

USE OF FIBER OPTIC TECHNOLOGY IN MONITORING STEEL SLEEVES AND COMPOSITE WRAP REINFORCEMENTS

Chris Alexander

ADV Integrity, Inc.
Magnolia, Texas

chris.alexander@advintegrity.com

Ryan LaVergne

Western Specialties, LLC
Houston, Texas

ryan.lavergne@westernspecialtiesllc.com

Alan Turner

Lloyd's Register
Houston, Texas

alan.turner@lr.org

ABSTRACT

The rehabilitation of damaged pipelines plays a critically-important role in maintaining the integrity management of pipeline systems. The repair techniques employed by pipeline operators typically include welded Type A and Type B sleeves, as well as composite repairs. Once repairs are made, operators must trust the integrity and soundness of the repairs based on various monitoring and inspection techniques; however, there are no current widely-accepted techniques for monitoring either the reinforcement or the pipe itself.

A research program was conducted that involved the embedding of fiber optics in a steel sleeve and E-glass / epoxy composite repair systems. Measurements from the fiber optic sensors included temperature, hoop strain, and axial strain, which allowed engineers to monitor conditions in both the repair and the pipe sample. The implications of embedded technologies in pipeline repairs are far-reaching, including the ability to monitor not only the reinforcement itself, but also serve as a resource for monitoring pipeline activities including third party damage and land movement. This paper presents results from the test program, but also concepts for continued use of pipeline repair embedded technologies and their impact on the generation of large-scale data and enhancement of integrity management efforts.

INTRODUCTION

The purpose of this test program was to evaluate the performance of fiber optic technologies in measuring strain in simulation corrosion regions for both the ComposiSleeve™ and Ultra-Wrap systems. Measuring strain in the steel half shells of the ComposiSleeve™ technology was also a major objective. The concept behind this program is to integrate sensors into repair technologies, which will allow pipeline operators to not only measure the performance of the repair systems, but also develop a greater understanding regarding the behavior of their pipeline systems. The integration of fiber optics as an embedded technology in composite repair systems is useful as a measurement device to allow operators to monitor the condition of the pipeline beneath the repair, as well as the repair itself.

Listed below are several uses for embedding fiber optic technologies into future repairs:

- Monitoring temperature of the pipeline, including thermal cycling conditions
- Monitoring strain in the reinforced region of the pipe / pipeline; this could be especially important for temporary repairs used to

reinforce internal corrosion where a “maximum strain threshold” can be used

- Measuring bending strains in critical application regions such as pipelines subject to land movement, piping in power plants, refineries, and chemical plants, and offshore risers.
- Leak detection, including the reinforcement of regions having internal corrosion.

Having already established the performance capabilities of both the ComposiSleeve™ and Ultra-Wrap system (including both systems meeting the requirements of the ASME PCC-2 [1] composite repair standard), this testing program was straightforward. Prior to testing the samples were fabricated using 12.75-inch x 0.375-inch, Grade X52 pipe material, welding end caps and threaded bosssets, and machining 8-inch long by 6-inch wide 75% deep simulated corrosion defects. Strain gages and fiber optic sensors were installed in the corrosion regions, as well as other areas on the pipe samples. The primary measurements of interest were those captured with the fiber optic sensors.

The sections of this paper that follow include the *Test Methods* section that provides details on the specific activities that occurred before and during testing. The *Test Results* section provides results from testing, including measurements made by the strain gages and fiber optic sensors. The *Discussion and Closing Comments* section includes a few comments to observations from the test results and their applicability to in-service conditions.

TEST METHODS

This section of the paper provides details on the test methods associated with the testing conducted to evaluate fiber optic performance in testing both the ComposiSleeve™ and Ultra-Wrap repairs. Two (2) samples with machined regions to simulate corrosion with 75% wall loss were fabricated for both burst tests. The details for the pipe material used to fabricate the 75% corrosion samples in this test program are listed below.

- Nominal Diameter: 12.75 inches
- Wall Thickness: 0.375 inches
- Grade: X52 (Actual yield strength of 70.3 ksi and ultimate tensile of 79.4 ksi)
- SMYS pressure: 3,058 psig
- MAOP: 2,202 psig (72% SMYS)
- Sleeve thickness: 0.25 inches

Sample Preparation

Listed below are the steps that were completed in preparing the corrosion test samples.

1. Welded end caps to samples and 1-inch NPT bosssets.
2. Machined simulated corrosion area in pipe as shown in Figure 1.
3. Sandblasted samples.
4. Installed strain gages as shown in Figure 2 and Figure 3; fiber optic sensor installed near Gage #3.
5. Installed Ultra-Wrap and ComposiSleeve™ repairs (completed by Western Specialties).

Photographic Presentation of Sample Preparation

A significant amount of work was completed prior to testing in association with installation of both repair systems. Provided below is a list of photographs showing various stages of the installation efforts.

