Assessment of flaws in pipeline and riser girth welds
FOREWORD

DNV GL recommended practices contain sound engineering practice and guidance.
CHANGES – CURRENT

This document supersedes the January 2006 edition of DNV-RP-F108.

Changes October 2017

This document is based on appendix A in DNV-OS-F101, October 2013 edition, revised with more guidance and clarifications, and the following fundamental changes:

— The plate reference stress solution has been reintroduced, but now with different approaches for implementing residual stresses and calculation of plastic collapse \(L_{r,max}\).
— Instead of two separate limit states, fatigue and fracture, one combined fatigue and fracture limit state has now been described.
— A new weld classification, fatigue-sensitive, has been introduced.
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SECTION 1 GENERAL

1.1 Introduction

The structural utilization of the pipelines is high, with nominal circumferential stresses of up to 90% of the yield stress.

The utilization in the axial direction is often even higher. Primarily this is due to nominal bending strains during installation (approx. 2%) and during operation (up to 1%).

DNVGL-ST-F101 provides firm criteria for the above limit states with the exception of the fracture limit state. The standard requires fracture assessment to be performed to establish weld repair criteria when strains exceeds 0.4% but does not state how this should be performed. Due to the potentially high bending strains fracture assessment is an important limit state. The applied fracture assessment has to consider the biaxial stress state that exists in a pipeline and a certain degree of displacement-controlled condition, and several methodologies can be applied. DNVGL-ST-F101 refers to this recommended practice (RP) as an example of how to perform this assessment.

The methodologies described are based on fracture mechanics principles and evaluate the criticality of circumferential flaws in metallic pipeline and riser systems. The methodologies described may also be used to evaluate the criticality of flaws in other types of metallic pipes.

The submarine pipeline system shall provide adequate safety against fatigue and fracture failures within the design life of the system. This is in general achieved by selecting materials with adequate fracture toughness properties, tensile properties and weld quality, combined with sound design principles.

A fracture is the separation of an object or material into two or more pieces under the action of stresses. Often the fracture occurs after a crack has developed and grown by cyclic loading until the remaining ligament cannot bear the applied stress and fails in an unstable manner, i.e. fractures.

A fracture is in general a consequence of an unfavourable combination of the geometry, possible flaws or fatigue cracks, stress level and fracture toughness.

A fracture is likely to happen in the welds because these may have weld flaws, higher stresses and lower fracture toughness. Significant weld flaws are typically oriented in the weld direction, so that the stresses normal to the weld direction are of concern. Because the hoop stress is always below $f_y$, fracture is not normally a concern for longitudinal welds.

Weld flaws in girth welds are typically subjected to fatigue loads and often also plastic strains which result in a general fracture concern. Hence, the focus for the fracture and fatigue limit state should normally be on girth welds.

The recommended assessment approaches for evaluating the fatigue and fracture limit state are:

— the S-N approach
— the fracture mechanics approach.

These two approaches are not fully comparable and their premises and objectives are somewhat different. When and how to use these two approaches is described and suggested in this RP. The S-N approach is a general check which should always be performed and satisfied. Recommendations for when to use the fracture mechanics approach depend on the severity of the loading, see [2.2].

1.2 Objective

The objective of this recommended practice is to describe how to determine maximum allowable planar flaws in girth welds, and to assess the criticality of known flaws.

1.3 Scope

The scope of this recommended practice is to describe the S-N and fracture mechanics approaches and how and when these two approaches may be used to meet the fatigue and fracture limit state required in DNVGL-ST-F101.
1.4 Application

The assessment procedures specified in this RP are valid for girth welds and the base material of pipelines and risers provided the materials inputs required represent the actual loading and environmental conditions calculated. This means that S-N curves, fracture toughness, tearing resistance and tensile properties, as relevant, shall be valid and representative for the actual condition assessed. Guidance on testing in environments which potentially degrade the fatigue and fracture resistance is given in App.C.

The simplified assessment procedures specified in Sec.4 and Sec.5 may also be used on lined and clad pipelines with CRA welds and 13Cr pipes with 25Cr welds, as well as other materials and material combinations if the weld metal is as least as strong as the parent pipe material, see [3.2.1].

If the stress-strain curve of the girth weld is not higher or only partially higher than the stress-strain curve of the parent pipe material, the procedures described in Sec.4 and Sec.5 may not be applicable. If this is not proven, the fracture limit state should be evaluated by solid 3D FE fracture mechanics analyses as briefly described in Sec.6.

1.5 Structure of the recommended practice

Sec.1 - Introduction
Gives the introduction, scope, applicability, definitions and symbols. References to standards are also given here and referenced throughout the document by their acronyms, while bibliographies are listed in Sec.7 and referenced by number, e.g. /2/.

Sec.2 - Fatigue and fracture limit state
Recommended procedures for performing fracture mechanics analyses on girth welds subjected to plastic deformations.

Sec.3 - Description of the fracture mechanics approach
General description of how fracture mechanics analyses can be used to determine the maximum allowable flaw sizes in girth welds.

Sec.4 - Fracture mechanics approaches – assessment category III, strain-based loading and non-fatigue-sensitive welds
Procedure for performing FAD-based assessment of girth welds subjected to $\varepsilon_{l,\text{nom}} > 0.4\%$.

Sec.5 - Fracture mechanics approaches – assessment category IV, combining fatigue crack growth and fracture
Procedure for performing FAD-based assessment of girth welds subjected to $\varepsilon_{l,\text{nom}} > 0.4\%$ where fatigue crack growth also needs to be evaluated.

Sec.6 - Use of finite element (FE) fracture mechanics analyses to assess maximum allowable flaw sizes
Recommended procedures and use of FE fracture mechanics analyses.

Sec.7 - Testing requirements for the fatigue and fracture limit state based on fracture mechanics
Recommended test methods, extent of testing and procedure for establishing necessary materials inputs to fracture mechanics assessments.

Sec.8 - Validation testing
Recommended procedure for performing testing to verify and validate fracture mechanics assessments.

Sec.9 - Bibliographies

App.A - How to understand the failure assessment diagram (FAD)
App.B - Finite element fracture mechanics assessments
App.C - Sour service testing guidelines for the fatigue and fracture limit state
1.6 References

1.6.1 Relationships to other standards

In the context of this document, the term standard shall be understood to cover document types such as codes, guidelines and recommended practices in addition to bona fide standards.

Standards are referred to throughout the documents by their acronym, e.g. ISO 9001, while bibliographies (papers and reports) are referenced by numbers.

The standards stated below include provisions which, through reference in the text, constitute provisions of this RP.

Guidance note:

Normative references are typically referred to as testing shall be performed in accordance with ISO xxx, while informative references are typically referred to as testing may be performed in accordance with ISO xxx or ISO yyy, or the recommended practice for testing is given in DNVGL-RP-F xxx.

---end of guidance note---

In case of conflict between this recommended practice and referenced DNV GL standards, the standard or recommended practice with the latest edition date shall prevail.

The latest valid edition of each of the DNV GL reference documents applies.

Guidance note:

Any conflict is intended to be removed in next revision of that document.

---end of guidance note---

Where reference is made to standards other than a DNV GL standard, the valid revision should be taken as the revision which was current on the date when this RP was issued.

Table 1-1 Referenced standards

<table>
<thead>
<tr>
<th>Document code</th>
<th>Title</th>
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<tbody>
<tr>
<td>API RP 579-1/ASME FFS-1</td>
<td>Fitness-For-Service</td>
</tr>
<tr>
<td>ISO 12135</td>
<td>Metallic materials – Unified method of test for the determination of quasistatic fracture toughness</td>
</tr>
<tr>
<td>ISO 15653</td>
<td>Metallic materials – Method of test for the determination of quasistatic fracture toughness of welds</td>
</tr>
<tr>
<td>BS 7910</td>
<td>Guide to methods for assessing the acceptability of flaws in metallic structures</td>
</tr>
<tr>
<td>DNVGL-ST-F101</td>
<td>Submarine pipeline systems</td>
</tr>
<tr>
<td>DNVGL-RP-C203</td>
<td>Fatigue design of offshore steel structures</td>
</tr>
<tr>
<td>DNVGL-RP-F112</td>
<td>Design of duplex stainless steel subsea equipment exposed to cathodic protection</td>
</tr>
<tr>
<td>ISO 5817</td>
<td>Welding – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections (ISO 5817:2014)</td>
</tr>
<tr>
<td>BS 8571</td>
<td>Method of test for determination of fracture toughness in metallic materials using single edge notched tension (SENT) specimens</td>
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1.7 Definitions

Table 1-2 Definitions of verbal forms

<table>
<thead>
<tr>
<th>Term</th>
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<tbody>
<tr>
<td>shall</td>
<td>verbal form used to indicate requirements strictly to be followed in order to conform to the document</td>
</tr>
<tr>
<td>should</td>
<td>verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required</td>
</tr>
<tr>
<td>may</td>
<td>verbal form used to indicate a course of action permissible within the limits of the document</td>
</tr>
</tbody>
</table>

Table 1-3 Definitions of terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>aging</td>
<td>a phenomenon that typically will change the tensile properties of the materials over time (strain-aging)</td>
</tr>
<tr>
<td></td>
<td>Typically, materials that have been cold formed or plastically deformed above some limit (at least above the yield stress) will change their tensile properties after some time</td>
</tr>
<tr>
<td>assessment</td>
<td>the temperature relevant for the stress condition considered in the fracture mechanics assessment</td>
</tr>
<tr>
<td>temperature</td>
<td></td>
</tr>
<tr>
<td>Bauschinger effect</td>
<td>the phenomenon that the yield stress is lowered and the strain hardening properties improved if a material is first deformed plastically in one direction and then deformed plastically in the opposite direction</td>
</tr>
<tr>
<td>crack</td>
<td>essentially the same as a flaw because flaws are considered to be cracks in fatigue and fracture assessments</td>
</tr>
<tr>
<td></td>
<td>However, a flaw is used to characterize a planar feature in the weld which is not necessarily a crack. A real crack is typically a hot crack, cold crack or fatigue crack etc. The word crack is used because terms like crack driving force and fatigue crack growth are widely used.</td>
</tr>
<tr>
<td>defect</td>
<td>used to describe a flaw which is deemed to be unacceptable, for instance by virtue of its size exceeding a specified acceptance criterion (which may be based on workmanship or ECA). If a weld flaw acceptance criterion is based on ECA, the maximum allowable flaw sizes assessed shall be adjusted to account for UT/AUT sizing inaccuracy (flaw sizing error is subtracted), see also DNVGL-ST-F101 App.D and DNVGL-ST-F101 App.E</td>
</tr>
<tr>
<td></td>
<td>All flaws that exceeds the flaw acceptance criteria shall be defined as defects and repaired.</td>
</tr>
<tr>
<td>flaw</td>
<td>a feature that has been detected by NDT, often caused by welding such as porosity, lack of fusion, lack of penetration etc. The size of a flaw may be an input to a fracture mechanics assessment (ECA) to determine its acceptability.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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</tr>
<tr>
<td>ECA static</td>
<td>a fracture mechanics analysis as described in Sec.4 where fatigue crack growth is not included</td>
</tr>
<tr>
<td>ECA fatigue</td>
<td>a fracture mechanics analysis as described in Sec.5 where fatigue crack growth is included</td>
</tr>
<tr>
<td>generic ECA</td>
<td>maximum allowable flaw sizes are extracted from tables for different pipe dimensions depending on test results</td>
</tr>
<tr>
<td>high-cycle fatigue</td>
<td>more than 1000 stress ranges in the elastic regime</td>
</tr>
<tr>
<td>low-cycle fatigue</td>
<td>fewer than 1000 stress ranges in the elastic-plastic regime</td>
</tr>
<tr>
<td>Miner sum</td>
<td>the summation of individual fatigue damage ratios caused by each stress cycle or stress range block according to the Palmgren-Miner rule</td>
</tr>
<tr>
<td>misalignment</td>
<td>the distance between the wall thickness centre lines on each side of the girth weld, see [4.3.5]</td>
</tr>
<tr>
<td>fatigue-sensitive</td>
<td>welds where fatigue cracks are likely to develop</td>
</tr>
<tr>
<td>non-fatigue-sensitive</td>
<td>welds where fatigue cracks are not likely to develop</td>
</tr>
<tr>
<td>notch</td>
<td>used related to fracture toughness testing and consists of the machined notch plus the fatigue pre-crack</td>
</tr>
<tr>
<td>Palmgren-Miner rule</td>
<td>the linear damage accumulation rule Fatigue failure is expected when the Miner sum reaches unity</td>
</tr>
<tr>
<td>plastic strain</td>
<td>the strain which means the distorted body does not return to its original size and shape after the deforming force has been removed, see Figure 1-1</td>
</tr>
<tr>
<td>pop-in</td>
<td>a discontinuity in the force versus displacement record during fracture toughness testing</td>
</tr>
<tr>
<td>Paris’ law</td>
<td>an experimentally determined relationship between the crack growth rate and stress intensity factor range ((da/dN=A(ΔK)^m))</td>
</tr>
<tr>
<td>strain hardening</td>
<td>describes the materials ability to resist more load after yielding, i.e. the increase in stress needed to increase the strain further</td>
</tr>
<tr>
<td>strain-based loading</td>
<td>should be understood as loading which is typically quantified by a strain level</td>
</tr>
<tr>
<td>stress-based loading</td>
<td>should be understood as loading which is typically quantified by a stress level</td>
</tr>
<tr>
<td>tearing</td>
<td>crack extension assessed considering the stress condition and the materials tearing resistance curve or the stable crack extension measured in a fracture toughness test</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
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<td>---------------------------</td>
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<tr>
<td>tensile strength, UTS</td>
<td>the max engineering stress level in a uniaxial tensile test, i.e. the maximum stress that a material can withstand while being stretched or pulled before local deformation starts (necking) and the stresses are reduced. The term true tensile strength is also used, but that is correlated to the engineering tensile strength, see also Figure 1-1 Several terms and abbreviations are used: $R_{\text{mv}}$, UTS, TS.</td>
</tr>
<tr>
<td>true stress</td>
<td>the stress determined by the instantaneous load acting on the instantaneous cross-sectional area. True stress is related to engineering stress assuming the material volume remains constant: $s = \sigma (1 + \varepsilon)$, where $s$ is the true stress, $\sigma$ is the engineering stress and $\varepsilon$ is the engineering strain.</td>
</tr>
<tr>
<td>true strain</td>
<td>the rate of the instantaneous increase in the instantaneous gauge length. $e = \frac{\int dl}{l} = \ln \left( \frac{l}{l_0} \right) = \ln \left( \frac{l_0 + \Delta l}{l_0} \right) = \ln(1 + \varepsilon)$, where $\varepsilon$ is the engineering strain. Strains extracted from FE simulations are true strains.</td>
</tr>
<tr>
<td>weld defect</td>
<td>used to describe a flaw which is deemed to be unacceptable. Typically, these are the maximum allowable flaw sizes specified for the NDT.</td>
</tr>
<tr>
<td>weld imperfection</td>
<td>a feature in the weld that should normally be considered a weld flaw.</td>
</tr>
<tr>
<td>weld flaw</td>
<td>a weld imperfection that is considered as a planar flaw which may be evaluated by the fracture mechanics approach.</td>
</tr>
<tr>
<td>weld quality</td>
<td>a general term which is used to characterize the weld with respect to for instance fatigue or resistance. Parameters such as weld toe shape and sharpness, size of weld flaws (in particular surface breaking), weld metal properties and possible geometrical tolerances may be important.</td>
</tr>
<tr>
<td>weld region</td>
<td>a special area or portion of the weld. Region A is the area against the outer surface, region B is the area in the middle of the girth weld and region C is the area nearest the inner surface, see Figure 2-2.</td>
</tr>
<tr>
<td>yield stress, YS</td>
<td>is not a unique value and shall be further specified to have an exact meaning. The yield stress is a value that indicates at which stage a material starts to plastically deform. To be unique the engineering yield stress shall be defined as e.g. $R_{0.2}$, $R_{0.5}$ or the proportional limit, see Figure 1-1. Unless otherwise stated, both $R_{0.2}$ and $R_{0.5}$ are acceptable definitions of yield stress if it is clearly stated which definition is used.</td>
</tr>
<tr>
<td>zone</td>
<td>a portion of the pipeline or riser where the girth welds are considered to have the same maximum longitudinal stress, cyclic stresses and combination of loads such that the same weld quality requirements can be specified (same NDT acceptance criteria)</td>
</tr>
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Table 1-4 Abbreviations

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>AUT</td>
<td>automated ultrasonic testing</td>
</tr>
<tr>
<td>BM</td>
<td>base material</td>
</tr>
<tr>
<td>CDF</td>
<td>crack driving force (applied CTOD, J or K)</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
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</tr>
<tr>
<td>C-Mn</td>
<td>carbon-manganese</td>
</tr>
<tr>
<td>CP</td>
<td>cathodic protection</td>
</tr>
<tr>
<td>CRA</td>
<td>corrosion resistant alloy</td>
</tr>
<tr>
<td>CTOD</td>
<td>crack tip opening displacement. Equally valid crack-tip-characterizing parameter as J. Equal definitions as for J; CTOD&lt;sub&gt;mat&lt;/sub&gt;, CTOD&lt;sub&gt;app&lt;/sub&gt;, CTOD&lt;sub&gt;u&lt;/sub&gt;, CTOD&lt;sub&gt;m&lt;/sub&gt;</td>
</tr>
<tr>
<td>CVN</td>
<td>Charpy V-notch</td>
</tr>
<tr>
<td>DFF&lt;sub&gt;S-N&lt;/sub&gt;</td>
<td>design fatigue factor used for fatigue assessment based on S-N</td>
</tr>
<tr>
<td>DFF&lt;sub&gt;FCG&lt;/sub&gt;</td>
<td>design fatigue factor used for fatigue crack growth assessments (fracture mechanics approach)</td>
</tr>
<tr>
<td>ECA</td>
<td>engineering critical assessment (general term used for fracture mechanics based assessment)</td>
</tr>
<tr>
<td>EOL</td>
<td>end of life (the fracture check performed to ensure that a flaw will not be unstable considering the maximum longitudinal stress in operation)</td>
</tr>
<tr>
<td>FAC</td>
<td>failure assessment curve (the assessment line in the FAD)</td>
</tr>
<tr>
<td>FAD</td>
<td>failure assessment diagram (consisting of the failure assessment curve (line), the assessment point or locus of assessment points (tearing assessment) and the cut-off, L&lt;sub&gt;r,max&lt;/sub&gt;)</td>
</tr>
<tr>
<td>FCDF</td>
<td>fatigue crack driving force</td>
</tr>
<tr>
<td>FCG</td>
<td>fatigue crack growth (assessment of fatigue based on fracture mechanics)</td>
</tr>
<tr>
<td>FL</td>
<td>fusion line (intersection between weld metal and parent pipe)</td>
</tr>
<tr>
<td>FE</td>
<td>finite element</td>
</tr>
<tr>
<td>HAZ</td>
<td>heat affected zone</td>
</tr>
<tr>
<td>HE</td>
<td>hydrogen embrittlement</td>
</tr>
<tr>
<td>HISC</td>
<td>hydrogen induced stress cracking</td>
</tr>
<tr>
<td>JIP</td>
<td>joint industry project</td>
</tr>
<tr>
<td>LOP</td>
<td>lack of penetration (type of weld flaw)</td>
</tr>
<tr>
<td>LP</td>
<td>liquid penetrant testing</td>
</tr>
<tr>
<td>MPI</td>
<td>magnetic particle inspection</td>
</tr>
<tr>
<td>NDE</td>
<td>non-destructive examination</td>
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<tr>
<td>NDT</td>
<td>non-destructive testing</td>
</tr>
<tr>
<td>PWHT</td>
<td>post weld heat treatment</td>
</tr>
<tr>
<td>RP</td>
<td>recommended practice</td>
</tr>
<tr>
<td>RT</td>
<td>radiographic testing</td>
</tr>
<tr>
<td>SCF</td>
<td>stress concentration factor</td>
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<tr>
<td>SENB</td>
<td>single edge notched bend specimen</td>
</tr>
<tr>
<td>SENT</td>
<td>single edge notched tension specimen</td>
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<tr>
<td>SIF</td>
<td>stress intensity factor</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
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</tr>
<tr>
<td>SMYS</td>
<td>specified minimum yield stress</td>
</tr>
<tr>
<td>SMTS</td>
<td>specified minimum tensile strength</td>
</tr>
<tr>
<td>TS</td>
<td>tensile strength (same as UTS)</td>
</tr>
<tr>
<td>UT</td>
<td>ultrasonic testing</td>
</tr>
<tr>
<td>UTS</td>
<td>ultimate tensile strength (same as TS). The maximum stress level of a uniaxial stress-strain curve (onset of necking)</td>
</tr>
<tr>
<td>WCL</td>
<td>weld centre line</td>
</tr>
<tr>
<td>WM</td>
<td>weld metal</td>
</tr>
<tr>
<td>YS</td>
<td>yield stress. Different definitions of yield stresses are applicable, $R_{p0.2}$, $R_{t0.5}$ etc. Unless otherwise specified $R_{t0.5}$ is governing</td>
</tr>
</tbody>
</table>

### 1.8 Latin symbols, characters and terms

- $A_{gt}$: uniform elongation, see Figure 1-1
- $a$: projected flaw height, surface flaw
- $a_0$: average original crack height
- $A$: constant in fatigue crack growth relationship
- $A_0$: original cross-sectional area
- $A_t$: elongation, see Figure 1-1
- $A_e$: length of yield plateau, see Figure 1-1
- $B$: width of a fracture mechanics specimen or the thickness of a structural component/fracture mechanics model according to BS 7910
- $D$: pipe outer diameter
- $d$: pipe internal diameter
- $D_{fat}$: S-N fatigue damage, see DNVGL-ST-F101
- $D_{fat,TOT}$: the total S-N fatigue damage where all individual load cases that contribute to fatigue damage are summarized
- $E$: elastic modulus (Young’s modulus), see Figure 1-1
- $e$: true strain (or logarithmic strain), see Figure 1-1
- $f_y$: characteristic yield stress defined as $f_y = (SMYS - f_{y,temp})\alpha_U$. Where, $f_{y,temp}$ is de-rated due to temperature above 500°C and $\alpha_U$ is the material strength value which is 1.00 for supplementary requirement U and 0.96 for all other cases. See also DNVGL-ST-F101
- $h$: height of undercut (type of weld flaw)
- $J$: $J$-integral, equally valid crack-tip-characterizing parameter as CTOD
- $J_{app, CTOD_{app}}$: value of $J$ or CTOD due to the applied loading (measure for the CDF)
- $J_{mat, CTOD_{mat}}$: material fracture toughness parameter (value of $J$/CTOD due to material resistance), either $J_c$, $J_u$ or $J_m$ or $CTOD_c$, $CTOD_u$ or $CTOD_m$
$J_c$, $\text{CTOD}_c$ specific value of $J_{\text{mat}}$ or $\text{CTOD}_{\text{mat}}$, the critical $J$/CTOD. Onset of brittle crack extension or pop-in when the $\Delta a$ is less than 0.2 mm

$J_m$, $\text{CTOD}_m$ specific value of $J_{\text{mat}}$ or $\text{CTOD}_{\text{mat}}$, Value of $J$/CTOD at the first attainment of a maximum force plateau for fully plastic behaviour

$J_u$, $\text{CTOD}_u$ specific value of $J_{\text{mat}}$ or $\text{CTOD}_{\text{mat}}$, Value of $J$/CTOD at the onset of brittle crack extension or pop-in when the event is preceded by $\Delta a$ equal to or greater than 0.2 mm

$K$, $\Delta K$ stress intensity factor (SIF), stress intensity factor range

$K_{\text{mat}}$ material fracture toughness described by $K$

$K_r$ fracture ratio of applied elastic $K$ value to $K_{\text{mat}}$. The vertical axis of the FAD

$L_r$ ratio of applied load to yield load. The horizontal axis of the FAD

$L_{r,\text{max}}$ limit (cut-off) of $L_r$ defined in the FAD. Value that should prevent plastic collapse of the remaining ligament

$L_r$ cut-off geometry function due to the weld toe, stress intensity factor magnification factor

$M_k$ the term notch is used in fracture toughness testing and consists of the machined notch plus the fatigue pre-crack. The term is also used to describe other fabricated notches, such as the CVN notch or electrical discharge machined (EDM) notch

$p$ ligament height, distance from embedded flaw tip to nearest surface (internal or external surface)

$R$ stress ratio relevant for fatigue testing/assessments, defined as minimum load to max load ratio or minimum stress to max stress ratio

$r_i$ internal pipe radius

$R_{\text{m}}$ tensile strength, see Figure 1-1

$R_{0.5}$ yield stress defined as the stress value at 0.5% total strain, see Figure 1-1

$R_{p0.2}$ yield stress defined as the stress value at 0.2% plastic strain, see Figure 1-1

$s$ true stress, see Figure 1-1

$S$-$N$, $S$-$N$ curve graphical presentation of the dependence of fatigue life ($N$) on fatigue strength ($S$ (stress range))

Specific ECA maximum allowable flaw sizes are determined based on dedicated and specific fracture mechanics assessments

$t_c$ characteristic wall thickness. $t_c=t_{\text{nom}}-t_{\text{fab}}-t_{\text{corr}}$ (operation) or $t_c=t_{\text{nom}}-t_{\text{fab}}$ (installation)

$t_{\text{corr}}$ corrosion allowance

$t_{\text{nom}}$ nominal wall thickness (without manufacturing tolerances and corrosion allowance)

$t_{\text{fab}}$ fabrication tolerances on wall thickness

$V$ notch opening displacement (fracture toughness testing)

$W$ thickness of the fracture mechanics specimen or the width of the structural component/ fracture mechanics model according to BS 7910

$WT$ pipe wall thickness
1.9 Greek symbols

δ  girth weld misalignment (distance between the wall thickness centrelines adjacent to a girth weld)  
(δ is also used as a parameter for CTOD, but not in this RP)

Δa  average stable crack extension, crack growth, increment in a either due to fatigue loading or crack driving force large enough to grow a crack (the term tearing is also used)

Δar  crack growth due to fatigue loading

Δat  crack growth due to tearing

ΔK  stress intensity factor range

Δσ  stress range (difference between maximum and minimum stress in a stress cycle)

ε  engineering strain (the ratio of total deformation to the initial dimension of the material body in which the forces are being applied). See also Figure 1-1

εl,nom  total nominal longitudinal strain (elastic plus plastic strain in pipeline or riser longitudinal direction)

σ  engineering stress (load divided with original cross-sectional area). See also Figure 1-1

σref  reference stress used for plastic collapse consideration. The reference stress relates to the stress in the structural section containing the flaw (net-section collapse)

2a  projected flaw height, embedded flaw

2c  flaw length

---

Figure 1-1 Illustration of the tensile stress-strain curves and definitions

Tensile properties are important information in fracture mechanics analyses and various parameters are illustrated and defined in Figure 1-1.
SECTION 2 FATIGUE AND FRACTURE LIMIT STATE

2.1 Introduction

The typical fatigue failure scenario for pipeline and riser girth welds involves fatigue crack initiation at either the cap or the root of the weld toe. When a fatigue crack has developed, it will continue to grow until a through thickness crack has developed and the pipeline or riser starts to leak. This failure mode is typically evaluated and avoided using the S-N approach, see DNVGL-ST-F101 and DNVGL-RP-C203. The characteristic resistance is normally given as S-N curves, i.e. stress ranges versus number of cycles to failure (N). A premise for the S-N approach is that the S-N curve used is applicable to the material, construction detail, NDT acceptance criteria (weld quality) and stress component (longitudinal vs. hoop), as well as to the surrounding environment.

