SENSURON

Strain Measurements Comparison Between Distributed Fiber Optic Sensing and Strain Gauges

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Table of Contents

1 Introduction

Fiber Optic Sensing (FOS) systems have an intrinsic advantage over traditional Strain Gauge (SG) technology, namely they are capable of measuring strain along the sensing fiber in multiple locations. Sensuron's FOS system developed in collaboration with NASA is capable of measuring strain at over 2000 locations along a 13m fiber. A single fiber that provides a high-density strain profile along its length can replace tens or hundreds of strain gauges depending on the length of the fiber. For instance, 2000 SG are required to replace a 13m sensing fiber. Using SG technology to obtain such a measurement would require an enormous number of strain gauges, wire conductors, significantly more labor, and would ultimately result in higher costs as outlined in a study performed previously at Sensuron.

However, fiber instrumentation is a topic that can benefit from the vast body of knowledge and experience in SG installation technology. Sensuron recommends a surface preparation procedure analogous to the standard procedure for SG installation. The procedure includes cleaning, abrading, conditioning/neutralizing, and use of comparable bonding agents. Installation of a limited number of gauges may not appear difficult. However, extra effort is required to accomplish clean and reliable connection between strain gauges and multi-conductor wires via soldering. Management of a large number of cables with fragile soldered ends is also an issue. One typical remedy is to limit the number of SG installed by predicting the most important locations and leaving supposedly unimportant areas with no measurement at all. In addition to potentially missing critical information, this approach is inefficient in health monitoring applications where a structure's continuous response along time and space is the essence of predictive algorithms. Due to these problems, SG technology is neither suitable nor practical for distributed sensing or effective structural health monitoring.

The distance between sensing points in all Sensuron systems can be as low as 1.6 mm. This ensures a truly high-density network of distributed strain or temperature sensors. Achieving any level of distributed sensing with SG requires significantly more time and effort, while the added total weight of wires can no longer be ignored in weight-sensitive structures. In such applications as lightweight structures and flying objects, the extra weight has traditionally been a major obstacle in using a distributed network of SG. This obstacle can now be overcome with the use of Sensuron's FOS technology in which the signal of all the sensors is transmitted optically through the same optical fiber.

One difficulty of implementing FOS systems for potential users arises from the fact that FOS systems have different characteristics regarding their hardware (e.g., laser and fiber) and implemented interrogation schemes namely OFDR, WDM, Raman, etc. Consequently, accuracy of these FOS systems must be ideally examined by direct comparison to an established framework. While there are several established methods for strain measurement, strain gauges are undoubtedly the most frequently used tools both in lab and field applications. They have been under continuous improvement for decades and have achieved a high level of maturity regarding hardware, installation methods, and driving/excitation techniques. It is notable that most SG manufacturers advocate a truly strict installation process to significantly reduce the uncertainty in the installation process and guarantee optimal performance.

In the present study, we examine the accuracy of strain measurements obtained by Sensuron's FOS technology in comparison to commonly used Strain Gauge technology installed on a cantilever beam as shown in Figure 1.

Figure 1. A demonstration cantilever beam with an installed fiber is part of Sensuron's offering included with Strain Sense interrogators to provide users with a simple and effective initial experience.

2 Fiber Strain Sensitivity

The two direct measurements of all Sensuron interrogators are mechanical strain (ϵ) and temperature (T). This is due to the inherent sensitivity of the Bragg wavelength (λ_b), as seen below in the well-known Bragg equation.

$$\frac{\Delta\lambda_B}{\lambda_B} = \kappa\epsilon + \Delta T(\alpha + \eta) \qquad (1)$$

In the absence of thermal effects, obtaining the strain from the above equation is very straight forward.

The temperature sensitivity stems from two phenomena, changes in the core refractive index with respect to temperature and thermally induced strain when the fiber is bonded to the surface of a material with a coefficient of thermal expansion much higher than the fiber. In equation (1), the temperature dependency of the refractive index is described by the thermo-optic coefficient (η). α is the coefficient of thermal expansion of pure silica, relating the thermally induced expansion/contraction of the Fiber Bragg Grating (FBG) to shifts in the reflected Bragg wavelength. The acquired strain data is always the apparent strain (ϵ_{app}) which includes effects due to mechanical strain (ϵ_{mech}) and temperature (ϵ_T).

$$\epsilon_{app} = \epsilon_{mech} + \epsilon_T \qquad (2)$$

A critical objective behind fiber optic strain sensing is eliminating the thermal strain component, such that the final strain is only the mechanical and load-induced strain. One approach is to remove the average strain measured before the load application and after the load removal. This type of baseline correction can be used effectively if the temperature change is small and gradual. These conditions are usually met in short duration loading within a contained space and in room temperature. Sensuron has developed more elaborate techniques for temperature compensation in environments with more complex and/or transient temperature changes. Please contact us at info@sensuron.com to discuss details.

