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Strain-based Design—Advances in Prediction Methods of Tensile Strain Capacity

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In recent years, ExxonMobil has undertaken a comprehensive experimental and numerical program to characterize tensile strain capacity of welded pipelines under different operational, geometric and material property conditions. Key parameters affecting tensile strain capacity have been identified through sensitivity studies and used in a large-scale FEA-based parametric study to develop closed-form tensile strain capacity equations for different limit states. A key parameter affecting tensile strain capacity of welded pipelines is the tearing resistance (CTOD R-curve). Small-scale testing techniques have been developed to characterize the tearing resistance (R-curve) of full-scale pipelines using single edge notched tension (SENT) specimens. Experimental and numerical results have shown that the SENT R-curves closely match the full-scale test R-curves. The generalized tensile strain capacity equations have been validated against 20 full-scale tests for pipe grades X65 to X80 grades. The equations correctly predict the observed failure mode in the full-scale tests as well as the tensile strain capacity. Simplified, conservative tensile strain capacity equations with fewer parameters have been developed by making reasonable assumptions for several key parameters. The generalized and simplified tensile strain capacity equations can form the basis of a multi-tier engineering critical assessment (ECA) procedure for strain-based design of welded pipelines.

INTRODUCTION

Pipelines operating in arctic and seismically active regions may be subjected to large ground movement that can lead to large plastic deformation in the pipelines. Deepwater flowline may also experience large lateral displacement in start-up and shut-down operations due to thermal and pressure variations. Traditional allowable stress design methods address scenarios where the global response is mainly elastic and may not be sufficient for design of pipelines experiencing large strains in challenging arctic and seismic conditions. There is a need to develop methods for pipeline design beyond yield, commonly termed strain-based design. These methods facilitate prediction of the tensile strain capacity of pipelines from a given set of geometry and material properties. This paper presents an overview of the tensile strain capacity prediction methodology recently developed by ExxonMobil. This methodology includes: An FEA-based tensile strain capacity prediction approach addressing all relevant limit states (ductile tearing and plastic collapse), closed-form, generalized tensile strain capacity equations for relevant limit states, and small-scale SENT testing procedure for tearing resistance measurement of full-scale welded pipes.

In recent years, increasing attention has been given to development of strain-based design methodologies for welded pipelines (Linkens, Formby and Ainsworth, 2000; Wang, Rudland, Denys and Horsley, 2002; Wang, Cheng and Horsley, 2004; Wang, Liu, Horsley and Zhou, 2006; Mohr, Gordon and Smith, 2004; Liu and Wang, 2007; Tyson, Shen and Roy, 2007; Østby and Hellesvik, 2007; Sandvik, Østby and Thaulow, 2008). These and other studies have served to gain understanding of the effect of various factors on strain capacity. For example, Wang, Rudland, Denys and Horsley (2002) and Wang, Liu, Horsley and Zhou (2006) related strain capacity to the following parameters: flaw depth, flaw length, yield-to-tensile (Y/T) ratio, weld overmatch, apparent crack-tip opening displacement (CTOD) toughness and weld cap height. Sandvik, Østby and Thaulow (2008) correlated tensile strain capacity of plain pipes to defect size, material strain hardening and biaxial loading.

ExxonMobil has undertaken a comprehensive experimental and numerical program to develop insights into characterization of the tensile strain capacity of welded pipelines. The program was conducted in various phases, including full-scale test development, prediction methodology, small-scale testing development and validation. A summary of published literature describing these phases appears below.

Details of large-scale testing techniques using unloading compliance to measure crack growth were published in the First Strain-based Design Symposium held at the 2007 ISOPE Conference in Lisbon. The testing program described the use of full-scale pressurized pipe tests to measure strain capacity and the use of curved wide plate tests (CWPT) to study weld performance and tearing resistance behavior (R-curve) (Gioielli, Minnaar, Macia and Kan, 2007; Fairchild, Cheng, Ford, Minnaar, Biery, Kumar and Nissley, 2007; Kibey, Minnaar, Issa and Gioielli, 2008; Lillig, 2008; Fairchild, Crawford, Cheng, Macia, Nissley, Ford, Lillig and Sleigh, 2008; Gioielli, Cheng, Minnaar and Fairchild, 2008; Kan, Weir, Zhang, Lillig, Barbas, Macia and Biery, 2008). The experimental results showed that internal pressure does not significantly influence the full-scale plain pipe tearing resistance (R-curve).

Numerical analysis by Minnaar, Gioielli, Macia, Bardi, Biery and Kan (2007) showed that pressure significantly influences crack growth driving force but does not affect the material resistance to crack growth (R-curve). Their work also showed that tangency of full-scale R-curves and full-scale pipe driving force can be used to estimate the tensile strain capacity of pipes. Kibey,

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KEY WORDS: Pipeline tensile strain capacity, fracture mechanics, strain-based design, tearing resistance, full-scale pipeline tensile test, model validation, single edge notched tension (SENT) specimen.

