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STRAIN CAPACITY PREDICTION FOR STRAIN-BASED PIPELINE DESIGNS

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Abstract

This paper is aimed at comparing the ExxonMobil and UGent predictive tensile strain capacity equations developed in 2011. In addition, the potential issues in their application are discussed. The equations, within their limits of applicability, provide very similar predictions. However, using large scale test results, one can remove the conservatism. It is concluded that Curved Wide Plate testing could be a better and effective means to estimate the strain capacity of flawed pipeline girth welds.

Introduction

Post-yield strains in pipelines subjected to an axial tensile load can easily be ensured when the girth welds are matching/overmatching in strength [1]. When girth weld flaws occur, the strain capacity depends on many more material and geometric factors. Numerical studies and pressurised full scale tension (FST) tests have shown that, once the threshold level of toughness ensuring ductile failure is achieved, the following material and geometrical factors influence axial strain capacity [2]:

- Tearing resistance (R-curve);
- Weld strength mismatch;
- Uniform strain (uEL) capacity of the pipe metal;
- Pipe and weld metal Y/T ratio;
- Flaw location and dimensions (length and height);
- Flaw height to wall thickness ratio;
- High-low weld misalignment;
- Internal pressure.

Since post yield strain capacity depends on the actual material properties, it is also important to point out that the material factors (tearing resistance, weld strength mismatch and uniform elongation) and the geometrical factors (misalignment and wall thickness) are not immune to natural scatter.

Curved Wide Plate (CWP) tests also show that the post yield stress-strain response of the weldment[1] with a defect is governed by that of the weakest pipe [3]. Another potential issue to be addressed is related to the effect of the shape of the pipe and weld metal stress-strain curves, on the crack driving force and tearing resistance [4-5]. Beyond that, flaw detection and flaw sizing are highly dependent on the operator's skills when a small flaw in combination with high-low misalignment occurs [6-8]. Consequently, the prediction of strain capacity of a defective girth weld is a challenging issue not only because of the many factors involved, but also because of the complex nature of the interaction between these factors.

This paper compares the ExxonMobil and UGent predictive tensile strain capacity equations developed in 2011, and addresses the potential issues in their application.

Strain Capacity Prediction Methodologies

Several methodologies for predicting the strain capacity have been proposed or are under development [9-32]. This paper focuses on the methodologies developed by ExxonMobil (EM) [32] and Gent Universiteit (UGent) in 2011 [11, 33].

EM Strain Capacity Equations

Using the results from numerical work and FST tests, EM developed a pioneering finite element analysis (FEA) based strain capacity prediction methodology (termed by EM as L3) which allows for the estimation of the tensile strain capacity as a function of pipe metal yield-to-tensile (Y/T) ratio, pipe metal uEL, weld overmatch at ultimate tensile strength (UTS), tearing resistance as measured with a modified SENT (Single Edged Notched Tension) test [34, 35], flaw depth, flaw height, pipe wall thickness and internal pressure [2, 15, 23-27]. The L3 methodology equates the ductile tearing resistance and the driving force for failure. Standard toughness and SENT tests are used to provide the information on Charpy and CTOD toughness (or resistance to brittle fracture) and tearing resistance. The driving force is derived from a 3D FEA. It is of interest to note already that, in order to facilitate the 3D FEA analysis, simplifying assumptions have been made. For example, the pipes on each side of the girth weld have the same tensile properties (such weldments are further termed as "laboratory" weldments). Added to this, the pipe metal's post yield stress-strain response was modeled by manually adjusted Ramberg-Osgood (R-O) stress-strain curve fits whereas the variation of strength and uniform elongation was modeled by shifting (along the stress-axis) and stretching or shrinking (along the strain axis) the "basic or parent" R-O stress-strain curve. However, the accuracy of the assumptions and simplifications used in the L3 analysis have been validated and improved through comparison of the FEA predictions and the results of about 50 FST tests, covering different pipe grades (X60-X80), wall thicknesses (12.7-25.2 mm), pipe diameters (8" to 42"), weld overmatch levels from 0% to 60% and high-low misalignment up to 3 mm [2,32].

Since L3 requires a complex, computationally intensive 3D FEA analysis, EM developed analytical equations (termed EM L1 and L2) by introducing simplifying assumptions and bounding values of the key input variables. The bounding values of the selected key input parameters are listed in Table I [32]. Equation (1) gives the generic form of the L1 and L2 equations.

