DNV·GL

RECOMMENDED PRACTICE

DNVGL-RP-C203

Edition September 2019
Amended January 2020

Fatigue design of offshore steel structures

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FOREWORD

DNV GL recommended practices contain sound engineering practice and guidance.

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CHANGES – CURRENT

This document supersedes the April 2016 edition of DNVGL-RP-C203.

Changes in this document are highlighted in red colour. However, if the changes involve a whole chapter, section or subsection, normally only the title will be in red colour.

Amendments January 2020

Topic	*Reference*	*Description*
Correction	Table A-5	Figure 4 and Figure 5 have been replaced.

Amendments December 2019

Topic	*Reference*	*Description*
Nominal stress and SCF in simple tubular joints	Figure F-17	An error in the figure showing the potential fatigue cracks with nominal stress and stress concentration factors has been corrected and explanatory text has been added.

Changes September 2019

Topic	*Reference*	*Description*
Application	[1.4]	The validity of the recommended practice for use in seawater with cathodic protection has been increased from 690 MP to 759 MPa.
Fatigue analysis based on S-N data	[2.3.2]	Added more information.
	[2.4.3]	Text related to the reference thickness has been corrected.
	[2.4.6]	Text has been added to explain the difference in S-N curves for the outside and the inside of tubular joints welded from the outside only.
	[2.9]	A section on friction welded bolts has been added.
Stress concentration factors	[3.1]	The recommended values of δ_0 has been changed for plated structures.
	[3.3.7.2]	Sentence with SCF = 1.0 for the inside has been removed as this is not always correct.
		The recommended values of δ_0 has been changed for tubular structures.
	[3.3.7.3]	The recommended values of δ_0 has been changed at girth welds in tubular structures with thickness transitions.
	[3.3.9]	Reference has been added to [F.17] with stress concentration factors where the thickness of the conical section is different from the tubular.

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Topic	*Reference*	*Description*
Calculation of hot spot stress by finite element analysis	[4.2]	Text has been added to explain that the dynamic stresses in the chord may increase the hot spot stress at the crown position of tubular joints. Also, a section on relation between stub length and effect on stress concentration factors at tubular joints and at the girth weld to the brace has been added.
	[4.3]	Guidance on hot spot stress derivation in thick plates has been added.
	[4.3.4]	More explanation has been added on stress range calculation where the direction of the stresses can change during a load cycle.
Classification of structural details	[A.2]	Additional text with respect to fabrication tolerances for bolts has been added. The explanation of difference in classification of cut and rolled threads has been improved. The classification of cut threads has been increased from W3 to G.
		A detail with friction welded bolts to base material has been added.
	[A.5]	The text related to δ_0 has been corrected to correspond to the changes made in [3.1] and [3.3.7].
	[A.6]	A detail showing grinding of single side welded joints to achieve C-N class C1 has been added.
	[A.7]	A clarification on potential fatigue cracking has been added.
Stress concentration factors for tubular joints	[B.1]	Equation (6b) and equation (7b) have been corrected. The SCF value for the attachment has been reduced from 1.27 to 1.20.
S-N curves for base material of high strength steel	[D.2]	This section has been revised.
Application of the effective notch stress method for fatigue assessment of structural details	[E.3]	Text has been added to explain that the target value corresponds to a plate thickness equal 25 mm.
Commentary	[F.10]	This section has been revised to be more in line with experience and performed detail analyses.
	[F.12]	This is a new section that has been added for time domain analysis where the principal stress direction changes during a load cycle.
	[F.14]	The text has been revised and an equation for stress concentration factor for the inside has been added.
	[F.17]	A new section on stress concentration factors for conical transitions have been added.

Editorial corrections

In addition to the above stated changes, editorial corrections may have been made.

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SECTION 1 GENERAL

1.1 Introduction

The aim of fatigue design is to ensure that the structure or the structural component has an adequate fatigue life.

The following design methods may be used when assessing fatigue life, where the choice of S-N curve depends on the selected design method:

- Nominal stress method which is typically used where the nominal stresses are well defined from structural analysis
- Hot spot stress method which is typically used in fatigue assessment of details in plated structures analysed by the finite element method
- Notch stress method which is typically used for details where it is difficult to arrive at a reliable design by using one of other methods

Selection of an S-N curve implies certain requirements to fabrication and inspection during fabrication to assure necessary quality to avoid that fatigue crack growth will occur from significant defects. This is further described in DNVGL-OS-C401, NORSOK M-101, ISO 5817:2014.

This recommended practice has been produced with the purpose of assessing fatigue damage in the high cycle region. For low cycle fatigue, see DNVGL-RP-C208.

Calculated fatigue lives also form the basis for efficient inspection programmes during fabrication and the operational life of the structure, see DNVGL-RP-C210.

1.2 Objective

The objective of this recommended practice is to provide methods for fatigue assessment of offshore steel structures and structural components with the aim to ensure safe fatigue design.

1.3 Scope

This recommended practice gives methods for fatigue analyses based on S-N data from testing for the following steel structures and components:

- Fixed and floating steel structures used for exploitation and for production of oil and gas
- Risers and pipelines
- Support structures for wind turbines
- Different types of welded connections
- Cast and forged joints
- Bolted connections
- Connectors
- Small diameter umbilicals made of super duplex steel.

The document specifies and gives guidelines for:

- S-N data in air environment, seawater with cathodic protection and seawater with free corrosion
- stress concentration factors for some details where these can be derived from analytical considerations or from detailed finite element analysis
- simplified fatigue design based on allowable stress ranges for various S-N data and Weibull long-term stress distributions
- the use of various design methods based on nominal stress, hot spot stress or notch stress
- post weld improvement such as grinding, TIG dressing and hammer peening.

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1.4 Application

This recommended practice is valid for carbon manganese steel materials (C-Mn) in air with yield strength less than 960 MPa. For the carbon and low alloy machined forgings for subsea applications in [D.2] the S-N curves are valid for steels with yield strength up to 759 MPa and tensile strength up to 897 MPa in air environment.

For steel (C-Mn) materials in seawater with cathodic protection or steel with free corrosion the recommended practice is valid up to a yield strengh 759 MPa and a tensile strength 897 MPa. This limit applies also to the carbon and low alloy machined forgings for subsea applications in [D.2].

This recommended practice is also valid for bolts in air environment or with protection corresponding to that condition of grades up to 10.9, ASTM A490 or equivalent.

This recommended practice is valid for material temperatures of up to 100°C for C-Mn steels in air condition.

1.5 Definitions

Table 1-1 Definition of verbal forms

Term	*Description*
shall	verbal form used to indicate requirements strictly to be followed in order to conform to the document
should	verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others
may	verbal form used to indicate a course of action permissible within the limits of the document

Table 1-2 Definition of terms

Term	*Definition*
butt weld	a butt weld is used to describe the weld between two plates or tubular sections that can be welded from both sides (double side weld) or from one side (single side weld)
classified structural detail	a structural detail containing a structural discontinuity including a weld or welds, for which the nominal stress approach is applicable, and which appear in the tables of this recommended practice Also referred to as standard structural detail.
constant amplitude loading	a type of loading causing a regular stress fluctuation with constant magnitudes of stress maxima and minima
crack propagation rate	amount of crack propagation during one stress cycle
crack propagation threshold	limiting value of stress intensity factor range below which the stress cycles are considered to be non-damaging
design fatigue factor	factor on fatigue life to be used for design
eccentricity	misalignment of plates at welded connections measured transverse to the plates
effective notch stress	notch stress calculated for a notch with a certain effective notch radius
fatigue action	load effect causing fatigue

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Term	*Definition*
fatigue damage	ratio of number of applied load cycles and the corresponding number of cycles to failure at a constant stress range
fatigue life	number of stress cycles at a particular magnitude required to cause fatigue failure of the component
fatigue limit	fatigue strength under constant amplitude loading corresponding to a high number of cycles large enough to be considered as infinite by a design code
fatigue resistance	structural detail's resistance against fatigue actions in terms of S-N curve or crack propagation properties
fatigue strength	magnitude of stress range leading to a particular fatigue life
fracture mechanics	a branch of mechanics dealing with the behaviour and strength of components containing cracks
geometric stress	see hot spot stress
girth weld	a welded butt weld around the circumference between tubular sections having the same or a similar longitudinal axis (this is not defined as a tubular joint)
hot spot	a point in structure where a fatigue crack may initiate due to the combined effect of structural stress fluctuation and the weld geometry or a similar notch in the base material
hot spot stress	the value of structural stress on the surface at the hot spot (also known as geometric stress or structural stress)
local nominal stress	nominal stress including macro-geometric effects, concentrated load effects and misalignments, disregarding the stress raising effects of the welded joint itself
local notch	a notch such as the local geometry of the weld toe, including the toe radius and the angle between the base plate surface and weld reinforcement The local notch does not alter the structural stress but generates non-linear stress peaks.
macro-geometric discontinuity	a global discontinuity, the effect of which is usually not taken into account in the collection of standard structural details, such as large opening, a curved part in a beam, a bend in flange not supported by diaphragms or stiffeners, discontinuities in pressure containing shells, eccentricity in lap joints
macro-geometric effect	a stress raising effect due to macro-geometry in the vicinity of the welded joint, but not due to the welded joint itself
membrane stress	average normal stress across the thickness of a plate or shell
miner sum	sum of individual fatigue damage ratios caused by each stress cycle or stress range block according to Palmgren-Miner rule
misalignment	axial and angular misalignments caused either by detail design or by fabrication
M-N curve	graphical presentation of the dependence of fatigue life (N) on fatigue moment capacity (M)
nominal stress	a stress in a component, resolved, using general theories such as beam theory
nonlinear stress peak	the stress component of a notch stress which exceeds the linearly distributed structural stress at a local notch

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Term	*Definition*
notch stress	total stress at a notch taking into account the stress concentration caused by the local notch Thus the notch stress consists of the sum of the structural stress and the non-linear stress peak.
notch stress concentration factor	the ratio of notch stress to structural stress
Paris' law	an experimentally determined relation between crack growth rate and stress intensity factor range
Palmgren-Miner rule	fatigue failure is expected when the Miner sum reaches unity See also Sec.9 on uncertainties.
rainflow counting	a standardised procedure for stress range counting
shell bending stress	bending stress in a shell or plate like part of a component, linearly distributed across the thickness as assumed in the theory of shells
S-N curve	graphical presentation of the dependence of fatigue life (N) on fatigue strength (S)
stress cycle	a part of a stress history containing a stress maximum and a stress minimum
stress intensity factor	factor used in fracture mechanics to characterise the stress at the vicinity of a crack tip
stress range	the difference between stress maximum and stress minimum in a stress cycle
stress range block	a part of a total spectrum of stress ranges which is discretized in a certain number of blocks
stress range exceedances	a tabular or graphical presentation of the cumulative frequency of stress range exceedances, i.e. the number of ranges exceeding a particular magnitude of stress range in stress history Here frequency is the number of occurrences.
stress ratio	ratio of minimum to maximum value of the stress in a cycle
structural discontinuity	a geometric discontinuity due to the type of welded joint, usually found in tables of classified structural detail The effects of a structural discontinuity are (i) concentration of the membrane stress and (ii) formation of secondary bending stress.
structural stress	a stress in a component, resolved taking into account the effects of a structural discontinuity, and consisting of membrane and shell bending stress components Also referred to as geometric stress or hot spot stress.
structural stress concentration factor	the ratio of hot spot (structural) stress to local nominal stress In this RP the shorter notation: stress concentration factor (SCF) is used.
tubular joint	welded connection between intersecting tubular members
variable amplitude loading	a type of loading causing irregular stress fluctuation with stress ranges (and amplitudes) of variable magnitude

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1.6 Symbols and abbreviations

Table 1-3 Symbols and abbreviations

Symbol	*Description*
BOP	blowout preventer
C	material parameter
D	accumulated fatigue damage, diameter of chord
DFF	design fatigue factor
D_j	cylinder diameter at junction
E	Young's modulus
EC	eddy current
F	fatigue life
FE	finite element
I	moment of inertia of tubulars
K_{max} K_{min}	maximum and minimum stress intensity factors respectively
K_w	stress concentration factor due to weld geometry
ΔK	K_{max} - K_{min}
L	length of chord, length of thickness transition
MPI	magnetic particle inspection
N	number of cycles to failure
N_i	number of cycles to failure at constant stress range $\Delta\sigma_i$
N	axial force in tubular
NDT	non-destructive testing
R	outer radius of considered chord, reduction factor on fatigue life, stress ratio
SCF	stress concentration factor
SCF_{AS}	stress concentration factor at the saddle for axial load
SCF_{AC}	stress concentration factor at the crown for axial load
SCF_{MIP}	stress concentration factor for in plane moment
SCF_{MOP}	stress concentration factor for out of plane moment
SMTS	specified minimum yield strength
SMYS	specified minimum tensile strength
XT	christmas tree
R_a	surface roughness (mean)

