UGENT GUIDELINES FOR CURVED WIDE PLATE TESTING

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Abstract - This paper provides the UGent guidelines for the design, testing and evaluation of tensile loaded CWP specimens for the assessment of flaw significance in pipeline girth welds. To allow a correct and independent interpretation of CWP test data, a summary of the required supplementary information that should be reported with CWP test data is provided. Laboratories providing CWP data are invited to evaluate and comment the guidelines. It is expected and desired that these comments will provide additional information for the development of an accepted CWP testing standard. Comments on the guidelines may be submitted to the above address.

INTRODUCTION

A cursory study of published CWP data allows concluding that significant differences in CWP test specimen dimensions and testing procedures exist [1-10]. It is also true that, all too frequently, CWP data appearing in the literature or in company reports is often inadequately documented. The issue is that the analysis and interpretation of CWP results could be doubted when the actual properties of the pipes and the girth weld in the immediate vicinity of the CWP specimen are not fully documented. Further, the use of the material properties derived from a “dummy” weld for the quantification of CWP behaviour can be questioned. Uniformity of instrumentation is also an issue which requires due consideration.

As there are currently no recommended guidelines for CWP testing available, this document outlines the is aimed at providing tentative guidelines for the design, testing and interpretation of a tensile loaded CWP specimen. Where needed, and to assist the reader in understanding the requirement’s implications, the rationale of some of the requirement is explained. Further, to ensure that the guidelines are correctly understood, brief comments on the background or typical examples, in the form of a graph or a photograph, are given. For convenience of reading, the explanatory “Notes” immediately appears after the requirement.

The UGent guidelines presented below would provide current and prospective CWP test laboratories the information needed to generate fully documented CWP data. Thus, when the suggested guidelines are applied, peers who wish to use CWP data will obtain test results that can confidentially be employed either for a direct assessment of a particular technical problem at hand or for the independent verification of the accuracy of numerical or analytical models.

HISTORICAL BACKGROUND OF CWP TESTING

The tensile loaded CWP test was developed at the Laboratory Soete, Universiteit Gent, Belgium, in 1979. The first CWP tests have been conducted to study the structural relevance of girth welds with low CTOD properties. These CWP tests, conducted to solve three unrelated field problems, demonstrated that low CTOD toughness does not automatically disqualify girth welds that are overmatching in strength. A further fundamental study of this interaction lead in 1986 to a
publication, which demonstrated that CWP testing is a very valuable tool to evaluate the strain capacity of defective girth welds [11].

Since 1979, the Laboratory Soete has conducted more than 1000 CWP tests in a variety of contexts. Nowadays, CWP tests are performed to obtain a more detailed understanding of the effects of:

- weld metal strength mismatch;
- toughness;
- flaw size (surface breaking, embedded flaws and flaw interaction);
- Y/T ratio and strain hardening capacity

on the strain capacity of girth welds containing either a single notch or multiple notches.

In the mid 1990s, CWP test results have been used to establish the EPRG-Tier 2 defect size limit for stress-based design and the world wide accepted EPRG 30 (min) / 40 (ave) J impact girth weld toughness requirement [12]. For reference, this toughness ensures plastic collapse at applied axial strains not greater than 0.5% provided:

- the defect area ratio (lh/Wt) of 3 mm high surface breaking defects is smaller than 7% of the cross section area (Wt),
- the yield-to-tensile ratio R (=Y/T) in the axial direction is not greater than 0.90, and
- the welds are matching / overmatching in yield strength.

In the last decade, the CWP test has developed into a widely applied technique for:

- optimising material requirements for strain based designs;
- validation of strain-based design flaw acceptance criteria;
- determining the failure characteristics and the maximum (limit) strain capacity;
- validating numerical models / flaw assessment concepts and identifying possible anomalies;
- studying phenomena (tearing behaviour, strength mismatch, ..) that cannot simply be modelled.

The CWP test is also used to quantify the sizing capabilities of AUT inspection, Figure 1. However, to obtain valuable information, the CWP test must be conducted at low temperatures (-50/-60°C) to force fracture to initiate from the defects and to exclude slow stable crack growth [14].

![Fig. 1 - Verification of defect dimensions](image)

Macro sectioning (salami technique) vs low temperature CWP tensile testing

1 The term “notch” is here used to indicate that the “flaw, defect, crack, anomaly or discontinuity” is intentionally placed in the weld region to be studied.
Note 1 - The CWP approach provides, in contrast to the classical “salami technique”, a direct visual access to the whole defect and prevents that the actual defect size (containment rectangle) is incorrectly estimated, Figure 1. In addition, the CWP technique allows assessing the severity of “natural” defects for the structural integrity. An additional benefit is that with the “AUT validation CWP test” the combined effects of “low temperature” toughness and weld strength mismatch on CWP performance can directly be assessed.

Finally, it is generally accepted that the CWP test provides structurally relevant information provided the loading mode of the structure is correctly simulated. Since the effect of internal pressure on weld performance cannot be simulated in a tensile loaded CWP, care should be taken in using CWP data in the analysis and interpretation of girth weld behaviour in the plastic loading range. However, despite this limitation, CWP test data is more useful than the results and analysis based on fracture mechanics (SEN, SENT, J-R) type tests.

Note 2 – The guidelines presented hereinafter can also be used for the testing of tensile loaded pressurized full-scale pipes (PFP). The CWP and the PFP are very similar tests. Apart from the fact the internal pressure causes a change of the constraint conditions at the defect tip, the performance levels of both tests are affected by the same variables.

PRIMARY CONSIDERATIONS FOR CWP TESTING

The CWP test cannot be standardised in the same way as, say, a CTOD test. Unlike the CTOD test, many more factors and the interaction between these factors affect CWP test performance. Consequently, the factors influencing CWP performance need to be identified and documented.

