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Solving Common Corrosion Problems with Non-Intrusive Fiber Optic Corrosion and Process Monitoring Sensors

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ABSTRACT

Some of the most common corrosion problems in refineries can be addressed with the help of non-intrusive corrosion and process monitoring tools. One of such tools is the long gage length FT fiber-optic sensor system which, in addition to monitoring wall loss, can also monitor pressure and temperature profiles. Being non-intrusive, the sensors can be installed without shutting down the equipment. For crude unit overhead piping suffering HCl condensation corrosion, the operators can rely on the wall loss measurements and temperature profile to adjust process parameters to minimize condensation or to inject optimum amounts of neutralizers or filming amines. For ammonium bi-sulphide corrosion, the changes in temperature profiles can be used to determine the amounts and frequency of wash water injection. In other equipment, which is affected by turbulence-enhanced erosion/corrosion, fiber optic sensors can be used to measure wall loss in real time to increase safety and to allow more efficient planning of turnarounds.

INTRODUCTION

One of the elements of a strategy to manage corrosion within a refinery is establishing corrosion indices for various components[1]. The corrosion index uses the type of crude feedstock, the sulpher, salt and TAN content along with the type of steel used in a refinery component to predict the typical mils per year (mpy) wall loss due to corrosion. Actual numbers can be higher or lower depending upon local variations in temperature or acid content. Operators need to monitor the corrosion rate so that mitigation programs can be implemented effectively.

Ideally, any monitoring technology employed for this purpose would be non-intrusive, very precise, and would be capable of real-time, continuous data. These features would allow installation and use without disrupting operations; detection of small changes in wall thickness in critical locations, and allow correlation of corrosion readings with process conditions. Unfortunately, technologies commonly in use today in refineries to monitor wall loss due to corrosion all have some limitations. Table 1 compares the capabilities of seven technologies to those of a non-intrusive fiber optic sensor system. As can be seen from the table, the FT sensor system meets or surpasses the other technologies in all categories.

FT SENSOR TECHNOLOGY

Sensor Principle

The fundamental principle behind the FT sensor is the interference of low coherence light. The sensor system, as modelled in Figure 1, is comprised of two optical paths – one through the sensor and one through the reference arm – with a light source and a detector. Each of the optical paths has a reflective surface at the end, so that any light travelling down that path is reflected back. Initially, with no load on the sensor, the two optical path lengths are exactly equal, so that $L_S = L_R$ and $\Delta L_S = \Delta L_R = 0$. In this instance, the light signals arrive in phase at the detector at the same time. This results in constructive interference and a peak in the magnitude of the optical signal occurs at the detector.

Table 1: Comparison of Different Corrosion Monitoring Devices (desirable features shaded)[2]

No.	Features	Coupon	ER Probe	Hydrogen Patch Probe	LPR	Electro-chemical Noise	UT	FSM-IT	FT Fiber Optic	Comments
1	Intrusive	Yes	Yes	No	Yes	Yes	No	No	No	
2	Presence of Electrolyte	No	No	No	Yes	Yes	No	No	No	
3	Interference from conductive solids	No	Slight	No	High	High	No	No	No	
4	Device surface condition	Dependent	Dependent	Independent	Dependent	Dependent	Independent	Independent	Independent	
5	Area of coverage	Point	Point	Point	Point	Point	Point/ section	Section	Section	
6	Shut down for installation	Yes	Yes	No	Yes	Yes	No/Yes	No	No	
7	Consumable	Yes	Yes	No	Yes	Yes	No	No	No	
8	Metal loss indication	Semi-direct	Semi-direct	No	No	No	Direct	Direct	Direct	
9	Trending Capability	No	Yes	Yes	Yes	Yes	Yes *	Yes	Yes	
10	Repeatability*	No*	Yes	?	?	?	No	Yes	Yes	
11	Resolution	5 mpy	1-2 mpy	N/A	1-2 mpy	1-2 mpy	10 mpy*	1.25 mpy*	$0.028t^2/(PD)$ mpy	*based on 250 mils wall thickness
12	Pitting indication	Yes	No	No	Not easy	Yes	Yes	Yes	Yes	
13	Temperature limitation	Threading	Threading + sealant	<70C	Threading + sealant+ Condensation point	Threading + sealant+ Condensation point	Operator safety	400C	>250C	
14	Pressure limitation	Threading	Threading + sealant	None	Threading + sealant	Threading + sealant	None	None	None	
15	Indication of remaining wall thickness	No	No	No	No	No	Yes*	Yes *	Yes *	* base line needed
16	Indication of surface temperature	No	No	No	No	No	No	No	Yes	
17	Indication of internal pressure	No	No	No	No	No	No	No	Yes	
18	Time required for obtaining one data point	8-10 hours*	Instantaneous	Instantaneous	Instantaneous	Instantaneous	>10 minutes per point*	Instantaneous	<10 seconds per point*	* scaffolding not included
19	Continuous data reporting	No	Yes	Yes	Yes	Yes	No	No	Yes	
20	Application	All services	All services	Mainly sour service	Conductive Aqueous	Conductive Aqueous	All	All	All	
21	Geometry limitation	Some	Some	?	Some	Some	None	None	None	
22	Retrieval limitation	Shut down / Pressure	Shut down / Pressure	None	Shut down / Pressure	Shut down / Pressure	None	None	None	

