Fiber-optic monitoring focuses on bending, corrosion

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Long gauge-length fiber-optic sensors (FOS), effectively used in detecting pipe movement by monitoring any change in the neutral plane of the pipe from its initial reference state, can also measure any bending strains that occur due to pipe movement. Monitoring these strains and associated stresses can provide warnings of potential pipe failures.

Detecting the presence of wall thinning due to general corrosion or erosion allows the operator to monitor a pipe section to ensure fitness for service. If a pipe section is known to be subject to local pitting and pinhole defects, FOS monitoring can predict, within some probability range, the presence of such defects.

This approach assumes that a sufficient database exists that shows a strong correlation of general wall thinning with the occurrence of such defects for that section of pipe.

FOS types

Fiber-optic sensors are a noninvasive tool for monitoring pipeline defects in real time. The ability to mount FOS to pipes and pressure vessels externally, without disrupting operations, makes them ideal tools for monitoring and ensuring fitness for service.

They offer significant advantages vs. conventional sensors as they are nonelectrical and intrinsically safe. They are also immune to electromagnetic interference and can be employed close to pumps, motors, and generators.

Optical fiber leads and communication cables have very low transmission losses and are ideal for long-distance sensing. With a suitable software interface, FOS can provide data that allow the operator to adjust process parameters in real time.

FOS systems can measure structural displacements, strains, pressure, vibration, and temperature. There are three types of sensor systems on the market; each operates on a different principle.

- Point sensors include fiber Bragg gratings and Fabry-Perôt sensors. The FBG sensors reflect light with a change in wavelength that is proportional to the strain experienced by the optical fiber at the grating location. FP sensors also respond to strain by producing a change in wavelength, measuring a change proportional to a change in gap length between opposing optical fibers.

These sensors are used for both static and dynamic measurements at discrete points. Both FBG and FP sensors have gauge lengths similar to electrical-based resistance strain gauges (3-5 mm) and are used to measure local strains and temperatures.

- Distributed sensors include Raman and Brillouin Scattering-based sensor systems. Both operate by measuring a change in wavelength of light scattered across a narrow range of frequencies due to displacements within an optical fiber.

Raman scattering primarily measures temperature distributions along an optical fiber at predefined gauge lengths that can vary from 1 m to several meters.

Brillouin scattering can measure thermal as well as mechanical strains along fiber of comparable gauge length. These distributed sensing systems can interrogate a single fiber across distances as great as 25 km.

Fiber Optic Systems Technology Inc. (FOX-TEK) has performed laboratory tests with a buried optical fiber to demonstrate the capability of a Brillouin system to detect third-party intrusion and leaks from a pipe.

- Long Gauge-length FOS. Sensors of this type measure average displacements in gauge lengths that are 10 cm to 100 m long. Dividing the displacement by the gauge length of the sensor converts these displacements to average strains.

This article describes the FOX-TEK FT long gauge-length fiber-optic sen-

Reprinted with revisions to format, from the February 20, 2006 edition of **OIL & GAS JOURNAL**

EQUATIONS

$$\varepsilon = (\alpha + \beta)\Delta T + \{\int_0^{L_s} \varepsilon(z)\,dz\}/L_s \qquad (1)$$

where:

ε = sensor strain

α = thermal coefficient of expansion for pipe

β = thermal optic coefficient for fiber sensor ($\sim 8 \times 10^{-6}$/°C.)

$\Delta T = T - T_0$, where T = temperature at time of measurement,
T_0 = temperature at the time of installation

L_s = sensor gauge length

z = axial coordinate along sensor defined by $0 \le z \le L_s$

$$\Delta T = \varepsilon_s/(\alpha + \beta) \qquad (2)$$

$$\varepsilon_z = (1/E)[\sigma_z - \nu\sigma_y] \qquad (3)$$

$$\varepsilon_y = (1/E)[\sigma_y - \nu\sigma_z] \qquad (4)$$

where:

$\sigma_z = 0$

$\sigma_y = pR/h$, where p = internal pressure and h = pipe wall thickness

$$p = -\varepsilon_z/(\nu R/Eh) \qquad (5)$$
$$= \varepsilon_y/(R/Eh)$$

$$\sigma_z(z) = M(z)y/I = E\varepsilon_z(z) \qquad (6)$$

where:

M(z) = bending moment function

y = distance from neutral plane to sensor

I = 2nd moment of area for the circular pipe cross–section

For thin pipes, $I \approx \pi hR^3$

$$\varepsilon_s = (\alpha + \beta)\Delta T + \{[\sin\theta/E\pi hL_sR^2]\{\int_0^{L_s} M(z)\,dz - \nu pR/Eh\} \qquad (7)$$

where:

θ is the angle from the neutral plane to the sensor

$$\varepsilon_s(\max) = \varepsilon_s(\theta)R/y = \varepsilon_s(\theta)/\sin\theta \qquad (8)$$

$$\varepsilon_s(\theta) = [\sin\theta/E\pi hL_sR^2]\int_0^{L_s} M(z)\,dz \qquad (9)$$

$$\varepsilon_z(z_m) = M(z_m)\sin\theta/E\pi hR^2 \qquad (10)$$

where:

$M(z_m)$ is the value of the bending moment function at $z = z_m$

$$dM(z)/dz = 0 \text{ and } d^2M(z)/dz^2 < 0 \qquad (11)$$

$$\varepsilon_z(z_m)/\varepsilon_s(\theta) = \{M(z_m)\sin\theta/E\pi hR^2\}/\{[\sin\theta/E\pi hL_sR^2]\int_0^{L_s} M(z)\,dz\}$$
$$= L_sM(z_m)/\int_0^{L_s} M(z)\,dz \qquad (12)$$

$$\varepsilon_z(z_m)/\varepsilon_s(\theta) = 1.5 \qquad (13)$$

$$\varepsilon_z(z_m)_{max} = 1.5\varepsilon_s(\theta)/\sin\theta \qquad (14)$$

assuming:

$\varepsilon_s \neq 0$ and does not lie on the neutral plane

$$\varepsilon_{zcr} = 0.6kh/R \qquad (15)$$

where:

k = knock–down factor due to geometric shape imperfections,
nominally around 0.5

$$h = 0.85L_s pR/E\delta \text{ for Poisson's ratio} = 0.3 \qquad (16)$$

where:

δ = sensor displacement

$$h = 0.525L_s pR/E\delta \qquad (17)$$

$$\delta(t) = (\delta_t - \delta_r) - L_s(\alpha + \beta)(T_t - T_r) \qquad (18)$$

where:

t = time

r = reference value at time of installation

$$h(t)/h_r = 1/[1 + Ct] \qquad (19)$$

$$C = [(\delta_t/\delta_r) - 1]/\Delta t \qquad (20)$$

sors. Some of its uses include monitoring wall thinning due to corrosion and erosion, pipeline movement, bending strains, and buckling. The focus of this article is the use of FOS to monitor pipelines, but the same principles apply in any industry and FOS sensors are in use monitoring the same parameters in refineries and civil structures.

Strain equations

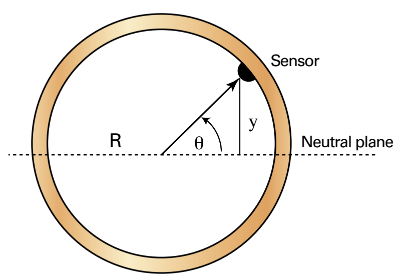
Installation of FT sensors on operating pipelines requires determination of the temperature and initial strain. A direct measurement typically determines temperature, while pressure and geometry data are typically used to calculate strain. Determination of the thermal component of the sensor data requires that the temperature of the pipe section be known at installation.

Pressure fluctuations also produce variations in the axial sensor data, due primarily to Poisson ratio effects and must be taken into account. FT long gauge-length fiber-optic sensors provide a measure of the average thermal and mechanical strains through their gauge length, L_s (Equation 1; see equation box above).

When an FT sensor is bonded to a pipe section not subject to mechanical stress, Equation 2 provides the change in temperature from the install-condition.

