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DEVELOPMENTS IN ECA METHODS FOR PIPELINES

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Abstract

It is now standard practice to perform an Engineering Critical Assessment (ECA) of fatigue and fracture critical pipelines to verify the pipeline design and assure pipeline integrity. Over the last 20 years a number of ECA methods have been developed for pipelines. These methods cover fracture control (dynamic fracture) of pipelines as well as fatigue and fracture of pipeline girth welds.

This paper reviews the current status of pipeline ECA methods including current R&D programs to refine and extend ECA methods. In addition the paper will include ECA results from several recent pipeline projects highlighting the differences in ECA predictions obtained using different methods and codes.

Introduction

Most pipeline codes include flaw acceptance criteria to ensure that flaws introduced during fabrication do not impact the performance of the pipeline during installation or operation. Historically the flaw acceptance criteria in pipeline codes have been based on a combination of good workmanship principles in conjunction with RT (radiography) inspection.

During the last two decades there has been an increasing trend to adopt alternative fitness-for-service concepts for critical pipeline applications. The concept of fitness-for-service has led to the development of alternative flaw acceptance criteria that are determined by performing an Engineering Critical Assessment (ECA).

It is now standard practice to perform an ECA for all fracture and fatigue critical pipelines. The adoption of ECA methods is ideally suited to modern construction methods that use mechanized welding in combination with automated ultrasonic testing (AUT).

The adoption of ECA concepts for critical pipelines will lead to improved integrity since the emphasis is placed on the most important aspects of overall quality including:

- Material Selection
- Procedure Qualification
- Improved Inspection Technology

The major features of the standard workmanship and ECA based approaches can be summarized as follow:

Standard Approach	ECA Approach
Empirical Approach	Consistent Approach
Experience Based	Engineering Based
Flaw Tolerance not defined.	Flaw Tolerance is defined
Normally RT Based	UT or AUT Based
Flaw acceptance criteria largely based on length.	Flaw acceptance criteria considers both depth and length.
Not suited for critical pipeline applications	Increasingly adopted for critical pipeline designs

The adoption of ECA based flaw acceptance criteria can also result in significant economic benefits through reduced repair rates.

Pipeline ECA Methods

General

Over the last twenty years a number of general ECA procedures have been developed. The most widely used ECA Code in the Oil and Gas industry is BS 7910(1). BS 7910 offers a multiple tier format to enable ECAs to be performed at a level of complexity appropriate to the situation under consideration. BS 7910 includes detailed fracture and fatigue assessment procedures so that fatigue, fracture and combined fatigue and fracture ECAs can be performed.

BS 7910 was first published by the British Standards Institute as BSI PD 6493 in 1980. The fracture assessment procedure included in PD 6493 was based on the CTOD Design Curve. The CTOD Design Curve is based on linear elastic fracture mechanics with a safety factor of 2 at applied stress levels below 50 percent of yield. For stress levels greater than 50 percent of yield the CTOD Design curve is based on an empirical correlation between small scale CTOD tests and large scale wide plate tests.

Although the CTOD Design Curve has been extensively validated, and has been adopted in a number of pipeline codes, including API 1104(2), it has a number of drawbacks. The major limitation of the CTOD Design curve is that it takes no account of failure by plastic collapse, i.e., it only considers failure by fracture. In addition, the CTOD Design curve does not permit ductile fracture assessments to be performed by incorporating a representative J or CTOD crack growth resistance curve (R-curve). With advances in modern steel manufacturing, ductile fracture and plastic collapse can be the limiting failure modes in many situations.

BS 7910 has gone through several major revisions since it was first issued in order to incorporate advances in fracture mechanics assessment methods. The more recent revisions to BS 7910 use the Failure Assessment Diagram (FAD) concept to assess structural integrity. FAD based assessment methods have the advantage that they provide an integrated method for assessing fracture (brittle and ductile) and plastic collapse simultaneously. The FAD approach has now become the standard method for performing an ECA.

Cross Country Pipeline Codes

The two most widely used cross country pipeline construction codes in North America are API 1104(2) and CSA Z662(3). Both of these codes include appendices that present procedures for deriving alternative flaw acceptance criteria for pipeline girth welds based on ECA methods.

The ECA method included in API 1104 Appendix A is based on the CTOD Design Curve and only considers failure by fracture. The user is required to perform a detailed pipeline stress analysis and qualify the pipeline girth welds to one of two specified CTOD toughness values (0.005 inch or 0.01 inch). The CTOD Design Curve method in API 1104 Appendix A includes an allowance for welding residual stresses but does not consider stress concentration factors (SCFs) associated with Hi-Lo misalignment or local weld toe geometry.

The ECA method included in CSA Z662 Appendix K requires the user to perform separate assessments for fracture and plastic collapse. The fracture assessment is performed using the CTOD Design curve. Unlike API 1104 Appendix A, the fracture assessment method in CSA Z662 Appendix A does not consider welding residual stresses since full scale tests performed to validate the ECA method demonstrated that the assessment method is still conservative, even if residual stresses are ignored. In addition, unlike API 1104 Appendix A, CSA Z662 Appendix K allows the user to qualify the girth welding procedure to the minimum measured CTOD toughness rather than a specific value. The CSA Z662 Appendix K fracture assessment procedures do not consider SCFs arising from Hi-Lo misalignment or local weld toe geometry.

Offshore Pipeline Codes

DNV OS F101(4) is probably the most comprehensive offshore pipeline code and covers design, construction and operation of offshore pipelines. DNV OS F101 allows users to develop ECA based flaw acceptance criteria for pipeline girth welds using the methods presented in BS 7910. The BS 7910 assessment procedures for pipeline girth welds are more comprehensive than the procedures presented in API 1104 Appendix A and CSA Z662 Appendix A. As stated earlier, BS 7910 uses a FAD approach and consequently fracture and plastic collapse are assessed simultaneously. In addition it is standard practice to take full account of welding residual stresses and SCFs arising from Hi-Lo misalignment and local weld toe geometry effects.