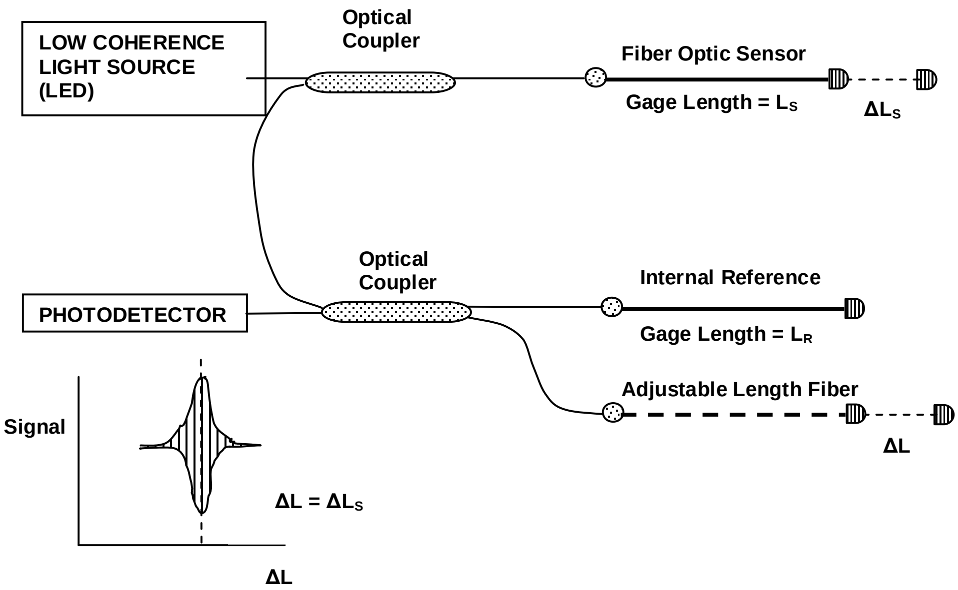

Figure 1: FT Fiber Optic Sensor system schematic

When the sensor is under load, the sensor is elongated or compressed and a change in the optical path length results such that $\Delta L_S \neq 0$. This change means that the two signals at the detector are no longer in phase and the signal at the detector is extinguished. If the length of the reference path is changed so that $\Delta L_S = \Delta L_R$, then two signals are brought into phase again and the interference peak is seen by the detector. Because the light source has a low coherence length, the interference peak only occurs when the path lengths are matched to within approximately 25 µm (microns). This narrow range means that the change in length of sensors from 10 cm to over 100 m long can be accurately measured to better than ±5 µm (±0.5 microstrain for a 10 m gage length sensor).

Sensor Configurations

The sensor itself is made from conventional single-mode optical fiber, with a diameter of 180-250 µm. The load-displacement response of the sensor, as shown in the example in Figure 2, is linear up to elongations of 3% (30,000 microstrain). The small diameter flexible fiber allows the sensor to be packaged into configurations that are suitable for monitoring almost any type of defect or problem.

