Considerations When Selecting Failure Stress Models for Prioritizing Cracks or Crack-like for Response and Remediation

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Abstract

An increasing number of in-line inspections (ILI) for assessing pipelines with cracking and seam weld anomalies are being carried out for the first time in more pipeline segments than before. These inspections have resulted in an increased need to evaluate and identify which planar defects pose an immediate or future safety concern to pipelines, since not all cracks and seam weld defects are injurious. For PHMSA regulated gathering and transmission pipelines, a prioritized response criteria for ILI reported cracks and crack-like now include response conditions based on failure pressure predictions. However, there is no unified single failure stress model nor method for estimating the failure pressure of pipelines with cracking and seam weld anomalies. The analyst is tasked with choosing from several failure stress models available to evaluate the rupture pressure capacity of a pipeline in the presence of planar defects and to estimate leak/rupture behavior.

In this paper, considerations for the selection of failure stress models are provided within the context of the type of defect being evaluated, the pipe known or expected fracture mechanism (brittle cleavage/quasi cleavage, or ductile/micro-void coalescence), fracture toughness data available or assumed, failure criteria, and the fracture mechanics basis of the models. A miss-match between any of these factors can result in unreliable predictions or overly conservative results.

Introduction

Pipe body cracking and seam weld crack-like defects can form in pipelines during the line pipe manufacturing process and initiate from existing material imperfections or damage during the operational life of a pipeline. The prediction from in-line inspections (ILI) or confirmation by non-destructive evaluations (NDE) of cracking or seam weld anomalies in pipelines does not automatically warrant such defects injurious. This was demonstrated fundamentally through experimental testing and engineering analysis carried out originally by A. A. Griffith, C. Inglis, G.R. Irwin, P.C. Paris, and contributions by others. For pipelines and pressure vessels, this was verified by analytical work done by E. Folias in 1960, Battelle Memorial Institute pipe testing in the 1970s, and additional analytical development by Newman-Raju in the 1980s. Now days, the fracture capacity of pipelines with a crack-like defect can be determined by a combination of knowing the crack characteristics, applied stresses, and the pipe material response to fracture. Figure 1 illustrates the interconnection of science and engineering disciplines, fittingly known as fracture mechanics.

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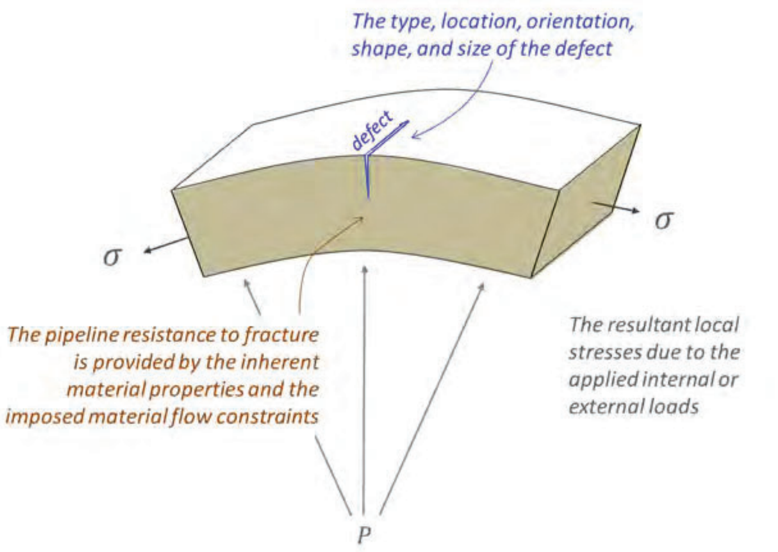

Figure 1. Interconnection of Defect Characteristics, Stresses, and Material Properties on Frature

An increasing number of in-line inspections for assessing pipelines for cracking and seam weld anomalies are being carried out which have resulted in higher demand to evaluate and identify which planar defects pose an immediate or future safety concern to pipelines. The severity of ILI reported and NDE confirmed cracks or seam weld anomalies for response and remediation can be established by means of a failure stress model. There is no unified failure stress model nor method for predicting the failure of pipelines in the presence of cracking and crack-like defects in the seam weld. There are models developed to evaluate axial planar defects in pipelines subjected to internal pressure (NG-18 ln-sec, CorLAS and MAT-8) and those that were created for a broad application for piping and pressure vessels (Newman-Raju, BS 7910, and API 579-1/ASME FFS-1). All these models are based on fracture mechanics principles to some degree dependent on the knowledge available at the time of the model development, assumption on material fracture behavior, description of the crack driving force, and calibration with empirical data. The models are only meaningful when they can be correlated to pipeline fracture toughness data and can be called failure stress models when their calculated crack driving force at fracture is higher than the known or assumed critical fracture toughness of the pipeline.

The model selection is influenced by the model performance published by the authors of the models themselves, by independent comparative model performance studies, and by the fracture toughness data available or a model prescribed limiting toughness value. It is advised not to use conformity or popularity as factors for choosing a model. The authors and supporters of currently available failure stress models have published the analytical derivations and experimental verifications behind the models [1-6], more recently during the International Pipeline Crack Forum on Failure Stress Models held on October 12, 2023 [7-11]. Theoretical analysis and comparative performance of the failure stress models with a fracture mechanics view have also been published many times before, and a summary of notable studies is listed next:

- Y. Miglis [12, publication year 2023] examined the performance of NG-18 ln-sec, Newman-Raju, CorLAS, API 579 FAD Level-II and MAT-8 models with respect to various hypothetical cracks sizes and fracture toughness ranges under pipe open-ended scenarios.
- S. Zhang et al. [13-14, 2019-2023] reported an expanded analysis of failure pressure prediction modelling error in terms of probabilistic parameters for a set of 58 SCC pipeline

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failures, for NG-18 ln-sec, Newman-Raju, CorLAS, API 579 FAD Level-II and MAT-8 models.