DNV has recently published DNV OS F108 “Fracture Control for Pipeline Installation Methods that Introduce Cyclic Plastic Strains”. DNV OS F108(5) uses a modified BS 7910 approach in which the installation strain is converted to an equivalent stress using a Neuber Analysis and the material stress – strain curve. In addition DNV OS F108 requires that the pipe and girth weld material toughness is characterized as a crack growth resistance curve (R-curve). Moreover, since the shape of an R-curve is dependent on the mode of loading and the associated level of constraint, it is recommended that the toughness tests are performed on SENT specimens, rather than the traditional highly constrained deeply notched SENB specimens, to ensure that the specimens more accurately represent the level of constraint experienced in a pipeline. R-curve testing will not only provide a more representative measure of material toughness but it will also increase the flaw tolerance in cases where failure is fracture controlled. Finally DNV OS F108 allows the Plastic Collapse cut-off (Lr_{max}) in BS 7910 to be extended out to the ratio of Tensile Strength to Yield Strength since the loading experienced during reeling is displacement controlled.

Comparison of Pipeline ECA Methods

The major features of the API 1104 Appendix A, CSA Z662 Appendix K, DNV OS F101 (BS 7910) and DNV OS F108 (BS 7910) ECA Methods can be summarized as follows:

Description	API 1104 Appendix A	CSA Z662 Appendix K	DNV OS F101 (BS 7910)	DNV OS F108 (BS 7910)
Fracture Assessment	Yes	Yes	Yes	Yes
Plastic Collpase Assessment	No	Yes	Yes	Yes
CTOD Toughness	Specified	Min Measured	Min Measured	R-Curve
CTOD Specimen Geometry	SENB	SENB	SENB	SENT
Residual Stresses	Yes	No	Yes	Yes
Weld Toe SCF	No	No	Yes	Yes
Hi-Lo SCF	No	No	Yes	Yes

It is clear from the above table that the ECA input assumptions vary considerably from code to code and this inevitably will result in differences in the predicted tolerable flaw sizes. Although it could be argued that all of the ECA methods should take account of welding residual stresses and SCFs due to Hi-Lo and weld toe geometry it is generally acknowledged that pipeline ECA methods tend to be unduly conservative. The reason for the excessive degree of conservatism is largely due to the method of measuring the material toughness that is used in the ECA.

It is standard practice to qualify girth weld procedures by testing standard deeply notched (highly constrained) single edge notch bend (SENB) specimens. Since the level of constraint produced in a deeply notched SENB specimen is much higher than the level of constraint associated with a pipeline girth weld, which is loaded predominantly in tension, the measured CTOD values from the weld procedure qualification tests are normally extremely conservative.

Although the ECA procedures in API 1104 and CSA Z662 do not take account of SCFs due to Hi-Lo and weld toe geometry and in the case of CSA Z662 do not take account of residual stresses but still are conservative is largely due to the extremely conservative toughness values used in the ECA. It is not unusual for SENT toughness values to be 3 times higher than toughness values obtained from SENB specimens (6, 7). As a result although the ECA procedures in API 1104 and CSA Z662 could be criticized because they do not take account of SCFS and/or residual stresses this is offset by the conservative CTOD values used in the assessment.

Pipeline ECA Examples

Cross Country Pipelines

The Cheyenne Plains pipeline, which was constructed in 2004, was the first major X80 pipeline in the US. The Cheyenne Plains pipeline was constructed using mechanized welding in combination with AUT inspection. In addition an ECA was performed to enable alternative flaw acceptance criteria to be derived.

The ECA included separate assessments to API 1104 Appendix A and CSA Z662 Appendix K. The ECA results are compared in Figure 1 as plots of tolerable flaw height versus tolerable flaw length. It can be seen from Figure 1 that the API 1104 and CSA Z662 ECA results exhibit different trends:

- The API flaw acceptance curves have larger flaw heights than the CSA Fracture curves. This is because the CSA ECA method does not include welding residual stresses.
- The CSA plastic collapse curve intersects the API 1104 curve at a flaw length of approximately 160 mm.
- The CSA flaw acceptance curves have a shorter cut-off on flaw length.

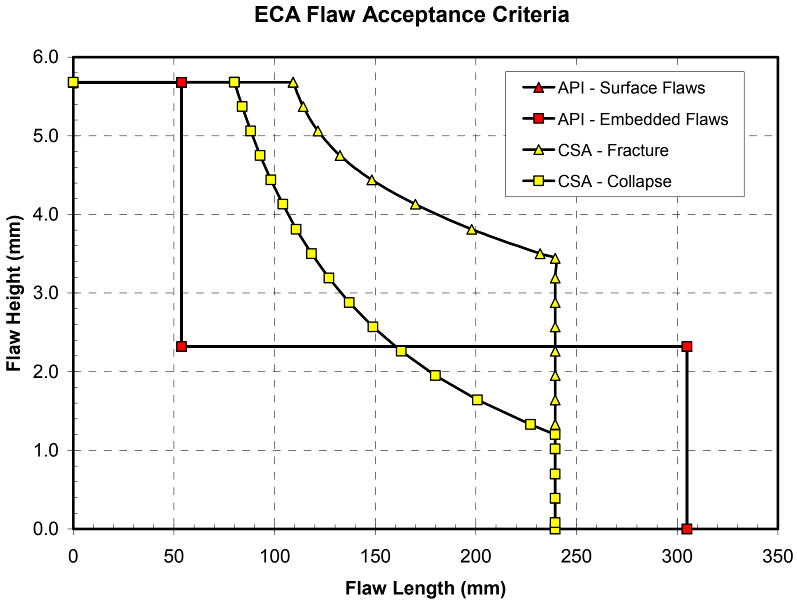

Figure 1. ECA Results for Cheyenne Plains Pipeline Project

Figure 1 indicates that the API 1104 ECA results could be potentially non-conservative at long flaw lengths (i.e., > 160 mm) since they do take plastic collapse into consideration. In recognition of this potential shortcoming a hybrid flaw acceptance criteria was adopted by the project that was based primarily on API 1104 but included the reduced CSA flaw tolerance for long flaws. The final hybrid ECA based flaw acceptance criteria is presented in Figure 2.

