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MATERIAL TEST REQUIREMENTS FOR STRAIN-BASED PIPELINE DESIGN

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Abstract

The pipe metal properties commonly derived from a standard tensile test are the yield strength, ultimate tensile strength and strain at failure. Knowledge of the yield strength and the yield to tensile (Y/T) ratio allows assessing, in stress-based designs, the condition of plastic collapse when defects occur. For strain-based designs, additional information is required. In particular, the strain hardening capacity or the Y/T ratio, the shape of the stress-strain curve, the uniform elongation and the level of weld strength mismatch determine the amount of plastic deformation that can be achieved. It is also to be noted that a strain-based design requires the actual properties and not the specified ones.

This paper addresses issues that arise in the determination of acceptable defect sizes of girth welds subjected to longitudinal plastic strains. The issues discussed include the effect of (a) the variability of the measured material properties, (b) the toughness and (c) the strength mismatch. For this purpose, reference is made to an empirical model that allows predicting the strain limit. This model, derived from the results of Curved Wide Plate (CWP) experiments, reflects the observation that, beyond a threshold level of toughness, the tensile properties have a much greater effect on the strain limit than increased toughness. By using data from welded Grade X70 and X80 pipe, it is demonstrated that high-toughness girth welds do not lead to a higher remote strain capacity than girth welds of moderate but adequate toughness. Throughout the paper, guidelines as to how to handle these issues are provided.

Introduction

In a strain-based design, it is a basic requirement that girth welds, which may contain defects, survive anticipated axial plastic deformations. This can be achieved by ensuring that both the pipe and girth welds have the required strength and toughness properties. The analysis required to define the value of the required properties (variables) is very complex. This is because the variables interact with each other whilst the representative values of these variables cannot easily be determined. This is a major issue since the strain capacity depends on the actual and not on the specified properties.

Information published on girth weld acceptance in pipelines subjected to non-elastic longitudinal strains provide three options. They make use of analytical modeling (FAD – Failure Assessment

Diagram), numerical modeling (FEA – Finite Element Analysis) or full-scale or Curved Wide Plate (CWP) test results [1-7].

The analytical approach is based on existing fracture mechanics formulations (FAD approach) and an FEA analysis that accounts for post-yield deformations. The rationale behind the numerical approach is that the interaction between crack tip driving force (CTDF), remotely applied strain, e, and associated input parameters affecting the CTDF-e relationship can be used to predict tolerable defect dimensions. The crack tip driving force is derived from an FEA analysis, while the critical condition or crack resistance is obtained from CTOD or wide plate tests.

Analytical or numerical assessment procedures assume that the toughness is the parameter that governs the strain limit. By contrast, wide plate test results show that there is a threshold level of toughness, above which the strain limit is virtually insensitive to toughness [2.4]. The other issue is that the CTDF in the plastic loading range is not necessarily proportional to the applied strain. This implies that the strain limit is not always proportional to CTOD toughness because the relationship between CTDF and the crack resistance (CMOD and CTOD) depends on defect size, strain hardening capacity and strength mismatch. In particular, overmatching is effective at shielding weld defects from high CTDF in the post-yield loading range. Thus, the focus on toughness alone can lead to overly conservative toughness requirements. Furthermore, the analytical or numerical procedures under development are not designed as predictors of failure. That is, the criticality of a defect cannot be predicted. The strain limit at instability / failure can only be inferred from notched full-scale or CWP (Curved Wide Plate) tests. The comparison of full-scale bend and curved wide plate (CWP) tensile tests has demonstrated that tensile loaded CWP specimens fail at lower strain and stress levels than the full-scale pipes under bending. Therefore, the failure characteristics of a flawed girth weld subject to bending can be conservatively derived from the failure characteristics of a tensile loaded CWP [8,9].

Experience has demonstrated that empirical correlations between wide plate or full-scale test results and the material properties (toughness and tensile properties) can be used for setting toughness requirements in material selection standards [10,11] or to develop defect acceptance criteria [12,13]. The CTOD design curve can be used as a typical example [12]. It is further important to mention that CWP data has contributed to the understanding of the fundamental questions related to strain-based design. Therefore, large-scale data obtained from CWP tests can be used to provide a reliable solution.

Strain limit

During the last five years, Universitieit Gent has conducted a substantial amount of research into the study of the post-yield behaviour of matched and overmatched pipeline girth welds with root defects. The investigations have provided an empirically derived strain-based girth weld defect acceptance model, Eq. 1 [14].

$$e = C\,uEL\;M\left[1 - f(R)\frac{lh}{st}\right] \qquad (1)$$

Where e = remote strain, C = safety factor, uEL = percentage uniform elongation, M = weld strength mismatch factor, R = pipe metal yield to tensile ratio (R = Y/T), l = defect length, h = defect height, t = wall thickness and s = arc length of default value equal to 300 mm. The ratio of lh/st is equal to the defect area ratio, d_r.

This equation represents the lower bound fit to CWP data of "tough" girth welds. Welds are considered to be tough if the toughness of the material containing the defect exceeds 30 J / 40 J (min/mean) and 0.10 mm / 0.15 mm (min/mean) CTOD. In a later section it will demonstrated that higher toughness levels have no effect on the strain limit. Therefore, these toughness requirements, hereafter termed as threshold toughness, were used to establish the lower bound fit to the CWP data.

When the values of C, uEL, M and f(R) are known, the model allows the defect length, l, to be derived from the defect height, h, the weld and pipe metal mechanical properties and the remotely applied strain, e. The model can be applied to plain pipe and girth welds provided the minimum values of the input parameters are used, because the strain capacity depends on the actual material properties rather than the specified ones. This basic requirement is a major challenge.

Validation

The effect of the input parameters Y/T and M on the predicted strain limit is illustrated in Figure 1. As can be seen, CWP test results of grade X70 and X80 pipe were used to perform the assessment. Figure 1 shows the variation of the CWP remote failure strains as a function of the defect area ratio, d_r (d_r = lh/st). The horizontal dashed line corresponds with a remote strain of 0.5 % or the onset of remote yielding. Line AB represents the lower bound fit to CWP data of tough girth welds if the Y/T ratio of the pipe metal in the axial direction is smaller than 0.90. The sloping lines XY and CB reflect the effect of Y/T and weld strength mismatch for tough welds on the strain limit, as discussed hereinafter.

