MY PIPES ARE CORRODING! WHEN SHOULD I REPAIR?
Getting the Answers You Need for Maintaining Pipeline Integrity

MICHAEL TURNQUIST, M.Sc., Senior Consulting Engineer at Quest Integrity
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INTRODUCTION
This article exhibits how modern inspection methodologies combined with innovative computational analysis practices demonstrate the value of conducting fitness-for-service (FFS) assessments on sectional piping. In this instance, a fitness-for-service assessment was performed on two sections of a pipeline experiencing external corrosion at the pipe-to-elbow seam welds. A full external laser scan and spot ultrasonic thickness (UT) readings were used to measure the corroded geometry and verify accurate measurement of the remaining thicknesses in various corroded locations. This allowed for the actual corroded profiles to be accurately modeled using finite element analysis (FEA).

Complications were present when modeling the observed metal loss. Using a fresh approach to finite element mesh generation modeling, the actual measured corroded geometry was modeled without the need for overly-conservative geometric simplification. A Level 3 FFS assessment was performed in addition to a remaining life assessment based on observed corrosion rates. The result of this analysis was that the piping could remain in service for at least two additional years before needing repair.

CASE STUDY OVERVIEW
A recent inspection of a portion of piping identified two instances of localized metal loss in the vicinity of two 48-inch pipe-to-elbow welds. This inspection consisted of a full external laser scan of the regions of metal loss, as well as various ultrasonic thickness (UT) readings of the corroded areas. The full external scan provided a depth of metal loss (measured from nominal) at every 0.04" axial increment, and every 0.04" circumferential increment throughout the corroded region. Spot ultrasonic thickness (UT) readings were also taken in order to verify accurate measurement of the remaining thicknesses at various corroded locations. These UT readings were used along with the external scan data to create the actual corroded geometry and position this corroded geometry with respect to the various structural discontinuities along the pipe-to-elbow configuration. This allowed for the use of finite element analysis (FEA) to precisely model the corroded profiles.

The complications in modeling the observed metal loss included a transition in nominal wall thickness from the pipe side to the elbow side of the circumferential seam weld, and the presence of metal loss across the weld. These complications presented a major challenge when efficiently and accurately modeling the corroded geometry. Through the use of innovative finite element mesh generation practices, the actual measured corroded geometry was modeled without the need for overly-conservative geometric simplification.

A Level 3 Fitness-for-Service (FFS) assessment of local metal loss was conducted using the external scan data and UT data gathered during the inspection. This FFS assessment was performed in accordance with API 579 Part 5 “Assessment of Local Metal Loss,” along with Annex 2D and Part 14. The results of the FEA were used in conjunction with the API 579 acceptance criteria to evaluate the risk of plastic collapse, local failure, buckling collapse, and cyclic loading.

A remaining life assessment which modified the corroded profile was then performed based on observed corrosion rates in order to determine how long the corroded area could remain in service before requiring repair. The information resulting from this assessment enabled the owner/operator to be confident in preparing a future inspection and repair schedule.

BACKGROUND
External metal loss was identified on two identical sections of piping. These sections will hereby be referred to as Section 1 and Section 2, with the only differences in these sections being the metal loss profiles. These sections both consisted of a 48-inch OD pipe with a nominal thickness of 0.462 inches welded to a 48-inch OD 1.5D elbow with a nominal thickness of 0.686 inches. For both sections, a support clamp was located approximately 3.5 to 4 inches upstream of the pipe-to-elbow weld on the pipe side.

Two inspection methodologies were used in order to quantify the observed metal loss. A full external scan was conducted for both sections using a Creaform™ laser scanning tool. The laser scan measures the depth of metal loss relative to the corresponding nominal outside surface. This external scan reported a depth of metal loss (measured from nominal) at every 0.04" axial increment and every 0.04" circumferential increment within the entire region of metal loss. The metal loss information was used to identify and model the corroded geometry of each pipe segment.

Spot UT readings were also taken in order to obtain an accurate measurement of the minimum remaining thickness at various locations of metal loss. These UT readings were used with the external scan data to create the actual corroded geometry, and to position this corroded geometry with respect to the various structural discontinuities (pipe-to-elbow weld, support clamp) along the pipe-elbow configuration. The two sets of inspection data were combined such that the minimum measured thickness profile of each section was accurately modeled. A summary of the inspection data is provided in Table 1.
For Section 1, the location of peak metal loss occurred on the pipe side of the weld. For Section 2, the location of peak metal loss occurred in the weld, while the rest of the metal loss extended into the elbow side of the weld. The location of peak metal loss was identified on the bottom side of the pipe for both sections.