The fracture mechanics approach calculates how an existing crack will develop when subjected to static and dynamic stresses. Hence, a premise for the approach is that an initial crack is postulated. The normal practice is to assume that planar weld flaws may be assessed reasonably by the fracture mechanics approach. Hence, the fracture mechanics approach may be used to determine maximum allowable flaw sizes in welds.

The suggestions for how these two approaches can be used to ensure that girth welds in pipelines and risers have sufficient fatigue and fracture resistance are discussed and outlined in this section.

S-N-based and fracture mechanics based fatigue assessments are different approaches with somewhat different premises. Fatigue analyses based on S-N curves are most applicable when evaluating fatigue initiation from weld toes or other geometrical stress concentrations that are included in the actual S-N curve, i.e. certain quality requirements are necessary in order to meet the dedicated S-N curve. Typically, the S-N curves used for pipeline and riser girth welds are applicable for welds without significant surface breaking flaws. However, in fracture mechanics based fatigue crack growth assessments, significant surface breaking flaws are typically assumed. Hence, the fatigue lives assessed by fatigue crack growth analyses are normally significantly shorter than the fatigue lives calculated using the S-N approach.

After a fatigue crack initiates, it is assumed to grow as a fatigue crack until a postulated length, through the thickness or unstable fracture is reached. This means that these two approaches estimate different fatigue lives and it is therefore necessary to make rules for how and when the approaches should be used. The differences between the two approaches are illustrated in Figure 2-1.
Figure 2-1 Illustration of fatigue crack growth and the relationship between the S-N and FCG assessment approaches

Special consideration should be given to girth welds subjected to low-cycle high strain fatigue, see [5.3.5] and [7.6].

Special consideration should be given to girth welds susceptible to hydrogen assisted cracking or other environments that may degrade the materials properties, see Sec.7 particularly [7.13].

The loading may vary significantly for different girth welds in a pipeline or riser and it is acceptable to divide the pipeline or riser into different zones with different weld quality requirements and flaw acceptance criteria.

All types of static and dynamic loads relevant for the girth welds in a pipeline or riser shall be considered for the fatigue and fracture limit state. Typical loads that need to be considered are (list not necessarily exhaustive):

— Maximum loads during installation at the installation vessel (S-lay, reeling, J-lay, etc.) shall be considered as displacement-controlled, with specified maximum strain levels, or load-controlled, specified as maximum longitudinal stress levels as relevant.
— Dynamic loads when the pipeline or riser is unsupported between the installation vessel and touch-down.
— Maximum longitudinal stress or strain at the sagbend.
— Dynamic loads in the temporary phases before production start-up (free spans, etc.).
— Dynamic loads in the operational phase (free spans, lateral buckles/expansion loops, etc.).
— Maximum longitudinal stress in operation.

Only stresses in tension need to be considered in fracture mechanics analyses assessing ductile tearing or unstable fracture. Cyclic stresses are normally defined as stress ranges where there is no distinction between tension and compression due to residual stresses.

The S-N approach methodology is specified in DNVGL-ST-F101 and is not further discussed in this RP.
2.2 Assessment categories

It is recommended to evaluate the limit state and decide on the assessment approach by performing the following steps:

1) Determine the maximum longitudinal strain levels $\varepsilon_{l,nom}$ as described in DNVGL-ST-F101.
2) Classify the girth welds as either fatigue-sensitive welds or non-fatigue-sensitive welds, see [2.3].
3) Divide the pipeline or riser into different zones as applicable, with different maximum longitudinal strain levels and, if welds are classified as fatigue-sensitive or non-fatigue-sensitive.
4) Determine the assessment category as summarized in Table 2-1.
5) Determine the weld quality requirements (NDT acceptance criteria), see [2.4].

Table 2-1 Classification of assessment categories and recommended assessment approaches

<table>
<thead>
<tr>
<th>Assessment category</th>
<th>Premises</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\varepsilon_{l,nom} &lt; 0.4%$ and non-fatigue-sensitive welds</td>
<td>Fracture mechanics approach not required. S-N fatigue damage to satisfy DNVGL-ST-F101. Required weld quality specified in Table 2-2. Fracture mechanics analyses may be used to adjust the weld quality requirements.</td>
</tr>
<tr>
<td>II</td>
<td>$\varepsilon_{l,nom} &lt; 0.4%$ and fatigue-sensitive welds</td>
<td>Same as for category I but with more stringent weld flaw acceptance criteria.</td>
</tr>
<tr>
<td>III ECA static</td>
<td>$\varepsilon_{l,nom} &gt; 0.4%$ and non-fatigue-sensitive welds</td>
<td>Fracture mechanics analyses required, see [4.2] to [4.4]. S-N fatigue damage to satisfy DNVGL-ST-F101.</td>
</tr>
<tr>
<td>IV ECA fatigue</td>
<td>$\varepsilon_{l,nom} &gt; 0.4%$ and fatigue-sensitive welds</td>
<td>Fracture mechanics analyses required, see Sec.5. S-N fatigue damage to satisfy DNVGL-ST-F101. The methods for assessing tearing or unstable fracture are identical to assessment category III, but it is necessary to include fatigue crack growth analyses in addition.</td>
</tr>
<tr>
<td>V environmental</td>
<td>Nominal longitudinal stress $&gt; f_y$ and/or fatigue-sensitive welds in environments expected to reduce the resistance compared with FCG parameters in BS</td>
<td>This assessment category is recommended if the fatigue crack growth parameters specified in BS 7910 or the traditional S-N curves are not representative due to an aggressive environment (e.g. sour service) and/or if the fracture toughness properties are expected to be significantly lower than in the air environment, see [7.13] and App.C</td>
</tr>
</tbody>
</table>

Assessment categories I to IV are not applicable for sour service or other conditions where the fatigue crack growth rate is likely to increase or the fracture toughness is likely to be degraded due to the surrounding environment unless the material is proven to be immune.

If the welds have lower or partially lower tensile properties than the parent material the fracture mechanics approaches described in Sec.4 and Sec.5 may not be safe because the crack driving force may be underestimated. For such situations, FE fracture mechanics analyses are recommended, see [3.2.2]. If girth welds have lower or partially lower tensile properties than the parent material, the 0.4% strain limit for requiring fracture mechanics analyses is still considered applicable. If the stresses in the girth weld are determined accounting for possible strength undermatch, both the S-N and fatigue crack growth approaches are considered valid.

Assessment category V is recommended for welds where the environmental conditions are likely to influence the fracture toughness properties or fatigue resistance. That is, the materials are expected to produce lower fracture toughness test results in the representative environment than in the air environment and the S-N curves specified in DNVGL-RP-C203 or the fatigue crack growth curves specified in BS 7910 are considered...
not to be valid due to the environmental conditions. The fatigue and fracture resistance of a weld procedure may be considered immune to the environment if the following two premises are satisfied:

— A minimum of two fatigue crack growth tests of the weld metal are performed in a representative or conservative environment after minimum 4 days soaking in the same environment. The results show lower fatigue crack growth rate than the mean crack growth parameters for marine environment (both -1100 and -850 mV) in BS 7910. See App.C for further guidance.

— Three SENB fracture toughness tests of the weld metal are performed in the representative environment after minimum 4 days soaking in the same environment. Loading rate should not exceed 0.5 MPa(m)^{0.5}\/s (0.0158 N/mm^{3/2}/s) within the linear elastic region. All CTOD values exceed 0.15 mm. See App.C for further guidance.

If the tests pass the requirements, the weld procedure may be considered immune and assessment approaches I to IV may be used as relevant. If the welds will be subjected to plastic deformation during installation, the testing should be performed in the strained and aged condition, see [7.13]. Further recommendations related to testing in various environments is provided in App.C.

If the tests fail the requirements, the weld procedure should be classified as assessment category V and all materials inputs to the fatigue and fracture limit state shall be established from testing in relevant environment after 4 days of soaking in the same environment. Fracture toughness testing under constant load is also recommended, see App.C. The relevant failure mechanisms for assessment category V may not be fully addressed based on fracture mechanics analyses and the approach for concluding the fatigue and fracture limit state should be agreed by all parties.

If the whole pipeline or riser is considered as one zone and the maximum longitudinal strain on any of the welds and the maximum cyclic stresses for any of the welds are assumed to be representative for all girth welds, the approach may be very conservative. Such a strategy is not recommended for category IV or V because unnecessarily stringent and challenging NDT acceptance criteria may be specified for girth welds where such quality is not necessary.

### 2.3 Classification of fatigue-sensitive and fatigue-non-sensitive girth welds

An important part of this procedure will be to classify fatigue-sensitive and non-fatigue-sensitive welds. A common and agreed definition does not currently exist and a should be agreed to by all parties. When classifying the welds as fatigue-sensitive and non-fatigue-sensitive, the following should be considered:

— How likely is it that the girth welds within the zone are subjected to the cyclic stresses specified?
— What is the weld quality?
— How severe are the cyclic stresses?

Girth welds in steel catenary risers and severe free spans are typical candidates for a fatigue-sensitive weld classification.

Some suggestions for how to evaluate and agree whether or not girth welds are fatigue-sensitive may be:

— Sufficiently low fatigue damage. This may for instance be $D_{\text{fat,TOT}} \cdot D_{\text{FF},S-N}$ below an agreed level using S-N class F1 for marine environments and $D_{\text{FF},S-N}$ in accordance with DNVGL-ST-F101. The $D_{\text{fat,TOT}}$ is the sum of all damage, from installation to the end of the design life, in the relevant zone.

Or

— Sufficiently low fatigue crack growth. The fatigue crack growth for the maximum weld flaw assumed exist after inspection and repair is below an agreed level for the relevant load case or accumulated considering all relevant cyclic loads.

Or

— A combination of sufficiently low fatigue damage or fatigue crack growth and an estimate of how likely the loadings are. Typically, this will be a defined limit of $D_{\text{fat,TOT}} \cdot D_{\text{FF},S-N}$ (or alternatively $\Delta a$) combined with arguments for how likely the cyclic loading is (for instance how many welds within the zone that are likely to be exposed to the cyclic stresses).

Or
— Welds satisfying DNVGL-ST-F101 Table E-2 and the general weld quality requirements specified in DNVGL-ST-F101 App.D may be classified as non-fatigue-sensitive if the S-N damage is acceptable. Welds not classified as non-fatigue-sensitive should be classified as fatigue-sensitive.

### 2.4 Weld quality requirements for assessment categories

Depending on the category in which the girth welds within a zone are classified, the quality requirements summarized in Table 2-2 are recommended. The requirements should be distinguished between regions A, B and C as illustrated in Figure 2-2.

![Figure 2-2 Illustration of various regions in girth welds](image)

It is not well established what kind of weld flaws and general weld quality that are needed to meet the various S-N curves. ISO 5817 and BS 7608 include requirements, but these not considered to be practical. Surface breaking flaws, especially at the weld toe, are critical and will reduce the fatigue resistance if fatigue cracks start. Hence, it is recommended that the maximum flaw sizes are limited by stipulating strict AUT acceptance criteria as specified in DNVGL-ST-F101 Table E-2 for fatigue-sensitive welds. The NDT accuracy requirements are also specified in DNVGL-ST-F101.

More accurate and maybe less stringent acceptance criteria may be determined based on fracture mechanics assessments as described in this RP. If larger acceptance criteria are determined it is not necessary to redo the S-N approach using a lower S-N curve to represent a lower weld quality.

### Table 2-2 Recommended weld quality requirements for categories I, II, III and IV

<table>
<thead>
<tr>
<th>Assessment category</th>
<th>Weld quality requirements for girth welds in a representative zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Weld quality to satisfy DNVGL-ST-F101 Table E-1. Alternatively, the NDT acceptance criteria may be determined or extended to longer flaws using the fracture mechanics approach, see [2.2], but this is not recommended.</td>
</tr>
<tr>
<td>II</td>
<td>Regions A and C: Weld quality to satisfy DNVGL-ST-F101 Table E-2. Region B: Weld quality to satisfy DNVGL-ST-F101 Table E-2. Alternatively, the NDT acceptance criteria may be determined or extended to longer flaws using the fracture mechanics approach, see Sec.5, but this is not recommended.</td>
</tr>
<tr>
<td>III ECA static</td>
<td>Regions A and C: Weld flaw acceptance criteria should be determined or verified following the category III fracture mechanics approach, see [4.2] to [4.4]. Region B: Same acceptance criteria as for regions A and C may be used, but it is acceptable to determine the maximum size for embedded flaws with a representative ligament height (position in the wall thickness, i.e. distance from either the external or internal surface)</td>
</tr>
<tr>
<td>IV ECA fatigue</td>
<td>Regions A and C: Weld flaw acceptance criteria should be determined or verified following the category IV fracture mechanics approach, see Sec.5 Region B: Same acceptance criteria as for regions A and C may be used or dedicated acceptance criteria may be determined following the category IV fracture mechanics approach, see [5.1.6]</td>
</tr>
<tr>
<td>Assessment category</td>
<td>Weld quality requirements for girth welds in a representative zone</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>V environment</td>
<td>The maximum allowable flaw sizes shall be assessed using representative fracture toughness properties and representative fatigue crack growth parameters where either assessment category III or IV is applied as relevant.</td>
</tr>
</tbody>
</table>

It is recommended that embedded flaws detected in regions A and C during inspection are re-characterized as surface breaking flaws if the height of the flaw is at least double the remaining ligament, see Figure 5-2. If the re-characterized flaw exceeds the NDT acceptance criteria, the flaw should be repaired.

It is acceptable to apply the fracture mechanics approach to adjust the NDT acceptance criteria for category I and II, but it is not recommended to use fracture mechanics analyses to reduce the weld quality below the requirements specified in DNVGL-ST-F101 App.D and DNVGL-ST-F101 App.E.
SECTION 3 DESCRIPTION OF THE FRACTURE MECHANICS APPROACH

3.1 General

3.1.1 Introduction

The methodologies specified can be used to satisfy the fatigue and fracture limit state required in DNVGL-ST-F101 by determining maximum allowable flaw sizes or to assess the criticality of known flaws. The assessments are based on fracture mechanics principles and the term engineering critical assessment (ECA) is used where unstable fractures, ductile tearing and fatigue crack growth may be assessed as relevant.

All static and dynamic loads that may contribute to crack growth should in general be considered if the fracture mechanics approach is used. Hence, crack growth due to tearing, fatigue crack growth and unstable fracture should be assessed as relevant.

The fracture mechanics approach specified does not explicitly refer to a defined safety level, but it is specified how the input parameters required to perform the analyses should be defined in order to obtain an acceptable fracture limit state. If the methodology described in this recommended practice is not followed, it is recommended to evaluate the safety level against the target safety level in accordance with DNVGL-ST-F101.

Since fatigue crack growth is a time-dependent degradation mechanism, the failure probability gradually increases and the annual target failure probability given by DNVGL-ST-F101 applies to the last year in the lifetime.

The general recommendation is not to use fracture mechanics analyses to allow for reduced weld quality. Typically, the fracture mechanics assessments are used to:

a) Derive weld flaw acceptance criteria.

b) Perform fitness-for-purpose evaluations considering the fatigue and fracture limit state, e.g.:
   — to assess the effect of different operating conditions (temperature, strain level, lifetime extension etc.)
   — to assess the significance of weld flaws or damage incurred after installation.

c) To avoid PWHT for large wall thicknesses.

The maximum allowable flaw sizes determined as specified in this RP should be adjusted for the probability of detection and flaw sizing error in the relevant NDT method in accordance with the recommendations and limitations of DNVGL-ST-F101 App.D and DNVGL-ST-F101 App.E as illustrated in Figure 3-1.
The different failure modes considered in this section are:
- fatigue crack growth (until critical crack size or through thickness)
- unstable fracture (typically tearing instability or plastic collapse)
- specified amount of tearing.

For girth welds, it is the loading that results in stresses (or strains) in the pipeline or riser longitudinal direction that is of most relevance because the flaw opening mechanism is mode I (see BS 7910). All strain requirements/limitations for girth welds are defined as the total nominal strain (elastic plus plastic), $\varepsilon_{l,nom}$, in the pipe longitudinal direction.

Girth welds between sections with different stiffnesses due to a shift in nominal wall thickness, counter boring, difference in average yield stress between adjacent pipes exceeding 100 MPa, etc., may result in considerable strain concentrations which also influence the weld. In such cases, it is recommended to determine local stress and strain situation in the weld, either by local FE analyses or global pipeline or riser analyses combined with sufficient stress or strain concentration factors.

Furthermore, girth weld misalignment effect, should be considered/analysed according to the methodology presented herein. For assessments of the operational stage, the effect of hoop stresses should also be considered, see [4.3.5].

Different words for describing a weld feature (crack, defect, flaw and notch) are used in this RP. The various words used have somewhat different meanings and are defined in Table 1-3.

Guidance note:
The definitions of weld flaws and weld defects given in Table 1-3 may not be consistent with the terms used elsewhere in DNV GL standards, see [1.6.1].

The assessment procedures specified in this RP, except for the FE fracture mechanics assessments, have been used successfully for many years and are based on the option 2 procedure in BS7910:2013 with tearing
(equivalent to Level 3B in BS 7910:2005). It is known that the crack driving force (CDF) for girth welds is inaccurately calculated (typically under-estimated) in many cases if the strain-based assessment approach using the reference stress solution for cylinders specified in BS 7910 is used without considering weld residual stresses, see /8/ and /9/. However, the weld metal has typically over-matching strength compared with the parent pipe material and this is not accounted for in the assessments. The available data on weld residual stresses related to girth welds in pipes is limited and scatter significantly. Furthermore, the definition of upper bound profiles of welding residual stresses recommended in BS 7910 is believed to be conservative. It is not recommended to relax the magnitude of weld residual stresses to lower than specified in this RP for the various approaches or to make other inputs less significant than specified in this RP without substantiating that the crack driving force assessment is sufficiently conservative. Assessment approaches not in accordance with this RP should be compared with CDF derived using dedicated FE analyses, see Sec.6 and App.A and App.B.

If procedures other than those specified in this RP are used to derive weld flaw acceptance criteria the results may not satisfy the safety classes specified in DNVGL-ST-F101 unless this is thoroughly documented and it is in such cases up to the end user to accept the final weld flaw acceptance criteria.

The recommended procedure should only assess the maximum allowable external surface flaws and to use these results as a basis for the AUT acceptance criteria for internal surface breaking and embedded flaws too, if the environmental condition is representative. However, in such case the simplified re-characterization rule in [4.2] and [5.1.6] should be used on embedded indications detected during AUT which are close to either the internal or external surface.

It is also acceptable to determine the maximum allowable size of embedded flaws with a corresponding minimum allowable ligament height as specified in [5.1.6].

### 3.1.2 Required inputs to fracture mechanics assessments

Required inputs to fracture mechanics assessments are:

- pipe dimensions, weld dimensions and dimensional tolerances
- tensile properties in the form of complete engineering stress-strain curves for the parent pipe material and evidence that the weld metal stress-strain curve over-matches the parent pipe stress-strain curve, see [3.2.1]
- fracture toughness, tearing resistance curve or critical fracture toughness, for specimens with notches located both within the weld metal and at FL/HAZ, see Sec.7 and DNVGL-ST-F101 App.B
- the \( L_{\text{max}} \) (\( L \) cut-off) value, see Table 3-1 and [4.3.6]
- maximum acceptable tearing (stable crack extension/growth), see [4.3.1]
- applied strain history during the installation phase and secondary stresses (e.g. residual stresses from the welding or installation processes)
- increased local stresses due to possible weld misalignment for all relevant load cases
- applied maximum longitudinal design stress/strain in the temporary and operational stage (end-of-life)
- cyclic stress history applicable to the pipeline or riser whilst it is in the lay catenary configuration and during the operational life
- fatigue crack growth parameters for different stages.