PIPE CROSS-SECTION

Fig. 1



Assuming the internal pressure induces tensile hoop strain ε_y, which in turn induces an axial compression strain resulting from Poisson's ratio effect (ν), Equations 3 and 4 show the results of the plane stress elastic equations.

Neglecting the associated tensile axial stress due to internal pressure, which is generally the case for "infinitely long" pipelines, allows the pressure in the line to be deduced from either the axial or hoop strain sensor readings (Equation 5)

Pipeline movement

Pipeline movement due to ground subsidence, slope instability, river and stream currents, or seismic activity can induce bending stresses. Differential movement of pipe sections between supports for aboveground pipes, and soil movement around buried pipes lead to these stresses. In the latter case, the liquid mass and the soil overburden

A compression machine at the University of Alberta tests a pipe spiral wrapped with an FT sensor for failure due to internal pressure, axial compression, and bending loads (Fig. 2).

above the pipe combine to create the loads.

Stresses in pipelines at exposed river crossings are similar to those for aboveground pipe but include additional stress from currents and varying water levels.

Seismic activity can cause differential movement for both aboveground and buried pipelines.

FT sensors, bonded to the pipe surface at three circumferential locations along the longitudinal axis of the pipe, detect pipe movement by measuring the axial strain, which can then be converted into the direction and magnitude of bending. Although the sensor strain includes components due to internal pressure and bending loads, only the bending strains cause changes to the location of the neutral plane.

Equation 6 shows the axial bending stresses in the pipe.

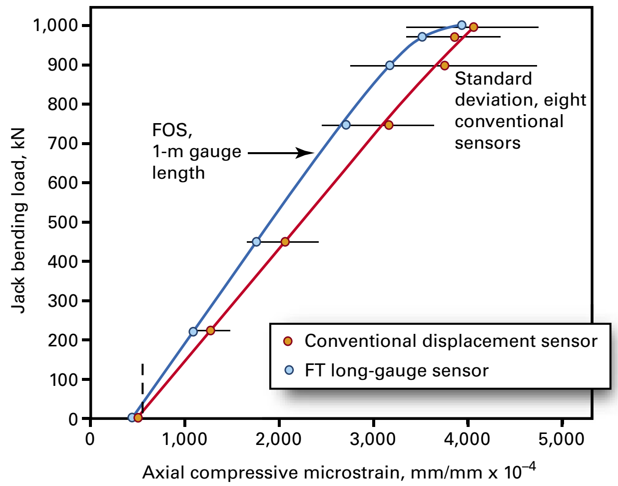
Using Equation 1 and bending analysis, Equation 7 provides the total sensor strain.

Experiments were conducted using three FT fiberoptic sensors bended to the outer surface of a cylindrical pipe in the axial direction, 120° apart around the circumference. The setup allowed rotation about the longitudinal axis so that the sensors could be varied in their location relative to the neutral plane of the tube.

The experiments loaded the pipe as a cantilever beam for four configurations. Measured strain ratios provided the basis for calculating the locations of the neutral plane from Equation 6 and comparison to the test case set-up summarized in Table 1.

FOS VS. CONVENTIONAL, MEASUREMENT TO BUCKLING

Fig. 3



The results of this process show that Equation 7 predicts the location of the neutral plane very well based on the FT sensor's measurements. The shift in the neutral plane indicates pipe movement relative to its initial reference state.

Maximum bending strains

Critical compression bending stresses can cause local pipe buckling. Internal pressure can also cause additional axial compressive stresses due to Poisson ratio effects that result from tensile hoop strains (Equation 3).

The same FT sensor data used to detect pipe movement can also estimate the maximum compression-tension bending strains acting on the pipe (occurring at ±90° to the neutral plane). Although the FT sensors measure the average displacement or strain (strain = displacement-sensor gauge length) over their gauge length, a relationship exists between the average sensor strain and the maximum strain that occurs within the gauge length.