- T. L. Anderson [15, 2017] described limitations in the analytical derivations of NG- 18 ln-sec, CorLAS, API 579 and MAT-8 and compared their performance with respect to a set of 29 pipe end-capped burst tests associated with V-shaped part-through wall notches in the pipe body.
- S. Tandon et al. [16, 2014] reviewed the analytical fracture mechanics derivation of NG-18 ln-sec, CorLAS, and API 579 FAD, and evaluated their failure pressure performance using 11 end-capped burst tests and 2 leaks end-capped pipe samples with SCC
- Z. Yan, et al. [17, 2014] quantified the failure pressure prediction error of CorLAS, API 579 FAD Level-II, and BS 7910 FAD Level 2A for 112 full scale pipe end-capped burst tests collected from literature.
- J. F. Kiefner et al. [18, 2013] analyzed the rupture pressure predictions of pipelines failures attributed to planar defects in the seam of low frequency ERW/EFW/DC pipelines using the NG-18 ln-sec and Newman-Raju models. 21 failures were due to cold welds, 59 associated with hook-like, and 12 with selective seam weld corrosion.
- R. Fessler et al. [19, 2012] evaluated the accuracy NG-18 ln-sec, CorLAS, Pipe Axial Flaw Failure Criteria-PAFFC, and API 579 FAD Level-II for 86 pipeline failures attributed to SCC flaws (62 failures and 24 pipe end-capped burst tests).
- A. Hosseini et al. [20, 2010] compared NG-18 ln-sec, CorLAS, and API 579 FAD Level-III using three end-capped pipe burst tests of single fatigue cracks that started from machined notches.
- M. Gao et al. [21, 2009] examined the leak prediction performance of NG-18 ln-sec and API 579 FAD Level-III for a gas pipeline that experienced a leak, and evaluated the rupture pressure prediction between the two models for a pipeline failure.
- A. Rothwell et al. [22, 2010] reviewed the failure pressure prediction of NG-18 ln-sec, CorLAS, and API 579 FAD Level-II and Level-III for SCC colonies and individual cracks for 8 pipeline failures.
- S. Kariyawasam et al. [23, 2007] evaluated the performance of CorLAS, and API 579 FAD Level-II for three burst tests of end-capped pipe samples with SCC.
- S. Cravero and C. Ruggieri [24, 2006] tested 3 end-capped pipe samples with V-shaped notches in the pipe body and compared the prediction of API 579 FAD Level-II and BS 7910 FAD Level 2A models.

The performance of NG-18 ln-sec, Newman-Raju, CorLAS, API 579 FAD Level-II/Level-III and MAT-8 models reported in literature varied according to the type and size of crack or notch-like in the pipe samples, if they were single or colony of defects, the fracture behavior experienced (brittle or ductile), the fracture toughness inputs (CVN to K or J correlation used, or the sub-size specimen measured K or J values), if the tests represented un-capped failures (in-service, hydrostatic pressure testing) or end-caped burst tests, the assumptions on the simplification of the crack profile, and the failure pressure level. There was much scatter reported when predicting the failure pressure of SCC colonies, attributed to the difficulty of estimating the cracks that would coalesce to initiate the fracture process. For failures associated with pipe body SCC at pressure ≥ 90% SMYS the failures were reported as ductile fractures and most models preformed well. A limited set of seam weld related failures has been published and therefore, the performance of the models for predicting failures of seam defects in low frequency ERW/EFW/DC pipelines needs further validation.

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Considerations When Choosing Failure Stress Models

We, the authors of this paper, have reviewed the theoretical nature and failure pressure performance of the five models and have published our conclusions and observations [8, 10, 16, 19, 21]. The intent of this paper is not to further review the mathematical limitations, level of inclusion of fracture mechanics principles, or experimental verifications of the models, but rather present a set of key practical parameters to assist practitioners of engineering assessments in deciding independently and using comfortably a failure stress model. The three focused areas are (1) match the pipeline known or assumed fracture behavior with the fracture behavior for which the model was developed and its solution space, (2) determine the performance of the model for the crack depth/crack length ratios that are of importance in the assessment, while accounting for the defect sizing uncertainties, and (3) identify the type of fracture toughness input, toughness values limits, and if there is recommended Charpy to K or J correlations in the models. A miss-match among any of these factors can result in unreliable predictions or overly conservative results.

Matching Failure Stress Model Fracture Behavior

Each failure stress model was derived with a fracture behavior and fracture condition in mind, that must be matched with the known or assumed pipeline fracture behavior at the crack or notch like defect. A verification that the model is based on and be consistent with principles of physics of material deformation and fracture is warranted. This is the analytical verification. Under burst/rupture conditions, the factors that control fracture of pipelines with cracks are the imposed pipe material flow constraints and the inherent fracture toughness.