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Symbol	Description
R_T	reduction factor on fatigue resistance due to temperature
R_{y5}	surface roughness (largest amplitude measured in 5 cycles)
R_z	surface roughness (largest amplitude out of 10)
RF	fatigue life reduction factor
T	thickness of chord
T_e	equivalent thickness of chord
T_d	design life in seconds
Q	probability for exceedance of the stress range $\Delta\sigma$
a	crack depth, distance between braces in K-joints
a_i	half crack depth for internal cracks
$\bar{a}$	intercept of the design S-N curve with the log N axis
d	diameter of brace
$e^{-\alpha}$	exp(-α)
g	gap = a/D, factor depending on the geometry of the gap between the brace intersections with the chord in for example a K-joint
h	Weibull shape parameter, weld size or weld leg length
k	number of stress blocks, exponent on thickness
l	segment lengths of a tubular
m	negative inverse slope of the S-N curve, crack growth parameter
n_i	number of stress cycles in stress block i
n_o	is the number of cycles over the time period for which the stress range level $\Delta\sigma_o$ is defined
t_{ref}	reference thickness
t	plate thickness, thickness of brace member
t_c	cone thickness
t_p	plate thickness
Q	Weibull scale parameter
Γ	gamma function
η	usage factor
α	the slope angle of the cone, α = L/D (parameter used in equation for stress concentration factors for T- and Y-joints)
β	d/D
δ	Eccentricity

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Symbol	*Description*
δ_0	eccentricity inherent in the S-N curve
γ	R/T
ν_o	average zero-up-crossing frequency
ν	Poisson's ratio
σ_{local}	local stress
$\sigma_{nominal}$	nominal stress
$\sigma_{hot\ spot}$	hot spot stress or geometric stress
σ_x	maximum nominal stresses due to axial force
$\sigma_{my}\sigma_{mz}$	maximum nominal stresses due to bending about the y-axis and the z-axis
$\Delta\sigma$	stress range
$\Delta\sigma_0$	stress range exceeded once out of n_0 cycles
τ	t/T, shear stress

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SECTION 2 FATIGUE ANALYSIS BASED ON S-N DATA

2.1 Introduction

2.1.1 General

The main principles for fatigue analysis based on fatigue tests are described in this section. The fatigue analysis may be based on nominal S-N curves for plated structures when appropriate. Additional stresses resulting from fabrication tolerances for butt welds and cruciform joints should be considered when the fabrication tolerances exceed that inherent the S-N data, see [3.1] and [3.3].

When performing finite element (FE) analysis for design of plated structures it is often found more convenient to extract hot spot stress from the analysis than that of a nominal stress. Guidance on finite element modelling and hot spot stress derivation is presented in [4.3]. The calculated hot spot stress is then entered a hot spot S-N curve for derivation of cycles to failure. Also here additional stresses resulting from fabrication tolerances for butt welds and cruciform joints should be considered.

For design of simple tubular joints it is standard practice to use parametric equations for derivation of stress concentration factors (SCF) to obtain hot spot stress for the actual geometry. Then this hot spot stress is entered a relevant hot spot stress S-N curve for tubular joints.

Results from performed fatigue analyses are presented in Sec.5 in terms of design charts that present allowable stresses as function of the Weibull shape parameter. The basis for the design charts is that long term stress ranges can be described by a two parameter Weibull distribution. The procedure can be used for different design lives, different design fatigue factors (DFFs) and different plate thickness.

2.1.2 Methods for fatigue analysis

To ensure that the structure will fulfil its intended function, a fatigue assessment, supported where appropriate by a detailed fatigue analysis, should be carried out for each individual member, which is subjected to fatigue loading. See also [2.12]. It should be noted that any element or member of the structure, every welded joint and attachment or other form of stress concentration, is potentially a source of fatigue cracking and should be individually considered.

The fatigue analysis should be based on S-N data, determined by fatigue testing of the considered welded detail, and the linear damage hypothesis. When appropriate, the fatigue analysis may alternatively be based on fracture mechanics. If the fatigue life estimate based on S-N data is short (shorter than 15 years) for a component where a failure may lead to severe consequences, a more accurate investigation considering a larger portion of the structure, or a fracture mechanics analysis, should be performed. For calculations based on fracture mechanics, it should be documented that there is a sufficient time interval between time of crack detection during in-service inspection and the time of unstable fracture.

All significant stress ranges, which contribute to fatigue damage, should be considered. The long term distribution of stress ranges may be found by deterministic or spectral analysis, see also /1/. Dynamic effects shall be duly accounted for when establishing the stress history. A fatigue analysis may be based on an expected stress history, which can be defined as expected number of cycles at each stress range level during the predicted life span. A practical application of this is to establish a long term stress range history that is on the safe side. The part of the stress range history contributing most significantly to the fatigue damage should be most carefully evaluated. See also [F.2] for guidance.

It should be noted that the shape parameter h in the Weibull distribution has a significant impact on calculated fatigue damage. For effect of the shape parameter on fatigue damage see also design charts in Figure 5-1 and Figure 5-2. Thus, when the fatigue damage is calculated based on closed form solutions with an assumption of a Weibull long term stress range distribution, a shape parameter to the safe side should be used.

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2.1.3 Validity

This recommended practice is valid for carbon manganese steel materials (C-Mn) in air with yield strength less than 960 MPa. For the carbon and low alloy machined forgings for subsea applications in [D.2] the S-N curves are valid for steels with yield strength up to 759 MPa and tensile strength up to 897 MPa in air environment.

For steel (C-Mn) materials in seawater with cathodic protection or steel with free corrosion the recommended practice is valid up to a yield strengh 759 MPa and a tensile strength 897 MPa. This limit applies also to the carbon and low alloy machined forgings for subsea applications in [D.2].

This recommended practice is also valid for bolts in air environment or with protection corresponding to that condition of grades up to 10.9, ASTM A490 or equivalent.

This recommended practice may be used for stainless steel.

2.1.4 Temperature

For higher temperatures than 100°C the fatigue resistance data for C-Mn steels in air condition may be modified with a reduction factor given as:

$$R_T = 1.0376 - 0.239 \cdot 10^{-3} T - 1.372 \cdot 10^{-6} T^2 \qquad (2.2.1)$$

where T is given in °C (derived from figure in IIW document XII-1965-03/XV-1127-03). Fatigue resistance is understood to mean strength capacity. The reduced resistance in the S-N curves can be derived by a modification of the $\log \bar{a}$ as:

$$Log\,\bar{a}_{RT} = Log\,\bar{a} + m\,Log\,R_T \qquad (2.2.2)$$

2.1.5 Low cycle and high cycle fatigue

This recommended practice has been produced with the purpose of assessing fatigue damage in the high cycle region. See also [F.1]. For low cycle fatigue see DNVGL-RP-C208.

2.1.6 Requirements to fabrication

Selection of an S-N curve implies certain requirements to fabrication and inspection during fabrication to assure necessary quality that fatigue crack growth will not occur from significant defects. See DNVGL-OS-C401, NORSOK M-101, ISO 5817:2014 and [F.6].

2.1.7 Fatigue failure modes

The following fatigue cracking failure modes are considered in this document, see also Figure 2-1:

— Fatigue crack growth from the weld toe into the base material.

  In welded structures fatigue cracking from weld toes into the base material is a frequent failure mode. The fatigue crack is initiated at small defects or undercuts at the weld toe where the stress is highest due to the weld notch geometry. A large amount of the content in this RP is made with the purpose of achieving a reliable design with respect to this failure mode.

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— Fatigue crack growth from the weld root through the fillet weld.

  Fatigue cracking from root of fillet welds with a crack growth through the weld is a failure mode that can lead to significant consequences. Use of fillet welds should be avoided in connections where the failure consequences are large due to less reliable non-destructive examination (NDE) of this type of connection compared with a full penetration weld. However, in some welded connections use of fillet welds can hardly be avoided and it may also be efficient for fabrication. The specified design procedure in this document is considered to provide reliable connections also for fillet welds.

— Fatigue crack growth from the weld root into the section under the weld.

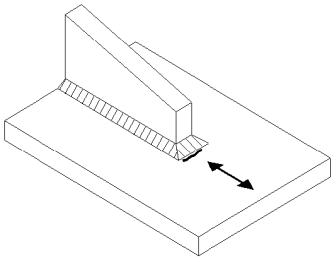
  Fatigue crack growth from the weld root into the section under the weld is observed during service life of structures and in laboratory fatigue testing. The number of cycles to failure for this failure mode is of a similar magnitude as fatigue cracking from the weld toe in as-welded condition. There is no methodology that can be recommended used to avoid this failure mode except from using alternative types of welds locally. This means that if fatigue life improvement of the weld toe is required, the connection is subjected to high dynamic stress ranges. Thus, the connection becomes also highly utilised with respect to dynamic loading and it is also required to make improvement for the root. This can be performed using a full penetration weld along some distance of the stiffener nose.

— Fatigue crack growth from a surface irregularity or notch into the base material.

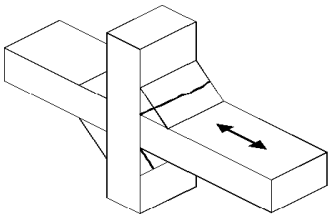
  Fatigue cracking in the base material is a failure mode that is of concern in components with high stress cycles. Then the fatigue cracks often initiate from notches or grooves in the components or from small surface defects/irregularities. The specified design procedure in this document is considered to provide reliable connections also with respect to this failure mode.

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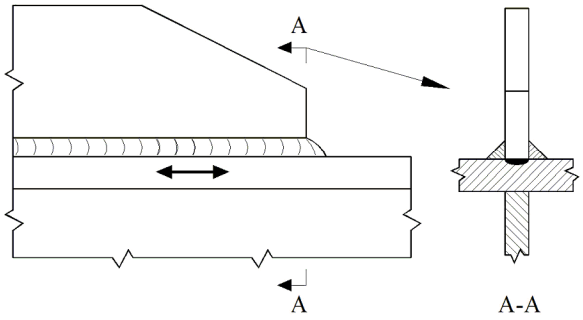
a) Fatigue crack growth from the weld toe into the base material.



b) Fatigue crack growth from the weld root through the fillet weld.



c) Fatigue crack growth from the weld root into the section under the weld.



d) Fatigue crack growth from a surface irregularity or notch into the base material.

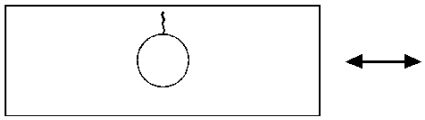


Figure 2-1 Explanation of different fatigue failure modes

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2.2 Fatigue damage accumulation

The fatigue life may be calculated based on the S-N fatigue approach under the assumption of linear cumulative damage (Palmgren-Miner rule).

When the long-term stress range distribution is expressed by a stress histogram, consisting of a convenient number of constant stress range blocks $\Delta\sigma_i$ each with a number of stress repetitions n_i the fatigue criterion reads:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{1}{\bar{a}} \sum_{i=1}^{k} n_i \cdot (\Delta\sigma)^m \leq \eta = \frac{1}{DFF} \qquad (2.2.1)$$

where:

D = accumulated fatigue damage

$\bar{a}$ = intercept of the design S-N curve with the log N axis

m = negative inverse slope of the S-N curve

k = number of stress blocks

n_i = number of stress cycles in stress block i

N_i = number of cycles to failure at constant stress range $\Delta\sigma_i$

η = usage factor
1/design fatigue factor from DNVGL-OS-C101 Ch.2 Sec.5 [1.2] *Design fatigue factors*.

DFF = design fatigue factor.

Applying a histogram to express the stress distribution, the number of stress blocks, k, should be large enough to ensure reasonable numerical accuracy, and should not be less than 20. Due consideration should be given to selection of integration method as the position of the integration points may have a significant influence on the calculated fatigue life dependent on integration method.