AXIAL MOUNTING TEST RESULTS

Table 1

Case number	Strain ratio, $\varepsilon i/\varepsilon j$	Neutral axis — location, Θ — Equation 6	Test case
1	$\varepsilon_2/\varepsilon_3 = 1$	30°	30°
2	$\varepsilon_1/\varepsilon_3 = 2.67$	44.8°	45°
3	$\varepsilon_1/\varepsilon_3 = 1$	30°	30°
4	$\varepsilon_2/\varepsilon_3 = 25.6$	58°	60°

Once the neutral plane has been located, factoring up any of the three sensor strains estimates the average bending strain occurring along the axis of maximum bending strain (tension or compression).

Since the major concern about bending is the potential occurrence of local pipe buckling, this analysis focuses on determining the maximum compression strain. Equation 8 deduces the average strain obtained if the sensor lay along the axis of maximum bending strain, with Equation 9 giving the sensor's bending strain.

In practice, the sensor will yield a measurement defined by Equation 6. Knowing α and β, and the pressure (p) at the time of reading, however, the residual strain component is $\varepsilon_s(\theta)$. It now becomes necessary to determine a relationship between the average bending strain along the axis of maximum compression and the actual value of the maximum compression strain in the pipe due to bending.

Adding the strain components due to internal pressure and temperature to this value determines if the pipe buckled.

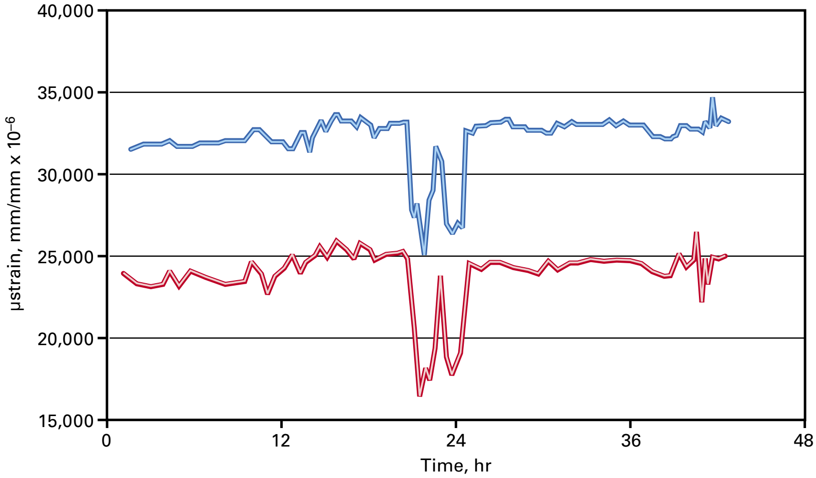
Equation 10 provides the axial location of maximum bending strain, z_m, for specific loading cases.

Equation 11 locates the value z_m.

Pipeline operators may choose serpentine (photo above) or hoop (photo below) applications of fiber-optic sensors, among others, depending on the needs of the particular project (Fig. 4).

TYPICAL SENSOR-DISPLACEMENT DATA

Fig. 5



A bending moment diagram can locate z_m for concentrated loading. The bending moment function M(z) allows the value of z_m to be determined, providing there are no discontinuities in the function. Equation 12 shows the relationship between the sensor's average bending strain and the maximum bending strain for the particular sensor location around the circumference.

For example, considering a pipe section simply supported at its ends on pylons, subject to a uniform distributed dead weight loading, can yield Equation 13.

The maximum bending strain equals 1.5 times the sensor strain, as measured at angle "θ" to the neutral plane (Equation 13). This value is then factored up to estimate the maximum strain at 90° to the neutral axis to assess the possible buckling state of the pipe (Equation 14).

Pipe buckling

Equation 15 gives the compressive elastic buckling strain for a circular cylindrical pipe.

When the compressive strain in the pipe reaches a value of ~0.3h/R, the pipe will be close to its buckling state.

A series of pipe bending tests were conducted at the University of Alberta on a large-diameter steel pipe (Fig. 2). The pipe was first subjected to internal pressure, then axial compression, followed by bending loads up to buckling. Fig. 3 compares the average FOS axial strains measured across a 1-m gauge length with the mean value of conventional displacement sensors.