3 Setup

3.1 Cantilever Beam

A cantilever beam setup resembling many thin-walled structures dominantly under bending deformation was selected to compare strains obtained from FOS vs SG. High strains, both in tension and compression, can be achieved with a relatively low and easily manageable force by using a beam with small thickness. Different strain levels can be achieved and measured both by changing the magnitude of the point force and by moving farther from the point force toward the base. It also structurally resembles an idealized airplane wing. A single fiber installed on the surface provides high-density distributed strain measurements covering a wide strain range while several SG can be installed adjacent to the fiber to provide multiple comparison points as shown in Figure 2.

Beam theory can present a baseline for the surface strain given the properties of the beam. However, surface strain is a function of h^3 (h=beam thickness). This makes the calculated strain values highly sensitive to fluctuations and measurement errors in h. Furthermore, the exact elastic modulus of the material which is required in strain calculation may not be known a priori with adequate certainty.

The 5051 Aluminum beam used in our test has the following specifications: measured thickness=2.93 mm; measured width=25.06 mm; free length= 235 mm. Figure 2 shows the details about the beam structure and loading mechanism.

3.2 Surface Preparation

The standard process recommended by most SG manufacturers for SG installation was implemented in the installation of both SGs and optic fiber to minimize measurement inaccuracies caused by inadequate bond between SG or fiber and the beam surface. The process involved degreasing, abrading with silicon carbide paper #320, cleaning, burnishing, and finally applying conditioner/neutralizer. M-bond 200 was used as the bonding agent for both installations. The sample was not loaded for at least 1 hour after SG and fiber installation to allow the adhesive to cure properly and completely.