Within the fracture mechanics context, a material behavior is the comportment of a material under loads, displacements, and constraints, it can be linear elastic, non-linear, fully plastic, and time dependent or independent. Brittle and fracture fractures are two distinctive fracture behaviors that pipelines can experience. Brittle fractures exhibit little to no material deformation requiring low fracture energies to occur, and metallurgists define it a cleavage fracture. Linear elastic fracture mechanics deals with fractures where the material must remain in the elastic regime of the stress-strain curve, thus little to plastic deformation is allowed. If the location of the planar defect in the pipeline is in an area with inherently brittle material behavior (plasticity is not expected) or is constrained from deforming, then the failure stress equation derivation must include linear elastic fracture mechanics principles which describe the failure stress in terms of the stress intensity factor-*K*. A ductile fracture is accompanied by plastic deformation requiring higher energies, and for metallurgists the fracture mechanism is microvoid coalescence. If the pipe material is intrinsically ductile or it’s allowed to deform plastically, then failure stress model must account for plasticity and be based on elastic-plastic fracture mechanics. The elastic-plastic parameters J-integral and Crack Tip Opening Displacement (CTOD) describe the non-linear material fracture behavior.

The K, J, and CTOD are stress intensity parameters that define the crack tip conditions and quantify the stress magnitude, from which strains and displacement can be calculated [25-26]. These parameters assume the crack to have a mathematically sharp tip. The underlying principle behind fracture mechanics as an engineering practice is to find a remote stress that causes the material ahead of the crack tip to fail locally. When this condition is found, then a limiting stress value has been achieved and corresponding critical values of K, J, or CTOD can be determined. Under these conditions, the critical values of K, J, and CTOD are a measure of fracture toughness, and each can be used a fracture criterion. Table 1 shows the fracture behavior for which NG-18 ln-sec, Newman-

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Raju, CorLAS, API 579 FAD Level-II/Level-III and MAT-8 models were developed, the type of cracks each model claims to evaluate, and the underlying stress intensity parameter. It is noted that all failure stress models listed take into account a defect with a sharp tip for which fracture mechanics principles apply, that is the defect tip bluntness is unaccounted in any of the models.

Table 1. Key Aspects and Solution Space of Selected Failure Stress Models

Fracture Stress Model & Underlying Stress Intensity Parameter	Applicable Fracture Behavior and Crack-like Flaws that Claims to Evaluate
NG-18 Ln-Sec *K-parameter*	Axial pipe body cracking or seam weld defects when assumed to be sharp, located in ductile behaving areas
Newman-Raju *K-parameter*	Axial and circumferential cracking or seam weld defects when assumed to be sharp, in areas of brittle fracture conditions
CorLAS *J-parameter*	Axial pipe body cracking or seam weld defects when assumed to be sharp, located in ductile behaving areas
API 579-1/ASME FFS-1, including BS 7910 *K-parameter*	Axial, circumferential, and embedded pipe body cracking or seam weld defects when assumed to be sharp, in brittle or ductile areas when used in conjunction with FAD approach
MAT-8 *J-parameter*	Axial pipe body cracking or seam weld defects when assumed to be sharp, in brittle or ductile areas when used in conjunction with FAD approach

Another verification to make is to understand the published model performance for predicting actual pipeline ruptures with planar defects for which they claim to evaluate. This is the experimental verification. After all, models are to predict failures close to what pipelines experience. Some models may be calibrated to certain laboratory pipe end-capped burst tests or actual in-service or pressure test failures, learn how the experiments were conducted and the conditions of the actual failures. Pipeline failures associated with SCC colonies produce a wider prediction scatter due to the difficulty in predicting and quantifying the possible coalescence of adjacent cracks. For burst test failures, the end-capped effect can be a factor in the actual burst pressure and none of the failure stress models were developed for an end-capped pipeline condition. For rupture/burst conditions, the ratio of the failure pressure of end-capped to the failure pressure without end cap has been established to be approximately 1.1, thus the predicted failure pressures of the pipe end-capped condition can be 10% higher than the un-capped burst pressure [16]. For other experimental cases, the failure pressure predictions were for pipe samples with V-shaped notch like defects for which currently none of the failure models listed in Table 1 can model notch-like defects, only sharp cracks. The assumption of notch-like defects to be sharp crack-like needs to be made outside the model calculations. And lastly, the location of the crack or notch-like defect in the pipeline is an important factor in verifying the predictions with actual results, because the fracture behavior at the location of the defect must be matched with the fracture behavior for which the model was designed to address. If the defect is in low frequency ERW/EFW/DC seam weld, the expected fracture behavior can conservatively be

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assumed to be brittle/cleavage or if the location is in the pipe body of vintage or modern pipelines the fracture behavior would be ductile in nature.

Each model, as a predictive failure stress model, must define when failure or fracture is predicted. This can be when the calculated stress intensity factor parameter is greater than an input value of pipeline fracture toughness, which can be considered critical related to the failure point or acceptable as in a fitness-for-purpose assessment. For the failure stress models used in conjunction with the failure assessment diagram (FAD) approach, they can report a limiting pressure when using FAD Level-II approach or a failure pressure when elevating the assessment to an FAD Level-III which will include determining if the failure mode is predicted as leak or rupture. Two models report failure stress by calculating the flow stress dependent failure and toughness-controlled failure separately from which the user will choose the lowest predicted value. Strength-dependent failures are those when fracture occurs as the local tensile properties are exceeded before exhausting the available fracture toughness, thus failures tend to be ductile. In such cases the fracture resistance is provided by the flow stress properties (yield and tensile) and it is insensitive to the fracture toughness input. Strength-based analyses are sufficient to predict this type of fracture. On the other side, toughness-controlled failures are manifested before general yielding or plasticity occur, and fracture is governed by toughness. Such failures tend to be present in materials with low to marginal fracture toughness or when material flow constraints exist that preclude the pipe from plastically deforming. Fracture mechanics principles apply to this class of fractures. The failure definitions for each of the models listed are listed next:

<u>NG-18 Ln-Sec</u>

1) when K_calulated by model > K_input (fracture toughness)
2) when Stress_calculated by model > Flow Stress_input.