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[1] The term weldment is used to define the unit formed by the girth weld and the neighbouring pipes.

$$\varepsilon = \beta_1 * \ln\left[\frac{a*C}{(t-a)^2}\right] + \beta_2 \tag{1}$$

where ε is the average applied remote strain or average tensile strain capacity, a the flaw height, $2C$ the flaw length and t the pipe wall thickness. The values of the β_1 and β_2 coefficients for pipe grades X60-X70 and X80 can be obtained from the Appendix in reference [32].

The difference between L1 and L2 is in the treatment of misalignment, pipe metal uniform strain to maximum load (*uEL*) and tearing resistance (R-curve). For L1, misalignment and uEL are fixed at single values, but for L2 they are variable, Table I. Additionally, L2 provides more flexibility in R-curve input [32]. Note also that, relative to L3, the L1 and L2 predictions are conservative when actual material properties are better than the selected bounding values.

The 2011 L1 and L2 strain capacity prediction equations for pipe grade X80 are given by Equations (2) and (3), respectively.

$$\varepsilon = \left[-0.01061.M_{TS} - 0.027598\right] * \ln\left[\frac{aC}{(t-a)^2}\right] + \left[0.019576.M_{TS} + 0.170802\right] \tag{2}$$

$$\varepsilon = \begin{bmatrix} 0.0011uEL * M_{TS} * e - 0.0059M_{TS} * e - 0.0017uEL * e + \\ 0.171 * e - 0.0017uEL * M_{TS} - 0.0034 * M_{TS} - 0.018 * uEL - 0.6507 \end{bmatrix}$$

$$* \ln\left[\frac{a*C}{(t-a)^2}\right] + \tag{3}$$

$$\begin{bmatrix} 0.0009uEl * M_{TS} * e - 0{,}0127M_{TS} * e - 0.0349uEL * e - 0.257 - \\ 0.0001uEL * M_{TS} + 0.0417M_{TS} + 0.1612uEL - 0.0916 \end{bmatrix}$$

The term M_{TS} (or λ [32]) is the weld strength overmatch at *UTS* and *e* the misalignment. The other variables are defined above. The geometric variables are input in mm and overmatch is input as percent, not the decimal equivalents; e.g. 10% is input into the equation as 10.

UGent Strain Capacity Equation

The UGent equation for strain capacity prediction, first published in 2004 and modified in 2011 to take account of internal pressure effects, is solely based on an analysis of CWP test results

[11, 33] [2]. The UGent equation represents the empirical relationship between the lower bound average remote strain capacity of 480 CWP tests and defect area ratio, d = lh/Wt. The generic form of this relationship is given by Equation (4):

$$\varepsilon = P_c * \left[\frac{R+1}{1-R} \frac{\left(0.5 - C_u * uEL * M_{FS}\right)}{C_d} \frac{lh}{Wt} + C_u * uEL * M_{FS} \right] \tag{4}$$

where the correction parameter P_c accounts for the effect of internal pressure, correction parameter C_d takes account of the decreasing mismatch effect with increasing flaw size, correction parameter C_m covers the effect of weld strength mismatch variability, R is the pipe metal *Y/T* ratio, uEL the uniform elongation to maximum load, t the wall thickness, l (= $2C$) is the flaw length and h (= a) the flaw height, W the arc length of default value equal to 300 mm for pipe diameters greater than 30” and M_{FS} the weld strength mismatch factor based on flow stress, FS ($M_{FS} = FS_{weld}/FS_{pipe}$) [39].

Equation (4) can be applied if the Charpy toughness of the weld metal and HAZ regions comply with the Charpy impact requirement of 40 J ave./30 J min at the minimum design temperature. However, this requirement might not be sufficient for Y/T ratios > 0.90. In addition, to exclude that at low levels of weld metal strength mismatch a stably growing flaw triggers an unstable ductile or cleavage fracture, UGent suggest to use the 60 J minimum/80 J average requirement. Finally, it can be noted that the UGent method does not formally require CTOD testing as it is assumed that, considering the allowable flaw sizes in strain based designs, the Charpy requirement will ensure a CTOD of minimum 0.10 mm [40-43].