The required inputs and recommendations for how to determine and establish the inputs are specified in Table 3-1.
### Table 3-1 Required input parameters and recommended definitions for strain-based assessments

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value/definition</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition of external surface breaking flaw</strong>(^1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stress intensity factor solution: BS 7910, plate solution M.4.1, where: ( W = \pi \cdot (D - t_c) ) or ( W = \pi \cdot (d + t_c) )  ( B = t_c )</td>
<td></td>
<td>The cylinder reference stress solution has been used successfully for many years and is considered as the main approach. Alternatively, the reference stress solution for plates may be used. Different approaches for including residual stresses and ( L_{r,\text{max}} ) (( L_r ) cut-off) are applicable to these two different solutions.</td>
</tr>
</tbody>
</table>
| Reference stress solution:  
  a) BS 7910, cylinder solution, P.10.4, or alternatively  
  b) BS 7910, plate solution, P.6.1. | | |
| **Definition of embedded flaw**\(^2\) | Recommended to be assessed equal to external surface flaws. Re-characterization rule should be used during inspection\(^2\) | Tearing and critical size of embedded flaws are recommended to be set equal to surface flaws. However, it is acceptable to use formulas for embedded flaws in plate when assessing fatigue crack growth, see [5.1.6]. |
| **Definition of internal surface breaking flaw** | It is acceptable to use the results from external surface flaws also for internal surface flaws if the material properties specified are representative. If specific analyses are performed, the following formulas are recommended: Stress intensity factor solution:  
  a) BS 7910, plate solution M.4.1  
  b) BS 7910, internal surface flaw in cylinder, M.7.3.2  
Reference stress solution:  
  a) BS 7910, cylinder solution, P.10.2  
  b) BS 7910, plate solution, P.6.1. | The stress intensity factor solution for internal surface flaws in cylinders has geometry limitations which makes it difficult to use. It is generally recommended to use the plate solution or the same formulas as for external surface flaws, but with SCF for the root. |
<p>| <strong>Stress-strain curve used in FAD</strong> | True stress-strain curve converted from high engineering stress-strain curve, see [7.10]. | The engineering stress-strain curve is used to determine the applied stresses and the converted true stress-strain curve is used to determine the FAD. |
| <strong>Determination of primary membrane stress, ( P_m )</strong> | High engineering uniaxial stress-strain curve, see [7.10] should be used. ( P_m ) is the engineering stress value at the applied strain specified. | |
| <strong>Determination of primary bending stress, ( P_b )</strong> | SCF is calculated as specified in [4.3.5]. ( P_b ) is determined using the Neuber rule, see [4.3.5]. | |</p>
<table>
<thead>
<tr>
<th><strong>Input parameter</strong></th>
<th><strong>Value/definition</strong></th>
<th><strong>Comment</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition of (weld) residual stress</strong></td>
<td>If the reference stress solution for cylinders is used: for the first strain increment ( Q_m = YS ) for the high stress-strain curve representing as-welded properties, relaxation allowed, see [4.3.3]. Next loads ( Q_m = 0.4 \cdot YS ), same ( YS ) as for the first strain increment. If the reference stress solution for plates is used: ( P_m ) is also extracted from the characteristic engineering stress-strain curve, see [7.10], but the applied strain is increased with ( YS / E ), where ( YS ) represents the stress-strain curve defined for the as-welded condition. The strain increase is used for all later load cases (further relaxation not allowed for). If later load cases are stress-based, residual stresses may be defined as ( Q_m = 0.4 \cdot YS ) (same ( YS ) as above). See also [4.3.3] and Table 5-1.</td>
<td>It is known that the reference stress solution for cylinders (Kastner) combined with applied stress extracted from the engineering stress-strain curve typically results in a too low crack driving force. Hence, it is necessary to define residual stresses conservatively. If the reference stress solution for plates is used, the CDF is more correct and the influence of residual stresses can be reduced.</td>
</tr>
<tr>
<td><strong>Use of stress intensity factor magnification for weld toe, ( M_k )</strong></td>
<td>Not required for strain-based situations.</td>
<td></td>
</tr>
</tbody>
</table>
| **\( L_{r,\text{max}} (L_r \text{ cut-off}) \)** | If reference stress formula for cylinder is used: \[
L_{r,\text{max}} = \frac{UTS}{YS}
\]
If reference stress formula for plate is used:
\[
L_{r,\text{max}} = \frac{(1 + \varepsilon_{UTS}) \cdot UTS}{(1 + \varepsilon_{YS}) \cdot YS}
\] where:
\( \varepsilon_{UTS} \) = engineering strain at UTS (uniform elongation)
\( \varepsilon_{YS} \) = engineering strain at YS. | |
| **Fracture resistance curve** | One of the following approaches is recommended:
- Multiple specimen method: Lower bound R-curve based on 6 valid results for each relevant microstructure, see BS 8571 and Sec.7.
- Single specimen method: Minimum 3 specimens are tested and a lower bound curve representing all tests is established, see Sec.7.
- Tearing resistance curve adjusted for tearing initiation, see Sec.7 (not applicable to first strain increment). | If longitudinal strain is below 0.4% it is acceptable to define fracture toughness as a specific (single point) fracture toughness (\( CTOD_{c,u\text{ or } m} \) or \( J_{c,u\text{ or } m} \) as relevant) |
<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value/definition</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>The maximum allowable sizes of embedded flaws may be assumed equal to the maximum allowable surface flaws assessed (dedicated analyses not necessary). However, then the re-characterization rule specified in [5.1.6] is required when the AUT acceptance criteria are evaluated.</td>
<td></td>
</tr>
<tr>
<td>2)</td>
<td>If the welds are considered non-fatigue-sensitive, see [2.3], it is not required to specifically assess embedded flaws where the distance to the nearest surface (ligament height) is such that the ligament height is more than half the flaw height itself. In such case the embedded flaw may be considered equally as a surface flaw with the same height and length. If the ligament height is less than half the embedded flaw height the flaw should be defined as a surface flaw where the flaw height is defined as the ligament height plus the embedded flaw height. It is however always acceptable to assess embedded flaws as embedded flaws in a plate in accordance with BS 7910 but this will give conservative results.</td>
<td></td>
</tr>
</tbody>
</table>

### 3.1.3 Comments about the input parameters

The ECA provides allowable flaw heights without UT/AUT flaw sizing error. Regarding the determination of weld flaw acceptance criteria, see DNVGL-ST-F101 App.D and DNVGL-ST-F101 App.E.

The assessment procedure is in general based on the assumption that the fracture mechanics model consists of one stress-strain curve (i.e. even-match strength procedure). However, because the procedure specifies that the applied stress may be extracted from the engineering stress-strain curve while the true stress-strain curve is used in the failure assessment diagram (FAD) the procedure describes a situation where the cross section with the flaw has higher strength. This means that the approach described in this RP in fact is as an over-match procedure and comparisons with FE fracture mechanics assessments have shown that the CDF is underestimated in some cases. The CDF calculation does not distinguish between flaws inside the weld and those at the fusion line boundary.

If weld metal strength overmatch is not confirmed for all material conditions, the procedure for determining applied stresses specified in [4.3.5] is not acceptable and solid 3D FE fracture mechanics analyses are recommended, see Sec.6.

Weld residual stresses will influence the crack driving force. However, the level and profile of weld residual stresses are complex and vary considerably between different welding methods, weld procedures, weld geometry, etc.

To evaluate the accuracy of the assessment approaches described in this RP, it is important to realise that all input parameters should be considered. Evaluations of the crack driving force using comprehensive 3D solid FE fracture mechanics analyses and comparisons with the crack driving force assessed using the assessment procedures described in this section have shown that the crack driving force is typically underestimated if the reference stress solution for cylinders is used, /8/ and /9/. However, if the reference stress solution for plate is used, the results compare better. It is nonetheless still questionable how the crack driving force is increased by residual stresses.

The approach using the reference stress solution for cylinders and assuming weld residual stresses as a secondary uniform membrane stress equal to the yield stress allowing for relaxation down to 40% has been used extensively for many years. This approach has proven to be safe and is therefore considered as the general recommendation.

However, a more appropriate solution would be to assess the crack driving force without weld residual stresses more accurately and then to include more exact weld residual stresses. An acceptable alternative is, hence, to use the reference stress solution for plate combined with weld residual stresses defined as an increased applied strain, YS/E, as specified for FE fracture mechanics analyses.

A further description and discussions of input parameters are given in [4.3].
3.1.4 Application

In general, procedures for assessing girth welds under load- or displacement-based conditions are described. The procedures are also applicable for assessing flaws in parent pipe, but girth welds with possible flaws and stress concentrations are normally most critical and relevant for the fatigue and fracture limit state.

A clear definition of load-based and displacement-based conditions is difficult, but it is important how the applied stresses and stress-strain curves are defined and determined in fracture mechanics analyses. It is suggested that all situations where the maximum longitudinal stress in the pipeline or riser exceeds 0.9·f_y (without SCF) should be classified as strain-based and that all situations where the maximum longitudinal stress is below 0.9·f_y (without SCF) should be classified as stress-based. Different methods for determining stress-strain curves and applied stresses are specified for these two different situations. For situations where the applied stress is around the yield stress, sensitivity analyses are recommended and the method which results in the smallest allowable flaw sizes should be chosen.

Fracture mechanics analyses require representative materials properties to be specified. Hence, tensile testing and fracture toughness testing should be performed for the actual and relevant material conditions, environment and assessment temperature as described in Sec.7.

Some materials are sensitive to environmentally induced embrittlement. In such cases, the choice of toughness and fatigue properties should reflect the actual environment. Examples include a reduction in toughness and accelerated fatigue crack growth in sour, sweet or seawater environments (with or without cathodic protection). See also Sec.7 and App.C.

The fracture mechanics assessment procedures described in [4.2] and [4.3] are based on BS 7910. Hence, the recommendations and requirements stated in these sections are only applicable if BS 7910 is the basis for the assessments, with the amendments and adjustments as described in this RP.

It is acceptable to conduct integrity assessment of welds using finite element (FE) analyses, see Sec.6. Other suitable standards such as API 579-1/ASME FFS-1 and R6 may also be applicable, but in such cases, it is recommended to compare the crack driving force calculated with solid 3D FE fracture mechanics analyses. The assessment procedure should also be thoroughly described, documented and accepted by all parties.

In general, the ECA procedures described in BS 7910 only consider uniaxial loading conditions and stress levels below yield. The recommended procedure for how BS 7910 may be adjusted to strain-based loading is described in this RP. Pipelines in operation are subjected to a biaxial stress-strain state and the recommended assessment procedure for operational conditions subject to biaxial stresses is described in [4.3.5].

Guidance note:

Full-scale testing and solid 3D FE fracture mechanics analyses show that the fracture capacity for circumferentially aligned flaws (such as those at girth welds) subject to an applied longitudinal strain is reduced if the pipeline or riser is pressurized. This phenomenon is mainly caused by the increased crack driving force. Assessment procedures considering internal overpressure combined with longitudinal tensile strains are under development, and a simple model is presented in this standard. Analysis for such situations should be well documented, based on well proven engineering principles, e.g. 3D FE fracture mechanics analysis, and accepted by all parties.

---end---of---guidance---note---

The assessment temperature is defined as the temperature representative for the stress-strain condition considered. It may be ambient (typically installation), elevated (e.g. lateral buckling) or sub-zero (e.g. shut-down). All testing should be performed at the assessment temperature, see Sec.7. If other test temperatures are chosen, it shall be substantiated that the testing gives conservative results compared to testing at the assessment temperature.

3.2 Definitions of weld strength mismatch

3.2.1 Weld metal with strength equal to or higher than the parent material

A girth weld is at least even-match to the strength of the parent pipes if all the following requirements are satisfied:
— The lowest yield stress (YS) from tensile testing of the weld metal (minimum 3 tests) is higher than the characteristic YS of the parent pipes defined in accordance with [7.10].
— The lowest ultimate tensile strength (UTS) from tensile testing of the weld metal (minimum 3 tests) is higher than the UTS of the parent material defined in accordance with [7.10].
— All the requirements for the linepipes specified in DNVGL-ST-F101 are fulfilled.
— All the requirements for the girth weld procedures in DNVGL-ST-F101 App.C are fulfilled.
— No indication of a lower or partially lower stress-strain curve for the girth welds compared with the stress-strain curves of the parent pipes is seen during testing for the fracture mechanics analyses, during production or during qualification.

If the lowest YS or lowest UTS result from one of the weld metal tensile tests is shown to be non-consistent with the results of the other specimens, it is acceptable to disregard that result if two additional tensile tests of the weld metal are performed.

In dissimilar material configurations, such as CRA girth welds in lined or clad pipes, a weld root which is at least as strong as the liner or clad material may also be important and should be documented, see [7.9]

### 3.2.2 Weld metal with partially lower strength than the parent material (under-match strength)

If the weld metal has a stress-strain curve which is partially lower than the stress-strain curve of the parent pipe material, the crack driving force may increase compared with if the stress-strain curve of the weld metal was at least as high as the stress-strain curve of the parent pipe material. In such cases, it shall be ensured that the crack driving force is not underestimated. Possible solutions may be as follows:

— Perform solid 3D FE fracture mechanics assessments as described in Sec.6, see also App.A and App.B.
— Confirmed that the CDF calculated by the procedure described in [4.3] is equal to or higher than the CDF assessed by solid 3D FE fracture mechanics analyses. Typically, both the maximum allowable flaw height with the corresponding flaw length and the maximum allowable flaw length with the corresponding flaw height used as a basis for the AUT acceptance criteria should be checked as a minimum.
— Adjust the inputs used to perform the assessments according to [4.3] or Sec.5 such that the CDF is at least as high as the CDF assessed by solid 3D FE fracture mechanics analyses. Such adjustments may be to use another reference stress solution, adjust the stress-strain curve applied, increased the applied stress, etc.
— Perform solid 3D FE fracture mechanics analyses that show a higher crack driving force for a strength even-match situation than analyses where representative stress-strain curves for the weld metal are specified. If this is the case, the simplified fracture mechanics assessment approach specified in [4.3] is acceptable.

**Guidance note:**
Caution should be exercised regarding the strength mismatch procedure described in BS 7910 if the loading being considered is defined as strain-based. However, if the loading is defined as stress-based, the BS 7910 approach should be sufficiently accurate.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

**Guidance note:**
Welds with stress-strain curve lower than the stress-strain curve of the parent material for all strain levels (full under-match) are not recommended if plastic strains need to be considered. However, with good quality control and sufficient cap and root reinforcement heights it might be possible to determine realistic maximum allowable flaw sizes based on dedicated solid 3D FE fracture mechanics analyses.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---
SECTION 4 FRACTURE MECHANICS APPROACHES - ASSESSMENT CATEGORY III, STRAIN-BASED LOADING AND NON-FATIGUE-SENSITIVE WELDS

4.1 Introduction

4.1.1 General

Depending on the level of monotonic and cyclic deformations, the assessments are divided into the following categories:

a) Category III, fracture mechanics assessments for welds classified as non-fatigue-sensitive - ECA static. ECA static may further be divided into:
   — Generic, $\varepsilon_{\text{nom}}$ up to 2.25% where the load case assessed does not include internal pressure (typically installation) and the maximum allowable flaw sizes are determined in accordance with [4.2]
   — Specific, girth welds subjected to a specific strain level where the pipeline or riser is not pressurized and the maximum allowable flaw sizes are determined in accordance with [4.3]
   — Internal overpressure, load scenarios where the pipeline or riser is pressurized to internal overpressure exceeding $0.15 \cdot f_y$ in hoop stress.

b) Category IV, combined fatigue crack growth and fracture assessments are required, ECA fatigue, see Sec.5.

The recommended procedure for ECA static, specific is described in [4.3]. As an alternative, generic maximum allowable flaw sizes may be extracted directly from the tables presented in [4.2] without detailed assessments if the required materials testing is performed and all the requirements specified are fulfilled.

4.1.2 Special considerations

If the load case is specified as strain-based, it may be applied up to 10 times and still be considered to fulfill the ECA static requirements if tearing assessments are performed for each load. Typical situations will be reeling installation including contingency. If more than 10 strain-based loads need to be assessed, the load scenario should be classified as low-cycle fatigue, see [5.3.5].

It should be evaluated whether the loading mode under consideration is displacement-controlled or load-controlled and the assessment methodology shall reflect this, see [3.1.4]. Offshore submarine pipelines are mainly displacement-controlled during installation (e.g. bending controlled by curvature) and it is acceptable to follow the displacement-controlled (strain-based) procedure presented in [4.3].

If the longitudinal strain $\varepsilon_{\text{nom}}$ is below 0.4%, single value fracture toughness may be established and used in the assessments (no fracture toughness resistance curve is required). It is recommended to define the characteristic fracture toughness as the lowest value of three, where all test results shall represent one homogeneous group (identical microstructure and testing conditions etc.), see BS 8571 and Sec.7.

4.2 Category III, generic engineering critical assessment (ECA)

4.2.1 General

The maximum allowable flaw sizes specified in Table 4-2 to Table 4-4, suitably adjusted to account for sizing accuracy, may be used for the final weld flaw acceptance criteria. This is only acceptable if all the requirements specified in [1.5] and this section are fulfilled.

The recommended amount of fracture toughness testing and tensile testing are specified in Table 4-1. See also Sec.7.
The generic ECA is based on pre-performed tearing analyses (tearing resistance curve needed) following the approach described in [4.3] where various inputs have been selected such that the specific limitations as described below apply. The number of fracture toughness tests for each microstructure may be limited to three, see Sec.7.

Flaws close to either the external or internal surface may be more critical than surface-breaking flaws of the same size. The generic tables, Table 4-2 to Table 4-4, have only considered surface-breaking flaws. Hence, re-characterization rules for flaws close to a surface are recommended during AUT. A simplified rule which is acceptable for static load conditions is that the height of weld flaws close to the internal or external surface discovered during NDT should be defined as the flaw height itself plus the height of the remaining ligament if the ligament is less than half the height of the weld flaw, see Figure 5-2, DNVGL-ST-F101 Table D-6 and DNVGL-ST-F101 App.E.

4.2.2 Premises

This generic ECA is not applicable to the following situations:

— clad or lined pipelines (detailed analyses considering penetration of CRA layer required)
— pipelines subjected to a combination of internal overpressure exceeding 0.15f_y hoop stress and \( \varepsilon_{l,nom} > 0.4\% \), see [4.4]
— where the girth welds have under-matching strength compared to the parent pipe, see [3.2.2]
— if more than five tensile strain cycles (plastic bending of pipe in the same direction up to five times) are applied (e.g. one contingency operation during reeling installation may be acceptable)
— if the girth welds are not tested in accordance with Table 4-1, Sec.7 and DNVGL-ST-F101 App.B
— if the linepipes have not been tested and designed according to DNVGL-ST-F101, Sec.6 and Sec.7
— if experimentally determined values of J do not meet the requirements specified in Table 4-2 to Table 4-5 (see Figure 4-1). No similar tables have been determined for CTOD. However, it is acceptable to convert the \( J_{mat} \) values to CTOD_{mat} values using the formula stated in [7.4]
— if significant pop-ins (see ISO 12135 and ISO 15653) or unstable fractures occurs prior to the maximum load during fracture toughness testing
— if the geometry, applied strain, fracture toughness and maximum misalignment are not within the limitations specified in Table 4-2 to Table 4-5
— if the following YS/UTS ratios are not met during the production qualification tests or during the parent pipe tensile testing specified in Table 4-1:
  — YS/UTS \leq 0.90 for C-Mn with SMYS \leq 555 MPa
  — YS/UTS \leq 0.85 for 13Cr.

If any of the requirements specified above are not met, a specific ECA should be performed according to [4.3] or Sec.5.
Figure 4-1 No $J_{\text{mat}} - \Delta a$ test results shall end-up inside the area indicated (values may be converted to CTOD$_{\text{mat}}$ if only CTOD is available from fracture toughness testing)

Table 4-1 Testing required for use of generic ECA for strain conditions equal to or larger than 0.4% $^1$, $^2$

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Location/weld procedure</th>
<th>Test quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld metal tensile testing $^4$, $^5$</td>
<td>Girth weld</td>
<td>3</td>
</tr>
<tr>
<td>Parent pipe tensile testing $^4$, $^5$</td>
<td>Parent pipe, longitudinal</td>
<td>5</td>
</tr>
<tr>
<td>R testing of SENT specimens $^5$, $^6$</td>
<td>Main line</td>
<td></td>
</tr>
<tr>
<td>R testing of SENT specimens $^5$, $^6$</td>
<td>Double joint</td>
<td></td>
</tr>
<tr>
<td>R testing of SENT specimens $^5$, $^6$</td>
<td>Through thickness repair (TTR)</td>
<td>Three specimens if multiple specimens approach is used or two if single specimen approach is used for each notch position, see DNVGL-ST-F101 App.B.</td>
</tr>
<tr>
<td>R testing of SENT specimens $^5$, $^6$</td>
<td>Partial repair $^3$</td>
<td></td>
</tr>
<tr>
<td>R testing of SENT specimens $^5$, $^6$</td>
<td>Tie-in weld3)</td>
<td></td>
</tr>
</tbody>
</table>

1) All weld procedures which have different essential variables according to DNVGL-ST-F101 Table C-2 should be tested.
2) The test temperatures and material condition to be tested should be as specified in Sec.7.
3) If the welding procedure and heat input are equal to those used in the through-thickness repair procedure, this testing may be omitted. If repeated repairs are permitted or agreed, the relevant microstructures shall be tested.
4) If production tensile testing is performed at the assessment temperature and full stress-strain curves are established, additional tensile testing is not required.
5) The specimen geometry and test requirements are specified in DNVGL-ST-F101 App.B.
6) The blunting should be included in the crack extension length (crack extension = blunting + tearing).
### Table 4-2 Maximum allowable flaw sizes, $a \times 2c$ [mm], maximum strain, $0.4\% \leq \varepsilon_{l,nom} < 1\%$ \(^1, 2, 3\), 8”-12” pipes

<table>
<thead>
<tr>
<th>J-Δa requirements, see Figure 4-1 [N/mm = kJ/m²]</th>
<th>C-Mn; SMYS ≤ 450</th>
<th>C-Mn; SMYS = 485</th>
<th>C-Mn; SMYS = 555</th>
<th>13Cr; SMYS = 550 (^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{0.5} = 400$</td>
<td>$15 \leq t_c &lt; 25$</td>
<td>$t_c \geq 25$</td>
<td>$15 \leq t_c &lt; 25$</td>
<td>$t_c \geq 25$</td>
</tr>
<tr>
<td>and $J_{1.0} = 600$</td>
<td>$4 \times 20$</td>
<td>$4 \times 25$</td>
<td>$4 \times 15$</td>
<td>$4 \times 25$</td>
</tr>
<tr>
<td>$J_{0.5} = 600$</td>
<td>$3 \times 15$</td>
<td>$5 \times 15$</td>
<td>$4 \times 25$</td>
<td>$5 \times 15$</td>
</tr>
<tr>
<td>and $J_{1.0} = 800$</td>
<td>$4 \times 30$</td>
<td>$4 \times 50$</td>
<td>$4 \times 45$</td>
<td>$5 \times 20$</td>
</tr>
<tr>
<td>$J_{0.5} = 800$</td>
<td>$5 \times 20$</td>
<td>$5 \times 35$</td>
<td>$5 \times 45$</td>
<td>$5 \times 20$</td>
</tr>
<tr>
<td>and $J_{1.0} = 1000$</td>
<td>$4 \times 40$</td>
<td>$4 \times 80$</td>
<td>$4 \times 70$</td>
<td>$4 \times 30$</td>
</tr>
<tr>
<td>$J_{0.5} = 1000$</td>
<td>$5 \times 25$</td>
<td>$5 \times 50$</td>
<td>$5 \times 45$</td>
<td>$5 \times 20$</td>
</tr>
<tr>
<td>$\delta_{max}$ [mm], see [4.3.5]</td>
<td>1.8</td>
<td>2.5</td>
<td>1.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

1) Larger allowable flaw sizes may be acceptable based on specific ECA.
2) Only acceptable if testing as specified in Table 4-1 has been performed.
3) The maximum allowable flaw size, $a \times 2c$, refers to height and length respectively of both surface-breaking and embedded flaws. If the embedded flaw is located close to the surface (ligament height less than half the flaw height) the ligament height between the flaw and surface should be included in the flaw height. The UT/AUT flaw sizing error shall be subtracted from the maximum allowable flaw height to establish the UT/AUT weld flaw acceptance criteria, see DNVGL-ST-F101 App.D and DNVGL-ST-F101 App.E.
4) Also acceptable for 22Cr and 25Cr pipelines.
### Table 4-3 Maximum allowable flaw sizes, $a \times 2c$ [mm], maximum strain, $0.4\% \leq \varepsilon_{l,nom} < 1\%^{1), 2), 3)}$, 12” $<D\leq 16”$

