

RECOMMENDED PRACTICE
DNV-RP-F108

FRACTURE CONTROL FOR
PIPELINE INSTALLATION METHODS
INTRODUCING
CYCLIC PLASTIC STRAIN

JANUARY 2006

DET NORSKE VERITAS

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This document is valid until superseded by a new revision. Minor amendments and corrections will be published in a separate document normally updated twice per year (April and October).

For a complete listing of the changes, see the "Amendments and Corrections" document located at: <http://www.dnv.com/technologyservices/>, "Offshore Rules & Standards", "Viewing Area".

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Introduction

This Recommended Practice is developed to give guidance regarding testing and analyses for fracture control of pipeline girth welds subjected to cyclic plastic deformation, e.g. during installation by the reeling method, but also for other situations with large plastic strains.

DNV-RP-F108 will complement DNV-OS-F101 and give more detailed guidance for:

- Tests for characterisation of the materials Fracture Resistance.
- Engineering Critical Assessment (ECA) procedures for determination of Acceptable Flaw Sizes in Girth Welds subjected to Large Cyclic Plastic Strain.
- A test program for Validation of the Assessment Procedure.

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11 Technical Reports, see Section 6 REFERENCES no's [3] - [13], were produced in the project and serve as background for the Project Guideline and hence also for this Recommended Practice.

CONTENTS

1.	GENERAL	7			
1.1	Introduction	7	3.4.1	Assessment level.....	11
1.2	Scope and application	7	3.4.2	Determination of reference stress	11
1.3	Structure of the Recommended Practice.....	7	3.4.3	Determination of $L_{r\ max}$	12
1.4	Relationship to general pipeline design codes.....	8	3.5	Determination of primary and secondary stresses.....	12
2.	FRACTURE RESISTANCE TESTING	8	3.6	Cyclic analysis	13
2.1	Purpose of the testing	8	4.	VERIFICATION BY TESTING	13
2.2	General	8	4.1	Purpose of the testing.....	13
2.2.1	Specimen type.....	8	4.2	The segment specimen	13
2.2.2	Cyclic loading.....	8	4.2.1	Dimensions	13
2.2.3	Hydrogen embrittlement.....	9	4.2.2	Notch size	14
2.3	Monotonic testing of SENT specimens	9	4.2.3	Instrumentation.....	14
2.3.1	General.....	9	4.3	Testing procedure	14
2.3.2	Crack orientation and location.....	9	4.4	Post test investigations and analyses	14
2.3.3	Specimen dimensions	9	5.	SENSITIVITY ANALYSIS	14
2.3.4	Loading conditions	9	6.	REFERENCES.....	15
2.3.5	Testing conditions.....	9	7.	FIGURES.....	16
2.3.6	Formulas to calculate J for SENT specimens	10	APP. A	DETERMINATION OF J	18
3.	ENGINEERING CRITICAL ASSESSMENT (ECA)	11	APP. B	DETERMINATION OF WALL THICKNESS AND MEMBRANE STRESS FOR ANALYSES OF PIPES WITH COUNTER BORE	21
3.1	Purpose of the ECA	11			
3.2	General	11			
3.3	Failure Criteria.....	11			
3.4	Failure Assessment Diagram (FAD).....	11			

1. General

1.1 Introduction

Modern pipeline design is normally based on the principles of Limit State Design. This implies that each failure mode shall be considered and designed for independently. Many design codes, e.g. DNV-OS-F101, Submarine Pipeline Systems, 2000 [1], give general requirements for such Limit State Design and for many of the failure modes specific requirements are given.

For pipelines installed by the reeling method, and also other methods introducing large plastic strains, fracture of the girth welds during installation is one of the potential failure modes and it needs to be demonstrated that the pipeline system has adequate resistance against both crack extension by tearing and unstable fracture during installation as well as during operation.

Common flaw assessment procedures, e.g. BS 7910:2005 [2], are not explicitly developed for such situations with large cyclic plastic strains.

This Recommended Practice is therefore developed to give guidance regarding testing and analyses for fracture control of pipeline girth welds subjected to cyclic plastic deformation, e.g. during installation by the reeling method, but also for other situations with large plastic strains.

1.2 Scope and application

This Recommended Practice considers plastic straining during the installation phase.

The plastic straining shall be limited to typical reeling situations (around 3% nominal strain)

In addition to installation, the commissioning and operation phases must be considered in order to assure safe operation during the whole life of the pipeline.

Although some advice is given in the Recommended Practice, more specific requirements are given in e.g. DNV-OS-F101 [1].

The Recommended Practice describes:

- tests for characterisation of the materials fracture resistance
- Engineering Critical Assessment (ECA) procedures for determination of acceptable flaw sizes in girth welds
- a test program for validation of the assessment procedure.

The Recommended Practice assumes that the weld strength (combined effect of tensile properties and geometry of both the weld and HAZ) over-matches or even-matches the parent pipe.

If the strength of the weld under-matches that of the parent pipe, the advice and recommendations of this Recommended Practice may not be sufficient and specialist advice is recommended.

Guidance note 1:

This Recommended Practice is mainly based on experience from tests and finite element analyses as well as practical installation experience from modern linepipe steels of type API 5L X52 to X65 welded by modern, well proven, welding methods giving ductile weldments. Pipe dimensions have typically been 6 to 16 inch OD and wall thickness of 15 to 25 mm. The methodology is also considered to be applicable for X70, 13Cr Martensitic Steels and 22Cr / 25Cr Duplex Stainless Steels provided ductile weldments are documented.

Additional work may be necessary if there is a significant difference between the materials and welding methods employed in the pipeline and those mentioned above (e.g. significantly higher strength, significantly lower fracture resistance or significantly different welding methods), or, the predictions of crack extension by tearing differ significantly from what is observed in the Segment tests (see Sec.4).

In cases where extensive experience exists and can be documented both with the linepipe material and welding procedure it may be possible to reduce the amount of testing and analyses recommended in this Recommended Practice.

For pipe dimensions significantly smaller than mentioned above, e.g. umbilical tubes, other testing and evaluation methods should be considered.

In all these instances expert advice is recommended in order to optimize testing and analyses.

It is recognised that testing and ECA methods are still evolving and, consequently variations to this Recommended Practice may be acceptable provided these are supported by appropriate test and analyses results.

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Guidance note 2:

Some steels may be susceptible to hydrogen embrittlement both from welding and from cathodic protection. This must be considered when specifying both welding and testing conditions.

In cases where the steel may be susceptible to hydrogen embrittlement and hydrogen could be introduced during welding it should be noted that after completion of welding, the hydrogen will diffuse out of the weld over time. If the time between completion of pipe welds and the plastic straining during pipe installation, is short compared to the interval between completion of the test welds and the testing, then the fracture resistance estimate may be unrepresentative of the real structural welds. This problem can be reduced by either reducing the interval between welding and testing, or by chilling the test weld after welding and maintaining the chill until start of testing; this will reduce diffusion of hydrogen out of the test weld.

Where hydrogen may be introduced during service, e.g. by cathodic protection or sour service operation, it may be necessary to pre-charge the specimen with hydrogen prior to the fracture resistance testing for the assessment of the operation phase.

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1.3 Structure of the Recommended Practice

This Recommended Practice contains 5 main sections. The various sections describe the steps to be taken from how to determine the fracture resistance to how to perform the analyses and how to assess the robustness of the predictions.

Section 2 describes the recommended Fracture Resistance Testing procedure based on Single Edge Notched Tensile (SENT) Specimens.

Section 3 describes the recommended Engineering Critical Assessment (ECA) procedure for the determination of Acceptable Flaw sizes.

Section 4 describes the recommended Validation Testing procedure based on Segment Specimen Testing.

Section 5 gives some guidance on Sensitivity Analyses for assessment of the robustness of the ECA predictions.

The main steps are schematically shown in Figure 1-1.