<u>Newman-Raju</u>

when K_calulated by model > K_input (fracture toughness).

<u>CorLAS</u>

1) when J_calulated by model > J_input (fracture toughness)
2) when Stress_calculated by model > Flow Stress_input.

<u>API 579-1/ASME FFS-1, including BS 7910</u>

As defined by the FAD curve set by the level approach chosen. Strength-controlled and toughness-governed analyses are conducted simultaneously in the same assessment.

<u>MAT-8</u>

When J_calulated by model > J_input (fracture toughness) or when fitted to an FAD curve approach, failure is set by the level approach chosen. Strength-controlled and toughness-governed analyses are conducted simultaneously in the same assessment.

A leak or rupture failure analysis is a toughness dependent assessment. A through-wall crack can be allowed to extend in a ductile stable manner until it reaches a length that is considered unstable at the assessment parameters, after which the leaking crack will fail by rupture. The other case is when a part-through wall crack is also allowed to grow in a ductile stable manner until it reaches an instability point where the pipeline cannot longer tolerate it. If the depth of the crack at such point is < 100% wt, then the crack will fail by rupture. Otherwise, the failure mode will be a leak. BS 7910 and API 579-1/ASME FFS-1 offer detailed ductile tearing instability analysis methods for determining the failure mode of pipelines with a crack. The other models can offer an approximation to leak or rupture boundary condition.

Defect Characterization

The defect size, location, orientation, known or assumed shape, and if single or multiple cracks are present, can influence the failure pressure prediction of any model, with the defect size and shape being the more consequential. All models make defect shape assumptions, with the most common assumption being an ideal semi-elliptical profile, while some models have the options of resolving the shape to rectangular, canoe, or take the irregular defect profile. The semi-elliptical shape is a reasonable approximation of stress related cracks, like stress corrosion cracking, and fatigue cracking, and the canoe or rectangular shapes are approximations to manufacturing related defects in the seam weld (e.g. lack of fusion, hook-like defects, and selective seam weld corrosion). Figure 2 shows the defect profile of natural SCC, Lack of Fusion, and Hook-like defects. In all cases, defects are assumed to have a sharp tip (like stress related cracks). Manufacturing related defects tend have a tip less sharp than stress cracks, therefore their failures stress prediction can be affected.

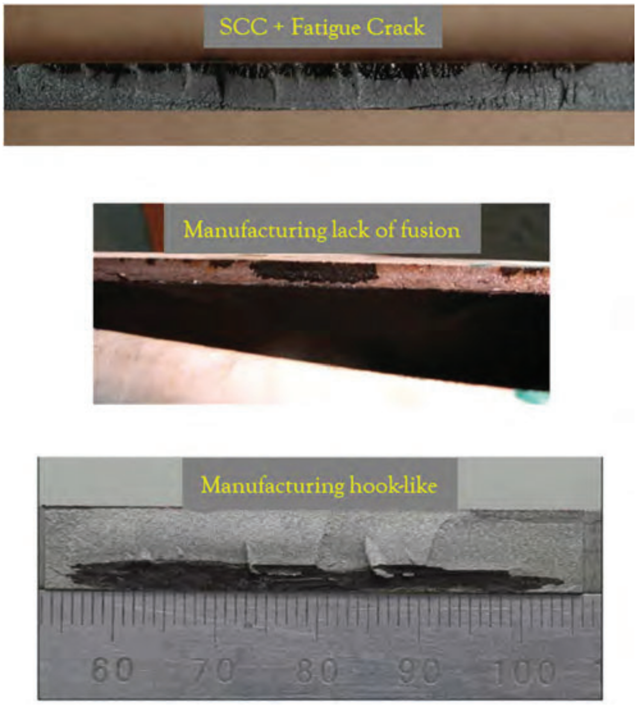

Figure 2. Profile of SCC, Lack of Fusion, and Hook-like Defects [Blade Energy, IPC2020-9251]

The defect dimensions are the more significant defect characteristics affecting the failure pressure prediction [24,27]. The selection of failure stress models should include a verification of the prediction performance with respect to the various ratios of cracks depth/crack length that are significant to the integrity of the pipeline. Defect dimensions to evaluate come from in-line inspection system reports and non-destructive evaluations, which have sizing uncertainties that are carried over onto the failure pressure predictions, often in a non-linear manner. Significant cracks can be a family cracks with various cracks depth/crack length ratios that could fail at operating pressures or operating pressures times a safety factor or at a target hydrostatic test pressure. As a part-through wall crack gets longer, small changes on the crack depth can result in significant variations on the predicted failure pressure. The prediction reliability of a model with respect to the defect dimensions can be demonstrated by choosing a few distinctive crack lengths and calculating the failure pressure at various crack depths for a prescribed set of tensile properties, fracture toughness and assumed crack shape. Figure 3 shows the results of such sensitivity analysis for three axial semi-elliptical cracks 2", 5", and 10" long. In this case, the drop on the predicted failure pressure starts to become significant when the cracks are 20% wt deep, while the largest difference is observed between 50% wt to 60% wt. This analysis can be done at a lower and upper range of fracture toughness values to ascertain the effects of toughness on the failure pressure prediction. It should not be assumed that the model prediction reliability will be the same long & deep, long & shallow, short & deep, and short & shallow cracks.