Compared to the EM-L1 and L2 equations, the UGent equation does not explicitly incorporate a factor that accounts for high-low misalignment. However, the effect of the factors such as weld bevel angle, weld cap height and tearing behaviour are directly accounted for. The other point worth emphasising is that the CWP test results were obtained from laboratory as well as from “field production” weldments. (The pipes on each side of the girth weld in production weldments have different mechanical properties). Furthermore, the CWP data was obtained for a wide range of pipe steel and weld metal combinations. In addition, for the majority of the CWP tests, a best estimate of the pipe and weld metal properties was obtained from tensile specimens taken adjacent to the CWP specimen. This all means that the important effects of the shape of the pipe metal’s early post-yield strain-stress response[3], the differences between the pipe properties adjacent to the weld and the interaction of these variables are implicitly incorporated in Equation (4). Consequently, when it is noted that the average strain at failure was used in the CWP analysis, the UGent strain capacity equation would be conservative since the strain in the weakest pipe in a production weldment, which is critical, is always higher than the average strain.

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[2] The CWP test involves an axially tensile loaded curved (un-flattened) girth welded pipe segment containing either a real defect or an artificial circumference surface-breaking crack-like notch at mid-length along the weld. Because of its dimensions, the test incorporates all influential factors intervening in the fracture/failure process.

[3] The early post yield pipe metal stress-strain response of contemporary pipeline steels does not necessarily follow that of an idealized Ramberg-Osgood stress-strain curve [4].

General consideration

Although the EM and UGent equations are based on different principles, it can be observed that Eqs (2) through (4) have the same structure. They are composed of a dimensionless flaw size parameter and parametric terms which account for the effects of weld strength mismatch (Equations (2), (3) and (4)), uniform elongation to maximum load (Equations (3) and (4)), misalignment (Equation (3)) and Y/T ratio (Equation (4)). Further, note that the EM equations are not designed to assess failure by pipe necking. In contrast, the UGent-equation allows for overmatched weldment, the estimation of the flaw dimensions, ensuring failure by pipe necking.

Table I. Summary of Assumptions, Bounding Requirements and Validity Limits for the EM L1 & L2 and UGent Tensile Strain Capacity Prediction Equations

	EM – L1	**EM-L2**	**UGent**
BASIS	FEA (L3) and FST test results		CWP test results
TOUGHNESS - Charpy V[1] - CTOD	To be determined To be determined		30 (60) J (min)/40 (80) J (ave)[2] Not required
TEARING RESISTANCE - CTOD-R curve	Default level $\delta = 0.9 - \eta = 0.5$	$\delta = 0.9 - \eta = 0.5$ + higher levels [32]	Not required
INPUT - Pipe grade	Max: X80		
- Pipe metal Y/T	0.90 (default)		0.90 (max 0.93)[3]
- Pipe metal uEL	6 % (default)	6 - 12% (X60 - X70) 4.4 - 8% (X80)	No requirement
- High-Low misalignment	3 mm	0 - 3 mm	Not included
- Internal pressure	80 % SMYS		via Pc factor[4]
APPLICATION LIMITS - Flaw height, a (EM) or h (UGent)	2 - 5 mm		30 % t[5]
- Flaw length, 2C (EM) or l (UGent)	20 -50 mm		To be calculated (no limit)
- Wall thickness, t	14.3 - 26 mm		30 mm
- Overmatch on UTS	5 - 50 % (X60 – X70) or 5 - 20 % (X80)		No min. requirement
FS (Flow stress)			Min. 0 %[6]
SAFETY FACTORS - Mismatch	To be defined		C_d (1 to 1+OM)
- uEL	6 % (default)	Free input	C_m (0.8 to 1)