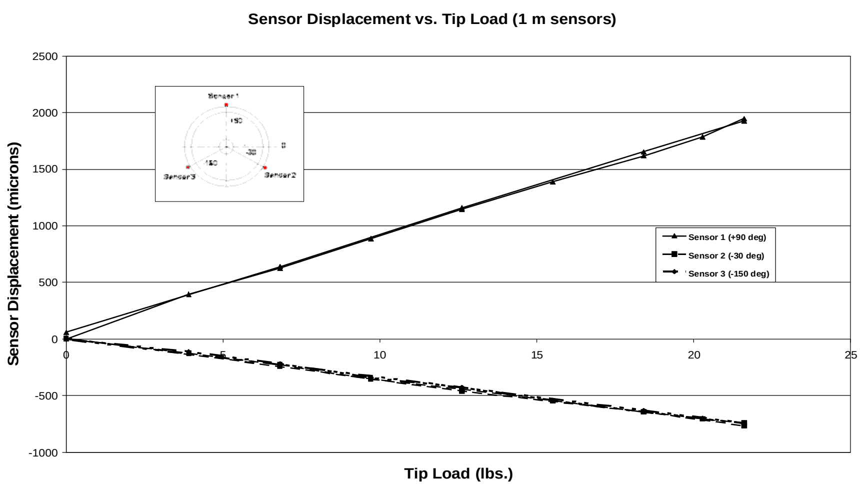

Figure 2: Typical linear displacement-load response of FT Sensor

Figure 3 shows a coil sensor for applications including measurement of wall loss due to erosion, corrosion, fatigue crack growth, ground movement, and process parameters such as temperature and pressure. Versions are currently available for use in environments where the operating temperature is up to 250°C (480°F). Higher temperature versions are in development.

Sensor Monitoring

Due to the unique way the FT sensors operate, their optical signals can only be demodulated using an FT 3400 series monitoring instrument (Figure 4). Total sensor displacements of up to ±15 mm (±1500 microstrain for a 10 m gage length sensor) can be monitored with this system. Remote monitoring, control, data collection, trend analysis, and alarm levels can all be accomplished in a local mode or over a network using a comprehensive companion software package (Figures 5-6).

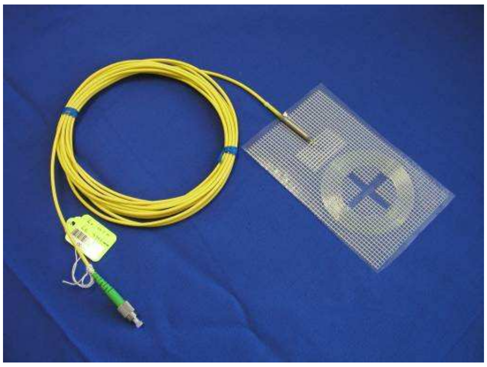

Figure 3: FT Coil Sensor for corrosion, crack, pressure, temperature

Figure 4: FT 3405 Monitor for FT Sensors

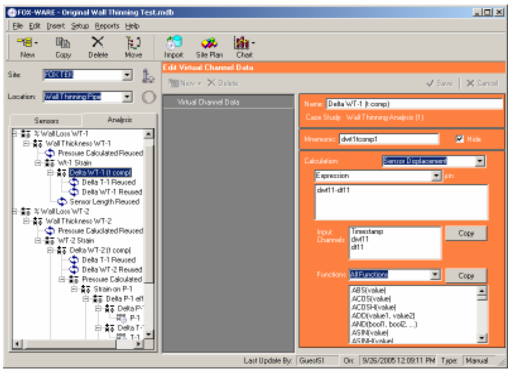

Figure 5: Screen shot of FOX-Ware database

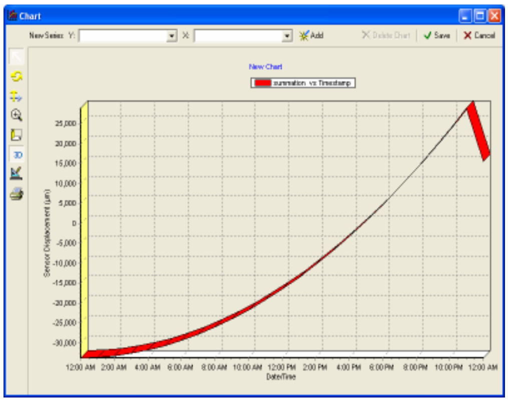

Figure 6: Plotting feature in FOX-Ware database

Conversion of Raw Data

FOX-Ware combines the measurements of change in strain from the FT sensor system monitor, with geometry information about the equipment, to convert the raw data into parameters including temperature, pressure, bending strain and wall loss. The following simple example shows the principle behind the translation. Suppose a typical steel pipe section, which is 508 mm (20 in) in diameter, has a 6.4 mm (0.25 in) nominal wall thickness and is operating at 102°C (215°F) and 6.895 MPa (1000 psi). Assuming no constraints exist, the average strain on the surface of the pipe due to the internal pressure is given by a straightforward calculation:

$$\varepsilon = \frac{3}{8}\frac{P \cdot D \cdot (1-\upsilon)}{E \cdot t} \tag{1}$$

where,

P = pressure = 6.895 MPa = 100 psi
D = pipeline diameter = 508 mm = 20 in
υ = Poisson's ratio ≈ 0.3 (carbon steel, typical)
E = Young's modulus ≈ 206 GPa = 30 x 10^6 psi (carbon steel, typical)
t = wall thickness = 6.4 mm = 0.25 in

For this case, $\varepsilon = 70 \times 10^{-6}$ or 70 microstrain. An FT sensor bonded to the surface of the pipe would report this strain value as the nominal reference strain.