Minnaar, Issa and Gioielli (2008) numerically investigated the effect of geometric factors such as wall thickness (WT), misalignment, flaw size, pipe diameter etc. on the tensile strain capacity of welded pipelines. Their numerical analyses showed that weld misalignment significantly reduces the tensile strain capacity of welded pipelines and may also cause a change in the failure mode from plastic collapse in base pipe to ductile tearing in the weld. A generalized FEA-based tensile strain capacity prediction methodology based on tangency analysis was presented recently (Kibey, Minnaar, Cheng and Wang, 2009; Kibey, Issa, Wang and Minnaar, 2009). This work demonstrated that:

- The methodology accounted for all relevant limit states, that is, weld/pipe plastic collapse and ductile tearing;
- Tangency of 3D FEA-based driving force and measured R-curves using SENT can be used to estimate the tensile strain capacity for ductile tearing limit state.

Subsequent work based on the physics approach was used to develop a simplified parametric equation presented by Kibey, Issa, Wang and Minnaar (2009).

Recently published results of single edge notched tensile (SENT) tests suggest that the SENT specimen can be used to characterize the tearing resistance R-curve for full-scale tests (Cheng, Tang, Gioielli, Minnaar and Macia, 2009). Both experimental and numerical studies were conducted to characterize R-curves of pipelines and to develop testing techniques correlating R-curves of SENT specimens with those of full-scale tests. The results indicate that the R-curve behavior measured by SENT tests is similar to the R-curve behavior measured during full-scale tests. This important result allows the use of small-scale testing results to be used in the strain capacity prediction methodology to predict the strain capacity of pressurized pipelines.

Initial validation of the proposed capacity prediction methodology was completed by comparing strain capacity predictions to full-scale pressurized test results. Results from the validation program showed good agreement between the predicted strain capacity from the FEA-based strain capacity prediction method and the measured strain capacity from the full-scale tests (Wang, Barbas, Kibey, Gioielli and Minnaar, 2009).

This paper provides an overview of key findings published in the papers above and provides details of recent developments to further the development of the tensile strain capacity prediction technology for welded pipelines. Subsequently, readers are referred to the collection of papers presented above for details of the discussion to follow. Where new material is presented, specific reference will be made to relevant publications. Specifically, this paper provides an overview of recently developed closed-form generalized tensile strain capacity equations, their validation using full-scale tests and development of a SENT test procedure to measure the R-curve that can be used as input for predicting tensile strain capacity of welded pipelines.

PREDICTION OF FULL-SCALE TEST TENSILE STRAIN CAPACITY USING SMALL-SCALE TEST DATA

Numerical analysis reported previously showed that 2 physical processes control the tensile limit state: ductile fracture and plastic collapse. Two modes exist for plastic collapse. The first, localization (necking), occurs at the flaw location in the remaining WT ligament in the weld region. The second mode occurs if sufficient fracture toughness and weld overmatch exist to protect the weld from strain localization and moves the localization into the parent pipe material away from the weld location. A key weld material parameter influencing the interaction between the failure modes—ductile tearing at the weld and plastic collapse in base pipe—is the tearing resistance (R-curve). Significant effort has been devoted to the development of the R-curve measurement procedure which is summarized below.

CHARACTERIZATION OF TEARING RESISTANCE

Tearing resistance of weld/HAZ material is an important property affecting the tensile strain capacity of welded pipelines, and it is a key input to the tensile strain capacity prediction approach. Key findings supporting the use of SENT tests for strain capacity prediction are summarized below.

Effect of Pressure and Misalignment on R-Curve

Both experimental and numerical results have shown that internal pressure does not affect tearing resistance of full-scale plain pipes and welded pipes. Fig. 1 shows that the R-curves from 2 welded X65 full-scale tests with different testing pressures are similar. The 2 tests were conducted with internal pressures corresponding to hoop stresses equal to 40% and 80% of the pipe material yield strength (YS). Non-dependence of R-curves on pressure has also been reported by Østby and Hellesvik (2007). Crack growth is estimated from the frequent measurements of compliance. Other methods, such as epoxy implant and potential variation during tests, have been used successfully by others.

Experimental full-scale R-curve results also showed that misalignment has limited influence on the CTOD R-curve of welded pipelines (Cheng, Tang, Gioielli, Minnaar and Macia, 2009). As shown in Fig. 2, the R-curves from two X65 welded full-scale tests with no misalignment and with 1-mm misalignment are similar. The difference between the measured R-curves in Fig. 2 is within the scatter associated with material variability and is not attributed to misalignment. The tensile strain capacity of welded pipelines, however, is strongly influenced by internal pressure and misalignment. This is because the crack growth driving force is significantly influenced by misalignment and pressure.

The observation that R-curves of full-scale pipelines are not significantly affected by pressure and misalignment promoted the development of small-scale SENT testing techniques to characterize the tearing resistance of pipelines, which is discussed next.