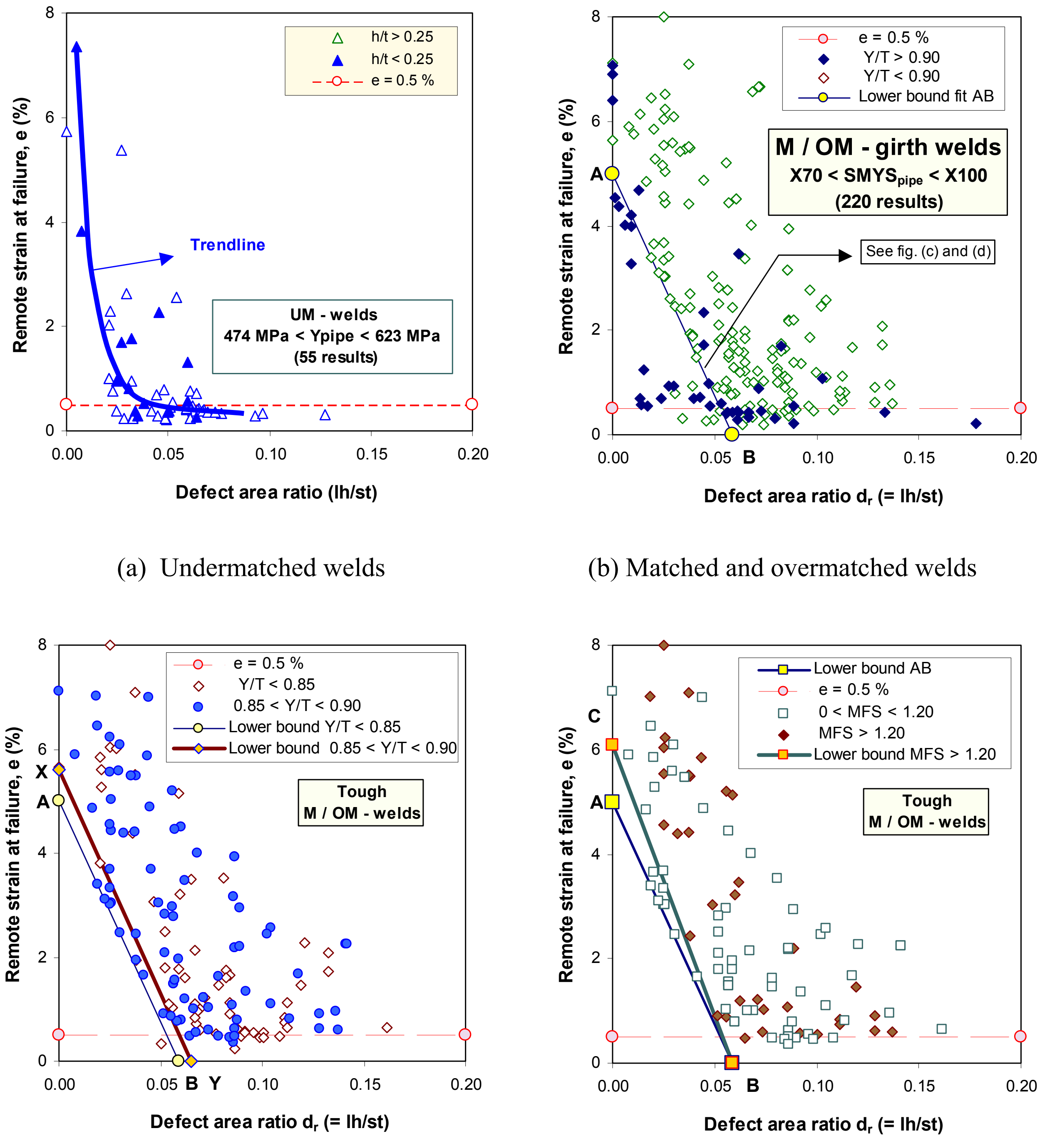
The original database of the Grade X70 and X80 single-notched CWP tests used to perform the assessment is reproduced in Figs 1a and 1b. As indicted, the database consists of 275 results. The actual yield strengths ranged form 486 to 664 MPa. This data set represents a fraction of the complete database containing the results of 720 fully documented test results of tensile loaded single and multiple notched CWP specimens extracted from plain pipe and welded large diameter pipe in the yield strength range from 370 to 980 MPa.

Figure 1a illustrates that undermatched girth welds (55 results) should be avoided since the low strength weld metal concentrates strain in the weld region; the likelihood of obtaining remote strains above 0.5 % is rather low. However, Figure 1a shows that remote failure strains greater than 0.5 % cannot be excluded. This possibility depends on the defect height to wall thickness ratio (h/t), the height of the weld reinforcement and the strain hardening properties of the region (weld metal/HAZ) containing the defect. For matched and overmatched girth welds (220 results), Figure 1b demonstrates that the achievable level of plastic strain is affected by yield-to-tensile (Y/T) ratio or strain hardening characteristics of the material surrounding the defect (see solid dots). Further, even when the results of matched /overmatched welds in pipe with Y/T greater than 0.90 are excluded, Figure 1c and 1d revealed that the relation between the strain limit and defect area ratio is far from unique. It should be noted that Figs 1c and 1d shows only the CWP test results of the tough girth welds.

The scatter in failure strains is attributable to the effects of (a) a range of variables, including: the level of weld yield strength mismatch, the Y/T ratio (or strain hardening capacity) of both pipe and weld metal, and the uniform elongation of the pipe metal, (b) the shape of the strain-stress response of the pipe metal in the post-yield loading range, (c) the variability of these variables and (d) the interaction between these variables. Note also that toughness is also a contributing factor to the scatter, Figure 1b.

Effect of uEl and Y/T Ratio

The intercept of line AB with the x-axis, point B, depends on the pipe material Y/T ratio because the strain hardening properties determine the maximum defect area ratio, d_r, ensuring the onset of remote plastic strain (e = 0.5 %) [15]. The intercept of line AB



(a) Undermatched welds

(b) Matched and overmatched welds

(c) Effect of Y/T ratio

(d) Effect of mismatch

Figure 1. Variation of remote failure strain as a function of defect area ratio (lh/st) for (a) undermatched, (b)(c) and (d) matched and overmatched girth welds. Data in (c) and (d) showresults of tough girth welds as a function of pipe metal Y/T ratio and strength mismatch (see key).

with the strain axis (y-axis) corresponds to the percentage uniform elongation, uEL, of a defect-free weld. Consequently, the value of uEL at point B should correspond with the lowest value of uEL of the range of steels tested. Further, if the actual value of the Y/T ratio is known or when the value of the Y/T ratio is smaller than 0.90, the lower bound will intersect the strain axis at a higher strain level. For example, if the Y/T ratio is lower than 0.85, Figure 1c shows that the lower bound line AB can be shifted to a less conservative lower bound line XY. Thus, pipe metals of increasing strain hardening capacity (or decreasing Y/T ratio) will permit higher remote plastic strains. For pipe metal Y/T ratios below 0.90, Eq. 1 provides conservative to over-conservative predictions. The factor C in Eq. 1 reflects this increase. For pipe metal Y/T ratios greater than 0.90, Figure 1b shows that the lower bound line fit AB can no longer be used. Because of the scarcity of CWP data, it is not yet possible to establish a representative lower bound fit for pipe metal Y/T ratios exceeding 0.90.

Effect of Weld Strength Mismatch

By constructing the lower bound line AB it was assumed that all welds were tough and matching in strength. That is, line AB does not reflect the effect of strength mismatch. If the effect of weld strength mismatch on the strain capacity is taken into account, Figure 1d illustrates that weld strength mismatch causes an upward shift of the lower bound line AB. A detailed study of the complete database (790 CWP results) allowed a conclusion that the effect of weld strength mismatch on the strain limit can be accounted for by using the multiplication factor, M, in accordance with the magnitude of the mismatch [4]. A discussion on the value of M to be used in the assessment is given in the last section of this paper.

