Proceedings of the 8th International Pipeline Conference
IPC2010
September 27-October 1, 2010, Calgary, Alberta, Canada

IPC2010-31661

TENSILE STRAIN CAPACITY EQUATIONS FOR STRAIN-BASED DESIGN OF WELDED PIPELINES

Sandeep Kibey
ExxonMobil Upstream Research Company
Houston, TX, USA

Xiangyu Wang
ExxonMobil Upstream Research Company
Houston, TX, USA

Karel Minnaar
ExxonMobil Upstream Research Company
Houston, TX, USA

Mario L. Macia
ExxonMobil Upstream Research Company
Houston, TX, USA

Doug P. Fairchild
ExxonMobil Upstream Research Company
Houston, TX, USA

Wan C. Kan
ExxonMobil Development Company
Houston, TX, USA

Steve J. Ford
ExxonMobil Development Company
Houston, TX, USA

Brian Newbury
ExxonMobil Development Company
Houston, TX, USA

ABSTRACT

Various industry efforts are underway to improve or develop new methods to address the design of pipelines in harsh arctic or seismically active regions. Reliable characterization of tensile strain capacity of welded pipelines is a key issue in development of strain-based design methodologies. Recently, improved FEA-based approaches for prediction of tensile strain capacity have been developed. However, these FEA-based approaches require complex, computationally intensive modeling and analyses. Parametric studies can provide an approach towards developing practical, efficient methods for strain capacity prediction.

This paper presents closed-form, simplified strain capacity equations developed through a large-scale 3D FEA-based parametric study for welded pipelines. A non-dimensional parameter is presented to relate the influence of flaw and pipe geometry parameters to tensile strain capacity. The required input parameters, their limits of applicability and simplified equations for tensile strain capacity are presented.

The equations are validated through a comprehensive full-scale test program to measure the strain capacity of pressurized pipelines spanning a range of pipe grades, thickness, weld overmatch and misalignment levels. It is shown that the current simplified equations can be used for appropriate specification of weld and pipe materials properties, design concept selection and the design of full-scale tests for strain-based design qualification. The equations can also provide the basis for codified strain-based design engineering critical assessment procedures for welded pipelines.

KEYWORDS: *Strain-based design, tensile strain capacity, finite element analysis, engineering critical assessment, ductile tearing, girth weld performance.*

INTRODUCTION

Pipelines operating in seismic or permafrost regions may be subjected to large plastic strains caused by ground displacements. Traditional stress based design may not be cost effective in such harsh environments. Consequently, strain-based design guidelines for qualification of welded pipelines subjected to large deformations are needed to facilitate future developments in arctic and seismically active regions.

Presently, no single code provides complete guidance on assessment of girth welds for strain-based design. The majority of existing codes are stress-based and provide limited guidance on strain-based design of pipelines operating in seismic and arctic conditions. The conventional allowable stress design (ASD) approaches available in codes and standards may not be adequate for design, specification and construction of strain-based design pipelines.

Any acceptable codified procedure for strain-based design needs to account for all applicable limits states. From a tensile strain capacity standpoint, two limit states exist: (1) plastic collapse in the pipe/weld and (2) fracture limit state associated with ductile tearing due to presence of a pre-existing weld flaw. Both these limit states should be accounted for in codified procedures to determine tensile strain capacity of welded pipelines.

Recently, some attention has been devoted to assessment of the tensile fracture limit state for strain capacity prediction. Investigations regarding fracture assessment procedures for strain-based design of welded pipelines have been reported by Linkens et al. [1] , Wang et al. [2,3,4], Mohr et al. [5] Liu et al. [6] , Tyson et al. [7], Ostby et al. [8] and Sandvik et al. [9]. While, these and other studies have served to expand understanding of strain-based fracture assessment procedures, a long-standing issue remains unresolved, namely, the need for a simplified, practical parametric equation for predicting the fracture tensile strain capacity of welded pipelines by accounting for all key parameters influencing strain capacity. The FEA-based approaches proposed in the literature are complex, and require computationally intensive modeling and analyses. In order to develop designs for strain-based applications efficiently and rapidly, it is desirable to reduce the physics of complex, computational models into simplified, practical parametric equations for strain capacity. FEA-based parametric studies can provide an approach towards developing such equations. Carefully developed parametric studies may be used to develop capacity equations that contain all the significant variables influencing strain capacity and accurately reproduce the results of FEA analysis.

Developing closed form equations has two distinct advantages. A closed form equation allows for further improvement in the predictive capability of this method through careful calibration of the FEA model results to experimental results. Such a calibration phenomenologically captures the effects of second order physical processes not explicitly captured in the FEA method. Furthermore, a generalized equation can be simplified by assuming conservative values for variables such as weld misalignment that are difficult to control through materials design or welding. Choosing conservative levels for a thoughtful set of variables reduces the number of variables in the equation resulting in a simple-to-use and appropriately conservative equation. Such simple-to-use equations may be more readily incorporated in standards and could be used to develop conservative estimates of capacity early in the project design phase when detailed information of weld properties are not available.

Two common fracture mechanics based engineering critical assessment (ECA) procedures are BS7910 [10] and API579 [11]. These procedures provide tiered options for ECA (referred to as Levels 1, 2 and 3). Level 1 is a “simplified assessment” procedure based on conservative assumptions, whereas Level 3 provides a “detailed assessment” procedure including use of elastic-plastic finite element analysis to give more accurate predictions of structural behavior.

In analogy to traditional ECA methods, this paper provides the basis for a multi-tiered, strain-based ECA technique. Simplified strain capacity equations based on conservative assumptions are presented which can be considered analogous to lower level allowable-stress based ECA procedures. A non-dimensional parameter is presented to relate the influence of flaw and pipe geometry to tensile strain capacity which forms the basis of tensile strain capacity equations. Generalized tensile strain capacity equations and the associated FEA approach are presented, these methods being analogous to higher level ECA procedures. The validation of a general, comprehensive strain capacity equation involving all key geometric parameters developed using the tangency-based approach is also presented.