SENT Specimen Configuration

The experimental and numerical work reported by Tang, Minnaar, Kibey, Macia, Gioielli and Fairchild (2010) discussed in

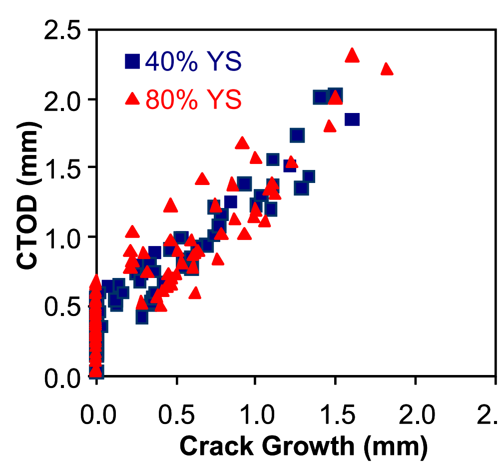

Fig. 1 Comparison of R-curves from 2 welded X65 full-scale tests with different testing pressures

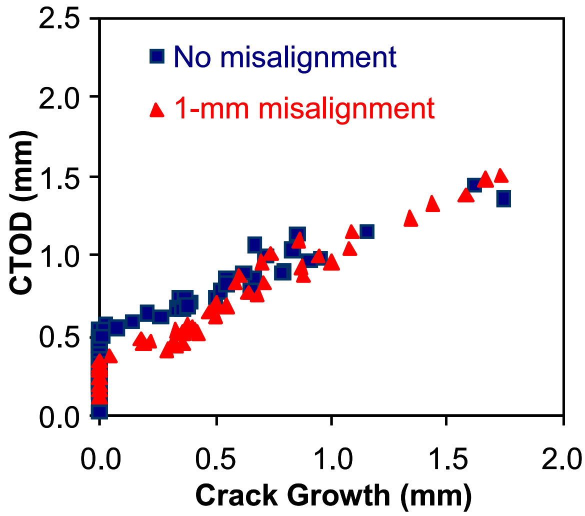

Fig. 2 Comparison of R-curves from two X65 full-scale tests with and without misalignment

detail the influence of specimen geometry, initial notch depth-to-specimen height ratio (a_0/W) and notch location on R-curve behavior. These results were used to develop the basis of a SENT testing procedure that may be used for standards development. Key results are summarized here.

For R-curve measurement, longitudinally oriented SENT specimens are machined around the circumference of a girth-welded pipe. The specimen sizes are thus limited by the pipe wall thickness and curvature. It can become difficult to machine specimens with a B = 2W cross-section from small-diameter pipes. Hence it is useful to determine the applicability of SENT specimen geometries with B < 2W. In addition, the experimental study has shown that side-grooves on both sides of the B × B SENT specimens can be used to elevate the constraint level in the region close to the free surfaces and promote an even crack growth. This finding is supported by the numerical studies completed to investigate the influence of specimen geometry (Tang, Minnaar, Issa, Cheng and Pakal, 2010). Fig. 3 shows the good agreement between the R-curve measured from B = W with side-groove configuration and that from B = 2W configuration. Both SENT specimens were extracted from the same plain pipe.

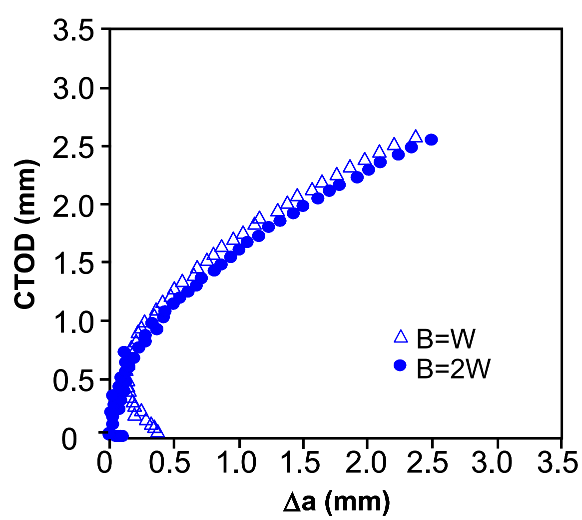

Fig. 3 Comparison of R-curves measured with 2 SENT specimen configurations: B = 2W configuration and B = W with side-grooves

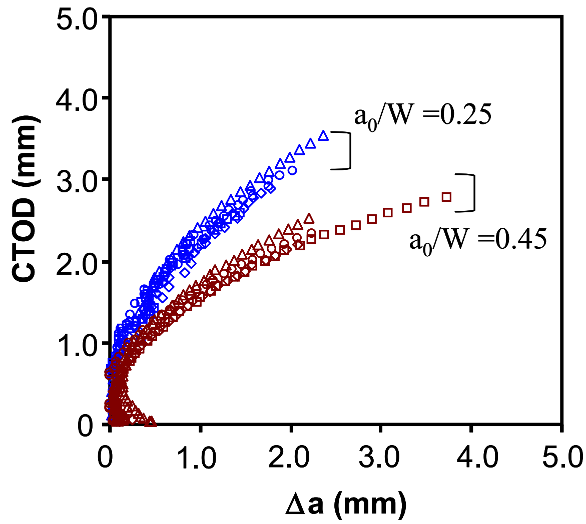

Fig. 4 Comparison of SENT R-curves extracted from pipe but with different a_0/W ratios