See Sec.5 for calculation of fatigue damage using design charts based on a two-parameter Weibull distribution of the long term stress ranges.

See [F.3] for derivation of fatigue damage calculated from different processes.

2.3 Fatigue analysis methodology and calculation of stresses

2.3.1 General

Fatigue analysis may be based on different methodologies depending on what is found most efficient for the considered structural detail. Different concepts of S-N curves are developed and referred to in the literature and in this RP. It is thus important that the stresses are calculated in agreement with the definition of the stresses to be used together with a particular S-N curve. Three different concepts of S-N curves are defined:

— Nominal stress S-N curve that is described in [2.3.2].
— Hot spot stress S-N curve that is described in [2.3.3] for plated structures and in [2.3.4] for tubular joints.
— Notch stress S-N curve that is presented in App.E. This notch stress S-N curve can be used together with finite element analysis where the local notch is modelled by an equivalent radius. This approach is

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foreseen used only in special cases where it is found difficult to reliably assess the fatigue life using other methods, see App.E for more guidance.

Nominal stress is understood to be a stress in a component that can be derived by classical theory such as beam theory. In a simple plate specimen with an attachment as shown in Figure 4-2 the nominal stress is simply the membrane stress that is used for plotting the S-N data from the fatigue testing. An example of fatigue design using this procedure is shown in the commentary section (example with fatigue analysis of a drum in [F.13]).

Hot spot stress is understood to be the geometric stress created by the considered detail. (The notch stress due to the local weld geometry is excluded from the stress calculation as it is assumed to be accounted for in the corresponding hot spot S-N curve. The notch stress is defined as the total stress resulting from the geometry of the detail and includes the non-linear stress field due to the notch at the weld toe).

Derivation of stresses to be used together with the different S-N curves are described in more detail in the following section.

The procedure for the fatigue analysis is based on the assumption that it is only necessary to consider the ranges of cyclic stresses in determining the fatigue endurance (i.e. mean stresses are neglected for fatigue assessment of welded connections due to presence of residual stresses).

The presence of residual tensile stresses at welds means also that compressive stress ranges may result in fatigue crack initiation and further fatigue crack growth until the crack has grown out of the tensile stress field. This means that also the stress range resulting from the minimum principal stress may need to be analysed in addition to the stress range from the maximum principal stress, see e.g. [4.3.4].

The selection of S-N curve is dependent on amount and type of inspection during fabrication, see App.A. The size of defects inherent the S-N data are described in [F.5].

2.3.2 Plated structures using nominal stress S-N curves

The joint classification and corresponding S-N curves takes into account the local stress concentrations created by the joints themselves and by the weld profile. The design stress can therefore be regarded as the nominal stress, adjacent to the weld under consideration. However, if the joint is situated in a region of stress concentration resulting from the gross shape of the structure, this shall be taken into account. As an example, for the weld shown in Figure 2-2 a), the relevant local stress for fatigue design would be the tensile stress, $\sigma_{nominal}$. For the weld shown in Figure 2-2 b), the stress concentration factor for the global geometry shall in addition be accounted for, giving the relevant local stress equal to SCF · $\sigma_{nominal}$, where SCF is the stress concentration factor due to the hole. Thus the local stress is derived as:

$$\sigma_{local} = SCF\, \sigma_{nominal} \qquad (2.3.1)$$

σ_{local} shall be used together with the relevant S-N curves D through G, dependent on joint classification (as welded condition with potential fatigue crack growth from the weld toe).

The maximum principal stress is considered to be a significant parameter for analysis of fatigue crack growth. When the principal stress direction is different from that of the normal to the weld toe, it becomes conservative to use the principle stress range together with a classification of the connection for stress range normal to the weld toe as shown in Figure 2-3. As the angle between the principal stress direction and the normal to the weld, φ, is increased further, fatigue cracking may no longer initiate along the weld toe, but may initiate in the weld and grow normal to the principal stress direction as shown in Figure 2-4. This means that the notch at the weld toe no longer significantly influences the fatigue capacity and a higher S-N curve applies for this stress direction.

For welded details, in the as welded condition, one can calculate separate fatigue damages for fatigue cracking along the weld toe and transverse to the weld toe. An example of this is shown in [F.11].

More guidance on this for use of nominal S-N curves is presented in [F.4]

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Stress ranges calculated based on von Mises form of component stress ranges can be used for fatigue analysis of notches in base material where initiation of a fatigue crack is a significant part of the fatigue life. More information on this is presented in [D.2].

2.3.3 Plated structures using hot spot stress S-N curves

For detailed finite element analysis of welded plate connections other than tubular joints it may also be convenient to use the alternative hot spot stress for fatigue life assessment, see [4.3] for further guidance. A relation between nominal stress and hot spot stress may be defined as:

$$\sigma_{hot\ spot} = SCF\,\sigma_{nominal} \qquad (2.3.2)$$

where SCF is structural stress concentration factor normally denoted as stress concentration factor.

The effect of stress direction relative to the weld toe as shown in Figure 2-3 and Figure 2-4 when using finite element analysis and hot spot stress S-N curve is presented in [4.3.4].

2.3.4 Tubular joints

For a tubular joint, i.e. brace to chord connection, the stress to be used for design purpose is the range of idealised hot spot stress defined by: the greatest value of the extrapolation of the maximum principal stress distribution immediately outside the region effected by the geometry of the weld. The hot spot stress to be used in combination with the T-curve is calculated as:

$$\sigma_{hot\ spot} = SCF\,\sigma_{nominal} \qquad (2.3.3)$$

where:

SCF = stress concentration factor as given in [3.3].

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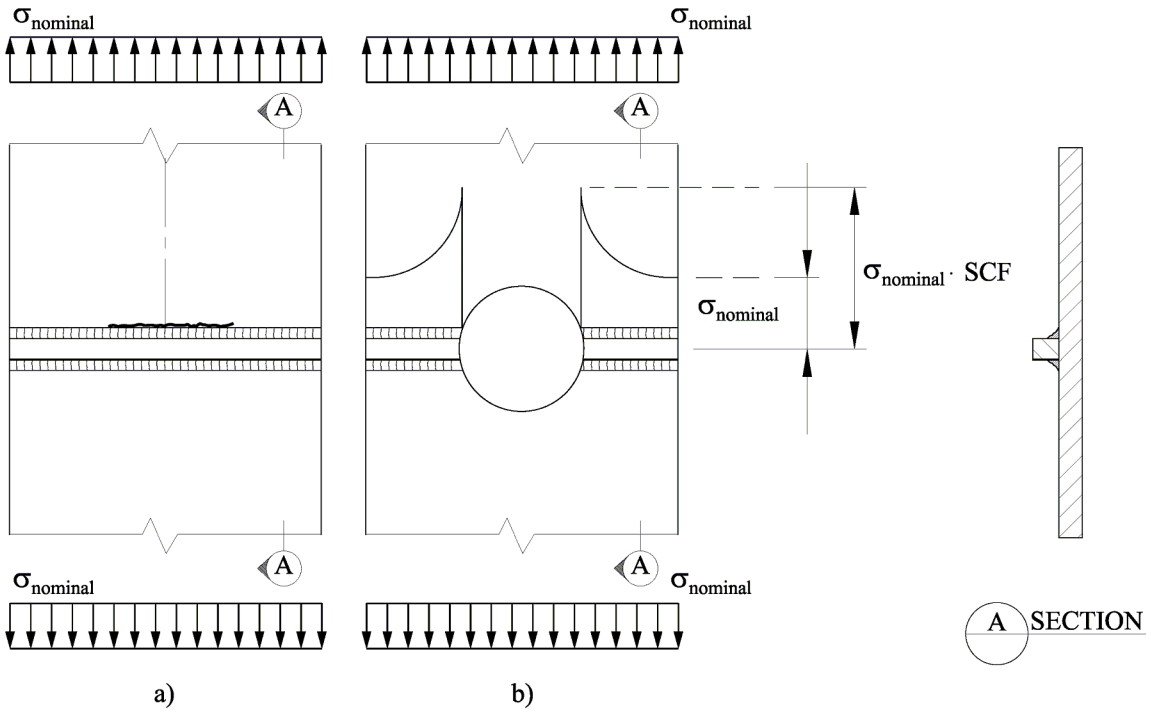


Figure 2-2 Explanation of local stresses

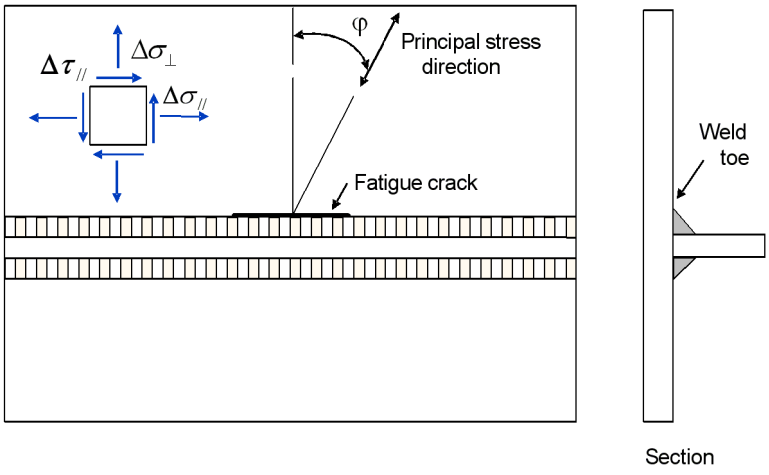


Figure 2-3 Fatigue cracking along weld toe

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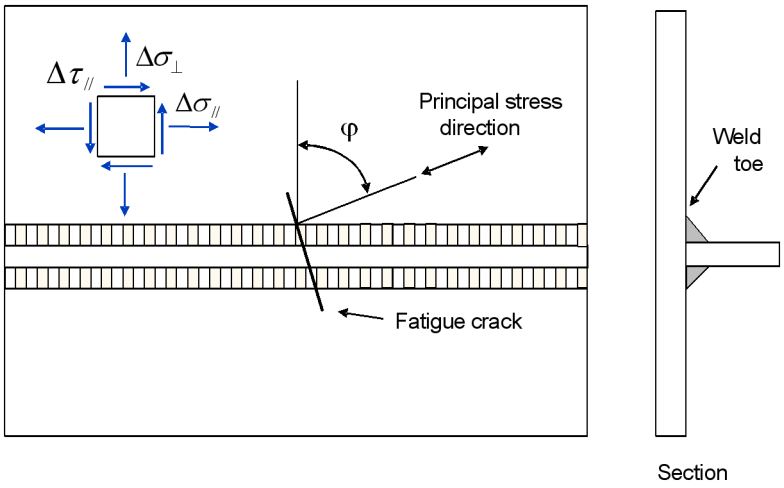


Figure 2-4 Fatigue cracking when principal stress direction is more parallel with weld toe

2.3.5 Fillet welds at load carrying joints

The relevant stress range for potential cracks in the weld throat of load-carrying fillet-welded joints and partial penetration welded joints may be calculated as:

$$\Delta\sigma_w = \sqrt{\Delta\sigma_{\perp}^2 + \Delta\tau_{\perp}^2 + 0.2\Delta\tau_{//}^2} \qquad (2.3.4)$$

where the stress components are explained in Figure 2-5.

The total stress fluctuation (i.e. maximum compression and maximum tension) should be considered to be transmitted through the welds for fatigue assessments.

See Table A-8 for selection of S-N curve.

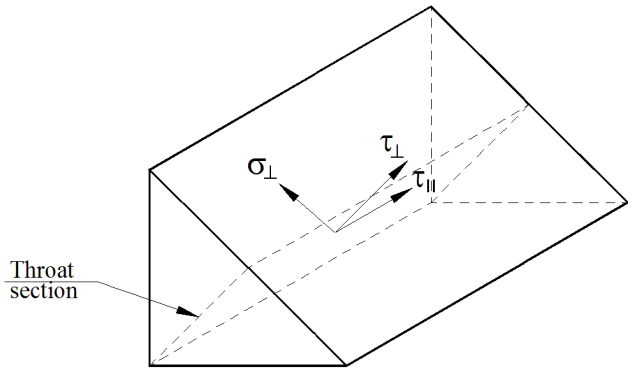


Figure 2-5 Explanation of stresses on the throat section of a fillet weld

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2.3.6 Fillet welds at doubling plates

Fillet welds at doubling plates as shown in Figure 2-6 will be subjected to bending stress over the throat thickness when the doubling plate is loaded by an axial force or a bending moment. It is recommended to perform a finite element analysis for assessment of fatigue of these connections. The bending stress can be analysed using a modelling of the weld with at least 2 second order solid elements over the throat thickness where each element represents a linear stress distribution. The calculated stress components at a position 0.25 a and 0.75 a, where a is throat thickness, can be extrapolated to the weld root where these stresses are used to calculate the principal stress. The range of the maximum principal stress can then be used together with the F3 curve for calculation of fatigue damage. The S-N curve for air environment can be used for fatigue assessment if there is a closure weld all around the detail.

