performance over foil strain gauges is in the fatigue testing of components, sub-assemblies, and full-scale structures. Demand for full-scale fatigue testing continues to increase, specifically in the aerospace industry where there is significant interest in extending the service life of aging aircraft well past the intended design life. One example is the C-130, shown in Figure 10.

Figure 10: The Lockheed C-130, one of many aging aircraft that the US Air Force intends to fly well past the intended design life.

In order to extract as much life out of these aging aircraft as possible, new fatigue tests are required to appropriately plan future maintenance schedules.

Strain gauges are not ideal for this purpose as they often fail prematurely when subjected to fatigue or cyclic loading. As strain gauges are sufficiently fatigued, a drift of the zero signal occurs due to permanent damage in the gauge, known as a “zero-shift”. Depending on the stress amplitude and number of cycles that the strain gauge is subjected to, the “zero-shift” can range from ten to several hundred microstrain before the sensor stops working entirely. Regardless of the application, the fatigue performance of FBG optical fiber is vastly superior. For example, the nominal fatigue life (where zero-drift remains below 100 $\mu\epsilon$) of a typical commercial strain gauge is 1500 – 2500 $\mu\epsilon$ at 10^6-10^7 cycles [9]. In comparison, optical fiber is essentially insensitive to fatigue. FBG fiber commonly used with Sensuron equipment has proven capable of withstanding over 20,000 $\mu\epsilon$ at several million cycles [10]. Thus, FOS strain sensors are ideal for fatigue testing as the fatigue limit for fiber is well above the strain amplitudes witnessed during the testing of common structural materials.

5 Summary

Reduced installation effort, increased sensor density, and excellent fatigue life are only a few of the unique advantages of FOS technology. Additional benefits include insensitivity to EMI, minimal measurement drift, corrosion resistance, and minimal lead cabling. Although FOS technology provides a variety of distinct advantages, it is not always optimal for all structural testing applications. For example, hard to reach areas or locations with restrictive space constraints are often best suited for traditional strain gauges. Additionally, traditional strain gauge rosettes are recommended to measure principal strains in areas with limited space. FOS technology has demonstrated its relevance as a critical structural testing tool. When used in conjunction with strain gauges, it provides the ability to thoroughly characterize the behavior of a structure or a component.

For more information, please contact info@sensuron.com

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