<table>
<thead>
<tr>
<th>$J$-Δ$a$ requirements, see Figure 4-1</th>
<th>C-Mn; SMYS $\leq 450$</th>
<th>C-Mn; SMYS $= 485$</th>
<th>C-Mn; SMYS $= 555$</th>
<th>13Cr; SMYS $= 550$ $^{4)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{\text{0.5}} = 400$</td>
<td>3 × 35</td>
<td>3 × 75</td>
<td>3 × 30</td>
<td>3 × 155</td>
</tr>
<tr>
<td>and</td>
<td>4 × 20</td>
<td>4 × 30</td>
<td>4 × 20</td>
<td>4 × 150</td>
</tr>
<tr>
<td>$J_{\text{1.0}} = 600$</td>
<td>5 × 15</td>
<td>5 × 25</td>
<td>5 × 20</td>
<td>5 × 15</td>
</tr>
<tr>
<td>$J_{\text{0.5}} = 600$</td>
<td>3 × 65</td>
<td>3 × 150</td>
<td>3 × 60</td>
<td>3 × 135</td>
</tr>
<tr>
<td>and</td>
<td>4 × 35</td>
<td>4 × 75</td>
<td>4 × 30</td>
<td>4 × 65</td>
</tr>
<tr>
<td>$J_{\text{1.0}} = 800$</td>
<td>5 × 25</td>
<td>5 × 45</td>
<td>5 × 20</td>
<td>5 × 40</td>
</tr>
<tr>
<td>$J_{\text{0.5}} = 800$</td>
<td>3 × 95</td>
<td>3 × 150</td>
<td>3 × 85</td>
<td>3 × 150</td>
</tr>
<tr>
<td>and</td>
<td>4 × 50</td>
<td>4 × 115</td>
<td>4 × 45</td>
<td>4 × 100</td>
</tr>
<tr>
<td>$J_{\text{1.0}} = 1000$</td>
<td>5 × 35</td>
<td>5 × 70</td>
<td>5 × 30</td>
<td>5 × 60</td>
</tr>
<tr>
<td>$\delta_{\text{max}}$ [mm], see [4.3.5]</td>
<td>1.8</td>
<td>2.5</td>
<td>1.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

1) Larger allowable flaw sizes may be acceptable based on specific ECA.
2) Only acceptable if testing as specified in Table 4-1 has been performed.
3) The maximum allowable flaw size, $a \times 2c$, refers to the height and length respectively of both surface-breaking and embedded flaws. If the embedded flaw is located close to the surface (ligament height less than half the flaw height) the ligament height between the flaw and surface should be included in the flaw height. The UT/AUT flaw sizing error shall be subtracted from the maximum allowable flaw height to establish the UT/AUT weld flaw acceptance criteria, see DNVGL-ST-F101 App.D and DNVGL-ST-F101 App.E.
4) Also acceptable for 22Cr and 25Cr pipelines.
### Table 4-4 Maximum allowable flaw sizes, $a \times 2c$ [mm], maximum strain, $0.4\% \leq \varepsilon_{l,\text{nom}} \leq 1\%$ 1), 2), 3) $D>16"$

<table>
<thead>
<tr>
<th>$J$-(\Delta a) requirements, see (\text{Figure 4-1} \ [N/mm = kJ/m^2])</th>
<th>C-Mn; SMYS ≤ 450</th>
<th>C-Mn; SMYS = 485</th>
<th>C-Mn; SMYS = 555</th>
<th>13Cr; SMYS = 555</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{0.5} = 400$</td>
<td>3 × 40</td>
<td>3 × 90</td>
<td>3 × 30</td>
<td>3 × 70</td>
</tr>
<tr>
<td>and</td>
<td>4 × 20</td>
<td>4 × 35</td>
<td>4 × 20</td>
<td>4 × 35</td>
</tr>
<tr>
<td>$J_{1.0} = 600$</td>
<td>5 × 15</td>
<td>5 × 25</td>
<td>5 × 15</td>
<td>5 × 25</td>
</tr>
<tr>
<td>$J_{0.5} = 600$</td>
<td>3 × 80</td>
<td>3 × 150</td>
<td>3 × 70</td>
<td>3 × 150</td>
</tr>
<tr>
<td>and</td>
<td>4 × 40</td>
<td>4 × 90</td>
<td>4 × 35</td>
<td>4 × 75</td>
</tr>
<tr>
<td>$J_{1.0} = 800$</td>
<td>5 × 25</td>
<td>5 × 50</td>
<td>5 × 25</td>
<td>5 × 45</td>
</tr>
<tr>
<td>$J_{0.5} = 800$</td>
<td>3 × 120</td>
<td>3 × 150</td>
<td>3 × 105</td>
<td>3 × 150</td>
</tr>
<tr>
<td>and</td>
<td>4 × 60</td>
<td>4 × 145</td>
<td>4 × 50</td>
<td>4 × 125</td>
</tr>
<tr>
<td>$J_{1.0} = 1000$</td>
<td>5 × 35</td>
<td>5 × 80</td>
<td>5 × 35</td>
<td>5 × 70</td>
</tr>
<tr>
<td>$\delta_{\text{max}}$ [mm], see [4.3.5]</td>
<td>1.5</td>
<td>2.0</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

1) Larger allowable flaw sizes may be acceptable based on specific ECA.
2) Only acceptable if testing as specified in Table 4-1 has been performed.
3) The maximum allowable flaw size, $a \times 2c$, refers to the height and length respectively of both surface-breaking and embedded flaws. If the embedded flaw is located close to the surface (ligament height less than half the flaw height) the ligament height between the flaws and surface should be included in the flaw height. The UT/AUT flaw sizing error shall be subtracted from the maximum allowable flaw height to establish the UT/AUT weld flaw acceptance criteria, see DNVGL-ST-F101 App.D and DNVGL-ST-F101 App.E.
4) Also acceptable for 22Cr and 25Cr pipelines.
Table 4-5 Maximum allowable flaw sizes, $a \times 2c$ [mm], maximum strain, $1.0\% < \epsilon_{l,nom} < 2.25\%$

<table>
<thead>
<tr>
<th>$J[N/mm = kJ/m^2]$</th>
<th>$C$-$Mn$; SMYS ≤ 450</th>
<th>$C$-$Mn$; SMYS = 485</th>
<th>$C$-$Mn$; SMYS = 555</th>
<th>$13$Cr; SMYS = 550 $^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$15 \leq t_c &lt; 25$</td>
<td>$t_c \geq 25$</td>
<td>$15 \leq t_c &lt; 25$</td>
<td>$t_c \geq 25$</td>
</tr>
<tr>
<td>$J_{0.5} = 400$</td>
<td>$3 \times 20$</td>
<td>$3 \times 35$</td>
<td>$3 \times 20$</td>
<td>$3 \times 35$</td>
</tr>
<tr>
<td>and</td>
<td>$4 \times 20$</td>
<td>$4 \times 40$</td>
<td>$4 \times 20$</td>
<td>$4 \times 40$</td>
</tr>
<tr>
<td>$J_{1.0} = 600$</td>
<td>$5 \times 10$</td>
<td>$5 \times 15$</td>
<td>$5 \times 10$</td>
<td>$5 \times 15$</td>
</tr>
<tr>
<td>$J_{0.5} = 600$</td>
<td>$3 \times 35$</td>
<td>$3 \times 85$</td>
<td>$3 \times 75$</td>
<td>$3 \times 85$</td>
</tr>
<tr>
<td>and</td>
<td>$4 \times 30$</td>
<td>$4 \times 65$</td>
<td>$4 \times 60$</td>
<td>$4 \times 65$</td>
</tr>
<tr>
<td>$J_{1.0} = 800$</td>
<td>$5 \times 15$</td>
<td>$5 \times 40$</td>
<td>$5 \times 30$</td>
<td>$5 \times 40$</td>
</tr>
<tr>
<td>$J_{0.5} = 800$</td>
<td>$3 \times 45$</td>
<td>$3 \times 95$</td>
<td>$3 \times 75$</td>
<td>$3 \times 95$</td>
</tr>
<tr>
<td>and</td>
<td>$4 \times 30$</td>
<td>$4 \times 65$</td>
<td>$4 \times 60$</td>
<td>$4 \times 65$</td>
</tr>
<tr>
<td>$J_{1.0} = 1000$</td>
<td>$5 \times 20$</td>
<td>$5 \times 40$</td>
<td>$5 \times 30$</td>
<td>$5 \times 40$</td>
</tr>
<tr>
<td>$\delta_{max}$ [mm], see [4.3.5]</td>
<td>1.5</td>
<td>2.0</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

1) Larger allowable flaw sizes may be acceptable based on specific ECA.
2) Only acceptable if testing as specified in Table 4-1 has been performed.
3) The maximum allowable flaw size, $a \times 2c$, refers to the height and length respectively of both surface-breaking and embedded flaws. If the embedded flaw is located close to the surface (ligament height less than half the flaw height) the ligament height between the flaw and surface should be included in the flaw height. The UT/AUT flaw sizing error shall be subtracted from the maximum allowable flaw height to establish the UT/AUT weld flaw acceptance criteria, see DNVGL-ST-F101 App.D and DNVGL-ST-F101 App.E.
4) Also acceptable for 22Cr and 25Cr pipelines.
4.3 Category III, specific engineering critical assessment (ECA) without internal overpressure

4.3.1 General

In a specific ECA all the inputs as described in Table 3-1 are specifically selected and determined for the actual situation.

It is recommended to perform the tests specified in Table 4-6 as a minimum for a specific ECA, see also Sec.7.

Table 4-6 Testing required for girth welds in pipelines with category ECA static – specific ECA¹), ²)

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Location/weld procedure</th>
<th>Test quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld metal tensile testing ⁴), ⁵)</td>
<td>Girth weld (all relevant procedures)</td>
<td>Three (full stress-strain curves should be established)</td>
</tr>
<tr>
<td>Parent pipe tensile testing ⁴), ⁵)</td>
<td>Parent pipe, longitudinal</td>
<td>Five (full stress-strain curves should be established)</td>
</tr>
<tr>
<td>Tearing resistance testing of SENT specimens ⁵), ⁶), ⁷) (r-curve)</td>
<td>Main line</td>
<td>One R-curve (minimum six SENT specimens) for each notch position, see BS 8571 and DNVGL-ST-F101 App.B</td>
</tr>
<tr>
<td>Tearing resistance testing of SENT specimens ⁵), ⁶), ⁷) (r-curve)</td>
<td>Double joint</td>
<td>One R-curve (minimum six SENT specimens) for each notch position, see BS 8571 and DNVGL-ST-F101 App.D.</td>
</tr>
<tr>
<td>Tearing resistance testing of SENT specimens ⁵), ⁶), ⁷) (r-curve)</td>
<td>Through thickness repair (TTR)</td>
<td>One R-curve (minimum six SENT specimens) for each notch position, see BS 8571 and DNVGL-ST-F101 App.D.</td>
</tr>
<tr>
<td>Tearing resistance testing of SENT specimens ⁵), ⁶), ⁷) (r-curve)</td>
<td>Partial repair ³)</td>
<td>One R-curve (minimum six SENT specimens) for each notch position, see BS 8571 and DNVGL-ST-F101 App.D.</td>
</tr>
<tr>
<td>Tearing resistance testing of SENT specimens ⁵), ⁶), ⁷) (r-curve)</td>
<td>Tie-in ³)</td>
<td>One R-curve (minimum six SENT specimens) for each notch position, see BS 8571 and DNVGL-ST-F101 App.D.</td>
</tr>
</tbody>
</table>

¹) All weld procedures which have different essential variables according to DNVGL-ST-F101 Table C-2 shall be tested.

²) The test temperatures and material condition to be tested should be as specified in Sec.7.

³) If the welding procedure and heat input are equal to those used in the through-thickness repair procedure, this testing may be omitted. If repeated repairs are permitted or agreed, relevant microstructures shall be tested.

⁴) If production tensile testing is performed at the assessment temperature and full stress-strain curves are established, additional tensile testing is not required.

⁵) The recommended specimen geometry and test requirements are specified in ISO 6892 (tensile testing) and BS 8571 (SENT testing). See also DNVGL-ST-F101 App.B and Sec.7.

⁶) It is recommended to include the blunting in the resistance curve. However, the curves may start at tearing initiation if this is determined in accordance with ISO 12135, Annex A. See also Sec.7.

⁷) It is not required to conduct three different types of fracture toughness testing to cover the external surface, internal surface and embedded surface if the result representing one flaw type is representative or conservative for another flaw type, e.g. fracture toughness testing in air at minimum installation temperature gives a representative fracture toughness description for all flaw types assessed in an ECA for the installation stage. See also Sec.7.
A specific ECA requires more testing than a generic ECA, see Table 4-1 vs. Table 4-6. Tests already performed for a generic ECA may be used when constructing the R-curves required for the specific ECA. See Sec.7 for further requirements and guidance.

It is recommended that the accumulated tearing from all installation strain cycles (not including fatigue) be limited to 10% of the wall thickness, but more tearing may be allowed depending on the loads to be considered after installation. The tearing assessed for one strain increment in the ECA should not exceed two-thirds of the tearing associated with the maximum load for the SENT specimens.

**Guidance note:**

The recommended limitation to tearing during installation should avoid tearing instability with some safety margin. However, if the safety margin is shown to be large based on evaluations (loading mode, tearing resistance, flaw size and pipe geometry, etc.), larger tearing may be acceptable.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

4.3.2 Tensile properties

The tensile properties and stress-strain curve for strain-based fracture mechanics assessments should describe a characteristic high stress-strain curve with low strain hardening as described in Sec.7.

4.3.3 Weld residual stresses

Depending on the reference stress solution applied, two different approaches or defining weld residual stresses are recommended:

a) The reference stress solution for surface-breaking flaws in cylinder is specified. The weld residual stress is defined as a uniform secondary membrane stress ($Q_m$) equal to the yield stress representing the specified stress-strain curve (high stress-strain curve in the as-welded condition). Relaxation according to Equation (4.1) is allowed. If the applied strain level exceeds 1%, it is acceptable to define the weld residual stress as being equal to 40% of the same yield stress for all later load cases. If the strain level is lower, the relaxed value obtained using Equation (4.1) should be used for later load cases.

\[
Q_m = \min \left[ YS', \left( 1.4 - \frac{\sigma_{ref}}{\sigma_f} \right) YS' \right]
\]  

(4.1)

where:

$YS'$ = the appropriate yield stress at the assessment temperature, except that the room temperature value of $YS'$ is used for temperatures below ambient

$\sigma_{ref}$ = the reference stress due to the applied stress ($P_m + P_b$)

$\sigma_f$ = the appropriate flow stress (assumed to be the average of the yield and tensile stress at the assessment temperature).

b) The reference stress solution for surface-breaking flaws in plate is specified. The weld residual stress is included by increasing the applied strain with $YS/E$ such that the applied primary membrane stress ($P_m$) extracted from the stress-strain curve will increase. $YS$ may be defined as SMYS for the parent material (room temperature and without plastic deformation). Possible additional bending stress over the thickness due to misalignment is included based on the increased $P_m$. If this option is used, the applied strain for all later strain-based load cases should be increased with $YS/E$. If a later load case is defined as stress-based (load-control), it is recommended to define a secondary membrane stress equal to 40% of the yield stress in the as-welded condition. It is also recommended to extend the $L_{r, \text{max}}$ value as stated in [4.3.6].
Non-uniform solutions available in different standards (BS 7910, R6, API 579 etc.) are not recommended because the suggestions presented show major differences and the procedures specified in this RP are based on the total crack driving force, a combination of the applied stress from loading and residual stresses, being reasonably accurate. Hence, other methods for determining residual stresses may not be safe.

4.3.4 Wall thickness

The following definitions of wall thicknesses are recommended:

— The nominal wall thickness minus the manufacturing tolerance of the pipe should be used in assessments considering installation (i.e. \( t_c = t_{nom} - t_{fab} \)). It is acceptable to define \( t_c \) based on measurements after manufacturing. The mean value minus two standard deviations is recommended.

— A suitable corrosion allowance should be included in the assessments during the operational life of the pipeline or riser. At the end of the design life, the whole corrosion allowance should be subtracted, (i.e. \( t_c = t_{nom} - t_{fab} - t_{corr} \)).

— In the case of fitness-for-purpose evaluations it is acceptable to base the thickness on inspected values.

4.3.5 Applied stresses

The recommended procedure for determining the applied stress condition \( (P_m \) and \( P_b \)) is as follows:

— For uniaxial loading, the nominal stress should be determined from the nominal strain or the nominal strain plus the assumed weld residual strain from the characteristic engineering stress-strain curve for strain-based loading (high curve with low strain hardening, see [7.10]). This stress is defined as the primary membrane stress, \( P_m \), according to BS 7910.

— For operational cases, considering the combined internal overpressure and longitudinal strain see [4.4].

— It is not recommended to relax applied stresses because local displacement-control from crack growth is assumed.

— The nominal stress should be increased because of an assumed stress concentration factor (SCF) due to misalignment at the girth weld. The Neuber approach /1/ may be applied. The stress magnification is defined as a primary bending stress, \( P_b \), according to BS 7910.

The SCF used in the ECA calculation may be calculated as follows:

External surface (girt weld, cap):

\[
SCF_{cap} = 1 + \frac{6.5 \cdot e^{-\alpha}}{t_c \left(1 + \left(\frac{L}{t_c}\right)^\beta\right)} \quad \text{(applicable for } T/t_c < 2) \tag{4.2}
\]

where:

\[
\alpha = \frac{1.82 \cdot L_{cap}}{\sqrt{D \cdot t_c \left(1 + \left(\frac{T}{t_c}\right)^\beta\right)}} \tag{4.3}
\]
\[ \beta = 1.5 - \frac{1.0}{\log \left( \frac{D}{T_c} \right)} + \frac{3.0}{\left( \log \left( \frac{D}{T_c} \right) \right)^2} \quad (4.4) \]

\[ T = t_c + |hi/lo_{cap} - hi/lo_{root}| \quad (4.5) \]

\( T \) and \( t_c \) = wall thickness of the pipes on each side of the girth weld, \( T > t_c \)
\( \delta \) = misalignment (wall thickness differences, out-of-roundness, centre eccentricities etc.)
\( L_{cap} \) = width of weld cap
\( D \) = outside diameter of pipe.

It is acceptable to calculate the SCF based on the following assumptions, see Figure 3-1:

\[ \delta = \frac{hi/lo_{root} + hi/lo_{cap}}{2} \quad (4.6) \]

The hi/lo should be in accordance with DNVGL-ST-F101 Table D-4. However, operators or weld contractors often specify maximum hi/lo values that are smaller than the allowable hi/lo. This is acceptable but should be substantiated. It is acceptable to specify a smaller hi/lo than the maximum values stated in DNVGL-ST-F101 if such values are substantiated.

**Figure 4-2 Recommended definition of girth weld misalignment**
For the internal surface and single-sided welds, a lower SCF may be calculated as follows:

\[
SCF_{root} = 1 + (SCF_{cap} - 1) \frac{L_{root}}{L_{cap}}
\]  

(4.7)

where:

- \( L_{cap} \) = width of weld cap
- \( L_{root} \) = width of weld root
- \( SCF_{cap} \) = SCF for external surface flaws determined from above equations.

The Neuber method /1/ was originally developed to assess strains at notches. It has been extensively and successfully used for pipeline or riser girth welds subjected to plastic strains and has been adopted for use in this RP. It is acceptable to apply the Neuber rule on the engineering stress-strain curve.

The Neuber method is defined by the following equation:

\[
\sigma_2 \cdot \varepsilon_2 = \sigma_1 \cdot \varepsilon_1 \cdot SCF^2
\]  

(4.8)

where:

- \( SCF \) = linear-elastic stress concentration factor
- \( \sigma_1 \) = nominal engineering stress (excluding SCF)
- \( \varepsilon_1 \) = nominal strain (excluding SCF)
- \( \sigma_2 \) = actual engineering stress (including SCF)
- \( \varepsilon_2 \) = actual strain (including SCF).

An illustration of the Neuber rule is shown in Figure 4-3.
Normally, the local stress intensity magnification factor $M_k$ is applied to welded connections. This increases the stress intensity factor to account for the presence of the weld toe. It is acceptable to exclude the $M_k$ factor for pipeline or riser girth welds in tearing and unstable fracture assessments provided the applied stress is defined according to the procedure specified above.

If the average difference in yield stress between adjacent pipes exceeds 100 MPa, the stiffness differences may increase the stress level in the girth welds significantly. In such cases it is recommended to perform solid 3D FE fracture mechanics assessments or to determine the applied stresses more accurately through dedicated FE analyses, see Sec.6, App.A and App.B.

4.3.6 $L_{r, \text{max}}$

The failure assessment diagram (FAD) should not be extended to arbitrarily large plastic deformations and a cut-off limit (referred as $L_r$ cut-off or $L_{r, \text{max}}$) for the $L_r$ ($L_r = \sigma_{\text{ref}} / \text{YS}$) axis is recommended. Depending on the reference stress solution used, the following $L_{r, \text{max}}$ values are recommended:

— Circumferential surface flaw in cylinder: it is acceptable for strain-based assessments to define the $L_r$ cut-off value as the engineering UTS/YS of the parent pipe representing the characteristic high stress-strain curve for the relevant material condition. The $L_r$ cut-off value should not exceed 1.5 for C-Mn materials.

— Surface flaw in plate: the true values of YS and UTS are used instead, see also Table 3-1. YS may be defined as $R_{\text{to0.5}}$ or $R_{\text{p0.2}}$. If the stress-strain curve has a yield plateau, the yield stress should be defined as $R_{\text{eL}}$, see Figure 1-1.
4.3.7 Fracture toughness

The fracture toughness properties should be described by a lower-bound tearing resistance curve as described in [7.6]. The resistance curve shall be representative for the materials, weld procedures and materials conditions considered (temperatures, deformation history and environment), see [7.6]. The fracture toughness shall be described with a lower-bound tearing resistance curve if $\varepsilon_{l,nom}$ exceeds 0.4%, see Sec.7.

4.4 Category III, internal overpressure

4.4.1 General

Research has shown that the combination of internal over-pressure and longitudinal strain, which introduce a biaxial stress condition, is more onerous than longitudinal loading alone /10/, /11/ and /12/. However, there is currently no validated and generally accepted procedure for how the BS 7910 approach, which is the basis for this RP, may be adjusted to account for biaxial stresses.

Research results indicate that the reduction in strain capacity is caused by an increase in the crack driving force (applied J or applied CTOD) but that the material fracture toughness is not influenced. This means that if the crack driving force is determined from dedicated solid 3D FE fracture mechanics analyses or well documented and validated research results, it is acceptable to use SENT testing to determine the fracture resistance also for the combination of internal overpressure and longitudinal loading.

4.4.2 Procedures for calculating crack driving force

If the hoop stress is less than $0.15\cdot f_y$, the biaxial effect is quite insignificant and biaxial correction is not necessary. Similarly, if the longitudinal strain is less than 0.2%, the biaxial effect will be quite insignificant and biaxial correction is not needed. If the longitudinal strains exceed 0.2% ($\varepsilon_{l,nom} \geq 0.2\%$) and the internal overpressure exceeds $0.15\cdot f_y$ hoop stress, the applied stress, $P_m$, may be determined according to one of the following approaches:

a) The maximum biaxial longitudinal stress in the pipeline or riser is determined by FE analyses that include the influence of internal overpressure.

Or

b) The biaxial longitudinal stress, $\sigma_{b-a}$, is calculated as:

$$\sigma_{b-a} = \frac{\sigma_h}{2} + \sqrt{\frac{\sigma_{u-a}^2}{4} - \frac{3}{4} \sigma_h^2} \quad (4.9)$$

where:

$\sigma_{u-a}$ = uniaxial longitudinal stress determined from $\varepsilon_{l,nom}$ and the uniaxial stress-strain curve

$\sigma_h$ = hoop stress (internal pressure)

$\sigma_{b-a}$ = biaxial longitudinal stress

or

c) The biaxial effect is not included in the applied stress but, to compensate for this effect, high constraint SENB specimens shall be tested to ensure conservative fracture toughness. This approach is not recommended for cases where the longitudinal strain $\varepsilon_{l,nom}$ exceeds 0.4%.
It may also be acceptable to adjust the crack driving force by changing other inputs, such as reference stress solution or the relative flaw height, but such approaches should be properly validated and agreed on by all parties.