Alternatively the notch stress methodology described in App.E can be used for fatigue analysis of the weld root.

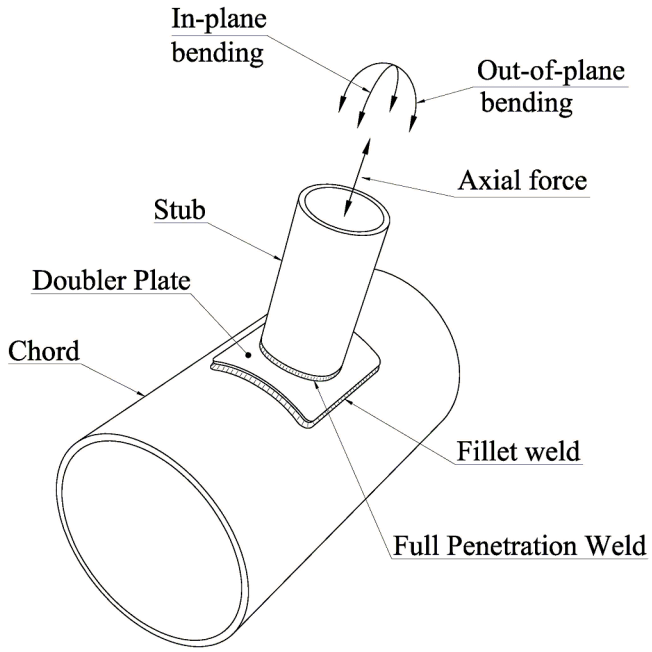


Figure 2-6 Fillet welded doubling plate

2.3.7 Fillet welded bearing supports

Where support plating below bearings are designed with fillet welded connection, it should be verified that fatigue cracking of the weld will not occur. Even though the joint may be required to carry wholly compressive stresses and the plate surfaces may be machined to fit, the total stress fluctuation should be considered to be transmitted through the welds for fatigue assessment.

If it is assumed that compressive loading is transferred through contact, it should be verified that the contact will not be lost during the welding. The actual installation condition including maximum construction tolerances should be accounted for.

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2.4 S-N curves

2.4.1 General

The fatigue design is based on use of S-N curves, which are obtained from fatigue tests. The design S-N curves which follows are based on the mean-minus-two-standard-deviation curves for relevant experimental data. The S-N curves are thus associated with a 97.7% probability of survival.

2.4.2 Failure criterion inherent the S-N curves

Most of the S-N data are derived by fatigue testing of small specimens in test laboratories. For simple test specimens the testing is performed until the specimens have failed. In these specimens there is no possibility for redistribution of stresses during crack growth. This means that most of the fatigue life is associated with growth of a small crack that grows faster as the crack size increases until fracture if the connection otherwise does not show significant redistribution of stress flow during crack growth.

For details with the same calculated damage, the initiation period of a fatigue crack takes longer time for a notch in base material than at a weld toe or at a weld root. This also means that with a higher fatigue resistance of the base material as compared with welded details, the crack growth will be faster in base material when fatigue cracks are growing as the stress range in the base material may be significantly higher than at the welds if they are designed with the same fatigue utilization.

For practical purpose one defines these failures as being crack growth through the thickness.

When this failure criterion is transferred into a crack size in a real structure where some redistribution of stress is more likely, this means that this failure criterion corresponds to a crack size that is somewhat less than the plate thickness.

The test specimens with tubular joints are normally of a larger size. These joints also show larger possibility for redistribution of stresses as a crack is growing. Thus a crack can grow through the thickness and also along a part of the joint before a fracture occur during the testing. The number of cycles at a crack size through the thickness is used when the S-N curve for tubular joints is derived. As these tests are not very different from that of the actual behaviour in a structure, this failure criterion for the S-N curve for tubular joints corresponds approximately to the thickness at the hot spot (chord or brace as relevant).

2.4.3 S-N curves and joint classification for plated structures

For practical fatigue design, welded joints are divided into several classes, each with a corresponding design S-N curve. All tubular joints are assumed to be class T as specified in Table 2-3. Other types of joint, including tube to plate, may fall in one of the 14 classes specified in Table 2-1, Table 2-2 and Table 2-4, depending upon:

— the geometrical arrangement of the detail
— the direction of the fluctuating stress relative to the detail
— the method of fabrication and inspection of the detail.

Each construction detail at which fatigue cracks may potentially develop should, where possible, be placed in its relevant joint class in accordance with criteria given in App.A. It should be noted that, in any welded joint, there are several locations at which fatigue cracks may develop, e. g. at the weld toe in each of the parts joined, at the weld ends, and in the weld itself. Each location should be classified separately.

The basic design S-N curve is given as:

$$\log N = \log \bar{a} - m \log \Delta\sigma \qquad (2.4.1)$$

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N = predicted number of cycles to failure for stress range Δσ

$\Delta\sigma$ = stress range with unit [MPa]

m = negative inverse slope of S-N curve

$log\bar{a}$ = intercept of the design S-N curve with the log N-axis by S-N curve.

$$\log\bar{a} = \log a - 2 s_{\log N} \qquad (2.4.2)$$

where:

$log\ a$ = intercept of mean S-N curve with the log N axis

s_{logN} = standard deviation of log N, see [F.5].

The fatigue strength of welded joints is to some extent dependent on plate thickness. This effect is due to the local geometry of the weld toe in relation to thickness of the adjoining plates. See also effect of profiling on thickness effect in [7.2]. It is also dependent on the stress gradient over the thickness, see [F.5]. The thickness effect is accounted for by a modification of the stress range such that the design S-N curve for thickness larger than the reference thickness reads:

$$\log N = \log \bar{a} - m \log\left(\Delta\sigma\left(\frac{t}{t_{ref}}\right)^{k}\right) \qquad (2.4.3)$$

where:

t_{ref} = reference thickness equal 25 mm for welded connections other than simple tubular joints. For simple tubular joints the reference thickness is 16 mm when using the T-curve. The reference thickness is equal 25 mm when other S-N curves are used for fatigue analysis of tubular joints. For bolts t_{ref} = 25 mm

t = thickness through which a crack will most likely grow. t = t_{ref} is used for thickness less than t_{ref}

k = thickness exponent on fatigue strength as given in Table 2-1, Table 2-2, Table 2-3 and Table 2-4.

k = 0.10 for tubular girth welds made from one side with fatigue cracking from the weld root

k = 0.25 for threaded bolts subjected to stress variation in the axial direction.

In general the thickness exponent is included in the design equation to account for a situation that the actual size of the considered structural component is different in geometry from that the S-N data are based on. The thickness exponent is considered to account for different size of plate through which a crack will most likely grow. To some extent it also accounts for local geometry at the weld toe. However, it does not account for weld length or length of component different from that tested such as e.g. design of mooring systems with a significant larger number of chain links in the actual mooring line than what the test data are based on. Then the size effect should be carefully considered using probabilistic theory to achieve a reliable design, see [F.5].

The thickness or size effect is also dependent on width of butt welds and attachment length in cruciform connections. This parameter is denoted L_t in Figure 2-7. For butt welds where the widths L_t may be different

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on the two plate sides, the width L_t for the considered hot spot side should be used. The size effect is lower than predicted from equation (2.4.3) for short lengths of L_t. Thus the thickness t in equation (2.4.3) for butt welds and cruciform joints may be replaced by an effective thickness t_{eff} which may be derived as:

$$t_{eff} = \min\left((14mm + 0.66L_t), T\right) \qquad (2.4.4)$$

where the parameters L and T are measured in [mm] and are defined in Figure 2-7. t_{eff} should not be less than t_{ref}. It should be noted that the width L_t for butt weld may be somewhat wider than that of the weld groove depending on the welding process. Also the possibility for weld repair should be considered when the width L_t to be used for fatigue analysis is decided.

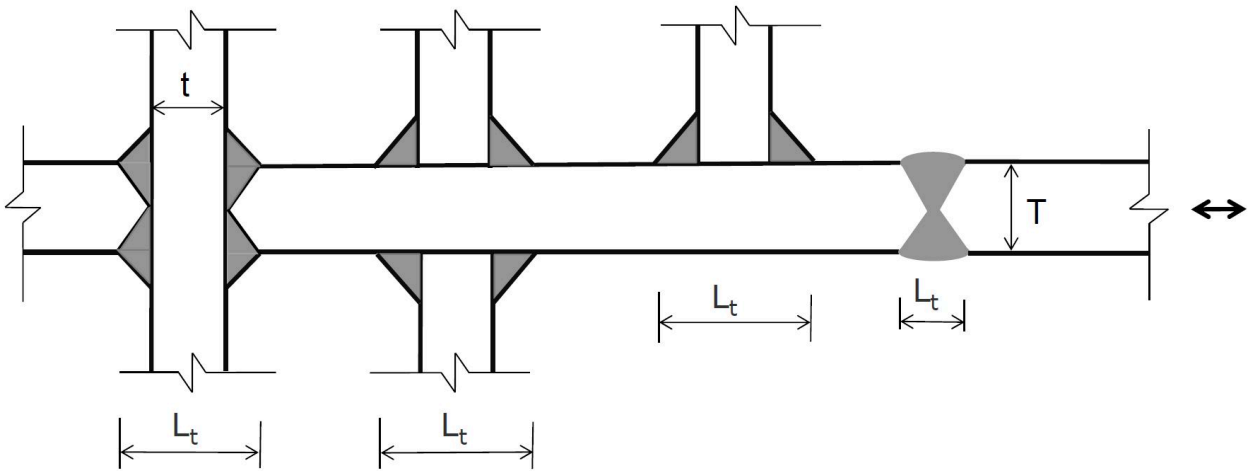


Figure 2-7 Definition of attachment length in cruciform joints and weld width in butt welds

2.4.4 S-N curves in air

S-N curves for air environment are given in Table 2-1 and Figure 2-8. The T curve for tubular joints is shown in Table 2-3 and Figure 2-10.

The maximum stress range is that of the B1 curve as shown in Figure 2-8. However, for offshore structures subjected to typical wave and wind loading the main contribution to fatigue damage is in the region N > 10^6 cycles and the bilinear S-N curves defined in Table 2-1 can be used.

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Table 2-1 S-N curves in air

S-N curve	$N \leq 10^7$ cycles		$N > 10^7$ cycles	Fatigue limit at 10^7 cycles [MPa] *)	Thickness exponent k	Structural stress concentration embedded in the detail (S-N class), see also equation (2.3.2)
	m_1	$\log \bar{a}_1$	$\log \bar{a}_2$ $m_2 = 5.0$			
B1	4.0	15.117	17.146	106.97	0	
B2	4.0	14.885	16.856	93.59	0	
C	3.0	12.592	16.320	73.10	0.05	
C1	3.0	12.449	16.081	65.50	0.10	
C2	3.0	12.301	15.835	58.48	0.15	
D	3.0	12.164	15.606	52.63	0.20	1.00
E	3.0	12.010	15.350	46.78	0.20	1.13
F	3.0	11.855	15.091	41.52	0.25	1.27
F1	3.0	11.699	14.832	36.84	0.25	1.43
F3	3.0	11.546	14.576	32.75	0.25	1.61
G	3.0	11.398	14.330	29.24	0.25	1.80
W1	3.0	11.261	14.101	26.32	0.25	2.00
W2	3.0	11.107	13.845	23.39	0.25	2.25
W3	3.0	10.970	13.617	21.05	0.25	2.50

*) See also [2.12].