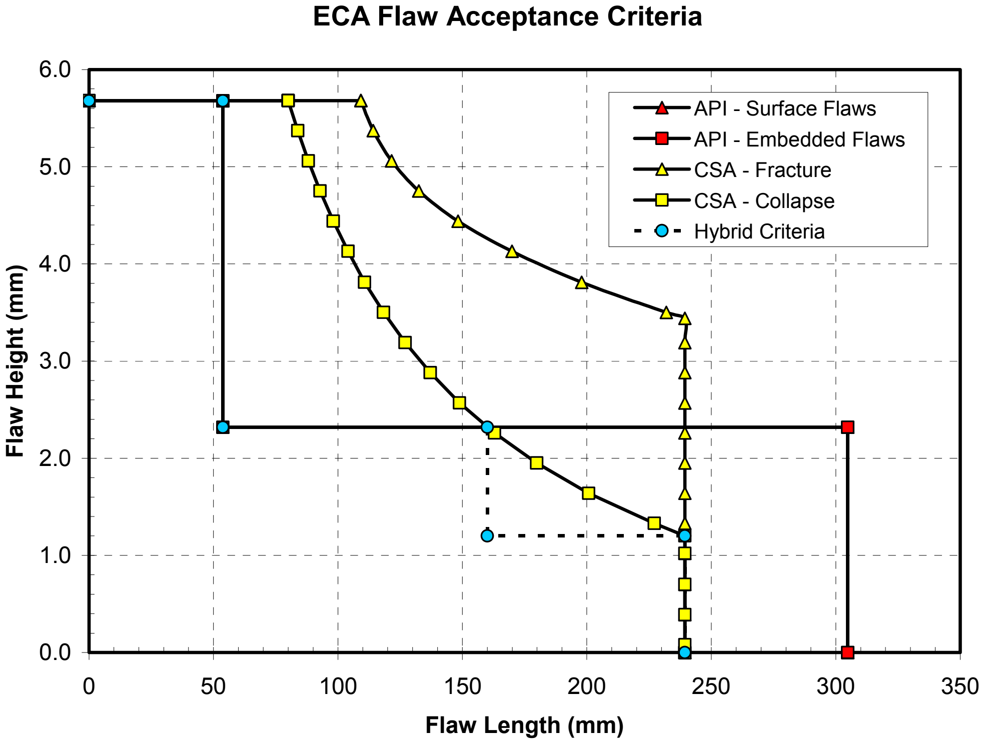

Figure 2. Hybrid Flaw Acceptance Criteria (API 1104 & CSA Z662)

Offshore Pipelines : S-Lay Installation

Offshore pipeline ECAs are performed using a variety of ECA procedures including API 1104 and BS 7910. Offshore pipelines can exhibit a larger range of diameters and wall thicknesses than cross country pipelines. Although offshore export pipelines can be reasonable large in diameter (e.g., > 500 mm diameter) offshore risers and flowlines are typically small diameter and heavy wall, e.g., the development of High Pressure, High Temperature (HPHT) reservoirs has resulted in flowlines with wall thicknesses in excess of 40 mm.

Another difference between offshore and onshore pipelines is that whereas the trend with onshore pipelines is to move to higher grade pipe (e.g., X80) offshore pipelines are more typically constructed using lower strength grades (e.g., X65) due to high installation loads and buckling considerations. Since the use of lower strength pipe generally results in excellent toughness the limiting failure mode for offshore pipelines is frequently plastic collapse.

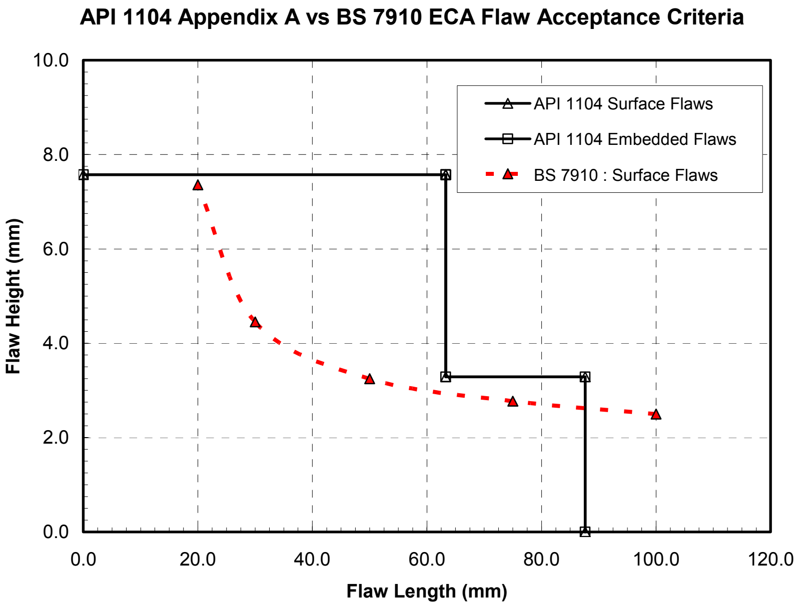

Figure 3. ECA Results of 220 mm Diameter Flowline (Wall Thickness 17 mm)