1. **EM toughness requirement** - EM does not provide specific standard toughness requirements. However, the EM approach implicitly assumes that all materials in the weldment/pipeline (pipe body, weld metal and HAZ) are brittle fracture resistant and that the standard Charpy V-notch and CTOD toughness tests can be used to verify ductile behaviour. However, since EM uses the modified single edge notched tensile (SENT) test to measure ductile tearing resistance (R-curve) it can be expected that the minimum (default) R-curve requirement of $\delta = 0.9$ - $\eta = 0.5$ ensures ductile material behaviour.
2. **UGent Charpy toughness requirement** – The 60/80 J requirement is recommended for low weld metal mismatch levels.
3. **Pipe metal Y/T ratio** - UGent recommends to restrict the assessment to 0.90. However, the UGent model can be used for higher Y/T ratios when the predictions are validated with large scale tests.
4. **P_c value** - The value of P_c can range from 0.5 and 0.8. This is because P_c depends on the level of strength mismatch, the difference in the hoop and axial tensile properties, the ratio of the actual hoop stress and SMYS, and the ratio of the actual hoop stress and pressure hoop stress [36]. It is expected that the results of ongoing research will provide more detailed information [37].
5. **Flaw height** - UGent restricts the assessment to h/t ratios smaller than 0.30. This limitation reflects the fact that about 80 % of the CWP results were obtained from tests with an h/t ratio in the range of 0.15 to 0.30. The proposed limit of 0.30 does not exclude the assessment of h/t ratios greater than 0.30. In this case, however, experimental validation is needed. EM allows a maximum flaw height of 5 mm. This restriction gives, for thin wall pipes, h/t ratios up 0.349 (= 5/ 14.3).
6. **Strength mismatch factor** - M_{FS} incorporates indirectly the effects of differing post-yield strain behaviours of the pipe and weld metal on strain partitioning between the girth weld and remote pipe regions. Further, EM requires a minimum tensile overmatch, M_{TS}, of 5 %. The UGent model can be applied for matching welds in terms of flow stress. However, recent CWP test results suggest that 10 % M_{FS} overmatch causes failure by pipe necking if the flaw dimensions are limited to 3 x 50 mm^2 [38].

Application of EM and UGent equations

As a further aid in understanding the differences between the EM-L1, EM-L2 and UGent equations, Figures 1 and 2 compare the predicted strain capacities, Figure 1, and predicted flaw height vs flaw length, Figure 2, for different levels of weld strength mismatch. The plots shown were generated for the input parameters listed in Table II.

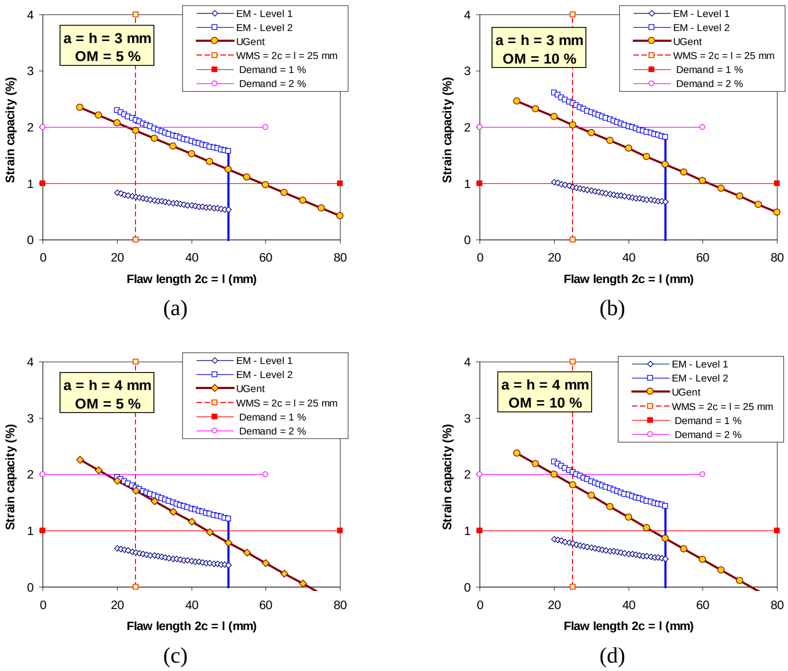
Table II. Input Variables Used for Predicting Strain Capacity (see Figures 1 and 2)

Pipe grade, wall thickness and Y/T ratio	X80 / 16 mm / 0.90		
Average strain demand, ε (%)	1 and 2		
Weld strength mismatch, M = $M_{TS\ (EM)}$ or $M_{FS\ (UGent)}$ (%)	5, 10 and 20		
	EM-L1	EM-L2	UGent
Uniform elongation, uEL (%)	6 (default)	5	
High/low misalignment, hi/lo (mm)	3 (default)	0	
CTOD/R curve and Charpy impact toughness (J)	$\delta = 0.9$ and $\eta = 0.5$		30/40
Internal pressure	0.80SMYS (default)		$P_c = 0.5$
UGent correction factors	-		$C_d = 1 + 0.5$ OM $C_m = 1$