Suppose that the pipe is experiencing internal corrosion such that, over the monitoring period, the FT sensor reports that the average strain has increased from the initial value ε = 70 microstrain to a final value ε = 75 microstrain. Assuming that the pressure and temperature have stayed nominally the same, the equation for average pipeline strain can be rearranged to determine the new wall thickness t_f.

$$t_f = \frac{3}{8}\frac{P \cdot D \cdot (1-\upsilon)}{E \cdot \varepsilon_f} \tag{2}$$

Which gives a value of t_f = 5.92 mm (0.233 in). The change in wall thickness is then determined from the change in FT sensor strain as Δt = 0.48 mm (0.017 in) or a loss of ≈7.1%.

In other cases where temperature and pressure change from the initial conditions, additional FT sensors are used to provide compensation data. Where the wall loss is non-uniform, more advanced models of the relationship between pressure, temperature, wall thickness and strain based upon finite element analysis are incorporated.

APPLICATIONS IN CORROSION MONITORING

In the refinery, many critical pieces of equipment are subject to localized corrosion that leads to wall loss. The following case studies demonstrate the capabilities of the FT system to monitor this degradation.

Case 1: Pipe Reducer with Localized Corrosion

A De-Ethanizer Plant 20"x12" reducer is known to have experienced corrosion rates up to 129 MPY due to H_2S and other constituents. The operating conditions are 54°C (130°F) and 2.76 MPa (400 psig). The following analysis shows the sensitivity of the FT system and the minimum monitoring time to detect a change in the wall thickness.

Modelling

For the purposes of the finite element model of the reducer, the forces exerted on the reducer by the internal pressure in the adjacent piping are simulated by creating a model of the reducer with flat end caps. The radius at each end is set to the mid-wall of the reducer. The nominal wall thickness is set to the reference reading of 16.993 mm (0.669"). The corroded area is modelled as a patch that is thinned to the minimum recorded thickness of 6.223 mm (0.245"). In this case, the thinned area is modelled as approximately the size of an FT coil sensor – 70 mm (2.75 in). The body of the reducer is modelled using 3072 shell elements and 3074 nodes. Boundary conditions are set to restrict movement at the central node on the small face to the z-axis only and movement is fixed at the central node on the larger face. Rotations are fixed around the circumference at both ends to enforce compatibility with capped ends.

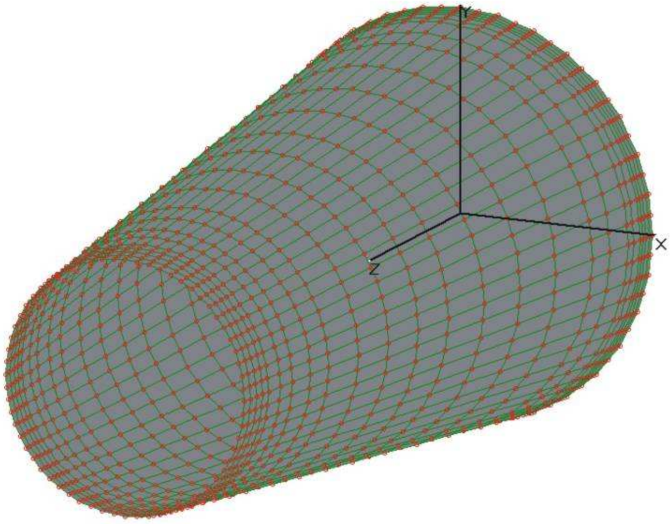

Figure 7: Finite Element Model of Reducer with 3072 Shell Elements and 3074 Nodes

Results

The results of the FE analysis are shown pictorially in Figures 8 and 9 below. Figure 8 shows the outer surface principal stress σ_1 distribution and Figure 9 shows the σ_2 distribution. Using plane stress analysis and the nodal stress values from the FE analysis, the local surface strains in the corroded and unaffected areas can be compared.