Another important factor studied was the influence of initial notch depth-to-specimen height ratio (a_0/W) on R-curve behavior. Fig. 4 compares the difference between the measured R-curves of SENT specimens with 2 different a_0/W ratios. All specimens were extracted from the same pipe material. One configuration had a smaller a_0/W ratio of 0.25, and the other a larger ratio of 0.45. Fig. 4 shows that specimens with a_0/W of 0.25 provided higher tearing resistance than those with a_0/W of 0.45. This result also suggests that the initial a_0/W ratio needs to be carefully selected to ensure that the SENT R-curve will adequately match the full-scale R-curve behavior. Additional studies showed that the R-curves for SENT and full-scale tests match closely if the a_0/W ratio for the SENT test is larger than the target a_0/t ratio in the full-scale test by an amount of 0.1.

Comparison of R-Curves from SENT Specimens to Full-Scale Pipes

Fig. 5 compares the R-curves measured from 6 SENT tests and 5 full-scale tests with 4 notches in each test on welded X65 pipes. The 5 full-scale tests were conducted under different combinations of internal pressure and misalignment. The comparison

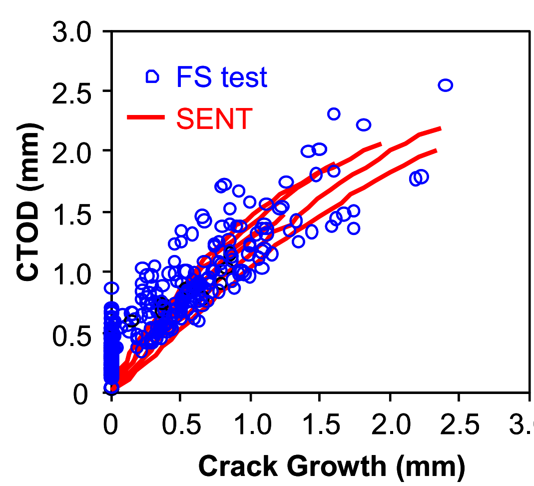

Fig. 5 Comparison of measured R-curves from full-scale (FS) and SENT tests on welded X65 pipes

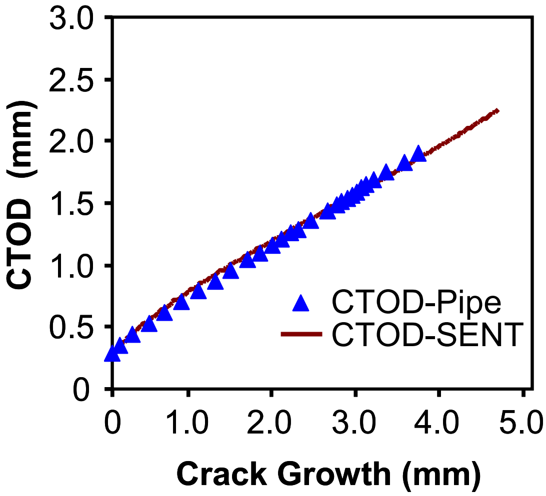

Fig. 6 Comparison of calculated CTOD-R curves between SENT specimen and full-scale pipe

shows that the R-curves measured from full-scale tests agree well with those from SENT tests. Consistently good agreement has also been observed between full-pipe and companion SENT R-curve in all other full-scale tests with OD ranging from 8 in to 30 in and pipe grades X65 to X80. These results support the use of SENT testing for R-curve measurement of full-scale welded pipes and for use as input for tensile strain capacity prediction. This also shows that an adequate number of representative SENT tests is required to capture the statistics of the R-curves for practical applications.

As a parallel effort to the testing program, the damage mechanics- based finite element (FE) analyses were performed to support the development of SENT testing procedure for measurement of full-scale welded pipe R-curves. The GTN model (Gurson, 1997; Tvergaard and Needleman, 1984), which accounts for the effects of void growth and coalescencence, was used to simulate crack growth. Details of the finite element modeling are given in Tang, Minnaar, Issa, Cheng and Pakal (2010). Fig. 6 compares the calculated CTOD-R curves of the SENT specimen to those of the full-scale pipe—both based on the damage mechanics-based FE simulations. The 2 numerically calculated CTOD-R curves—the SENT specimen and the full-scale pipe—are seen to be in good agreement. This provides additional numerical evidence that SENT specimens are suitable to be used for the characterization of tearing resistance of full-scale pipes.