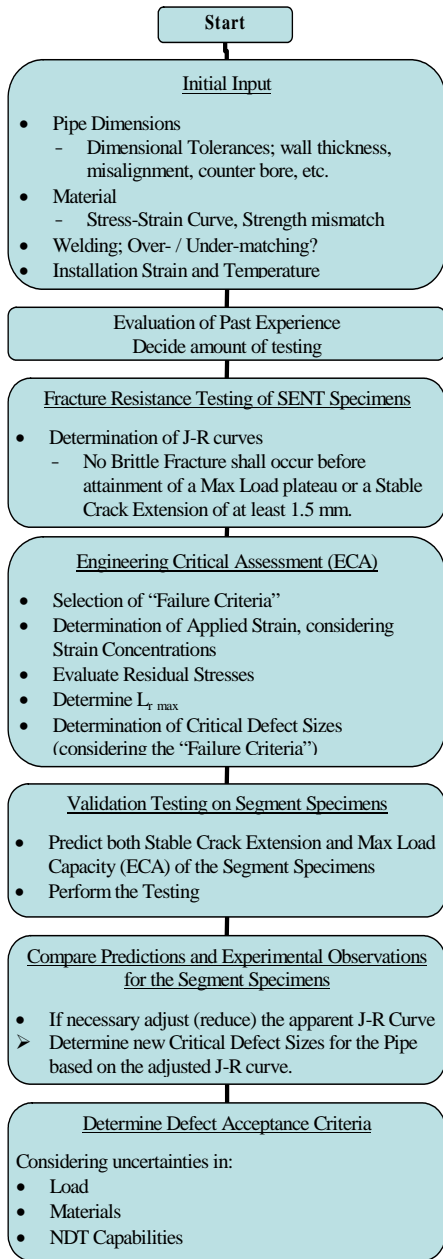


Figure 1-1
The main steps in the assessment procedure

1.4 Relationship to general pipeline design codes

This Recommended Practice complies with DNV-OS-F101, [1]. It can also be used independently, provided it is complemented by another recognised pipeline design code in order to ensure that all pipeline design aspects are covered.

2. Fracture Resistance Testing

2.1 Purpose of the testing

The purpose of the testing described below is to determine the fracture resistance of both the pipe and the girth welds enabling the determination of acceptable flaw sizes as further described in Sec.3.

2.2 General

2.2.1 Specimen type

The recommended specimen for fracture resistance testing, for the installation phase, is the SENT (Single Edge Notched Tension) specimen (Figure 7-1).

Guidance note 3:

A material’s fracture resistance is usually described by a single parameter, either K (Stress Intensity Factor), CTOD (Crack Tip Opening Displacement) or the J-integral. It is however known that the stress and strain state at a crack tip is not fully characterised by such a single parameter alone but that the crack tip constraint, i.e. the degree of crack tip stress tri-axiality, will also influence the fracture resistance.

Commonly used testing standards, e.g. BS 7448 [14] and ASTM E 1820 [15], describe methods for determining the fracture resistance from deeply notched SENB (Single Edge Notched Bend) or CT (Compact Tension) specimens. These specimens, both predominantly loaded in bending, have high crack tip constraint and will hence give lower bound estimates for the fracture resistance that can be used for conservative fracture assessments for a large range of engineering structures.

During installation, pipeline girth welds are however predominantly loaded in tension even if the pipe is globally subjected to bending. Furthermore, the flaw sizes of interest are usually controlled by the weld pass height and are therefore relatively small, typically 2-6 mm in height. Both these aspects result in reduced crack tip constraint in the pipe as compared to the deeply notched standard specimens mentioned above. It is therefore acceptable to determine the fracture resistance from a specimen with a crack tip constraint that is closer to the actual crack tip constraint in the pipe.

The SENT specimen is such a specimen. This specimen has both a loading mode and crack tip constraint which is close to the loading mode and constraint for a crack in the girth weld of a pipe subjected to bending and axial loading, ref. [12, 16].

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Guidance note 4:

The standard, deeply notched, SENB specimen can also be used but this is likely to result in unnecessarily conservative assessments. SENB specimens with reduced notch depth will give lower constraint and may reduce this conservatism. If the SENB specimen is used the procedures in references [1, 14, 15, 16] shall be followed.

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2.2.2 Cyclic loading

During reeling installation the pipe will be subjected to cyclic loading, i.e. reeling-on, reeling-off, bending over the aligner and finally straightening. In some cases this installation cycle may be repeated a number of times.

Consequently, it is necessary to generate information about both the monotonic and cyclic fracture resistance. However, testing within the JIP, both small scale and large scale, showed that the fracture resistance was not significantly altered by cyclic loading for the tested pipe and welds [5, 7, 9].

It is therefore recommended:

- to determine the fracture resistance for the ECA by monotonic testing of SENT specimens as described in 2.3
- the cyclic fracture resistance is verified by testing of Segment specimens as described in Sec.4.

2.2.3 Hydrogen embrittlement

Some steels may be susceptible to hydrogen embrittlement both from welding and from cathodic protection. This must be considered when specifying both welding and testing conditions. See also *Guidance note 2*, in 1.2.

2.3 Monotonic testing of SENT specimens

2.3.1 General

Installation methods involving significant plastic strain normally require high toughness materials in order to allow acceptance of realistic flaw sizes in the girth welds.

- the fracture resistance shall normally be characterised by J-R (or CTOD-R) curves
- no brittle fracture shall occur before attainment of a max load plateau or a stable crack extension of at least 1.5 mm.

Guidance note 5:

If the materials fracture toughness cannot be characterised by a J-R (or CTOD-R) curve because brittle fracture takes place (possibly after some stable tearing), the procedures described in this document may not be applicable. In such cases specialist advice is recommended to interpret the data and to assess if the results may be used for the ECA.

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The testing shall, in general, be in accordance with a recognised standard, e.g. [14, 15], except that it is recommended to test SENT specimens, Figure 7-1, in which the loading mode and crack tip constraint is similar to that of a circumferential surface or embedded flaw in a pipe [12, 16].

2.3.2 Crack orientation and location

- The SENT specimen shall normally be designed with a Surface Notch (SN), see Figure 7-2, since this is the relevant orientation for defects in the girth welds.
- All relevant defect locations shall be evaluated.

Guidance note 6:

Since flaws most likely to occur in girth welds could be located in the weld metal and at the fusion boundary, testing of the HAZ/Fusion Line and weld metal shall be considered for all relevant welding procedures, including repair procedures.

For testing of weld metal the surface notch may be from the cap or root side considering the microstructure assumed to be most critical.

For testing of the HAZ/Fusion Line the surface notch shall normally be from the cap side such that the direction of crack extension cross the fusion line from the weld metal side.

The actual amount of testing will depend on material and prior experience, see also *Guidance note 1*.

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- The notch tip shall be sharpened by fatigue pre-cracking in accordance with [14, 15].

2.3.3 Specimen dimensions

The recommended dimensions for the SN specimen are $B = 2W$ where W represents the pipe wall thickness (t) less the minimum amount of machining necessary to obtain a rectangular specimen (see Figures 7-1 and 7-2 for definition of the various dimensions).

If the reduction in wall thickness, due to pipe dimensions (D/t), will be more than 15% (i.e. $W < 0.85 \times t$) the specimen width, B , may be reduced, but not to less than $B \geq W$.

Notch orientations and their relationship to a circumferential flaw in a pipe are illustrated in Figure 7-2.

Analyses have shown [20] that the crack tip constraint of both

the clamped SENT specimen and circumferential cracks in the pipe is relatively insensitive to the pre-crack depth (a/W , machined notch + fatigue pre-cracking). The actual pre-crack depth in the clamped SENT specimen is thus not essential; as long as it is between $0.2 \leq a/W \leq 0.5$.

The actual microstructure sampled by the crack tip, and its relevance for the subsequent defect assessment, should however be considered when determining the pre-crack depth of the SENT specimen.

2.3.4 Loading conditions

The SENT specimens may be either clamped (as indicated in Figure 7-1 or pin-loaded (i.e. the ends are free to rotate) in the test machine. Both loading conditions give acceptable constraint as compared to flaws in pipe girth welds.

- For clamped specimens the free length, or “day-light”, (H) between the grips of the test machine shall be equal to $10W$ (see Figure 7-1) when using the formulas for estimating J that are given in 2.3.6.

For pin loaded specimens the clamping distance will not influence the results. Pin loaded means that it is no restraining bending moment from the testing machine on the SENT specimens. It may be difficult, in practice, to obtain ideally pin loaded specimen gripping. The expressions in 2.3.6.3 will however be usable (slightly conservative) if the specimen is gripped, e.g., in an ordinary wedge clamp that is connected to the testing machine with a bolt bearing.

2.3.5 Testing conditions

- It is recommended that the J-R (or CTOD-R) curves are generated using the multiple specimen approach with minimum 6 specimens (6 valid results) for each crack location.

The specimens shall be loaded to tearing lengths between 0.2 and 3 mm. The majority of data shall be between 0.5 and 1.5 mm.

The J-R (or CTOD-R) curves shall be established as a lower bound curve for the experimental results. Often a curve of the form $J = x \cdot \Delta a^m$ fits the data well.

If $L_{r,max}$ is to be determined from the SENT tests at least three specimens shall be loaded beyond maximum load, see 3.4.3.

When determining the tearing length for the J-R curve the blunting shall be included in the tearing length (Δa).

For assessment of the installation phase testing shall normally be conducted for the as-welded (un-deformed) condition.

Testing shall normally be conducted at the lowest anticipated temperature for reeling-on and reeling-off.