- Figure 4: Fiber optic packaging
- Figure 5: Close-up view of fiber optic sensor in simulated corrosion region (near Gage #3)
- Figure 6: Photograph showing installation of fiber optic sensor in steel sleeve
- Figure 7: Photograph showing installation of filler material
- Figure 8: Make-up of ComposiSleeve™ to specified torque value

Steps for Pre-testing and Testing

Provided below are steps completed prior to testing as part of the set-up process, as well as specific steps carried out during testing.

1. Labeled sample numbers as follows:
 - a. WS-LR-CS-1 (ComposiSleeve™ sample: steel half shells)
 - b. WS-LR-UW-2 (Ultra-Wrap sample: composite material)
2. Used UT meter to measure wall thicknesses wherever strain gages installed.
 - a. Gage #1 ComposiSleeve™ sample: 0.102 inches Ultra-Wrap sample: 0.099 inches
 - b. Gage #2 ComposiSleeve™ sample: 0.104 inches Ultra-Wrap sample: 0.099 inches
 - c. Gage #3 ComposiSleeve™ sample: 0.102 inches Ultra-Wrap sample: 0.097 inches
 - d. Gage #4 ComposiSleeve™ sample: 0.362 inches Ultra-Wrap sample: 0.365 inches
3. Took photos during various stages of testing.
4. Installed strain gages as shown in Figure 3
5. Monitored pressure and strain during testing, recording data at 1 scan per second.
6. Five (5) minute pressure holds at:
 - a. 2,202 psi (72% SMYS)
 - b. 3,058 psi (100% SMYS)
 - c. 4,135 psi (100% AYS)
7. Expected burst at 4,670 psi (based on material UTS)
8. Output: EXCEL file for each burst test that includes time stamp, internal pressure, and hoop / axial strain gage results.

TEST RESULTS

This section of the paper provides results associated with burst tests for both the ComposiSleeve™ and Ultra-Wrap systems. Included are the respective burst pressures, as well as strain measurements made using the conventional strain gages and fiber optic sensors.

Of primary interest to pipeline operators and regulators is the level of reinforcement provided by composite repair technologies. Based on extensive burst testing conducted on more than 20 different composite repair technologies as part of an industry-wide Joint Industry Program involving 12 composite repair technologies dating back to 2009 [3],

the average hoop strain at 72% SMYS in 75% corrosion defects (12.75-inch x 0.375-inch, Grade X42 pipe material) was measured to be 3,794 $\mu\epsilon$. As noted in Table 1, the hoop strains measured for both samples in this particular study were less than two-thirds the industry average. Also shown in this table is the strong correlation that exists when comparing measurements made by the strain gages and fiber optic sensors.

Ultra-Wrap Test Sample

The Ultra-Wrap sample was pressurized to the designated 5-minute holds at 72% SMYS, 100% SMYS, and 100% AYS pressure levels. The sample was then pressurized to failure. Figure 9 plots hoop strain as a function of internal pressure for the Ultra-Wrap sample; included in this plot are results for the four strain gages, as well as results for the fiber optic sensor located in the simulated corrosion region adjacent to Gage #3 (refer to the photograph in Figure 5) and the sensor located 180° from the corrosion feature on pristine (un corroded) pipe beneath the composite repair. Note that Gage #4 is located on the base pipe away from the corrosion feature and repair zone.

Figure 10 and Figure 11 are photographs of the Ultra-Wrap sample before and after testing, respectively. The maximum pressure this sample reached before failure was 4,732 psi (155%) and failed outside the repair as shown in Figure 11.

ComposiSleeve™ Test Sample

The ComposiSleeve™ sample was pressurized to the designated 5-minute holds at 72% SMYS and 100% SMYS pressure levels. Figure 12 plots hoop strain as a function of internal pressure for the ComposiSleeve™ sample; included in this plot are results for the four strain gages, as well as results for the fiber optic sensor including those embedded in the steel half shells and simulated corrosion region. Unlike the Ultra-Wrap sample that only employed one fiber optic sensor, the ComposiSleeve™ sample integrated five fiber optic sensors as noted below (all measurements relative to 12 o'clock position, or 0° where corrosion feature installed):

- 45° sensor located in top half shell
- 135° sensor located in bottom half shell
- 225° sensor located in bottom half shell
- 315° sensor located in top half shell
- 0° sensor located in corrosion feature near Gage #3 (as shown in Figure 5)

Annotations are made in Figure 12 to assist the reader in identifying results for the top side (45° and 315° sensors) and the bottom side (135° and 225° sensors) half shells. In general, the measurements made by the fiber optic sensors embedded in the top side half shell track closely with strain gage measurements made in the corrosion region, while the bottom side sensors generally track with measurements made on the base pipe.

The following photographs of the ComposiSleeve™ sample are provided:

- Figure 13: Photograph of ComposiSleeve™ sample before pressure testing
- Figure 14: Photograph of ComposiSleeve™ sample after pressure testing

As shown in Figure 14, failure of the ComposiSleeve™ sample occurred in the repaired region. However, this result was not unexpected as a composite overwrap was not installed over the steel half shells. Had the Ultra-Wrap system been installed over the steel half shells as is typically done for this system, the failure would have

occurred outside the reinforcement. The composite overwrap was not included in this particular test to maximize strain in the steel half shells and ensure that appreciable strain levels would be imparted to the steel half shells during pressure testing, especially in the vicinity of the simulated corrosion feature.