The true uniaxial stress-strain curve should be used to define the FAD and the uniaxial yield stress should be used to determine the value of \( L_r \). Possible misalignments should be accounted for, also including for biaxial stress conditions. It is acceptable to apply the Neuber rule based on the biaxial stress and the uniaxial stress-strain curve.

For assessment of situations with considerable longitudinal strains under internal overpressure, approach b) has shown to be very conservative in some cases and solid 3D FE fracture mechanics (see Sec. 6) analyses are recommended and may be required in order to achieve applicable results.

In the case of external overpressure, the crack driving force is expected to be reduced compared with internal overpressure and no pressure. This has not been investigated in detail, but it is acceptable not to include the effect of external overpressure.

For stress-based loading it will normally not be necessary to assess the allowable flaw sizes for external overpressure because the allowable flaw sizes will typically be considerably larger than what is considered as normal good workmanship.
SECTION 5 FRACTURE MECHANICS APPROACHES – ASSESSMENT CATEGORY IV, COMBINING FATIGUE CRACK GROWTH AND FRACTURE

5.1 Introduction

5.1.1 General

The quality of welds subjected to plastic strains or welds that are fatigue-sensitive, is important and may be determined based on fracture mechanics assessments that combine fatigue crack growth, tearing and unstable fracture analyses as relevant.

The maximum allowable flaw sizes may also be determined using the procedure specified in this section even if the maximum longitudinal strain is below 0.4% and fracture mechanics analyses are not required.

If the maximum longitudinal stress during operation is below \( f_y \) and the materials are ductile, the critical flaw size at the end of life (EOL) will be large. For welds classified as fatigue-sensitive, the exact critical flaw sizes at EOL will not be very important to the allowable flaw sizes assessed. In such cases, it is acceptable not to assess the critical flaw size at EOL and fracture toughness testing for the operational stage is not necessary, see [5.2.3].

The AUT acceptance criteria may be determined based on the maximum allowable flaw sizes assessed when the flaw sizing error is subtracted.

This assessment approach may also be used to determine AUT acceptance criteria for the inside of pipelines with a CRA liner or clad. However, in such case penetration of the CRA layer should be defined as failure.

5.1.2 Description of the assessment approach

All types of static and dynamic loads relevant for the girth welds in a pipeline or riser shall be considered for the fatigue and fracture limit state. Typical loads that need to be considered are:

— loads during installation (reel lay, S-lay and J-lay, etc.), typically considered as displacement control with specified maximum strain levels
— dynamic loads when the pipeline or riser is between the installation vessel and touch-down
— high stress or strain as the pipe is bent towards the seabed (sagbend)
— dynamic loads in the as-laid stage before production start-up (free spans, etc.)
— dynamic loads in the operational phase (free spans, lateral buckles/expansion loops, etc.)
— maximum longitudinal stress in operation (end of life (EOL) fracture check).

Combined fatigue crack growth and fracture analyses may be used to allow for a lower quality than required according to the relevant S-N curve. Based on such results, less strict AUT acceptance criteria may be developed. If acceptable fatigue resistance cannot be concluded based on the S-N approach, combined fatigue crack growth and fracture assessment may be used and form the basis for AUT acceptance criteria.

The fracture mechanics approach consists of assuming an initial flaw size which will eventually grow due to the relevant load cases. If the flaw is growing, the flaw size is increased before the next load case is assessed. This process is continued until end of life. If the flaw size at any stage will become critical or grow through the thickness, the assessments shall start over with a smaller initial flaw size. By repeating such iterative analyses, it will be possible to establish maximum allowable flaw size curves which might be used as the basis for AUT acceptance criteria. A typical combined fatigue and fracture assessment approach is illustrated in Figure 5-1.
Assessment of flaws in pipeline and riser girth welds

5.1.3 Loads to be considered

All loads that may contribute to tearing and unstable fracture or fatigue crack growth shall be evaluated. The assessment should in general confirm that the largest weld flaws expected to remain after NDT and repair will not increase during pipe laying to the extent that fracture or fatigue failure will occur during operation of the pipeline or riser. Some guidance for how to combine loads is provided in [5.1.4].

An additional bending stress due to presumed misalignment should be assumed for all tearing assessments, fracture checks and FCG analyses by assessing a representative SCF, see [4.3.5], [5.2.3] and [5.3.1].

5.1.4 Load combinations in engineering critical assessment fatigue

The loading is typically not the same for all girth welds in a pipeline or riser or within a zone of the pipeline or riser and it might be very conservative to base the weld flaw acceptance criteria on worst case loading. When combining this with other worst case inputs, such as large misalignment and unfavourable material properties, the allowable flaw sizes assessed may be unnecessarily strict.

Figure 5-1 Illustration of how a flaw may develop during different stages of a pipeline’s or riser’s lifetime

The critical flaw size considering the static load case (fracture check) should be determined according to [4.3] and considered when determining the fatigue life. The fatigue crack growth assessment should be performed using the relevant fatigue loading and fatigue crack growth law to determine the fatigue life from the initial flaw size and until the critical flaw size is reached.

If satisfactory fatigue life cannot be demonstrated or there is a risk of an unstable fracture before or at the end of the operational life, either the maximum allowable flaw size shall be reduced or actions shall be taken to reduce the fatigue loading.

Dedicated maximum allowable flaw sizes may be determined for surface-breaking and embedded flaws using the relevant fatigue crack growth parameters for the flaw position considered. For embedded flaws, the stress situation at the cap or in the root should be specified depending on the surface that is closest to the flaw.

For lined or clad pipelines and risers, the fatigue life should be assumed equal to the time necessary for flaws in the root to grow through the clad/liner thickness.
The ECA fatigue may be assessed either for the whole pipeline or for the riser where all girth welds are considered equally. This means that the girth weld with the highest fatigue loads and the girth weld with the highest longitudinal stress are assumed for all girth welds. Alternatively, the pipeline or riser may be divided in various zones where the specific fatigue and static loads are assessed for the different zones. With this strategy, the loading is more accurately specified and it will be possible to specify less challenging weld flaw acceptance criteria for most of the girth welds.

In some situations, it is recommended to combine different dynamic loads and static loads in the fracture-mechanics-based fatigue and fracture assessment. Such situations may be as follows:

— It is known that many welds will be subjected to large plastic strain (system effect such as reeling installation) and that many of these welds are classified as fatigue-sensitive in accordance with Table 1-3 and [2.3].
— It is known that a specific girth weld has a weld flaw with a known size and will be subjected to various combined maximum loads and dynamic loads. Such assessments are often referred as fit-for-purpose or fit-for-service assessments. In such cases the DFF_{ECA} should be half of the relevant DFF_{S-N}.

If fatigue crack growth analyses are combined with maximum stress or strain assessments, for instance a combination of tearing during installation, possible fatigue because of a stoppage during laying and different fatigue scenarios based on lateral buckles or free spans in the post-lay phase, it is acceptable to base the combined assessments on probabilistic analyses. Such a procedure should consider all relevant input parameters. However, there is no common and agreed procedure for how probabilistic analyses should be performed. Hence, it is recommended that probabilistic analyses should be agreed on and accepted on by all parties.

If it can be substantiated that the probability for that a girth weld will be subjected to two different load cases is less than $10^{-3}$, it is acceptable not to combine them in the category IV assessment. However, all loads exceeding $\varepsilon_{1,\text{nom}} > 0.4\%$ shall be proven to have acceptable fracture limit state in accordance with assessment category III assuming weld flaws equal to the AUT acceptance criteria plus the defined flaw sizing error in accordance with DNVGL-ST-F101 App.E.

5.1.5 Special considerations when assessing external surface flaws

If the external surface may be exposed to seawater, the fatigue crack growth parameters specified in BS 7910 for marine environments (free corrosion, cathodic protection at -1100 mV or cathodic protection at -850 mV as relevant) are recommended.

Fracture toughness or tensile testing in marine environments should not be necessary unless these material properties are expected to be degraded and the welds are subjected to strain-based loading.

5.1.6 Special considerations when assessing embedded flaws

If only maximum external surface breaking flaws are assessed and used to derive AUT acceptance criteria for all types of weld flaw indications, embedded flaws close to the surface should be re-characterized as larger surface-breaking flaws as relevant during inspection, see DNVGL-ST-F101 App.D and DNVGL-ST-F101 App.E. The recommended rule should consider embedded flaws as surface breaking flaws where the flaw height is defined as the sum of the measured height of the embedded flaw plus the ligament height if half the height of the embedded flaw is larger than the ligament height, see Figure 5-2.
Assessment of flaws in pipeline and riser girth welds

Figure 5-2 Illustration of the re-characterization of an embedded flaw as a surface-breaking flaw

It is acceptable to directly determine dedicated acceptance criteria for embedded flaws based on fracture mechanics assessments using the reference stress and stress intensity factor solutions provided in BS 7910. However, this may give very conservative allowable flaw sizes because the reference stress formula provided in BS 7910 for embedded flaws overestimates the net-section stress considerably for strain-based conditions. Hence, it is recommended to perform tearing and unstable fracture assessments are performed where the flaw is specified to be surface-breaking, while the flaw should be specified as an embedded flaw when assessing dynamic loading. This will reduce the conservatism. If an embedded flaw is subjected to large plastic strain (or several increments, like reeling) followed by dynamic loading, the following assessment approach is acceptable:

— A surface-breaking flaw is defined (chosen length and height) and subjected to the relevant strain.
— The flaw is increased by tearing before a new strain increment is applied as relevant. This is continued until all strain increments have been assessed.
— It is checked that the flaw is not critical and that it does not grow more than is desired.
— When cyclic loads need to be considered, the original initial surface flaw size plus the accumulated tearing assessed in previous bullets is defined as an embedded flaw with a selected ligament height.
— Fatigue loads are applied to the embedded flaw and the fatigue crack growth is calculated. If the ligament becomes unstable as defined in the next bullet point, the flaw needs to be considered as a surface flaw for remaining load cases, as relevant.
— Ligament failure should be defined when the ligament height, p, is the minimum of:
  — Ligament, \( p < a' \), where \( a' \) is half the flaw height including accumulated tearing and fatigue crack growth (this will typically be governing in cases where quite significant maximum longitudinal stresses need to be assessed), see Figure 5-2.
  — Ligament failure due to plastic collapse, where the flaw is defined as an embedded flaw using the reference stress and stress intensity factor solutions for plate in accordance with BS 7910 (this will typically be governing in cases with quite small maximum longitudinal stresses).
— It is acceptable to continue conducting fatigue crack growth analyses after a surface flaw has developed if this flaw is not critical. If the flaw grows through the thickness during the design life, the analyses shall start over with a smaller initial flaw size or increased ligament height.
— This process is continued until the maximum allowable flaw heights have been established for each initial ligament height and the flaw lengths have been specified.

With this approach, it will be possible to assess both small embedded flaws close to a surface and larger flaws with a longer distance from the surface (larger ligament).

For embedded flaws in environments not classified as sour, it is acceptable to use the FCG parameters for air specified in BS 7910. However, when the crack has grown to a surface crack, the relevant environmental condition should be considered when appropriate FCG parameters are selected.

If tearing or unstable fracture assessments are performed for embedded flaws, it is recommended that the fracture toughness properties be specified as for surface flaws in the relevant environment.
5.1.7 Special considerations when assessing internal surface flaws
The fatigue crack growth parameters should reflect the environment inside the pipeline or riser.
If the pipes are lined or clad, internal flaws growing through the thickness of the CRA layer (liner, clad or overlay weld as relevant) should be defined as failure.

5.2 Tearing and unstable fracture assessments

5.2.1 General
Strain-based loading may grow a crack by tearing and potentially result in an unstable fracture. Tearing and an unstable fracture shall be assessed as described in [4.3] and [4.4] as relevant.

5.2.2 Wall thickness at end-of-life
If an unstable fracture is assessed for end of life, the wall thickness shall be defined as \( t_c = t - t_{fab} - t_{corr} \). If reliable wall thickness measurements are available for the actual pipe end it is acceptable to base the assessment on such measurements, i.e. it will not be necessary to include fabrication tolerances, \( t_{fab} \).

5.2.3 Unstable fracture considering stress-based loading for fatigue-sensitive welds
If the maximum longitudinal stress is below 0.9·\( f_y \) (stress-based) and the material is expected to be ductile, fatigue cracks may grow almost through the wall thickness without causing an unstable fracture, see also Figure 2-1. In such cases, it may be acceptable not to assess the critical flaw size at EOL (critical flaw size in operation). This also means that dedicated fracture toughness and tensile testing taking into consideration that load case and the relevant material condition may be omitted.
The following different approaches are recommended for determining the critical flaw sizes for stress-based loading and welds classified as fatigue-sensitive:

— If the longitudinal stress including stress concentrations is below 0.5·\( f_y \) and embrittlement is not likely, the critical flaw height may be specified as 0.75·\( t_c \) without assessing unstable fractures (no unstable fracture assessment or fracture toughness testing for the load case is necessary).
— If the longitudinal stress including stress concentrations is below \( f_y \) and embrittlement is not likely, the critical flaw height may be defined as 0.5·\( t_c \) (no unstable fracture assessment or testing for the load case is necessary).

If the premises listed above are not satisfied, unstable fractures should be assessed.
If an unstable fracture assessment considering stress-based loading is conducted, the inputs summarized in Table 5-1 shall be used.
### Table 5-1 Inputs to unstable fracture assessment considering stress-based loading

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-strain curve</td>
<td>As defined in [7.11]</td>
</tr>
<tr>
<td>( L_r ) cut-off</td>
<td>( L_{r,max} ) (( L_r ) cut-off), see [4.3.6], is recommended to be defined as: ( L_{r,max} = \frac{YS + UTS}{2YS} ) where UTS is the engineering tensile strength and YS is the engineering yield stress of the parent pipe represented by the stress-strain curve defined for the load case considered</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>Lowest value of three single values is acceptable (tearing resistance curve not required), see Sec.7</td>
</tr>
<tr>
<td>Weld residual stresses</td>
<td>Secondary membrane (i.e. uniform) stress equal to yield, ( Q_m = YS ), where YS represents the as-welded condition (normally ( f_y )). Relaxation as described in [2.5.7] is acceptable. If the pipeline or riser has been subjected to plastic deformation, new residuals stresses will develop in the pipeline or riser and residual stresses should still be assumed. In such cases, it is acceptable to define residual stresses as 40% of ( f_y ) in the as-welded condition, ( Q_m = 0.4 \cdot f_y ). Non-uniform solutions available in different standards are not recommended because the understanding of residual stresses is in general not good enough. Hence, such solutions may not be safe.</td>
</tr>
<tr>
<td>Additional bending stress from possible misalignments</td>
<td>( P_b = (SCF_{cap} - 1)P_m ) or ( P_b = (SCF_{root} - 1)P_m ) as relevant or the Neuber rule [4.3.5]. The Neuber approach will always give correct results, even if the total stress ( (P_m + P_b) ) is within the linear-elastic area of the stress-strain curve.</td>
</tr>
</tbody>
</table>

### 5.3 Fatigue crack growth analyses

#### 5.3.1 Cyclic stresses

The fatigue loads should normally be specified as a stress range spectrum (histogram) based on global pipeline or riser analyses and should in general be identical to the stress range spectrum specified for fatigue assessment based on the S-N approach without any safety factors. Further, guidance may be found in DNVGL-RP-F105 and DNVGL-RP-F204.

A stress intensity magnification factor (local stress concentration factor at weld toe) \( M_p \) in accordance with the BS 7910 factor should be defined in all FCG assessments if the weld is not ground. If possible, the 3D solution in accordance with BS 7910 is recommended. More accurate \( M_p \) solutions or an accurate stress profile based on the Weight Function may alternatively be determined from FE analyses.

In FCG analyses, the additional bending stress from possible misalignment should be assessed as: \( \Delta P_b = (SCF_{cap} - 1)\Delta P_m \) or \( \Delta P_b = (SCF_{root} - 1)\Delta P_m \).

#### 5.3.2 Fatigue crack growth parameters

External and internal surface flaws should be assessed in addition to embedded flaws. The recommended assessment approach for the different flaw types is summarized in Table 5-2.
Table 5-2 Recommended fatigue crack growth parameters and use of $M_k$ for various flaw types to be used in fatigue crack growth analyses

<table>
<thead>
<tr>
<th>Type of flaw</th>
<th>Crack growth law</th>
<th>$M_k$ according to BS7910</th>
</tr>
</thead>
<tbody>
<tr>
<td>External surface flaw</td>
<td>Based on either project-specific testing or the BS7910 curves for marine environments with CP as relevant. Air curve acceptable if the risk of exposing the external surface to sea water is considered insignificant.</td>
<td>2D or 3D solution. L equal to the width of the weld at the external surface</td>
</tr>
<tr>
<td>Internal surface flaw</td>
<td>Based on either project-specific testing (sour service, for instance) or the most representative curve specified in BS7910 if proven conservative.</td>
<td>2D or 3D solution. L equal to the width of the weld at the internal surface</td>
</tr>
<tr>
<td>Embedded flaw</td>
<td>The air curve is acceptable for environments not classified as sour or if it can be substantiated that the fatigue performance is not reduced due to the environment. It will always be acceptable to use fatigue crack growth parameters representing the most critical environment of the external and internal surface.</td>
<td>Not required</td>
</tr>
</tbody>
</table>

If dedicated testing is not performed, the curves presented in BS 7910 are recommended. If the BS 7910 curves are used for welds, the mean plus two standard deviation curves for stress ratio, $R$ equal to or larger than 0.5 ($R \geq 0.5$) shall be used. The same curves are also recommended if the welds have been plastically deformed. If the welds are normalized and not plastically deformed, the actual $R$ ratio may be specified. PWHT is not considered adequate for specifying $R$ values below 0.5.

Due to possible weld residual stresses or the generation or redistribution of residual stresses from plastic deformation during installation or operation, the compressive part of cyclic stresses may contribute to fatigue crack growth and the whole stress range should be considered in the assessment.

If the girth welds are coated, it is considered acceptable, due to short duration, to use the FCG parameters for air specified in BS 7910 when conducting fatigue crack growth assessments during installation.

### 5.3.3 Safety factors in fatigue crack growth assessments

As crack initiation is not included in the fracture mechanics approach and there is not a clear relationship between S-N fatigue and flaw sizes, shorter fatigue lives are more often predicted by the fracture mechanics approach than by the S-N approach. However, no well-defined and validated procedure for including a possible initiation period in the fracture mechanics fatigue approach currently exists. In order to allow for the additional period associated with initiation, it is considered acceptable to perform the fracture mechanics fatigue crack growth assessments with a $DFF_{ECA}$ based on the following premises:

— If analyses are performed to determine the remaining life of known flaws, but these flaws are not suspected of being growing fatigue cracks (e.g. they are normal weld flaws detected by NDT during fabrication) and the girth weld containing the flaw is unlikely to be located at a position that experiences the fatigue loads considered in the ECA (e.g. for flaws detected in pipeline girth welds prior to installation, where operational fatigue loads are a worst case that will not be experienced at all girth weld locations) then it is recommended to specify a $DFF_{ECA}$ equal to 1. This should normally be the case for assessment category IV, where the maximum allowable flaw sizes are assessed for determining AUT acceptance criteria.

— If analyses are performed to determine the remaining life of known flaws, but these flaws are not suspected of being growing fatigue cracks (e.g. they are normal weld flaws detected by NDT during fabrication) and the fatigue loads considered in the ECA are a conservative estimate of the loads experienced at the specific girth weld in question, then it is recommended to specify a $DFF_{ECA}$ equal to half of $DFF_{S-N}$.
\[ DFF_{ECA} = \frac{DFF_{S-N}}{2} \]  

— If analyses are performed to determine the remaining life of known flaws (detected) that are suspected of being growing fatigue cracks, and the fatigue loads considered in the ECA are a conservative estimate of the loads experienced at the specific girth weld in question, then it is recommended to specify a \( DFF_{ECA} \) equal to \( DFF_{S-N} \).

The \( DFF_{ECA} \) is typically included in the FCG assessments by increasing the number of load cycles by the factor \( DFF_{ECA} \).

**Guidance note:**

In general, the safety factors used should depend on the level of confidence with which the key input parameters have been defined. The values above are recommended on the basis that all input parameters, including the stress range spectra, have been defined on a worst case basis. Where this is not the case, higher safety factors may be required.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

5.3.4 Wall thickness

In an FCG assessment, it is recommended that the wall thickness be defined as \( t_{fat} = t - t_{fab} - t_{corr}/2 \).

5.3.5 Low-cycle fatigue

Low-cycle fatigue may result in a somewhat different failure mode than that intended for the assessment procedures described in this section and special consideration is recommended. However, no well-defined, validated and generally accepted procedure for assessing low-cycle fatigue in pipeline or riser girth welds has been commonly agreed on.

Any assessment method, test procedure, environment, etc. used for assessing low-cycle fatigue should therefore be justified, well documented and agreed on by all parties.

In general, it is recommended to perform accumulated tearing analyses in accordance with [4.3] and [4.4] as relevant validated by full-scale fatigue testing of girth welds with a representative weld quality (weld flaws, misalignments etc.).

Full-scale fatigue testing may typically be in 4-point bending rigs where the strain level is accurately measured during testing. It is recommended to clearly define how to determine and define the strain level in the pipe prior to testing. Good alternatives may be the instrumentation of a sufficient number of strain gauges, direct measurement of the global curvature, rotation of the pipe ends or a combination of all these.

**Guidance note:**

Low-cycle loading is normally understood to be cycles of less than around 1,000 and stress/strain ranges in the elastic-plastic regime.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---
SECTION 6 USE OF FINITE ELEMENT FRACTURE MECHANICS ANALYSES TO ASSESS MAXIMUM ALLOWABLE FLAW SIZES

6.1 General

6.1.1 Application

FE fracture mechanics analyses may be used to assess maximum allowable flaw sizes, but in such cases it should be recognized that the safety margin might not be the same as if the procedure specified in Sec.4 was used. In general, it is recommended that the probability of fracture should be evaluated to ensure that the target safety class requirements are satisfied, see DNVGL-ST-F101. However, methods for conducting this type of assessment have not been fully developed.

In general, solid 3D FE fracture mechanics analyses are recommended. The use of other dedicated FE-based software programs is acceptable if the geometry and flaw sizes assessed are benchmarked against dedicated solid 3D FE fracture mechanics analyses that meet the requirements specified in this subsection. The use of such tools should also include an increase in the CDF (crack driving force) due to possible weld misalignments and weld residual stresses and the accuracy of the increase in the CDF shall be justified. Some general guidance and requirements for solid 3D FE fracture mechanics analyses are given in [6.2].

FE fracture mechanics analyses may be used to check unstable fracture, assess tearing or to confirm the procedures specified in Sec.4 and Sec.5 are valid and sufficiently conservative. FE fracture mechanics analyses may be used if some requirements or premises specified for fracture mechanics approaches in Sec.4 and Sec.5 are not fulfilled.

6.1.2 Weld metal with lower strength than the parent material

Typically, FE fracture mechanics analyses may be used for cases where the weld metal shows partially lower strength than the parent pipe material (a partially lower stress-strain curve). Possible ways to evaluate if the procedures in Sec.4 and Sec.5 are valid may be to:

— Demonstrate that the CDF calculated by FE fracture mechanics analyses is lower than the CDF calculated in accordance with Sec.4 (and Sec.5)
— Demonstrate that the CDF calculated by FE fracture mechanics analyses where representative stress-strain curves are designated for all materials (portions) is lower than the CDF calculated for the same model where the parent pipe stress-strain curve (e.g. even-match) is designated for all materials
— FE fracture mechanics analyses may also be used to validate that an adjusted Sec.4 (or Sec.5) approach is sufficiently conservative. Possible ways to adjust the Sec.4 or Sec.5 approaches may be to manipulate the applied load, adjust the stress-strain curve applied in the assessments or change the wall thickness such that the CDF assessed will be at least as high as the CDF derived by FE fracture mechanics analyses

Each approach should be fully documented and agreed on by all parties.

