SENSURON

Fiber Installation Methods for High-Resolution Fiber Optic Sensing

www.sensuron.com

Table of Contents

1 Introduction

Fiber Optic Sensing (FOS) systems have been in use for more than three decades. However, there still is some confusion about the possible and best installation methods. Sensuron's FOS provides hundreds to thousands of sensing points with a resolution of 1.6-6.4mm along a single sensing fiber. While the maximum sensing length for a single fiber is currently 13m, this combination of length and resolution has been found to be very useful in many applications especially in the Civil and Aerospace industries.

To obtain a good strain measurement, proper fiber installation is a must. However, what is a proper fiber installation? Fiber, unlike foil strain gauges (SG), is intrinsically suitable for embedment. The actual 3D shape of sensing fiber makes a surface installation more on par with an embedment; again, quite different from the almost 2D shape of a super thin strain gauge, creating a surface bond with minimal glue use. For comparison, common sensing fibers' diameters vary between 0.1 to 0.2 mm while most foil strain gauges are 0.02 to 0.04mm thick. Unlike set-in-stone rules for strain gage installation, some high-density FOS users are still experimenting with different bonding techniques in their endeavor for best practices.

At Sensuron, we have had the opportunity to be involved with projects that require a wide range of installation methods. The goal of this document is to provide a review of the installation methods that we have had hands-on experience with and ultimately engage the reader to consider how a high-density FOS can be implemented in their application to provide high-fidelity distributed strain measurements.

2 Surface Installation Using Adhesives

Fiber surface instrumentation is a topic that can benefit from the vast body of knowledge and experience in SG installations. Sensuron recommends a surface preparation procedure analogous to standard procedures for SG installation. It includes cleaning, abrading, conditioning/neutralizing, and use of comparable bonding agents. While installation of a limited number of SGs may not appear difficult, extra effort is required to accomplish clean and reliable connections between strain gauges and multi-conductor wires via soldering. On the other hand, FOS has the unique feature of measuring and transferring the data through the same optical fiber.

The standard sensing fiber has a diameter of 0.195 mm while thinner fibers (diameter = 0.1 to 0.115 mm) are also available for fine applications. This small diameter also makes fiber exclusively suitable for measuring strain on the edge of thin structures. We have installed fiber on the edge of a beam with only 2.5mm thickness. This capability opens doors for measuring strain in unprecedented situations such as in-plane bending of thin structural members.

When space is available, we recommend having an 8 to10mm wide glue line with the fiber at the center. This helps to ensure that the fiber is sufficiently bonded to the surface.

Most adhesives used for strain gauges can be used for fiber too. For instance, M-Bond 200 is a fast-curing adhesive suitable for installations that are not expected to be long-term. For installations with a life-expectancy of several months and beyond, a 2-part epoxy glue, e.g. AE-10, is more suitable. In addition, due to its longer work time the application is much easier, especially for installers and technicians with limited prior exposure to FOS. It has very good thermal resistance as it can be used for applications up to 200 °C which is the same as the thermal rating of Sensuron's standard sensing fiber.

After the recommended cure time (generally 24 hours or less), the fiber will be ready for mechanical testing. While fiber is covered by the adhesive, an additional protective layer is recommended to provide more protection for the fiber and adhesive when subjected to external and environmentally harsh effects such as water exposure, mishandling and unintentional contact by hard or sharp objects. Silicon in the form of RTV is the most readily available material to cover the entire glue line (Figure 1). Based on different requirements and conditions, other options frequently used for protecting strain gauges can also be applied to fiber installations.

Figure 1. Fiber installed with adhesives can be covered with RTV for environmental protection.

In a test performed to compare the pure bending strain measurements obtained by Sensuron FOS with multiple foil strain gauges, a very good agreement between the two methods was observed for several strain levels both in tension and compression. The average difference between the two methods was 0.2% for a total of 32 data points obtained at 4 locations under 8 load cases (Figure 2).