NOMENCLATURE

Flaw depth (mm)	a
Flaw length (mm)	$2C$
Full-scale test	FST
Misalignment (mm)	e
Weld overmatch at UTS (%)	λ
Outer diameter (inches)	OD
Inner diameter (inches)	ID
Pressure, internal (% SMYS)	P
R-curve parameters (power law fit)	δ, η
Single edge notched tension specimen	SENT
Yield to tensile ratio, pipe	Y/T
Uniform elongation, pipe (%)	UEL_{pipe}
Wall thickness, pipe (mm)	t, WT
Heat affected zone	HAZ
Specified minimum yield strength (ksi)	SMYS
Weld center line	WCL

BACKGROUND

The tensile strain capacity program, on which this paper is based focused on the following objectives:

1. Determine an appropriate small scale specimen to measure material tearing resistance (R-curves) for predicting the tensile strain capacity of welded pipelines.
2. Develop and validate an FEA-based methodology for prediction of the tensile strain capacity of welded pipelines.
3. Develop and validate closed-form, parametric equations for tensile strain capacity prediction using FEA-based parametric studies.

An extensive full-scale test program was completed to support validation of the developed tensile strain capacity prediction methodology. The fracture limit state capacity prediction is based on the tangency analysis described in [12-14]. Details of the full-scale test experimental program to support validation were also previously published [12, 13, 15]. It was established through experimental work [16] that internal pressure and misalignment do not affect the material resistance (CTOD R-curve) to crack growth. FEA-based numerical studies [14] and full-scale tests established that weld misalignment can significantly affect the tensile strain capacity of welded pipelines. Recent FEA-based sensitivity studies [14, 17] established the key material and geometric parameters influencing tensile strain capacity and include parameters such as wall thickness (WT), misalignment, flaw size, pipe yield-to-tensile (Y/T) ratio, R-curve, weld overmatch at UTS etc. Single edge notched tensile (SENT) specimen testing was conducted and the R-curves were compared to those measured on full-scale tests. The comparison showed that the SENT specimen can be used to characterize the R-curve for full-scale tests [16, 18]. Preliminary validation of the tangency-based FEA approach was presented in a recent paper [19] and the initial validation results supported the use of CTOD R-curve tangency approach for strain capacity prediction.

This paper focuses on developing simplified, parametric equations for tensile strain capacity prediction using a tangency-based approach. The paper also discusses validation of the generalized strain capacity equations developed using these FEA-based parametric approaches.

GENERALIZED TENSILE STRAIN CAPACITY EQUATIONS

The following approach was adopted to develop generalized tensile strain capacity equations for welded pipelines. First, FEA-based sensitivity studies were conducted to identify key geometric, material and loading parameters influencing tensile strain capacity. The results of these studies were discussed in previous publications [14, 17] and the following key parameters were identified:

Geometric parameters:

1. Pipe Wall thickness
2. Flaw depth

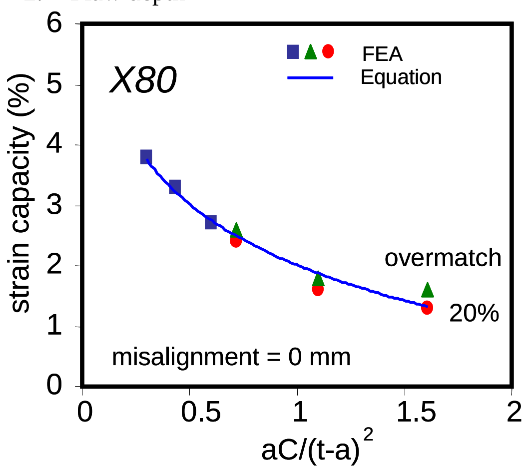

FIGURE 1. TENSILE STRAIN CAPACITY FOR TEARING LIMIT STATE AS A FUNCTION OF NON-DIMENSIONAL PARAMETER

3. Flaw length
4. Misalignment
5. Flaw location (OD/ID, WCL/HAZ)

Material parameters:

1. Pipe Y/T ratio
2. Weld overmatch at UTS
3. Weld/HAZ CTOD R-curve
4. Pipe uniform elongation

Loading parameters:

1. Internal pressure

Second, a large-scale FEA-based parametric study was conducted whereby the above parameters were used to develop generalized, closed-form tensile strain capacity equations for grades X65-X80. Driving force predictions for four different flaw locations (OD HAZ, ID HAZ, OD WCL and ID WCL) revealed that the largest driving force occurred at the ID HAZ flaw location. Hence, this location was chosen as the most conservative on which the FEA-based parametric study was conducted.

Based on the conducted parametric study, a generalized strain capacity equation involving all key parameters can be expressed as follows:

$$\varepsilon_c = f\left(a, C, e, \lambda, t, \frac{Y}{T}, UEL_{pipe}, \delta, \eta, P\right) \tag{1}$$

where, e is the misalignment, C is the half flaw length, a represents the flaw depth, Y is the pipe yield strength, T the pipe UTS, UEL_{pipe} represents uniform elongation of the pipe, λ represents weld overmatch at UTS (in %), P represents pressure, δ and η are the R-curve parameters for a power-law fit [17] and t represents pipe wall thickness.

Further simplification of the generalized Equation (1) is possible by making reasonable assumptions about key parameters such as misalignment, uniform elongation, Y/T and R-curve that will lead to a conservative strain capacity prediction of the different pipe material grades and weld procedures. Such assumptions lead to a simplified equation (2) – shown below – that can be considered analogous to a traditional Level 1 ECA procedure provided in codes for allowable stress design:

$$\varepsilon_c = f(a, C, t, \lambda) \tag{2}$$

Development of simplified strain capacity equations given by Equation (2) for various pipe grades is discussed in detail in later sections of this paper.