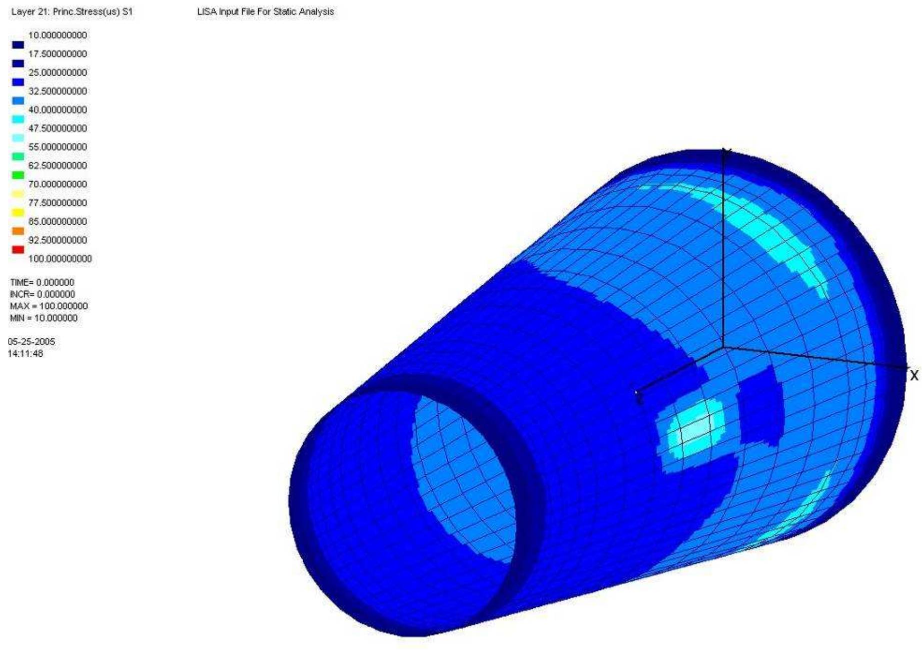

Figure 8: Outer surface principal stress (σ_1) distribution

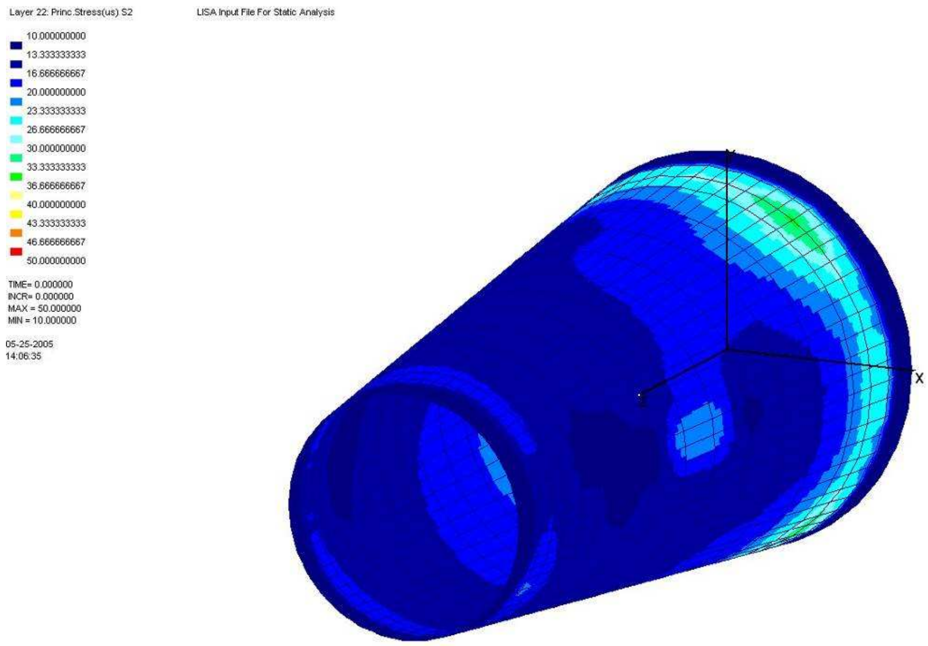

Figure 9: Outer surface principal stress (σ_2) distribution

The surface stresses are used to compute the average surface strain. In the thinned region, averages taken over the approximate surface area of an FT coil sensor give values that correspond to the expected sensor readings. Averages taken in the far field correspond to reference values that are used to measure the internal pressure.