If the pipe temperature during installation, e.g. due to the application of field coating, may be higher than 50°C (25°C for Duplex stainless steels), testing at the highest anticipated temperature shall also be considered because the stable crack tearing resistance may be lowered at high temperatures.

Guidance note 7:

For assessment of the operation phase the testing shall normally be conducted for the pre-strained and aged condition, i.e. prior to notching and fatigue pre-cracking the specimen blanks shall be subjected to a strain cycle simulating the installation cycle ending in tension and then aged at 250°C for one hour.

Testing shall normally be conducted at the lowest design temperature.

For pipelines operating at high temperatures (above 50°C or 25°C for Duplex stainless steels), testing at the highest operating temperature shall also be considered, because this situation may result in lower tearing resistance than testing at a lower temperature. This may be relevant, especially if the pipeline is subjected to repeated plastic deformation due to e.g. temperature variations.

Operation normally involves internal pressure plus axial strain i.e. a bi-axial stress state. If SENT specimens are employed for assessing the operation phase it must be substantiated, by analysis or experience, that the constraint in the pipe, under operational conditions, is not higher than in the specimen.

Possible influence of the bi-axial stress state on the crack driving force must also be considered in the ECA.

Otherwise, for the operational phase, reference should be made to generally recognised codes and standards, e.g. DNV-OS-F101 [1].

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Guidance note 8:

The testing for the installation phase and the operation phase may be considered to be combined and be carried out in the pre-deformed and aged condition and at the lowest of the installation and design temperatures. This may however result in unnecessary conservative assessments.

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Post-test metallography of specimens testing the HAZ/Fusion Line region shall be conducted in order to establish the microstructure at the fatigue crack tip. Procedures are described in e.g. [1] and [14].

If hydrogen embrittlement is of concern this must be considered when specifying both welding and testing conditions, see *Guidance note 2* in 1.2.

2.3.6 Formulas to calculate J for SENT specimens

As mentioned in 2.3.1 it is recommended that the crack growth resistance be characterised by J-R curves.

The total J-integral is calculated by considering the elastic and plastic parts separately.

The following simplified equations are used to compute J when the amount of the ductile crack growth is less than 10% of the initial remaining ligament ($W - a_0$).

$$J = J_e + J_p \cong J_e + J_{p0} \tag{1}$$

where:

- J_e = elastic part of the J-integral
- J_p = plastic part of the J-integral

J_{p0} = plastic part of the J-integral without crack growth correction.

The elastic part of the J-integral is directly linked to the Stress Intensity Factor K through the relation:

$$J_e = \frac{K^2}{E'} \tag{2}$$

where:

$E' = E$ for plane stress (E is Young's modulus)

$$E' = \frac{E}{(1 - \nu^2)} \quad \text{for plane strain}$$

ν is Poisson's ratio.

The plastic part of the J-integral is calculated through the plastic work applied to the cracked specimen:

$$J_p = \frac{\eta_p U_p}{B(W - a_0)} \tag{3}$$

where:

- η_p is a dimensionless function of the geometry
- U_p is the plastic part of the area under the Load vs. Crack Mouth Opening Displacement (CMOD) curve (Figure 7-3)
- B is the width of the specimen (Figure 7-1)
- $(W - a_0)$ is the remaining ligament (Figure 7-1)
- a_0 is the initial crack length.

The CMOD may be measured directly at the crack mouth of the specimen or estimated from e.g. double clip gauges.

Formulae to determine the stress intensity factor, K, for determination of J_e in Eq. (2) and η_p for determination of J_p in Eq. (3) are given in Appendix A for both clamped and pinloaded specimens.

3. Engineering Critical Assessment (ECA)

3.1 Purpose of the ECA

The purpose of the ECA described below is to determine acceptable flaw sizes that will not cause "Failure" during the installation.

The fracture resistance properties of the pipe and girth welds shall be determined in accordance with Sec.2.

3.2 General

Engineering Critical Assessments (ECA's) are carried out in order to confirm that "Failure" from possible weld flaws will not occur during the installation and operation of the pipeline, i.e. acceptable flaw sizes shall be determined.

The term "Failure" is further defined in 3.3.

This Recommended Practice considers the ECA for the installation phase.

Common flaw assessment procedures, e.g. BS 7910:2005 [2], are not explicitly developed for the situation with large cyclic plastic strains as occurring during installation by reeling.

However, results from the JIP have shown that a procedure essentially based on BS 7910:2005 [2], but with modifications and clarifications as outlined below, is appropriate.

For nomenclature reference should be made to BS 7910:2005 [2].

For analyses of the operation phase some guidance is given in this Recommended Practice but it is generally referred to e.g. DNV OS-F101, [1].

3.3 Failure Criteria

The term "Failure" has to be defined for each case considered, and can be:

- a prescribed amount of stable crack extension, Δa
- a prescribed final crack size, a_{\max}
- "plastic collapse"
- unstable fracture.

For most situations, the recommended "Failure Criteria" for the installation phase is a prescribed small amount of stable crack extension, Δa , or a prescribed final crack size, a_{\max} .

This gives information about the flaw size that may be present in the pipeline after installation (initial flaw size plus possible crack growth during installation) which is needed for the subsequent assessment of the operation phase.

It is recommended that the total crack extension during the whole installation process shall be less than 1 mm.

The margin to unstable failure shall also be assessed.

When defining the "Failure Criteria", sensitivity analyses should be conducted to ensure that small variations in the assumptions will not significantly influence the reliability and robustness of the calculations and conclusions drawn, see also Sec.5.

3.4 Failure Assessment Diagram (FAD)

3.4.1 Assessment level

The Failure Assessment Diagram (FAD) is the locus separating the acceptable and unacceptable conditions, i.e. "Failure" is assumed if the assessment point falls on or outside the FAD-curve while safe conditions are assumed if the assessment point falls inside the FAD-curve.

It is recommended that the assessment is carried out based on the BS 7910:2005 [2] Level 3B, which is a tearing analysis using the material specific FAD.

I.e. both the material stress-strain curve and the fracture resistance, J-R curve (or CTOD-R curve) must be known for the re-

spective flaw locations to be assessed.

- If the stress-strain curve show a Lüders plateau it is important that that plateau is also included when constructing the FAD and assessing the applied stress.
- Adjustments to the J-R curve as well as the materials stress-strain curve may be necessary based on the Verification Testing as further described in 4.4.

For assessing flaws at the Fusion Line or within the HAZ, the FAD shall be derived from the parent pipe tensile tests. Since the "applied load" is determined from the applied strain the stress-strain curve used to derive the FAD shall be representative for the higher end of the pipe strengths, i.e. representing a pipe with high yield strength and low strain hardening, e.g. mean plus two standard deviations or "highest expected value" of the strength for the material to be employed.

Guidance note 9:

The shape of the stress-strain curve will change due to the cyclic plastic straining (the Bauschinger effect). This must be considered in the ECA.

It is however normally conservative to base the assessment (both the FAD and the applied stress) on the as-received Parent Pipe stress-strain curve. This is because a high yield strength and a low strain hardening will result in a high Crack Driving Force when the "applied load" is determined from a given applied strain.

The change in stress-strain curve due to the Bauschinger effect is normally a decrease of the yield strength (typically 15-20 %) but the tensile strength is essentially unaffected, i.e. a decrease in yield strength and an increase in strain hardening (but the stress-strain curve is still below the as-received stress-strain curve), which means that the Crack Driving Force is lowered as compared to an assessment based on the as-received stress-strain curve.

However, in case both the yield strength and the tensile strength are lowered due to the Bauschinger effect it may be necessary to consider this in the assessment.

(In case the "applied load" is in load control, e.g. in service, the Bauschinger effect may have a significant onerous effect).

In cases of no prior experience with the stress-strain behaviour of the material, testing of material that has undergone straining simulating installation may be necessary. See also 4.4.

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Even though this Recommended Practice assumes over-matching weld strength, see 1.3, it is recommended to assume the same strength properties as for the parent pipe (even-matching) when assessing flaws in the weld metal. The reason for this is that the strength of the weld metal varies from the HAZ and into the un-affected weld metal and it is not always obvious how to determine the exact location of a weld flaw. Furthermore, the amount of over-matching varies due to variability in both parent pipe and weld metal strength.

In certain cases, when the exact defect location is known, it may be justified to derive the FAD from weld metal tensile properties. The weld metal properties should then be determined in the cross weld direction, either by notched tensile specimens, e.g. as described in ref. [19], or specimens instrumented with strain gauges or a small extensometer in the weld metal. Since the "applied load" on the weld is determined from the bending moment set up by the parent pipe, the weld metal stress-strain curve shall be representative for the lower end of the weld metal strengths, e.g. mean minus two standard deviations or "lowest expected value" of the strength for the weld metal to be employed. The Bauschinger effect due to cyclic plastic straining should then also be considered. Expert advice is recommended for such cases.