There is a need to develop a multi-tiered ECA approach for strain-based design and Equations (1) and (2) can be used for this purpose. Equation (1) can be considered a Level 3 type assessment for the range of parameters considered in the parametric study. More broadly, the underlying FEA approach may be used to conduct a Level 3 type assessment for property or geometry ranges not considered as part of the generalized capacity equation development. Further, the simplified Equation (2) with fewer input parameters may be considered analogous to a Level 1 or 2 ECA approach.

Central to the development of tensile strain capacity equations of the forms (1) and (2) is the identification of a non-dimensional parameter that captures tensile strain capacity trends across various pipe sizes and flaw sizes for all grades. Figure 1 shows an example result from a large parametric study to determine the functional form of Equations (1) and (2). The strain capacity shown in Figure 1 corresponds to the ductile tearing limit state. The ductile tearing tensile strain capacities for three different pipe sizes (OD and WT) with different flaw depths, but identical flaw lengths, have been plotted against the non-dimensional parameter $aC/(t\text{-}a)^2$ assuming identical pipe and weld material properties, flaw location and misalignment. For a fixed flaw length $2C$, the plot suggests a unique relationship between geometric parameters flaw depth a, half-flaw length C, pipe wall thickness t versus the pipe performance parameter, tensile strain capacity: the tensile strain capacities for the three pipe sizes with different flaw depths (fixed flaw length) fall on a single curve. This relationship was found to hold for all the grades (X65-X80) for all levels of misalignment, overmatch levels, R-curves pipe UEL and Y/T ratios and can be expressed as:

$$\varepsilon_c = \beta_1 \ln\left[\frac{aC}{(t-a)^2}\right] + \beta_2 \quad (3)$$

where, β_1 and β_2 are functions of flaw length, misalignment, overmatch, pipe properties and R-curves. Equation (3) becomes asymptotic for very large or very small flaw sizes. This is addressed as follows. First, limits of applicability specified for flaw size parameters in the equation are discussed in the later sections. Additionally, it is noted that for very small flaw sizes, the failure mode will switch from ductile tearing at the flaw to plastic necking in the base pipe away from the flaw and will be predicted by a base pipe plastic collapse equation that is not discussed in this paper. Physically, the non-dimensional parameter $aC/(t-a)^2$ in the ductile tearing Equation (3), represents the ratio of flaw area to the area of the un-cracked ligament (t-a) in the welded pipe. This non-dimensional parameter forms the basis of the tensile strain capacity equation for the fracture limit state.

VALIDATION OF GENERALIZED TENSILE STRAIN CAPACITY EQUATIONS USING FULL-SCALE TEST DATA

Validation of tensile strain capacity equations developed for grades X65-X80 has been based on comparison with full-scale test data. The full-scale data covers a wide range of materials, flaw sizes, flaw type, flaw location, pressure loading, and misalignment. Material grades ranged from X65-X80. To limit material variations and data scatter, all welds were conducted in the 1G-rolled position using the GMAW process. The pipe OD varied from 8 inches to 30 inches. Weld misalignment varied from 0-3 mm and the weld overmatch at UTS varied from 5% to 50%. Flaw locations in these full-scale tests included OD WCL, OD FL, ID WCL and ID FL. All flaws were surface breaking defects. Applied loading was bi-axial and included internal pressure and longitudinal displacement.

Details of the full-scale test program have been previously published [12, 13, 15, 16, 18]. Initial validation of the proposed tangency-based strain capacity prediction methodology using early (limited) full-scale test results has been previously discussed [19] and it was concluded that the predictions agreed well with test results. The initial validation results suggested that proposed approach accounted for the key physical processes governing the strain capacity of welded pipelines. However, developing generalized tensile strain capacity equations based on large FEA based parametric studies allows for further improvement in the prediction capability through calibration of FEA model results to a more complete full-scale database. Such a calibration phenomenologically captures the effects of second order physical processes such as crack deflection and large, near-tip plastic strains etc. not explicitly captured in the FEA method. In order to demonstrate that the generalized equation captures key physical processes, validation of the equations for various grades was completed. The generalized equations were validated by comparing the equation predicted strain capacities against the measured strain capacities from the full-scale pipe strain capacity tests.

The following requirements were considered essential to produce quality, valid comparisons between the equation predictions and the measured tensile strain capacities from full-scale tests:

1. All material properties should be measured using small-scale tests conducted on dedicated companion pipes/welds.
2. All input parameters for each full-scale test should be defined consistently over all tests and grades. Hence, mean values of the input parameters were used to ensure valid comparisons of predictions with measured strain capacities for all full-scale tests, and
3. Both measured tensile strain capacity and the observed failure mode in the full-scale test must be captured by the predictive equations.

With respect to the testing of companion materials, the relevant small-scale tests (longitudinal tensile and SENT) were conducted using carefully selected or prepared pipe and welds. Specimens were extracted as near as possible to the pipe pieces used for full-scale testing and numerous specimens were taken around the circumference to account for statistical variations. The companion welds were all produced by the same equipment and operators on short pipe segments welded to the full-scale specimens and then cut off after welding. CTOD R-curves for WCL and HAZ flaw locations were measured using the SENT test and the details of the SENT test procedure are discussed in a companion paper [20].

Predicted strain capacity for each full-scale test is based on the following inputs to the generalized strain capacity equations:

1. Geometric parameters: nominal pipe geometry, measured misalignment, and machined flaw size.
2. Material property parameters: mean values for pipe *Y/T* ratio, pipe UEL, overmatch at UTS, and R-curve.