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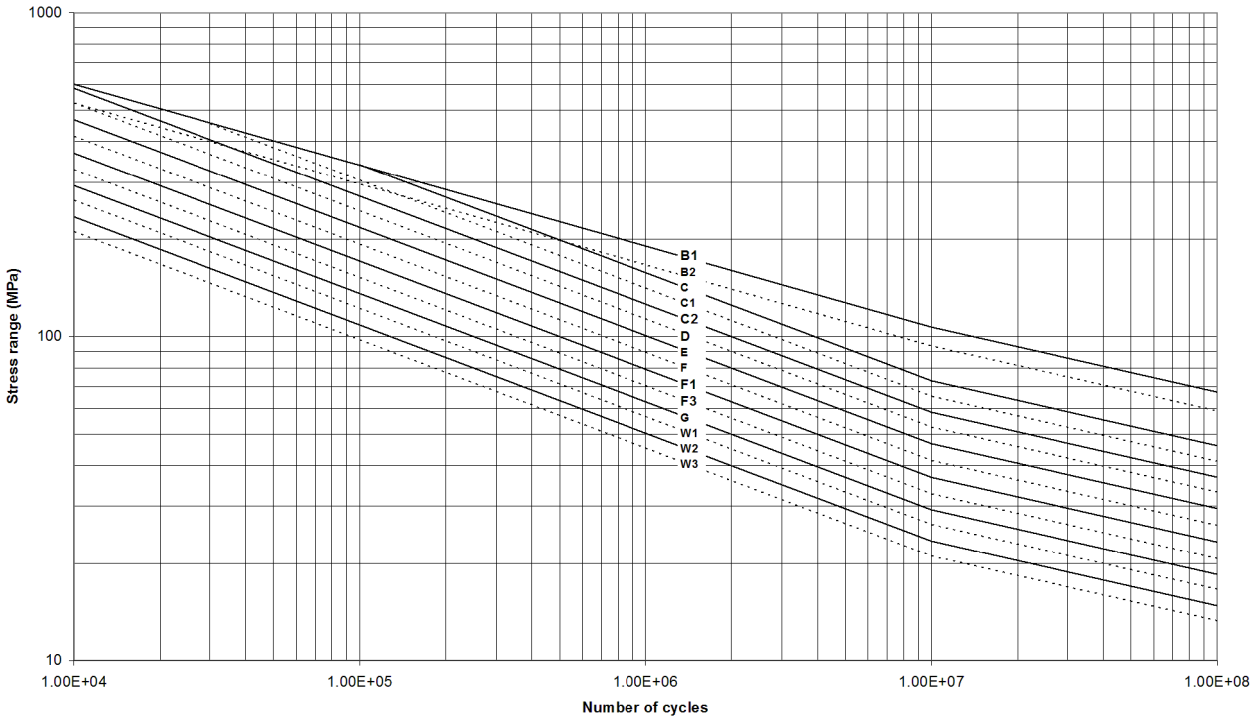


Figure 2-8 S-N curves in air

2.4.5 S-N curves in seawater with cathodic protection

S-N curves for seawater environment with cathodic protection are given in Table 2-2 and Figure 2-9. The T curve is shown in Table 2-3 and Figure 2-10. For shape of S-N curves see also comment in [2.4.4].

Table 2-2 S-N curves in seawater with cathodic protection

S-N curve	*$N \le 10^6$ cycles*		*$N > 10^6$ cycles*	*Fatigue limit at 10^7 cycles [MPa] *)*	*Thickness exponent k*	*Structural stress concentration embedded in the detail (S-N class), see also equation (2.3.2)*
	m_1	$\log \bar{a}_1$	$\log \bar{a}_2$ *$m_2 = 5.0$*			
B1	4.0	14.917	17.146	106.97	0	
B2	4.0	14.685	16.856	93.59	0	
C	3.0	12.192	16.320	73.10	0.05	
C1	3.0	12.049	16.081	65.50	0.10	
C2	3.0	11.901	15.835	58.48	0.15	
D	3.0	11.764	15.606	52.63	0.20	1.00
E	3.0	11.610	15.350	46.78	0.20	1.13

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S-N curve	$N \le 10^6$ cycles		$N > 10^6$ cycles	Fatigue limit at 10^7 cycles [MPa] *)	Thickness exponent k	Structural stress concentration embedded in the detail (S-N class), see also equation (2.3.2)
	m_1	$\log \bar{a}_1$	$\log \bar{a}_2$ $m_2 = 5.0$			
F	3.0	11.455	15.091	41.52	0.25	1.27
F1	3.0	11.299	14.832	36.84	0.25	1.43
F3	3.0	11.146	14.576	32.75	0.25	1.61
G	3.0	10.998	14.330	29.24	0.25	1.80
W1	3.0	10.861	14.101	26.32	0.25	2.00
W2	3.0	10.707	13.845	23.39	0.25	2.25
W3	3.0	10.570	13.617	21.05	0.25	2.50
*) See also [2.12].						

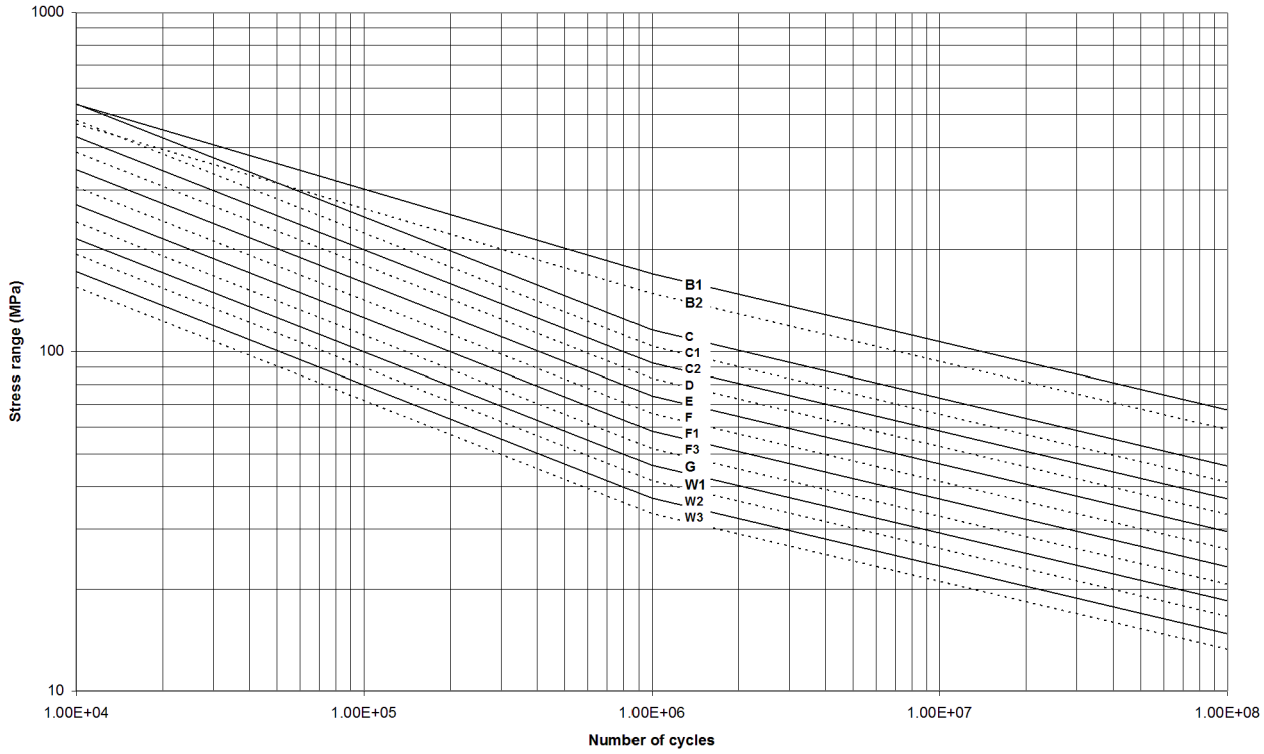


Figure 2-9 S-N curves in seawater with cathodic protection

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2.4.6 S-N curves for tubular joints

S-N curves for tubular joints in air environment, seawater with cathodic protection and free corrosion are given in Table 2-3 and Figure 2-10. These S-N curves are denoted T-curves and apply to the outside hot spots at tubular joints. The T-curves are used for the outside hot spots for tubular joints that are welded from both outside and inside as well as for tubular joints welded from the outside only. Only the outside of a tubular joint needs to be assessed with respect to fatigue when it is welded from both outside and inside. The reference thickness is 16 mm for these S-N curves. For tubular joints welded from outside only see [3.3.3]. The reference thickness for S-N curves used for the weld root in tubular joints welded from the outside only is listed in [2.4.3].

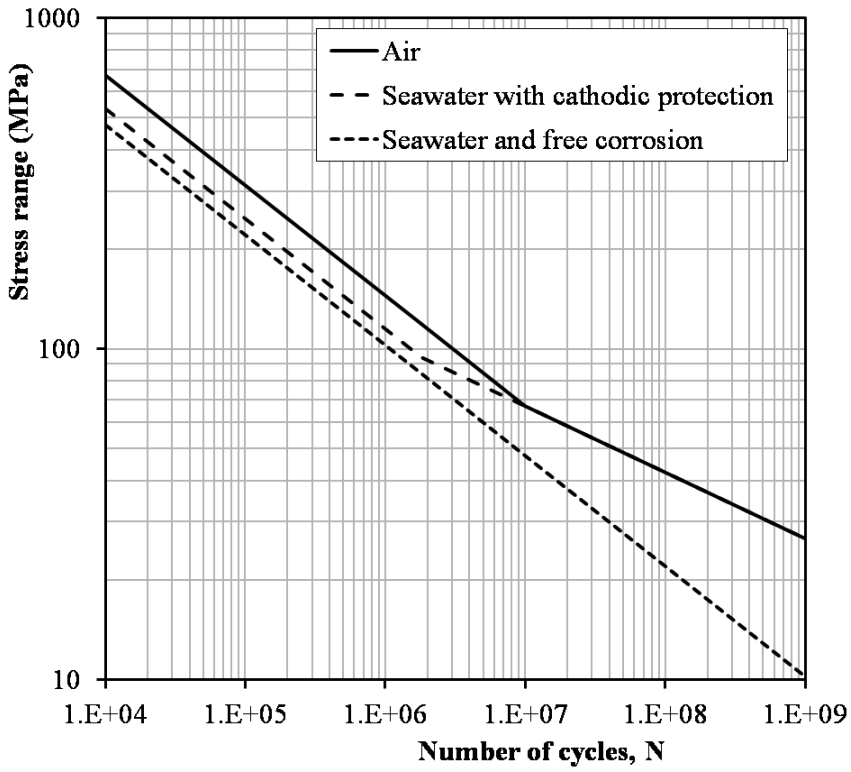


Figure 2-10 S-N curves for tubular joints in air and in seawater with cathodic protection

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Table 2-3 S-N curves for tubular joints

Environment	m_1	$\log \bar{a}_1$	m_2	$\log \bar{a}_2$	*Fatigue limit at 10^7 cycles [MPa]*)*	*Thickness exponent k*
Air	N ≤ 10^7 cycles		N > 10^7 cycles			
	3.0	12.48	5.0	16.13	67.09	0.25
Seawater with cathodic protection	N ≤ $1.8 \cdot 10^6$ cycles		N > $1.8 \cdot 10^6$ cycles			
	3.0	12.18	5.0	16.13	67.09	0.25
Seawater free corrosion	3.0	12.03	3.0	12.03	0	0.25
*) See also [2.12].						

2.4.7 S-N curves for cast nodes

It is recommended to use the C-curve for cast nodes. Tests may give a more optimistic curve. However, the C-curve is recommended in order to allow for weld repairs after possible casting defects and possible fatigue cracks after some service life. The probability of a repair during service life depends on accumulated fatigue damage. See [9.1] and Figure 9-3 which indicates fatigue failure probability as function of the design fatigue factor that is used.

For cast nodes a reference thickness t_{ref} = 38 mm may be used provided that any possible repair welds have been ground to a smooth surface.

For cast nodes with a stress gradient over the thickness a reduced effective thickness may be used for assessment of thickness effect. The effective thickness to be used in equation (2.4.3) can be calculated as:

$$t_e = t_{actual}\left(\frac{S_i}{S_0}\right)^{1/k} \qquad (2.4.5)$$

where:

S_0 = hot spot stress range on surface
S_i = stress range 38 mm below the surface, under the hot spot
t_{actual} = thickness of cast piece at considered hot spot measured normal to the surface
t_e = effective thickness. t_e shall not be less than 38 mm
k = thickness exponent = 0.15.