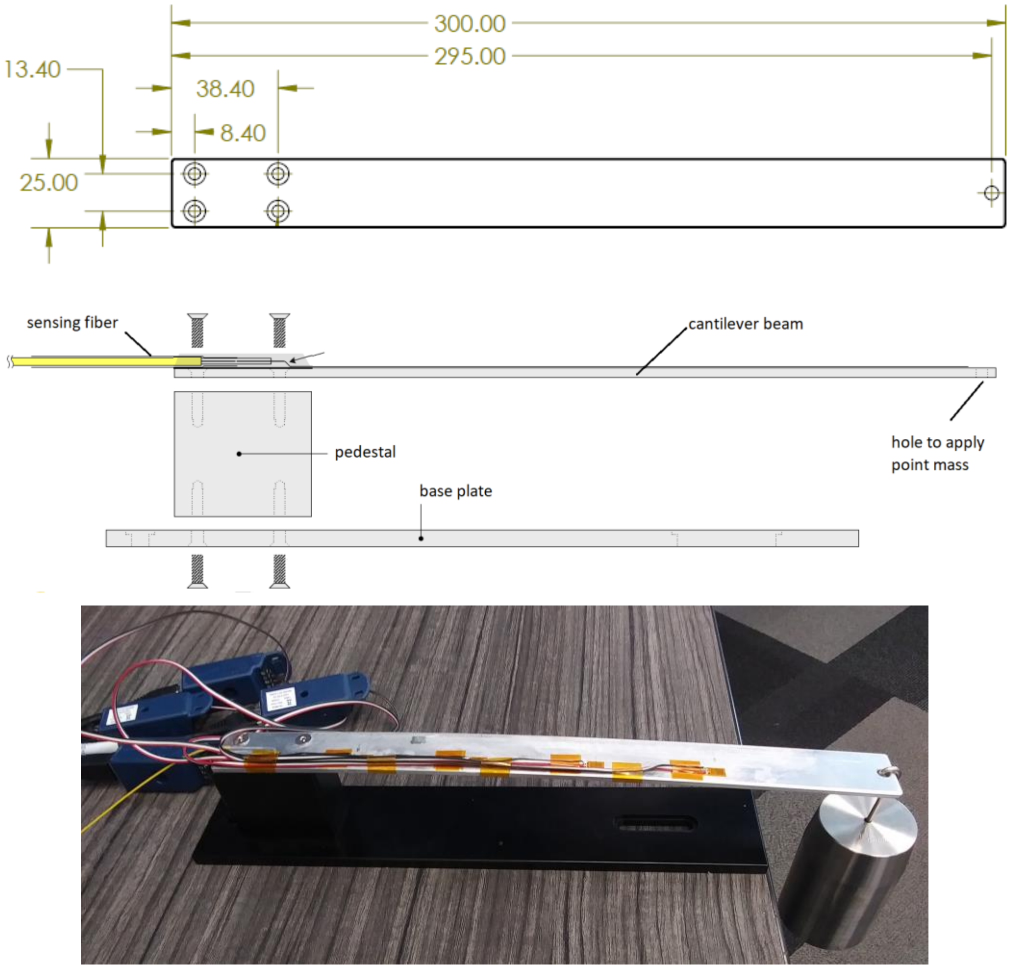

Figure 2. The cantilever beam setup: drawings, assembly, and the actual test sample with FOS and 4 strain gauges subjected to a point load creating positive tensile strain in sensors.

3.3 Strain Gauge System

Strain gauges come in different shapes and resistance. They require a signal conditioner and I/O hardware to convert mechanical strain to changes in electrical voltage by a data acquisition unit.

The specifications of the four 350 ohms strain gauges are as follows: Type: SGD-5/350-LY43, Gauge Factor= 2.12.

The distance between four SGs was set to 32 times the FOS system's resolution to facilitate correlating SG results with the correspondent strain measurement from the FOS's distributed strain.

A National Instruments NI 9237 4-channel Strain/Bridge Input Module was mounted on an NI cDAQ-9185 Ethernet CompactDAQ Chassis. A LabView VI was developed to obtain strain data from the DAQ system and store the data. Quarter bridge configuration with 3 wires was used. Micro Measurements 326-DFV 3-conductor cable with a length of 0.4 m was used to connect each SG to an NI-9945 Quarter Bridge Completion Module. High precision soldering was performed under microscope by an experienced electrical technician. Prior to each test, a software-based calibration provided with NI-9237 was performed which included shunt scaling. While the system has a maximum sampling rate of 19 kHz, in this study the sampling frequency was set to 100 Hz.

3.4 FOS System

An FBG sensing fiber with an approximate length of 194 mm and diameter of 0.125 mm was properly installed on the cantilever beam coupon. An optical patch cable with a length of 5 m was used to connect the sensing fiber to a broadband reflector (BBR). Sensuron’s Summit system was used to measure strain with an acquisition rate of 16.25 Hz and a spatial resolution of 1.61 mm. Spatial resolution is the distance between the centers of two adjacent strain measurement points and is equal to the portion of the fiber along which the strain is surveyed, averaged, and reported by the interrogator. Based on this configuration, a total of 120 sensing points were achieved along the fiber.

Unlike the SG system which separately reports strain measurements for each gauge, FOS system reports measurements along the total length of a sensing fiber. In the case of this installation, a 194 mm sensing fiber will result in 120 sensing points (194/1.61= 120) along its length.

An extensive calibration procedure is not required for ensuring the overall accuracy of a fiber optic strain sensor. When the system is turned on, it automatically sets all initial strain values to zero.

4 Empirical Results

4.1 Static response

The beam response subjected to a point force was obtained by hanging a weight with known magnitude at the end of the beam for a short period. Four different weights (500, 1000, 1500 and 2000 grams) were used to obtain eight instances of the beam response producing tensile and compressive strains at the instrumented surface. Both FOS and SG systems were turned off after each loading/unloading. Generated data files were processed afterwards and average strain over a 10 second window was calculated for 4 strain gauges as well as all 120 sensing points along the fiber. The window was selected in the middle of the testing period when the initial vibration response of the beam had completely dissipated. All tests were short duration (3-4 minutes) and performed at room temperature with limited temperature change.

The diameter of the sensing optical fiber is very small (0.125 mm); however, when installed on a thin beam and subjected to bending moment, the fiber will experience higher strains in comparison to the beam’s outer surface. This is because the fiber core is at a greater distance from the neutral axis than the beam’s surface. Note that based on Euler-Bernoulli beam theory, even under pure bending, the difference between fiber strain and surface strain is of importance only in applications that deal with thin structures (relative to the fiber diameter). For the present setup, to estimate the strain on the beam’s surface and make a comparison with foil strain gauges, measurements made by the FOS are multiplied by a factor of 0.96, which is calculated from the beam theory.