Users of CWP data have to appreciate that the overall or the remote strain capacity is a function of [15]:

- the specimen dimensions;
- the flaw size (length and height);
- the notch location;
- the toughness properties of the flawed region;
- the post yield stress-strain response (strain hardening characteristics, uniform elongation capacity, ..) of the materials in the flawed (weld) region and the remote pipe sections;
- the ductile tearing characteristics;
- the level of yield and flow strength mismatch;
- the geometry of the weld bevel;
- the weld reinforcement, etc.,...

Knowledge of the natural variation of weld and pipe tensile and toughness properties is also a prerequisite to comprehend CWP test performance. All in all, this implies that, in reporting CWP test results, all meaningful details of the pipe and weld metal properties, and the test procedure must be provided. On the other hand, the above introductory considerations allow emphasizing that technical proficiency is needed to perform and interpret CWP test results.
NOMENCLATURE AND DEFINITION OF TERMS RELATED TO CWP TESTING

This document uses CWP-specific terminology and symbols to exclude confusion with the standard definitions of terms and symbols used in established ECA, tensile and toughness testing standards. It is not claimed that the standard nomenclature is "wrong". The CWP terminology is simply created to aid communication and to emphasize that the data has been derived from a CWP test.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>Ave</td>
<td>Average value</td>
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<tr>
<td>CGHAZ</td>
<td>Coarse Grained Heat Affected Zone;</td>
</tr>
<tr>
<td>CMOD</td>
<td>Crack Mouth Opening Displacement (mm) (measured under tensile load)</td>
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<tr>
<td>CTOD</td>
<td>Crack Tip Opening Displacement (mm) (3-point bend test)</td>
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<tr>
<td>CVN</td>
<td>Charpy V impact test;</td>
</tr>
<tr>
<td>CWP</td>
<td>Curved Wide Plate test;</td>
</tr>
<tr>
<td>e</td>
<td>Average gross (or overall) strain limit of a girth weld with notch (%)</td>
</tr>
<tr>
<td>e_{pipe}</td>
<td>Pipe metal strain limit derived from average overall strain limit measurement (%)</td>
</tr>
<tr>
<td>e_A or e_B</td>
<td>Pipe metal strain limit occurring in pipe section A (or B) (%)</td>
</tr>
<tr>
<td>FL</td>
<td>Fusion line</td>
</tr>
<tr>
<td>FS</td>
<td>Flow stress (MPa)</td>
</tr>
<tr>
<td>M_{FS}</td>
<td>Weld strength mismatch (YS - Y)/Y</td>
</tr>
<tr>
<td>h</td>
<td>Notch height (mm)</td>
</tr>
<tr>
<td>l</td>
<td>Notch length (mm)</td>
</tr>
<tr>
<td>l_g</td>
<td>Gauge length (mm)</td>
</tr>
<tr>
<td>MWYS</td>
<td>Minimum weld metal yield strength (MPa or ksi)</td>
</tr>
<tr>
<td>OM</td>
<td>Weld metal yield strength overmatching</td>
</tr>
<tr>
<td>P</td>
<td>Tensile load at instability or maximum load (kN)</td>
</tr>
<tr>
<td>SMYS</td>
<td>Specified Minimum Yield Strength in the axial direction (MPa or ksi)</td>
</tr>
<tr>
<td>t</td>
<td>Wall thickness (mm)</td>
</tr>
<tr>
<td>T</td>
<td>Actual pipe metal ultimate tensile strength in axial direction (MPa or ksi)</td>
</tr>
<tr>
<td>TS</td>
<td>Actual weld metal ultimate tensile strength (MPa or ksi)</td>
</tr>
<tr>
<td>uEL</td>
<td>Percentage uniform elongation of the pipe metal in axial direction (%)</td>
</tr>
<tr>
<td>UM</td>
<td>Weld metal yield strength undermatching</td>
</tr>
<tr>
<td>UTS</td>
<td>Specified Ultimate Tensile Strength in the axial direction (MPa or ksi)</td>
</tr>
<tr>
<td>W</td>
<td>Plate width / arc length (mm)</td>
</tr>
<tr>
<td>WMC</td>
<td>Weld Metal Center</td>
</tr>
<tr>
<td>Y</td>
<td>Actual pipe metal yield strength in axial direction - 0.5% total (MPa or ksi)</td>
</tr>
<tr>
<td>YS</td>
<td>Actual weld metal yield strength - 0.5% total (MPa or ksi)</td>
</tr>
<tr>
<td>Y/T</td>
<td>Pipe metal Yield to Tensile ratio</td>
</tr>
<tr>
<td>YS/TS</td>
<td>Weld metal Yield to Tensile ratio</td>
</tr>
<tr>
<td>Δl</td>
<td>Average gross (or overall) elongation (mm)</td>
</tr>
<tr>
<td>Δl_{pipe}</td>
<td>Pipe metal elongation (mm)</td>
</tr>
<tr>
<td>σ</td>
<td>Applied remote (or gross) stress (MPa or ksi)</td>
</tr>
<tr>
<td>σ_n</td>
<td>Net section stress (MPa or ksi)</td>
</tr>
</tbody>
</table>

The terms “must”, “shall”, “will”, “should”, “may”, “might” and “can” identify the criticality of the requirements. In this document these terms have the following meaning:

- “must” or “shall” expresses a mandatory or imperative requirement;
- “will” indicates an anticipated future action or result;
- “should” is a recommendation (not a requirement);
- “may” or “might” expresses permission (but not a requirement);
- “can” expresses a capability available to the user.

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2 The inability to satisfy a “must” or “shall” requirement seriously affects the usefulness of the test result.
BASIC REQUIREMENTS

Test weld - As it is the objective to produce structurally relevant CWP data, the girth weld and the pipe-pup pieces shall be in the condition in which they will be used.

Note 3 - Pipe aged during plant and/or field coating process might exhibit a higher yield strength and Y/T ratio than “as-received” (bare) pipe [16].

