An Applied Approach to Crack Assessment

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Inspection and assessment capabilities in the pipeline industry are constantly improving thanks to competitive technology developments. More advanced in-line inspection (ILI) tools yield better data on pipeline condition, which in turn drives the need for advanced assessment capabilities to leverage the improved data quality and accuracy. Damage mechanisms like internal and external corrosion, dents and cracks can now be accurately quantified. The combination of better inspection and superior assessment procedures is rapidly demonstrating the weaknesses in older procedures. Using these more advanced assessment technologies, validated and supported through extensive field research, operators can now assess defects in pipelines and determine fitness-for-service (FFS) quickly and confidently.

Fitness-for-service assessments have become increasingly accepted across the pipeline industry over the past few years. FFS standard API 579/ASME FFS-1 (API 579-2007) provides guidelines for assessing types of damage affecting pipelines across all industries. These damage mechanisms include corrosion, weld misalignment, dents, laminations and cracks, among others. Of particular interest are cracks forming near welds where residual stresses from the welding process have the potential to rapidly progress crack growth.

Crack-like flaws may develop in pipelines for a variety of reasons in a variety of locations. In 1950s vintage steel plates connected by low-frequency electric resistance welds, hook cracks are not uncommon in weld metal and the heat affected zone. Cracks may form at the edge of a dent or gouge caused by third party mechanical damage. Sour service lines may experience hydrogen induced cracking (HIC) at the edges of hydrogen blisters. Stress risers at weld misalignment locations are also likely locations for crack initiation.

As described above, cracks can be present in the base metal, weld metal or the heat affected zone at the edge of a weld. Depending on the mechanism, the cracks can be internal, external or buried mid-wall. Cracks oriented along the axis of the pipe are propagated by hoop stresses from internal pressure and cracks oriented circumferentially around the pipe are propagated primarily by axial loads. The high number of variables makes assessing crack-like flaws complex and highlights the need for more comprehensive fracture mechanics assessment methods rather than a one-size-fits-all approach. Figure 1 illustrates several possible crack locations and orientations.
Assessing crack-like flaws with hydrostatic testing has been a common practice in the pipeline industry for decades. While this method often detects the worst of the cracks existing in the pipeline at the time of testing, hydrostatic testing is not a reliable method for determining inspection intervals and it provides an indication of FFS only at a single point in time. Moreover, it is an inefficient way of “detecting” cracks as the detection method requires a failure of the line which leads to costly reactive repairs.

Traditional models for crack assessment are considered conservative because they tend to predict a smaller than actual critical crack size. However, underestimating the maximum flaw size that will survive a hydrostatic test means that larger than expected flaws can remain in the pipe. This scenario is particularly hazardous because large cracks grow more rapidly than smaller cracks. Those larger than expected cracks remaining in the pipeline can subsequently grow to a critical size under normal operating conditions, resulting in a failure during service rather than during the less risky hydro test. This model is described in more detail and illustrated later.

Crack-like flaws are described by length, typically surface breaking, and a depth in the through-wall direction. While the sensitivity of modern ultrasonic inspection tools is good with a probability of detection (POD) of about 90%, there remains some uncertainty in the measurement of the crack depth. There are companies with commercially available ILI tools which utilize shear wave ultrasonics and detect cracks less than 40 mils in depth.

Once flaws have been identified and sized, an assessment calculation is required to evaluate the stability of the crack or determine a critical size. Modern fracture mechanics use the Failure Assessment Diagram (FAD) described in API 579-2007. The FAD enhances linear elastic fracture mechanics (LEFM) assessments by incorporating ductility.

This calculation starts with a stress profile at a critical location calculated from a finite element analysis (FEA) of the un-cracked structure. Using the stress profile at the critical location, the stress intensity factor ($K_I$) is calculated along the crack front for this stress profile. The stress intensity factor depends on the loading condition, the component geometry and the crack
configuration. For a brittle material, the crack becomes unstable when the stress intensity factor ($K_I$) exceeds the fracture toughness ($K_{IC}$).

The FAD extends the crack stability assessment to structures experiencing both brittle and ductile fracture. The FAD is a plot with a limiting curve and points representing the structure of interest. Figure 2 shows a sample FAD. The $x$-axis of the plot is the load ratio ($L_r$) which is the ratio between the reference stress and the material yield strength. The reference stress is proportional to the far-field stress and is computed based on the loading condition, the component geometry and the crack configuration. The $y$-axis of the plot is the toughness ratio ($K_r$) which is the ratio of the stress intensity factor ($K_I$) computed for the primary and secondary loads and the fracture toughness of the material ($K_{IC}$). The through-thickness stress profiles from the FEA model are incorporated in the computation of $L_r - K_r$.

For a particular crack size of length $2c$ and depth $a$, an $L_r - K_r$ point is computed and plotted on the FAD. A point falling under the limiting curve is considered acceptable or safe. A point falling on the curve is considered critical. A point falling outside the curve is considered unacceptable or unsafe. A point lying towards the right end of the diagram fails due to plastic collapse. A point lying towards the upper left corner of the diagram fails due to brittle fracture.

![Figure 2. Example of failure assessment diagram method of assessing the stability of crack-like flaws.](image)
Assessing one or two flaws is reasonable when done with a spreadsheet. The calculations are not overly complicated and many of the critical parameters are publicly available. However, assessing hundreds of flaws along miles of pipelines is a different story. It can take weeks of an engineer’s time to create a spreadsheet tool that would be mildly reusable. It becomes obvious very quickly that the amount of data collected with an ILI tool requires automated assessment.

There are commercially available software programs like Quest Integrity Group’s Signal™ Fitness-for-Service which are capable of assessing hundreds of flaws at once as well as computing a range of critical flaw sizes. An automation tool like this allows the computation of the “what if” conditions in a matter of minutes. A user can not only assess hundreds of flaws along an entire pipeline at once, but the operating parameters, pipe sizes and material properties may all be varied for a probabilistic approach. A critical flaw size curve, describing the entire range of critical crack sizes for a particular set of operating conditions, can be completed as quickly as a spreadsheet or more manual-based assessment of a single flaw.

Automated flaw assessments can also be helpful in predicting the remaining life of a crack or determining the initial size of an existing flaw. Pipelines are typically subject to pressure cycles during normal operation and fatigue crack growth occurs during these pressure cycles. This type of calculation can prove to be much more cost effective and accurate than periodic hydrostatic testing in predicting the remaining life of a pipeline. As noted above, cracks that were predicted to have failed a hydro test using the conservative NG-18 critical flaw curve but that survive the pressure test, may subsequently fail under operating pressure within the inspection interval because they grow to critical size. This scenario is illustrated in Figure 3.
Advances in ultrasonic ILI and fracture mechanics have enabled solutions for assessing cracks in pipelines which are superior in several ways to the traditional methods. Overly conservative models of crack failure sizes can ironically lead to less conservative critical crack size estimates when used to define pipeline testing intervals. As a result, cracks that were predicted to have failed during the hydro test remain in the pipeline and can lead to fracture failure during operation. The conclusion upon reviewing these shortcomings, validated and supported through extensive field research, is clear: detecting and sizing flaws with advanced ultrasonic ILI tools, coupled with the API 579-2007 Fitness-for-Service approach to crack assessment, is a more efficient, reliable approach to determining pipeline FFS than hydro testing.