KEY PARAMETERS AFFECTING TENSILE STRAIN CAPACITY

FEA-based sensitivity studies using the tangency approach were used to identify key parameters affecting tensile strain capacity. The parameters were classified into 3 categories: material parameters, geometric parameters and operational/loading parameters. They are briefly discussed below.

Effect of Material Parameters on Tensile Strain Capacity

The following key material parameters were identified: Pipe Y/T ratio, pipe UEL, weld overmatch at UTS and R-curve. The effect of R-curve on tensile strain capacity was captured through 2 fitting parameters. The CTOD R-curve measured from SENT specimens was idealized as a power-law fit with δ as the fitting coefficient parameter and η as the fitting exponent parameter. A sensitivity study showed that increase in geither δ or η led to an increase in tensile strain capacity.

Effect of Geometric Parameters on Tensile Strain Capacity

Tensile strain capacity of welded pipelines was found to depend strongly on wall thickness, flaw depth and flaw length, but it exhibited a weak dependence on pipe outer diameter. Tensile strain capacity increases with wall thickness, but decreases with flaw depth and flaw length. The effect of misalignment on the tensile strain capacity of X65 and X80 welded pipelines was found to be twofold: Misalignment reduced the strain capacity, and it changed the failure mode from plastic collapse in the base pipe to plastic collapse in the vicinity of the weld region, provided the tearing resistance of the weld region was high enough to prevent failure due to ductile tearing. In the absence of a high enough tearing resistance, misalignment changed the failure mode from necking in the base pipe to ductile tearing at the weld/HAZ flaw.

Effect of Loading/Operational Parameters on Tensile Strain Capacity

It is known from both numerical and experimental investigations that an increase in the internal pressure reduces the ductile tearing strain capacity (Mohr, Gordon and Smith, 2004; Liu and Wang, 2007; Tyson, Shen and Roy, 2007; Østby and Hellesvik, 2007; Gioielli, Minnaar, Macia and Kan, 2007; Minnaar, Gioielli, Macia, Bardi, Biery and Kan, 2007).

All of the above key geometric and material parameters have been included to develop generalized tensile strain capacity equations for welded pipes (X65 to X80), and they are discussed below.

GENERALIZED TENSILE STRAIN CAPACITY EQUATION FOR WELDED PIPELINES

Development of generalized, closed-form parametric tensile strain capacity equations for grades X65 to X80, including all key geometric and material parameters discussed above, was presented in a recent paper (Kibey, Wang, Minnaar, Macia, Fairchild, Kan, Ford and Newbury, 2010). The developed generalized strain capacity equations are of the form:

$$\varepsilon_c = f(a, C, e, \lambda, t, Y/T, UEL_{\text{pipe}}, \delta, \eta, P) \qquad (1)$$

where e is the misalignment; C, the half flaw length; a, the flaw depth; Y, the pipe yield strength; T, the pipe UTS; UEL_{pipe}, the uniform elongation of the pipe; λ, the weld overmatch at UTS; P, the pressure; δ and η, the R-curve parameters from a power-law fit; and t, the pipe wall thickness.

A nondimensional geometric parameter was identified to develop the generalized Eq. 1. Fig. 7 shows an example result from the large-scale parametric study conducted to determine the functional form of Eq. 1. The strain capacity shown in Fig. 7 corresponds to the ductile tearing limit state. The ductile tearing tensile strain capacities for 3 different pipe sizes with different flaw sizes are plotted against a nondimensional parameter $aC/(t-a)^2$ assuming identical pipe and weld material properties, flaw location and misalignment. The plot suggests a unique relationship between the nondimensional parameter and strain capacity: It is seen that strain capacities for the 3 pipe sizes with different flaw sizes fall on a single curve when plotted against $aC/(t-a)^2$. This relationship was found to hold for all the grades (X65 to X80)

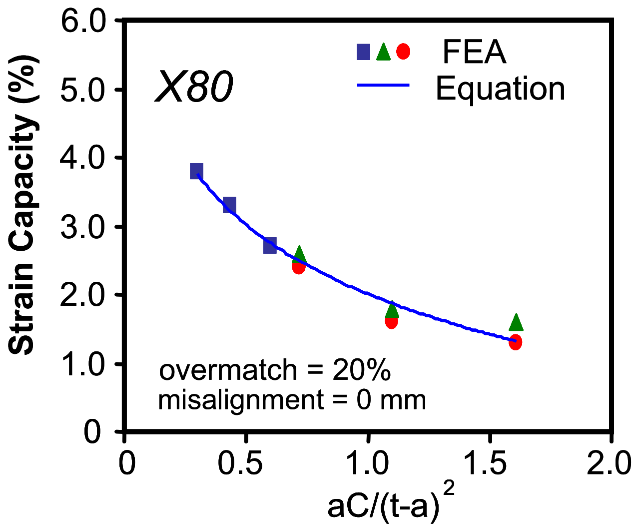

Fig. 7 Tensile strain capacity for tearing limit state as function of nondimensional parameter

for other levels of misalignment, overmatch, R-curves, pipe UEL and Y/T ratios, and Eq. 1 was expressed as:

$$\varepsilon_c = \beta_1 \ln \frac{aC}{(t-a)^2} + \beta_2. \quad (2)$$

Physically, the nondimensional parameter $aC/(t-a)^2$ represents the ratio of area of the flaw to the area of the uncracked ligament $(t-a)$ in the welded pipe. This nondimensional parameter formed the basis of the tensile strain capacity equation for the fracture limit state.