As shown in Figure 3, the FOS system provides high-density distributed strain values along the fiber. Obtaining a comparable strain profile of this small beam with a larger number of SG requires extra efforts with SG installation, soldering and wire management.

The strain values for four SG as well as their corresponding FOS measurements are reported in Table 1A. One can calculate the relative difference percentage as (strain_FOS – strain_SG)/strain_SG. These results are shown in Table 1B. Applying higher magnitudes of hanging weight on one end of the beam may introduce torsion-induced strain and error in bending strain measurements for both FOS and SG. Despite these uncertainties present in the test setup, the average difference between FOS and SG measurements using 32 data points is -0.1% while the STDEV is 1.5%.

Furthermore, R-squared can be calculated for the best linear fit for SG and FOS data, with the notable difference that SG data only consists of 4 strain measurements, while FOS provides 120 points along the single fiber. Since the strain values on a surface of a beam with uniform width and thickness should change linearly with distance from the point load, R-squared shows how well the measurement points represent the ideal linear regression fit. In Table 2, values for R^2 are presented. Strain measurements obtained by both technologies along the length of the beam are very close to an expected straight line.

In addition, both systems were tested for repeatability of measurements under increasing and decreasing stepwise loading as shown in Figure 4. The total duration of the experiment was about 10 minutes. Both FOS and SG systems demonstrated good repeatability and return to zero. This test was performed with a different resolution of 6.443 mm for FOS resulting in 29 strain measurement points.