$$\varepsilon_{average} = \frac{(\sigma_1 + \sigma_2)(1 - \nu)}{2E} \tag{3}$$

Result of the FE analysis show that the mean values of the principal stresses in the thinned region are

$$\begin{aligned} \sigma_1 &= 40.1 \ MPa \\ \sigma_2 &= 19.8 \ MPa \end{aligned} \tag{4}$$

Using values of E = 210 GPa, ν =0.3

$$\varepsilon_{average\ (thinned)} = 100.0 \ \mu s \tag{5}$$

Now comparing to the far field or nominal wall thickness values

$$\begin{aligned} \sigma_1 &= 32.5 \ MPa \\ \sigma_2 &= 16.2 \ MPa \end{aligned} \tag{6}$$

so that

$$\varepsilon_{average\ (nom)} = 81 \ \mu s \tag{7}$$

For this case, the difference in strain reading between the far field and thinned regions indicates that, with a conservatively assumed sensitivity of the FT system of 5 μm or 0.5 μs for a 10 m gage length sensor, the minimum detectable wall thickness change is

$$\Delta t = \frac{Sensitivity}{(\varepsilon_{average(thinned)} - \varepsilon_{average(nom)})}(t_{nom} - t_{thinned}) \tag{8}$$
$$= 0.283\ mm \quad (0.011\ in)$$

If the wall loss rate is assumed to be a maximum of 3.175 mm/yr (129 mpy), then the minimum time required for the FT system to indicate a change in wall thickness is

$$T = \frac{\Delta t}{3.175} = \frac{0.283}{3.175} = 0.089\ yr \cong 1\ month \tag{9}$$

Case 2: Overhead Line Corrosion

The analysis described below was undertaken to determine the feasibility of using FT sensors to detect corrosion growth in a typical refinery overhead. For modelling purposes, an overhead line was chosen of diameter 457.2 mm (18") with a NPT of 8.89 mm (0.35") with an internal pressure of 1.0-1.4 kPa (15-20 psi) and a normal operating temperature of 107-115°C (225-240°F). For purposes of analysis, it was assumed that regular ultrasonic NDE has found patches of internal corrosion 50-500 mm in diameter, with depths up to 45% wall penetration. The corrosion rates are not known at present. The currently used ultrasonic (UT) measuring technology provides measurements of wall thickness with a confidence of no better than 0.13-0.26 mm or 1.4-2.8% of the nominal wall thickness.

To assess the feasibility of using FT sensors to monitor wall loss due to corrosion, the sensitivity of the system must be determined; in other words, the strain resolution of the sensor system must be expressed in terms of an equivalent percent wall thickness change.

Modelling

Because the patches of corrosion produce local perturbations in the stress/strain fields in the wall of the pipe, finite element analysis is used to model the behaviour of a representative section of the overhead line. A section of the line is modelled with 4608 four node shell elements as shown below in Figure 10.

The forces exerted by the internal pressure in the pipe are simulated by applying normal pressure of 1.034 kPa (15 psi) to the interior surface and using thick end caps to simulate the influence of the adjacent piping. The nominal wall thickness is set to 8.89 mm (0.35"). Anecdotally, the areas of corrosion range from roughly circular and 50 mm (2") in diameter up to "football" sized areas, which are taken as a maximum of about 200 x 250 mm (8 x 10") in area.

For this case, the wall thickness of a group of 93 elements was set to 5.08 mm (0.2"), which is the typical thickness measured by NDE in the corroded areas. Each element is nominally 20 x 22.5 mm (0.8" x 0.9").This element group represents an area approximately "football" shaped patch 260 mm axial x 200 mm circumferential (10" x 8"). The location of this group of elements is shown in Figure 11 below.