DISCUSSION AND CLOSING COMMENTS

This paper has provided detailed results associated with a study focused on the assessment of fiber optic sensors used to measure strains in pipe samples with simulated corrosion reinforced with the Western Specialties' Ultra-Wrap and ComposiSleeve™ composite repair technologies. In addition to measurements made in the simulated corrosion region, the fiber optic sensors successfully measured strains in the steel half shells of the ComposiSleeve™ system. Referring once again to results plotted in Figure 12, it is apparent that the fiber optic sensors located in the top half shell (i.e., 45° and 315°) accurately tracked with the hoop strains measured in the corrosion feature. These sensors could have also been used to provide an indication of excessive strains being generated in the vicinity of the corrosion feature, as strains in both of these sensors “took off” once pressure in the sample exceeded 2,202 psi (72% SMYS). The results in Table 1 show the strong correlation that exists when comparing measurements made by the strain gages and fiber optic sensors for both composite repair systems.

The fiber optic sensor is better-suited than conventional strain gages for in situ measurements as it is not subject to voltage “drift” and can be disconnected from data acquisition systems without fear of data loss. Also, the fiber optic sensor is preferred over vibrating wire gages due to their low profile and their ability to not be influenced by magnetization generated by in-line inspection magnetic flux leakage (MFL) tools. Having demonstrated performance of the fiber optic sensors, there are numerous other future-oriented applications where these devices can be used such as those listed below.

- One of the best-suited applications is the measurement of strain in buried pipelines subject to lateral displacement. Pipelines running through regions with unstable soil conditions can be monitored using fiber optic sensors. Several layers of the Ultra-Wrap system could be installed over the fiber optic sensors to prevent damage to the sensors, but also not generate potentially undesirable increased stiffness in the pipeline that might occur with the ComposiSleeve™ system (in regions where reinforcement is required, both the Ultra-Wrap and ComposiSleeve™ systems are ideally-suited).
- Another potential application is pipelines subject to overburden loading, such as railroad and road crossings. The installation of either the Ultra-Wrap or ComposiSleeve™ system will provide increased stiffness, while the presence of the embedded fiber optics will provide operators with comfort in being able to monitor strains induced in the pipe generated by transient transportation loading.
- Finally, a question that is often posed to composite repair manufacturers concerns the “temporary” reinforcement of internal corrosion. As demonstrated in this study, the installation of fiber optics either beneath the Ultra-Wrap system or embedded in the ComposiSleeve™ system will provide operators with a monitoring technology that can be used to indicate when unacceptable levels of corrosion have been reached due to increased strains in the reinforced region of the pipe.

There are numerous other applications including temperature monitoring and leak detection; however, the above three certainly

represent “low hanging fruit” that should be attractive to many operators of high pressure gas and liquid transmission pipelines. The results presented in this paper demonstrate the usefulness in having embedded fiber optic sensors. This study is a model for how to effectively evaluate innovative technologies for the repair and reinforcement of high pressure pipeline systems.

APPENDIX: SMART SLEEVE MONITORING SYSTEM USING FIBER BRAGG GRATINGS

Creating the Smart Sleeve Monitoring System came about by combining two existing technologies: fiber optics and composite repair technologies. Having two ASME PCC-2 certified reinforcement technologies combined with the latest advances in sensor and software technology now permit more accurate methods of pipeline condition monitoring.

Fiber optic sensing technology and associated data analytics have evolved to a point where industry can derive an accurate understanding of what is happening inside a repair or the health of the repair, the condition of the anomaly on the pipe and the condition of the pipeline itself by integrating the sensors into the repair. Using two Fiber Bragg Grating (FBGs) arrays with a total of six sensors each allows measurements at each 90-degree location. There is a hoop sensor (mounted circumferentially), and axial sensor (mounted longitudinally) and a temperature compensation gage. Once a base measurement is established with strain and temperature then the sensors can then be calibrated/converted to monitor strain, pressure, bending and temperature. The main advantage of FBGs for mechanical sensing is that these devices perform a direct transformation of the sensed parameter to an optical wavelength, independent of light levels, connector or fiber losses, or other FBGs at different wavelengths. A typical fiber structure is depicted in Figure 15 and an example of the FBGs used in this study shown in Figure 16.

Some other advantages of FBGs over resistive foil strain gages include:

- Totally Passive (no resistive heating)
- Small Size (can be embedded or laminated)
- Narrowband and wide wavelength operating range (can be highly multiplexed)
- Non-conductive (immune to electromagnetic interference)
- Environmentally more stable (glass compared to copper)
- Low fiber loss at 1550 nm (sensors can be located many kilometers/miles from source)
- Low cost due to device simplicity and high-volume telecommunication usage

A FBG is a wavelength-dependent filter/reflector formed by introducing a periodic refractive index structure, with spacing on the order of a wavelength of light, within the core of an optical fiber. Whenever a broad-spectrum light beam impinges on the grating, a portion of its energy is transmitted through while another is reflected off as depicted in Figure 17.