Threshold toughness

The CVN and CTOD tests conducted in conjunction with the CWP tests shown in Figure 2 were used to verify whether the minimum and average EPRG-Tier 2 toughness requirements (see below) are sufficient for strain based designs, Table I and Figure 2. The EPRG requirements ensure the onset of remote yielding ($e = 0.5$ %) if the defect area ratio within an arc length of 300 mm is less than 7 % of the cross sectional area. Remember that girth welds that comply with one of these requirements are termed as tough [15].

Table I. EPRG Tier 2 - toughness requirements

	Min. / Mean**	Additional requirements
Charpy V impact (CVN)	30 / 40 J	• Weld metal is matching or overmatching
CTOD	0.10 / 0.15 mm	• Y/T of pipe and weld metal < 0.90

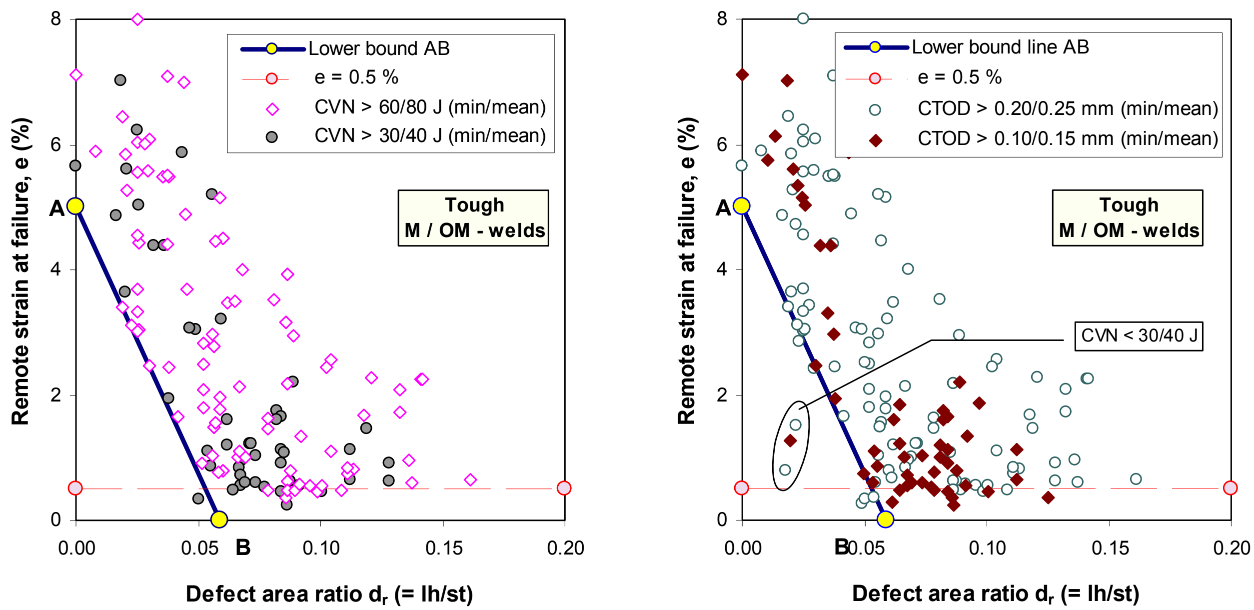
*** : to be achieved at design (wide plate) temperature.**
**** : girth welds that comply with one of these requirements are termed as being a tough weld.**

The CWP-data points in Figure 2a are annotated to the Charpy (CVN) requirements of 30 J (min) / 40 J (mean) (open circles) and 60 J / 80 J (solid dots). By contrast, the data points in Figure 2b are identified to the CTOD toughness levels of 0.10 / 0.15 mm (open circles) and 0.20 / 0.25 mm (solid dots). As discussed, the lower bound line AB represents the lower bound to the experimental CWP data for which the EPRG toughness requirements are satisfied (Table I).

If the CVN toughness requirements are increased by a factor of two (60/80 J), it can be observed that the position of the lower bound line AB is not affected by increasing toughness. A similar conclusion can be drawn if the CTOD toughness criterion is used. More specifically, the CTOD requirements of 0.10/0.15 mm and 0.20/0.25 mm enable drawing of the same lower bound line, AB, to the CWP data. In comparing Figs. 2a and 2b, it can be verified that either CVN or CTOD requirements can be used to establish the lower bound line AB.

Since toughness levels exceeding the EPRG threshold values of 30/40 J (CVN) or 0.10 / 0.15 mm (CTOD) have no direct effect on plastic strain capacity, one can also state that specifying toughness levels greater than the EPRG requirements can exclude acceptable welds?

However, a closer examination of the data points below the lower bound line AB (Figure 2b, CTOD criterion - see encircled data points) reveals that these welds are low toughness welds if they are evaluated in terms of CVN toughness. These welds qualified for the CTOD criterion but failed to meet the CVN > 30/40 J or 60/80 J requirement. This suggests that the indiscriminate use of CTOD tests might produce misleading information. Therefore, it would be a safe requirement to specify that the toughness of the region containing the defect should exceed both CVN <u>and</u> CTOD threshold levels. This is further explored in Figure 3.



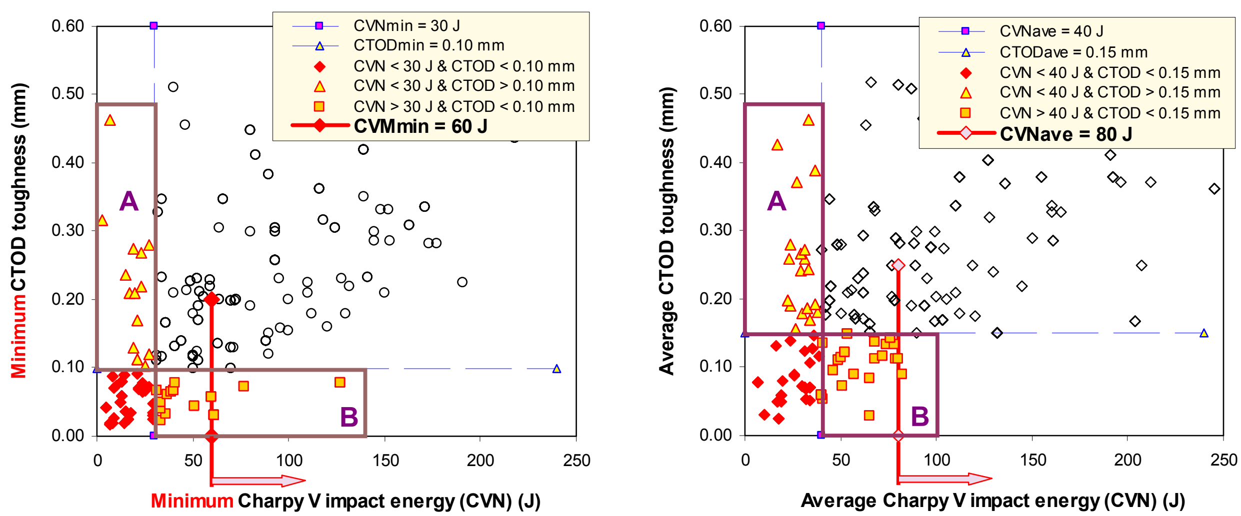
(a) CVN criterion (b) CTOD criterion

Figure 2. Variation of overall remote strain, e, with defect area ratio, d_r, in overmatched welds as a function of CVN or CTOD toughness (see insert to the plots).