Three separate equations have been developed for the three limit states: ductile tearing, plastic collapse in the pipe and plastic collapse in the weld. For each full-scale test, the lowest of the three strain capacities is reported as the tensile strain capacity and the corresponding limit state as the predicted

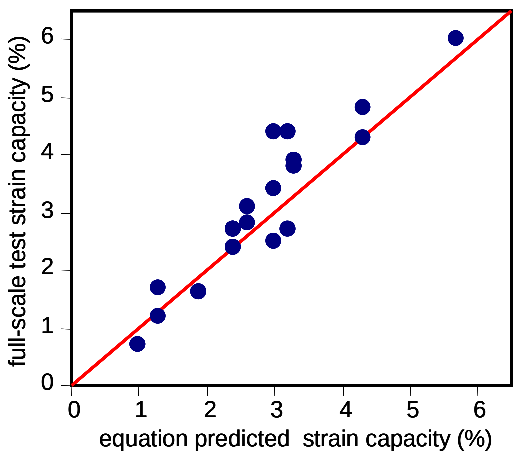

FIGURE 2. VALIDATION OF GENERALIZED TENSILE STRAIN CAPACITY EQUATIONS FOR GRADES X65-X80 USING FULL-SCALE TEST DATA.

failure mode. Figure 2 shows the comparison of measured versus equation-predicted tensile strain capacity for 20 full-scale tests. These results covered pipe grades X65-X80. Currently, efforts are underway to extend the generalized equations to X60.

The comparison in Figure 2 includes test results that failed in either plastic collapse in the pipe or due to ductile tearing at the flaw. The pipe diameters ranged from 8 inches to 30 inches. Weld overmatch at UTS ranged from 5% to 50%, and the misalignment levels ranged from 0-3 mm. The generalized equations predicted the correct failure mode (plastic collapse or ductile tearing) in all full-scale tests.

As part of the validation exercise, the model error was defined as the ratio of equation-predicted capacity to the measured full-scale test capacity. Assuming that the model error for all grades follows the same distribution, a model error distribution for all full-scale tests was determined. The mean and standard deviation of the model error was estimated to be 1 and 0.3, respectively. Figure 2 demonstrates that within the model error, and based on mean material input values, the predicted strain capacities are in good agreement with the measured full-scale test capacities. As expected, some differences exist between predicted and measured capacities. These differences may be due to the uncertainties in material property inputs and/or modeling simplifications. The results in Figure 2 support the validity of the generalized strain capacity equations including the underlying basis: namely, the tangency approach for strain-based design applications.

DEVELOPMENT OF SIMPLIFIED TENISILE STRAIN CAPACITY EQUATIONS FOR X65-X80 GRADES

The complexity of Equation (1) and the amount of input data required to use this equation can be cumbersome relative to many engineering scenarios that would suffice with a simpler approach. In order to produce simplified, yet conservative, closed-form tensile strain capacity equations, Equation (1) was further modified. Conservative assumptions were made regarding the following material and geometric properties: pipe uniform elongation, pipe *Y/T* ratio, misalignment, internal pressure and R-curves. A power-law equation was fitted to the CTOD-Δa R-curve data (in millimeters) for each grade as discussed in detail in a previous paper [17]. The fitting parameters δ and η represent the R-curve inputs to the strain capacity equation, where δ is the power-law fit coefficient and η is the power-law fit exponent. Figure 3 shows a plot of the assumed X65/X70 and X80 R-curves. The selected assumptions for X65, X70 and X80 grades are summarized in Table 1.

TABLE 1 ASSUMPTIONS FOR X65-X80 SIMPIFIED, CONSERVATIVE CAPACITY EQUATIONS

Grade	e (mm)	Pipe Y/T	UEL_{pipe} (%)	R-curve $\delta\times\eta$	Pressure (% SMYS)
X65,X70	3	0.9	8	1×0.6	80
X80	3	0.93	6	1×0.2	80

Assumptions for Capacity Equations:

The following assumptions were made while developing the tensile strain capacity equations:

1. The flaw location was assumed to be ID HAZ to ensure a conservative estimate of driving force.
2. A uniform 5% HAZ softening was assumed for X80 grade and zero HAZ softening/hardening was assumed for X65/X70 grades.
3. Crack growth path was conservatively assumed to be nominally straight and perpendicular to the applied displacement. This assumption leads to a conservative prediction of tensile strain capacity.
4. Idealized pipe and weld stress-strain curves (Ramberg-Osgood fits) were assumed to reduce the number of material property inputs.
5. Previous sensitivity studies have shown that pipe OD and weld uniform elongation have a small impact on tensile strain capacity [14, 17]. Therefore, these parameters were not included in the generalized/simplified equations.
6. Isotropic, uniform pipe and weld material properties were assumed.
7. SENT R-curves were idealized by a power law fit [17].
8. Weld uniform elongation (longitudinal) is assumed to at least equal to the base pipe uniform elongation.
9. The equations assume isolated weld defects i.e. no flaw interaction is assumed.