3.4.2 Determination of reference stress

The full scale pipe tests with surface cracks reported in [5] showed reasonable agreement between experiments and pre-

ditions when the so called Kastner solution, as generalised in BS 7910:2005 [2], was used to determine the reference stress (σ_{ref}).

It is therefore recommended that the Kastner solution, as generalised in BS 7910:2005 (Equ. P.12) [2], is used to determine the reference stress (σ_{ref}) for the assessment of surface cracks.

For the assessment of embedded defects BS 7910:2005 [2] uses the flat plate solution. This is however considered to be conservative.

The use of other, less conservative, reference stress solutions, whether for embedded or surface defects, must however be justified.

Guidance note 10:

It is normally acceptable to only analyse surface breaking defects and use the same acceptance criteria also for embedded defects (note that the defect height, $2a$, of an embedded defect is then the same as the defect height, a , of a surface defect). If the embedded defect is located close to the surface (ligament less than half the defect height) the ligament between the defect and the surface shall be included in the defect height.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

3.4.3 Determination of $L_{r\ max}$

The FAD can not be extended to arbitrarily large plastic deformations and a cut-off limit for L_r ($L_r = \sigma_{ref} / \sigma_Y$) must be defined.

For displacement controlled or displacement restricted situations, such as reeling, it is acceptable to increase the cut-off level in the FAD, $L_{r\ max}$, (from $L_{r\ max} = \sigma_{flow} / \sigma_Y$ as suggested in BS 7910:2005 [2]) provided there is experimental support for such an extension.

Such support can be provided by testing specimens with a constraint similar to the constraint in the pipe, e.g. the SENT specimen or the Segment specimen with crack depth similar to the flaw size considered in the pipe.

If results from testing are available the following procedure for determining $L_{r\ max}$ is acceptable:

- the maximum load shall be determined from at least three tests. The location of the cracks in the specimens must correspond to the location considered in the pipe
- $L_{r\ max} = \sigma_{ref} / \sigma_Y$, corresponding to the recorded maximum loads shall be calculated and used to define $L_{r\ max}$
- the actual value of $L_{r\ max}$ to be used in the analyses shall be chosen taking scatter in the results into consideration.

In lieu of such experimental results it is acceptable to determine $L_{r\ max}$ as:

$$L_{r\ max} = \sigma_U / \sigma_Y \tag{4}$$

where σ_U and σ_Y is the engineering tensile strength and yield strength, respectively.

3.5 Determination of primary and secondary stresses

The nominal strain in the pipe is determined as the ratio of the outer radius of the pipe to the radius of curvature of the bent pipe (normally determined from the radius of curvature of the reel drum). This strain is typically of the order of 1-3%.

The actually applied strain in the cross section under consideration may be higher than the nominal strain because of, e.g.:

- misalignments
- counter boring
- variations in stiffness between abutting pipes, e.g. due to:
 - variations in wall thickness and/or pipe diameter
 - variations in material strength

- variations in the stiffness of the pipe coating.

The applied strain (less welding residual strain as described below) shall be calculated from the nominal strain and taking all strain concentration factors (SNCF's) into consideration.

All sources of strain concentrations shall be identified and quantified based on elastic-plastic principals.

For determination of the Elastic Stress Concentration Factor (SCF) from eccentricities from wall thickness differences and misalignment the following equations may be used [21]:

$$SCF = 1 + \frac{6(\delta_t + \delta_m)}{t} \cdot \frac{1}{\left(1 + \left(\frac{T}{t}\right)^{2.5}\right)} \cdot e^{-\alpha} \tag{5}$$

where:

$$\alpha = \frac{1.82L}{\sqrt{Dt}} \cdot \frac{1}{\left(1 + \left(\frac{T}{t}\right)^{2.5}\right)} \tag{6}$$

and:

- T and t = wall thickness of the pipes on each side of the girth weld, $T > t$
- δ_t and δ_m = eccentricities from wall thickness differences and misalignment (including out-of-roundness, centre eccentricity, different diameters etc.)
- L = width of grith weld cap
- D = outside diameter of pipe (nominal value is acceptable)

The Neuber analysis method may be used to determine the design strain considering the stress and strain concentrations mentioned above.

Guidance note 11:

Although the Neuber method was originally developed to assess strains at notches it has been found useful for reeling analyses and there have not been any failures reported that can be attributed to non-conservatism due to the use of this method.

The Neuber method can be defined by the following equation:

$$\sigma \times \varepsilon = S \times e \times K_t^2 \tag{7}$$

where:

- K_t = elastic stress concentration factor (SCF)
- S = nominal stress (excluding SCF)
- e = nominal strain (excluding SCF)
- ε = actual strain (including SCF)
- σ = actual stress (including SCF)

The intersection of the Neuber curve ($S \times \varepsilon \times K_t^2 / \sigma$ plotted against S) with the stress-strain curve for the material defines the actual stress and strain as a result of the elastic SCF.

It is recommended that the increased stress from eccentricities estimated by the Neuber method is applied as a primary bending stress, P_b .

Alternative methods may be used when supported by appropriate documentation.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

A simplified and conservative method to account for counter boring is suggested in Appendix B.

Welding residual stresses must be considered.

They may be included as secondary stresses as described in BS 7910:2005 [2] with relaxation enabled as the primary stress increases.

An acceptable alternative is to add the corresponding welding strain (welding stresses divided by the modulus of elasticity) to the applied strain determined above. In the latter case no relaxation shall be enabled for increasing primary stress.

The primary stress for the assessment of flaws located at Fusion Line/HAZ is the engineering stress corresponding to the applied strain for the parent pipe.

As recommended in 3.4.1 flaws located in the weld metal should be assessed based on the assumption of even-matching weld metal strength, i.e. based on the parent pipe stress-strain curve.

Guidance note 12:

The stress-strain curve used to determine the primary stress shall be that of the parent pipe. The same stress-strain curve shall be used to construct the FAD.

In certain cases, e.g. in a Fitness for Service analysis of a known flaw that is located completely in the weld metal, it may be justified to utilise the weld metal over-matching in the analyses and hence construct the FAD from the weld metal stress-strain curve. In such cases the weld metal over-matching as well as possible effects due to the Bauschinger effect must also be taken into consideration when determining the primary stress for the assessment.

A simplified and conservative way of assessing the weld metal primary stress is to calculate the bending stress distribution over the weld cross section, considering the weld metal stress-strain curve, that is in equilibrium with the global bending moment applied to the pipe, determined from the parent pipe stress-strain curve, assuming that plane sections remain plane, as schematically illustrated in Figure 7-6.

FEM calculations in [4] have confirmed that the stress in the weld metal is increased as compared to the parent pipe in the case of weld metal over-matching.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

3.6 Cyclic analysis

FEM analyses [4] have shown that the range of the Crack Driving Force, ΔJ or $\Delta CTOD$, both for the first strain cycle and subsequent strain cycles, is essentially determined by the positive strain increment for the respective loading steps.

For a typical reeling installation sequence this means:

- for the 12 o'clock position the flaw will experience two major positive strain increments:
 - 1) During reeling-on; O-A in Figure 7-4.
 - 2) During bending over the aligner; B-C in Figure 7-4.
- for the 6 o'clock position the flaw will experience two major positive strain increments:
 - 1) During reeling-off; A'-B' in Figure 7-4.
 - 2) During straightening; C'-D' in Figure 7-4.

Furthermore, tests [5, 7, 9] have shown that, for the materials considered in the JIP, the crack growth increment, Δa , is similar for the first and second load cycle when the positive strain increments are similar.

When assessing the total stable crack extension for the whole installation sequence it is hence necessary to carry out one analysis for each positive strain increment, with an updating of the crack size for possible crack extension for each analysis.

The primary stress for the second, and subsequent load cycles, may be calculated from the positive strain increment in the same way as for the first load cycle.

Guidance note 13:

The installation sequence may differ between the various installation vessels and the particular installation sequence must be considered.

For a typical reeling installation the 6 o'clock position is often

the most critical position because the second load cycle, in the straightener, will normally induce the largest strain increment, i.e. the strain increment from C'-D' will normally be larger than the strain increment from O-A (see Figure 7-4).

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4. Verification by Testing

4.1 Purpose of the testing

Installation methods introducing large cyclic plastic strains have extended the use of engineering materials and structures into a region with limited experience both regarding testing and analyses.

It is therefore necessary to validate the ECA of the pipe by testing under conditions resembling the actual installation conditions and, if the predictions would turn out to be non-conservative compared to the experimental observations, adjust the analysis procedure to assure conservative assessments.

A reduced scale specimen that resembles the conditions at the girth weld of a pipe during installation is the Segment specimen as shown in Figure 7-5.