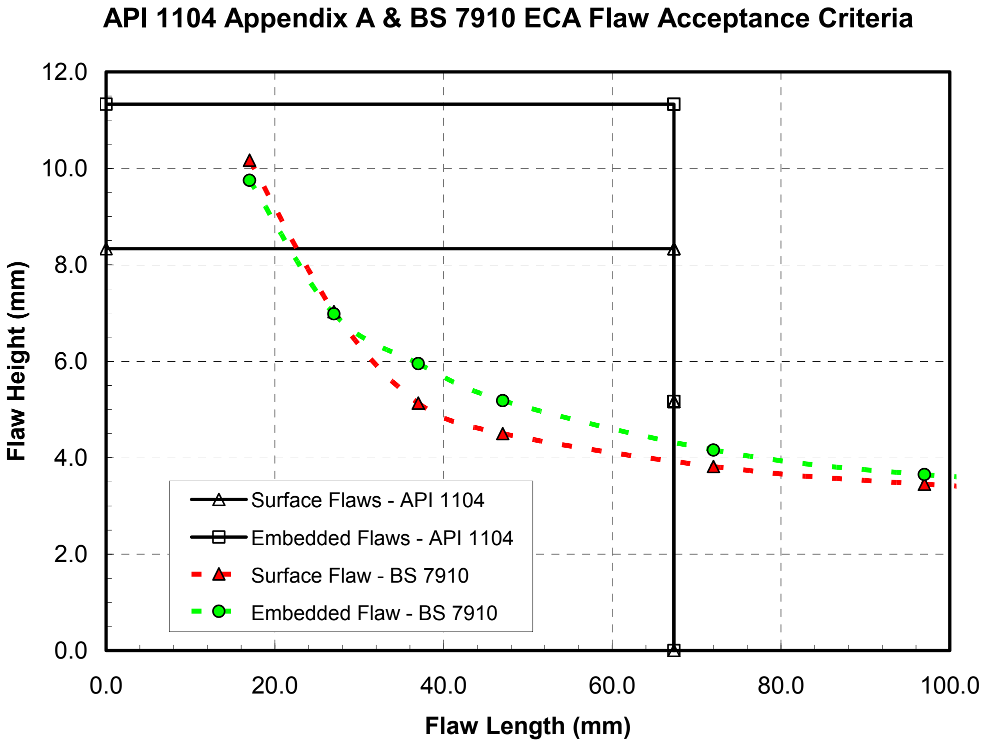

Figure 4. Results for 168 mm Diameter Flowline (Wall Thickness 24.6 mm)

Figures 3 and 4 present ECA results for two offshore small diameter heavy wall pipelines. The ECA analyses were performed with the same input data. All of the ECAs were performed assuming maximum installation strains of 0.20 percent and a toughness of 0.25 mm. Both sets of results have assumed a 1.0 mm sizing error in flaw height, i.e., the tolerable flaw size plots have been reduced in height by 1.0 mm. The BS 7910 ECA analysis included SCFs to account for weld toe effects and the maximum permitted Hi-Lo of 3.0 mm. It is apparent that the BS 7910 and API 1104 ECA results are markedly different with the BS 7910 procedures predicting much smaller flaw tolerance. Although the agreement would improve if the BS 7910 ECA was performed using the minimum measured CTOD rather than the specified minimum value the results clearly demonstrate that applying API 1104 to offshore pipelines can result in potentially non-conservative flaw size predictions, particularly at longer flaw lengths where failure will in general be plastic collapse dominated.

Although it is more common to perform a standard Level 2A ECA for offshore pipelines installed using S-Lay, it is also permissible to perform a Level 2B ECA using a material specific FAD derived from the material stress-strain and toughness data presented in the form of a crack growth resistance curve. The FAD in the Level 2B and 3B BS 7910 ECA procedures is based on the measured pipe material axial stress strain curve. This is illustrated in Figure 5 which shows Ramberg Osgood stress-strain curves for three work hardening levels (Y/T = 0.85, 0.90 and 0.95) and the corresponding Level 2B FADs.