The conservative assumptions above and the assumptions listed in Table 1 lead to a simplified equation for the ductile tearing limit state. This equation is analogous to a Level 1 ECA assessment and can be expressed in the following form:

$$\varepsilon_c = [(x_1\lambda + x_2)C + x_3\lambda + x_4]\ln\left[\frac{aC}{(t-a)^2}\right] + (x_5\lambda + x_6)C + x_7\lambda + x_8 \qquad (4)$$

where, a is the flaw depth, C is the half-flaw length, λ is weld overmatch at UTS in % (e.g.: 5 and not 0.05 for a 5% overmatch at UTS) and t is the pipe wall thickness. The coefficients $x_1,\ldots, x_8$ represent constants for the conservative assumptions made for grades X65-X80. The form of the tensile strain capacity equations (for the tearing limit state) given by

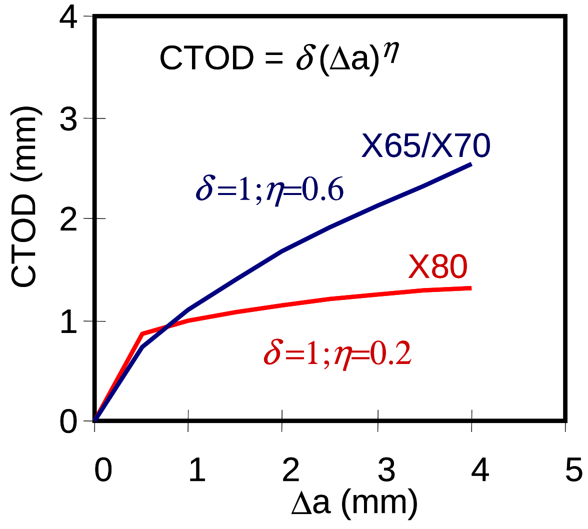

FIGURE 3. PLOT OF THE ASSUMED X65 AND X80 R-CURVES. POWER LAW FIT IS USED TO INPUT THE R-CURVES IN THE STRAIN CAPACITY EQUATIONS.

Equation (4) is identical for all the grades. The constants x_1,..., x_8 are summarized in Table 2. The constants x_1,…, x_8 are identical for grades X65 and X70 making the equations identical for the two grades. The constants for X80 grade are different from those for X65/X70 due to the assumption of 5% HAZ softening, see Table 2.

TABLE 2 COEFFICIENTS FOR X65-X80 SIMPLIFIED EQUATIONS (ASSUMING R-CURVES PER TABLE 1)

Grade	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
X65, X70	2×10^{-4}	-0.02	-9×10^{-3}	0.05	0.001	-0.06	-0.01	1.8
X80	8×10^{-4}	0.001	-0.03	-0.2	0.002	-0.004	-0.023	0.3

Limits of applicability exist for the simplified Equations (4) for all grades (X65-X80) and are summarized below:

$$\begin{array}{ll} 3\text{mm} \le a \le 5\text{mm} & \\ 20\text{mm} \le 2C \le 50\text{mm} & \\ e \le 3\text{mm} & \\ 15\text{mm} \le t \le 26\text{mm} & \\ \text{pipe } Y/T \le 0.9 & \text{for X65/70} \\ \text{pipe Y/T} \le 0.93 & \text{for X80} \\ UEL_{pipe} \ge 8\% & \text{for X65/X70} \\ UEL_{pipe} \ge 6\% & \text{for X80} \\ 5\% \le \lambda \le 50\% & \text{for X65/X70} \\ 5\% \le \lambda \le 20\% & \text{for X80} \\ P \le 80\% SMYS & \end{array} \quad (5)$$

In addition to (5), the following limits apply to the R-curve parameters δ and η for X65, X70 and X80 grades:

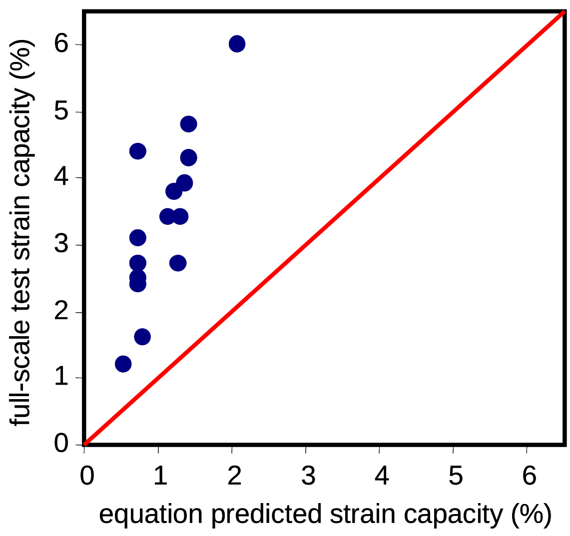

FIGURE 4. COMPARISON OF FULL-SCALE TEST CAPACITY WITH PREDICTED STRAIN CAPACITY USING THE SIMPLIFIED CONSERVATIVE EQUATION.

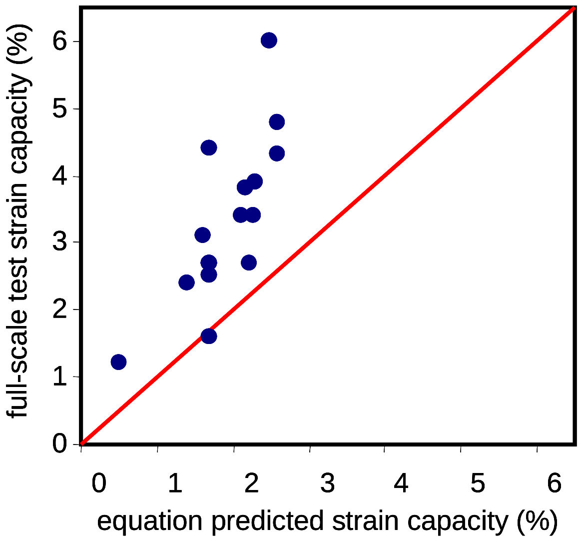

FIGURE 5. COMPARISON OF FULL-SCALE TEST CAPACITY WITH PREDICTED STRAIN CAPACITY USING TEST SPECIFIC MISALIGNMENT, BUT CONSERVATIVE R-CURVES, PIPE Y/T AND UEL PER TABLE 1.

$$\begin{array}{ll} \delta \ge 1; \eta \ge 0.6 & \text{for X65, X70 only.} \\ \delta \ge 1; \eta \ge 0.2 & \text{for X80 only.} \end{array} \quad (6)$$

The simplified equations (4) for X65-X80 grades are applicable only to those welding procedures that ensure the CTOD R-curves are equal or better than the R-curves shown in Figure 3 or given by Equation (6).