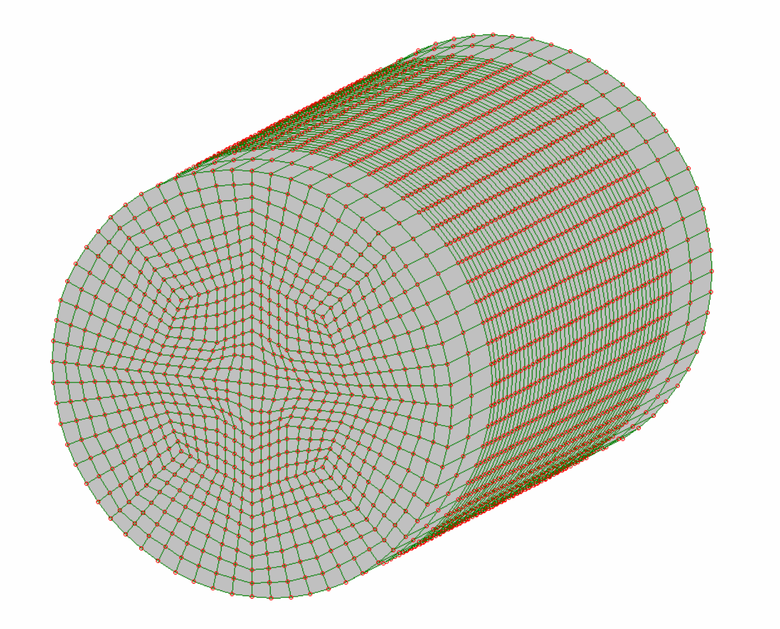

Figure 10: Finite element model of overhead line section with 4608 shell elements

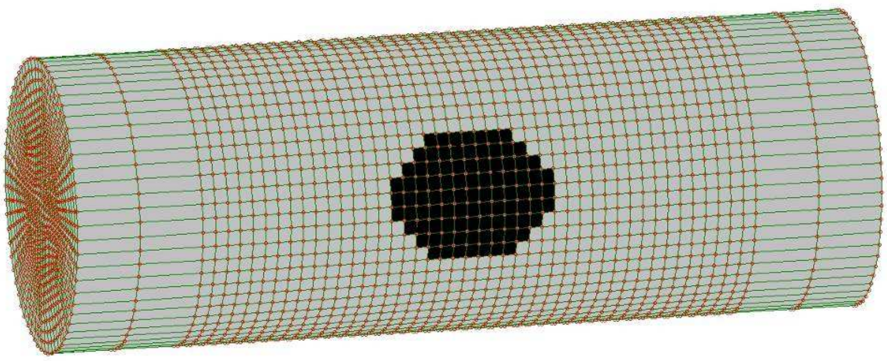

Figure 11: Location of reduced thickness elements to simulate corroded area

The finite element results for the distributions of σ_1 and σ_2, the two principal stresses are shown in Figures 12 and 13 below.