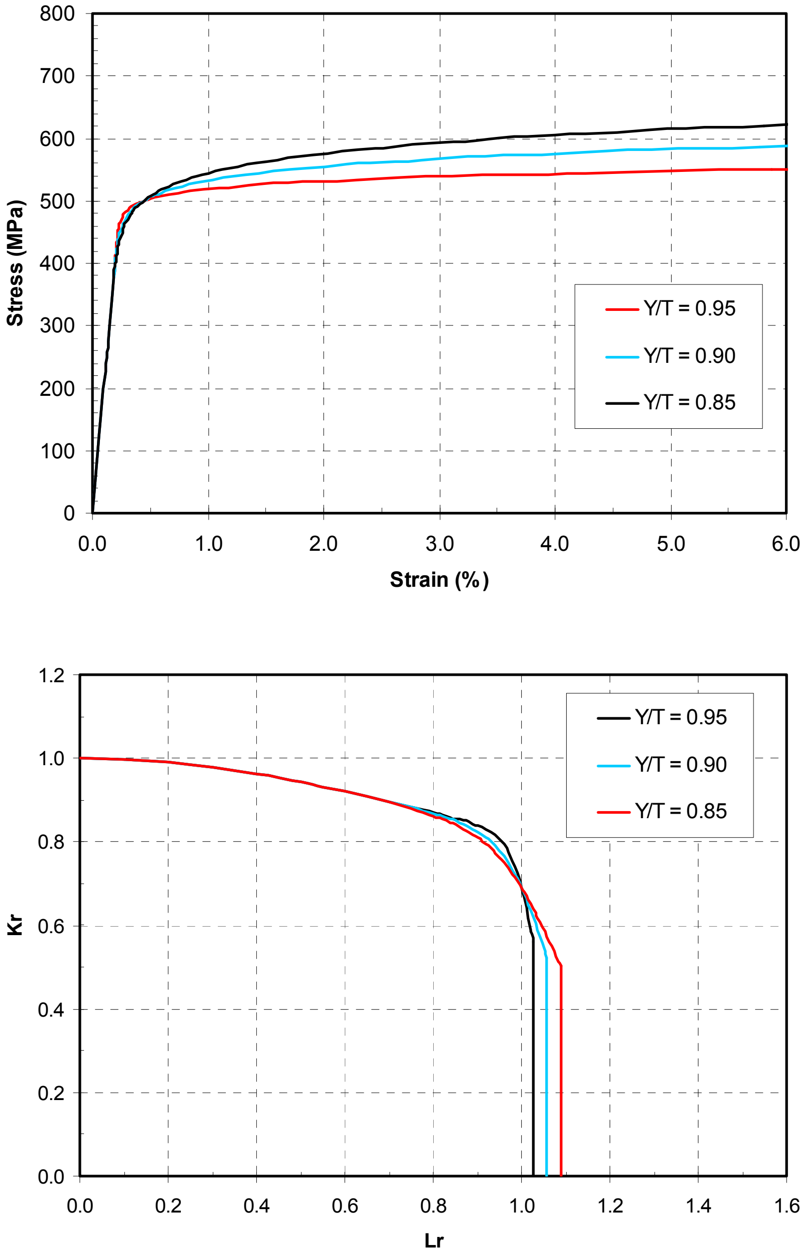

Figure 5. Ramberg Osgood Stress Strain Curves with Different Y/T Ratios and Corresponding BS 7910 Level 2B FADs

The variability in the Y/T (Yield Strength divided by Tensile Strength) ratios for a pipe that was free issued to an offshore pipeline installation contractor on a recent S-Lay pipeline project is shown in Figure 6. The installation contractor was also provided with a pipe material stress-strain curve which had been measured on a specimen which exhibited a Y/T ratio of 0.84 which represents the extreme low end of the Y/T ratios. To assess the effect of the material Y/T ratio on the predicted flaw tolerance a series of ECA analyses were performed using fitted Ramberg Osgood stress-strain curves with different Y/T ratios.

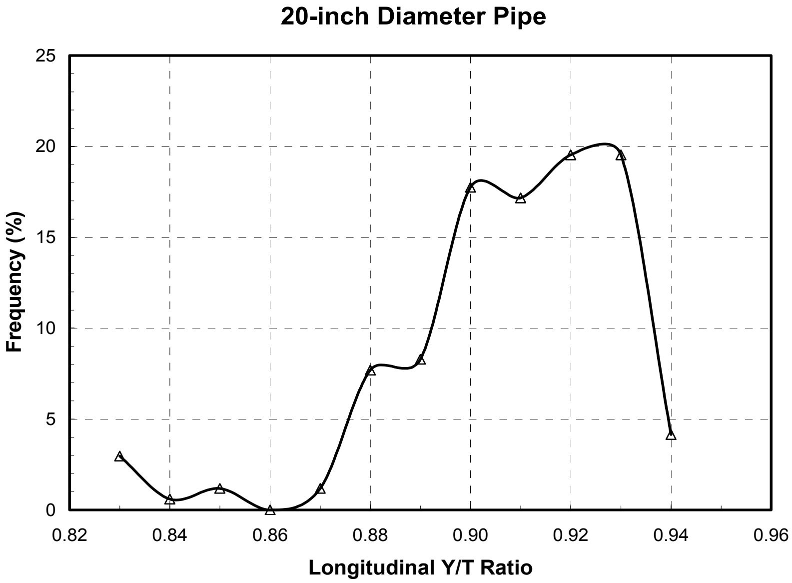

Figure 6. Variability in Free Issue X65 Project Pipe

The material toughness was characterized by performing R-curve tests. The results of the R-curve tests are presented in Figure 7. These R-curves were generated by testing SENB specimens. Although the option existed to test SENT specimens the tests were performed on SENB test specimens to expedite the test program.