Figure 4 shows a comparison of equation-predicted tensile strain capacities using simplified conservative Equation (4) and the measured capacities from the X65-X80 full-scale tests presented in Figure 2. The simplified equations for X65-X80 grades leads to a conservative prediction of full-scale test capacities.

The conservatism of Equation (4) seen in Figure 4 is primarily due to two factors: (a) misalignment = 3 mm, and (b) the assumed R-curve. Figure 5 shows the effect of changing the misalignment for all the tests from the conservative 3 mm in Equation (4) to test-specific misalignment. Figure 5 shows that the changed misalignment assumption produces reduced conservatism in the capacity predictions. Figure 6 shows the comparison of predicted capacities with full-scale test capacities when both misalignment and R-curves are test-specific. The conservatism is further reduced.

Figures 5 and 6 demonstrate that the conservatism in the simplified equations (Figure 4) is driven primarily by the choice of misalignment and R-curves. In actual pipeline project scenarios, when it is impractical to use restricted misalignment (< 3 mm) as a design parameter, the 3mm misalignment assumption may be appropriate due to typical construction tolerances. Further, weld R-curves will depend on the specific welding procedures and project-specific data may not be available in the initial stages of a project. In such scenarios it may be desirable to use a reasonably conservative R-curve such as shown in Figure 3 to develop simplified equations which can be used for screening level studies and ECA applications.

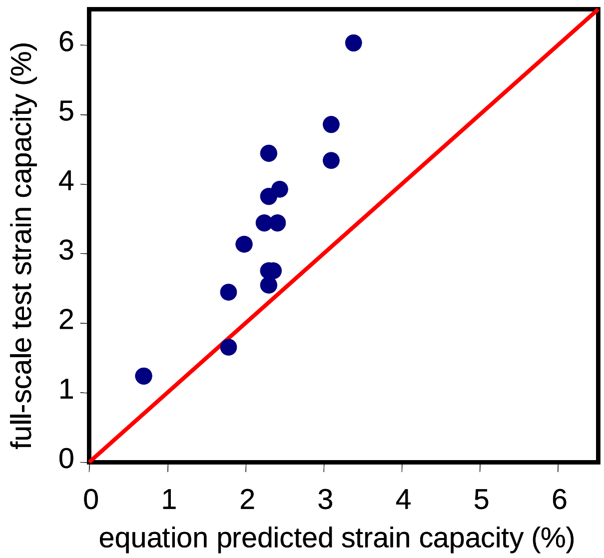

FIGURE 6. COMPARISON OF FULL-SCALE TEST CAPACITY WITH PREDICTED STRAIN CAPACITY USING TEST SPECIFIC MISALIGNMENT AND R-CURVES, BUT CONSERVATIVE PIPE Y/T AND PIPE UEL PER TABLE 1.

EXAMPLE APPLICATIONS OF SIMPLIFIED TENISILE STRAIN CAPACITY EQUATIONS FOR X65-X80 GRADES

Within their limits of applicability, the simplified equations for X65-X80 grades can be used to develop conservative estimates of tensile strain capacities as a function of various parameters. In Figure 7, the tensile strain capacity for an X80 pipe has been predicted using Equation (4) and is plotted against the non-dimensional parameter $aC/(t\text{-}a)^2$ for two overmatch levels: 5% and 15%. As throughout this paper, overmatch is defined at UTS. These curves demonstrate how the predicative equations can be used to facilitate rapid optimization of flaw depth, flaw length, pipe wall thickness and weld overmatch for strain-based design applications.

Figure 8 shows an example failure assessment diagram (FAD) developed for an X80 pipe with 20 mm WT using Equation (4). The plot in Figure 8 is specific to the conservative assumptions for X80 summarized in Table 1 and is for ductile tearing limit state only. This is due to the assumed R-curve for X80 grade shown in Figure 3. A target strain capacity of 1% was assumed for illustration and flaw sizes ($a \times 2C$) were estimated at two different overmatch levels, 10% and 15%. The bounding curves at each overmatch level generate the boundary for flaw acceptance within the limits of applicability for flaw depth (3-5mm) and flaw length (20-50mm). The cut-off lines bounding the FADs are based on the flaw depth and flaw length limits summarized in Equation (5). The example in Figure 8 shows that it is possible to develop conservative failure assessment diagrams for various grades using the simplified tensile strain capacity Equations (4).

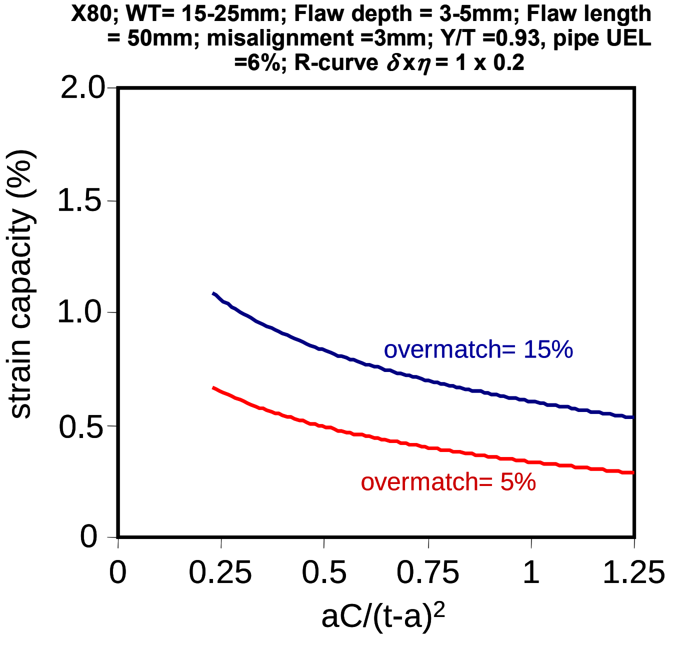

FIGURE 7. TENSILE STRAIN CAPACITY (FROM SIMPLIFIED EQUATIONS) AS A FUNCTION OF PROPOSED NON-DIMENSIONAL PARAMETER.