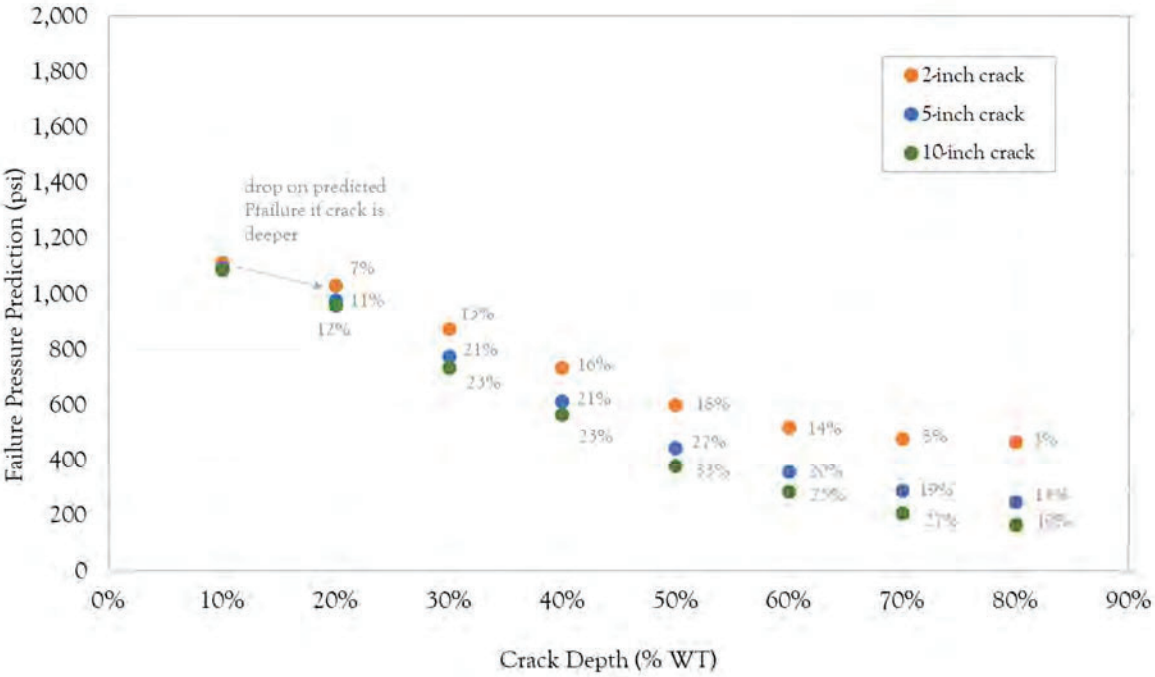

Figure 3. Effects on Failure Pressure Prediction for Various Cracks Sizes

The derivation of a closed-form solution for models accounting for non-linear fracture behavior is challenging to achieve, and the solution is often derived using approximation techniques that can result in defect length and depth limitations in order to converge to a reasonable solution at a target level of reliability. Even those models with a closed-form solutions have a crack solution space for which they are deemed reliable.

Fracture Toughness Input

Fracture toughness does not have the same meaning across the pipeline industry, and this can lead to an assumed definition of fracture toughness that is applied incorrectly across all failure stress models. A general definition of fracture toughness is the resistance of a material to fracture in the presence of a crack. Specific definitions are found in standardized fracture toughness test methods and analysts are encouraged to be familiar with them. Toughness definitions outside the applicable standards are not governed nor maintained by fitness-for-service recommended practices, governmental agencies, industry trade associations or individuals. Specific fracture toughness definitions in standard test methods are listed below. The toughness values measured from theses standardized testing is obtained using sub-size test specimens that approximate the stress field and crack tip constraints of part through wall or through wall cracks in pipelines, resulting in conservative fracture toughness values as compared to what the pipeline has the capacity to exhibit [28-29].

- Plain Strain Fracture Toughness K_{IC} (ASTM E399, ISO 12737): brittle fracture initiation
- Fracture Toughness Arrest K_{Ia} (ASTM E1221): brittle fracture propagation arrest
- Plain Strain J-Fracture Toughness J_{IC} (ASTM E1820, ISO 12135): on-set of ductile stable fracture propagation
- Crack Growth Resistance, *J-R* (ASTM E1820, ISO 12135): Stable ductile fracture propagation
- J-Fracture Toughness at Maximum Load, J_U or J_{max} (ASTM E1820, ISO 12135): ductile fracture instability