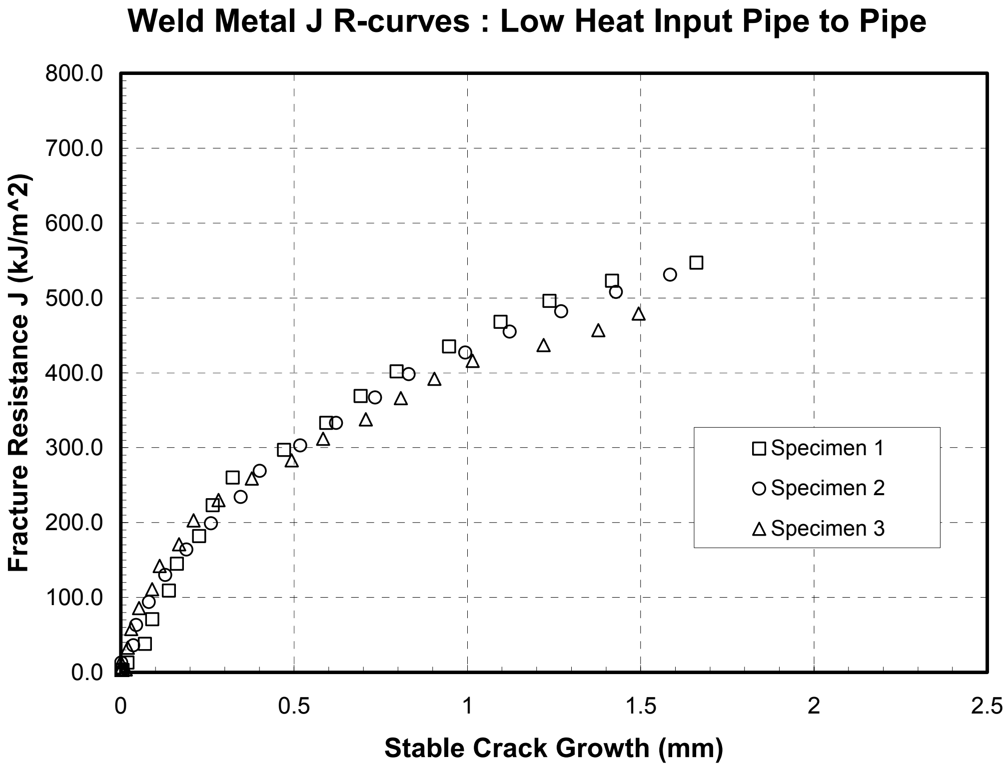

Figure 7. Weld Metal J R-curves for Offshore Reel Lay Pipeline Project

The results of the ECA are presented in Figure 8 as plots of tolerable flaw height versus tolerable flaw length. The ECA results incorporate a 1.0 mm sizing error in flaw height, i.e., the tolerable flaw size plots have been reduced in height by 1.0 mm. It is clear from Figure 7 that the tolerable flaw size plots are very sensitive to the Y/T ratio with the largest flaw tolerance produced by the lowest Y/T ratio. This highlights the need to assess the variability in Y/T ratio when performing an ECA. If also highlights the benefit in low Y/T ratio for S-Lay and reeled pipeline installations. In cases where the pipe is free issued to the pipeline installation contractor it is important that the installation contractor specifies an upper bound limit on Y/T ratio to avoid unacceptably small tolerable flaw sizes.

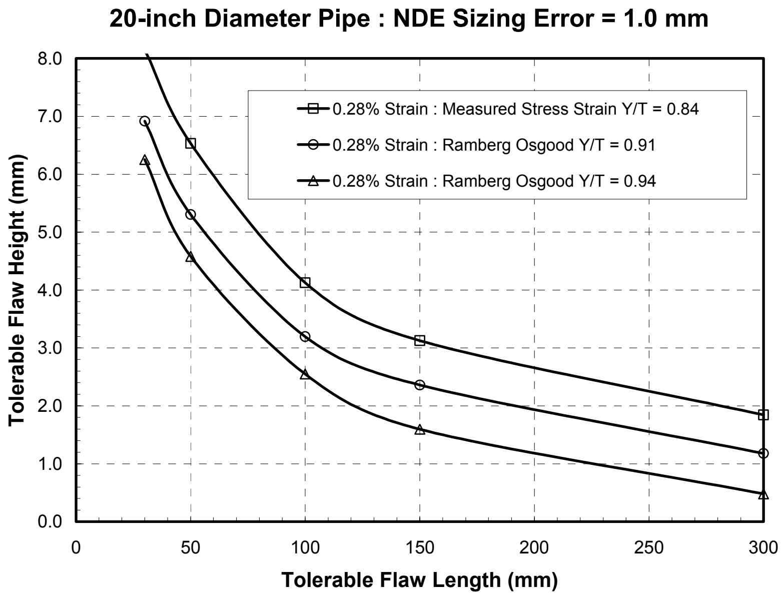

Figure 8. Tolerable Flaw Size Plots for S-Lay Pipeline

Offshore Pipelines : Reel Installation

DNV RP F108 provides a recommended procedure for performing ECAs of reeled pipe. The ECA procedure is a modified BS 7910 Level 2B or 3B procedure. Since the BS 7910 FAD assessment method is a stress based approach the design installation strain must be converted to an 'equivalent' stress to perform a Level 2 strain based assessment. Since girth welds normally overmatch the longitudinal parent pipe properties the overall curvature of the pipe during pipe lay is controlled by the longitudinal parent pipe. The Equivalent Installation Stress is determined as the intersection point between the Neuber curve and the parent pipe material stress-strain curve. A typical Neuber construction is illustrated in Figure 9.

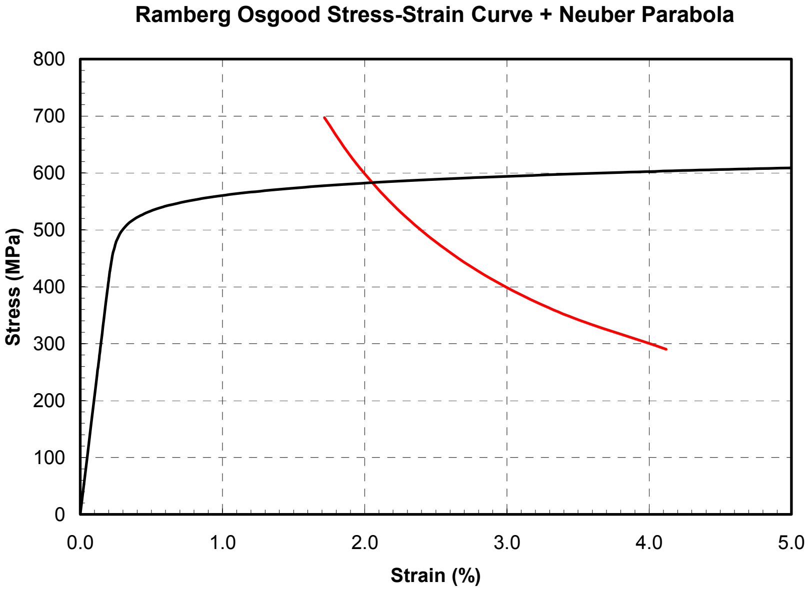

Figure 9. Typical Neuber Construction for Reel Lay ECA

ECAs of reeled pipelines have become increasingly common over the last few years with the increasing trend towards reeled installation of pipelines flowlines and riser systems. In such cases it is standard practice to characterize pipe material and girth weld toughness in the form of crack growth resistance curves.