DISCUSSION

Presently, no single code provides complete guidance on assessment of girth welds for strain-based design. Development of any strain capacity codified method will be faced with a significant challenge to account for multiple variables, but still provide an easy-to-use, conservative assessment method. Development of strain-based ECA procedures can benefit from considering approaches already developed for conventional stress-based fracture assessments. The stress-based assessments serve as a close analog in terms of the number and variables that need to be considered. Industry codes such as BS7910 [10] and

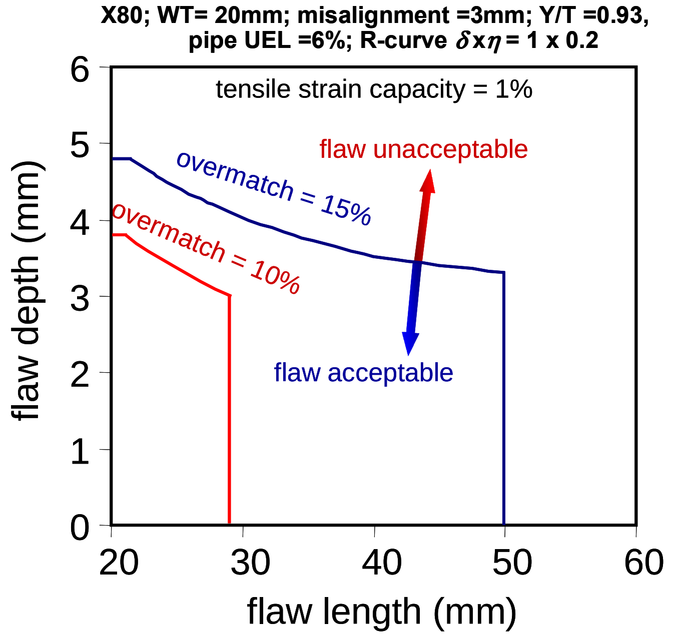

FIGURE 8. EXAMPLE FAILURE ASSESSMENT DIAGRAMS (FADs) FROM THE SIMPLIFIED CONSERVATIVE STRAIN CAPACITY EQUATIONS.

API579 [11] provide guidance for three levels of assessment. Although there are differences between BS7910 and API579, the basic principle for the various assessment levels remains the same. The complexity of the analysis is increased from Level 1 to Level 3 by progressively allowing users to characterize material properties and geometric parameters. This avoids the use of conservative, simplifying assumptions used to develop the lower level assessments. For example, API579 Level 1 procedures are intended to provide conservative screening criteria that can be utilized with a minimum amount of inspection or component information. Level 2 procedures are more detailed and precise: Level 2 procedures require the use of specific material stress-strain information. Level 3 is intended to provide the most detailed evaluation, is more precise than Level 2, and the recommended analysis is based on numerical techniques such as the finite element method.

Multi-tier approaches similar to traditional ECA procedures are needed for strain-based design of pipelines. The generalized Equation (1) and the simplified Equation (4) provide a multi-tiered approach for strain-based ECA (SBECA).

To generate a robust SBECA methodology, additional considerations beyond the development of easy-to-use equations are required. For example, the predictive equations require calibration to ensure an appropriate safety margin between strain capacity and strain demand. The safety margin and corresponding safety factors should be aligned with the code assumptions relative to probabilities of failure. In addition, the standard needs to address inspection criteria that are aligned with the use of the equations and safety factor assumptions.

It is noted that while the Equation (4) permits use of low weld overmatch levels at UTS and assumes low weld/HAZ R-curve toughness as shown in Figure 3, significantly high overmatch levels and R-curve tearing resistance are needed in practice to achieve large strain capacity. The use of Equation (4) should be limited to screening level studies and fitness for purpose assessments only. While it is possible to use the simplified Equation (4) for a limited Monte Carlo simulation using only four parameters, namely, pipe WT, flaw length, flaw depth and overmatch at UTS, the resulting strain capacity distribution from such as a Monte Carlo study will be conservative. The generalized Equation (1) or a case-specific FEA assessment enables detailed design through reliability-based design approaches. Additional issues for strain-based design and the role of the developed strain capacity prediction equations, as well as the FEA approach, are discussed in a companion paper [21].

CONCLUSIONS

In this paper, closed-form, generalized strain capacity equations developed through a large-scale 3D FEA-based parametric study for welded pipelines were presented. A non-dimensional parameter relates the influence of flaw and pipe geometry parameters to tensile strain capacity. The non-dimensional parameter was shown to be applicable to various grades, various pipe sizes, flaw sizes, etc. The predictive strain capacity equations were validated using full-scale, pressurized pipe tests for grades X65-X80. These tests spanned a range of pipe sizes, flaw sizes, pipe and weld material properties, pressures and misalignment values. The equation predictions were shown to be in good agreement with the full-scale tests across all grades. The generalized equations and the FEA approach are candidates for a Level 3 ECA assessment procedure. Simplified strain capacity prediction equations were produced by making conservative assumptions regarding certain input parameters. It was shown through various examples that these simplified equations are candidates for a Level 1 ECA assessment procedure for strain-based design applications.

ACKNOWLEDGMENTS

The authors wish to thank the management of ExxonMobil Upstream Research Company and the ExxonMobil Development Company for their support in this work and permitting the release of this paper.