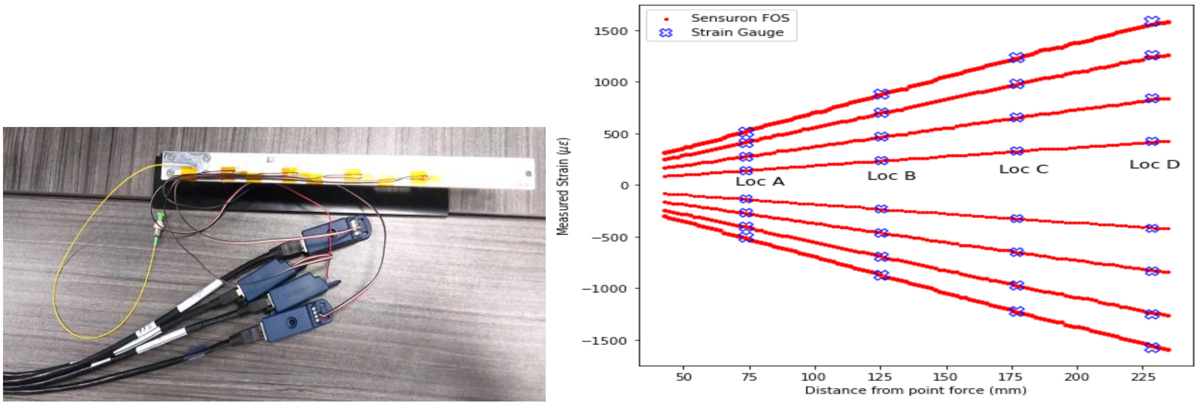


Figure 2. (Left) A single 20cm sensing fiber can provide 30, 60, or 120 strain measurement points. In contrast, each strain gauge requires wires and bridge completion modules. (Right) Sensuron's distributed strain vs strain gauge measurements for a cantilever beam under a load point applied at the end. Linear strain patterns under multiple tensile and compressive load cases are shown.

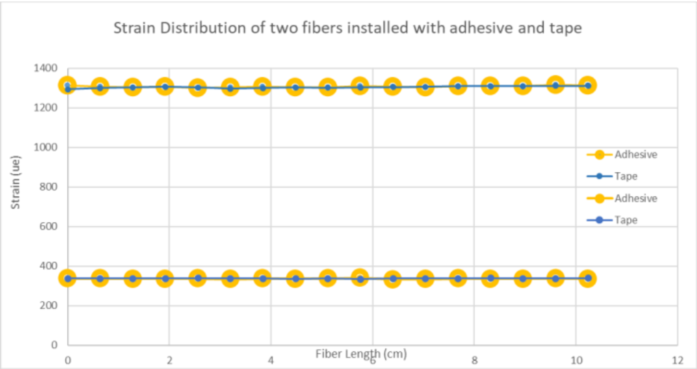
3 Surface Installation Using Tape

Tape installation is an easy method for fiber surface installation. It can be particularly useful in non-horizontal sites e.g. overhead or vertical walls where pouring glue on top of a tacked fiber and obtaining a uniform glue distribution may be found to be challenging in practice. We received short tape samples with fiber already attached from a tape provider. The application is straightforward. The user spreads the liquid activator on the prepared surface and then applies the tape. The bond needs 24 hours to fully cure.

A simply supported aluminum beam setup under 4-point constant bending was selected to compare strains obtained from fiber with two installation techniques: M-Bond 200 vs tape. The tape was 195mm long, 20mm wide and 1mm thick. The aluminum beam was 2.5mm thick and 50mm wide (Figure 3).

Figure 3. Tape installation and M-Bond 200 installation.

Two sets of tests were performed. First, a static test in which the distribution of strain under uniform bending loads was measured. Different strain levels were achieved by changing the magnitude of the point force. The constant bending eliminated any ambiguity in the location of sensing points on two adjacent fibers. Sixteen sensing points (6.4mm apart with a total length of 10.2 cm) from each fiber were used to calculate the mean and STD of strain measurements (Figure 4).