In a recent reeled pipeline project a screening ECA was performed prior to procuring the pipe to assess the effect of pipe tensile properties on flaw tolerance. The maximum axial strain produced in the pipeline during installation was 2percent. Since the linepipe specification included a maximum permissible Y/T ratio of 0.92 a series of ECAs were performed for Y/T ratios of 0.88, 0.90 and 0.92 to determine the effect of Y/T ratio on flaw tolerance.

The ECA results for the reeled pipeline are presented in Figure 10 for an assumed CTOD value of 0.25 mm. The ECA results demonstrate that for long flaws the flaw tolerance is a function of Y/T ratio. However at short flaw lengths the flaw tolerance for different Y/T ratios collapse together. This is illustrated in Figure 11 which present the tolerable height of a 25 mm long external surface flaw as a function of the parent pipe axial Y/T ratio and material toughness. It is apparent that for Y/T ratios greater than 0.90 the tolerable flaw size does not increase with further increases in toughness. This highlights that a limiting toughness exists above which the failure conditions are plastic collapse dominated. This serves as a further demonstration of the importance of a low Y/T ratio for pipeline installations that experience high strains.

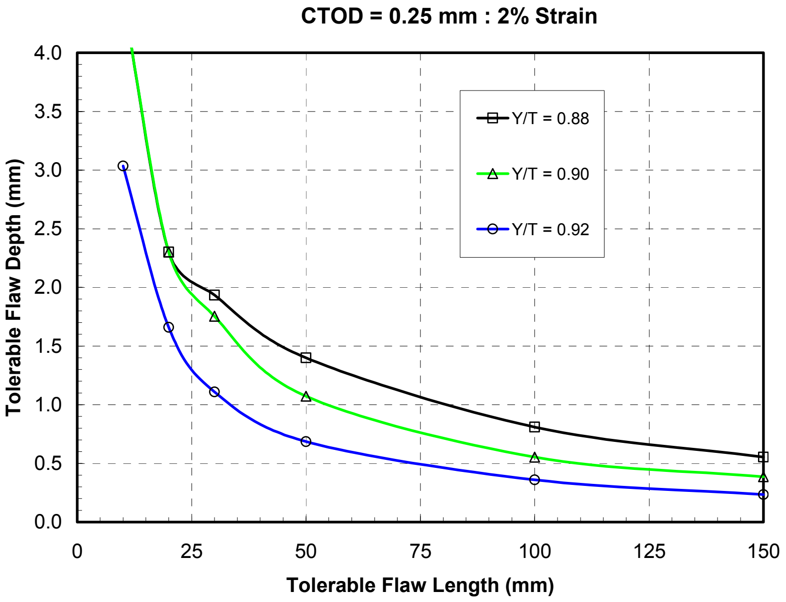

Figure 10. Tolerable Flaw Size Plots for Reel Pipe Installation.

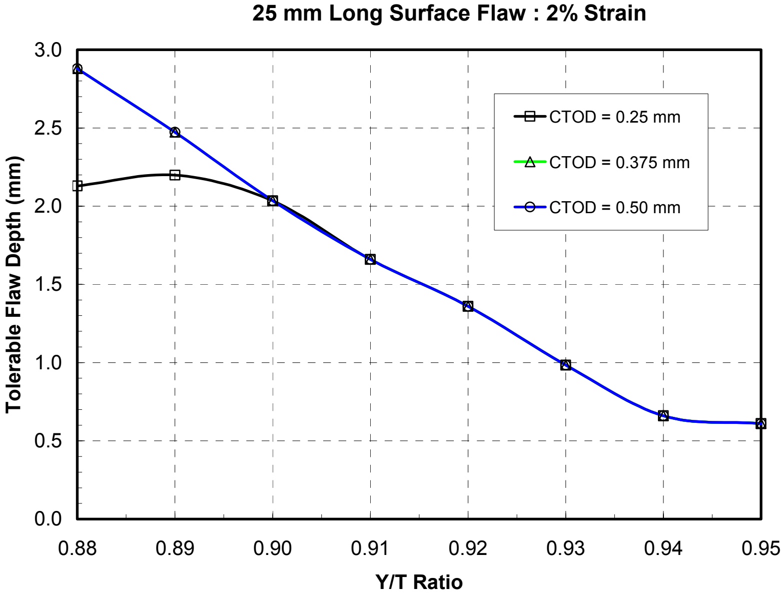

Figure 11. Tolerable Flaw Height of 25 mm Long Surface Flaw versus Y/T Ratio

Future Challenges : Strain Based Design

General

The majority of existing pipeline design codes are stress based and provide limited guidance on the design and assessment of pipelines that may experience high local strains in service. High strains can occur in service due to ground movement, bending over an unsupported span, and seismic loading. In such cases pipelines should be designed based on strain capacity.

The design, specification, and construction of a strain-based design pipeline demands particular care to ensure appropriate code compliance and fitness-for-service. In the simpler mechanistic approaches that are appropriate for conventional stress-based designs, it is possible to be guided almost entirely through the process by the code documents. This is not the case for strain-based design where, at each stage of the process, it may be necessary to demonstrate that a sound engineering approach has been adopted and implemented.

In any strain-based design application there is a need to ensure that localized strain accumulation is limited. In pipeline girth welds, strain accumulation can occur in the parent pipe, weld metal, or heat-affected zone (HAZ) region.

The design of pipelines that may experience high strains during installation or in service presents a number of challenges. In cases where the pipe is subjected to axial tension loading (e.g., pressure loading or ground movement) the limiting failure mode is either fracture or collapse. In cases where the pipe is subjected to axial compression loading (e.g., compression loading resulting from a temperature differential – difference between operating temperature and temperature during construction) the limiting failure mode is buckling which can take multiple forms, e.g., global buckling or local buckling. In cases where the pipe is subjected to axial bending loads (e.g., bending over an unsupported span) failure can occur by fracture, collapse, or buckling.