The CVN and CTOD data shown in Figure 3 for girth welds in Grade X52 to X100 pipe at the same test temperature can be used to verify whether adequate CTOD properties correlate with adequate CVN energies.

It is apparent from Figure 3 that the CVN properties of girth welds complying with the minimum (or average) CTOD requirement of 0.10 mm (or 0.15 mm) can be lower than the minimum (or average) CVN requirement of 30 J (or 40 J), see data points located within box A. This correlation simply illustrates that the weld metal is brittle in terms of CVN energy. A similar observation can be made with respect to welds of adequate CVN toughness (CVN_{min} or $CVN_{ave} >$ 30 J / 40 J). Tough welds in terms of Charpy energy can be rejected by the CTOD test ($CTOD_{min}$ $<$ 0.10 mm or $CTOD_{ave} <$ 0.15 mm), box B. This unexpected issue can be solved by specifying, as discussed, (a) CVN and CTOD testing, and (b) the 60J / 80 J (min/mean) impact energy, see horizontal arrow.

The vertical thick lines annotated with ‘diamonds’ in Figure 3a (CVN = 60 J) and Figure 3b (CVN = 80 J) show that the likelihood of obtaining CTOD values below 0.10 mm (min) / 0.15 mm (mean) is small if the 60 J / 80 J criterion is specified. Further, since the correlations in Figure 3 disclose that the 60/80 J CVN toughness level provides an adequate description of the threshold toughness needed to ensure post-yield plastic strains, one can consider the possibility of focusing toughness testing on CVN. Thus, the current belief that defect assessment procedures based on CVN toughness can be non-conservative is not necessarily correct.



(a) – Minimum values (b) – Average values

Figure 3. Variation of Charpy V Notch impact energy and CTOD properties of the girth weld metals at wide plate test temperature.

Finally, the above analysis provides the experimental evidence that the lower bound fit AB to the CWP results can used to predict the strain limit of matching (and overmatching) girth welds, Eq. 1. The analysis also illustrates why Eq. 1 does not directly address the effect of toughness on the strain limit. This greatly simplifies the defect assessment while the toughness requirement can be achieved with contemporary welding procedures. However, as will become apparent in what follows, the assessment remains complicated because the representative values of weld strength mismatch around the defect (variable M), and the uniform strain capacity (variable uEL) of the pipe metal still need to be determined.

Pipe Metal Tensile Properties

It is clear from the above discussion that the pipe and weld metal tensile properties are the key variables in a strain-based girth weld defect assessment. In particular, the **actual** tensile properties need to be known because the plastic strain capacity is determined by the stress-strain response in the post yield loading range. In addition, the plastic strain limit of a girth weld with a defect under longitudinal tensile loading is proportional with the uniform plastic strain, uEL, and not with the total strain at failure. Thus, the knowledge of the full stress-strain curve is an essential element in a strain-based design. This is not the case for conventional stress-based pipeline designs. Stress-based defect assessments use minimum specified values while the effect of the natural variation in tensile properties, within the range specified in pipe metal standards, needs not be considered.

The technical literature abounds with studies concerning tensile testing. However, little information on uEL is available. In a way, this is understandable because material specifications do not require the full stress-strain curve to be recorded during the tensile test. When needed, the (true) value of uEL is normally derived from the strain-hardening exponent. Further, there is very few published statistical data to judge the natural variation of the stress-strain response and the uniform elongation capacity at different locations within an individual pipe.

To place these issues in a broader perspective, one should know that the thermo-mechanical and mechanical processes involved in making the steel plate and forming of the plate into pipe are non-uniform. This causes not only differences in the longitudinal and transverse tensile properties, but also local variations around the circumference and along the longitudinal axis of the pipe. The effects of these differences must be determined and be accounted for. Therefore, the traditional way of testing a single or even a limited number of specimens could provide insufficient information.

High Strength Pipe Line Steels

Compared to conventional pipeline steels, the modern high strength grades typically have higher a Y/T ratio for a given yield strength and a differing stress-strain response in the post-yield loading range, Figure 4. The stress-strain response in the plastic loading range of high-grade pipe steels differs from that of lower strength steels in that they generally show a reduced capacity for strain hardening and a reduced uniform elongation, uEL. This is because the steel strengthening mechanisms used to obtain high-grade pipe steel specifically increase the yield strength and have less influence on the tensile strength. In particular, grain refining through thermo-mechanical rolling (TMCP) causes a significant decrease of the uniform elongation, uEL, with increasing strength because the development of a neck into final failure occurs more rapidly with decreasing grain size [16].

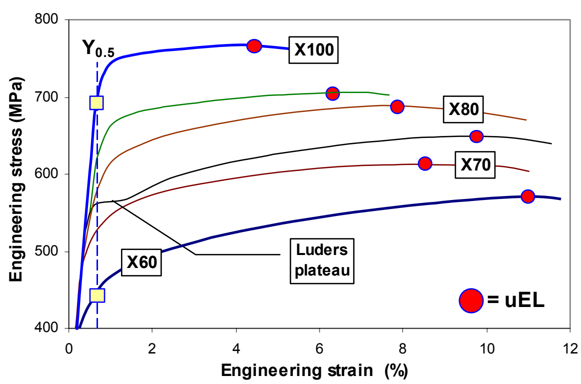


Figure 4. Effect of steel grade (X60 – X100) on stress strain response and uniform elongation, uEL.

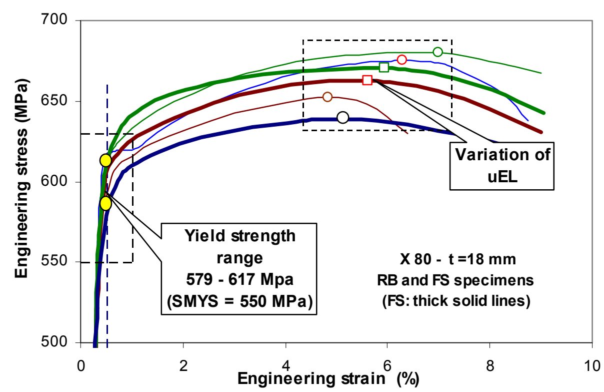


Figure 5. Effect of specimen geometry and sampling location on tensile stress-strain behaviour of grade X80 pipe [50]

Apart from the effect of the process variables in pipe making, there are other factors that can have an influence on the measured tensile properties. For example, the specimen geometry and sampling location need to be considered. These issues are discussed hereinafter.