Considerable scatter exists in the displacement sensor's data, but general agreement exists within the standard deviation scatter range. The FOS sensor detected nonlinear prebuckling, and the FOS data agree well with classical pipe theory for internal pressure loading.

Thinning, corrosion

Corrosion and erosion subject steel pipes to wall thinning. Corrosion can be either external or internal and is a leading cause of natural gas and oil pipeline failures. Corrosion can be general corrosion across an area or more localized pitting. Pitting involves localized wall thinning and can occur as isolated pits or in colonies.

In either case, internal pressure causes the pipe to strain and can eventually lead to failure. Pitting is more likely to result in pinhole leaks than is generalized corrosion, whereas generalized corrosion is more likely to result in a rupture.

FT sensors monitor general wall thinning with good sensitivity, and are a noninvasive, remote monitoring alternative to corrosion coupons. Under certain conditions, they can also provide statistical information to predict the presence of pitting and associated pinhole defects.

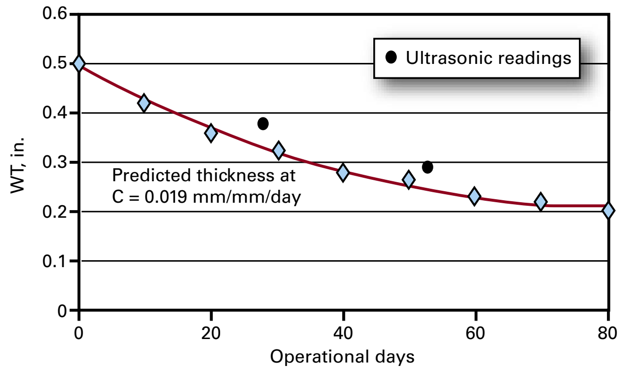
Consider a pipe under internal pressure and subject to wall thinning across some area. Assuming a plane stress state (Equation 2) and neglecting boundary conditions, Equation 16 gives the pipe wall thickness.

This equation is valid for hoop and spiral wrap sensors, given that the initial values of the wall thickness, temperature, and sensor's reference reading are known.

For a coil sensor, which consists of a long gauge-length sensor wrapped in a circular or oval configuration, the displacement reading that results from uniform hoop expansion represents an integrated value of the strain around the coil. Equation 17 gives the wall thickness.

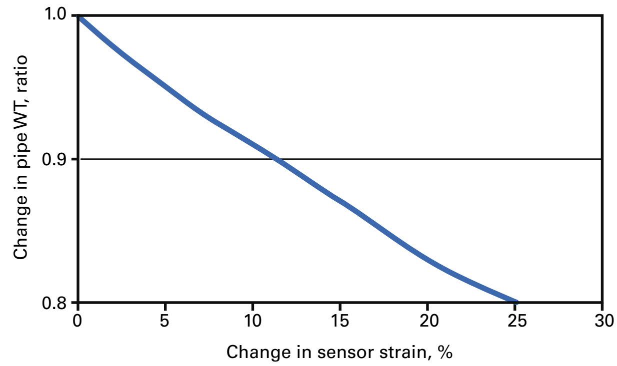
Operational lifetime prediction

Fig. 6



FT sensor strain sensitivity

Fig. 7



The sensor readings include thermal variations from the installation conditions that must be factored into the calculation of h. Equation 18 gives the corrected value of δ to be used in calculating wall thickness at any time, t.

Equation 19 describes a general model for predicting wall thinning of the pipe as a function of corrosion rate, while Equation 20 provides the corrosion rate.