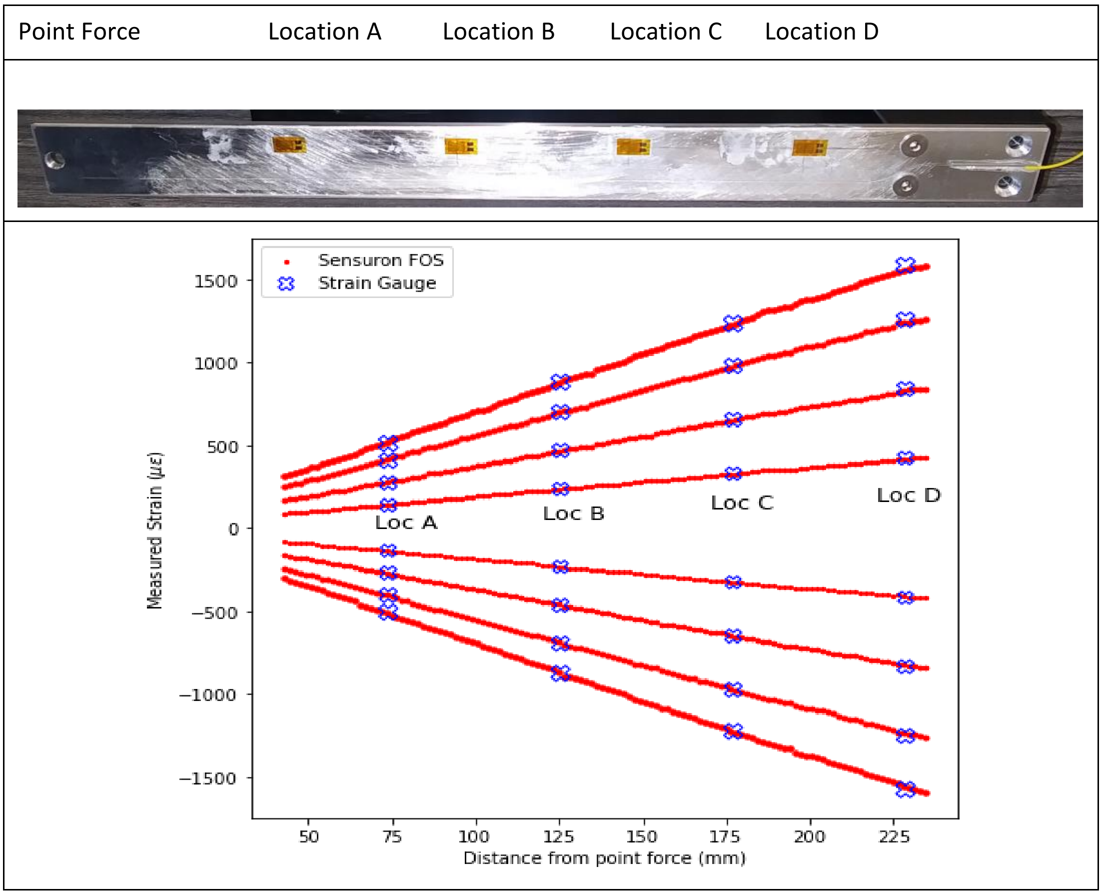

Figure 3. Comparison of strain obtained by a single optic fiber (delivering 120 measurement points) and 4 strain gauges installed at locations A, B, C, and D. Strains produced by beam bending vary linearly with distance from the point force applied on the left end of the Aluminum cantilever beam. The test was repeated 8 times with different point loads producing tensile and compressive strains in the instrumented surface of the beam.

A

	Measured Strain (micro strain)							
	Load Case							
	Tension 1		Compression 1		Tension 4		Compression 4	
Location	**FOS**	**SG**	**FOS**	**SG**	**FOS**	**SG**	**FOS**	**SG**
A	139	136	-138	-137	526	510	-519	-508
B	234	234	-235	-233	883	879	-878	-877
C	325	327	-326	-327	1230	1233	-1229	-1228
D	417	420	-414	-420	1558	1585	-1560	-1579

B

	Difference in Measured Strains between FOS and SG (%)							
	Load Case							
Location	**T1**	**C1**	**T2**	**C2**	**T3**	**C3**	**T4**	**C4**
A	2.5	0.9	2.9	1.3	3.1	0.9	3.1	2.2
B	0.2	0.3	-0.8	-0.2	0.2	-0.4	0.5	0.1
C	-0.6	-0.2	-0.3	-0.2	-0.5	-0.3	-0.2	0.1
D	-1	-1.9	-1.3	-1.0	-1.3	-1.2	-1.7	-1.2

Table 1. (A) Strain measured by FOS and SG presented in Fig. 3 for 2 tension and 2 compression load cases. (B) Difference percentage between FOS and SG measurements. The average difference is -0.1% while the STDEV is 1.5%.

Location	Goodness of Linear Fit (R^2) for Strain Vs. Distance from Point Force							
	Load Case							
	T1	C1	T2	C2	T3	C3	T4	C4
120 FOS measurment points	0.9995	0.9992	0.9996	0.9996	0.9996	0.9997	0.9994	0.9996
4 Strain Gauges	0.9999	0.9999	0.9998	0.9998	0.9998	0.9999	0.9999	0.9998

Table 2. R-squared calculated for best linear fit for Strain Vs. Distance from Point Force for each Load Case. 120 FOS measurement points along the fiber as well as 4 strain gauges are used to obtain the best linear fit and its corresponding R^2.

Figure 5 shows the repeatability and return to zero at Locations A and D for the FOS system for this typical load/unload cycle. SG measurements also showed good repeatability and return to zero as expected. We examined the linearity and repeatability of strain measurements at all 29 FOS points as well as 4 strain gauges. As reported in Table 3, the mean of R^2 values for repeatability/linearity is 0.9999 for both FOS and SG systems.