2.4.8 S-N curves for forged nodes

The B1 curve may be used for forged nodes designed with a design fatigue factor equal to 10. For designs with DFF less than 10 it is recommended to use the C-curve to allow for weld repair if fatigue cracks should occur during service life.

2.4.9 S-N curves for free corrosion in plated structures

S-N curves for free corrosion in plated structures, i.e. without corrosion protection, are given in Table 2-4.

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See also [F.6] for consideration of corrosion protection of connections in the splash zone and inside tanks in FPSOs.

Table 2-4 S-N curves in seawater for free corrosion

S-N curve	$\log \bar{a}$ *For all cycles m = 3.0*	*Thickness exponent k*
B1	12.436	0
B2	12.262	0
C	12.115	0.15
C1	11.972	0.15
C2	11.824	0.15
D	11.687	0.20
E	11.533	0.20
F	11.378	0.25
F1	11.222	0.25
F3	11.068	0.25
G	10.921	0.25
W1	10.784	0.25
W2	10.630	0.25
W3	10.493	0.25

2.4.10 S-N curves for base material of high strength steel

The fatigue capacity of the base material is depending on the surface finish of the final component and its yield and tensile strength. S-N curves for components of high strength steel with yield strength above 500 MPa subjected to high mean tensile stress such as in tether connectors are presented in [D.1].

S-N curves for high strength steel for subsea applications are presented in [D.2].

2.4.11 S-N curves for stainless steel

For duplex and for super duplex steel one may use the same classification as for C-Mn steels.

Also for austenitic steel one may use the same classification as for C-Mn steels.

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2.4.12 S-N curves for small diameter umbilicals

For fatigue design of small diameter pipe umbilicals (outer diameter in the range 10 -100 mm) made of super duplex steel with a yield strength larger than 500 MPa with thicknesses in the range 1.0 to 10 mm the following S-N curve can be used for fatigue assessment:

$$
\begin{aligned}
&For\ N \le 10^7: \\
&\log N = 15.301 - 4.0 \log\left\{\Delta\sigma \left(\frac{t}{t_{ref}}\right)^{0.25}\right\} \\
&and\ for\ N > 10^7 \\
&\log N = 17.376 - 5.0 \log\left\{\Delta\sigma \left(\frac{t}{t_{ref}}\right)^{0.25}\right\}
\end{aligned}
\qquad (2.4.6)
$$

where:

t = actual thickness of the umbilical

t_{ref} = 1.0 mm.

A normal good fabrication of the umbilicals is assumed as basis for this design S-N curve. The welds on the inside and outside of the pipes should show a smooth transition from the weld to the base material without notches and/or undercuts. A detailed NDE inspection for each connection is assumed.

The NDE methods are visual inspection and X-ray. For single pass welds, no indications are acceptable. For multipass welds the acceptance criteria shall be according to ASME B31.3, chapter IX high pressure service girth groove. Dye penetrant shall be used as a surface test in addition to visual inspection when relevant indications, as defined by ASME VIII div. 1, app.4. are found by X-ray.

The S-N curve is based on fatigue testing of specimens subjected to a mean stress up to 450 MPa.

The given S-N curve is established from test specimens that are not prestrained from reeling. However, based on a few test data with prestrained specimens it is considered acceptable to use the S-N curve also for umbilicals that have been reeled. Thus this S-N curve applies also when number of cycles under reeling is less than 10 and the total strain range during reeling is less than 2%.

The following design S-N curve can be used for the base material of umbilical tubes:

$$
\begin{aligned}
&For\ N \le 10^7: \\
&\log N = 15.301 - 4.0 \log \Delta\sigma \\
&and\ for\ N > 10^7 \\
&\log N = 17.376 - 5.0 \log \Delta\sigma
\end{aligned}
\qquad (2.4.7)
$$

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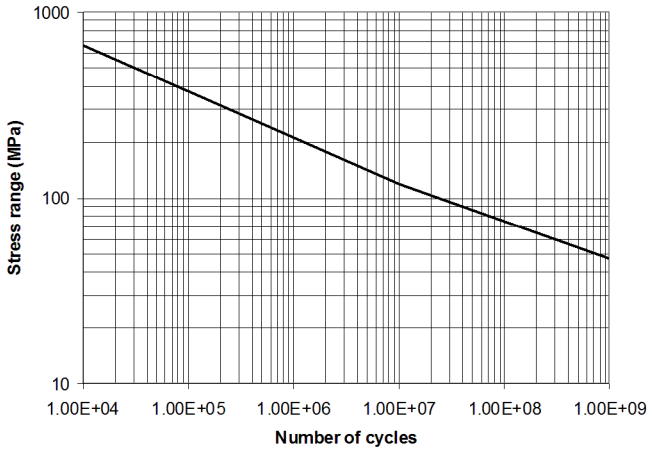


Figure 2-11 S-N curve for small diameter pipe for umbilicals

2.4.13 S-N data for piles

The transition of the weld to base material on the outside of tubular girth welds can normally be classified to S-N curve E. If welding is performed in a flat position, it can be classified as D. If welding is performed from outside only, it should be classified as F3 for the weld root.

S-N curve E applies to weld beads.

S-N data corresponding to air environment condition can be used for the pile driving phase.

S-N data corresponding to environment of seawater with cathodic protection can be used for the operational life when the structure above the mud line is cathodically protected.

The effect of toe grinding is described in [7.3] and [F.15]. When flush grinding of the weld is performed, the improvement is obtained through use of a better S-N curve as presented in Table A-5.

2.4.14 Qualification of new S-N curves based on fatigue test data

For qualification of new S-N data to be used in a project it is important that the test specimens are representative for the actual fabrication and construction. This includes possibility for relevant production defects as well as fabrication tolerances. The sensitivity to defects may also be assessed by fracture mechanics.

For new types of connections it is recommended to perform testing of at least 15 specimens in order to establish a new S-N curve. At least three different stress ranges should be selected in the relevant S-N region such that a representative slope of the S-N curve can be determined, see [F.7], for a broader assessment of how to derive S-N curves from few fatigue test data.

See also /55/, /76/, /86/, /89/ for statistical analysis of the fatigue test data. Normally fatigue test data are derived for number of cycles less than 10^7. It should be noted that for offshore structures significant fatigue damage occurs for $N \geq 10^7$ cycles. Thus how to extrapolate the fatigue test data into this high cycle region is important in order to achieve a reliable assessment procedure. In addition to statistical analysis one should use engineering judgement based on experience for derivation of the S-N data in this region. It is well known that good details where fatigue initiation contribute significantly to the fatigue life show a more horizontal S-N curve than for less good details where the fatigue life consists mainly of crack growth. See also S-N curves with different slopes shown in this chapter.

The residual stresses at weld toes of small scale test specimens are normally small as compared with that in actual full size structures due to different restraints during fabrication. This is an item that is of importance when planning fatigue testing and for assessment of design S-N curves, see [F.7]

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It should also be remembered that for N ≥ 10^7 cycles there is additional uncertainty due to variable amplitude loading. This is an issue that should be kept in mind if less conservative S-N curves than given in this RP are aimed for by qualifying a new S-N curve.

Also the probability of detecting defects during a production should be kept in mind in this respect. The defects that normally can be detected by an acceptable probability are normally larger than that inherent in the test specimens that are produced to establish test data for a new S-N curve.

Fatigue testing may be needed when stainless steel is used in corrosive environment like scour service, see DNVGL-RP-F108 App.C.

2.5 Mean stress influence on fatigue strength

2.5.1 Base material without significant residual stresses

For fatigue analysis of regions in the base material not significantly affected by residual stresses due to welding or cold forming, the stress range may be reduced if part of the stress cycle is in compression.

This reduction may e.g. be carried out for cut-outs in the base material. The calculated stress range obtained may be multiplied by the reduction factor f_m as obtained from Figure 2-12 before entering the S-N curve.

In this figure σ_m = mean stress. If the residual stress is known, this stress can be added to the tensile part of the stress and subtracted for the compressive part before the reduction factor in equation (2.5.1) is calculated.

The reduction factor can be derived from the following equation:

$$f_m = \frac{\sigma_t + 0.6|\sigma_c|}{\sigma_t + |\sigma_c|} \qquad (2.5.1)$$

where:

σ_t = maximum tension stress where tension is defined as positive

σ_c = maximum compression stress where compression is defined as negative.

This implies in particular that f_m is 1.0 when the material is in tension during the entire stress cycle, 0.8 when it is subject to zero-mean stress, and 0.0 when it is in compression during the entire stress cycle provided low residual stresses can be documented. If the stress exceeds the yield stress locally also during compressive stress cycles, residual stresses may be introduced in the base material and this reduction factor should not be used.

It should be noted that cold forming of tubular sections implies yielding in the circumferential and the longitudinal directions of the sections being formed meaning that significant residual stresses may be left in both directions in the base material. The residual stresses are compressive on the inside and tensile on the outside of the formed tubular section. Therefore stress reduction should not be accounted for in cold formed tubulars with residual tensile stresses.

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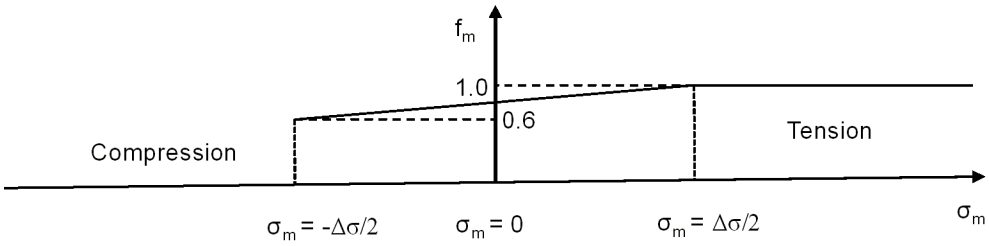


Figure 2-12 Stress range reduction factor to be used with the S-N curve for base material

2.5.2 Welded connections without significant residual stresses

For fatigue analysis of regions in welded structural details, which have been subject to post weld heat treatment or where correspondingly low residual stresses can be documented, the stress ranges may be reduced prior to the fatigue analysis depending on whether part of the stress range is tensile stress or compressive stress.

The calculated stress range at the hot spot may be multiplied by the reduction factor f_m as obtained from Figure 2-13 before entering the S-N curve. In this figure σ_m = mean stress.

The reduction factor can be derived from the following equation:

$$f_m = \frac{\sigma_t + 0.8|\sigma_c|}{\sigma_t + |\sigma_c|} \qquad (2.5.2)$$

where:

σ_t = maximum tension stress where tension is defined as positive

σ_c = maximum compression stress where compression is defined as negative.

This implies in particular that f_m is 1.0 when the material is in tension during the entire stress cycle, 0.9 when it is subject to zero-mean stress, and 0.8 when it is in compression during the entire stress cycle provided low residual stresses can be documented. If the stress exceeds the yield stress locally also during compressive stress cycles, residual stresses may be introduced in the connection and this reduction factor should not be used.

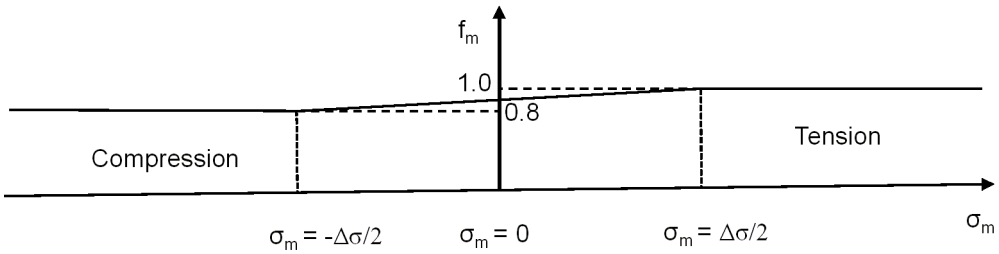


Figure 2-13 Stress range reduction factor at post weld heat treated connections or welds with corresponding low residual stresses

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2.6 Effect of fabrication tolerances

Normally larger fabrication tolerances are allowed in real structures than that accounted for in the test specimens used to derive S-N data, see DNVGL-OS-C401 *Fabrication and testing of offshore structures*. Therefore, additional stresses resulting from normal fabrication tolerances should be included in the fatigue design. Special attention should be given to the fabrication tolerances for simple butt welds in plates and tubulars as these give the most significant increase in additional stress. Stress concentration factors for butt welds in plated structures are given in [3.1.2] and at tubular circumferential welds in [3.3.7].