The solid line decorated with open circles represents the UGent predictions. The lines decorated with squares and diamonds depict the EM-L1 and EM-L2 predictions. The horizontal lines in Figure 1 correspond with the strain demand levels of 1 and 2%. The dashed vertical lines at a flaw length of 25 mm represent the workmanship limit as used for stress-based designs. The "WMS"-box in Figure 2 delineates the workmanship limit of 25 mm (it is assumed that the height is 3 mm). Figures 1 and 2 illustrate the following key points:

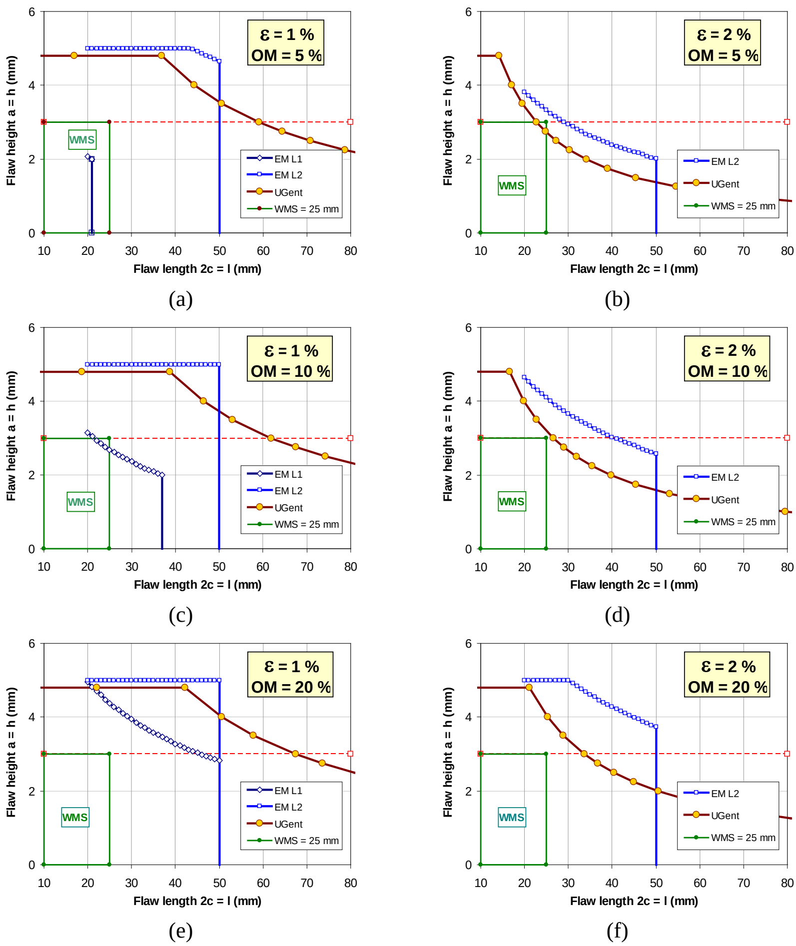
- The EM-L2 (high-low = 0 mm) and UGent predictions agree reasonably well for flaw lengths between 20 and 50 mm. This is a surprising result since equations 2 through 4 are based on very different approaches.
- EM-L1 does not appear in Figure 2 for a weld mismatch level of 5% (plots a and b) and for strain demands greater than 1% (plots b, d and f). This illustrates that low strain capacity is inevitable if a high-low misalignment of 3 mm occurs for strain demands of 1% and beyond.
- When the overmatch is smaller than 10%, Figure 1 shows that EM-L1 becomes very restrictive. For example, for a workmanship flaw of 3 x 25 mm, the predicted strain capacity is smaller than 1%.
- The UGent equation allows the determination of the length for shallow flaws (h < 2 mm). On the other hand, UGent provides no guidance for defect heights greater than 0.30 x t. The reason is that no experimental data exists to justify the use of the UGent equation above this limit. This observation also applies for the EM flaw limits given in Table I.
- As expected, the plots c and e in Figure 2 illustrate that the detrimental effect of high-low misalignment on strain capacity decreases with increasing weld strength mismatch. This observation suggests that the detrimental high-low effects at 1% strain can be alleviated by strength overmatch. Adequate weld reinforcement could produce similar effects.
- The plots b, d and f in Figure 2 collectively show a rapid decrease in predicted flaw dimensions with increasing flaw height at the target strain of 2%.
- EM-L2 and UGent have a similar sensitivity to weld strength mismatch at 2% strain.