However, the Segment specimen does not strictly simulate all aspects of the girth weld of a pipe in bending. This means that the results of the testing will not be directly related to the acceptable defect sizes in the pipe but the results will serve as a validation of the analysis procedure.

The main purpose of the Segment specimen testing is to:

- show that the resistance to stable crack growth is not degraded by cyclic plastic straining
- show that the pipe is likely to behave in a ductile manner in the event of a failure during installation (i.e. brittle or fast ductile fracture shall not occur)
- give confidence that the ECA of the pipe will give safe assessments.

This means that the results of the tests shall be compared with an ECA of the Segment specimen and, if necessary, the analysis procedure should be adjusted, as further described in 4.4, to be consistent with the experimental results.

4.2 The segment specimen

4.2.1 Dimensions

The cross-section of the specimen shall be as large as possible but not so large that the pipe curvature will cause problems with clamping into the test machine and with excessive secondary bending.

Figure 7-5 indicates specimen dimensions that have proved to be practical for typical reeling situations with pipe OD 10"-12" and wall thickness around 15-25 mm:

A test section width of around 35-50 mm has proved to be practical.

In order to be able to apply compressive loads without causing buckling of the test section it is necessary to limit the free length of the specimen. For typical reeling situations, as described above, a length of around 50 mm has proved to be practical.

In order to avoid buckling of the specimen during the compression part of the loading cycle, it is furthermore important that the test machine is sufficiently stiff such that buckling of the specimen due to lateral displacement and/or rotation of the machine grips is prevented.

It is recognised that Segment specimen testing will not exactly simulate all conditions in the pipe, but rather give information about the general behaviour, e.g.: the materials response to cyclic loading, the resistance to stable crack growth and the abil-

ity to fail in a ductile manner.

4.2.2 Notch size

It is normally not possible to have the same notch size in the specimen as the flaw size considered for the pipe. The length of the notch in the specimen is limited to around 1/3 to 1/2 of the specimen width, i.e. around 15- 25 mm. The notch depth in the specimen should be as close as possible to the deepest flaw considered acceptable for the pipe. In addition, the same region of the weld should be tested (normally, the notch in the specimen would be located in the region giving the lowest R-curve or the region assessed to have the lowest tolerance to welding flaws).

The notch size in the specimen should, within these limitations, be determined to give similar "criticality", as the "criticality" of the flaws considered for the pipe (i.e. similar assessment point for similar applied strain).

The notch may be introduced into the specimen by Electro-Discharge Machining (EDM) provided that the final notch width does not exceed 0.2 mm.

4.2.3 Instrumentation

The specimen shall be instrumented to enable the registration of the strains resulting from the applied load cycle. This can be by means of displacement transducers measuring over a certain gauge length or by using strain gauges as illustrated in Figure 7-5.

4.3 Testing procedure

In order to carry out the validation and if necessary adjust of the ECA procedure it is recommended, for a typical reeling installation, that, as a minimum, three sets of Segment specimens are tested as follows:

- 1) One set of specimens tested monotonically to failure.
The purpose of this testing is to assess the maximum load capacity.
- 2) One set of specimens tested cyclically for three load cycles and to an estimated stable crack growth of about 0.5 mm per cycle.
The specimens shall be heat tinted and broken open at low temperature. Subsequently the crack growth corresponding to each load cycle shall be measured.
The purpose of this testing is to check the predictions of the stable crack growth and to confirm that cyclic loading, simulating installation, does not degrade the crack growth resistance.
Because the purpose of this testing is to check the predictions of stable crack growth it is desirable that some crack growth (about 0.5 mm) is obtained per cycle in the specimens which can be compared to the predictions. It may be necessary to adjust the loading of the specimens from what is estimated from the applied strain in the pipe in order to obtain the desired crack extension.
- 3) One set of specimens tested cyclically for three load cycles to an estimated stable crack growth of about 0.5 mm per cycle and finally loaded to failure.
Subsequently the stable crack growth for each load cycle shall be measured.
The purpose of this testing is to obtain further information about the cyclic crack growth and to confirm that cyclic loading does not degrade the maximum load capacity.

For each set of specimens it is recommended to test at least two specimens, i.e. totally a minimum of six Segment specimens.

This testing should, as a minimum, be carried out for the crack location considered most critical from the J-R testing of small scale standard specimens and considerations of the fabrication, i.e. where weld flaws are likely to occur.

The testing shall be carried out at the same temperature as the J-R testing described in Sec.2.

Guidance note 14:

For other installation methods the above recommendation may be modified to better simulate the actual installation sequence. Expert advice is recommended for such modifications.

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Guidance note 15:

In case of buckling of the Segment specimen, further testing may be necessary or specialist advice is recommended to interpret the data.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

4.4 Post test investigations and analyses

After the testing the fracture surface shall be examined and any cyclic stable crack growth shall be measured as described in points 2 and 3 above.

The crack growth increment for each loading cycle shall be similar confirming that there is no significant increase of the stable crack growth during the cyclic loading.

The final failure shall be ductile (max load failure) and the failure load shall be similar for the monotonically and cyclically loaded specimens

Possible influence of increase in crack size due to the cyclic loading shall be considered when interpreting the results.

If the above two requirements are not fulfilled specialist advice is recommended to interpret the data.

Possible sources of inconsistency are:

- degradation of the crack growth resistance caused by the cyclic straining
- a change in the crack driving force caused by a change in the stress-strain properties due to the Bauschinger effect
- excessive buckling.

Additional testing and analyses may be necessary in such cases.

Finally, if the above two requirements are fulfilled, an ECA of the Segment specimens shall be performed based on the loads measured during the test; both the cyclic load and the final failure load.

Both the stress-strain curve and the J-R curve used in these analyses shall be best estimates for the actually tested specimens.

The measured stable crack growth and maximum load capacity shall be compared with the ECA predictions.

If the predictions should be non-conservative compared to the experimental observations it is recommended that the J-R curve, determined from the small scale standard specimens (see 2.2) is adjusted to force an agreement between the predicted crack growth and the experimental results from the Segment specimens [5].

This adjusted J-R curve shall then be used to conduct the ECA for the full scale pipe.

5. Sensitivity Analysis

The results of the ECA, i.e. acceptable flaw sizes, are often sensitive to small variations in input parameters, such as strain level (including SNCF), material strength, fracture resistance and the $L_{r \max}$ cut off level.

In order to assess the confidence that the results from the ECA will give robust and conservative, but not overly conservative, predictions of acceptable flaw sizes a sensitivity analysis shall be carried out where the main input parameters are varied with-

in reasonable limits. Appendix K of BS 7910:2005 [2] gives some guidance regarding such sensitivity analyses.

In some cases, a full probabilistic analysis may be advisable. In such a case specialist advice is recommended.

The accuracy and reliability of the NDT system and procedure must also be considered when determining the acceptance levels for flaws, i.e. is it possible to reliably detect and size all flaws in excess of the acceptance limits.

6. References

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7. Figures

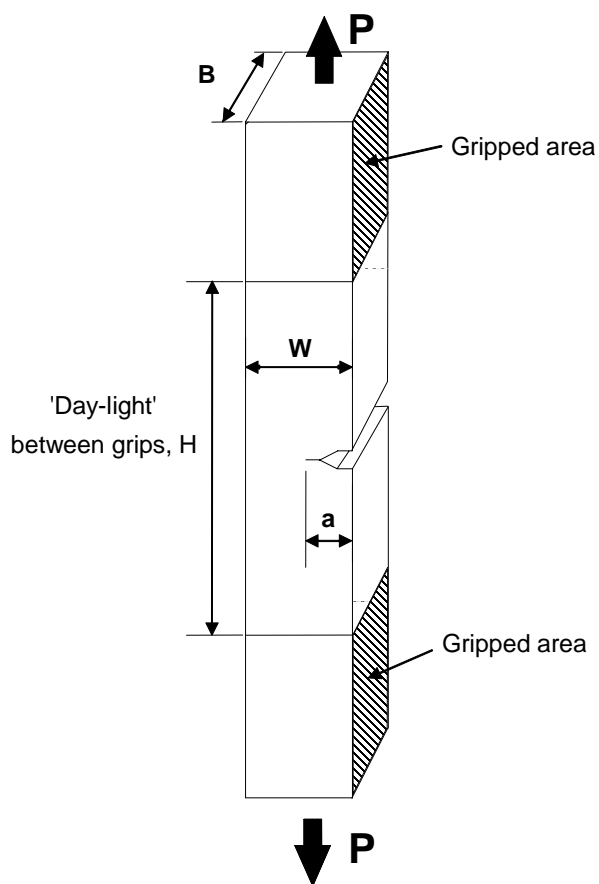


Figure 7-1
 The clamped SENT (Single Edge Notched Tension) specimen. The pin-loaded specimen is similar but the ends are free to rotate. This can be achieved by using an ordinary wedge clamp that is connected to the testing machine with a bolt bearing.