2.7 Requirements to non-destructive examination and acceptance criteria

See DNVGL-OS-C401 *Fabrication and testing of offshore structures* for requirements to non-destructive examination (NDE). See also DNVGL-OS-C401 with respect to acceptance criteria. Some acceptance criteria related to the different classification of structural details are also presented in App.A, see also [F.5].

For umbilical pipes requirements to NDE are presented in [2.4.12]. For partial penetration welds requirements to NDE are presented in [2.8].

In general the requirements to NDE and acceptance criteria are being increased when going from the lower to the high level S-N curves. This should also be considered when designing connections showing a high fatigue utilisation, see also [F.5].

2.8 Design chart for fillet and partial penetration welds

Design should be performed such that fatigue cracking from the weld root is less likely than from the toe region. The reason for this is that a fatigue crack at the toe can be found by in-service inspection while a fatigue crack starting at the root cannot be discovered before the crack has grown through the weld. Thus the design of the weld geometry should be performed such that the fatigue life for cracks starting at the root is longer than the fatigue life of the toe. Figure 2-15 can be used for evaluation of required penetration. The notation used is explained by Figure 2-14.

It should be added that it is difficult to detect internal defects by NDE in fillet/partial penetration welds. Such connections should therefore not be used in structural connections of significant importance for the structural integrity.

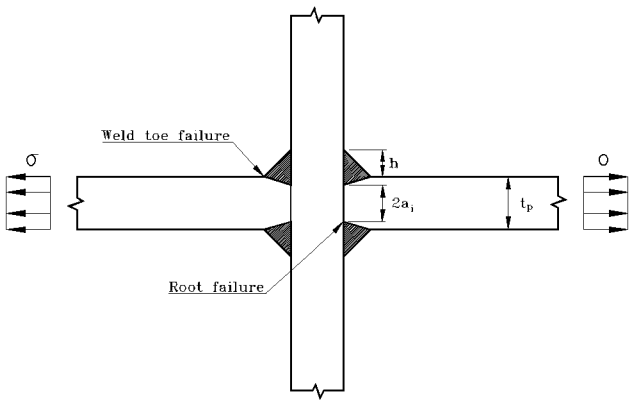


Figure 2-14 Welded connection with partial penetration weld

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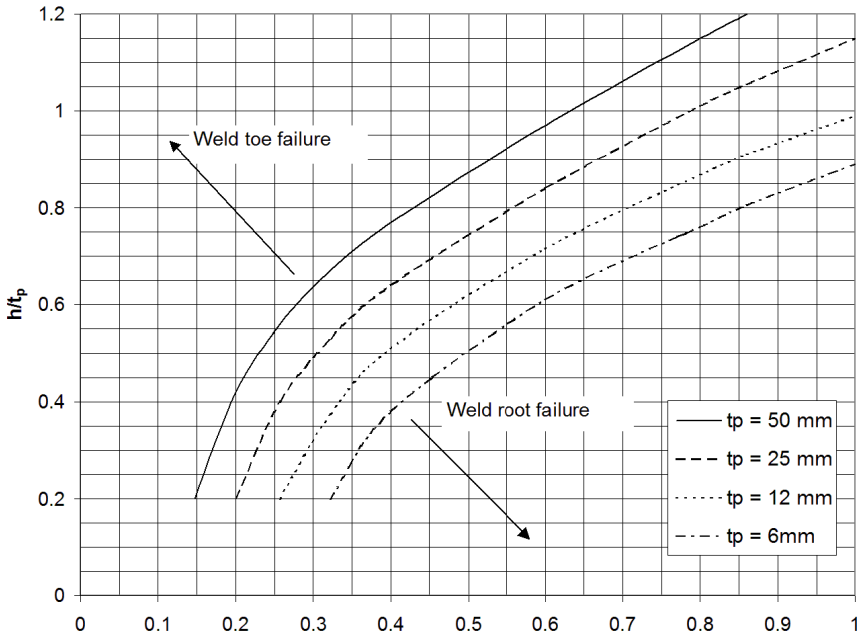


Figure 2-15 Weld geometry with probability of root failure equal toe failure

2.9 Bolts

2.9.1 General

A bolted joint connection subjected to dynamic loading should be designed with pretensioned bolts. The pretension should be high enough to avoid slipping after relevant loss of pretension during service life.

It is recommended to develop a technical specification for procurement of heavy-duty bolts for marine structures. Some guidance can be found in /103/. General thread tolerances for bolts and nuts are defined in ISO 965-1 /117/.

2.9.2 Bolts subjected to tension loading

Connections where the pretensioned bolts are subjected to dynamic axial forces should be designed with respect to fatigue taking into account the stress range in the bolts resulting from tension and compression range. The stress range in the bolts may be assessed based on e.g. *Maskindeler 2* /23/, or *Systematic Calculation of High Duty Bolted Joints* /26/. The cyclic stress in the bolts may be a combination of membrane stress (constant over the cross-section) and bending stress (linear over the cross-section). The bolt stress should include the sum of the membrane stress and the bending stress.

For S-N classification see Table A-2. The stress in the bolt should be calculated based on the bolt stress area (which is different from the root area, see equations for the bolt stress area in for example /103/).

2.9.3 Bolts subjected to shear loading

For bolts subject to shear loading the following methodology may be used for fatigue assessment. The threads of the bolts should not be in the shear plane. The methodology may be used for fitted bolts or for

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normal bolts without load reversal. The shear stress to be calculated based on the shank area of the bolt. Then number of cycles to failure can be derived from:

$$log\ N = 16.301 - 5.0\ log\ \Delta\sigma \qquad (2.9.1)$$

where:

$\Delta\sigma$ = shear stress based on shaft area of bolt.

2.9.4 Friction welded bolts

Fatigue tests of friction welded bolts installed below or above water give S-N curve C1 as shown in Table A-2 and /114/.

2.10 Pipelines

2.10.1 Stresses at girth welds in pipes and S-N data

Welds in pipelines are normally made with a symmetric weld groove with welding from the outside only. The tolerances are rather strict compared with other structural elements with eccentricity less than 0.05 t or maximum 3 mm (t = wall thickness). The fabrication of pipelines also implies a systematic and standardised NDT of the weld root area where defects are most critical. Provided that the same acceptance criteria are used for pipelines with larger wall thickness as for that used as reference thickness (25 mm), a thickness exponent k = 0 may be used for the hot spot at the weld root and k = 0.15 for the weld toe without grinding of the weld. Provided that these requirements are fulfilled, the detail at the root side may be classified according to the S-N curves in Table 2-5 with SCF from equation (2.10.8).

See Table 2-5 for ground welds and welds made from both sides.

The following stress concentration for the weld toe due to maximum allowable eccentricity should be included:

$$SCF_{cap} = 1 + \frac{6\delta_m e^{-\alpha}}{t_c\left(1 + \left(\frac{T}{t_c}\right)^{\beta}\right)} \qquad (2.10.1)$$

where:

$$\alpha = \frac{1.82 L_{cap}}{\sqrt{D t_c}\left(1 + \left(\frac{T}{t_c}\right)^{\beta}\right)} \qquad (2.10.2)$$

$$\beta = 1.5 - \frac{1.0}{\log\left(\frac{D}{t_c}\right)} + \frac{3}{\left(\log\left(\frac{D}{t_c}\right)\right)^2} \qquad (2.10.3)$$

$$T = t_c + \left[hi/lo_{cap} - hi/lo_{root}\right] \qquad (2.10.4)$$

T and t_c = wall thickness of the pipes on either side of the girth weld, $T > t_c$

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δ_m = misalignment (wall thickness differences, out-of-roundness, centre eccentricities, etc.)

D = outside diameter of pipe.

It is acceptable to calculate the SCF based on the following expression, see Figure 2-16.

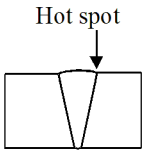
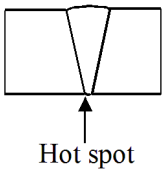
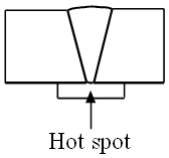
$$\delta_m = \frac{hi/lo_{cap} + hi/lo_{root}}{2} \qquad (2.10.5)$$

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

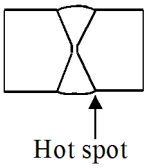
The nominal stress on the outside of the pipe should be used for fatigue assessment of the outside and the nominal stress on the inside of the pipe should be used for fatigue assessment of the inside. The membrane stress in the considered section should be used for calculation of local bending stress over the thickness together with stress concentration factor from equation (2.10.1).

See also [F.14] where a more detailed guidance on stress range calculation in pipes subjected to combined axial load and bending is included.

Table 2-5 Classification of welds in pipelines

Description		*Tolerance requirement (mean hi/lo-value)*	*S-N curve*	*Thickness exponent k*	*Stress concentration factor*
Welding	*Geometry and hot spot*				
Single side			D	0.15	Eq. (2.10.1)
Single side		$\delta_m \leq 1.0$ mm	E	0.00	Eq.(2.10.8)
		1.0 mm < $\delta_m \leq 2.0$ mm	F	0.00	
		2.0 mm < $\delta_m \leq 3.0$ mm	F1	0.00	
Single side on backing		$\delta_m \leq$ min(0.1t, 2 mm	F	0.00	Eq. (2.10.8)
		$\delta_m >$ min(0.1t, 2 mm	F1	0.00	

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Description		Tolerance requirement (mean hi/lo-value)	S-N curve	Thickness exponent k	Stress concentration factor
Welding	*Geometry and hot spot*				
Double side			D	0.15	Eq. (2.10.1)
Ground weld outside and inside			C	0.00	Eq. (2.10.1) for outside and Eq. (2.10.8) for inside

The width of the girth welds in the root in pipelines and risers may be larger than that shown in Figure 3-8 and may also be narrower on the outside to reduce the welding volume and increase fabrication efficiency. A more typical weld section through a girth weld is shown in Figure 2-16. For this geometry the stress due to local bending is less for the root than for the weld toe (weld cap). The local bending stress at the weld toe due to axial misalignment, δ_m, and membrane stress, σ_m, can be expressed as:

$$\sigma_{bt} = \left(SCF_{cap} - 1\right)\sigma_m \qquad (2.10.6)$$

The width of the weld at the root in Figure 2-16 is L_{Root}. Then the bending stress in the pipe wall at the transition from the weld to the base material at the root can be obtained from the linearized moment in Figure 2-16 as:

$$\sigma_{br} = \sigma_{bt}\frac{L_{root}}{L_{cap}} \qquad (2.10.7)$$

Thus, for the weld root the effect of axial misalignment can be included by the following *SCF* for the weld root:

$$SCF_{root} = 1 + \left(SCF_{cap} - 1\right)\frac{L_{root}}{L_{cap}} \qquad (2.10.8)$$

where:

SCF_{cap} is defined by equation (2.10.1).

If knowledge about the weld shape is missing, one may put L_{root} equal L_{cap} in equation (2.10.8) such that it reduces to that of equation (2.10.1). The background for this equation is presented in /103/.