Simply put, the above illustrates that a high overmatch allows larger flaws, or higher strain capacity for a given flaw, so it is evident that this feature must be fully explored. However, the welding process used can be a limiting factor in obtaining ample weld metal strength overmatch. In addition, experience shows that, as will be discussed later, the standard material quantification codes do not provide the guidelines necessary to document and quantify the variation of the pipe and weld metal tensile properties of production weldments [44-51].



uEL (EM-L1) = 6 % (default) - uEL (EM-L2) = 5 %
Misalign. L1 = 3 mm (default) - Misalign. L2 = 0 mm
$OM = OM_{TS}$ (=λ [32]) = OM_{FS}

Figure 1. Comparison of strain capacity vs flaw length (Pipe wall = 16 mm, Pipe grade X80).



uEL (EM-L1) = 6 % (default) - uEL (EM-L2) = 5 %
Misalign. L1 = 3 mm (default) - Misalign. L2 = 0 mm
$OM = OM_{TS}$ (=λ [32]) = OM_{FS}

Figure 2. Comparison of flaw height vs flaw length (Pipe wall = 16 mm, Pipe grade X80).

Assessment of Production Weldments

As discussed, the UGent equation is a lower bound match to a wide range of CWP test data. Consquently, Equation (4) does not necessarily predict the critical flaw dimensions. In contrast, the EML1 and L2 equations would predict critical dimensions when the specified bounding values, Table I, are used and, as assumed by EM, the pipes on each side of the girth weld have the same or very comparable properties.

Since pipes are welded in a random order in the pipeline string, it is highly unlikely that the pipes on each side of the girth weld have the same tensile properties. This fact has an effect on strain partitioning or remote strain capacity of the neighbouring pipes and average strain capacity. For example, Figure 3 illustrates that a minor difference in pipe metal yield strength and or stress-strain response has a significant effect on the remote and average strain capacities. The plots in Figure 3 also demonstrate that for an average strain demand of 1.6%, it has to be demonstrated that the softer side of the weldment (Pipe A) qualifies for a remote strain of 2.4%.

Note also that pipe wall thickness differences, which usually may - by specification - vary up to 1.5 mm, have a similar effect. Thus, the application of equations 2 through 4 requires engineering judgment.

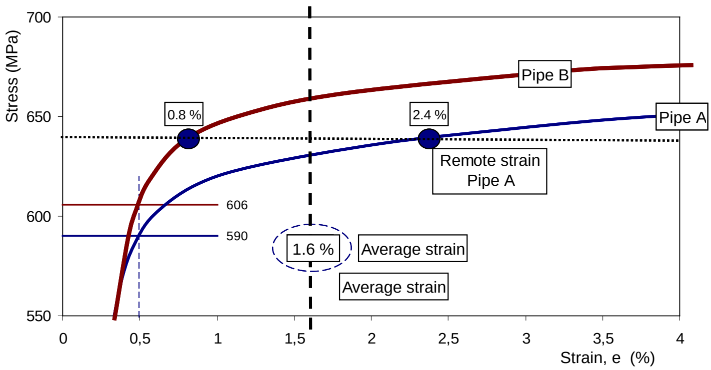


Figure 3. Comparison of average and remote strains.

Weld Metal Strength Mismatch

Weld strength mismatch has a strong effect on strain capacity since the driving force for failure is highly sensitive to the level of strength mismatch. Highly overmatched girth welds are also effective to alleviate the detrimental effects of misalignment and high Y/T ratio on strain capacity. Therefore, care must be exercised when determining the weld metal tensile properties. The problem is that the actual material properties determine girth weld performance in the post yield loading range. However, this issue is not directly a matter of concern for low grade pipes since conservative lower bound strength overmatch levels can readily be ensured. The point is that it is much easier to obtain ample overmatch in lower strength (X60-X70) pipelines than in their high strength (X80) counterparts.