Charpy V-Notch (CVN) impact absorbed energy toughness testing is a class of toughness testing that represents the energy required to break a notched specimen under dynamic conditions and test temperature. It is not considered a fracture mechanics toughness test because the starting point of fracture is a notch, rather than a crack, the test is dynamic, and most fractures occur under monotonic/quasistatic loading conditions. It is a qualitative measure of toughness. There are no mathematical expressions directly relating impact toughness to the mathematical equations predicting fracture of engineering structures (K, J, or CTOD stress intensity factor equations). Only experimentally derived correlations of CVN data to K, J, or CTOD data exist. Since none of the failure stress models available take Charpy toughness directly in their calculations, Charpy values must be converted to K, J, or CTOD using appropriate correlations matching fracture behavior in the model and location of the defect in the pipeline. Figure 4 presents Charpy to J or K correlations commonly used in structural integrity assessment of pipelines. It is noted that the Rofle-Novak-Barsom [30] and Wallin [31] correlations are recommended in API 579-ASME FFS-1 [6] and the K_(mat 0.2) and K_mat in the BS 7910 [5]. The Roberts-Newton is a correlation developed as a conservative boundary [32]. These correlations were based on toughness data measured from sub-scale tests with the exception of the Battelle correlation which is based on back calculating the toughness of a series of burst tests of pipeline samples with machined axial through-wall flaws [1].

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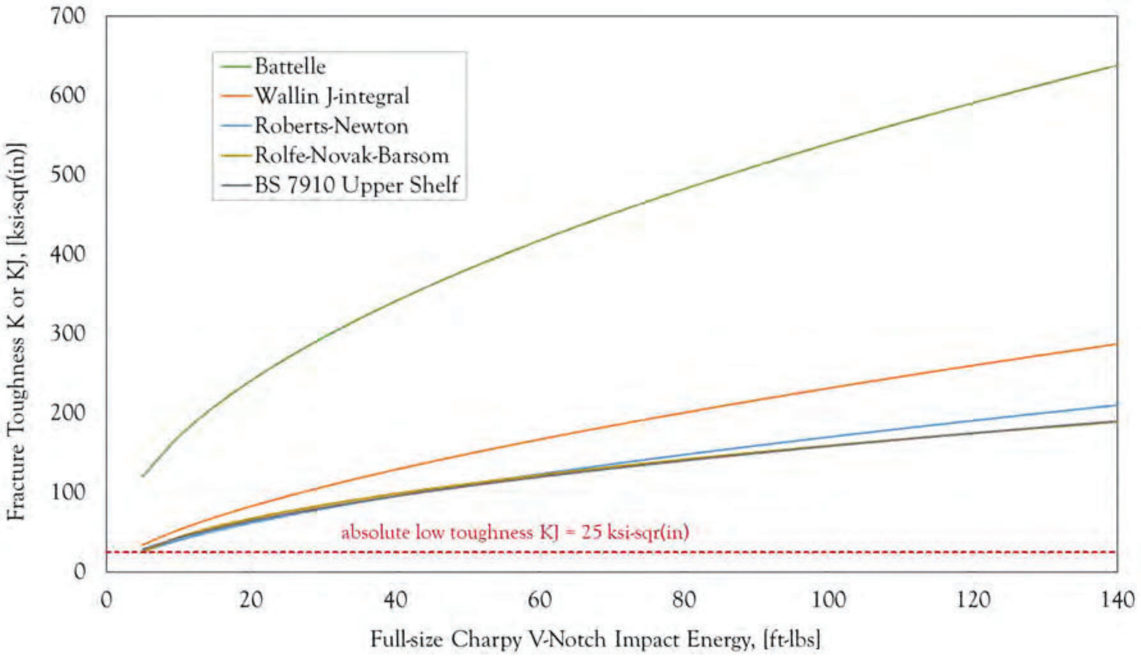

Figure 4. Selected CVN to K or J Correlations

For engineering assessments of pipeline with planar defects, those developing failure stress models have a broad leeway to define fracture toughness for its inclusion in their models. This rises issues when comparing fracture toughness inputs among different failure stress models and can lead to questions if the fracture toughness input realistically represents the fracture behavior for which the models were developed. The fracture toughness inputs recommended by the authors of each failure stress model listed are listed in Table 2. Two models have been calibrated experimentally to specific CVN to K, J correlations, while the others let the user justify the selection.

Table 2. Fracture Toughness Definitions in Standardized Testing

Fracture Stress Model	Input Fracture Toughness
NG-18 Ln-Sec	*K_toughness* from CVN as follows $K_c = \sqrt{\frac{12C_vE}{A_c}}$, for CVN values ≥ 15 ft-lbs, lower values are starting to be justified [7]
Newman-Raju	Measured K_{Ic} User to justify a correlation to convert CVN data to K_{Ic}
CorLAS	Measured *J_ toughness* or *J* from CVN as follows $J = \frac{12CVN}{A_c} \rightarrow K = \sqrt{\frac{12C_vE}{A_c}}$ for CVN data to ≥ 15 ft-lbs, lower values are starting to be justified [9]
API 579-1/ASME FFS-1, including BS 7910	For determining limiting operating pressure or crack sizes: single value toughness *K* or *J* For failure pressure predictions or tearing insatiability analysis: crack growth resistance curve *J-R* User to justify a correlation to convert CVN data to *K* or *J* values
MAT-8	Measured *J_ toughness* or user to justify a correlation to convert CVN data to *J* values For upper shelf CVN behavior, it recommends Wallin J_{1mm} $J_{1\,mm} = 4.482\ CVN^{1.28}$ and a Wallin J_{1mm} with Constraint Correction $J_{burst} = J_{1\,mm}\left[12.585\left(\frac{J_{1\,mm}}{\sigma_{YS}\,a}\right) + 0.715\right]$

There is no numeric threshold that represents ‘low’ or ‘high’ fracture toughness, as they depend on the fracture behavior, crack characteristics, and constraints. Low toughness implies brittle fracture while high toughness ductile failure.