The reflected light signal will be very narrow (i.e., few nanometers) and centered at the Bragg wavelength (λ_b), which corresponds to twice the periodic unit spacing, Λn_m . This is the so-called Bragg condition and is expressed as:

$$\lambda_b = 2\Lambda n_m$$

Where Λ is the grating's period and n_m is the average index of refraction seen by the propagating light wave inside the fiber's core. Any change in the modal index, or grating pitch, of the fiber caused by strain, temperature or polarization changes will result in a Bragg wavelength shift. In general, the temperature sensitivity of a grating occurs principally as a result of the temperature dependence of the refractive index in the fiber material and, to a lesser extent, the thermal expansion in the material which changes the grating period spacing. Typically, the fractional wavelength change in the peak Bragg wavelength, for temperature, is of the order of 10pm/°C at 1550nm.

The basic relationship between wavelength and strain for a Fiber Bragg grating based gage is:

$$\epsilon = \frac{\left(\frac{\Delta WL}{\Delta WL_0}\right)}{F_G}$$

Where:

ϵ = Strain (m/m)

ΔWL = Wavelength shift (nm)

WL_0 = Initial Reference Wavelength (nm)

F_G = Gage factor (dimensionless)

REFERENCES

1. ANSI/ASME PCC-2-2015, Repair of Pressure Equipment and Piping, Repair Standard, Article 4.1, Non-metallic Composite Repair Systems for Pipelines and Pipework: High Risk Applications, American Society of Mechanical Engineers, New York, 2015.
2. Alexander, C., and Brooks, C., " Development and Evaluation of a Steel-Composite Hybrid Composite Repair System", Proceedings of IPC 2012 (Paper No. IPC2012-90573), 9th International Pipeline Conference, September 24 – 28, 2012, Calgary, Alberta, Canada.
3. Alexander, C., “Advanced Techniques for Establishing Long-Term Performance of Composite Repair Systems”, Proceedings of IPC 2014 (Paper No. IPC2014-33405), 10th International Pipeline Conference, September 29 - October 3, 2014, Calgary, Alberta, Canada.

Table 1: Burst pressures and hoop strains for reinforced corrosion samples at 72% SMYS

Repair Type	Hoop Strain ($\mu\epsilon$)				Burst Pressure (psi)
	Center Under Repair (Gage #1)	2-inch off Center (Gage #3)	Fiber Optic (near Gage #3)	Base Pipe	
Ultra-Wrap	2,546	2,555	2,504	1,277	4,732 (155% SMYS)
ComposiSleeve™	2,192	2,432	2,441	1,260	3,064 (100% SMYS)

Note: Hoop strains listed in microstrain, $\mu\epsilon$ (10,000 microstrain = 1% strain)