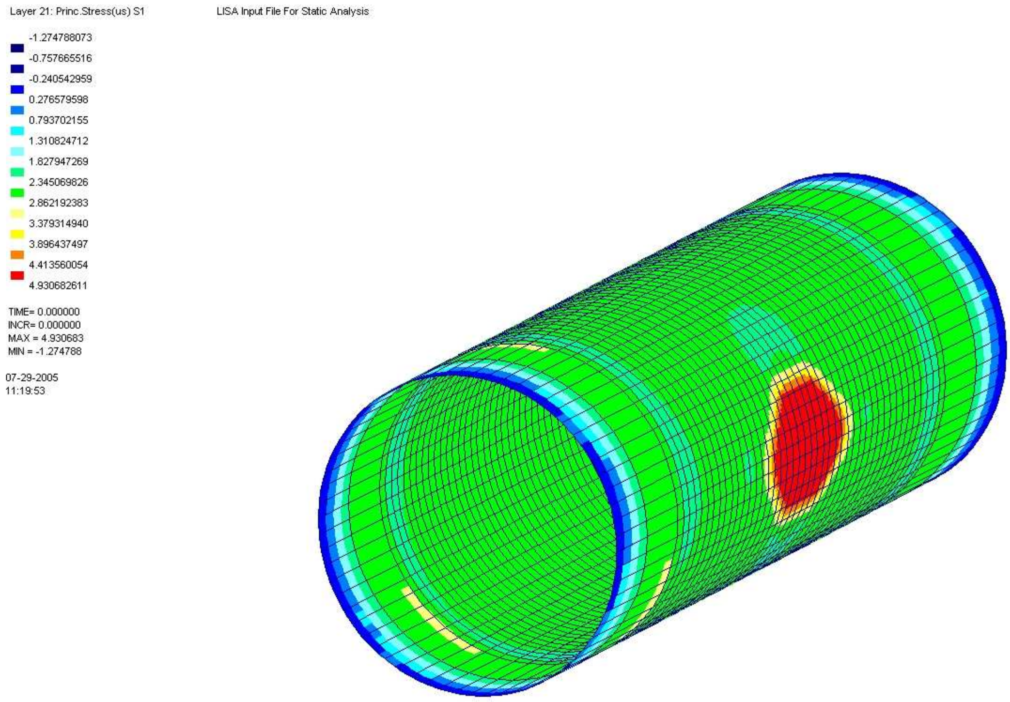

Figure 12: Principal stress (σ_1) distribution in hoop direction

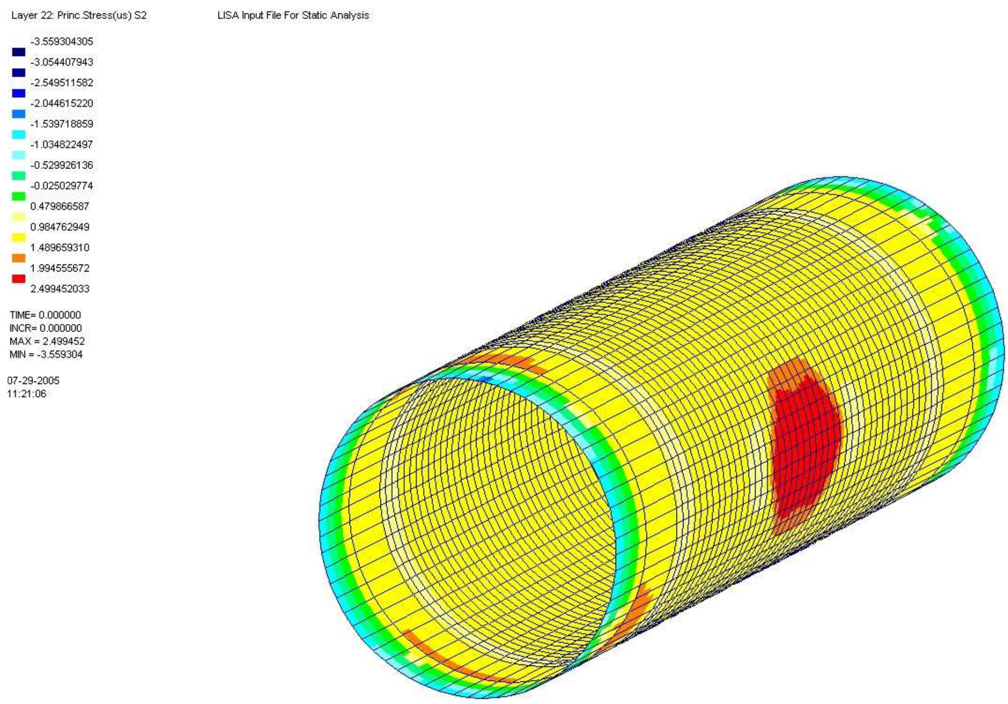

Figure 13: Principal stress (σ_2) distribution in axial direction

To determine how an FT coil sensor would respond to these surface stresses, the nodal values of the principal stresses that lie within an area bounded by the circumference of the sensor are used to calculate the average strain under the sensor. This value is then compared to the average across the affected area and to the far field average strain taken from nodes that lie in an area of nominal pipe wall thickness. Table 2 summarizes these results.

Table 2: Comparison of surface strains

	Average Strain ε (µs)	$\varepsilon/\varepsilon_o$	Average Wall Thickness t (mm)	t_o/t	Average Wall Loss (%)
FT Sensor	11.95	1.97	5.08	1.88	46.7
8”x10” Pit Maximum	12.00	1.97	5.08	1.88	46.7
Far field (ε_o, t_o)	6.08	1.00	9.53	1.00	0.0

For this case, the sensor results match the corroded area maximum. The change in strain from this simple model is proportionally higher than the average wall thickness loss. Based upon the resolution limit of the FT system, the minimum detectable average wall loss for the case is 3.7% of the remaining wall thickness or 2.0% of the NPT. These results compare well with ultrasonic NDT methods. Assuming a best possible field measurement resolution with NDT of 0.1 mm (0.004”), the remaining wall thickness could be measured to no better than 2%.

CONCLUSIONS

The case studies described in this paper show that the FT sensor system can be used to detect wall loss in refinery components, such as reducers and overhead lines, with accuracy comparable to the best conventional methods. However, the FT sensor system offers additional benefits:

- Remote data tracking and database storage
- Non-electrical based sensor
- Ability to measure temperature and pressure with one sensor monitor
- Continuous monitoring
- Data trending
- Large sensor area

These features make the FT system ideally suited for corrosion monitoring in areas not routinely examined due to inaccessibility, critical or single point failure areas, and where process controls can be used to mitigate damage when corrosion rates are immediately known. Such monitoring can lead to increased safety, increased productivity, reduced turnaround times, fewer unplanned shutdowns, and lower refinery operating costs.

REFERENCES

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2. Force Technology Canada, “FSM-IT™ Enclosure No. 1, 2298-1en.