When the CWP test is planned to demonstrate post yield strain capacity, every effort should be made to avoid weld strength undermatch. If possible, the pipe pieces shall be taken from the upper end of the yield strength distribution while the weld metal should be from the lower end of its distribution. A simple way to avoid this issue would be to select, for pipe complying with the CEN yield strength requirements (SMYS + 120 MPa)³, a weld metal with a yield strength (MWYS) of at least SMYS + 100 MPa [17].

Note 4 – Standard ECA methods assume or require that the weld metal yield strength is matching or overmatching the longitudinal yield strength of the pipe. However, weld metal specifications do not warrant that this is effectively the case. On the other hand, for thin wall pipe, a certain level of undermatching can be tolerated if the effect of weld reinforcement on CWP strain capacity is taken into account.

Note 5 - The value of MWYS is based on the pipe metal’s SMYS in the hoop direction. Since the longitudinal tensile properties are normally lower than those in the transverse/hoop direction, the required MWYS can be somewhat lower. However, this may not be the case for spirally welded pipe.

Specimen sampling - Figure 2 shows a typical arrangement of the specimens to be tested in CWP programme. However, irrespective of the number of CWP specimens to be extracted from the weld, the weld portion between the 5 to 7 o’clock position shall always be tested.

Fig 2 – Typical sampling plan (Not to scale) – See also Figs. 5 and 7

Note 6 - The 5 to 7 o’clock position represents the worst-case scenario for weld strength overmatching. The 6 o’clock position gives normally lower weld metal tensile properties than the 12 o’clock position. The difference between the highest and lowest values can amount to 70 MPa [18]. Consequently, this position has also the lowest level of strength overmatch while it is also very likely that the 6 o’clock position will have the lowest toughness properties.

³ The 2nd edition of ISO 3183:2007 increases the allowable range of yield strength for PSL 2 pipe to 150 MPa for grades L415 and higher.
Note 7 - The specimen arrangement shown in Figure 2 takes account of the possible differences in the longitudinal tensile properties of the pipe-pup sections (Pipe A and Pipe B) and the natural variation of the tensile properties of both the pipe metals and the weld metal around the circumference [T]. These variations are a critical variable in a defect assessment. In particular, the variation in the weld pass bead shape around the circumference has a significant effect on the weld metal properties. Thus, Figure 2 simply illustrates that CWP test results are only useful if the tensile and toughness properties of the pipes and the girth weld as close as possible to the CWP specimen are known.

Traceability - A unique code number shall be assigned to each test specimen. The code number shall include the exact sampling location and position to facilitate the analysis of the CWP test results. It is recommended to provide a sketch of the sampling location and positions from which the test samples are taken.

PIPE AND WELD METAL CHARACTERISATION

The tensile data of both pipe and weld, and the standard toughness (CVN and/or CTOD) properties shall be measured from the weld assigned for CWP testing. The tests shall be performed in accordance with established international standards. In addition, complementary hardness measurements on macro cross-sections normal to girth weld shall be made.

Note 8 - Even when welds were made under virtually identical conditions, experience shows that the tensile (and toughness) properties of a dummy weld might not be representative of those of the weld assembly from which the CWP specimen is taken. For this and other reasons, material property data from weld procedure qualification tests are also not suitable.

Macro sections and hardness measurements - The polished and etched transverse weld cross section(s) shall be photographed at a magnification of x2. The macro section shall be hardness tested using a 5kg pyramid diamond indenter (HV5). The indentations shall be made along traverses, each 2 mm below the pipe surface in the weld metal and at either side of the weld. A minimum of four indentations shall be made into the unaffected pipe metals. Hardness traverses shall be made at the cap and root positions.

Note 9 - The macro section(s) can be used to illustrate the general configuration and sequence of the weld runs within them. More importantly, macro sections are needed to assist the notch tip placement in the CWP specimen.

Note 10 - Since, as shown in Figure 3, it is not to be excluded that the test pipes have different tensile properties, hardness data can be used to quickly guess which pipe is weaker or stronger and should be monitored. The data can also be used to confirm whether the weld metal is under- or overmatched. Remark that this information can also be obtained from surface hardness tests.

Fig. 3 – Moiré fringe pattern showing the homogeneous and heterogeneous strain distributions in pipes adjacent to the girth weld.
Note 11 - Using established relationships between hardness and tensile strength, the measured hardness values can also be used to obtain a (crude) estimate of the level of pipe (tensile) strength mismatch.

Note 12 – The difference in tensile properties of the adjacent pipe pup-pieces in the test weld can be significant. This difference can also be the result of the natural variation of the tensile properties around the pipe circumference.

Tensile testing - The pipe and weld metal tensile properties and the shape of their post yield stress-strain response are essential parameters for the quantification of the level of strength mismatch and the measured strain capacity [15,19].

Note 13 – Figure 4 illustrates that the level of strength mismatch depends on many interdependent variables. Although a detail discussion of Fig. 4 is beyond the scope of this paper, it cannot be overemphasizes that for each pipe and for each all-weld metal tensile test the complete load-elongation curve shall be provided. These records are needed to provide information on the strain hardening characteristics (shape of the tensile curve), to determine the uniform elongation and to estimate the level of weld metal strength mismatch. Note that the determination of the all-weld metal tensile properties is a critical step in this process. The microstructural variations within the weld deposit can complicate the determination of representative properties (Figure 5).

Fig. 4 - Factors affecting the level of weld metal yield strength mismatch

Note 14 - The shape of the transition from elastic loading to post-yield loading (continuous vs discontinuous – Luder’s plateau - yielding) has a significant effect on the amount of crack tip blunting.
and ductile tearing behaviour. Further, the shape of the whole stress-strain is needed to understand and quantify the measured strain capacity [20].

**Pipe metal tensile tests** – Full-thickness 25 mm wide longitudinal specimens shall be tested. The specimen inner and outer surfaces shall not be machined. Both pipe pup-pieces shall be tested.

*Note 15* - Round bar pipe metal specimens shall not be used since the specimen dimension effects on the measured tensile properties can be significant for thick wall and TMCP pipe. This provision avoids the situation that the level of (yield) strength-mismatch is over-estimated.