The advantages of these approaches may be that some flaw sizes are investigated using FE fracture mechanics analyses, and if it is confirmed that the crack driving force is higher for the FAD-based approach, the FAD-based approach in Sec.4 (or Sec.5) will be shown to be applicable.

The whole maximum flaw size envelope should be validated by FE fracture mechanics analyses, i.e. the maximum flaw height with associated flaw length and the maximum flaw length with the associated flaw height as illustrated in Figure 6-1. To confirm this, the FE fracture mechanics analyses of flaw sizes A and B should result in a lower CDF than the BS 7910 FAD-based approach as illustrated in Figure 6-2.
Figure 6-1 Illustration of how FE fracture mechanics analyses may be used to determine allowable flaw sizes

Figure 6-2 Illustration of how CDF determined by FE fracture mechanics assessments may be compared with the CDF in accordance with the BS 7910 FAD-based approach, see also Figure 6-1

It is acceptable not to include weld misalignment and weld residual stresses in such comparisons. However, misalignment and weld residual stresses shall be included when the maximum allowable flaw sizes are assessed as indicated in Figure 6-1. It is also acceptable to compare the CDF where misalignments and weld residual stresses are included if these features are implemented in a well-documented and agreed way in the FE fracture mechanics analyses.
If it is validated that the Sec.4 or Sec.5 assessment approaches give a CDF that is at least as high as the CDF derived by FE fracture mechanics analyses, the assessment approaches in Sec.4 and Sec.5 may be considered applicable.

If it is proven that the CDF is conservatively assessed using the assessment approach in Sec.4 without including residual stresses in the comparison, it is acceptable to account for residual stresses by increasing the applied strain with YS/E.

### 6.2 Finite element approach

#### 6.2.1 General

When finite element (FE) fracture mechanics analyses simulating strain-based loading are performed and the maximum allowable flaw sizes should be determined considering one single strain event, one of the following procedures is recommended:

- A minimum of three FE analyses of stationary flaws with different heights but equal length are performed and the CDF is plotted vs. the flaw height. The failure criterion may be either tearing instability or a specified maximum allowable amount of tearing.
- An FE analysis simulating crack growth is conducted, for instance the Gurson-Tvergaard-Needleman formulation, /2/-/7/.

Both methods require representative stress-strain curves and tearing resistance curves to be determined. See also App.A.

The CDF depends on the model quality. To obtain accurate results, it is important that:

- The mesh refinement is adequate and validated as necessary, for example by undertaking a mesh convergence study.
- Appropriate elements are selected.
- The material stress-strain properties are defined accurately.
- The total model length is sufficient to ensure that the CDF is not unduly influenced by end effects.
- The boundary conditions and loads are applied in such a way as to simulate the actual loading condition as closely as possible.

If multiple strain increments (e.g. reeling installation) are assessed, it is recommended that each strain increment be assessed as a monotonic event where the tearing is determined by comparing the crack driving force for different flaw heights with the tearing resistance curve as shown in App.B. The stress-strain relationship should be updated for each strain increment to represent the actual material condition considered. This should preferably be based on the tensile testing of pre-strained material to simulate the second and subsequent strain increments (e.g. reeling installation), see [7.12]. In most cases, it should be acceptable to use the tearing resistance curve representing the as-manufactured material condition, see [7.6].

The Gurson-Tvergaard-Needleman material model or equivalent may also be used to assess tearing. However, such methods are highly dependent on the material models. Hence, the crack growth model should be calibrated and validated against relevant experimental results (e.g. SENT results and tensile testing) and the damage parameters should be calibrated against the characteristic tearing resistance curve.

#### 6.2.2 Stress-strain curves

For strain-based loading, a characteristic high stress-strain curve with low strain hardening should be the basis for the stress-strain curve assigned to the parent material, see [7.10]. The characteristic weld metal stress-strain curve should be low, see [7.11]. For stress-based loading, both the characteristic parent pipe material and the characteristic weld metal stress-strain curves should be low.

If the stress-strain curve of the weld metal is confirmed to be at least as high as the stress-strain curve representing the parent material, it will be acceptable to designate the parent stress-strain curve for the weld
metal too (even-match model). Temperatures and pre-loading to plastic strain levels (e.g. reeling) shall be considered.

If FE fracture mechanics analyses are performed for cases with dissimilar materials (e.g. CRA welds in lined or clad pipes) or cases with potential weld strength under-matching, it may be difficult to know the kind of stress-strain curve combinations that will result in the highest crack driving force, so sensitivity analyses are recommended.

### 6.2.3 Applied strain

The applied strain may be defined either based on the rotation of the pipe ends or as the strain at the outer curvature approximately midway between the notch and the pipe end. For reeling installations etc., it is acceptable to simulate that the pipe is bent against a curvature with the actual radius. If reeling simulation is performed where pipes with different stiffnesses (different wall thicknesses, stress-strain curves, etc.) adjacent to a girth weld are considered, it is recommended to simulate bending against the representative curvature.

### 6.2.4 Weld residual stresses

If the weld residual stress profile through the thickness is known, it is acceptable to simulate this directly in the FE fracture mechanics analysis. However, the methodology should be validated, justified and agreed on by all parties.

It is also acceptable to include residual stresses by increasing the applied strain with YS/E, where YS may be defined as SMYS for the parent material (room temperature and without any plastic deformation). Relaxation due to plastic deformation is not recommended.

Stress-based loading will normally not be evaluated by FE fracture mechanics analyses unless the material has low fracture toughness properties or large detected flaws need to be assessed. However, if stress-based loading is assessed using FE fracture mechanics analyses, the increase in the CDF due to weld residual stresses may be calculated as follows:

\[
CDF_{WRS} = CDF \cdot 2.5 \cdot \left( \frac{\sigma}{YS} \right)^{-1.8}
\]  

(6.1)

where:

- \( CDF_{WRS} \) = the crack driving force including weld residual stress
- \( CDF \) = the crack driving force according to the FE analysis without weld residual stress
- \( YS \) = the yield stress representing the parent pipe material in the as-welded condition
- \( \sigma \) = the longitudinal stress in the FE analysis.

If the girth welds have been subjected to plastic strain, the increase in the CDF due to residual stresses in subsequent stress-based load cases may be calculated as follows:

\[
CDF_{RS} = CDF \cdot 1.8 \cdot \left( \frac{\sigma}{YS} \right)^{-1.2}
\]  

(6.2)
where:

\[ CDF_{RS} = \text{the crack driving force including residual stress after plastic deformation} \]
\[ CDF = \text{the crack driving force according to the FE analysis without residual stress} \]
\[ YS = \text{the yield stress representing the parent pipe material in the as-welded condition} \]
\[ \sigma = \text{the longitudinal stress in the FE analysis}. \]

These formulas have been determined based on fitting the curve to traditional stress-based assessments of external surface flaws allowing for relaxation as specified in BS 7910, see [5.2.3]. The formulas are expected to be conservative for situations involving biaxial stresses.

### 6.2.5 Weld geometry and misalignments

Possible weld misalignment and stiffness variations between adjacent pipes (cross-sectional differences or a difference in average yield stress exceeding 100 MPa) should be included in the FE fracture mechanics analyses if the results are used directly to determine maximum allowable flaw sizes (i.e. FE fracture mechanics analyses compensate for the analyses specified in [4.3]).

Alternatively, if the FE fracture mechanics analyses are used to adjust the crack driving force calculation described in [4.3] where misalignment is not considered, it may be acceptable to use the approach specified in [4.3] for including misalignments. Such adjustments to the crack driving force calculations may be to change the stress-strain curve or the reference stress solution such that a correct crack driving force is assessed for a girth weld without misalignment. This approach should be fully documented and agreed on by all parties.
SECTION 7 TESTING REQUIREMENTS FOR THE FATIGUE AND FRACTURE LIMIT STATE BASED ON FRACTURE MECHANICS

7.1 General

Tensile properties in the form of stress-strain curves and fracture toughness (critical value or tearing resistance) are required to perform instability or tearing analyses. Hence, dedicated tensile and fracture toughness testing should always be carried out when fracture mechanics analyses are performed. However, for fatigue crack growth analyses the fatigue crack growth parameters in BS 7910 will be acceptable if the properties are not influenced by the environment and the temperature for the loading assessed is limited to maximum +100°C for air and maximum +20°C for marine environments.

It is not recommended to perform fracture mechanics assessments where the fracture toughness testing is based on results from another project, even if the dimensions, materials, welding methods and weld procedures are equal. The reason for this is that there will always be scatter in results and even small dissimilarities may cause significant changes in the results. Hence, results from earlier testing (other projects) should only be used if they represent the lower bound of a larger quantity of representative test results.

This also means that dedicated testing will in most cases result in less conservative weld flaw acceptance criteria.

Materials properties are influenced by the temperature, plastic deformation, environment and the loading rate, etc. Hence, it is important that the correct and relevant material condition is tested for the load scenario assessed. Some guidance about environmental effects on fracture resistance and testing is provided in App.C.

It is acceptable to perform testing at the relevant temperature representing the stress condition considered in the fracture mechanics assessment. This temperature is defined as the assessment temperature, $T_{ass}$. Hence, the assessment and test temperatures are not necessarily the design temperatures if the stresses associated with the design temperatures are sufficiently lower than the maximum stresses.

**Guidance note:**
The meaning of relevant material condition is that the material in the test specimens should have the same level of deformation, temperature, environment, etc., as the condition of the load case being assessed. This means, for instance, that if a pipe coupon arrives at test lab for tensile and fracture toughness testing, the material should be subjected to relevant simulations which might change its properties prior to testing. Necessary simulations may be:

- Pre-straining of the material to obtain the correct yield stress and strain hardening properties (examples are typically the operational phase after a pipeline or riser has been plastically deformed during installation)
- Aging. This is an effect that will occur over time on materials that have been plastically deformed
- Temperature. The testing should be performed at a relevant temperature if the temperature is such that it is likely to change the properties of the material
- Environment. The testing should be performed at a relevant temperature if the environment is such that it may influence the results

This means for instance that if cold deformation has been part of the pipe manufacturing and the pipes will be coated, resulting in a temperature that may introduce an aging effect, aging should be simulated prior to materials testing if the pipe coupon received by the test laboratory has not been coated or coating has not been simulated.

---end---of---guidance---note---

7.2 Materials conditions to be tested

It is recommended that the fracture toughness testing and tensile testing be performed on the materials and material conditions specified in Table 7-1.
Table 7-1 Recommended material conditions to be subjected to fracture toughness and tensile testing

<table>
<thead>
<tr>
<th>Condition</th>
<th>Material condition to be tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture mechanics assessments where the material has not been subject</td>
<td>As-welded (as-manufactured) in the relevant assessment environment and temperature(^1)</td>
</tr>
<tr>
<td>ed to plastic deformation before the loading considered in the assessment</td>
<td></td>
</tr>
<tr>
<td>Fracture mechanics assessments where the material has been subject</td>
<td>Strained and aged at the relevant assessment environment and temperature(^1), (^2), (^3), (^4)</td>
</tr>
<tr>
<td>ed to plastic deformation before the loading considered in the assessment</td>
<td></td>
</tr>
</tbody>
</table>

1) Test temperature is specified in Table 7-2  
2) If several large strain increments are applied to the girth welds, e.g. reeling installation, subsequent strain increments in tension will typically take place after compression and it will acceptable to perform pre-compression of the material prior to tensile testing (little effect on tearing resistance curves). This will reduce the conservatism. Alternatively, the as-received properties may be used. See also [7.12].  
3) Some materials show little change in fracture toughness and tearing resistance due to plastic deformation, and testing in the as-welded condition is acceptable if this can be substantiated.  
4) Aging should be considered to occur after the first operational start-up where a pipeline or riser has experienced increased temperature. Aging is most significant for the tensile properties and show often quite insignificant changes in fracture toughness and tearing resistance. Hence, fracture toughness testing in the strained and aged condition may be omitted if this is substantiated.

Dedicated testing is not always required for the operational phase, see [5.2.3]. If it is necessary to conduct testing to perform fracture mechanics analyses that consider operations where the pipelines have been subjected to plastic deformation, testing in the representative strain and aged condition shall be performed, see [7.12] and DNVGL-ST-F101 App.B. Experience has shown that the tearing resistance curve may not be sensitive to plastic pre-deformation. If this is substantiated, it is acceptable to use a tearing resistance curves for the as-welded material condition to assess all strain increments during reeling installation.

7.3 Test temperatures

The test temperatures should consider the relevant assessment temperatures \(T_{ass}\) and testing may be relevant for both low and high temperatures as specified in Table 7-2.

Table 7-2 Recommended test temperatures for fracture toughness and tensile testing

<table>
<thead>
<tr>
<th>Test temperature(^1)</th>
<th>(T_{ass,min}) (^2)</th>
<th>(T_{ass,max})</th>
<th>C-Mn and 13Cr pipelines</th>
<th>22Cr and 25Cr pipelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_{ass,min})</td>
<td>Only necessary if (T_{ass,min} &lt; 0^\circ C)</td>
<td>Only necessary if (T_{ass,min} &lt; 0^\circ C)</td>
<td>Acceptable if the assessment temperature (T_{ass}) is (0^\circ C \leq T_{ass} \leq 50^\circ C)</td>
<td>Acceptable if the assessment temperature (T_{ass}) is (0^\circ C \leq T_{ass} \leq 20^\circ C)</td>
</tr>
<tr>
<td>Room temperature (RT)</td>
<td>Acceptable if the assessment temperature (T_{ass}) is (0^\circ C \leq T_{ass} \leq 50^\circ C)</td>
<td>Only necessary if (T_{ass,max} &gt; 50^\circ C)</td>
<td>Only necessary if (T_{ass,max} &gt; 20^\circ C)</td>
<td></td>
</tr>
</tbody>
</table>

1) If it is necessary to perform fracture mechanics analyses for both low and high temperatures, testing at both high and low temperatures is recommended. E.g. if significant loads are relevant for temperatures in the region of e.g. -20\(^\circ\)C to +100\(^\circ\)C, both temperatures should be tested. It is the combination of the loading, the relevant material condition and the relevant temperature that shall be considered. Hence, it is not necessarily the minimum or maximum design temperatures that should be tested, see also [7.1].  
2) For tensile tests, testing at \(T_{min} < 0^\circ C\) may be replaced by testing at RT if the loading assessed is load-controlled (stress-based).
7.4 Fracture toughness testing, general

The fracture toughness properties should be determined in a fracture toughness test programme using single edge notched tensile (SENT) specimens in accordance with BS 8571. Typical SENT configuration and recommended geometry are shown in Figure 7-1, see also DNVGL-ST-F101 App.B. However, other fracture toughness test methods and specimen geometries may be used if it can be demonstrated that the results will be sufficiently conservative in relation to the situation assessed.

![Figure 7-1 Recommended geometry for single edge notched tension (SENT) specimens, see BS 8571 for further details](image)

**Guidance note:**
The fracture mechanics assessment procedures described in this RP require fracture toughness testing to be performed. Hence, the pipe dimensions which may be assessed according to this RP depend on the limitations on the fracture toughness testing, see Figure 7-1. A standard notch with a standard fatigue pre-crack is difficult to obtain for W less than approx. 8 mm. Thinner specimens may be fabricated with an EDM notch if it is substantiated that the material is ductile. In general, it is recommended that $B = 2W$ and that the specimens be as large as possible, see BS 8571 for further details.

Fracture toughness properties should be established from all relevant weld procedures and both the weld metal and FL/HAZ microstructure should normally be tested. See also DNVGL-ST-F101 App.B. SENT testing in accordance with BS 8571 and SENB testing in accordance with ISO 12135 and ISO 15653 should be performed.

The testing should be performed on specimens extracted from the relevant material condition and at the relevant temperature for the loading considered, see [7.1]. Experience has shown that the fracture
toughness and tearing resistance are insignificantly changed if the material is plastically deformed, and testing of the as-welded or as-manufactured material condition should be acceptable in many situations if this is substantiated.

If the material has been subjected to plastic deformation (e.g. reeling installation) and unstable fracture assessment is performed at a later stage (e.g. during operation) where the maximum longitudinal stress is below YS, it should be acceptable to use fracture toughness test results for the installation or to define critical flaw sizes as described in [5.2.3].

If fracture toughness testing is not possible and the $\varepsilon_{\text{nom}}$ exceeds 0.4%, full-scale testing or pipe segment testing (strip specimen) is recommended as described in Sec.8.

The fracture toughness may be expressed in terms of the $J_{\text{mat}}$ value or the crack tip opening displacement ($\text{CTOD}_{\text{mat}}$). The procedure for calculating CTOD and $J$ as relevant should be in accordance with BS 8571.

It is in general not recommended to convert CTOD values to $J$ or vice versa. If $J$ is calculated from fracture toughness testing, $J$ should also be used in the FAD assessment, and vice versa. However, if it is for some reason is necessary to convert $J_{\text{mat}}$ values to $\text{CTOD}_{\text{mat}}$ or $\text{CTOD}_{\text{mat}}$ values to $J_{\text{mat}}$, it is acceptable to use Equation (7.1), see BS 7910.

$$J_{\text{mat}} = \text{CTOD}_{\text{mat}} \cdot R_{p0.2} \cdot 1.517 \left( \frac{R_{p0.2}}{R_m} \right)^{-0.3188}$$

(7.1)

where:

$R_{p0.2}$ = the yield stress representing the material tested (same material condition and test temperature)

$R_m$ = the ultimate tensile strength representing the material tested (same material condition and test temperature).

If $J_{\text{mat}}$ is converted from $\text{CTOD}_{\text{mat}}$ values, low $R_{p0.2}$ and $R_m$ values should be used to give conservative results. If $\text{CTOD}_{\text{mat}}$ values are converted from $J_{\text{mat}}$, high $R_{p0.2}$ and $R_m$ values should be used to ensure sufficient conservative results. High and low values may be determined as described in [7.9] and [7.10] respectively.

It may be challenging to perform fracture toughness testing of girth welds with dissimilar weld deposits and to test girth weds in lined and clad materials. Procedures and methods should be agreed on and accepted by all parties.

It is possible to estimate $K_{\text{mat}}$ from Charpy V-notch test results using justified Charpy in fracture toughness correlations (for example procedures in BS 7910). However, the results are considered to be less reliable and it is not recommended to assess the integrity of pipeline or riser girth welds based on Charpy V-notch test results. Such assessments are only considered to be indications.

### 7.5 Special considerations for fracture toughness testing of corrosion resistant alloy girth welds in lined and clad pipes

If different materials combinations and weld deposits are used, it may be difficult to test the fracture toughness properties of all representative microstructures using standard fracture toughness test specimens as specified in BS 8571.

The microstructures in the root of CRA girth welds are an example of where standard testing is difficult. One possible way may be to test smaller specimens with notching as illustrated in Figure 7-2.
7.6 Determination of tearing resistance curves (required for $\varepsilon_{\text{l,nom}} > 0.4\%$)

The R-curves (J or CTOD R-curves) to be used in a tearing assessment according to this RP should be a characteristic low curve determined as follows:

- Multiple specimen method with a minimum of six valid test points. A lower-bound R-curve is fitted and used in the assessments. No data points from the testing should be below the characteristic tearing resistance curve.
- Single-specimen method with a minimum of three valid tests and a lower bound curve representing all results is used in the assessments (the characteristic tearing resistance curve is fitted such that no parts of the individual three single-specimen resistance curves are above the characteristic resistance curve).
- An R-curve based on multiple specimens where the tearing initiation is not included as described below and in Figure 7-3.

The tearing resistance curve applied in the assessments should not exceed the maximum crack extension measured for the representative SENT tests. Test specimens that give significant pop-ins or unstable fractures should not be used to generate the R-curve. Specimens giving pop-ins or unstable fractures before a maximum load plateau is reached (see BS 8571 and ISO 12135) may indicate that the materials are unsuitable for strain-based applications. In such cases, it is recommended to obtain specialist advice to interpret the data and evaluate if the results may be used in the fracture mechanics analyses. In general, changes to the weld procedures or weld deposits are recommended.

If more than six SENT tests are performed and used to construct the R-curve, it is acceptable not to consider the lowest values as defined in Table 7-3. However, it is not acceptable to ignore specimens with significant pop-ins or unstable fractures before a maximum load plateau is reached, see Figure 7-3.

Table 7-3 Recommended rule for constructing an R-curve if more than six SENT tests are performed (multiple specimens)

<table>
<thead>
<tr>
<th>Number of valid fracture toughness SENT results</th>
<th>R-curve based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>All six values, no point below the R-curve</td>
</tr>
<tr>
<td>8 to 10</td>
<td>The lowest test result may be ignored before or after the R-curve is defined, none of the remaining test results should be below the R-curve</td>
</tr>
<tr>
<td>$\geq 12$</td>
<td>The two lowest test results may be ignored before or after the R-curve is defined, none of the remaining test results should be below the R-curve</td>
</tr>
</tbody>
</table>

If a single-specimen procedure is used, it is recommended that the characteristic R-curve be constructed such that no part of the R-curves obtained from the testing is lower than the characteristic curve used in the
assessments. One good way may be to first generate a mean power regression curve and then to lower this curve until no test points are below the curve.

It is acceptable not to include blunting, i.e. crack extension below the tearing initiation, if the tearing initiation (CTOD<sub>i</sub> or J<sub>i</sub>) is determined in accordance with ISO 12135, Annex A, as illustrated in Figure 7-3, for situations where the welds are not compressed between the strain increments. Hence, this approach to tearing initiation is not recommended for reeling installation unless it is demonstrated that flaws will not grow in subsequent strain increments.

The resistance to crack extension, expressed in terms of J<sub>mat</sub> or CTOD<sub>mat</sub> at 0.2mm crack offset to the blunting line as defined in BS 7910 and BS 7448, is not recommended as a definition of tearing initiation. The ISO 12135 approach requires the use of SEM to measure the stretch zone on all fracture surfaces. As long as the crack driving force (CDF) is below J<sub>i</sub> or CTOD<sub>i</sub>, the flaw will not grow and the tearing resistance curve in Figure 7-3 b) may be specified for all strain increments except the first, e.g. the complete R-curve is used for reeling-on while the R-curve adjusted for tearing initiation is used for subsequent strain increments.

This approach is only applicable for the multiple-specimen test approach and only for series where no pop-ins or unstable fractures were obtained before the maximum load.

![Figure 7-3 Illustration of approach for adjusting tearing resistance curve accounting for tearing initiation](image)

This approach may be advantageous for considering low-cycle-fatigue where the welds are not compressed between the cyclic loads, such as buckling scenarios or buckling arrestors installed by S-lay where plastic strain is introduced between each roller on the stinger.

If the generic ECA approach is followed and only three SENT specimens are tested, the crack growth including blunting (total a minus a<sub>0</sub>) shall be measured for all the SENT tests. For each set (three specimens), one specimen should be tested beyond the maximum load (notch opening displacement (V) at maximum load multiplied, by for instance, 1.1), one specimen should be tested to approx. maximum load and one specimen should be unloaded before maximum load.

The resistance curve testing requirements may be refined as follows:

— three specimens with a notch in the centre of the weld and three specimens with a notch at the FL/HAZ microstructure are tested using different notch openings, at least one past the maximum load
— three final tests are performed at the location showing the lowest tearing resistance.

### 7.7 Determination of single value (single point) fracture toughness, applicable to ε<sub>l.nom</sub> ≤ 0.4% and stress-based loading

For load cases considering longitudinal strain levels lower than 0.4%, tearing assessments are not required and it is acceptable to determine single parameter fracture toughness represented by the lowest of a
minimum of three SENT tests for each notch location. If more than three specimens are tested, the value equivalent to the lowest of three may be established as described in Table 21.

**Table 7-4 Recommended rule for defining single value fracture toughness**

<table>
<thead>
<tr>
<th>Number of fracture toughness results</th>
<th>Equivalent fracture toughness value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 to 5</td>
<td>Lowest</td>
</tr>
<tr>
<td>6 to 10</td>
<td>Second lowest</td>
</tr>
<tr>
<td>11 to 15</td>
<td>Third lowest</td>
</tr>
</tbody>
</table>

All test results shall represent one homogeneous group (identical microstructure and testing conditions etc.). If the minimum fracture toughness is less than 70% of the average of three, or if the maximum is more than 140% of the average of three, the scatter is considered excessive and additional test data are recommended as stated in BS 7910.