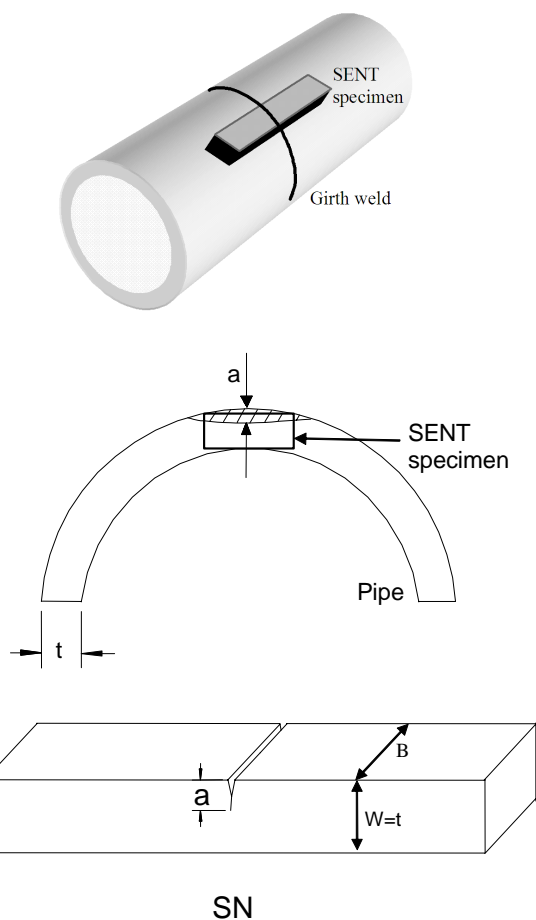


Figure 7-2
 Relationship between flaw orientation and height in the pipe and the crack orientation and size in the specimen

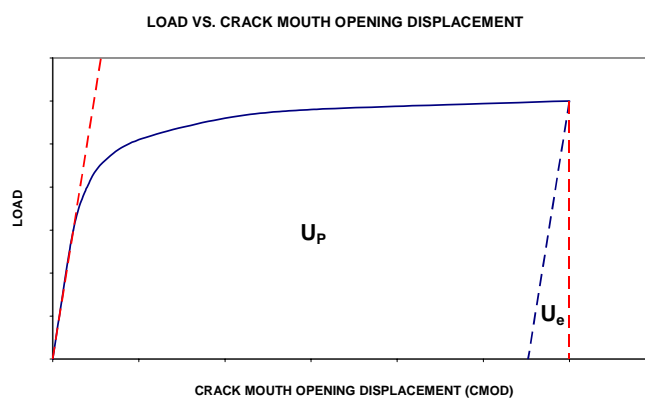


Figure 7-3
 Plastic Energy, U_p , for the determination of J

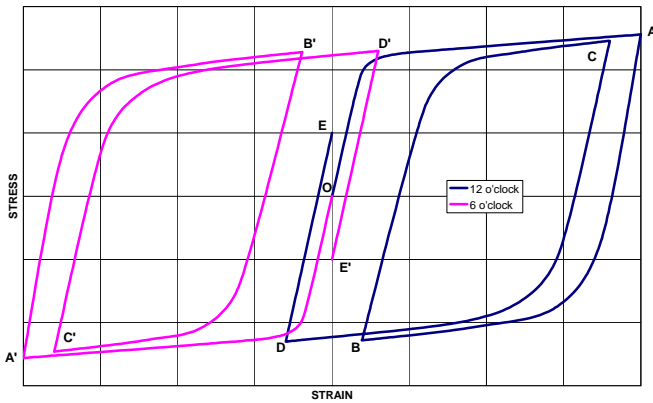


Figure 7-4
Stresses and strains in the pipe during reeling (schematic)

- O – A, A' : Reeling-on**
- A, A' – B, B' : Reeling-off**
- B, B' – C, C' : Bending over the aligner**
- C, C' – D, D' – E, E' : Through the straightener.**

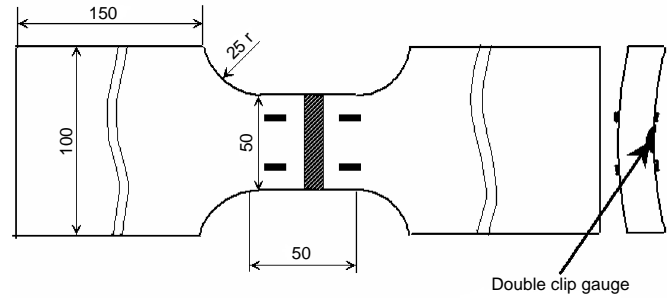


Figure 7-5
The segment specimen with recommended dimensions

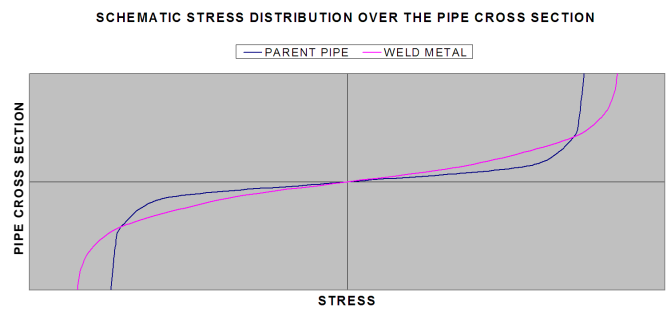


Figure 7-6
Schematic stress distribution over a pipe cross section subjected to bending, assuming that plane sections remain plane. The Weld Metal is over-matching the Parent Pipe and the two stress distributions equals the same applied bending moment.

APPENDIX A DETERMINATION OF J

A.1 Clamped Specimens

A.1.1 Stress Intensity Factor for determination of J_e in Eq. (2)

The most accurate solution for the Stress Intensity Factor for clamped specimen is considered to be the one proposed by Ahmad et al. [17]:

$$K = \frac{P}{BW} \sqrt{\pi a} (f_1 - 6\xi_3 f_2) \quad (8)$$

where:

P is the applied load
B is the width
W is the thickness
a is the crack length.

ξ_3, f_1, f_2 are defined as follows:

$$\xi_3 = \frac{\xi_1}{\xi_2 + 12 \frac{H}{W}} \quad (9)$$

where:

H is the length of the specimen between the grips, see Figure 7-1.

$$\xi_1 = 12\pi \left(\frac{a}{W}\right)^2 \sum_{i=0}^8 q_i \left(-\frac{a}{W}\right)^i - U_+ \left(\frac{a}{W} - 0.6\right) \times \left[19.95 - \frac{3.99(3a/W - 1)}{(1 - a/W)^2} \right] \quad (10)$$

$$\xi_2 = 72\pi \left(\frac{a}{W}\right)^2 \sum_{i=0}^8 r_i \left(-\frac{a}{W}\right)^i - U_+ \left(\frac{a}{W} - 0.6\right) \times \left[99.38 - \frac{15.9}{(1 - a/W)^2} \right] \quad (11)$$

where:

q_i, r_i are constants given in Table A-1

U_+, U_- are Heaviside functions defined as follows:

$$\begin{aligned} U_+(x) &= 0 && \text{for } x \leq 0 \\ U_+(x) &= 1 && \text{for } x > 0 \\ U_-(x) &= 0 && \text{for } x < 0 \\ U_-(x) &= 1 && \text{for } x \geq 0 \end{aligned}$$

$$f_1 = U_- \left(0.6 - \frac{a}{W}\right) \times \sum_{i=0}^4 n_i \left(-\frac{a}{W}\right)^i + U_+ \left(\frac{a}{W} - 0.6\right) \times \frac{(1 + 3a/W)}{3.545(a/W)^{1/2} (1 - a/W)^{3/2}} \quad (12)$$

$$f_2 = U_- \left(0.6 - \frac{a}{W} \right) \times \sum_{i=0}^4 m_i \left(-\frac{a}{W} \right)^i + U_+ \left(\frac{a}{W} - 0.6 \right) \times \frac{0.375}{(a/W)^{1/2} (1-a/W)^{3/2}} \quad (13)$$

where:

n_i, m_i are constants given in Table A-1.

i	n_i	m_i	q_i	r_i
0	1.120	1.122	0.629	0.629
1	0.231	1.400	0.609	1.047
2	10.550	7.330	5.093	4.602
3	21.720	13.080	11.097	9.975
4	30.390	14.000	26.757	20.295
5	-	-	48.997	32.993
6	-	-	81.820	47.041
7	-	-	77.953	40.693
8	-	-	42.456	19.600