Weld Metal Tensile Properties

Considering the variety of microstructures within a single girth weld, determination of the all-weld metal tensile properties representing those of the many girth welds in the pipeline string is a real challenge. In addition, the pipe metal tensile properties also vary in the through-thickness and circumferential directions, and along the pipe axis. However, the inherent scatter of the all-weld metal tensile properties is more complicated. Unfortunately, existing mechanical test standards do not address the natural scatter of the all-weld metal tensile properties.

Aside from the variation of the through-thickness (cap versus root) and circumferential weld metal tensile properties, specimen geometry (round bar vs rectangular specimens) and specimen dimensions affect the measured all-weld metal tensile properties [45]. Therefore, the testing of a single girth weld does not produce a representative estimate of the possible spread of the girth weld metal tensile properties in a pipeline string. It should also be noted that the tensile properties of production weldments differ from those determined in qualification testing. Tests on production weld cut outs often reveal that the data scatter is higher than measured in qualification testing [52].

The welding process is another factor that needs to be considered. For SMAW welds, the tensile properties of the weld root are lower than those of the fill passes. The root region of narrow gap GMAW welds is generally stronger than the fill and capping passes. Allied to this, the effect of the through-thickness variation of the weld metal/HAZ properties on tearing resistance is also an unexplored field.

Pragmatic Approach

Even when it is accepted that Equations 2 through 4 are perfect, the above suggests that the accuracy of the predictions strongly depends on the available material data. This drawback may lead to (very) conservative predictions. As discussed, it is not to be excluded that the bounding limits of the input parameters are not identified during material qualification testing. In that case, Equation 2 through 4 can produce non-conservative predictions. In addition, when the safety factors on the predictions and inspection error are added to the prediction equations discussed, it is believed that large scale test results are useful to establish realistic project specific tolerable flaw dimensions [53-55]. Such information can be generated by using FST or CWP tests containing a notch in the weld metal/HAZ of weldments made under field conditions.

FST or CWP Testing?

The FST test is the most suitable test to assess defect acceptance for strain based designs. However, FST testing is expensive and, moreover, the material properties controlling the crack driving force in the FST test have to be derived from a dummy weld. That is, even if the dummy weld is made with pipe pup pieces sampled from the same (parent) pipe and the same welding procedure, the inherent weld-to-weld variability makes it difficult to obtain the required information with sufficient precision. In contrast, CWP testing largely overcomes this concern. However, this does not exclude that, if desired, complementary FST tests on plain pipe could be executed to validate the pressure correction factor.

The CWP test permits the study of the material variation effects on strain capacity in a more flexible way. Figures 1 and 2 also illustrate that, by applying a correction factor, the CWP test is an effective means to estimate strain capacity. For matching welds, the measured strains have to be reduced by a factor of two. The correction can be reduced for overmatched welds [56]. Beside the obvious practical and economic advantages, the specific benefits of CWP testing are:

- The pipe and girth weld metal tensile properties affecting CWP strain capacity can be obtained from test specimens taken out adjacent to the CWP specimen. CWP testing has shown that this is essential for the correct understanding of large test results.
- Because of the better accessibility of the weld root region, it is also easier to place the notch tip in the target WM/HAZ microstructure and to study the effect of weld root flaws on strain capacity.
- Considering the variability of the material properties around the circumference, and since several CWP specimens can be removed from a single weld, it is also possible to conduct a sensitivity analysis.

Finally, it must be accepted that the CWP (as well as the FST) test has its own issues. For example, the selection of pipe and weld materials allowing the determination of the lower bound strain capacity remains largely an unexplored problem. However, the weld procedure screening methodology developed by ExxonMobil already offers a possible scenario and a series of very useful guidelines [57].

Conclusion

The ExxonMobil and UGent parametric analytical equations developed in 2011 permit the conservative prediction of the axial tensile strain capacity of defective girth welds. Although these equations, within their limits of applicability, provide very similar predictions, they do not provide obvious advantages over FST or CWP testing to obtain project specific strain capacity predictions. By using FST or CWP test results one can remove the conservatism.

Since, leaving aside the difference in crack driving force, CWP and FST test performance are controlled by the same factors, it is recommended to use the (uni-axially loaded) CWP test. However, this option requires that the internal pressure effect is accounted for in the translation of the test results. For matching welds, the measured strains have to be reduced by a factor of two. The correction can be reduced for overmatched welds. Consequently, once the threshold impact toughness is met, one can develop a "tailor-made" set of tolerable defect length-height curves as a function of the tensile properties.

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