The strain hardening or the shape of the stress-strain relation in the post-yield loading range is another factor that affects the strain limit and thus merits further study. This is investigated in a later section by considering the interaction between the post-yield portion of the stress-strain curve and the failure stress of the section containing the defect.

Stress-Strain Curve

Properties specified and controlled by the pipe suppliers in current practice include minimum yield strength, ultimate tensile strength and elongation at failure. The full stress-strain curve is not needed to determine these properties. Consequently, full stress-strain curves are not normally recorded. Moreover, the longitudinal tensile properties are not measured.

When the longitudinal tensile properties are specified, the requirements can be verified by testing either round-bar (RB) or full-wall strap (FT) specimens. The round bar specimen is machined from a strip of pipe material and has a machined surface. The diameter of a round bar test specimen is smaller than the pipe wall thickness while the material under test is taken from the mid-wall thickness location so that the inner and outer surfaces are not tested. The amount of material sampled with a full-wall strap specimen is greater than for a round-bar specimen while surface texture is the same as the pipe. Thus one can expect that RB and FT specimens will produce different results, Figure 5. Note that the measured properties complied with the standard requirements and the specified supply range.

The stress-strain curves reproduced in Figure 5 demonstrate that the pipe metal tensile properties in the longitudinal direction can exhibit a wide variation around the pipe circumference. As indicated, the curves represent the stress-strain response of RB and FT tensile test specimens extracted from a grade X80 pipe of 18 mm wall [17]. The RB and FT specimens were machined from side-by-side coupons while these coupons were sampled from three different locations. Note also that the tensile properties of RB specimens produce lower tensile properties than those derived from full thickness strap specimens while both specimen types exhibit a similar variability. The specimen-to-specimen variability observed could not be correlated with the sampling position around the circumference. However, it must be clear that full thickness specimens are desired if the full wall stress-strain response has to be established because RB specimens test only the lower yield strength material at mid-wall. In particular, the yield strength can vary through the wall as a result of cooling rate effects. This is particularly the case for thick wall pipe because the material at the core of the section cools more slowly and consequently has lower strength. Therefore, full-thickness specimens will measure the average of the comparatively stronger material towards the surfaces and the lower yield material at mid-wall.

The variability of the individual test results illustrated in Figure 5 is not exceptional. In this context, however, it must be noted that the different proprietary TMCP processing routes produce different variations. For pipe steels of the same grade, the different processing routes, as will the differences in chemical composition, affect the variability of the tensile properties. That is, pipes from different suppliers will exhibit a different pattern of variation in tensile properties.

These observations have also implications with respect to:

- the prediction of the strain limit. One single tensile test does not necessarily provide representative information on the stress-strain response of a full pipe
- the determination of a representative level of weld metal yield strength mismatch (see the next as well as the last section).

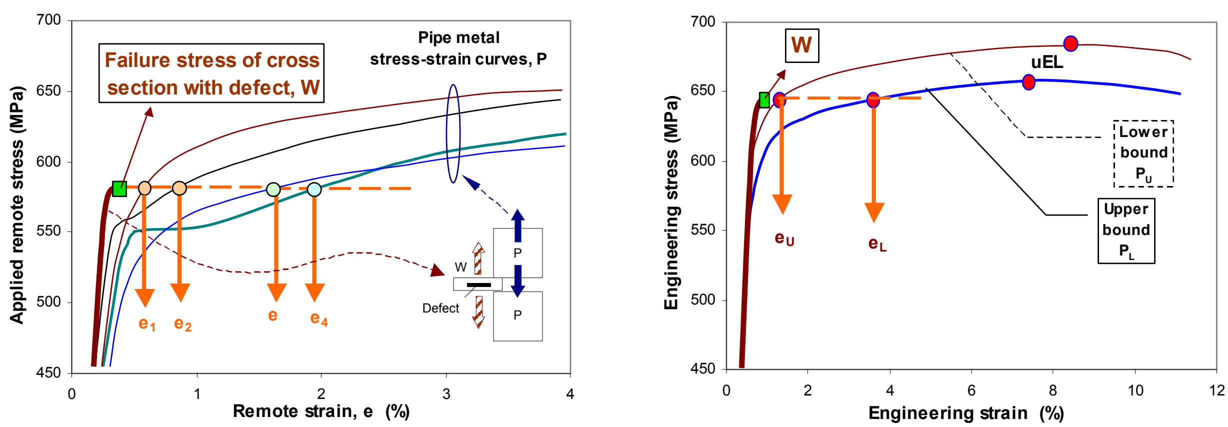
- finite element modeling. At present, FEA studies use linear power-law stress-strain curves, which are assumed to represent the actual stress-strain curve in the lower as well as the higher strain range.

Further, the impending introduction of a new grade of steel will most likely mean that these future materials may not have properties that are as well understood as currently available materials, at least in the short term. Statistically valid characterization of these new grades is necessary for the development of a reliable strain-based design procedure.

Shape of Stress-Strain Curve.

The ability to predict the stress-strain response in the post-yield loading range by a power-law curve fit is attractive, widely applied and useful as long as the model represents the actual behaviour. Current power law models have been developed using tensile data of structural steels and assume power law hardening behaviour at fixed rate. However, the stress-strain response of modern high Y/T ratio pipe steels can deviate from that seen in traditional steels, Figure 6a. The issue is that the strain-hardening exponent can vary with increasing plastic strain. This also implies that the Y/T is not a unique measure of how the steel behaves between yield and ultimate tensile strength because steels with very different stress-strain curves can have the same value of Y/T. Since the accuracy of the popular parabolic power law or offset power law expressions used for numerical modeling is always satisfactory, it must be verified whether this limitation has a significant effect on the predicted strain limit.

CWP tests demonstrate that the stress-strain response of a tough strain-hardening overmatched girth weld with a defect coincides with that of the pipe metal. Thus, the strain limit depends on the failure stress of the section containing the defect, W, and the shape of the pipe metal stress-strain curve in the post-yield loading range [18]. As shown in Figure 6a, the intersection of the horizontal line passing through point W, representing the failure stress of the defective section, with the pipe metal stress-strain response defines the remote failure strain, e_i. It will be noted that the stress-strain curves, P, reproduced in Figure 6a are representative of those observed by testing contemporary pipeline steels in the longitudinal direction.



(a) (b)

Figure 6. Effect of strain hardening behaviour on remote strain

Figure 6a illustrates that the shape of the post-yield response of the pipe metal has a significant effect on the strain limit. Pipe steels characterized by a steep slope (high strain-hardening rate) in the early post-yield range have a lower plastic strain capacity in their welded form than pipe steels with (a) a Luders plateau and (b) displaying a gradual strain-hardening behaviour (e_1 or $e_2 < e_3$ or e_4), Figure 6a. In addition, Figure 6b shows the effect of the variation of measured stress-strain response around the pipe circumference on the strain limit. The curves are a re-plot of the actual measured upper and lower stress-strain curves shown in Figure 5. Accepting that the defective area fails at the stress level, W, Figure 6b illustrates that the predicted strain limit depends on the stress-strain curve selected. That is, if the actual variation is taken into account, the predicted strain limit can vary from e_L (Reference Pipe P_L) to e_U (Reference P_U).