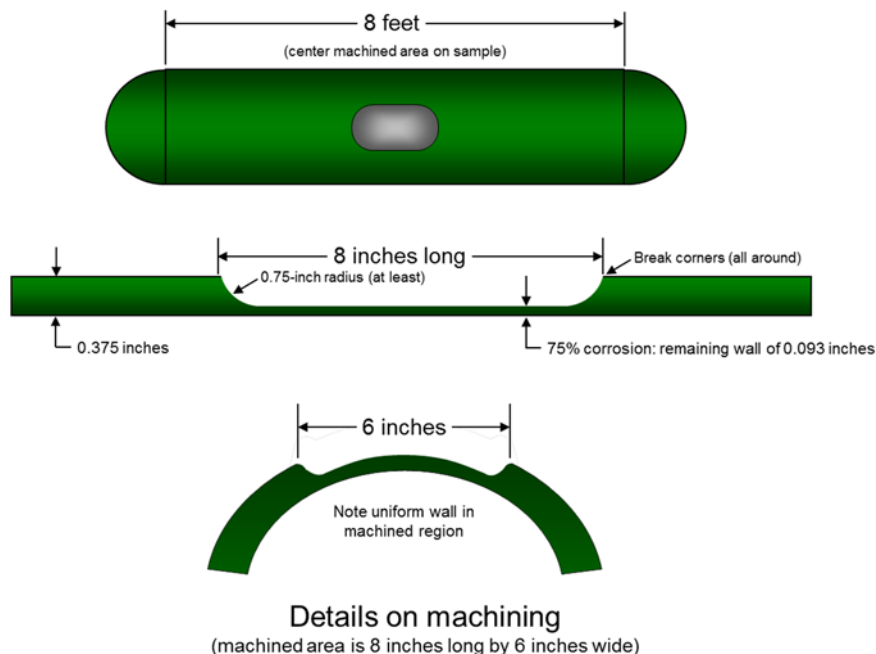


Figure 1: Simulated corrosion details

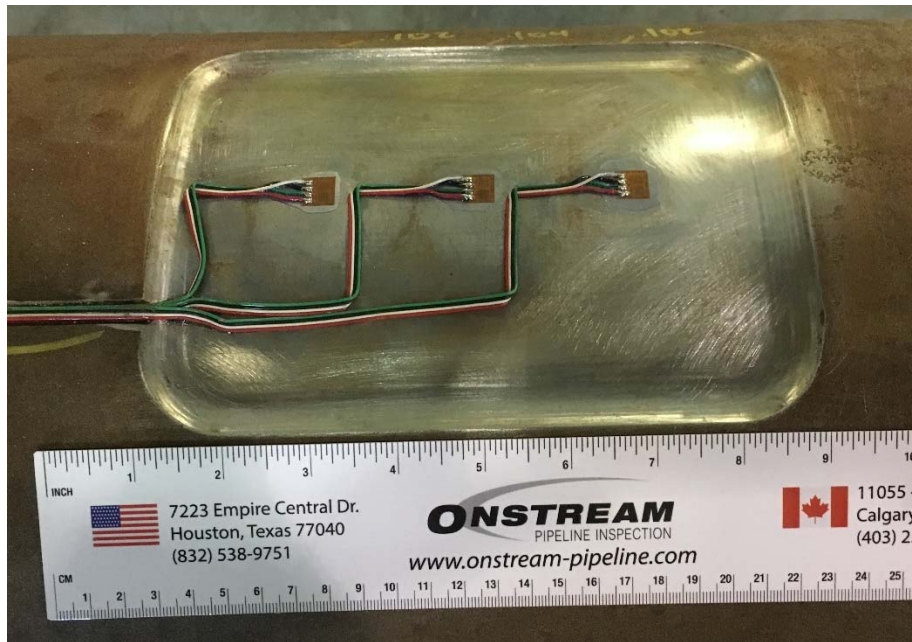
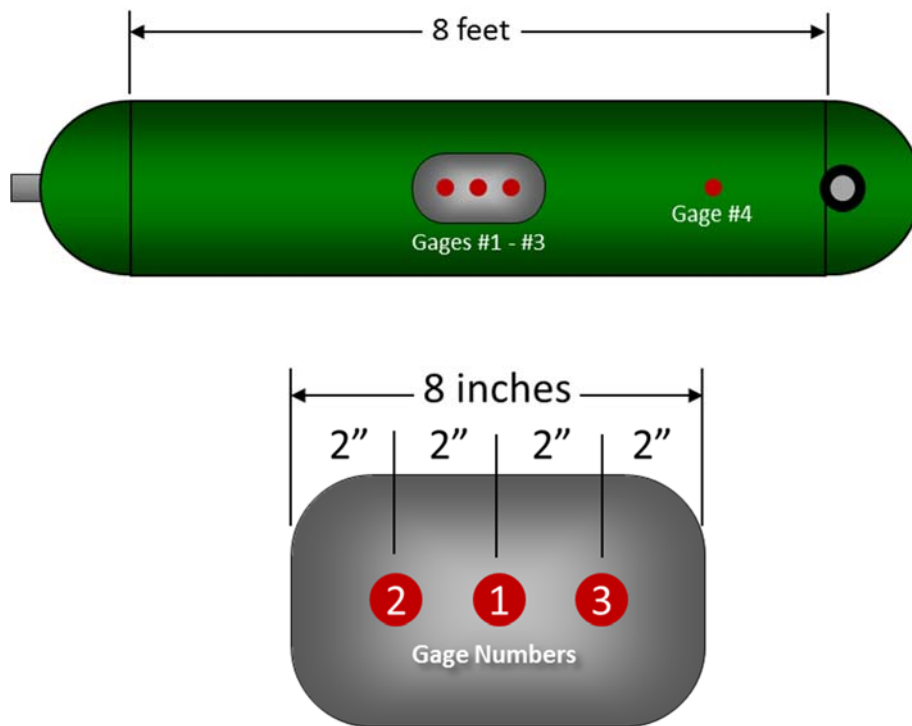