For situations where J_e is small compared to J_p simpler Stress Intensity Factor solutions may be acceptable, e.g.:

$$K_I = \frac{F}{B\sqrt{W}} \cdot \frac{\sqrt{2 \tan\left(\frac{\pi a}{2W}\right)}}{\cos\left(\frac{\pi a}{2W}\right)} \cdot \left[0.752 + 2.02 \left(\frac{a}{W} \right) + 0.37 \left(1 - \sin\left(\frac{\pi a}{2W} \right) \right) \right] \quad (14)$$

η_p for determination of J_p in Eq. (3)

For clamped specimens the equation below shall be used when the Deformation Energy, U_p , is calculated from the area under the Load vs. Crack Mouth Displacement curve (Figure 7.3) [13].

$$\begin{aligned} \eta_p = 0.85 \times & \left\{ \left(196,719 \cdot e^{-\left(\frac{B}{W}\right)} - 64,642 \right) \cdot \left(\frac{a}{W} \right)^5 + \left(-493,511 \cdot e^{-\left(\frac{B}{W}\right)} + 138,837 \right) \cdot \left(\frac{a}{W} \right)^4 + \right. \\ & + \left(463,503 \cdot e^{-\left(\frac{B}{W}\right)} - 106,207 \right) \cdot \left(\frac{a}{W} \right)^3 + \left(-201,862 \cdot e^{-\left(\frac{B}{W}\right)} + 34,532 \right) \cdot \left(\frac{a}{W} \right)^2 + \\ & \left. + \left(39,413 \cdot e^{-\left(\frac{B}{W}\right)} - 4,525 \right) \cdot \frac{a}{W} + \left(-2,064 \cdot e^{-\left(\frac{B}{W}\right)} + 1,039 \right) \right\} \quad (15) \end{aligned}$$

The equation above can be used for:

$$0.2 \leq a/W \leq 0.5$$

$$1 \leq B/W \leq 5$$

$$H = 10 W$$

Work hardening, and weld metal mismatch have only a weak influence on η_p . The factor 0.85 above is included in order to account for such influence.

A.2 Pin-loaded Specimens

A.2.1 Stress Intensity Factor for determination of J_e in Eq. (2)

Several analytical models are available to calculate the Stress Intensity factor for pin-loaded specimens.

The model proposed by Brown et al. [18] is chosen because of its reliability and simplicity:

$$K = F\left(\frac{a}{W}\right) \times \sigma \sqrt{\pi a} \quad (16)$$

where:

$F\left(\frac{a}{W}\right)$ is the geometry factor for the SENT specimen

σ is the nominal load

a is the crack length.

The geometry factor for the SENT specimen is defined below:

$$F\left(\frac{a}{W}\right) = 1.12 - 0.231\left(\frac{a}{W}\right) + 10.55\left(\frac{a}{W}\right)^2 - 21.72\left(\frac{a}{W}\right)^3 + 30.39\left(\frac{a}{W}\right)^4 \quad (17)$$

where:

a is the crack length

W is the specimen thickness.

η_p for determination of J_p in Eq. (3)

For pin-loaded specimens the equation below shall be used when the Deformation Energy, U_p , is calculated from the area under the Load vs. Crack Mouth Displacement curve (Figure 7-3) [13].

$$\begin{aligned} \eta_{pi} = 0.88 \times & \left\{ \left(209,747 \cdot e^{-\left(\frac{B}{W}\right)} - 85,668 \right) \cdot \left(\frac{a}{W}\right)^5 + \left(-467,666 \cdot e^{-\left(\frac{B}{W}\right)} + 195,032 \right) \cdot \left(\frac{a}{W}\right)^4 + \right. \\ & + \left(393,925 \cdot e^{-\left(\frac{B}{W}\right)} - 163,572 \right) \cdot \left(\frac{a}{W}\right)^3 + \left(-160,931 \cdot e^{-\left(\frac{B}{W}\right)} + 61,334 \right) \cdot \left(\frac{a}{W}\right)^2 + \\ & \left. + \left(32,319 \cdot e^{-\left(\frac{B}{W}\right)} - 9,568 \right) \cdot \left(\frac{a}{W}\right) + \left(-1,72 \cdot e^{-\left(\frac{B}{W}\right)} + 1,333 \right) \right\} \quad (18) \end{aligned}$$

The equation above can be used for:

$$0.2 \leq a/W \leq 0.5$$

$$1 \leq B/W \leq 5$$

Work hardening, and weld metal mismatch have only a weak influence on η_p . The factor 0.88 above is included in order to account for such influence.

APPENDIX B

DETERMINATION OF WALL THICKNESS AND MEMBRANE STRESS FOR ANALYSES OF PIPES WITH COUNTER BORE

B.1 Determination of wall thickness and membrane stress for analyses of pipes with counter bore

Counter boring, in order to improve the alignment of the internal pipe diameter, will reduce the wall thickness locally in the weld. The wall thickness and membrane stress for such cases may conservatively be assessed as shown below. The weld cap shall not be included in the wall thickness determination.

For surface defects in the root, the depth of the counter bore shall be regarded as part of the crack i.e. the actual defect depth in the pipe is equal to the crack depth established from the ECA less the depth of the counter bore, see. Figure B-1.

For long surface defects in the root, this method becomes overly conservative. Therefore an assessment shall also be per-

formed for a surface crack at the root going around the whole circumference of the pipe. In this assessment the wall thickness and membrane stress shall not be adjusted due to the counter bore, but the counter bore shall be regarded as part of the crack depth, see Figure B-2. This method gives a lower bound defect depth for all defect lengths. The defect depth as a function of defect lengths shall be plotted for the two approaches, and the curve that gives the deepest defect depth for a certain defect length may be used as the critical value, see Figure B-3.

Similarly, the assessments for defects at the weld cap and for embedded defects shall be in accordance with Figures B-4 and B-5 respectively.

$$WT_{ECA} = WT_{PIPE} - CB$$

$$a_{ECA} = a_{PIPE} + CB$$

$$2C_{ECA} = 2C_{PIPE}$$

$$\text{Membrane stress}_{ECA} = \text{Membrane stress}_{PIPE} \times WT_{PIPE} / WT_{ECA}$$