The above observation has significant implications with respect to the prediction of the critical defect as well as with the numerical treatment of the plastic strain capacity of defective girth welds. An assessment based on the result of a single test can either produce over-conservative or non-conservative predictions. The upper bound stress-strain response of the pipe metal has to be determined if conservative strain limits are to be determined. This means that multiple tensile tests have to be performed to identify the upper bound tensile properties.

<u>Uniform Elongation</u>

The assessment of the CWP data, Figures 5 and 6, has demonstrated that the strain at ultimate tensile strength or the uniform elongation, uEL, is of fundamental importance in the prediction of the strain limit. In particular, Eq. 1 demonstrates that the choice of the value of uEL has a significant bearing on the predictions. More specifically, the dependence of uEL on pipe grade needs to be considered. Associated issues not covered by codes or technical literature are related to the determination of uEL and the effects of yield strength or Y/T ratio on uEL. The pertinent questions are:

- is the value of uEL to be determined at the first attainment of the maximum load or at the onset of instability (end of maximum load plateau)?

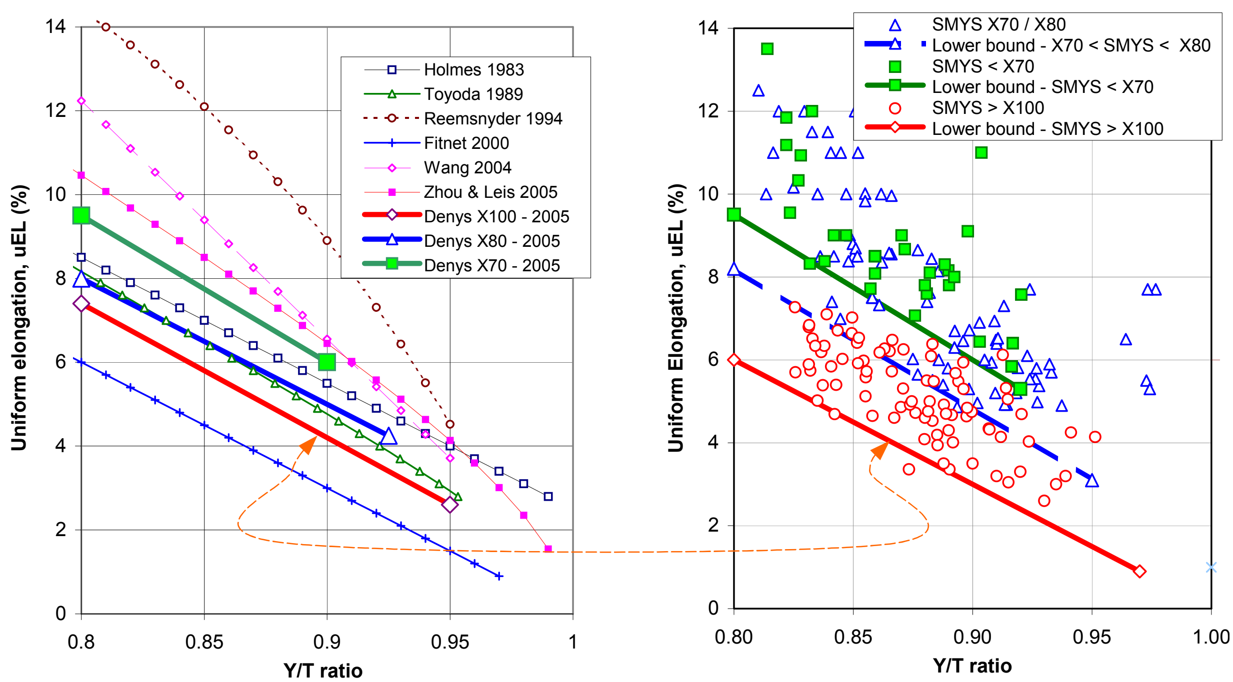
- to what extent do the measured values of uEL depend on yield strength or Y/T ratio, and can current models that relate these variables be used to estimate the value of uEL?

Our present understanding regarding the relationship between uniform elongation and Y/T ratio is summarized in Figure 7. The full details of the correlations will be published in the very near future. Figure 7 reveals that the uniform strain is inversely related to Y/T ratio, as expected. Figure 7a shows a range of relationships between the Y/T ratio and the uEL derived from either experimental correlations or linear power law representations of the non-linear elastic portion of the stress-strain curve. These correlations are used by designers who do not have uEL data for their pipeline steels, but have tensile data. By contrast, Figure 7b, shows experimental data obtained from tensile tests on longitudinal full-section 25 mm wide on strap specimens extracted from pipe grades in the range from X65 to X100. The grades are identified in the key to the plot. The steels were produced by several pipe suppliers after 2001 [19]. The wall thickness varied between 14 mm and 25 mm. The percent uniform elongation was determined at the onset of the maximum load plateau. The straight lines represent lower bound (solid lines) or 'Denys" fits to the relevant experimental data. For example, the thick line annotated with open squares represents the lower bound fit to the X80 data. These lines are also shown in Figure 7a.

Predicted Correlations

The predicted correlations are not very consistent as they produce significantly different values of uEL for a fixed Y/T ratio, Figure 7a. [20-25]. Since the origin of the proposed correlations are not always known and the objectives of the current study focus on the determination of lower bound correlations, only a brief discussion will be presented.

As intended, the prediction proposed by FITNET gives the most conservative estimates. By contrast, the predictions proposed by Reemsnyder, Wang and Zhou are more generous as compared with the relationships proposed by Holmes and Toyoda. It will also be noted that the Holmes, Wang and Zhou predictions have been proposed for assessing pipeline steels [20,24,25].



(a) Predicted correlation (b) Experimental correlations

Figure 7. Relationship between Y/T ratio and percentage uniform elongation

Experimental Correlation

The lower bound fits developed by Denys illustrates that uniform strain decreases with increasing yield strength, Figure 7b. The plots also show that a pipeline steel of comparable Y/T ratio can exhibit significantly different uniform strains. For example, at a Y/T ratio of 0.90, the uniform strain varies between 5.0 % (lower bound X80) and 9.3 %. For X100 pipe, the uniform strain varies between 3.5 % (lower bound) and 6.2 %. The occurrence of the large scatter is not unexpected since steels of the same nominal strength supplied by different manufacturers have a different mechanical behaviour. Differences in chemical composition, level of process control and rolling technology applied affect the tensile properties. However, as shown in Figure 5, a similar degree of scatter can be observed in pipe of the same supplier because the steps taken in pipe making also affect the tensile properties around the pipe circumference and through the wall thickness, thus causing different sampling positions to produce different results. Further, since codified tensile testing codes do not require uEL measurements, the determination of the value of uEL from a load-elongation chart can also contribute to the scatter. Specifically, the measurement presents a problem in identifying the exact point to measure if a very flat load maximum occurs. To avoid discussions, it is recommended to determine the value of uEL at the first attainment of the maximum load.