Figure 2: Simulated corrosion strain gage locations



Machined region details

Figure 3: Strain gage locations and numbering



Figure 4: Fiber optic packaging

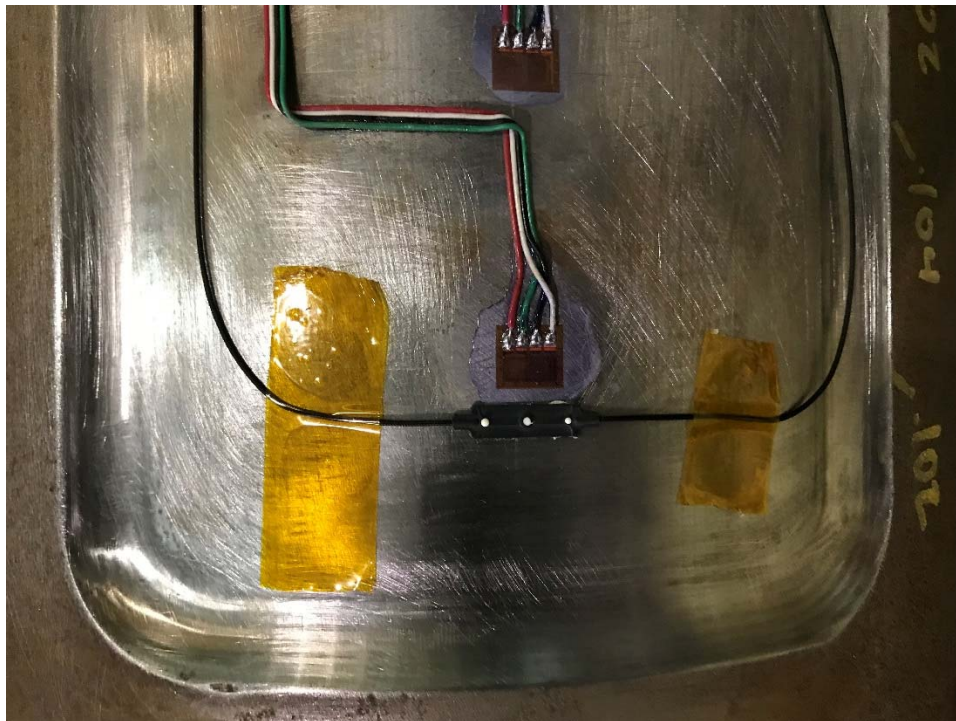


Figure 5: Close-up view of fiber optic sensor in simulated corrosion region



Figure 6: Photograph showing installation of fiber optic sensor in steel sleeve



Figure 7: Photograph showing installation of filler material



Figure 8: Make-up of ComposiSleeve™ to specified torque value

Pressure Test of the Ultra-Wrap Test Sample

12.75-inch x 0.375-inch, Grade X52 pipe with 75% corrosion defect | $P_{failure} = 4,732$ psig