The choice of fracture toughness input to use would depend on the location of the defect to be evaluated, pipeline vintage, toughness data available, and the desired level of conservatism. For toughness dependent failures (when fracture occurs before yielding or for materials with ‘low’ to ‘moderate’ fracture toughness), the fracture toughness is a relevant input parameter that affects the failure pressure prediction. For ‘high’ toughness value, further increases on toughness have little effect on the failure pressure prediction, as shown in Figure 5 for three hypothetical crack sizes. At a lower fracture toughness range of 25-35 ksi-sqr(in), the predicted failure pressure is linear or almost linear with respect to toughness and as affected by the crack size. The sensitivity of failure pressure predictions to small changes on toughness values can be established by analyzing the changes in the linear and non-linear regions of the failure pressure prediction-to-fracture toughness curves for a set of prescribed crack sizes.

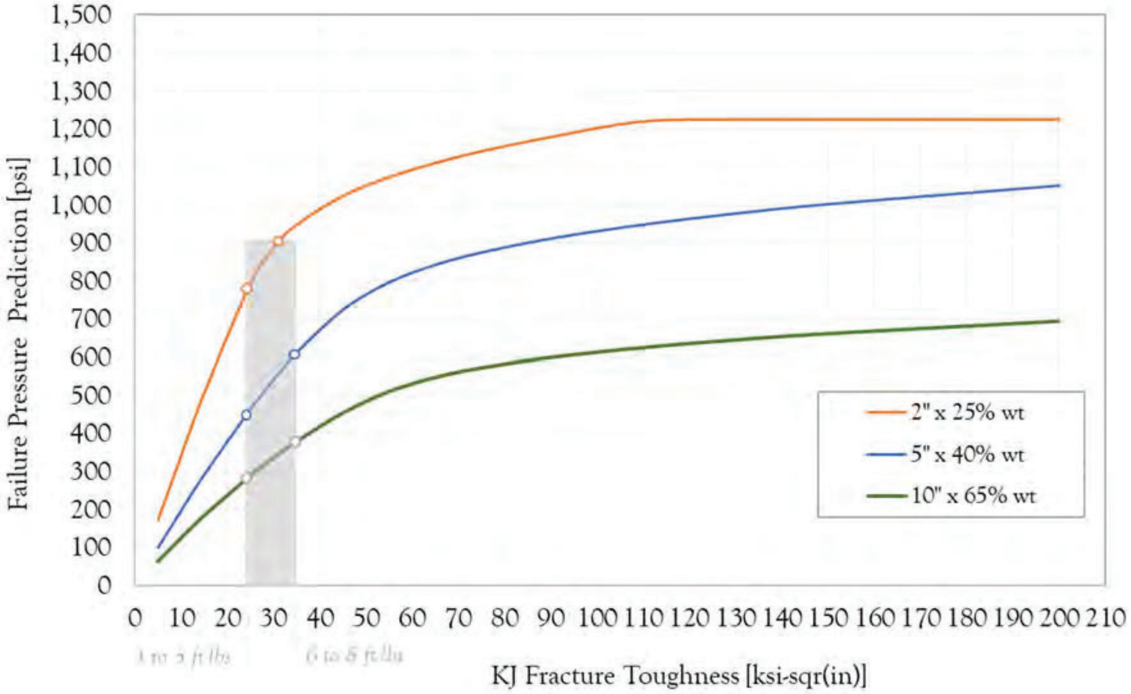

Figure 5. Failure Pressure Prediction as a Function of Fracture Toughness

There is measurement uncertainty in fracture toughness testing, and often toughness is not available for the pipeline of interest and assumptions must be made to justify the use of a lower bound toughness range. Two fracture toughness databases of measured J-integral in accordance with ASTM E1820, converted to KJ, and corresponding to API 5L have been published [28-29]. From these sets, conservative values may be chosen by assuming the toughness data represent Mean – 1STD or – 2STD depending on the desired conservatism. Alternatively, the fracture toughness data listed can be used in probabilistic engineering assessments.

Low carbon steels, as those use in API 5L pipeline applications, do not inherently have fracture toughness near zero. Steels are alloyed, produced, and shaped to carry loads. However, unintended operating conditions can induce material flow constraints that can lead to low toughness behavior. According to ASME lower bound toughness reference curves, carbon steels for pressure vessel applications have a lower bound fracture toughness of around 25 ksi-sqr(in) [33] and the J-integral fracture toughness data reported for API 5L steels point to this lower bound KJ toughness suggesting an absolute value of carbon steel to be near 25 ksi-sqr(in) [28-29].

Prioritizing Cracks or Crack-like Defects for Response and Remediation

A common way of evaluating the severity of cracks and seam weld defects reported by ILI or confirmed by NDE is to calculate their failure pressure for a set of input parameters and divide the prediction by the operating pressure or a safety factor. Those cracks with a predicted failure to operating pressure ratio lower than a target threshold will be considered for field evaluation or repair.

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A graphical visualization of this analysis is shown in Figure 6, where target response criteria consist of defects with depths > 50% WT of any length (blue area) and those with a predicted failure pressure ≤ 1.25 times the Maximum Allowable Operation Pressure, MAOP, (orange area). The limiting curves shown were calculated for a 10.750" O.D., 0.250" W.T., X-46 pipeline for a fracture toughness KJ= 35 ksi-sqr(in). These criteria are the immediate response in the newly published PHMSA regulations for gas pipelines. Considerations should be given to verify the performance of the selected model to estimate failure pressures for short & shallow, long & shallow, short & deep, and long & deep cracks for the measured or assumed fracture toughness values.