Further, a simplified form of Eq. 1 was also developed by Kibey et al. (2010) by making reasonable conservative assumptions for the following parameters: weld misalignment, pipe uniform elongation, pipe Y/T ratio and weld/HAZ R-curves. The simplified equation was expressed in the following form:

$$\varepsilon_c = f(a, C, t, \lambda) \quad (3)$$

Current strain-based design codes provide limited guidance on a multi-tier assessment approach similar to approaches provided for traditional fracture mechanics-based design in BS7910 (BS7910, 2005) and API579 (API, 2007). There is a need to develop a similar multi-level assessment approach for strain-based design. Eq. 1 can be considered to represent a Level 3-type assessment procedure for strain-based design for the range of parameters considered in the parametric study. In addition, the underlying FEA approach may be used to conduct a Level 3-type procedure for property or geometry ranges not considered in the development of the generalized capacity equation. The simplified Eq. 3 with limited parameters for strain-based design may be considered analogous to the traditional fracture mechanics Level 1 procedure for allowable stress design. Incorporation of the framework proposed above requires careful calibration of the equation to ensure that the level of conservatism implied with the equations is aligned with the probability of failure assumed for the various assessment levels assumed in codes.

VALIDATION OF GENERALIZED TENSILE STRAIN CAPACITY PREDICTION EQUATIONS

Validation of the generalized tensile strain capacity equations (Eq. 1) developed for grades X65 to X80 was based on a comparison with full-scale test data. The latter covered a wide range of materials, flaw sizes, flaw type, flaw location, pressure loading and misalignment. Material grades ranged from X65 to X80. The geometry, material properties and internal pressure of the pipe specimens were chosen to cover a wide range for all key parameters. Key variables and ranges considered included:

- material grade: X65 to X80
- outer diameter (OD): 8.625 in to 30 in
- weld overmatch: 5% to 50%
- weld misalignment: 0 mm to 3 mm
- flaw depth: 3 mm–7 mm
- flaw length: 14 mm–50 mm
- Pressure (expressed as hoop stress): 40% to 80% of SMYS
- flaw location: weld-centerline (WCL) and fusion line (FL)

The relevant small-scale tests (longitudinal tensile and SENT) required for the prediction methodology were conducted on the pipe materials and weld materials used in the full-scale testing program. Small-scale 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/FL flaw locations were measured using the SENT test as discussed above.

Wang, Barbas, Kibey, Gioielli and Minnaar (2009) presented validation of the proposed FEA-based strain capacity prediction methodology using full-scale test results, and it was concluded that the predictions agreed well with test results. Validation results suggested that the proposed approach accounted for the key physical processes governing the strain capacity of welded pipelines.

The validation of the generalized tensile strain capacity equations (Eq. 1) for X65 to X80 has been discussed in a recent paper (Kibey, Wang, Minnaar, Macia, Fairchild, Kan, Ford and Newbury, 2010). Fig. 8 shows the comparison of the predicted strain capacity from the generalized tensile strain capacity equations against the measured tensile strain capacity from full-scale tests for X65~X80 welded pipes. Currently, efforts are underway to extend the parametric equations to X60 grade, and they will be the subject of future papers. The comparison in Fig. 8 includes twenty X65~X80 full-scale tests that were found to fail in either plastic collapse in the pipe or due to ductile tearing at the flaw. The

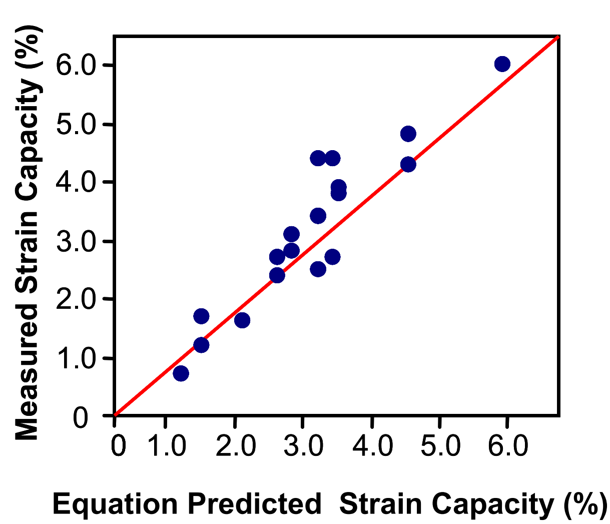

Fig. 8 Validation of parametric tensile strain capacity equations for grades X65 to X80 using 20 full-scale tests