Table 1. Summary of Inspection Data.

<table>
<thead>
<tr>
<th>Section</th>
<th>Min. Measured Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section 1</strong></td>
<td></td>
</tr>
<tr>
<td>External Scan Data</td>
<td>0.151 in. (1)</td>
</tr>
<tr>
<td>Spot UT Readings</td>
<td>0.262 in.</td>
</tr>
<tr>
<td>Min. Measured Thickness used in FEA</td>
<td>0.151 in.</td>
</tr>
<tr>
<td>Nominal Thickness</td>
<td>0.462 in.</td>
</tr>
<tr>
<td><strong>Section 2</strong></td>
<td></td>
</tr>
<tr>
<td>External Scan Data</td>
<td>0.294 in. (2)</td>
</tr>
<tr>
<td>Spot UT Readings</td>
<td>0.145 in.</td>
</tr>
<tr>
<td>Min. Measured Thickness used in FEA</td>
<td>0.145 in. (3)</td>
</tr>
<tr>
<td>Nominal Thickness</td>
<td>0.686 in.</td>
</tr>
</tbody>
</table>

(1) Calculated with respect to the nominal thickness of the pipe.
(2) Calculated with respect to the nominal thickness of the elbow.
(3) Since the location of the minimum remaining thickness for Section 2 was determined to be in the weld, the scan data was positioned with respect to the weld such that the critical profile of metal loss corresponded with a minimum remaining thickness of 0.145 in.

MATERIAL PROPERTIES

The piping was constructed of API 5L X60 material. A typical elastic modulus of 2.9∙10⁴ ksi and a Poisson’s ratio of 0.3 were assumed for this material. Specified minimum yield and tensile strength values of 60 ksi and 75 ksi were used, as indicated in API Specification 5L. Thermal properties were not required for this analysis as the operating temperature of the piping was ambient.

To conduct the elastic-plastic finite element analysis, a material stress-strain curve was determined based on yield and tensile properties and the methodology provided in Annex 2E of API 579 [1]. The resulting stress-strain curve is shown in Figure 1 below.

FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) was conducted on the two identified corroded configurations. This was done by converting the scan data into a mesh using a proprietary internally developed mesh generator. Two FEA models were constructed; one for Section 1 and one for Section 2. Both models included approximately 48-inches of straight pipe upstream of the circumferential weld attaching the pipe to the elbow. In the field, this segment of pipe was enclosed in a support clamp for both sections. Since the clamp was removed to measure corrosion under the clamp for Section 1, this segment of pipe included the measured corrosion. The clamp was not removed for Section 2, so the segment of pipe under the clamp was modeled as nominal. This assumption was supported by the observation that the corrosion on the elbow side of Section 2 appeared to stop before reaching the clamp on the pipe side of the weld.

The FEA model of the Section 1 geometry is shown in Figure 2 and Figure 3. The FEA model of the Section 2 geometry can be seen in Figure 4 and Figure 5.
Loads and Boundary Conditions

For both Section 1 and Section 2 models, gravity loads were applied in addition to an internal pressure load representing the transient surge condition. An equivalent axial pressure thrust load was also applied to the end of the elbow where a free body cut was made. The applied loads are illustrated in Figure 6.

In regards to the support clamp located upstream of the vertical seam weld, two cases were considered. The “clamped” case assumed that the clamp was engaged and the segment of pipe where the clamp was present was fixed radially. The “unclamped” case assumed that the clamp was not engaged, and all locations within the entire assembly were allowed to expand radially. The boundary conditions used for the clamped and unclamped cases are shown in Figure 7.

Contour plots of the peak von Mises stress for Section 1 are shown in Figure 8 and Figure 9. Contour plots of the peak von Mises stress for Section 2 are shown in Figure 10 and Figure 11. The stress scale of these contour plots is in psi.

RESULTS

The FEA results are summarized in Table 2. For all cases, with the exception of the clamped Section 2 case, the von Mises stress exceeded the minimum specified yield strength of the material (60 ksi). While these stresses were high, they were highly localized. Localized yielding is not necessarily a concern as long as the FFS local failure evaluation demonstrates that the localized plastic strains do not exceed the corresponding limiting strain.