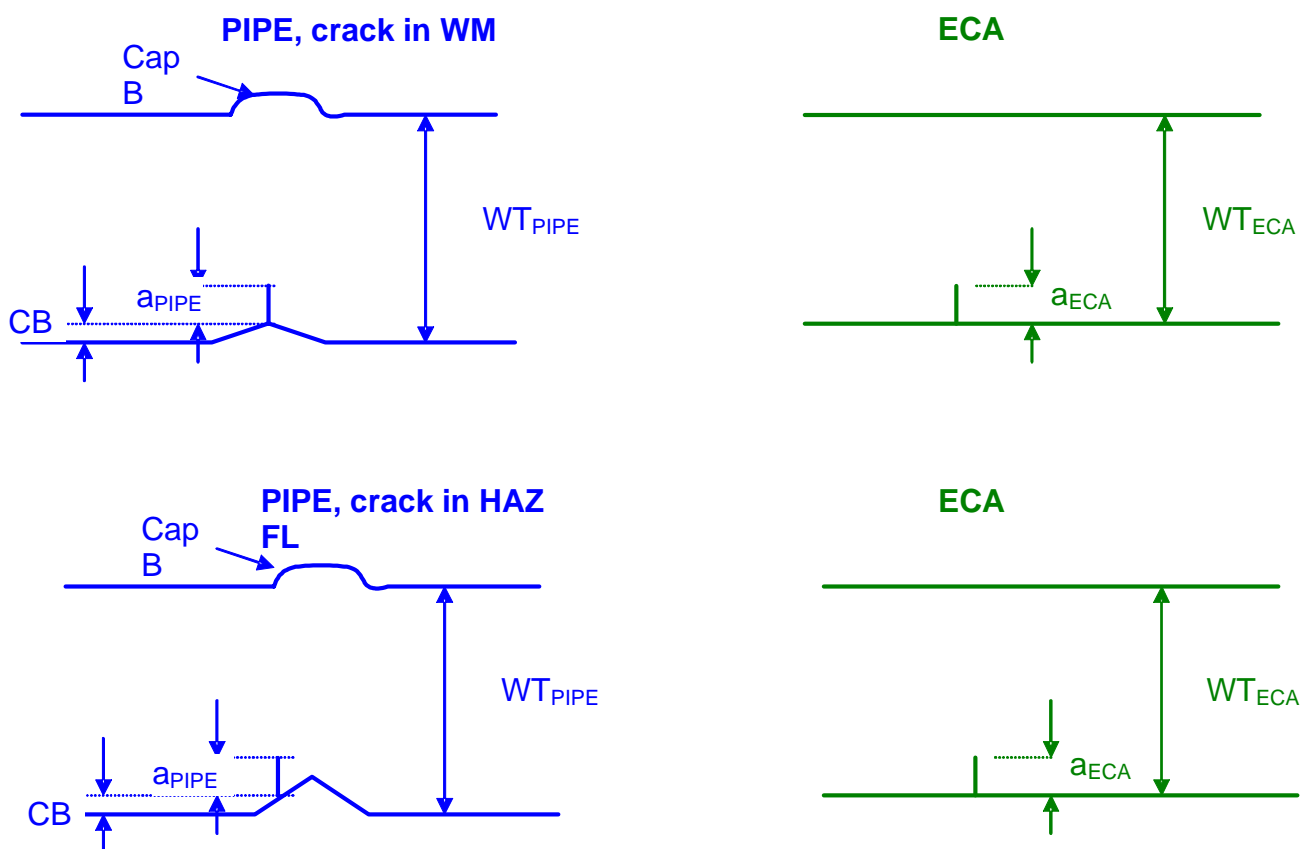


Figure B-1
Internal circumferential surface defects

$$WT_{ECA} = WT_{PIPE}$$

$$a_{ECA} = a_{PIPE} + CB$$

$$\text{Membrane stress}_{ECA} = \text{Membrane stress}_{PIPE}$$

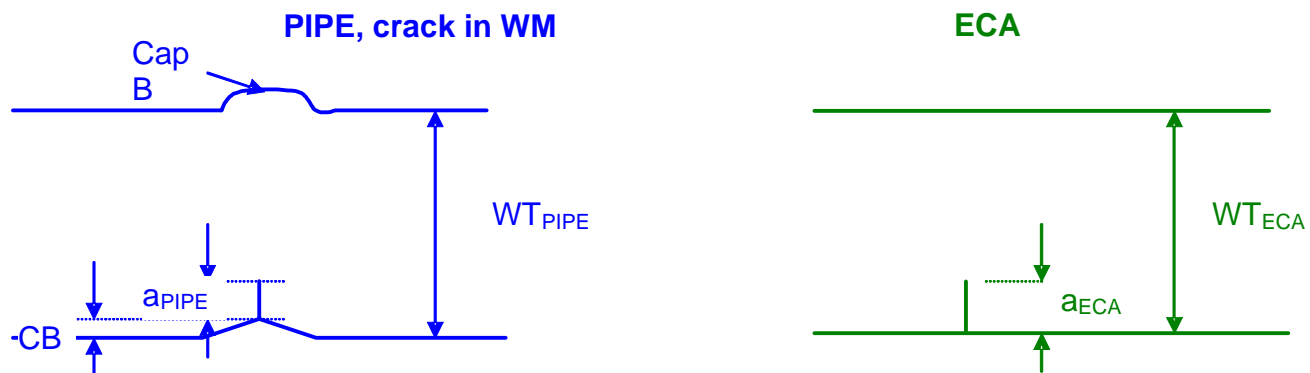


Figure B-2
 Internal circumferential surface defect that goes around the whole circumference of the pipe

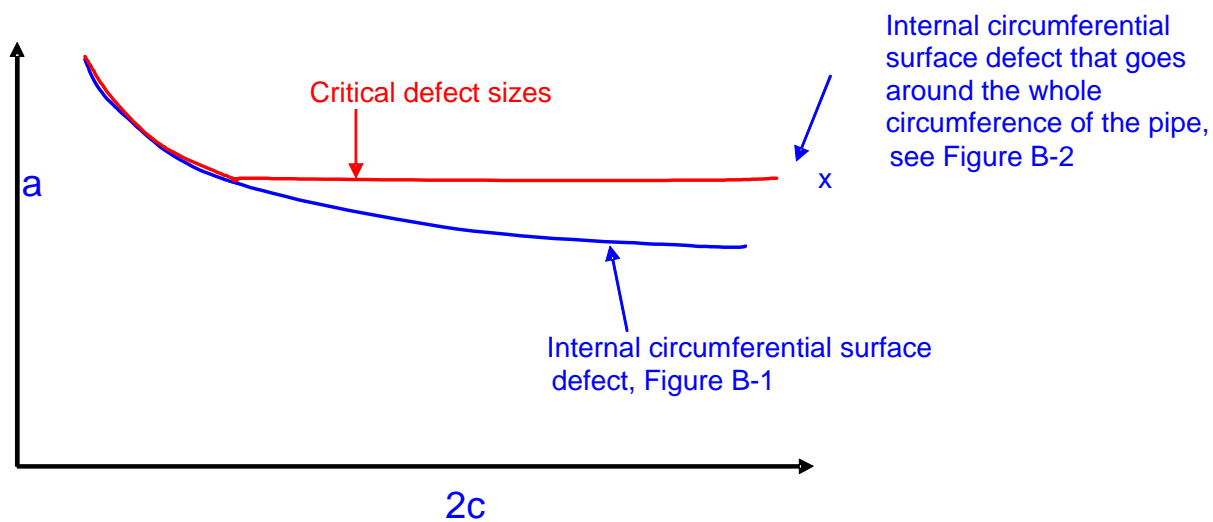


Figure B-3
 Critical circumferential surface defect, combination of the assessment method described in Figs. B-1 and B-2

$$WT_{ECA} = WT_{PIPE} - CB$$

$$2a_{ECA} = 2a_{PIPE} + CB$$

$$2c_{ECA} = 2c_{PIPE}$$

$$\text{Membrane stress}_{ECA} = \text{Membrane stress}_{PIPE} \times WT_{PIPE} / WT_{ECA}$$

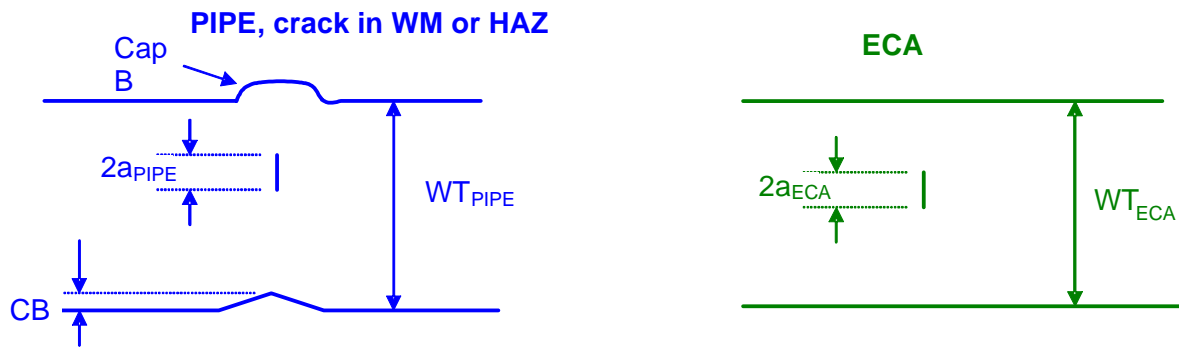


Figure B-4
Embedded defects

$$WT_{ECA} = WT_{PIPE} - CB$$

$$a_{ECA} = a_{PIPE}$$

$$2c_{ECA} = 2c_{PIPE}$$

$$\text{Membrane stress}_{ECA} = \text{Membrane stress}_{PIPE} \times WT_{PIPE} / WT_{ECA}$$

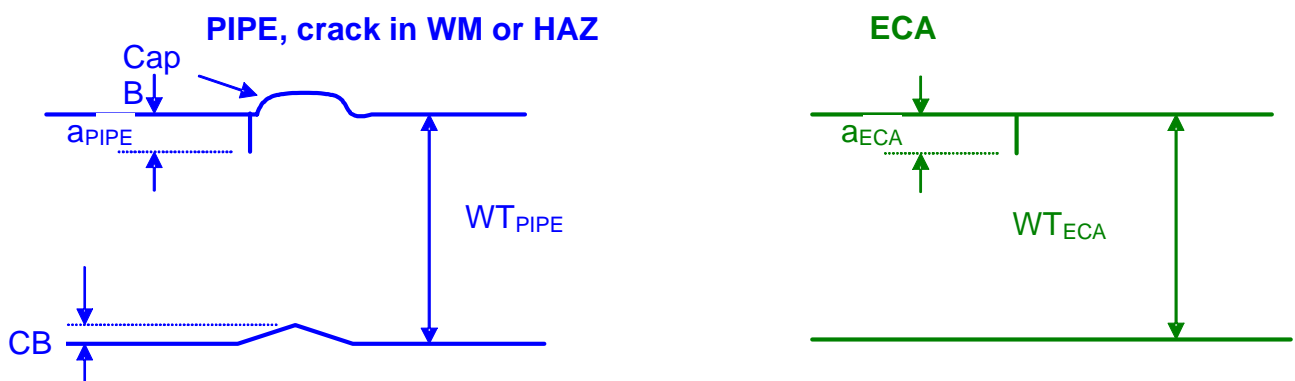


Figure B-5
Outer circumferential surface defect