generalized equations predicted the correct failure mode (plastic collapse or ductile tearing) of each full-scale test. Also reported was a model error, defined as the ratio of the equation-predicted strain capacity to measured full-scale test capacity. The mean and the standard deviation of the model error were estimated to be 1 and 0.3, respectively. Fig. 8 shows 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 for all grades. These results indicate that the generalized capacity equations capture the effect of the most dominant, measurable parameters affecting strain capacity. The generalized equations and the FEA approach are candidates for a Level 3 ECA assessment procedure, and they can form the basis of engineering critical assessment (ECA) methodologies for the characterization of tensile strain capacity of welded pipelines. This work is mainly based on surface flaw results considered to be critical to strain capacity of welded pipelines. Embedded flaws have not been fully investigated and further work is required to ensure that they are not more critical than the surface flaws in certain conditions.

CONCLUSIONS

The tensile strain capacity research program undertaken by ExxonMobil has shown that tensile strain capacity of welded pipelines is strongly influenced by pipe Y/T, pipe UEL, weld overmatch at UTS and tearing resistance R-curves, while it is weakly affected by weld UEL. Additionally, the numerical results indicate that strain capacity also depends on geometric parameters such as flaw depth, flaw length and pipe wall thickness, but it exhibits weak dependence on pipe diameter.

Closed-form generalized tensile strain capacity equations have been developed and validated against an extensive full-scale test program.

The validation results showed that the equation predictions were in good agreement with the full-scale tests across all grades. A SENT testing procedure was also developed to measure full-scale weld pipe R-curves for use as input in capacity prediction equations. The similarity between SENT and full-scale R-curves indicated that the SENT test is a good candidate small-scale test method to characterize welded pipeline tearing resistance behavior. The generalized equations, the FEA approach and the simplified equations can form the basis of a multi-tier engineering critical assessment (ECA) methodology for characterization of tensile strain capacity of welded pipelines.

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REFERENCES

Anderson, T (1995). *Fracture Mechanics: Fundamentals and Applications*, CRC Press, Boca Raton, Florida.

API (2007). *Recommended Practice for Fitness-for-Service. API 579*, Amer Petrol Inst.

ASTME 8M-08 (2008). *Standard Test Methods for Tension Testing of Metallic Materials*.

British Standards Institution (2005). *Guidance to Methods for Assessing the Acceptability of Flaws in Metallic Structures*, BS7910, London.

Cheng, W, Tang, H, Gioielli, PC, Minnaar, K, and Macia, ML (2009). “Test Methods for Characterization of Strain Capacity—Comparison of R-curves from SENT/CWP/FS Tests,” Presented at *5th Pipeline Tech Conf*, Ostend, Belgium.

Fairchild, DP, Cheng, W, Ford, SJ, Minnaar, K, Biery, NE, Kumar, A, and Nissley, NE (2007). “Recent Advances in Curved Wide Plate Testing and Implications for Strain-Based Design,” *Proc 17th Int Offshore and Polar Eng Conf*, Lisbon, ISOPE, Vol 4, pp 3013–3022.

Fairchild, DP, Crawford, MD, Cheng, W, Macia, ML, Nissley, NE, Ford, SJ, Lillig, DB, and Sleigh, J (2008). “Girth Welds for Strain-Based Design of Pipelines,” *Proc 18th Int Offshore and Polar Eng Conf*, Vancouver, ISOPE, Vol 4, pp 48–56.

Gioielli, P, Minnaar, K., Macia, M., and Kan, W (2007). “Large-Scale Testing Methodology to Measure the Influence of Pressure on Tensile Strain Capacity of a Pipeline,” *Proc 17th Int Offshore and Polar Eng Conf*, Lisbon, ISOPE, pp 3023–3027.

Gioielli, PC, Cheng, W, Minnaar, K, and Fairchild, DP (2008). “Characterization of Stable Tearing During Pipeline Strain Capacity Tests,” *Proc 18th Int Offshore and Polar Eng Conf*, Vancouver, ISOPE, Vol 4, pp 86–89.

Gurson, AL (1977). “Continuum Theory of Ductile Rupture by Void Nucleation and Growth. Part I—Yield Criteria and Flow Rules for Porous Ductile Media,” *J Eng Mat and Tech*, Vol 99, pp 2–15.

Kan, WC, Weir, M, Zhang, MM, Lillig, DB, Barbas, ST, Macia, ML, and Biery, NE (2008). “Strain-Based Pipelines: Design Consideration Overview,” *Proc 18th Int Offshore and Polar Eng Conf*, Vancouver, ISOPE, Vol 4, pp 174–181.

Kibey, S, Minnaar, K, Issa, J, and Gioielli, P (2008). “Effect of Misalignment on Tensile Strain Capacity of Welded Pipelines,” *Proc 18th Int Offshore and Polar Eng Conf*, Vancouver, ISOPE, Vol 4, pp 90–95.