**All-weld metal tensile tests** – The weld metal tensile properties shall be determined on all-weld-metal round bar (AW) tensile test specimens. The largest specimen diameter, which can effectively be removed from the girth weld shall be tested. The specimen size shall be such that the parallel length consists entirely of weld metal corresponding to a particular extraction position. When possible, the cap and root locations shall be tested. The extraction position(s) in the through-wall direction shall be clearly identified and documented.

*Note 16* - The variation of the weld heat from the 12 to 6 o’clock position affects the weld metal strength properties in the through-wall directions. Obviously, this is also an issue for welds made by filler metals of different strength.

*Note 17* - For narrow gap welds, it is recommended to demonstrate that the all-weld-metal test specimen sampled weld metal without any influence from dilution with the pipe metal, Figure 5.

*Note 18* – The dilution of the weld metal by the pipe metal has a direct influence on weld metal strength. For example, Figure 5 demonstrates that, in the case of an undermatched weld metal, the all-weld yield strength increases with the amount of (higher strength) pipe metal sampled. Thus, a post-test verification of the microstructure(s) sampled by the AW-specimen can provide useful information on the measured all-weld metal properties in a narrow gap weld.

*Note 19* - The validation of the microstructures sampled in the through-thickness for any type of weld preparation could also be useful to explain weld metal strength variation.

![Fig. 5 - Sampling effect on measured AW properties of an undermatched weld.](image)

**Properties to be measured** - For each pipe metal and each all-weld metal tensile test performed, the full stress-strain diagram shall be recorded. From these diagrams, the proportional limit, the \( R_{p0.2} \) and \( R_{0.5} \) yield strengths, the ultimate tensile strength and the uniform elongation (\( u\text{EL} \)) shall be determined.

**Toughness testing** - Charpy V notch impact (CVN) toughness tests shall be performed to verify whether the weld region (weld metal or HAZ) containing the flaw meets the project specific or any
other requirement. The Charpy test specimens shall be prepared in accordance with internationally accepted standards.

**Note 20** - For pipe wall thickness greater than 25 mm, CVN and CTOD toughness tests shall be performed for every CWP specimen tested.

**Note 21** - Although the CVN test cannot directly be used in a quantitative analysis, toughness testing can be focused on CVN. However, when the CWP test is aimed at the validation of numerical or analytical defect assessments, complementary CTOD and or J/R tests should be performed.

**Note 22** - Fracture mechanics tests have limitations. For example, the tearing behaviour observed in a bend loaded J/R test is not transferable to a post-yield tension loaded “component”. An associated issue is the resistance to ductile tearing under tension load depends on specimen size. Although a more detailed discussion is beyond the scope of this guideline, it might be said that the transferability of tearing behaviour observed in a J/R test is hopelessly complicated since the level of weld strength mismatch and defect size also intervene in this process (Note 27).

The CVN specimen blanks shall be taken in the transverse direction to the girth weld from either the weld root or cap at 2 mm below the pipe surface. However, unless the weld cap requires a specific assessment, it is a standard practice to focus testing on the weld root. The test piece size shall be the largest standard size that can be obtained. The notch in the CVN specimen shall be perpendicular to the pipe surface.

One set of three CVN specimens at both the weld centerline and the weld / pipe metal interface (HAZ) shall be tested. Testing should be concentrated on the weld / pipe metal interface of the low-strength pipe, as the highest plastic strains will be concentrated in this area. If the pipe metal tests identify strength differences of greater than 5 %, the impact toughness of both weld / pipe metal interfaces shall be tested.

**Toughness requirement** - If the defect area ratio in the CWP specimen is smaller 7 % of the remote cross sectional area, it is recommended to use, for each set of three tests, the EPRG requirement impact requirement of 30 J minimum and 40 J average. This requirement is to be obtained at minimum design temperature and applicable to full-size standard (10x10) test pieces. The requirement shall be reduced pro rata according to the cross sectional area of the test piece.

**Note 23** - If the impact toughness properties of the 5 to 7 o’clock location exceed the 30/40 J requirement by a factor of two, no further toughness testing is needed. It is considered that the safety factor of two compensates the effect of sampling location on toughness.

**Note 24** - CTOD testing could be considered if either one out of the three individual CVN test specimens or the average EPRG impact requirement cannot be met.

**Note 25** - The EPRG CVN toughness levels, assure that the CWP specimen will fail at a minimum applied remote applied strain of 0.5 % provided the EPRG provisions in terms of Y/T ratio (< 0.90) and defect area ratio (> 7 %) are satisfied. Moreover, when the weld region complies with the “threshold” 30/40 J toughness requirement, experience has shown that strain capacity is more significantly affected by the Y/T ratio and / or yield strength mismatch than the toughness [17].

**CWP TEST SPECIMEN**

**Specimen preparation** - The CWP test specimen(s) can be extracted from the welded pipe-pups by flame cutting. After flame cutting, the CWP specimen(s) shall not be flattened while the longitudinal specimen edges within the reduced prismatic (test) section shall machined straight and parallel to each other. The reinforcements at either side of weld shall not be removed. However, in

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4 This paper does not provide specific requirements on CTOD and J-R fracture mechanics testing.
the region of the notch, the weld reinforcement shall be ground flush to facilitate the accurate placement of the notch.

Note 26 – The weld crown (weld reinforcement) provides “geometric” overmatch. The effect of weld reinforcement on strain capacity can be very effective for slightly undermatched welds in thin wall pipe.

Specimen dimensions - The nominal dimensions of a “standard UGent” CWP specimen are shown in Figure 6. The overall specimen dimensions are 1,4 W (length of attachment weld) by 4W (overall specimen length).