REFERENCES

1. Linkens, D., Formby, C.L., and Ainsworth, R.A., 2000, “A Strain-based Approach to Fracture Assessment – Example Applications,” *Proc. 5th International Conference on Engineering Structural Integrity Assessment*,
2. Wang, Y.Y., Rudland. D., Denys, R., Horsley, D., 2002, “A Preliminary Strain-based Design Equation For Pipeline Girth Welds,” *Proc. 4th International Pipeline Conference*, Calgary, Alberta, Canada, pp. 415-427.
3. Wang, Y.Y., Cheng, W., Horsley, D., 2004, “Tensile Strain Limits of Buried Defects in Pipeline Girth Welds”, *Proc. 4th International Pipeline Conference*, Calgary, Alberta, Canada, pp. 1-8.
4. Wang, Y.Y., Liu, M., Horsley, D., Zhou, J., 2006, “A Quantitative Approach for Tensile Strain Capacity of Pipelines”, *Proc. 6th International Pipeline Conference*, Calgary, Alberta, Canada, pp. 1-8.
5. Mohr, W., Gordon, R., Smith, R., 2004, “Strain-based Design Guidelines for Pipeline Girth Welds”, *Proc. 4th International Offshore and Polar Engineering Conference*, Toulon, France, pp. 10-17.
6. Liu, M., Wang, Y.Y., 2007, “Significance of Biaxial Stress on the Strain Concentration and Crack Driving Force in Pipeline Girth Welds with Softened HAZ, *Proc. 26th International Conference on Offshore Mechanics and Arctic Engineering*, San Diego, CA, USA , pp. 1-10.
7. Tyson, W.R., Shen, G., Roy, G.., 2007, “Effect of Biaxial Stress on ECA of Pipelines under Strain-based Design”, *Proc. 17th International Offshore and Polar Engineering Conference*, Lisbon, Portugal, pp. 3107-3113.
8. Østby, E., Hellesvik, A.O., 2007, “Fracture Control – Offshore Pipelines JIP Results from Large Scale Testing of the Effect of Biaxial Loading on the Strain Capacity of Pipelines with Defects”, *Proc. 17th International Offshore and Polar Engineering Conference*, Lisbon, Portugal, pp. 3231-3237.
9. Sandvik, A., Østby, E., Thaulow, C., 2008,“A Probabilistic Fracture Mechanics Model including 3D Ductile Tearing of Bi-axially Loaded Pipes with Surface Cracks”, *Engg. Frac. Mech.*, 75, pp 76-96.
10. BS7910:2005 Guidance on Methods for Assessing Acceptability of Flaws in Fusion Welded Structures.

11. API. Recommended Practice for Fitness-For-Service. API 579. American Petroleum Institute, 2007.
12. Minnaar, K., Gioielli, P. C., Macia, M., Bardi, F., Biery, N., Kan, W., 2007, “Predictive FEA Modeling of Pressurized Full-Scale Tests”, *Proc. 17th International Offshore and Polar Engineering Conference,* Lisbon, Portugal, pp. 3114-3120.
13. Gioielli, P. C., Minnaar, K., Macia, M., Kan, W. C., “Large-Scale Testing Methodology to Measure the Influence of Pressure on Tensile Strain Capacity of a Pipeline”, *Proc. 17th International Offshore and Polar Engineering Conference*, Lisbon, Portugal, pp. 3023-3027.
14. Kibey, S., Minnaar, K., Issa, J., Gioielli, P., 2008, “Effect of Misalignment on the Tensile Strain Capacity of Welded Pipelines”, *Proc. 18th International Offshore and Polar Engineering Conference*, Vancouver, Canada, pp. 90-95.
15. Gioielli, P.C., Cheng, W., Minnaar, K., Fairchild, D.P., 2008, “Characterization of Stable Tearing During Pipeline Strain Capacity Tests”, *Proc. 18th International Offshore and Polar Engineering Conference,* Vancouver, Canada, pp. 86-89.
16. Cheng, W., Gioielli, P.C., Tang, H., Minnaar, K., Macia, M.L., 2009, “Test Methods for Characterization of Strain Capacity – Comparison of R-curves from SENT/CWP/FS Tests”, *Proc. 5th Pipeline Technology Conference*, Ostend, Belgium.
17. Kibey, S., Issa, J., Wang, X., Minnaar, K., 2009, “A Simplified Parametric Equation for Prediction of Tensile Strain Capacity of Welded Pipelines”, *Proc. 5th Pipeline Technology Conference*, Ostend, Belgium.
18. Kibey, S., Minnaar, K., Cheng, W., Wang, X., 2009, “Development of a Physics-based Approach for the Prediction of Strain Capacity of Welded Pipelines”, *Proc. 19th International Offshore and Polar Engineering Conference*, Osaka, Japan, pp 132-137.
19. Wang, X., Barbas, S.T., Kibey, S., Gioielli, P.C., Minnaar, K., 2009, “Validation of Strain Capacity Prediction Method – Comparison of Full-Scale Test Results to Predictions from Tearing Analysis Based on FEA”, *Proc. 5th Pipeline Technology Conference*, Ostend, Belgium.
20. Tang, H., Minnaar, K., Kibey, S., Macia, M.L., Gioielli, P.C., Fairchild, D.P., 2010, “Development of SENT Test Procedure for Strain-Based Design of Welded Pipelines”, *Proc. 8th International Pipeline Conference*, Calgary, Alberta, Canada.
21. Macia, M., Kibey, S., Arslan, H., Bardi, F., Ford, S.J,, Kan, W.C., Cook, M.C., Newbury, B., 2010, “Approaches to Qualify Strain-based Designed Pipelines”, *Proc. 8th International Pipeline Conference*, Calgary, Canada.