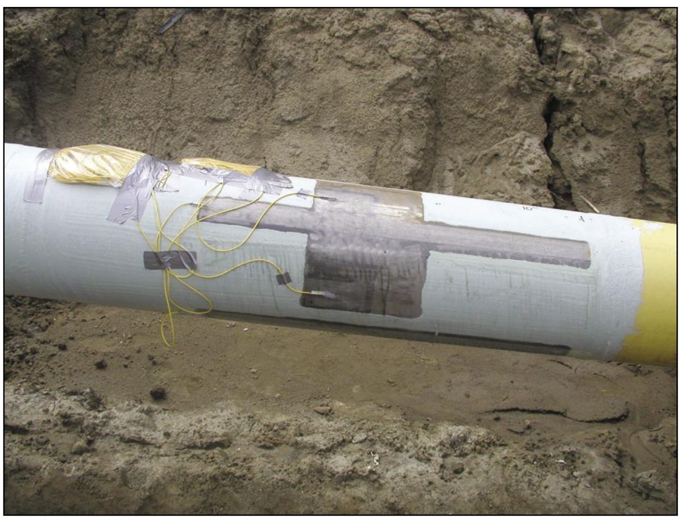
Although the long-term corrosion (or erosion) rate may not be a constant, interrogating the sensors at time intervals, Δt, allows a linear interpolation to estimate C, which is then used to project what the wall thickness will be at some future time. This allows predictions to be made of residual safe life operation.

Field test

An FT sensor system was installed on a tailings pipeline in Fort McMurray, Alta. The system provided continuous, remote monitoring for real-time detection of pipe corrosion-erosion and estimate operational lifetime based on a minimum wall thickness required to prevent pipe burst.

Long gauge-length FT fiber-optic sensors monitored the pipe in several configurations, including hoop and serpentine (Fig. 4). The complete system consisted of the sensors, an FTI-3300 sensor scanner, and notebook computer equipped with a cellular modem. The notebook controlled the scanner and stored the data for later transmission and analysis.

Fig. 5 shows typical sensor displacement data as a function of time. Presenting both the hoop and serpentine sensor data shows that the wall strain suddenly drops when there is a pressure drop in the line. The sensor data allow plotting of the wall strains as a function of time, to provide an estimate of C. Fig. 6 presents the operational lifetime prediction for this pipe, based upon the estimated corrosion rate C~0.019 mm/mm/day, given by the sensor.



Bagging coils of sensor leads protects them from the weather before installation into conduit. One linear (parallel to pipe) and two coil sensors (either side of the linear) extend from the leads mounted on the pipe and are covered with a protective coating of epoxy (Fig. 8).

The predicted curve agrees reasonably well with ultrasonic thickness measurements.

Strain sensitivity

Noninvasive corrosion and process monitoring tools can help address some of the most common corrosion problems. Comparing the capabilities of seven other technologies to those of a noninvasive fiber-optic sensor system shows that the FT sensor system meets or surpasses the other technologies in all categories.

Providing timely information for process control and mitigation of corrosion requires that FT sensors be very sensitive to small strain changes in the pipe wall associated with wall thinning. Independent of sensor configuration, Fig. 7 shows the change in pipe wall thickness as a function of percent change in pipe strain.

A typical steel pipe section, with 20-in. OD and 0.25-in. WT and operating at 102° C. (215° F.) and 100 psi, illustrates FT sensitivity. Assuming the sensors were installed when the pipe was not operational (T_0 = 22° C.) and no constraints exist, Equation 2 and Equation 17 give the average strains on the surface of the pipe due to thermal and the internal pressure respectively: pressure, $\varepsilon_p = 70 \times 10^{-6}$ or 70 microstrain; temperature, $\varepsilon_T = 1{,}600 \times 10^{-6}$ or 1,600 microstrain.

The FT 3400 measuring instrument detects about 5 µm displacement, which translates into a strain accuracy of 0.25 µstrain for a 20-m gauge length coil sensor. This corresponds to a strain change of about 0.35%, assuming the pipe's temperature is constant, leading to a minimum WT ratio sensitivity of less than 1% change from the initial WT. In practice, mitigation procedures might not be implemented until the FT signal showed about a 3% change in WT ratio.

Application

Enbridge Pipelines Inc. has made a commercial order to have FOX-TEK's FT system installed on its largest pipeline in Canada. Enbridge was one of the first customers to participate in a pilot project with the technology.

The order with Enbridge involves the placement of an FT 3400 series system at one discrete site on the line to monitor wall thickness and potential corrosion. FOX-TEK will provide on-going analysis of the data generated by the monitoring.

Fig. 8 shows an in-field pilot installation on another company's pipeline. ✦

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