### 7.8 Tensile testing, general

All tensile testing performed for establishing inputs to fracture mechanics analyses should document full engineering stress-strain curves in the pipeline or riser longitudinal direction. This may be obtained by an extensometer with sufficient extension, strain gauges or a combination of these.

The tensile properties change due to the temperature and plastic deformation. Because the crack driving force depends on the shape and level of the stress-strain curves, it is important that the stress-strain curves are representative in fracture mechanics assessments. Relevant material conditions and temperatures as described in Table 7-1 and Table 7-2 should be tested, see also [7.12].

It is recommended to perform the tensile testing in accordance with ISO 6892. See also DNVGL-ST-F101 App.B.

Investigations have shown that the tensile properties of girth welds are quite isotropic. Hence, equal results should be obtained when using all-weld specimens (specimens oriented in the pipe circumferential direction, weld longitudinal direction) and specimens in the pipe longitudinal direction (cross weld, as for instance illustrated in DNVGL-ST-F101 Figure B-13). However, because the stress condition in notched tensile specimens is not uniform, it will be necessary to adjust the results and thus introduce additional uncertainties to the results. Hence, all-weld specimens are in general recommended. If specimens similar to DNVGL-ST-F108 Figure B-13 are tested, it is recommended to adjust the values as specified in DNVGL-ST-F101 App.B.

### 7.9 Tensile testing, special considerations for corrosion resistant alloy welds in lined or clad pipes and other girth welds with dissimilar materials combinations

The crack driving force (CDF) is influenced by different parameters such as the geometry containing the flaw considered, the flaw size, weld residual stresses and the tensile properties of the materials in addition to the applied load. These parameters are included in the fracture mechanics approach described in Sec.4 and Sec.5, but the procedure requires the weld metal to be at least an even-match in strength compared with the parent material.

For CRA welds in lined or clad pipes it will be necessary to either demonstrate that weld deposits are at least as strong as the parent pipe material in order to use the fracture mechanics approaches specified in Sec.4 and Sec.5 or determine stress-strain curves representing the different materials as input to FE fracture mechanics analyses if fracture assessments are required, e.g. $\varepsilon_{l,nom} > 0.4\%$. Hence, tensile testing of the materials is needed.
There are mainly five materials and areas of a girth weld where tensile testing is of interest. These areas are indicated in Figure 7-4 and are as follows:

- parent pipe material
- filler weld
- root/hot pass (if different from filler weld)
- clad/liner material
- overlay welds.

Figure 7-4 Illustration of materials/areas for which material stress-strain curves are required

Suggestions for how to perform tensile testing of the root/hot passes are illustrated in Figure 7-5. This specimen design may also be applicable for the overlay weld.

Figure 7-5 Recommended specimen for determining the tensile properties of the weld root/hot pass. This specimen might also be used for overlay welds and for filler welds in a cross-weld direction. \( l_c \) should in general be as long as possible

Tensile testing of the liner, clad layer and overlay weld (shorter specimen) will be possible using rectangular specimens as indicated in Figure 7-6.
Because CRA materials and C-Mn materials typically have some different elastic modulus, it is suggested to allow for some lower stress-strain curves for CRA materials compared with C-Mn parent pipe if this is limited to up to 0.5% strain, i.e. the CRA materials should cross the C-Mn stress-strain curves before 0.5% strain. A suggestion for how to define at least even-match when dissimilar materials are compared is illustrated in Figure 7-7.

If it is not possible to determine the stress-strain curves of the various materials, it will be acceptable to use cross-weld tensile testing to demonstrate that the weld is at least as strong as the parent material, such that the assessments approaches described in Sec.4 and Sec.5 can be used.
7.10 Determination of stress-strain curves for strain-based assessments

The stress-strain curve used in strain-based fracture mechanics analyses should represent a high yield stress combined with low strain-hardening properties because this will result in a higher CDF and ensure sufficiently conservative results.

If the pipeline or riser is plastically deformed and is later subjected to plastic deformation such that strain-based fracture mechanics analyses are required, the material should be strained and aged prior to testing, see [7.12].

Tensile properties and stress-strain curves for strain-based assessments should be determined as follows:

— Tensile testing performed during production or qualification should be issued to the ECA contractor and the results should be considered when the material specific stress-strain curves are constructed.
— Stress-strain curves up to the uniform elongation (strain at UTS) should be reported from the tensile testing.
— The tensile properties used in the ECA should describe a characteristic high stress-strain curve with low strain hardening. This high stress-strain curve should be constructed, based on tensile test results, from the relevant material condition as follows:
  — characteristic yield stress (YS), defined as either the specified maximum yield stress, or the mean yield stress established from testing plus factor Z multiplied by the standard deviation, where Z should be taken from Table 7-5
  — tensile strength (UTS), defined as the minimum UTS/YS ratio existing in the test population (i.e. the tensile tests with the lowest UTS/YS ratio) multiplied by the characteristic high YS. It is also acceptable to derive a characteristic UTS in the same way as for YS
  — the stress-strain curve should have a yield discontinuity (Lüder plateau) as relevant and the strain at UTS (uniform elongation) should not be lower than the mean uniform elongation value established from the testing.

Table 7-5 Number of standard deviations Z to be added to the mean YS to derive characteristic stress-strain properties for strain-based loading

<table>
<thead>
<tr>
<th>Number of tests, n</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>5.01</td>
</tr>
<tr>
<td>5</td>
<td>2.82</td>
</tr>
<tr>
<td>10</td>
<td>1.93</td>
</tr>
<tr>
<td>15</td>
<td>1.69</td>
</tr>
<tr>
<td>20</td>
<td>1.57</td>
</tr>
<tr>
<td>30</td>
<td>1.44</td>
</tr>
<tr>
<td>50</td>
<td>1.32</td>
</tr>
<tr>
<td>100</td>
<td>1.22</td>
</tr>
<tr>
<td>∞</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Notes:

— Table 7-5 gives the characteristic yield stress for strain-based loading defined as the 84.1% fractile (mean value plus one standard deviation) with 95% confidence
— if parametric formulas are used, the resulting stress-strain curve should fit the shape of the experimental results reasonably well, especially around the yield
— true uniaxial stress-strain curves should be used as the basis for the failure assessment curve. Engineering stress-strain curves should be converted to true stress-strain curves as follows:

\[ s = \sigma(\varepsilon+1) \text{ and } e = \ln(\varepsilon+1) \]

where \( s, e \) represent true stress and true strain and \( \varepsilon, \sigma \) represent engineering stress and strain. These correlation formulas are only valid up to the engineering UTS.

### 7.11 Determination of stress-strain curves for stress-based loading

The stress-strain curve used in stress-based fracture mechanics assessments should be low because this will result in a higher CDF, which will ensure sufficiently conservative results. Provided the strength of the weld metal is equal to or higher than that of the parent pipe, the stress-strain curve representing the parent pipe should be used. The curve should represent the pipe longitudinal direction.

The characteristic stress-strain curve for stress-based loading should be determined using one of the following approaches:

— based on SMYS (R\(_{t0.5}\)) and SMTS with justified uniform elongation and adjusted for temperature if the pipeline or riser has not been subjected to plastic strain
— based on tensile test results for a representative material condition where the YS and UTS are determined as mean values minus \( Z \) multiplied by the standard deviation, where \( Z \) should be taken from Table 7-6. The tensile properties determined in this way correspond to tensile properties with a 2.3% survival probability estimated with at least 95% confidence.

The stress-strain curve should include a yield discontinuity (Lüder plateau) as relevant.

**Table 7-6** Number of standard deviations \( Z \) to be subtracted from the mean YS and UTS to derive characteristic tensile parameters for stress-based loading. The values based on the standard deviation being known (almost the same for different grades and dimensions, etc.)

<table>
<thead>
<tr>
<th>Number of tests, ( n )</th>
<th>( Z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2.95</td>
</tr>
<tr>
<td>5</td>
<td>2.74</td>
</tr>
<tr>
<td>10</td>
<td>2.52</td>
</tr>
<tr>
<td>15</td>
<td>2.42</td>
</tr>
<tr>
<td>20</td>
<td>2.37</td>
</tr>
<tr>
<td>30</td>
<td>2.30</td>
</tr>
<tr>
<td>50</td>
<td>2.23</td>
</tr>
<tr>
<td>100</td>
<td>2.16</td>
</tr>
<tr>
<td>( \infty )</td>
<td>2.00</td>
</tr>
</tbody>
</table>
### Guidance note:

The data from which the mean and standard deviations are derived should be representative of the overall population of material under relevant of temperature, pre-straining, etc., conditions. Depending on the data available, it may be appropriate to use a combination of laboratory test data (to establish the influence of key parameters and the shape of the stress-strain curve under relevant conditions) and mill test data in the longitudinal direction (to gain a better picture of the overall population statistics). In such cases, the approach should be documented and accepted by all parties.

---end-of-guidance-note---

### 7.12 Straining and aging

For strain-based ECAs, a material with high yield stress and low strain hardening [7.10] should be assessed and tested so far as possible to ensure sufficient conservatively results. For stress-based ECAs, a material with minimum tensile properties [7.11] should be assessed and tested in so far as possible. To achieve this, it may be necessary to pre-strain and age the material prior to testing. Pre-straining and aging is normally not required for ECA static when considering the first load increment, but shall be considered for subsequent load cases.

Three important material mechanisms shall be considered when the pre-straining and aging procedure is established. These are:

- the Bauschinger effect, as illustrated in Figure 7-8
- strain hardening, as illustrated in Figure 7-9
- aging.

![Bauschinger effect](image)

**Figure 7-8** The Bauschinger effect is a phenomenon which occurs when materials are strained into the non-linear stress-strain area in one direction followed by straining in the opposite direction. The effect of such cycling is that the reverse yield stress decrease
Figure 7-9 Cyclic strain hardening is the effect seen if a material is strained in one direction followed by unloading before the material is strained in the same direction once more. The effect of such cycling is that the yield stress increases and the strain-hardening decreases.

Figure 7-10 illustrates typical moment/curvature cycles for reeling installation. The most critical situation is theoretically reeling-on at 12 o’clock, because the tensile properties are represented by the highest stress-strain curve with little strain hardening. However, the strain increment may be larger at the 6 o’clock location in the straightener and this situation should also be considered. For other installation methods introducing longitudinal strain above 0.4%, it is important that the whole installation sequence is evaluated in order to determine the largest strain increment and how to assess the various increments.

Figure 7-10 Illustration of reeling installation with typical moment-curvature plot

If the ECA includes situations where the pipeline or riser has already been subjected to plastic strains, the tensile testing and fracture mechanics testing should be performed on material representing strained material that has been aged if relevant. If it can be documented, based on earlier experience, that the fracture toughness properties are not reduced because of pre-straining and aging it is acceptable to perform fracture toughness testing in the as-received condition. For reeling installation where the pipes will be compressed...
before subsequent strain increments in tension, it is acceptable to base tearing assessments on fracture toughness testing in the as-welded material condition.

If the loading situation to be evaluated takes place a given time after the material was plastically deformed, the tensile properties have changed further. This effect is referred to as the aging effect. The length of time that is needed varies and is in general uncertain, but the effect accelerates at higher temperature. A general recommendation is that aging should be accounted for after the first operational start-up where a pipeline or riser has experienced increased temperature.

If the load condition to be assessed after the pipe has been subjected to plastic deformation is strain-based, the pre-straining shall end in tension to give representative results. This is most important for the tensile properties, as this will ensure a high stress-strain curve with low strain-hardening properties which will increase the CDF.

If the load condition is stress-based and the pipeline or riser has already been subjected to plastic deformation, the pre-straining shall end in compression to give a low stress-strain curve which is most conservative for stress-based assessments.

The pre-straining should simulate one complete strain history (i.e. the whole installation sequence, but not contingency, etc.) if ECAs are required for the operational phase. However, this is unnecessary if it can be substantiated that simulations where the material is relaxed and only plastically deformed in tension will give same results as if the material is simulated to a full reeling cycle where the last increment ends in tension. This reduces the complexity and costs of the testing.

The straining simulation should normally be performed on segment specimens that are instrumented sufficiently such that it is possible to simulate the actual loading accurately. The specimen and simulation may in general be similar to that described in [8.2]. See also DNVGL-ST-F101 App.B. After straining the materials, test specimens are extracted from the segment specimen such that the material tested has the relevant straining condition.

Full-scale bend testing of pipes is also acceptable, but then it is important that the specimens are extracted at the representative location. Some guidance may also be found in DNVGL-ST-F101.

If aging is relevant, artificial aging at 250°C for one hour is recommended. Aging simulation is performed after the pre-straining but before materials testing.

### 7.13 Special considerations for environments that potentially reduce the fatigue and fracture resistance of the girth welds

The fracture toughness and fatigue crack growth properties are sensitive to the surrounding environment. Special care is recommended if the fracture toughness is expected to be reduced due to the surrounding environment or if it is uncertain whether the fatigue crack growth parameters specified in BS 7910 are representative.

Further guidance on the effect of the environment, particularly a sour environment, on fatigue and fracture resistance is given in App.C.

A typical source for such degradation is hydrogen. Hydrogen may exist in the manufacturing and welding material or may ingress into the material either from the surrounding environment or because of cathodic protection (CP) combined with a metallic surface exposed to seawater.

**Guidance note:**
Other terms used include e.g. hydrogen embrittlement stress cracking, hydrogen induced cracking and hydrogen cracking. However, none of these terms, or HISC, is specific to the source of the hydrogen.

If hydrogen is likely to degrade the materials ductility and fatigue resistance, all tensile testing, fracture toughness testing and fatigue testing should reflect this. This means that the testing should be performed under realistic conditions such that relevant inputs to the fracture mechanics assessments are provided.

The testing conditions, such as the specific environment, temperature, loading rate, test frequency (fatigue testing), pre-soaking time etc., may be important and should be evaluated carefully. More guidance is provided in App.C.
HISC is only relevant for a certain combination of load/stress and local hydrogen embrittlement and the actual trigger for HISC depends on the materials, manufacturing and actual environment, loading and weld quality. 22Cr, 25Cr and 13Cr materials have shown to be susceptible to HISC and special care is recommended. More information about duplex steels exposed to cathodic protection is provided in DNVGL-RP-F112.

Guidance note:
It has not been common practice to perform testing of C-Mn materials in seawater and CP even though it has been documented that such tests lead to significant reductions in fracture toughness and ductility. If the coating integrity is robust and the loading during operation is low, hydrogen embrittlement should not be a concern.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---
SECTION 8 VALIDATION TESTING

8.1 General

In cases where there is limited experience or there are uncertainties related to the accuracy of the assessment approaches or where required fracture toughness testing is impossible, full-scale tests, segment testing or a combination of these is recommended as validation. Full-scale testing is most representative, but segment (strip) specimens are a good alternative.

The testing should in general reflect the worst-case loading condition, relevant temperature and unfavourable material properties as far as possible. Alternatively, a reasonable safety margin should be applied to the strain level or flaw size.

Segment validation testing was originally developed for validating situations involving uniaxial plastic strain and not biaxial stresses. Hence, the approach is not suited for evaluating situations where girth welds are subjected to plastic strain combined with significant internal pressure.

Full-scale testing or segment validation testing is recommended for the following situations:

— girth welds subjected to low-cycle fatigue. See also [5.3.5]
— clad or lined pipelines subjected to $\varepsilon_{l,nom} > 2.25\%$
— C-Mn linepipe materials with SMYS larger than 555 MPa and $\varepsilon_{l,nom} > 2.25\%$
— 13Cr martensitic steels if $\varepsilon_{l,nom} > 2.25\%$
— 22Cr and 25Cr duplex stainless steels if $\varepsilon_{l,nom} > 2.25\%$
— if other materials of which there is little experience are used and the longitudinal strain exceeds 2%.

The main purpose of such testing should be to prove that the fatigue and fracture limit state is qualified. Hence, the testing should be performed as representatively as possible considering the:

— material condition for the loading considered
— temperature condition for the loading considered
— loading condition (strain/stress level, stress/strain range, internal pressure, number of cycles, etc.)
— test frequency if relevant (especially when testing in special environments)
— weld quality (worst case weld flaws and misalignments etc.).

Typically, validation testing should be performed on girth welds with realistic weld flaws. The flaws may be real flaws detected during manufacturing or fabricated flaws. Examples of fabricated flaws may be weld flaws simulated during welding, electro-discharge machined (EDM) notches or pre-tested fatigue cracks. It is recommended that the EDM notch corresponds with the AUT acceptance criteria plus the sizing error, such that the notch tested equals the maximum height of possible flaws after inspection and repair.

It might be challenging to simulate the representative loading. Segment specimens will typically bend and might buckle if compression loads are applied, and full-scale bending tests will typically show quite different strain levels along the surface if, for instance, instrumented by strain gauges. Hence, it is recommended to agree, prior to testing, how the relevant loading should be simulated and how it should be documented that the target loading is achieved.

8.2 Special considerations when validating tearing and unstable fracture assessments using segment specimens (typically reeling installation)

The objective of the testing should be to demonstrate that the maximum allowable flaw sizes determined are conservative. The recommended way for to demonstrate this is to demonstrate that the tearing is lower than that assessed when the maximum allowable flaw sizes were determined and that the strain capacity is considerably higher than the maximum longitudinal strain levels the girth welds will be subjected to.

It is normally acceptable to do the validation testing on the most critical weld procedure only and the notch position should represent the position with the lowest tearing resistance curve. The notch should normally
be fabricated from the external cap. It is acceptable to test specimens without grinding the cap and root
reinforcement heights.

Based on the geometry of the specimens a notch is fabricated at the relevant position. The height of the
notch should represent the maximum allowable height assessed for the relevant notch length for the pipeline
or riser. It is recommended that the notch be fabricated by electro-discharge machining (EDM), with the
width that is as small as possible and does not exceed 0.2 mm.

Residual stresses may be reduced substantially when segment specimens are fabricated and it is
recommended that the critical flaw size assessment which is the basis for the size of the EDM notch be
conducted without residual stresses. However, the stress-strain curve and tearing resistance curve used to
assess the maximum allowable flaw sizes should be used.

The strain level in the specimen shall be measured during testing such that it is possible to verify that the
simulation of the actual loading is sufficiently accurate. This can be by means of displacement transducers
measuring over a certain gauge length or by using strain gauges as illustrated in Figure 8-1. If strain gauges
are used, both the external and internal surfaces on both sides of the weld should be instrumented. It is
recommended to use the average of the strain gauges at each side of the weld as a measure of the strain
level and to use the side that shows the smallest strain value to simulate the actual strain increments.

Figure 8-1 Illustration of segment specimen used to validate the maximum allowable flaw size

If the specimens are subjected to plastic deformation in compression, it is important that the buckling
tendency is limited as far as possible. The buckling tendency will be limited if the test machine is as stiff as
possible and the daylight length of the specimens is as short as possible.

If multiple plastic strain cycles are considered, as for instance in reeling, it is recommended that three
specimens be tested as follows:

— One specimen is loaded monotonically to failure. The objective is to demonstrate that the strain capacity
is larger than the maximum longitudinal strain relevant for the loading simulated (e.g. maximum reeling
strain). The strain capacity for the pipe when worst case inputs are specified in the fracture mechanics
assessment without residual stresses should also be compared with the maximum strain in the segment
specimen. The maximum strain (strains capacity) in the segment specimen should be higher than the
strain capacity in the pipe.

— One specimen is simulated to several strain increments for reeling, a full installation cycle simulating 12
o’clock is recommended such that the last cycle is in compression. After testing, the specimen should be
heat tinted and broken up at low temperature such that it is possible to measure tearing. The objective
of this simulation should validate that the tearing in the specimen is lower than that assessed for the pipe
when worst case inputs without residual stresses are used.

— One specimen is simulated to several strain increments (typically one complete reeling cycle 12 o’clock)
followed by monotonically loading to failure. The objective of this testing should verify that the strain
capacity in the segment specimen is higher than that calculated for the pipe also after plastic cycling.
SECTION 9 BIBLIOGRAPHY

9.1 Bibliography


APPENDIX A HOW TO UNDERSTAND THE FAILURE ASSESSMENT DIAGRAM

The ECA procedure described in this RP is basically BS 7910 but is somewhat modified such that it can be used for strain-based conditions well into the plastic regime. The main modification is how the plastic collapse (the $L_r$ cut-off) value is increased.

Further, the way in which the applied stress, including possible strain concentrations, should be determined and applied in the assessments is specified in detail.

The methodology has been developed over several years and proven to give overall conservative predictions of fracture, but the accuracy of the procedure is not well verified. The accuracy of the FAD approach may, however, be compared quite easily with that of FE fracture mechanics analyses by comparing the crack driving forces (CDF).

The CDF may be derived from any failure assessment diagram (FAD) approach and plotted as a function of the applied loading (applied strain or stress). This curve can then be compared directly with the CDF versus the same applied load derived by FE analyses as illustrated in Figure A-1.
Figure A-1 Illustration of how the CDF may be extracted from a FAD assessment such that it is possible to compare the results with, for instance, those from FE fracture mechanics analyses.

In further detail, the CDF may be extracted from the BS 7910 Option 2 analysis as follows:

The failure assessment curve (FAC) is defined as:

$$\text{FAC} = \left( \frac{J_{el}}{J_{TOT}} \right)^2 = f(L_r),$$

hence

$$J_{TOT} = J_{app} = J_{el} \cdot (\text{FAC})^{-2},$$

where

$$J_{el} = \frac{K_f^2}{E'},$$

which means that
\[ J_{\text{app}} = \frac{K_I^2}{E^2} \cdot (FAC)^{-2} = \frac{K_I^2}{E^2} \left( 1 - \nu^2 \right) \left( \frac{E \cdot \varepsilon_{\text{ref}}}{L_r \sigma_{\text{YS}}} + \frac{L_r^2 \sigma_{\text{YS}}}{2 E \varepsilon_{\text{ref}}} \right)^{-2} \], or

\[ J_{\text{app}} = \frac{K_I^2}{E^2} \cdot (FAC)^{-2} = \left( \frac{K_I}{K_r} \right)^2 \left( 1 - \nu^2 \right) \], where

\[ K_r = \left( \frac{E \cdot \varepsilon_{\text{ref}}}{L_r \cdot \sigma_{\text{YS}}} + \frac{L_r^2 \cdot \sigma_{\text{YS}}}{2 E \cdot \varepsilon_{\text{ref}}} \right)^{-0.5} \]

\( K_I \), represents the stress intensity factor for the flaw size and geometry considered. \( L_r = \sigma_{\text{ref}}/\sigma_{\text{YS}} \), where \( \sigma_{\text{ref}} \) represents the reference stress for the flaw size and geometry considered.

The \( K_I \) and \( \sigma_{\text{ref}} \) solutions should reflect the actual flaw type and structural geometry. The formulas in Table 3-1 are recommended.

If the CDF expressed as CTOD is required, \( J_{\text{app}} \) may be converted to CTOD_{app} as follows:

\[ CTOD_{\text{app}} = \frac{J_{\text{app}}}{R_{p0.2} \cdot 1.517 \left( \frac{R_{p0.2}}{R_m} \right)^{0.3188}} \]

It is now possible to compare the CDF calculated using the FAD approach with the CDF calculated using solid 3D FE fracture mechanics analyses as illustrated in Figure A-2.
Figure A-2 Illustration of how the CDF obtained using the FAD approach may be compared with that obtained using solid 3D FE fracture mechanics analyses.

Figure A-3 Illustration of how the CDF obtained using the FAD approach may be compared to that obtained using solid 3D FE fracture mechanics analyses for flaws with different heights and a constant length, X, for a specific strain level, Y. Each dot represents one calculation.
APPENDIX B FINITE ELEMENT FRACTURE MECHANICS ASSESSMENTS

From FE fracture mechanics analyses the CDF versus the relevant loading can be compared with the fracture toughness of the material represented by either the fracture toughness at the stable/unstable crack extension, Figure B-1 and Figure B-2, or the tearing resistance as illustrated in Figure B-3 and Figure B-4.

It is important that such comparisons reflect the loading considered in the assessment. If the loading is strain-based, the CDF vs. applied strain should be compared and if the loading is stress-based, the CDF vs. applied stress should be compared.