![Specimen Dimensions Diagram](image)

Note 27 – To obtain structurally representative CWP data, the prismatic section of the specimen should be long and wide enough to simulate an infinite plate, since corrections for finite length and width are not available. The issue is that the geometric effects produced by changing specimen dimensions relative to notch size on the net section stress and thus on tearing behaviour is not yet understood. Our present understanding is based on analytical models that do not take account of ductile tearing. The complexity is that the amount of ductile tearing depends on the level of both the in-plane (through-thickness) and the lateral (width direction) constraint. For example, for a notch of fixed size in a matching weld, decreasing specimen width causes a decrease of the lateral constraint around the notch tip thereby introducing ductile tearing at a lower level of remote stress. Note that a decrease in wall thickness for a notch of fixed height has a similar effect. The relief of constraint causes an increase of the net-to-gross section stress ratio with the result that failure will occur at lower gross stress levels. In other words, the net section stress, the amount of ductile tearing and thus the CMOD will increase more rapidly in a narrow specimen, Figure 7.

The CMOD-remote strain plots in Figure 7 illustrate that the critical condition in a narrow specimen will occur at lower levels of CMOD and remote strain. Consequently, data from narrow or “mini” CWP test provides a distorted picture of the strain capacity occurring in wider specimens. In a (very) wide specimen, the lateral relief of constraint is inhibited so that the geometrical related relief of constraint solely depends on the notch area ratio (in-plane constraint). Therefore, care is required in using mini/sub-sized/intermediate wide plate test data. However, is not claimed that a 300 mm wide CWP specimen is the perfect analogue of the full-scale pipe under internal pressure. Recall also that, as mentioned above, the effects of the complex interaction of the strain hardening capacity (represented by the all inclusive Y/T ratio), the loading mode (tension vs bending) and the level of strength mismatch intervene in the ductile tearing process.

Notch - The CWP specimen shall be provided with either a weld metal centre or a HAZ surface-breaking notch introduced from either the root or the cap side. The notch shall be oriented parallel
with respect to the welding direction. The notch dimensions shall represent a worst-case weld anomaly that might occur within the weld metal or heat-affected zone of the girth weld.

![Fig. 7 - Effect of specimen width on CMOD and strain capacity.](image)

**Note 28** - By placing the notch in the HAZ of the strongest pipe, the effect of the lowest level of weld strength overmatch on strain capacity will be evaluated. Note also that wall-thickness variations might have a similar effect. It can also argued that HAZ testing should be concentrated on the HAZ/weld metal interface of the weakest pipe, as the highest plastic strains will be concentrated in this area.

**Note 29** – No specific guidance can be given for HAZ/fusion line testing. Considerable trial-and-error experience is needed to ensure that the notch is properly positioned.

**Notch location** - For HAZ testing and if the pipe metal hardness measurements reveal significant yield strength differences, the notch should be located in the HAZ zone of the strongest pipe.

**Note 30** - The above restrictions on notch area ratio assume matching welds. For overmatched welds, larger notch area ratio can be tested. This in turn means that the application of the 7% (or 3%) limit for overmatched welds will allow greater remote strain.

**Note 31** - The presence of a weld crown in thin wall pipe (cap weld reinforcement) and “ample” strength overmatch might allow a relaxation of the 7% (or 3%) limit(s).

**Note 32** - The 7% (or 3%) notch area ratio limit(s) ensures the onset of remote yielding (applied remote strain = 0.5%) and have significant implications for defect acceptance in strain-based designs. That is, researchers who currently attempt to develop ECA based defect acceptance criteria for strain-based designs need to take account of the experimentally observed fact that the allowable defect area ratio must be smaller than the 7% (or 3%) limit(s).

**Notch preparation** - The flaw shall be made using a thin (0.15 mm wide) jewelers’ cutting wheel or by electro erosion. The leading edge of the notch needs only to be sharpened with a fatigue crack if the notch toughness of the flawed area is smaller than 30/40J.
Note 33 - If the weld region complies with the EPRG CVN toughness requirements, there is no need to pre-fatigue the notch in the CWP specimen.

Specimen measurements

The plate width and thickness within the prismatic section of each pipe shall be measured at two locations within the pipe metal gauge lengths prior to testing. From these four measurements, the minimum gross cross sectional area shall be retained to determine the gross section stress at failure. In addition, the high-low at the inner pipe surfaces shall be measured.

Load application

The CWP specimen shall be welded to (re-usable) rigid loading pull-tabs to assure uniform distribution of the load over the prismatic cross-section. To minimise possible out of plane bending during testing, precautions shall be taken to assure that the centroid of the cross sectional area of the prismatic (test) section coincides as nearly as possible with the load application line.

SPECIMEN COOLING

The CWP test shall be conducted at the design temperature. Cooling can be achieved either by liquid nitrogen or by a refrigerated liquid (methanol, iso-pentane, anti-freeze, …). By circulating, in closed-loop, refrigerated liquid (methanol, iso-pentane, anti-freeze, …) at high speed through cooling (curved) boxes, firmly clamped against the specimen surfaces, it is quite easy to obtain homogeneous cooling throughout the prismatic section of the test specimen. Cooling by liquid nitrogen can be implemented by spraying (or pouring) liquid nitrogen onto the specimen surface or by using pads with copper piping through which liquid nitrogen is circulated.

The specimen sections not in direct contact with the cooling medium shall be insulated in order to reduce sharp temperature differences between the cooled and un-cooled specimen sections.

Note 34 - Warmer specimen sections might cause premature deformations. These deformations affect the deformation pattern of the cooled sections, which in turn might result in an overestimate of the measured deformations. To minimize heat gain from the loading lugs, the specimen and the loadings lugs additional cooling with solidified CO₂ (dry-ice) can be used.

Note 35 - Since the strain energy causes a rise in temperature during the test, a cooling unit with sufficient "cooling capacity" shall be used. Therefore, cooling by a liquid is the preferred method because of its higher refrigerating capacity. Further, unlike liquid nitrogen cooling, cooling by a liquid, circulated at high speed, allows a better control of the cooling temperature during the test.