<table>
<thead>
<tr>
<th>Model</th>
<th>Clamp Configuration</th>
<th>Peak von Mises Stress (psi)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
<td>Clamped</td>
<td>62,124</td>
<td>Between 6 and 7 o’clock</td>
</tr>
<tr>
<td></td>
<td>Unclamped</td>
<td>61,475</td>
<td>Between 6 and 7 o’clock</td>
</tr>
<tr>
<td>Section 2</td>
<td>Clamped</td>
<td>58,253</td>
<td>Between 3 and 4 o’clock</td>
</tr>
<tr>
<td></td>
<td>Unclamped</td>
<td>63,416</td>
<td>Between 3 and 4 o’clock</td>
</tr>
</tbody>
</table>

Note that for Section 2, the location of peak von Mises stress (between 3 o’clock and 4 o’clock) did not occur at the location of minimum measured thickness (between 6 o’clock and 7 o’clock). This was due in part to the nominal bending stresses caused by the elbow. The nominal stresses were more tensile at the 12 o’clock position, and more compressive at the 6 o’clock position. Additionally, the minimum measured thickness was localized, resembling a pit. The metal loss between the 3 o’clock and 4 o’clock position was more widespread. These two factors resulted in slightly higher stresses at the 3 o’clock to 4 o’clock position, even though the minimum remaining thickness occurred between the 6 o’clock and 7 o’clock position.
Requirements for performing a Level 3 assessment utilizing finite element analysis (FEA) are described in Annex 2D and Part 14 of API 579. These sections describe criteria for performing a FFS assessment. These criteria determine if the damaged structure has sufficient protection against plastic collapse, local failure, collapse from buckling, and failure from cyclic loading. Based on the FEA results, these criteria were satisfied and the component was shown to be fit for continued service.

REMAINING LIFE ASSESSMENT

After receiving the results of the initial FFS assessment, the owner/operator expressed the desire for the piping to remain in service for at least another two years when a planned shutdown was scheduled. A remaining life assessment was performed in order to determine whether the piping would be safe if exposed to two additional years of operation.

In order to perform this remaining life assessment, an estimated corrosion rate for each section was required. The estimated corrosion rate was calculated by dividing the peak amount of metal loss measured to date by the amount of time the piping had been in service. The results of this calculation are summarized in Table 3.

The thickness of each corroded section was uniformly reduced based on the corresponding corrosion rate. This was done in order to assess the two sections after two additional years of corrosion. The new minimum thickness in Section 1 was 0.135 inches, and the new minimum thickness in Section 2 was 0.117 inches.

Once the corroded geometry was modified, the finite element analysis (FEA) was repeated and the same evaluation of plastic collapse, local failure, buckling collapse, and cyclic loading was performed for each section.

The criteria for plastic collapse, local failure, buckling collapse and cyclic loading were satisfied for both sections when an additional two years of corrosion was simulated. This result provided the owner/operator with confidence that the corroded piping could remain in service for an additional two years. Based on the results of this remaining life assessment, occasional monitoring of the corroded areas was recommended. This monitoring would consist of UT measurements to be taken periodically in order to ensure that the minimum remaining thickness does not fall below 0.135 inches for Section 1, and 0.117 inches for Section 2.

CONCLUSIONS

Advanced inspection techniques consisting of a full external scan and supporting UT readings identified two instances of localized metal loss near two identical pipe-to-elbow welds. The data gathered from this inspection was used to generate finite element meshes of the actual corroded geometry. These meshes were then used to conduct finite element analysis and perform a Level 3 FFS Assessment of local metal loss.

The results of this FFS assessment concluded that the two corroded sections were fit for continued service in their current state. Additionally, a remaining life assessment was performed by simulating future corrosion based on observed and predicted corrosion rates. The results of this remaining life assessment demonstrated that the two corroded areas were safe to operate for an additional two years when a planned shutdown was scheduled.

For more information on this subject or the author, please email us at inquiries@inspectioneering.com.

REFERENCES

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Michael Turnquist is a Senior Consulting Engineer with Quest Integrity’s Advanced Engineering group in Boulder, Colorado. His project experience includes various types of engineering fitness-for-service assessments, with the majority of that experience in the application of finite element analysis (FEA) and fracture mechanics to the assessment of asset integrity. Michael has a BS degree in Civil Engineering and a MS degree in Structural Engineering from the University of Colorado, Boulder.
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