![Figure B-1 Illustration of the CDF assessed by FE fracture mechanics analyses versus applied strain and how to determine the maximum allowable flaw size (similar to a FAD approach with single fracture toughness specified)]
Figure B-2 Illustration of the CDF assessed by FE fracture mechanics analyses versus applied stress and how to determine the maximum allowable flaw size (similar to a FAD approach with single fracture toughness specified) \( a_1 \) and \( a_2 \) are acceptable, while \( a_3 \) is critical

As indicated in Figure B-1 and Figure B-2, several FE fracture mechanics assessments with different stationary flaw sizes need to be performed in order to assess, for instance, the critical flaw height. It is in general recommended to vary the flaw height and keep the length constant, but it is also possible to keep the flaw height constant and solve the critical flaw length.

As illustrated the CDF curves that target the intersection point between the applied load and the materials fracture toughness represent the critical flaw height \( (a_3) \). This assessment will be similar to a FAD assessment without tearing.

Quite similarly, it is possible to perform a tearing assessment based on 3D solid FE fracture mechanics analyses as illustrated in Figure B-3. This analysis is similar to a tearing assessment as specified in BS 7910, but is more accurate because the crack driving force is calculated from more accurate 3D solid FE fracture mechanics analyses.

The CDF is usually assessed for a specific strain level for different flaw sizes, keeping the flaw length constant and vary the flaw height. The CDF and tearing resistance curves are plotted in the same diagram. If, for instance, the CDF curve is fixed and the tearing resistance curve is moved as illustrated in Figure B-3, it will be possible to determine either the tearing for a certain flaw height or the maximum allowable initial flaw size which just will grow to a critical value when subjected to the relevant loading.
Figure B-3 Illustration of the CDF assessed by FE fracture mechanics analyses versus applied strain and how to determine the maximum allowable flaw size (similar to a FAD tearing analysis)

Alternatively, the tearing resistance curve may be fixed and the CDF curve be moved as illustrated in Figure B-4. The result will be the same.
Figure B-4 Illustration of the CDF assessed by FE fracture mechanics analyses versus applied strain and how to determine the maximum allowable flaw size
APPENDIX C SOUR SERVICE TESTING GUIDELINES FOR THE FATIGUE AND FRACTURE LIMIT STATE

C.1 Introduction

Sour environments are known to have a detrimental effect on the fracture and fatigue performance of welded C-Mn line pipe steels. Therefore, an engineering critical assessment (ECA) approach is recommended for determining the maximum allowable flaw sizes for girth welds in pipelines and risers designed for sour service. This appendix provides guidelines for fracture toughness (FT) and fatigue crack growth rate (FCGR) testing of welded C-Mn line pipe steel in sour environments, to ensure that reliable and conservative material properties are developed for ECA calculations.

In the context of this guidelines document, a sour environment is defined as having a partial pressure of \( \text{H}_2\text{S} (p_{\text{H}_2\text{S}}) \) above 0.05psia (0.003bara), in accordance with standard NACE/ISO criteria (\cite{1}). However, it is important to note that having a \( p_{\text{H}_2\text{S}} \) of less than 0.05psia (0.003bara) does not preclude environmental degradation of C-Mn steel properties and in-air properties should not be assumed (\cite{2-3}). Fracture mechanics testing to quantify environmental effects in sweet and very mild sour environments also requires careful consideration and is the subject of ongoing research, but this is beyond the scope of the current document.

For C-Mn steels exposed to sour environments, hydrogen embrittlement effects are known to be most pronounced at room temperature (RT). The cracking of C-Mn steel in sour environments is widely accepted to be a hydrogen embrittlement phenomenon. Therefore, conducting FT and FCGR tests at RT should provide conservative properties for ECA calculations.

Sour service testing is the subject of ongoing research in the oil and gas industry. The intention of this appendix is not to provide a comprehensive review of all the sour service test methods that exist or are under development, it is rather to provide helpful baseline information that considers the current state of knowledge in this area and to support the design and installation of welded C-Mn steel pipelines and risers that will be exposed to sour service conditions. It is anticipated that this appendix will be updated and expanded in future editions of DNVGL-RP-F108 as more information becomes available and more consensus is reached in the industry.

C.2 Test environment

It is recommended to perform tests in project-specific environments. The following key environmental variables should be reproduced accurately and conservatively based on available project information and considering the discussion below.

1) pH
2) partial pressure of \( \text{H}_2\text{S} (p_{\text{H}_2\text{S}}) \)
3) salt concentration
4) temperature
5) inhibitor.

The solution’s pH and \( p_{\text{H}_2\text{S}} \) should replicate the expected field conditions. There is ongoing work in the industry to establish the most accurate method to represent field conditions in laboratory tests. Historically, the partial pressure based on the total pressure of the well has been used, but more recently there have been efforts to more accurately model the field conditions using fugacity calculations. There is also ongoing discussion in the industry regarding the role of buffer (in particular sodium acetate vs. sodium bicarbonate) on the corrosion behaviour of steels. The choice of buffer could influence the fracture and fatigue behaviour of line pipe steels and should be selected based on the expected pH level. For a pH of less than 4.5, it is recommended to use an acetate buffer. However, for a pH of greater than 4.5, either acetate or carbonate buffers may be used. The selection of laboratory \( \text{H}_2\text{S} \) concentrations and buffer type should be documented and accepted by all parties. Tests are typically conducted at ambient pressure although testing at elevated pressure may be necessary to replicate field conditions.
If possible, the salt concentration associated with the specific field conditions should be replicated. However, if the exact concentrations in the field are not known at the time of testing, it is recommended that tests for assessing production systems be performed in a 5wt% sodium chloride (NaCl) solution. For gas transmission systems, it is recommended to perform tests in non-buffered 1000 ppm NaCl solution at the appropriate pH level, in order to simulate the gas condensate environment.

Some parameters may be expected to change over the design life, or during operations, e.g. during shutdowns or outages. In general, laboratory test conditions should be selected on a conservative basis to take account of foreseeable changes. However, the philosophy may differ between FT tests and FCGR tests. For FT tests, it should be recognized that extreme loading events may occur at any time and testing should be carried out under the most onerous of foreseeable environmental conditions. However, as fatigue is a progressive failure mode that takes place over an extended period of time, tests may instead be carried out under the environmental conditions that are expected to apply over most of the lifetime, or over the majority of fatigue cycles.

The temperature during pipeline and riser operations will range from the seabed temperature to the maximum operating temperature (i.e. from 4°C/40°F up to approximately 150°C/302°F). Typical loading of flowlines, including those designed to buckle laterally, occurs as the lines become heated, hence they are subjected to fatigue loading under varying temperatures. For flowline applications, it is recommended that tests be performed at RT where the susceptibility to hydrogen embrittlement is higher than at elevated temperatures. In the case of risers, which are primarily subjected to fatigue loading at the operating temperature (e.g. due to wave- or vessel-induced motions, VIV, etc.), FCGR tests may be performed at the operating temperature, but FT tests should be performed at RT to capture conservative material properties. The selection of test temperatures should be documented and accepted by all parties.

Corrosion inhibitors can have a dual influence on sour service fracture and fatigue behaviour. The presence of inhibitors lowers the corrosion rate and the associated hydrogen pick-up, which would be expected to reduce the fracture and fatigue susceptibility of C-Mn line pipe steels in sour environments. However, in some instances, such as fatigue crack growth at very low values of K or ΔK, the reduction in corrosion rate can have an apparently detrimental effect on the measured crack growth rate, as it may reduce crack tip blunting or crack closure effects. When performing FCGR tests, it is recommended to use a representative inhibitor concentration. However, for FT tests, it is recommended to use the worst-case environment because a fracture event could occur at any time during operation. The most susceptible condition may be in the absence of an inhibitor (e.g. during an inhibitor outage). However, it is also possible that slow stable cracking could occur more readily if inhibitor concentrations are high, due to it being possible to maintain a sharp crack tip system.

C.3 Sample details

C.3.1 Geometry

Standard fracture mechanics samples should be used for testing. Samples should be compliant with recognized international standards such as ASTM, BS and ISO. SENB, CT or SENT specimens are typically used for sour FT testing. SENB or CT specimens are typically used for FCGR testing. At present, the use of low constraint samples (such as SENT) also requires that biaxial loading effects to be included in the CDF. There are on-going efforts in the industry to standardize the use of SENT samples for sour FT testing.

C.3.2 Notching

Samples should be notched and fatigue pre-cracked in air. For preliminary screening purposes, it is recommended to test three different notch locations: the weld centre line (WCL), heat affected zone (HAZ) and parent pipe (PP). The notch locations should be established in accordance with DNVGL-ST-F101 App.B. Samples can be notched in the L-C (i.e. through thickness) or L-R (i.e. surface notch) orientation. Data generated from samples notched in the L-C orientation tend to be more consistent and representative of the overall pipe properties. L-R orientation more closely matches the geometry of the flaw being assessed and is commonly used for SENT samples. The choice of notch orientation should be accepted by all parties.
Full thickness samples (or as close to full thickness as possible) should be tested, however in many cases this may not be practical. In cases where it is not practical to test full thickness samples, it is recommended to extract samples from the mid-wall location for L-C orientation or from the inner surface for L-R orientation.

C.3.3 Coating configuration

Tests can be performed on uncoated samples (i.e. exposed on all sides), but it is recommended to coat samples on 5/6 sides to simulate one-sided diffusion. Only the front face of the sample (and the crack flanks) should be left uncoated, so as to simulate a crack located inside a sour pipeline or riser. It is recommended to use a non-metallic coating that is compatible with the test environment. The coating selected should adequately protect the metal surface during testing to prevent corrosion interactions between the sample and sour environment.

C.3.4 Pre-soaking

The pre-cracked samples should be pre-soaked in the sour environment for a sufficient period of time before testing starts to allow the concentration of diffusible hydrogen in the sample to reach steady-state. Various methods exist for estimating an appropriate pre-soaking duration, for example hydrogen flux measurements and diffusion simulation. However, based on published work (55/-6/), for a typical fracture mechanics sample geometry coated to simulate one-sided diffusion, where hydrogen entry is primarily from the crack flanks, it has been found that the hydrogen concentration will typically reach a steady-state after approximately 4 days for pre-cracks that are typically about 2mm deep. Hence a minimum pre-charging period of 4 days is recommended, acknowledging that a longer pre-soak may be required for specimens with long fatigue pre-cracks (e.g. greater than 2mm). A shorter pre-soaking period would require separate technical justification. If specimens are uncoated (i.e. exposed on all sides), then the time to reach a steady-state hydrogen concentration will depend on the sample thickness.

C.4 Test methodologies

C.4.1 Fracture toughness

In addition to the environmental variables discussed above, the fracture toughness (FT) in sour environments depends on the loading method (dynamic vs. static) and loading rate. Many FT test methods exist, however for sour service pipeline applications, threshold values for the onset of crack growth in the environment have primarily been developed using two methodologies:

1) Rising displacement tests
2) Constant load tests.

1) Rising displacement tests

The objectives of a rising displacement FT test should:

a) Establish the J value associated with crack initiation.
b) Develop a complete J-R curve in the environment to quantify the resistance to crack propagation.

Rising displacement test considerations:

- J-R curves can be generated using single or multiple specimen methods. A single specimen approach is more economical when conducting tests in sour environments.
- Rising displacement tests should be performed at a conservative loading rate. A preliminary set of K-rate sensitivity tests should be performed to select an optimum K-rate for subsequent tests, defined as the highest initial K-rate below which the K-rate has no effect of the measured FT.
- It is recommended that the K-rates used for the K-rate sensitivity tests span at least one order of magnitude.
— It is recommended that the highest initial K-rate considered be no higher than $0.1 N \text{mm}^{-3/2}/\text{s}$. The optimum initial K-rate is typically found to be in the order of about $0.005 N \text{mm}^{-3/2}/\text{s}$, but in some conditions, it may be necessary to test at a lower rate.

— It is recommended to test three initial K-rates be tested. The tests should be performed at a constant displacement rate under displacement control throughout the test. This will provide a constant initial K-rate until the onset of crack growth.

— K-rate sensitivity tests can be performed on a single microstructure. While not critical, it is recommended that tests be performed on PP samples to minimize the variation in microstructure between samples.

— Alternatively, rising displacement tests can be performed at a K-rate that is representative of the actual worst case loading conditions. The technical justification for testing at a representative (but still conservative) K-rate would need to be accepted by all parties. For flowlines designed to buckle laterally, possible crack growth during both buckling and hold periods associated with normal operation should be considered when establishing an appropriate loading rate.

— It is recommended to perform rising displacement FT tests on all three microstructures; WCL, HAZ and PP.

— Assuming a single specimen approach is adopted, a minimum of one test per microstructure is required. Duplicate tests per microstructure are recommended.

— The validity of tests on HAZ samples should be established in accordance with DNVGL-ST-F101 App.B /4/.

Interpretation of rising displacement test results:

— The interpretation of J-R curves generated in air is covered by recognized international standards such as ASTM, BS and ISO. Beyond the details provided in the air testing standards, particular emphasis should be placed on defining the onset of crack propagation in the sour environment, which is used to estimate a conservative lower bound FT. The purpose of the rising displacement tests is not to define a lower bound J-R curve, it is only to define the lower bound fracture toughness value corresponding to the onset of crack propagation.

— The J value at 0.2 mm stable crack extension is often used to define the onset of crack propagation. However, it should be noted that values associated with the onset of any measurable stable crack extension, as well as the J value associated with 0.05mm of crack extension have also been used as thresholds for crack propagation in sour environments (/7-8/).

— The selection/interpretation of FT values from rising displacement tests should be accepted by all parties. It is important to recognize that whatever J value is selected, it is effectively allowing for a very small but finite amount of stable crack extension.

— If the material tested in a sour environment exhibits stable crack propagation after the onset of crack propagation, it may be possible to justify using the full J-R curve with a prescribed limit on the maximum crack extension in the ECA as long as the J-R curve is demonstrated to be a lower bound. However, it is important to note that if a portion of the J-R curve above the initiation value is used, it is also necessary to account for possible time dependent crack extension during hold periods associated with normal operation. The technical justification for allowing stable crack extension after the onset of crack propagation would need to be accepted by all parties.

2) Constant load tests

The objective of a constant load test is to establish the FT threshold value, i.e. the value of J or K below which crack propagation will not occur.

Constant load test considerations:

— Like all other sour tests, it is recommended that constant load test samples be pre-charged for a minimum of four days prior to loading.

— A preliminary step load test, where the load is increased in steps approximately every 12 hours, can be performed to determine the point at which crack propagation occurs. The magnitude of the load increase at each step and the hold time at each load may influence the measured value of initiation toughness.
— Based on the results of the step load test, a set of preliminary 30-day constant load tests is performed to bracket the crack initiation threshold.
— It is recommended that constant load tests be performed on all three microstructures; WCL, HAZ and PP. Duplicate tests per microstructure are recommended.
— If needed, additional 30-day constant load tests can be performed to further refine the crack initiation threshold value.

Interpretation of constant load tests:
— The results of constant load tests that do not fail catastrophically in 30 days are determined based on post-test inspection of the sample fracture surface. Typically, any evidence of crack extension is treated as failure.
— The highest K/J value where no crack extension is observed after 30 days of exposure to the environment is used as the threshold K/J value for the onset of crack propagation.

While both of the above test methods provide K/J values for the onset of crack propagation, the rising displacement test applies additional dynamic strain during the test, which may facilitate crack initiation and provide a more conservative FT value in the environment. A 30-day constant load test typically only provides a pass/fail result. The effects of test duration as well as any crack initiation/blunting processes during the 30-day period are not usually captured unless the samples are extensively instrumented. The effect of subsequent FT values of applying a pre-load during pre-soaking on is also the subject of ongoing research.

C.4.2 Fatigue crack growth rate

In addition to the environmental variables discussed above, the fatigue crack growth rate (FCGR) in sour environments is dependent on the ∆K and loading frequency. In order to measure representative FCGR properties, the following methodology is recommended.

1) Perform frequency scan FCGR tests at constant ∆K.
   The objectives of the frequency scanning tests should:
   a) Evaluate the effect of a range of cyclic loading of frequencies and determine the increase in the FCGR with respect to performance in air.
   b) Determine the plateau frequency (defined as the frequency below which there is no further increase in the FCGR).
   c) Determine the microstructure (notch location) that exhibits the highest FCGR.

Frequency scan FCGR test considerations:
— It is recommended to test at a high ∆K value to avoid/minimize environmental crack closure and crack tip blunting effects at high to intermediate frequencies (e.g. 0.3 - 0.03Hz).
— The ∆K value and stress ratio (R) should be selected to ensure steady FCGRs can be measured at high to intermediate frequencies (i.e. the FCGR is not changing over time at a fixed frequency).
— It is important to recognise that there could be competing effects of ∆K and R. At high ∆K and low R, the FCGR will be high, which will likely prevent crack tip blunting due to metal dissolution occurring along the crack flanks. It is also likely that under these conditions there would be convective flushing of the crack, which would prevent the build-up of corrosion products and reduce environmental crack closure effects. Therefore, the plateau frequency would be expected to be lowest at high ∆K and low R.
— Based on the above discussion, and subject to specimen size limitations, it is recommended to select R in the range of 0.1 to 0.5, with ∆K in the range of 1000-1400Nmm$^{-3/2}$. Other values of ∆K and R should be accepted by all parties.
— It is recommended to perform the frequency scan tests under decreasing frequency conditions to facilitate the transition from an in-air fatigue pre-crack to an environmentally assisted fatigue crack.
— It is recommended that the frequency scan tests be started at approximately 1Hz and decreased in increments to at least 10mHz or until a plateau in the FCGR is observed.
— It is possible that in some cases a plateau may not be observed even at very low frequencies, which may be a result of static crack growth at $K_{\text{max}}$. This is the subject of ongoing research and the subsequent assessment approach would need to be evaluated and accepted by all parties.

— It is recommended that frequency scan tests be performed on all three microstructures: WCL, HAZ and PP.

— A minimum of one test per microstructure is required. Duplicate tests per microstructure are recommended.

— Based on the results of the frequency scan tests, it is recommended that one microstructure be selected for subsequent Paris curve testing: typically the notch location exhibiting the highest FCGRs will be selected.

If tests are performed significantly below the plateau frequency, an appropriate solution may be to shift the developed curves by a factor based on the frequency scan tests. This may be more practical if the plateau frequencies are significantly lower than 3mHz.

2) Perform Paris curve FCGR tests over a range of $\Delta K$.

Paris curve tests are used to validate and supplement the frequency scan tests by measuring FCGRs over a wider range of $\Delta K$.

Paris curve FCGR test considerations:

— The loading frequency for Paris curve tests should be conservative and representative of the loading frequency for the fatigue cycles in question. For riser assessments, fatigue cycles associated with waves, vessel motions or VIV are typically in the range 0.01 to 0.3 Hz. For flowline assessments, it is impractical to test at loading frequencies associated with start-up and shutdown cycles and tests should be carried out at the plateau frequency.

— The plateau frequency identified in the frequency scan test is considered to be conservative for $\Delta K$ values less than or equal to the value used in the frequency scan test.

— If the plateau frequency is very low (e.g. less than 0.003Hz), an acceptable practical approach is to calculate the factor between the FCGR measured at the plateau frequency and a higher frequency and run the Paris curve tests at the higher frequency (typically no higher than 0.01Hz). The measured FCGRs would then be increased based on the factor calculated from the frequency scan data.

— Paris curve tests can be performed under either decreasing or increasing $\Delta K$ conditions. In both cases, the potential for environmental crack closure and crack tip blunting retarding crack growth should be recognized, particularly at low frequency and low $\Delta K$. In particular, it is recommended to perform decreasing $\Delta K$ tests at constant $K_{\text{max}}$ to try to minimize crack closure during the test. For increasing $\Delta K$ tests, crack closure effects may be minimized by maintaining a high $R$. The optimum $R$ to ensure reliable FCG measurements will be dependent on several factors, including $DK$, metal dissolution rate, CGR and to a lesser extent the resolution of the crack length measurement system.

Interpretation of FCGR tests:

— The measured FCGRs should be compared to the mean FCGR for steels in air ($R \geq 0.5$) from BS 7910 /9/. The determined factor should then be applied to the upper bound FCGR for steels in air ($R \geq 0.5$) from BS 7910 /9/, to provide an upper bound sour FCG law.

— The choice of FCG threshold ($\Delta K_{\text{th}}$) for applications where a high number of small amplitude loading events will be experienced (e.g. risers) requires special attention. It is important to note that the use of the in-air $\Delta K_{\text{th}}$ recommended in BS 7910 /9/ may not always be conservative for sour environments. The choice of $\Delta K_{\text{th,env}}$ should be accepted by all parties. A conservative approach should not include an FCG threshold.

— The limited set of Paris curve tests recommended above is primarily aimed at validating the FCGRs measured at a single $\Delta K$ value in the frequency scan tests by generating data over a wider range of $\Delta K$. However, if a project-specific multi-stage Paris curve needs to be developed, a greater number of Paris curve tests spanning the entire $\Delta K$ range from near-threshold to high $\Delta K$ values would be required. Triplicate tests are recommended over the full range of $\Delta K$ to support statistical analysis.
Additional frequency scan tests may also be required in this case to identify the plateau frequency at lower ΔK values.

### C.5 Effect of installation strain on fracture toughness and fatigue crack growth rate in sour service during operation

It is necessary to consider the possible effects of cyclic plastic straining associated with reeling and other high-strain installation methods on sour fracture and fatigue performance during operation. In general, sour FCGRs are not expected to be influenced by cyclic plastic straining associated with reeling installation (/10/). However, there is some evidence to support reduced FT properties as a result of cyclic plastic straining associated with reeling installation and subsequent exposure to sour service conditions (/11/). Therefore, for reeling installation, in addition to testing as-welded (i.e. unstrained) samples, it is recommended to test strained and aged samples extracted from girth welds that have been subjected to representative reeling simulation. It is recommended that the material be simulated with the last cycle ending in tension.

### C.6 Recommended fatigue crack growth acceleration factors for use in preliminary design calculations

Table C-1 provides recommendations for environmental FCGR acceleration factors with respect to air. In the absence of better information, these values can be used during the preliminary design stages and prior to project-specific testing taking place. The values used in final ECA calculations should, however, be confirmed by project-specific testing as outlined above. Although this document currently only covers testing in sour environments, FCGR acceleration factors are provided for seawater with cathodic protection, sweet (i.e. defined above as having a p_{H2S} of less than 0.05 psia) and sour environments. The factor for seawater with cathodic protection is primarily based on tests undertaken by the SAFEBUCK JIP for pipelines designed to buckle laterally (/12/). The factor for sour conditions is a semi-empirical model that was fitted to laboratory test data generated under various environmental conditions (/13/).

**Table C-1 Environmental FCGR acceleration factors for use in the early stages of design.**

<table>
<thead>
<tr>
<th>Environment</th>
<th>FCGR acceleration factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seawater with cathodic protection</td>
<td>10*</td>
</tr>
<tr>
<td>Sweet</td>
<td>10**</td>
</tr>
<tr>
<td>Sour</td>
<td>$10 \leq 2 \times 10^{2.63+0.34 \log p_{H2S}-0.46pH} \leq 40***$</td>
</tr>
</tbody>
</table>

* For very low cyclic loading frequencies, e.g. associated with lateral buckling, a factor of 10 should be used. For typical wave loading frequencies, the marine environment curves in BS 7910 /9/ may be used (these are typically a factor of 2-3 higher than in air).

** For very low cyclic loading frequencies, e.g. associated with lateral buckling, FCGRs in sweet environments are typically around 10 time faster than in air, but can be as much as 20 times faster than in air (/2-3/). For typical wave loading frequencies around 0.1Hz, FCGRs are typically 3-6 times higher than in air.

*** In the presence of a high concentration of inhibitors, FCGRs at very low cyclic frequencies may be significantly higher than 40 times faster than in air (e.g. /14-15/).
C.7 References


/4/ DNVGL-ST-F101, 2017: Submarine pipeline systems, DNV GL.


CHANGES – HISTORIC

There are currently no historic changes for this document.
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