Cooling shall be maintained for at least one hour before CWP testing is started. The temperature shall be monitored by two spot-welded thermocouples. One thermocouple shall be located in the very near vicinity of the notch. The second thermocouple shall be located on the remote (unnotched) surface, at a distance of 1.7W from the plane of the notch.

INSTRUMENTATION

The specimen shall, as a minimum, be instrumented with four (4) spring loaded Linear Variable Differential Transducers (LVDT). The LVDTs shall measure the relative displacement of steel pins spot-welded onto the longitudinal specimen edges (GL 1 & GL2) and the pipe body surface (GL3 & GL4).

Figure 8 details the recommended placement of the gauge lengths. The accuracy of the LVDT transducers should be better than 0,01 mm on their full range.
**Note 36** - When strain gauges are used, the measurements might provide misleading information. In particular, a single strain gauge cannot capture the heterogeneous nature of the deformations over larger areas in the early post-yield loading range.

**Note 37** - The location of the gauge lengths GL3 & GL4 with respect to the plane of the notch takes account of the fact that, the spread of yield occurs in a direction of about 45° to the tensile axis on either side of the crack axis. The direction of these yielding bands is dependent on the material's strain hardening response and the length of the crack. For a material of high initial strain hardening (or with a low Y/T ratio) the orientation of the yielded zones will effectively approach the direction of 45° to the tensile axis, whereas a low strain-hardening rate (or a high Y/T ratio) will produce plastic zones, which have an orientation closer to the crack axis.

**MEASUREMENTS**

Throughout test, the applied tensile load, $P$, the crack mouth opening displacement, $\text{CMOD}$, the overall and remote elongation shall continuously be monitored and recorded using a data acquisition system at a sampling rate of minimum 5 measurements per second.

**Load measurement** - The accuracy of the load measuring system should be better than 1% of the full scale capacity of the test rig.

**CMOD** - The crack mouth opening displacement, $\text{CMOD}$, shall be measured by means of a clip-on measuring device which follows the relative displacement of two steel pins, straddling the notch at mid-length. These pins should be installed as close as practical to plane of the notch. The clip-on gauge, mounted between knife-edges, should have a linear stroke of 10 mm and an accuracy of 0.01 mm.

**Note 38** - A CMOD measurement gives information on the crack mouth opening and is thus not directly comparable with a CTOD value as measured in the CTOD bend test. As a matter of fact, CMOD measurements give a relatively crude estimate of the increase of the crack driving force with applied strain. However, for an experienced eye, CMOD-elongations records provide valuable information on the variations in the strain behaviour during CWP testing. Figure 9. The CMOD-remote strain responses shown in Figure 9 were obtained from CWP specimens containing a notch of fixed size).
Curve A (Failure mode: Net Section Yielding)
- Undermatched girth weld

Curves B through F (Failure by remote yielding)
- Overmatched welds: $M_F > M_E > M_D > M_C > M_B$ ($M$ = level yield strength mismatch)
- Plot F: Girth weld failed in the pipe body.

Remark: The yielding behaviour of pipe metal in girth weld E was discontinuous (Luder’s plateau).

Fig. 9 - Comparison of CMOD (driving force) versus remote strain plots.

Overall deformation measurements - The overall elongation, $\Delta l_0$, shall be measured on a gauge length, $l_0 = 2W$ (GL1 and GL2), straddling the girth weld at mid-span. The elongation measuring devices have a linear stroke of nominally 40 mm.

Note 39 - The use of two LVDTs ensures compensation for any in-plane bending effects, which might be caused by any eccentricity of the load application line.

Remote deformation measurements - The remote elongations of the homogenously strained pipe sections at either side of the girth weld, $\Delta l_{\text{Pipe A}}$ and $\Delta l_{\text{Pipe B}}$, shall be measured on a gauge length $l_{A(B)} = W/2$ along the longitudinal axis of symmetry onto the inner walls. The LVDTs used for these measurements should have a linear stroke of nominally 20 mm.

TEST PROCEDURE

The CWP test procedure shall be similar to that of conventional tension testing practice. However, special care has to given to the post-test investigations.

Duration of the test - The test shall be performed under displacement control at a constant actuator displacement rate of 1 mm/minute. Straining shall be continued until the critical event (i.e. at maximum load instability or unstable fracture) or shall be interrupted after exceeding the maximum load (onset of pipe necking).

In the event of maximum load instability, straining shall be continued to slightly beyond maximum load, i.e., until clear evidence of the occurrence of maximum load is obtained.

Post-test specimen handling – Upon completion of testing, the notch region and the fracture surfaces shall be protected with a water displacing corrosion preventive compound to ensuring that the fracture faces remain in a condition suitable for subsequent visual and optical examinations.

If no failure occurs, the compound shall be sprayed into the notch. Subsequently, photographs of the test specimen and the notched region shall be taken. Further, for convenience of handling and access, the fracture faces or a 50 mm wide strip containing the notched shall be separated from the specimen by saw cutting.
DATA ANALYSIS

From the load and elongation data recorded, the following graphs shall be generated:

- $\sigma - e_0$ and CMOD – e_0
- $\sigma - e_{\text{pipe}}$ and CMOD - e_{pipe}
- $\sigma - e_A$ and CMOD - e_A
- $\sigma - e_B$ and CMOD - e_B

These graphs shall be used to determine the gross (remote) and net section stress, the average gross (or overall) strain, $e_0$, the average remote (pipe metal) strain, $e$, the remote (pipe metal) strains $e_A$ and $e_B$, and the CMOD at the critical event, i.e. at the occurrence of either maximum load instability, unstable fracture or maximum load, as applicable.

Note 40 – In the event that the specimen can be strained beyond maximum load, there exists no generally accepted procedure for determination of the “critical” stress and strain when the stress-strain curve displays a “flat” portion around maximum load. The inherent noise of the raw stress-strain data also complicates the exact determination of the “actual” maximum load. However, by using an enlarged portion of the stress-strain plot at maximum load, one of the following methods can be used to estimate the maximum load, Figure 10.