The comparison of the published correlations (Figure 7a) and the experimentally determined lower bound correlations developed by Denys (Figure 7b) indicates that that the former can be very conservative in some cases, and unconservative in others. The other issue is that the derivation of uEL from tensile data should take account of the effect of yield strength. That is, the assumption that uEL is uniquely proportional to the Y/T can render non-conservative predictions. Rather, it is recommended to use actual uEL data, or in the absence of such information it is suggested to use one of the lower bound correlations shown in Figure 7a. In addition, since pipes in "PE-aged" condition can also exhibit higher Y/T ratios and lower uniform elongations than pipes in "as-received" condition, the possible effects of strain ageing induced by coating should be determined. The tensile properties should be derived from test coupons, which have undergone a thermal cycle representative of the plant and or field coating [26].

Finally, it will also be noted that the minimum value of 5.0 % (grade X80 pipe) corresponds with the plastic strain limit of a CWP specimen at zero-defect (Figure 1). Since an increase in yield strength is associated with an increased Y/T ratio and a decrease in uniform strain, one can conclude that high-grade pipes will have a lower level of defect tolerance than lower grade pipe. The intersection of the lower bound line to the X100 CWP test results with the strain axis should correspond to 3.5 % if the Y/T is smaller than 0.90. However, it not clear whether the stress-strain response obtained from uni-axial strap tensile tests can be used to evaluate the plastic behaviour of a pipeline under biaxial loading. Available data indicate that the Y/T ratio of a wide plate is higher than for strap specimens [27,28]. This suggests that the cross sectional area of a wider specimen experiences some degree of bi-axiality whereas the stress state in a 25 mm wide trip specimen is uni-axial tension. A study of this dependence should be the subject of future research.

Weld Strength Mismatch

As discussed, for a fixed defect size, overmatched welds permit more remote plastic strain than undermatched, Figure 1a, or matched, Figure 1d, ones. [29-32]. Consequently, the lower line AB, established by assuming that all welds were matching, can be shifted to the line XY according to the level of strength mismatch, Figure 1d. However, for a strain-based design, the selection of the value of the weld strength mismatch requires special consideration.

It is standard practice to define the weld strength mismatch in terms of yield strength. The percentage yield strength mismatch, OM_{YS}, and the corresponding mismatch factor in terms of yield strength are defined by:

$$OM_{YS} = \frac{YS - Y}{Y} 100 \quad (\%) \qquad \text{or} \qquad M_{YS} = \frac{YS}{Y} \qquad (2)$$

Where Y = pipe metal yield strength in the axial direction and YS = weld metal yield strength. Because of their definition OM_{YS} and M_{YS} have a similar significance.
The value of OM_{YS} or M_{YS} ignores the strain hardening effects of both pipe and weld metal on the post-yield strain capacity. Strain hardening is an essential variable when the nominal strain is

beyond yield. Therefore, the combined effects of yield strength mismatch and strain-hardening should be quantified by a mismatch factor based on flow stress:

$$M_{FS} = \frac{YS + TS}{Y + T} \qquad (3)$$

FSw (weld metal flow stress) and FSp (pipe metal flow stress) are defined by

$$FS_p = \frac{Y + T}{2} \qquad = FS_w = \frac{YS + TS}{2} \qquad (4)$$

Where T = pipe metal ultimate strength in the axial direction and TS = weld metal ultimate strength. The subscripts p and w refer to pipe and weld metal respectively.

The flow strength mismatch factor, $M_{FS,}$ defined by Eq. 3 combines the effect of yield strength and ultimate tensile strength mismatch into a single parameter. The value of M_{FS} also incorporates the effects of differing post-yield strain behaviours of the pipe and weld metal on strain partioning between the weld and remote regions. This can be understood by making reference to Figure 8, in which it is shown that yield strength overmatch does not automatically ensure that strength overmatching is maintained in the post-yielding loading range. The reverse also applies for yield strength undermatch. Note that, for easier illustration, the materials are assumed to have a linear strain hardening behaviour.