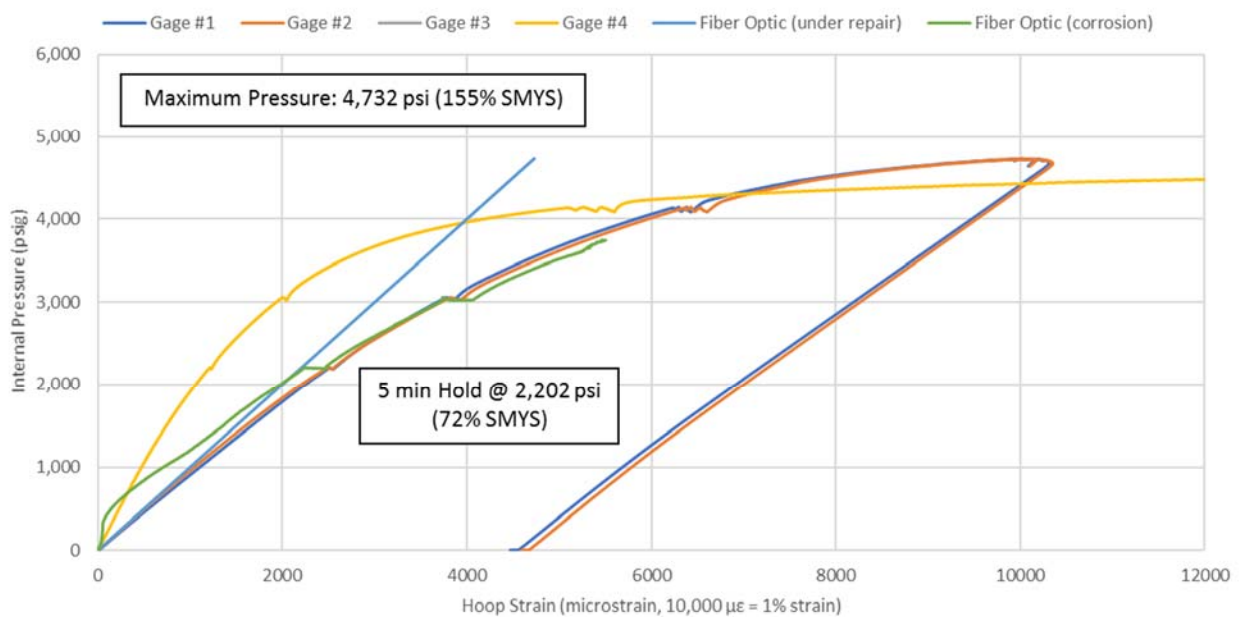


Figure 9: Hoop strain versus internal pressure for Ultra-Wrap Sample



Figure 10: Photograph of Ultra-Wrap sample before pressure testing



Figure 11: Photograph of Ultra-Wrap sample after pressure testing

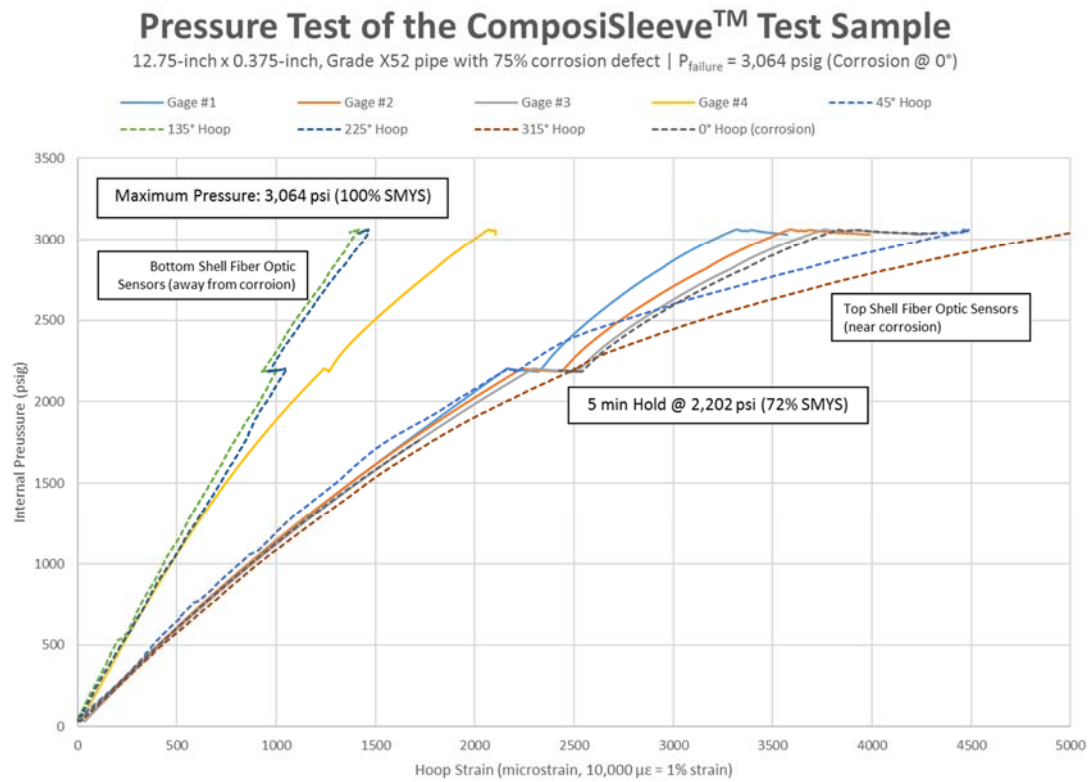


Figure 12: Hoop strain versus internal pressure for ComposiSleeve™ Sample



Figure 13: Photograph of ComposiSleeve™ sample before pressure testing



Figure 14: Photograph of ComposiSleeve™ sample after pressure testing

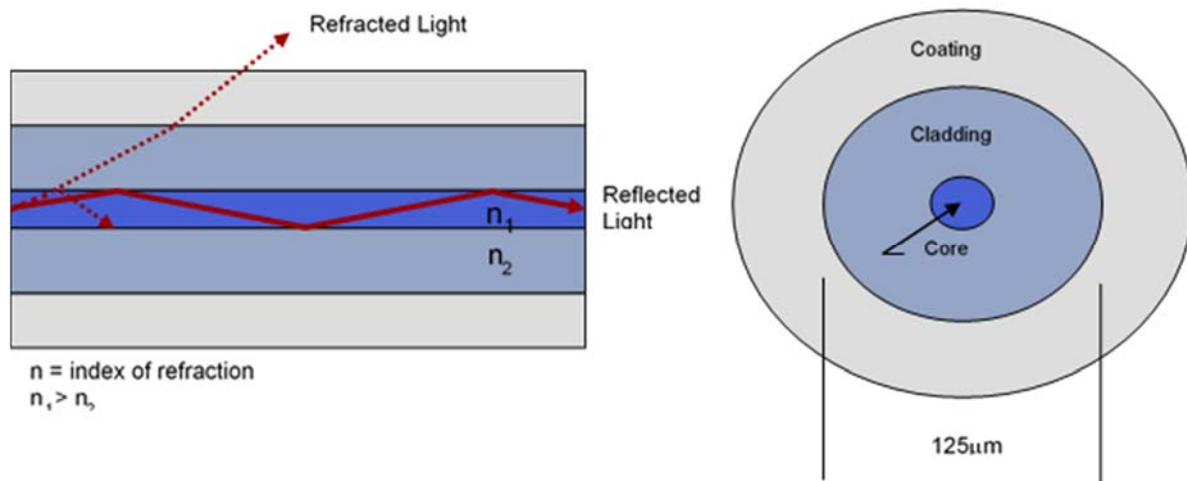


Figure 15: Schematic of a Single Mode Optical Fiber
(125 micrometers, approximately 0.005 inches)