Ongoing R&D Initiatives

Over the last 5-10 years there have been a number of R&D projects(6-10) aimed at developing design and assessment guidelines for pipelines that may experience high strains in service. Specific topics that have been addressed include:

- ∆ Parent Pipe specifications (Y/T limits, stress-strain behavior, material toughness, etc.)
- ∆ Welding specifications (joint design, joint geometry, weld strength mismatch, etc.)
- ∆ Engineering Critical Assessment (ECA) Methods for strain based loading
- ∆ Validation test methods to verify pipeline performance (criteria for full-scale testing)

Although these projects have provided valuable insight into the challenges and issues associated with strain based design it is clear that much more work is needed before comprehensive design guidelines can be developed. PRCI and DOT has recently launched a major international project aimed at developing Tensile Strain Limits for Pipeline Girth Welds. This project will involve extensive FEA analysis in combination with small and large scale testing. One of the major objectives of the PRCI / DOT study is to determine and quantify the effect of pressure induced bi-axial loading on structural performance.

The effect of biaxial loading on applied crack driving force was highlighted in a recent research project(8) undertaken for the US DOI minerals Management Service (MMS) and US DOT Office of Pipeline Safety. This work highlighted the significant effect of internal pressure on applied crack driving force. This effect is illustrated in Figure 12 which presents a plot of applied crack driving force (CTOD) versus applied strain for a 3 x 25 mm long surface flaw in a pipeline girth weld for the following conditions:

- ∆ Zero Internal Pressure (Hoop Stress = 0)
- ∆ Internal Pressure (Hoop Stress = 80% SMYS)

The effect of biaxial loading is very dramatic. For the example presented the ratio of $\text{CTOD}_{\text{Pressure}}$ / $\text{CTOD}_{\text{No Pressure}}$, for a given applied strain, is approximately 2.0. An alternative way of considering the results presented in Figure 12 is that under conditions where failure is fracture controlled and failure occurs at a specific value of CTOD, then the axial strain capacity of the pipeline under biaxial loading is approximately one half of the capacity under zero internal pressure.

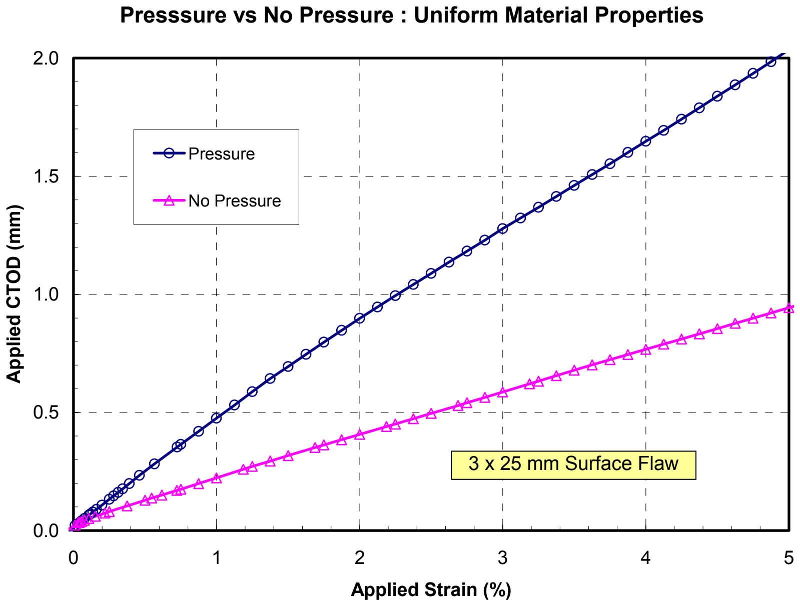

Figure 12. FEA Results Illustrating Effect of Biaxial Loading on Crack Driving Force

In cases where pipelines experience high strains during installation or in-service, it is common practice to conduct full scale tests to validate the design. DNV OS F101 requires that the characteristic strain capacity from ECA be "validated by realistic testing of girth welded pipe, e.g., by full-scale bend testing." This requirement is applied only for installation methods introducing plastic strains where the accumulated plastic strain is >2%. The extent of testing and the details of the test procedure are subject to agreement. The purpose of the testing is to demonstrate that possible weld defects will not result in fracture during pipe laying or will not extend by stable growth to a size that will be unacceptable under normal operation.

When performing full-scale tests it is important to simulate operating conditions as closely as possible. Historically, full-scale pipe bend tests and curved wide plate tests have been used to validate strain-based designs and assessment procedures. However, based on the results presented in Figure 12, it is recommended that in cases where a pipeline may experience high strains in operation (not installation) full-scale validation pipe tests should be performed with internal pressure. This will ensure that the full-scale tests simulate operating conditions and include the effect of internal pressure on the development of local strains in pipeline girth welds and HAZ regions.

Summary

This paper has reviewed the current status of pipeline ECA methods including current R&D programs to refine and extend ECA methods. In addition the paper has presented and compared ECA results from several recent pipeline projects highlighting the differences in ECA predictions obtained using different methods and codes.

The current status of pipeline ECA methods can be summarized as follows;

- The adoption of ECA methods has become the accepted and preferred practice for critical offshore pipelines.

- ECA methods are ideally suited to modern construction methods that use mechanized welding in combination with automated ultrasonic testing (AUT).

- The adoption of ECA concepts will lead to improved pipeline integrity since the emphasis is placed on the most important aspects of overall quality namely:
  - Design
  - Material Selection (Specification)
  - Procedure Qualification
  - Improved Inspection Technology

- Adoption of ECA methods has major financial benefit through reduced repair rates.

Although existing ECA methods provide a sound basis to assess pipeline integrity and develop ECA based flaw acceptance criteria there are still several areas where ECA methods need to be refined, most notably, strain based design and in particular the effect of biaxial loading on tensile strain capacity.

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