Kibey, S, Issa, J, Wang, X, and Minnaar, K (2009). “A Simplified, Parametric Equation for Prediction of Tensile Strain Capacity of Welded Pipelines,” Presented at *5th Pipeline Tech Conf*, Ostend, Belgium.

Kibey, S, Minnaar, K, Cheng, W, and Wang, X (2009). “Development of a Physics-based Approach for the Prediction of Strain Capacity of Welded Pipelines,” Presented at *19th Int Offshore and Polar Eng Conf*, Osaka, ISOPE, Vol 4, pp 132–137.

Kibey, S, Wang, X, Minnaar, K, Macia, ML, Fairchild, DP, Kan, WC, Ford, SJ, and Newbury, B (2010). “Tensile Strain Capacity Equations for Strain-based Design of Welded Pipelines,” Presented at *8th Int Pipeline Conf*, Calgary.

Lillig, DB (2008). “The First (2007) ISOPE Strain-based Design Symposium—A Review,” *Proc 18th Int Offshore and Polar Eng Conf*, Vancouver, ISOPE, Vol 4, pp 1–12.

Linkens, D, Formby, CL, and Ainsworth, RA (2000). “A Strain-based Approach to Fracture Assessment—Example Applications,” *Proc 5th Int Conf Eng Struct Integrity Assessment*, EMAS 63, pp 45–52.

Liu, M, and Wang, YY (2007). “Significance of Biaxial Stress on the Strain Concentration and Crack Driving Force in Pipeline Girth Welds with Softened HAZ,” *Proc 26th Int Conf Offshore Mech and Arct Eng*, San Diego, California, CD-ROM.

Minnaar, K, Gioielli, PC, Macia, ML, Bardi F, and Biery, NE (2007). "Predictive FEA Modeling of Pressurized Full-Scale Tests," *Proc 17th Int Offshore and Polar Eng Conf*, Lisbon, ISOPE, Vol 4, pp 3114–3120.

Mohr, W, Gordon, R, and Smith, R (2004). “Strain-based Design Guidelines for Pipeline Girth Welds,” *Proc 14th Int Offshore and Polar Eng Conf*, Toulon, France, ISOPE, Vol 2, pp 10–17.

Østby, E, and Hellesvik, AO (2007). “Fracture Control—Offshore Pipelines JIP Results from Large-Scale Testing of Effect of Biaxial Loading on the Strain Capacity of Pipelines with Defects,” *Proc 17th Int Offshore and Polar Eng Conf*, Lisbon, ISOPE, Vol 4, pp 3231–3237.

Sandvik, A, Østby, E, and Thaulow, A (2008). “Probabilistic Fracture Mechanics Model Including 3D Ductile Tearing of Biaxially Loaded Pipes with Surface Cracks,” *Eng Fracture Mech*, Vol 75, pp 76–96.

Tang, H, Minnaar, K, Issa, J, Cheng, WC, and Pakal, R (2010). “Constraint Effects on Ductile Fracture Behavior of Small-Scale Fracture Specimens and Surface-Cracked Pipes.” To be submitted.

Tang, H, Minnaar, K, Kibey, S, Macia, ML, Gioielli, P, and Fairchild, DP (2010). “Development of SENT Test for Characterization of Pipeline Steel and Girth Weld Fracture Behavior,” Presented at *8th Int Pipeline Conf*, Calgary.

Tvergaard, V, and Needleman, A (1984). “Analysis of Cup-cone Fracture in a Round Tensile Bar,” *Acta Metallur*, Vol 32, pp 157–169.

Tyson, WR, Shen, G, and Roy, G (2007). “Effect of Biaxial Stress on ECA of Pipelines Under Strain-based Design,” *Proc 17th Int Offshore and Polar Eng Conf*, Lisbon, Vol 4, pp 3107–3113.

Wang, X, Barbas, ST, Kibey, S, Gioielli, PC, and Minnaar, K (2009). “Validation of Strain Capacity Prediction Comparison of Full-Scale Test Results to Predictions from Tearing Analysis Based on FEA,” Presented at *5th Pipeline Tech Conf*, Ostend, Belgium.

Wang, YY, Rudland, D, Denys, R, and Horsley, D (2002). “A Preliminary Strain-based Design Equation for Pipeline Girth Welds,” *Proc 4th Int Pipeline Conf*, Calgary, pp 415–427.

Wang, YY, Cheng, W, and Horsley, D (2004). “Tensile Strain Limits of Buried Defects in Pipeline Girth Welds,” *Proc 4th Int Pipeline Conf*, Calgary, pp 1–8.

Wang, YY, Liu, M, Horsley, D, and Zhou, J (2006). “A Quantitative Approach for Tensile Strain Capacity of Pipelines,” *Proc 6th Int Pipeline Conf*, Calgary, pp 1–8.