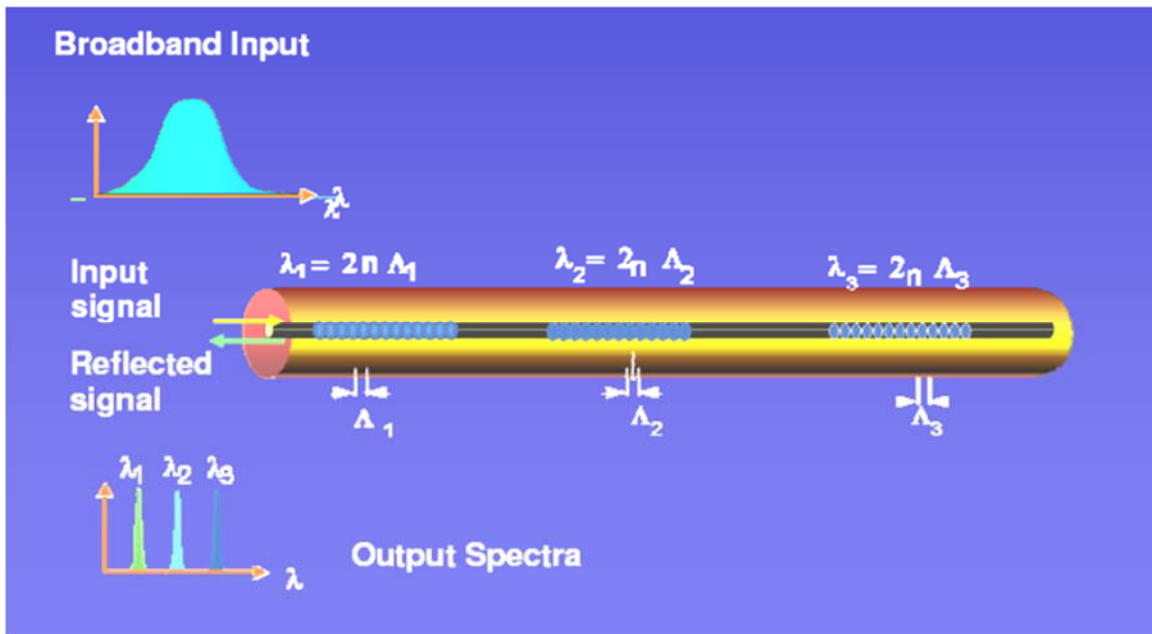


Figure 16: Fiber Bragg Grating with 3 separate and unique sensor locations

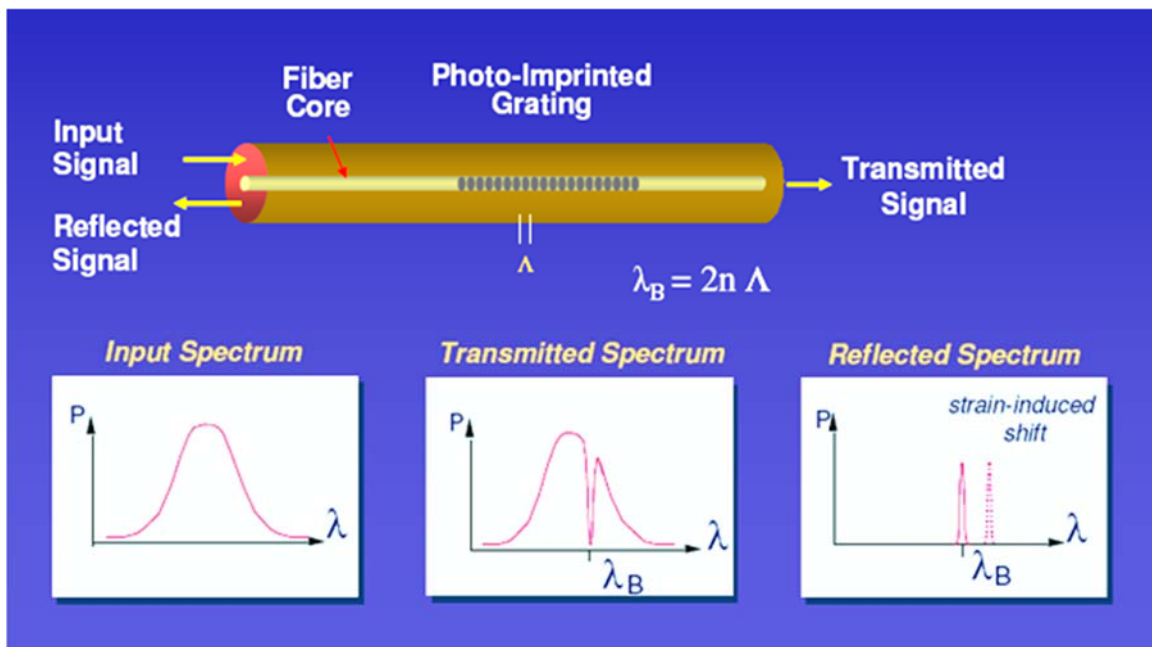


Figure 17: Transmission and Reflection Spectra of a Fiber Bragg Grating