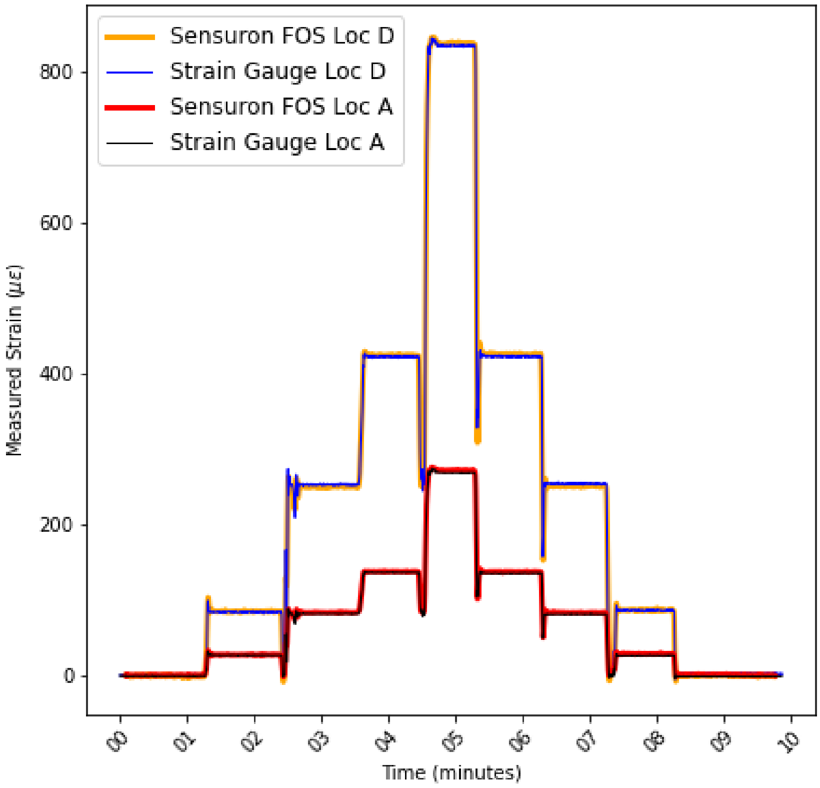

Figure 4. Strain history at Loc A and Loc D measured by FOS and SG. The cantilever beam is subjected to stepwise loading/unloading. Results of FOS and SG show comparable repeatability and return to zero.

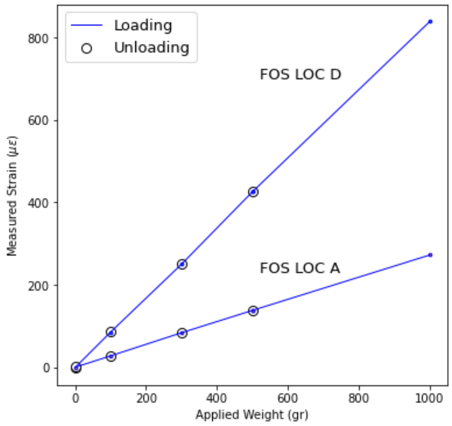

Figure 5. Strain vs Load at location A and D measured by Sensuron FOS. Strain measurements in loading/unloading showed high linearity and repeatability.

Technology	Number of sensors	R^2 values for Strain Vs. Load			
		Lowest	Highest	Mean	STD
FOS	24	0.9996	1.0000	0.9999	0.0001
Strain Gauge	4	0.9999	1.0000	0.9999	0.0000

Table 3. Comparison of linearity of Strain Vs. Point Force Magnitude during loading and unloading. R^2 for Strain Vs. Point Force is calculated for each of 29 FOS points as well as 4 SG and statistics of those values are reported here. Mean R^2 for both systems is 0.9999.

5 Summary

A major advantage of Sensuron's FOS systems is the ability to provide high-density distributed strain or temperature measurements. However, each FOS system has some unique features, and it is highly valuable to quantify the accuracy of any FOS system. A direct comparison of strain measurement carried out by Sensuron's FOS system and common Strain Gauge technology is presented. Based on multiple experiments inducing both tensile and compressive strain, the average difference between strains measured by Sensuron's FOS and strain gauges is found to be about 0.1%. FOS strain measurements and strain gauges were found to be in close agreement with respect to repeatability and linearity during loading and unloading. Finally, the fundamental benefits of performing distributed fiber optic strain sensing with the Sensuron technology are discussed.

6 Technology Benefits

Sensuron's fiber optic sensing technology provides a paradigm shift for high-density distributed strain and temperature measurement systems. Achieving this level of data fidelity is impractical using traditional strain gauges. Due to its small size, chemical inertness, and immunity to electromagnetic interference, optical fibers can be installed in environments that alternative sensing technologies cannot operate in.

In the aerospace industry, active controlling of flexible structures and wings has become a top priority in ensuring the survivability of fuel-efficient flying devices. Distributed strain sensing is critical in optimization and weight-reduction studies. Other applications include monitoring pipeline, bridges, and infrastructure of national interest.

A vast majority of applications that intrinsically require distributed strain profiles but currently employ traditional strain gauge technology would benefit from having thousands of additional measurement points. The primary reasons that strain gauges are currently deployed in limited quantities are the installation time associated with each SG, the cumbersome wire bundles, and the associated weight penalty. Sensuron's FOS technology with its high signal to noise ratio and the resulting dynamic measurement capabilities overcomes all these issues, enabling engineers to capture information that would otherwise be impractical to obtain.

For more information, please contact info@sensuron.com