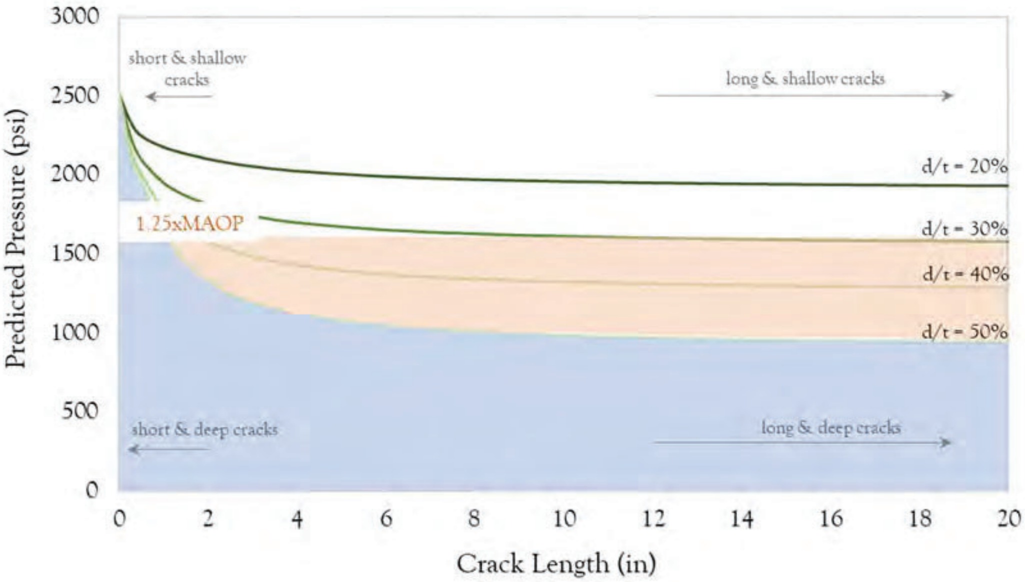

Figure 6. Predicted Failure Pressure and Crack Dimensions for Toughness KJ= 35 ksi-sqr(in)

For higher fracture toughness values, the sentence curves will shift upward reducing the number of shallow defects that need to be remediated. There can be a toughness value high enough that would result in defects with depths <50% WT to be acceptable. For the 10-inch pipeline example, that fracture toughness value is estimated to be 120 ksi-sqr(in) as shown in Figure 7. This toughness is in the range of pipe body toughness of API 5L line pipe steels [28-29].

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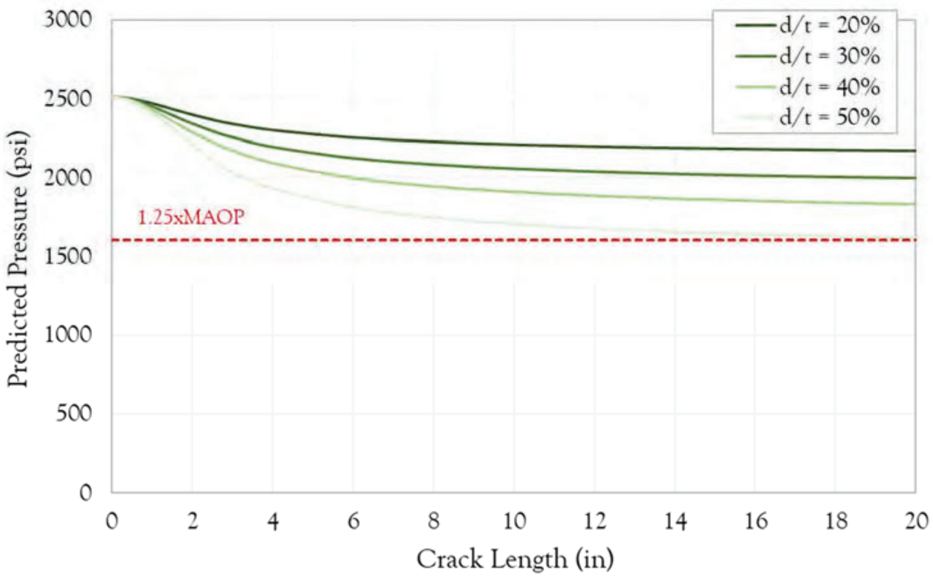

Figure 7. Predicted Failure Pressure and Crack Dimensions for Toughness KJ =120 ksi-sqr(in)

Conclusions

There is no unified single failure stress model or method for estimating the failure pressure of pipelines with cracking and seam weld anomalies, there is however enough knowledge available to assist in selecting a model from those currently available and those that could be published in the future. Three key inputs areas were discussed with the aim of deciding independently and using comfortably a failure stress model. These focused areas are (1) match the pipeline known or assumed fracture behavior with the fracture behavior for which the model was developed and its solution space, (2) determine the performance of the model for the crack depth/crack length ratios that are of importance in the assessment, while accounting for the defect sizing uncertainties, and (3) identify the type of fracture toughness input, toughness values limits, and if there is a recommended Charpy to K or J correlation that is recommended. A miss-match among any of these factors can result in unreliable predictions or overly conservative results.

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