Figure 10 – Comparison of procedures for the determination of maximum load

- The first method involves the direct observation of the point where maximum load “peak” occurs (see encircled load peak);
- The second method involves the construction of an average curve and using the maximum “average” load;
- The third method defines the maximum as the load corresponding to maximum “average” (bell-shaped) load minus 1 MPa on the increasing portion of the average curve (see encircled circle at the intersection of the average curve and the horizontal dashed line);
- With the fourth method, it is assumed that the maximum load can be represented by the average of the three maximum load peaks.

Although, a detailed discussion of advantages and drawbacks of these methods is beyond the scope of the paper, Figure 10 and similar comparisons reveal that the second (maximum of average curve) and fourth method provide comparable estimates. Therefore, the fourth method is recommended, as it is easy to apply. Note also the estimates based on either the maximum load peak (first method) or the third method can either overestimate or underestimate the real maximum value. The differences can be more than 1 % [21].
**Gross and net section stress** - The gross section stress, $\sigma$, shall be determined by dividing the tensile load at the critical event by the minimum gross cross sectional area. The net section stress, $\sigma_n$, shall be determined by dividing the tensile load at the critical event by the net sectional area. For uniformity of analysis, the notch dimensions (length and height) are to be determined from the dimensions of the rectangle that fully contains the original notch, i.e. ductile crack extension shall not be included.

**Average gross and remote strains** - The average gross strain, $e_o$, shall be determined by dividing the overall elongation, $\Delta l_0$, by the gauge length $l_0 = 2W$ ($e = \Delta l / l_0$).

The average remote pipe metal strain, $e_{pipe}$, shall be calculated from the overall elongation, $\Delta l_0$, and the CMOD measurement. Since the overall elongation, $\Delta l$, is composed of the crack mouth opening displacement (CMOD) and the elongation of the adjacent pipes, $\Delta l_{pipe}$, the “average” remote elongation/strain capacity can be estimated from:

$$\Delta l_0 = \Delta l_{pipe} + \text{CMOD}$$

By dividing by the gauge length, $l_0$, and re-arrange the terms, one obtains:

$$e_{pipe} = e_o - \frac{\text{CMOD}}{l_0}$$

**Pipe metal strains** - The strains in the pipes at either side of the weld ($e_{pipeA}$ and $e_{pipeB}$) shall be determined by dividing the pipe metal elongations, $\Delta l_A$ or $\Delta l_B$, by the gauge length $l_A$ or $l_B$ (=W/2).

**Note 41** - The average remote pipe metal strain, $e_{pipe}$, derived from Eq. 1 underestimates its actual value since CMOD, as measured in a CWP test, is greater than the “true” CMOD, Figure 11a. The difference increases with increasing strain levels because of effects of local rotation on CMOD.

**Note 42** - The average gross strain, $e_o$, is smaller than the average remote pipe metal, $e_{pipe}$ (Eq. 1). However, the pipe metal strains, $e_{pipeA}$ and $e_{pipeB}$, provide the best estimates of the strains occurring in each of the pipes, Figure 11b. These strains are also needed to judge and analyse CWP performance.

Data obtained from CWP tests using the instrumentation shown in Fig. 8

![Graph (a)](image1)

![Graph (b)](image2)

Fig. 11 - Comparison of (a) the average gross strain with the overall remote strain and (b) the pipe metal strains.
Post-test examinations – The post-test examinations shall include the accurate measurements of the notch dimensions and the determination of notch tip position with respect to the target. This will be achieved by metallographical investigations as detailed below. Photographs of the fracture faces shall be made and described.

Note 43 - The characterisation of the failure modes encountered in CWP testing is given in the companion paper [22].

Post-test metallography - Post-test metallography shall be performed to visualise the microstructure sampled by the notch tip (validity check) and to illustrate the fracture path in the vicinity of the notch tip and through-thickness direction relative to the fusion boundary. In other words, macrographic and micrographic examinations shall be conducted to verify whether the notch tip effectively intercepted the target microstructures. However, the method of investigation differs for unbroken and fractured specimens.

In the event of complete (unstable) fracture, cross sections perpendicular to both the weld metal and pipe metal side of the fracture face shall be extracted for the metallographic examinations. The sections shall be extracted through the crack initiation point, if any, or through the deepest point of the notch. The initiation point shall be determined by visual inspection under the stereomicroscope.

Note 44 – The use of one single cross-section might provide incomplete information. When the variation of weld bead height along the notch bottom and the waviness of the fusion boundary complicate the identification of the target microstructure, the investigations might require the study of additional cross sections. This investigation might involve an examination by a scanning electron microscope (SEM) if this is thought to be necessary.

When the wide plate had remained unbroken the central portion of the weld, incorporating the flaw, shall be separated from the CWP specimen by saw cutting. This portion shall be either left intact (Option 1) or opened up in three-point bending after cooling in liquid nitrogen to reveal the notch dimensions and the extent of tearing (Option 2). When the notch is opened up in bending in liquid nitrogen, the examinations shall be performed as described for the case of a broken specimen.

The extracted cross sections shall be ground, polished and etched in 2 % nital to reveal the weld and heat affected zone (HAZ) microstructures. After etching, the sections shall be studied under an optical microscope. Both a macro photograph (magm: x1/2) and two microphotograph (magm: x50 and x200) of the notch tip region should be taken. On these photographs, an arrow shall identify the original notch tip, Figures 12a and 12b.

Fig. 12a – Cross sections of the notch showing blunting (and ductile tearing) - Notch sampled the target location (Fusion line)
The photographs shall be used to:

✓ illustrate and measure the actual notch tip placement relative to the weld metal centreline or the target CGHAZ / FL microstructures. The shortest distance between the fusion line and the notch tip shall be reported;

✓ determine whether slow stable crack extension (ductile tearing) occurred in the weld metal, heat affected zone (HAZ) or pipe metal,

✓ measure and quantify the linear extent of through-thickness slow stable crack growth (stable ductile tear) at the initiation point or at mid-length of the notch, as applicable.