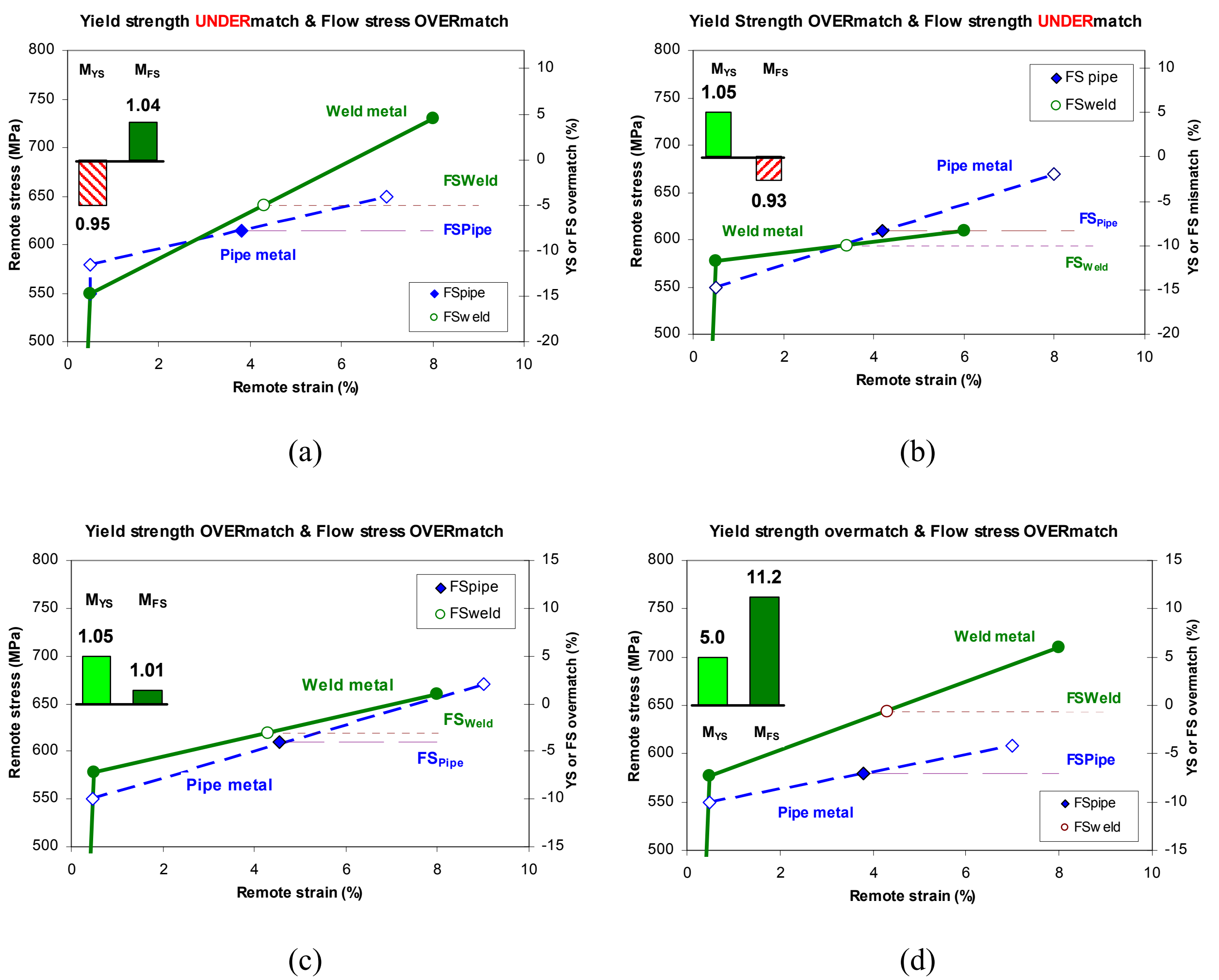
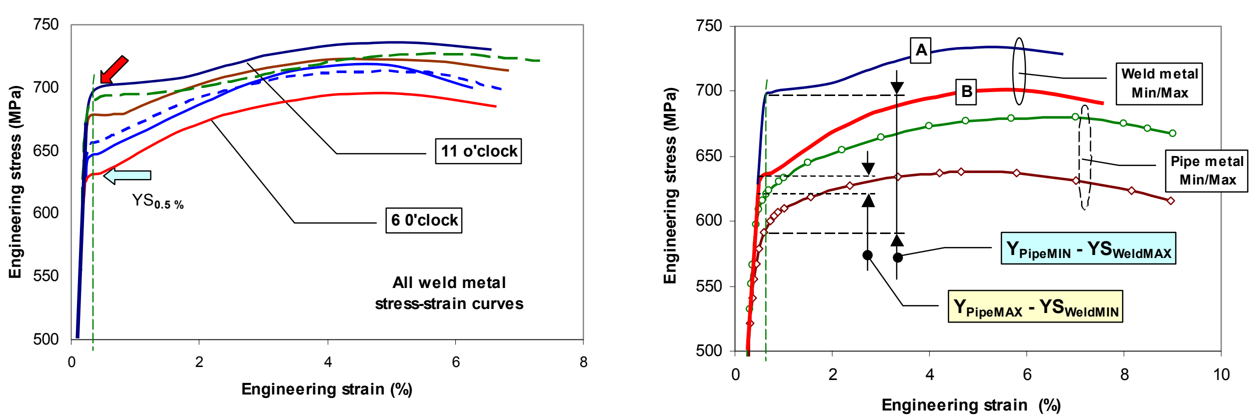


Figure 8. Effect of post-yield stress-strain behaviour on strength mismatch

Specifying that both mismatch factors M_{YS} and M_{FS} exceed unity ensures that the weld is effectively overmatched. This requirement may be conservative, but it excludes situations judged as overmatched in terms of yield strength are effectively undermatched in terms of post-yield deformation behaviour or ultimate tensile strength.

When the actual stress-strain curves are compared, it must be evident that the natural variability of the properties complicates the selection of a safe estimate of M_{FS}. This issue is illustrated in Figure 9. The plots in Figure 9a show the all-weld stress-strain curves of specimens sampled at various locations around the circumference. The outer curves A and B, representing the minimum and maximum all-weld metal tensile properties are compared against the minimum and maximum pipe metal tensile properties in Figure 9b.

Figure 9a illustrates that the weld metal tensile properties are sensitive to the sampling location. In general, the 6 o'clock position gives lower values than the 12 o'clock position for SMAW welds. The difference between the highest and lowest values can easily amount to 70 MPa [33]. This difference is due to the variation in weld bead shape around the circumference. For GMAW welds, the spread of the tensile properties is usually less prominent. On the other hand, it is easier to obtain strength overmatch in GMAW welds than for SMAW welds.



(a) – Weld metal stress-strain curves (b) – Effect on strength mismatch

Figure 9. Variation of weld metal tensile properties in a pipeline girth weld and effect of weld metal variation on weld strength mismatch

Since the actual and not the minimum specified material properties determine the strain limit, one can understand that statistical information must be available to determine the representative values of M_{YS} and / or M_{FS}.

Figure 9b demonstrates that the difference between the minimum and maximum value of M_{YS} can be very significant. The minimum value of M_{YS} is based on the minimum YS of the weld metal and the maximum Y of the pipe metal, the maximum is based on the maximum YS of the weld metal and the minimum Y of the pipe metal. Thus, the challenge is to determine the minimum value of M_{YS} and M_{FS}. In other words, when the information with respect to the tensile properties is limited to one single all-weld metal and one single pipe metal tensile test, significant errors can be made.

The practical implication is that the variation in weld metal tensile properties must be identified for each welding consumable / procedure combination. In addition, the complete load-elongation curve should be recorded. for both plate and weld metal. These records allow determining the values of the Y/T ratio, uniform elongation and level of weld metal strength mismatch. This requirement, considering the effect of the distribution of the pipe and weld metal tensile properties, may lead to more stringent material specifications.

Conclusion

This paper addresses issues that arise in the determination of the strain limit of girth welds containing a defect in the weld region. The issues discussed include the effect of (a) the variability of material properties, (b) the toughness and (c) the strength mismatch. This paper also provides guidelines as to how to handle these issues in a strain-based defect assessment.

The discussions are based on a simple empirical model that allows predicting the strain limit. This model, derived from the results of the CWP experiments, reflects the observation that, beyond a certain level of toughness, the tensile properties have a much greater effect on the strain limit than increased toughness has. By using data from welded Grade X70 and X80 pipe, it is demonstrated that high-toughness girth welds do not lead to greater remote strain capacity than girth welds of moderate but adequate toughness.

Although the predictions solely depend on the pipe and weld tensile properties, it is important to keep in mind that it is difficult to achieve great accuracy in the predictions. The inherent variability of the tensile properties hampers this. The issue is that a strain based design defect assessment requires the actual material properties as an input.

Despite this limitation, the investigations have shown that the material qualification procedures should account for the 'natural' pipe and weld metal variability. That is, the tensile properties need to be measured in sufficient number because individual pipes in a pipeline have different properties. Further, the study has demonstrated that the effect of the shape of the stress-strain on the strain limit can be substantial. In particular, this variable can have an important repercussion when analytical or numerical (FEA) procedures are used. Therefore, caution is advised when using standard linear power-law fit stress-strain curves for (a) low strain hardening materials and (b) for materials displaying discontinuous yielding behaviour. Rather, it is recommended to model the actual stress-strain response as correctly as possible. The modeling must encompass the entire inelastic stress-strain range up the ultimate tensile strength. This advice is given to avoid situations where analytical or numerical (FEA) strain-based defect assessment procedures render predictions that significantly deviate from the experimental facts reported in this paper.

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