Test#	M bond 200		Nitto Tape		Difference
	AVG	STD	AVG	STD	
1	2.3	1.0	1.9	1.4	Baseline
2	333.4	2.1	333.5	2.2	0.0%
3	336.9	1.5	337.9	1.1	0.3%
4	504.6	1.3	506.5	1.7	0.4%
5	789.3	3.8	793.3	3.5	0.5%
6	907.6	4.6	907.6	5.4	0.0%
7	1309.1	3.8	1305.8	4.9	0.3%

Figure 4. (Left) Strain distribution in constant bending tests for adhesive and tape installation. The 10cm middle section was used for comparison. Results shown are for 2 different loads. Glue and tape installation results were very close, with a mean difference of 0.3% for both load cases. (Right) The average strain along the fiber installed by adhesive and tape for 7 different load levels.

In the following dynamic tests, we measured strain due to the free vibration of the beam caused by applying an initial displacement with different magnitudes. A sampling rate of 66.7 Hz was used. Then the natural frequency of the response was extracted for each of those 16 sensing points (Table 1).

Results: Strain measurements from both techniques were found to be in good agreement. These results suggest that using tape installation may be a viable option in certain applications and will not jeopardize the well documented accuracy of strain measurements obtained by Sensuron FOS technology. In scenarios such as overhead (upside-down), vertical, or surfaces with high pitch, this technique can tremendously benefit the fiber installation process.

Test#	# of cycles	Natural frequency (Hz)	
		M bond 200	Nitto Tape
1	8	4.0	4.0
2	11	4.0	4.0
3	13	4.0	4.0
4	12	4.0	4.0
5	12	4.0	4.0

Table 1. Natural frequency obtained by adhesive and tape installation matched extremely well.

4 Fiber Embedment in Concrete

Although fiber is intrinsically suitable for embedment, the standard sensing fiber’s diameter of approximately 0.2 mm is not well suited for the harsh environment of concrete. Some users experimented with creative and alternative methods e.g. putting a groove in a non-metallic or metallic rebar and installing the fiber inside that groove. This basically will provide adequate protection for the thin fiber but there is considerable time and cost involved.

The alternative is to use concrete-embeddable sensing fiber with a diameter of 0.5 or 1.0mm. This type of sensing fiber has an additional GFRP coating providing high strength while maintaining adequate flexibility.

Similar to standard thin fiber, the GFRP fiber can be spliced to patch cables with different lengths. The sensor then can be placed in a concrete form and optionally attached to the reinforcement rebar with cable ties or glue. After the concrete is poured and cured, embedded sensors will be used to measure the distribution of internal strain or strain on the reinforcement rebars to which they are attached.

In a joint project with a state department of transportation, we provided several GFRP (OD= 0.5 and 1.0mm) and thin sensing fibers (OD=0.195mm) to lab personnel with no previous experience with FOS surface installation or embedment. While general installation guidelines were provided, there was no in-person training or demonstration prior to the actual embedment. After the concrete was cured, signals were obtained from all sensors. Lengthwise only 17% of thin 0.195mm sensing fibers were functional, while 92% of GFRP fibers produced usable signals and consequent strain measurements (Figure 5).

Results: An embedded GFRP fiber can be used to measure the true strain it is experiencing along its length. To make this strain a representative for steel or composite reinforcement bars, using glue or cable ties to attach sensing fiber to a rebar are both found to be effective.

In Figure 6, the strain plots for two sensing fibers attached to two longitudinal composite bars are shown. Each line represents a sensing point, 15/10/5/0cm from the center of the beam on both left and right side. The cyclic force was sufficient to cause a central crack. Both fibers show some permanent strain after full removal of the force, but results show minimal crack propagation after completion of the 2nd cycle.

Sensing fiber can capture the location of cracks with high accuracy by providing the strain distribution of the fiber with ultra-fine resolution. Figure 7 demonstrates strain distribution of two fibers at three different time stamps.