Metallurgical validity requirement – When the notch tip placement is aimed at sampling the CGHAZ / fusion line, the test shall be considered to be acceptable when the distance between the target microstructure and the actual notch tip is smaller than 0.5 mm. When this requirement is not achieved, Figure 12b, additional investigations shall be performed to allow a re-qualification of the practical significance of the test results.

Reporting

All pertinent information gathered during the test shall be reported to allow independent experts to assess the test result. Table 1 itemises, as a minimum, the essential variables to be reported. In addition, the following information shall be provided:

✓ The full strain curves of the pipe / all-weld metal tensile and CWP tests;
✓ The gross stress – remote strain curves;
✓ The CMOD – remote strain curves;
✓ Photographs of the fracture faces and macro section(s).

Photographic documentation - The photographs of both fracture faces (weld and pipe metal side) and fracture path in the circumferential direction shall be used to illustrate

---

5 The examples shown in Figure 12 were obtained from a CWP specimen that failed in the body.
### Table 1 – CWP test data sheet

#### A - IDENTIFICATION OF TEST WELD

<table>
<thead>
<tr>
<th>Pipe / Sample #</th>
<th>Pipe diameter and wall thickness</th>
<th>Pipe supplier</th>
<th>SAW, spiral, …. welded pipe</th>
<th>Welding process (girth weld)</th>
<th>Location of CWP specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>inch</td>
<td>mm</td>
<td></td>
<td>d’clock</td>
<td></td>
</tr>
</tbody>
</table>

#### B - MATERIAL PROPERTIES

<table>
<thead>
<tr>
<th>PIPE METAL PROPERTIES</th>
<th>Pipe A</th>
<th>Pipe B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength (R_{0.2})</td>
<td>Y_{0.2}</td>
<td>MPa</td>
</tr>
<tr>
<td>Yield to tensile ratio</td>
<td>(Y/T)_{0.2}</td>
<td>MPa</td>
</tr>
<tr>
<td>Uniform elongation</td>
<td>uEL_{0.2}</td>
<td>%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WELD METAL PROPERTIES (Average of 2 values)</th>
<th>Pipe A</th>
<th>Pipe B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength (R_{0.2})</td>
<td>YS</td>
<td>MPa</td>
</tr>
<tr>
<td>Yield to tensile ratio</td>
<td>YS/TS</td>
<td>MPa</td>
</tr>
<tr>
<td>Uniform elongation</td>
<td>uEL</td>
<td>%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LEVEL OF STRENGTH MISMATCH</th>
<th>Min.</th>
<th>Ave.</th>
<th>Max.</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength mismatch</td>
<td>M_{YS}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow stress mismatch</td>
<td>M_{FS}</td>
<td>%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOUGHNESS PROPERTIES* **</th>
<th>Pipe A</th>
<th>Pipe B</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTOD - Weld metal</td>
<td>CTOD_{W}</td>
<td>mm</td>
</tr>
<tr>
<td>CVN - Weld metal</td>
<td>CVN_{W}</td>
<td>J</td>
</tr>
<tr>
<td>and/or</td>
<td>CTOD_{HAZ}</td>
<td>mm</td>
</tr>
<tr>
<td>CVN - HAZ</td>
<td>CVN_{HAZ}</td>
<td>J</td>
</tr>
</tbody>
</table>

* of notched region
** at CWP temperature

#### C - CWP TEST RESULTS

<table>
<thead>
<tr>
<th>SPECIMEN DIMENSIONS</th>
<th>Pipe A</th>
<th>Pipe B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc length prismatic specimen</td>
<td>W</td>
<td>mm</td>
</tr>
<tr>
<td>Wall thickness prismatic specimen</td>
<td>t</td>
<td>mm</td>
</tr>
<tr>
<td>Length prismatic section</td>
<td>L</td>
<td>mm</td>
</tr>
<tr>
<td>High-low hilo</td>
<td>hilo</td>
<td>mm</td>
</tr>
<tr>
<td>Cap en root weld re-inforcement (or macro section)</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Cooling medium / test temperature</td>
<td>T</td>
<td>°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NOTCH DETAILS</th>
<th>Pipe A</th>
<th>Pipe B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (WMC or HAZ)</td>
<td>l</td>
<td>mm</td>
</tr>
<tr>
<td>Height</td>
<td>h</td>
<td>mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEST RESULTS (at maximum load instability)</th>
<th>Pipe A</th>
<th>Pipe B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross stress</td>
<td>σ</td>
<td>MPa</td>
</tr>
<tr>
<td>Net stress</td>
<td>σ_{n}</td>
<td>MPa</td>
</tr>
<tr>
<td>CMOD</td>
<td>CMOD</td>
<td>mm</td>
</tr>
<tr>
<td>Pipe metal strain A</td>
<td>e_{A}</td>
<td>%</td>
</tr>
<tr>
<td>Pipe metal strain B</td>
<td>e_{B}</td>
<td>%</td>
</tr>
<tr>
<td>Average overall strain</td>
<td>e</td>
<td>%</td>
</tr>
<tr>
<td>Average remote (pipe metal) strain</td>
<td>e_{r}</td>
<td>%</td>
</tr>
<tr>
<td>Failure mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length ductile tear</td>
<td>LT</td>
<td>mm</td>
</tr>
</tbody>
</table>

Table 1 – CWP test data sheet
✓ the fracture appearance;
✓ the linear extent of through-thickness ductile flaw extension;
✓ the location of the fracture path relative to the girth weld;

Miscellaneous measurements and investigations such as SEM investigations, etc, shall equally be reported.

Finally, when a CWP specimen with a fatigue pre-sharpened crack is tested, the type of loading for fatigue cracking, stress level used, R ratio and number of cycles shall be reported.

ACKNOWLEDGEMENT

The authors, “Tony and Rudi” wish to emphasize that they acknowledge the very valuable suggestions made by the many users of CWP data for perfecting the UGent CWP test procedure.

References