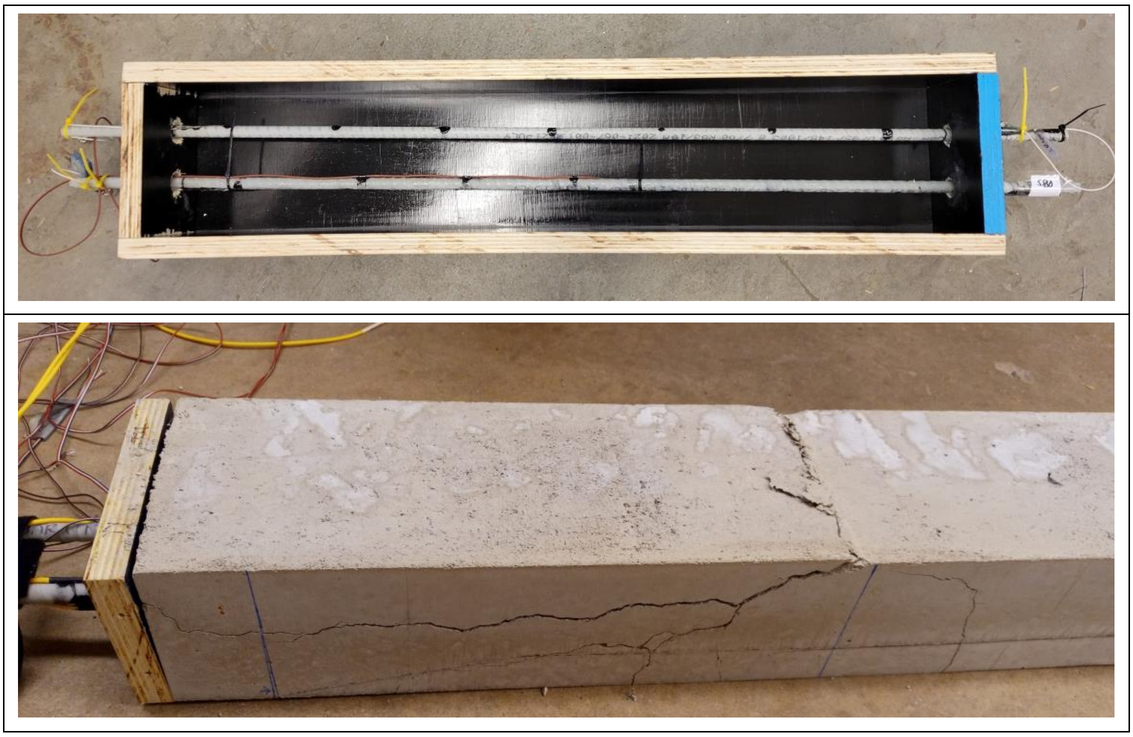


Figure 5. Sensor fiber (GFRP OD=1mm) was attached to glass fiber reinforced bars with different techniques. Concrete samples were then subjected to 3-point bending tests while each sensor fiber provided longitudinal strain measurements with a resolution of 6.4 mm. With an acquisition rate reaching 200 Hz, Sensuron's FOS can be used to identify the location and onset of cracks in concrete structures subject to static and dynamic loads.

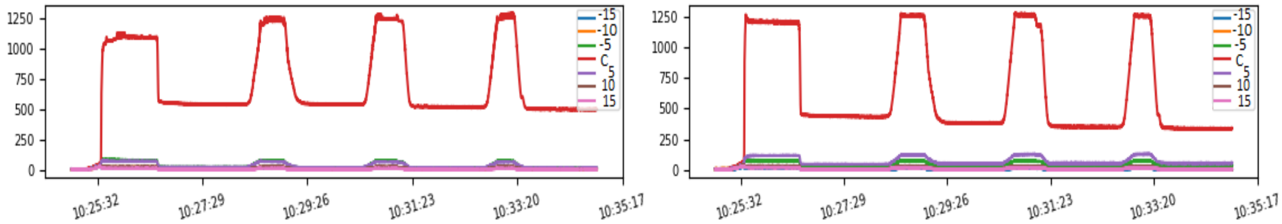


Figure 6. Strain history of two fibers at 7 locations 15/10/5/0cm from the left and right of the beam's center. Horizontal axis is time and vertical axis is strain (με). The beam is under cyclic load. Although fibers were attached with different techniques to two parallel reinforcement bars, the strain measurements were in good agreement. Note that at the location of the central crack, strain never returned to zero after the force's removal.

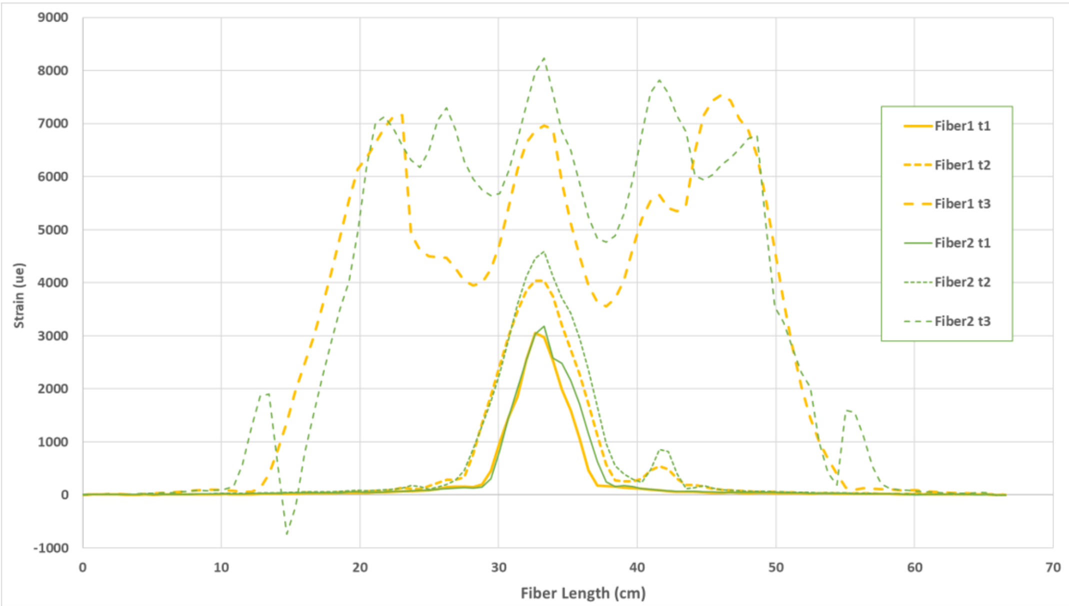


Figure 7. Strain distribution along two fibers connected to two pieces of rebar. The sample was under a monotonic bending test at the center. Strain plots are shown at three time-stamps: fully developed central crack (t1), initiation of 2nd crack at L=42cm (t2), and final stage of the test when the sample was crushed at multiple locations (t3). Both fibers were still functional with a max strain = 0.8%.

Sensuron's FOS systems can measure strain along multiple 13m embedded fibers while the interrogator can be placed up to 1000m from the location of the structure. This enables users to embed multiple sensing fibers anywhere deemed necessary inside a concrete structure such as a bridge girder or column. Ruggedized optical patch cables are available to facilitate the connection between sensor fibers and the interrogator in field applications involving harsh environments. These examples should clarify the advantages of fiber sensing in obtaining internal strain in concrete samples for SHM purposes.

5 Fiber Embedment in Composites

As reported in the previous section, optical fiber is inherently suitable for embedment. The diameter can be made small enough to make embedment an attractive option for advanced composites (carbon, glass, or MMC). However, despite all efforts and published work, this application is still not commonly practiced among composite engineering teams for SHM or in the design process of critical components. One reason has been the lack of a robust high-density distributed FOS system that can obtain measurements in a wide range of dynamic environments. It is known that the sensing fiber may have an adverse effect on the mechanical properties of a composite component. However, this adverse effect can be minimized by running sensing fiber in parallel to surrounding structural fibers and using thinner sensing fibers. Moreover, by using Sensuron's system, hundreds or thousands of strain measurements can be performed along a single fiber with a reasonable sampling rate, making the cost-benefit relationship much more attractive in comparison to discrete (WDM) or low resolution (OTDR) FOS technologies. Measurements obtained by Sensuron's FOS technology are robust and low noise in part because of using a fiber with semi-continuous low-reflectivity fiber Bragg gratings (FBG) providing a much stronger signal compared to backscatter-based FOS systems. After curing, embedded fiber may experience hundreds of micro-bends and curves, each causing a negligible attenuation. However, the sum of these minor attenuations may become a large value. Sensuron's OFDR-based FOS measurements will perform well even if the fiber experiences a total attenuation of -10dB due to its intrinsic high signal to noise ratio.

The main advantage of embedment is that embedded fibers are out of the way and naturally protected. Full distribution of strains in critical structural components can be easily obtained, contributing to the idea of smart structures. By embedding two fibers on different planes of a laminate, a 2D smart shape sensor can be made with no visible and vulnerable fiber. High temperature sensing fibers are also available for embedment in high-temperature composites used in oil/gas and nuclear applications. Fiber can also be efficiently used to monitor and study the curing process for different classes of composites.

To demonstrate this capability, we embedded super thin 0.115mm sensing fiber in carbon composites to obtain static, dynamic, and 2D shape responses. After experimenting with a few ingress/egress techniques, using thin PTFE tubing was found to be the best option for protecting the fiber. As a first step to verify the accuracy of embedded fiber strain measurement, a good agreement was obtained between embedded fiber and two other techniques: fiber surface installation and Digital Image Correlation (Figure 8).

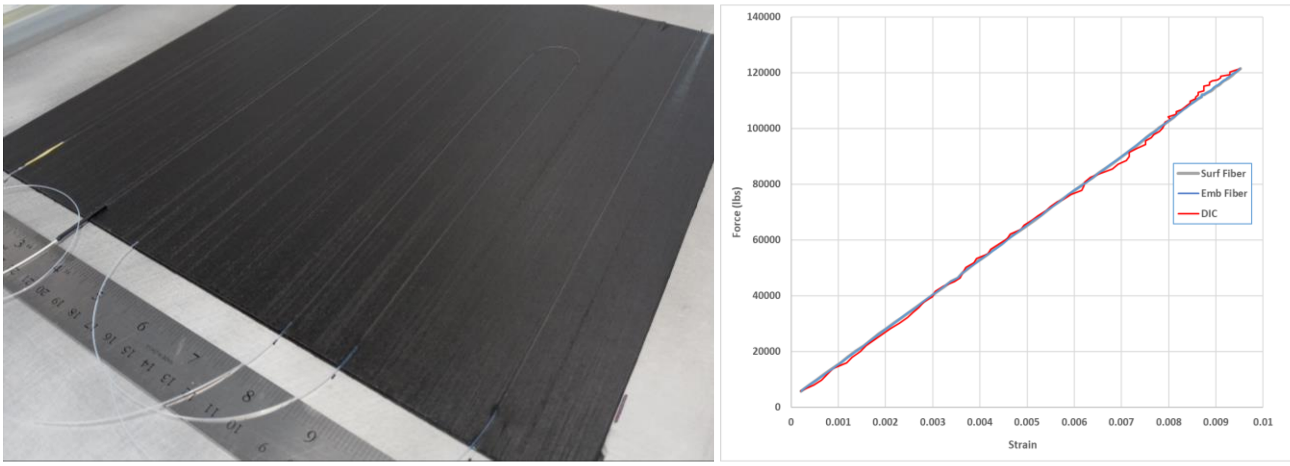


Figure 8. (Left) Layout of fiber placement on a carbon laminate. While optical fiber is placed in parallel to structural fibers, a single fiber can have several bends to cover a greater area of the composite sample. (Right) Strain vs force was obtained from uniaxial tension tests of a composite sample which included embedded fiber, surface fiber glued to one side and digital image correlation (DIC) on the opposite surface. The average difference between strain measured by the embedded fiber and surface fiber was 0.2%.

6 Summary

Four different methods of fiber installation are discussed in this article. A good transfer function between the solid material subject to strain measurement and the fiber can be achieved with all these techniques ensuring an accurate strain measurement. Fiber is natively suitable for embedment with sturdy GFRP fiber for concrete embedment and super thin fiber for advanced composites.