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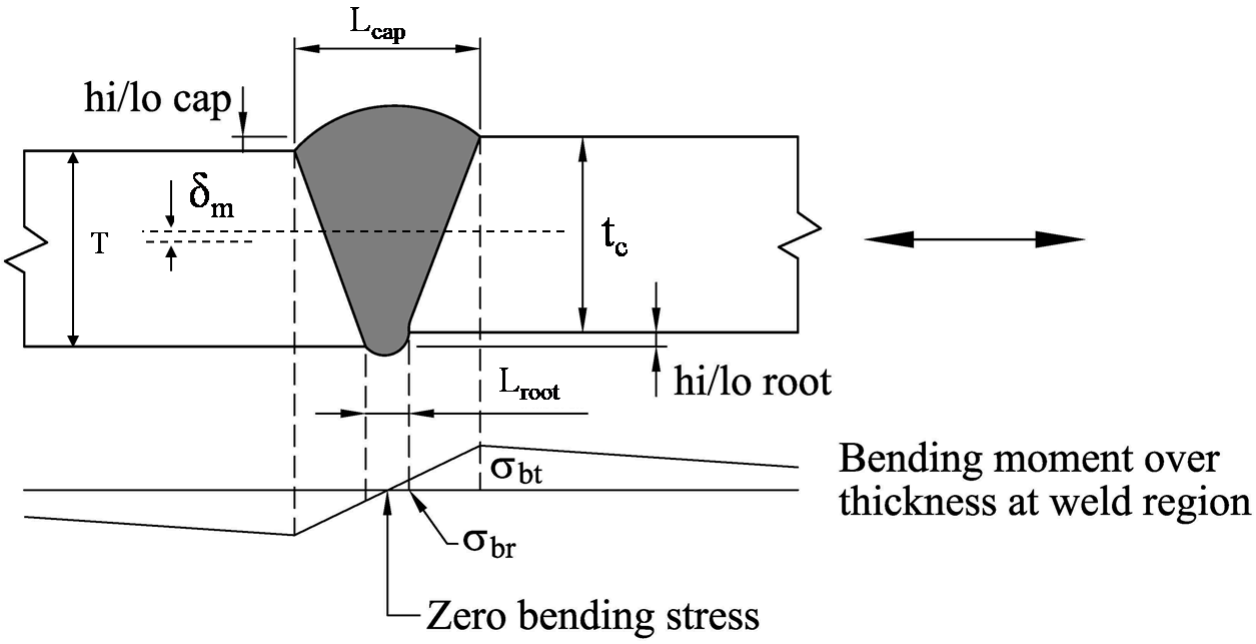


Figure 2-16 Stress distribution due to axial misalignment at single-sided welds in tubular members

2.10.2 Fatigue analysis of pipes and cylindrical tanks subjected to cyclic internal pressure

Pipes and cylindrical tanks may be subjected to fatigue from cyclic loading when subjected to significant variation in internal pressure. See [F.8] for stress concentration factors for thickness transitions at girth welds and at ring stiffeners/supports. It also gives stress concentration factors for the longitudinal welds (or seam weld) due to out-of-roundness of pipes and cylindrical tanks. For very long welds the fatigue capacity is considered to be reduced due to a system effect. The fatigue capacity for long welds can be accounted for as described under system effects in [F.5] .

2.11 Combined eccentricity for seamless riser pipes

For seamless pipes the eccentricity is governed by the thickness and out of roundness tolerances. A resulting tolerance at girth welds for use in equation (2.10.1) for calculation of stress concentration factor may also be obtained as:

$$\delta_m = \sqrt{\delta^2_{Thickness} + \delta^2_{Out\ of\ roundness}} \qquad (2.11.1)$$

where:

$\delta_{Thickness}$ = $(t_{max} - t_{min})/2$

$\delta_{Out\ of\ roundness}$ = $D_{max} - D_{min}$ if the pipes are supported such that flush outside at one point is achieved (no pipe centralising)

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$\delta_{Out\ of\ roundness}$ = $(D_{max} - D_{min})/2$ if the pipes are centralised during construction

$\delta_{Out\ of\ roundness}$ = $(D_{max} - D_{min})/4$ if the pipes are centralised during construction and rotated until a good fit around the circumference is achieved (if one part is made perfect circular by machining, this equation is not applicable).if one part is made perfect circular by machining, this equation is not applicable).

See DNVGL-RP-F108 /109/, for measurements of tolerances..

2.12 Guidance to when a detailed fatigue analysis can be omitted

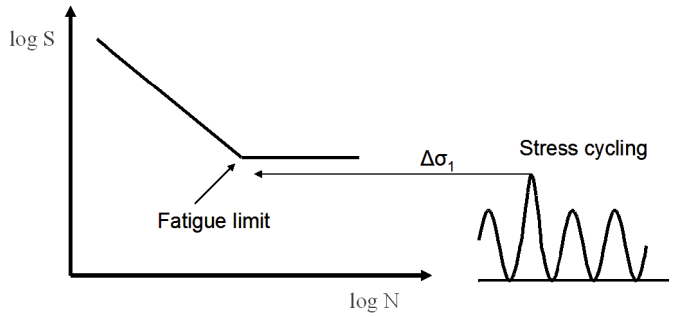
A detailed fatigue analysis can be omitted if the largest local stress range for actual details defined in equation (2.3.1) is less than the fatigue limit at 10^7 cycles in Table 2-1 for air and Table 2-2 for seawater with cathodic protection. For design fatigue factors larger than one the allowable fatigue limit should also here be reduced by a factor $(DFF)^{-0.33}$. See also /103/ for a more detailed derivation. For definition of DFF see DNVGL-OS-C101 /28/.

Requirements to detailed fatigue analysis may also be assessed based on the fatigue assessment charts in Figure 5-1 and Figure 5-2.

The use of the fatigue limit is illustrated in Figure 2-17 a) for DFF = 1.0 and in Figure 2-17 b) for DFF larger than 1.0. A detailed fatigue assessment can be omitted if the largest stress cycle is below the fatigue limit. However, in the example in Figure 2-18 there is one stress cycle $\Delta\sigma_1$ above the fatigue limit. This means that a further fatigue assessment is required and the fatigue damage from the stress cycles $\Delta\sigma_2$ has also to be included in the fatigue assessment.

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a) DFF = 1.0



b) DFF larger than 1.0.

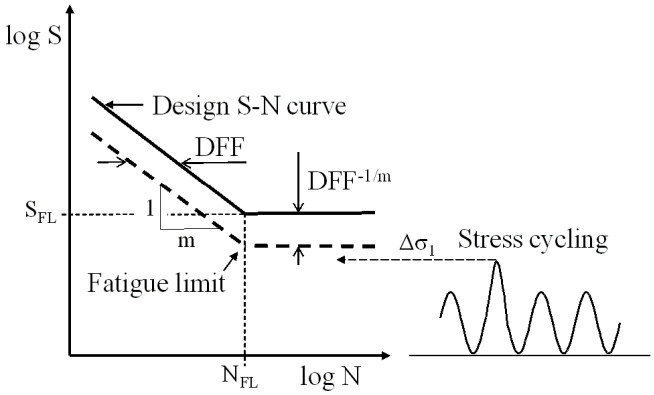


Figure 2-17 Stress cycling where further fatigue assessment can be omitted

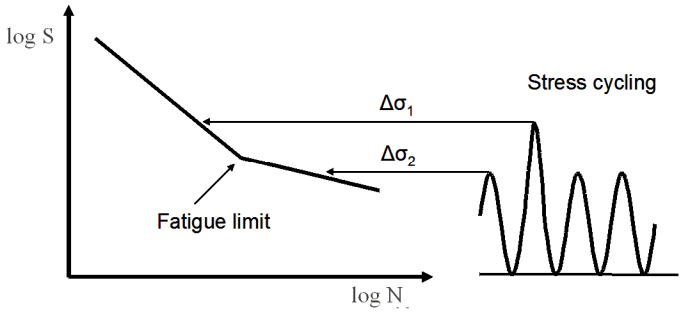


Figure 2-18 Stress cycling where a detailed fatigue assessment is required

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SECTION 3 STRESS CONCENTRATION FACTORS

3.1 Stress concentration factors

3.1.1 General

A stress concentration factor is defined as the ratio of hot spot stress range over nominal stress range. Fabrication tolerances increase the stress range at butt welds and cruciform joints. For as welded butt welds and cruciform joints there are already included some tolerances in the S-N curves that are used. However, the value of fabrication tolerance to be included in design calculation depends also on what is the expected as-built tolerance as compared with that required in the fabrication standard. This means that for some details a misalignment value δ_0 may be subtracted from the fabrication tolerance when the stress concentration factor to be used in design is calculated. See Table 3-1 for recommended δ_0 for butt welds in different structural details.

Table 3-1 Recommended values of δ_0 for butt welds in different types of structures

Structural detail	*As welded*	*Ground flush*
Plated structures	0.05t	0
Tubular girth welds in structures	0.05t	0
Girth welds in tethers	0	0
Girth welds in pipelines and risers	0	0

3.1.2 Stress concentration factors for butt welds in plated structures

The eccentricity between welded plates with a similar thickness may be accounted for in the calculation of stress concentration factor. The following formula applies for a butt weld in an unstiffened plate:

$$SCF = 1 + \frac{3(\delta_m - \delta_0)}{t} \qquad (3.1.1)$$

where δ_m is eccentricity (misalignment) and t is plate thickness, see Figure 3-8.

δ_0 = 0.05t is misalignment inherent in the S-N data for butt welds and analysis procedure for plated structures with an expected fabrication tolerance that is lower than that allowed in fabrication specification and as used in design, see also Table 3-1. See DNVGL-OS-C401 for fabrication tolerances.

The stress concentration for the weld between plates with different thickness in a plate field on the side of the thickness transition may be derived from the following formula:

$$SCF = 1 + \frac{6(\delta_m + \delta_t - \delta_0)}{t\left[1 + \frac{T^{1.5}}{t^{1.5}}\right]} \qquad (3.1.2)$$

where:

δ_m = maximum fabrication misalignment

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δ_t = ½ (T- t) eccentricity due to change in thickness
Note: this applies also at transitions sloped as 1:4.

δ_0 = 0.05t is misalignment inherent in the S-N data for butt welds and analysis procedure for plated structures with an expected fabrication tolerance that is lower than that allowed in fabrication specification and as used in design, see also Table 3-1
See DNVGL-OS-C401 for fabrication tolerances

T = thickness of thicker plate

t = thickness of thinner plate.

See also Figure 3-8.

The stresses at the weld on the opposite side of the thickness transition in the plate can be calculated using the following formula for stress concentration factor:

$$SCF = 1 - \frac{6(\delta_t + \delta_0 - \delta_m)}{t\left[1 + \frac{T^{1.5}}{t^{1.5}}\right]} \qquad (3.1.3)$$

This equation applies to the weld on the opposite side of the thickness transition with δ_0 = 0.05t when the butt weld is made from both sides. For the root side of a single sided weld δ_0 = 0.0 should be used together with a relevant S-N curve. The value of δ_0 is based on actual tolerances accounted for in S-N curves and experience from fabrication of different structural details. Thus, it is also based on the relation between specified tolerances in fabrication standards versus actual fabricated values.

3.1.3 Stress concentration factors for cruciform joints in plated structures

The stress concentration factor for cruciform joint at plate thickness t_i may be derived from the following formula:

$$\mathrm{SCF} = 1 + \frac{6t_i^{\,2}(\delta - \delta_0)}{l_i\left(\frac{t_1^3}{l_1} + \frac{t_2^3}{l_2} + \frac{t_3^3}{l_3} + \frac{t_4^3}{l_4}\right)} \qquad (3.1.4)$$

where:

δ = $(\delta_m + \delta_t)$ is the total eccentricity

δ_0 = 0.15 t_i is misalignment embedded in S-N data for cruciform joints and analysis procedure when including effect of fabrication tolerances
See DNVGL-OS-C401 for fabrication tolerances.

t_i = thickness of the considered plate (i = 1, 2)

l_i = length of considered plate (i = 1, 2).

The other symbols are defined in Figure 3-1.

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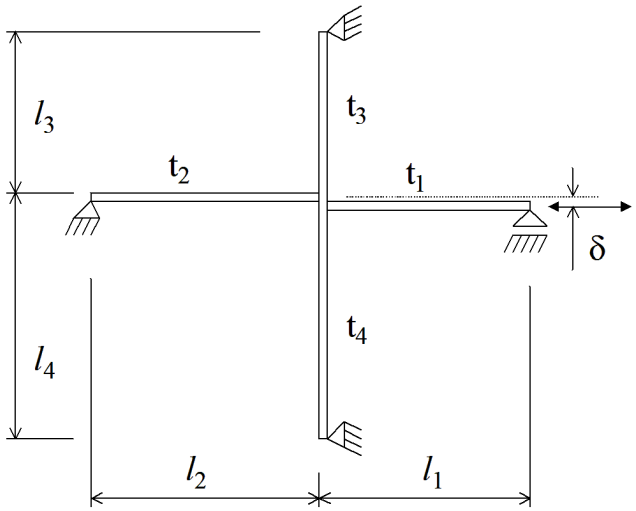


Figure 3-1 Cruciform joint

3.1.4 Stress concentration factors for rounded rectangular holes

Stress concentration factors for rounded rectangular holes are given in Figure 3-2 based on analytical expressions presented in the literature /106/.

Where there is one stress raiser close to another detail being evaluated with respect to fatigue, the interaction of stress between these should be considered. An example of this is a welded connection in a vicinity of a hole. Then the increase in stress at the considered detail due to the hole can be evaluated from Figure 3-3.

Some guidelines on effect of interaction of different holes can be found in Peterson's *Stress Concentration Factors*, /15/.

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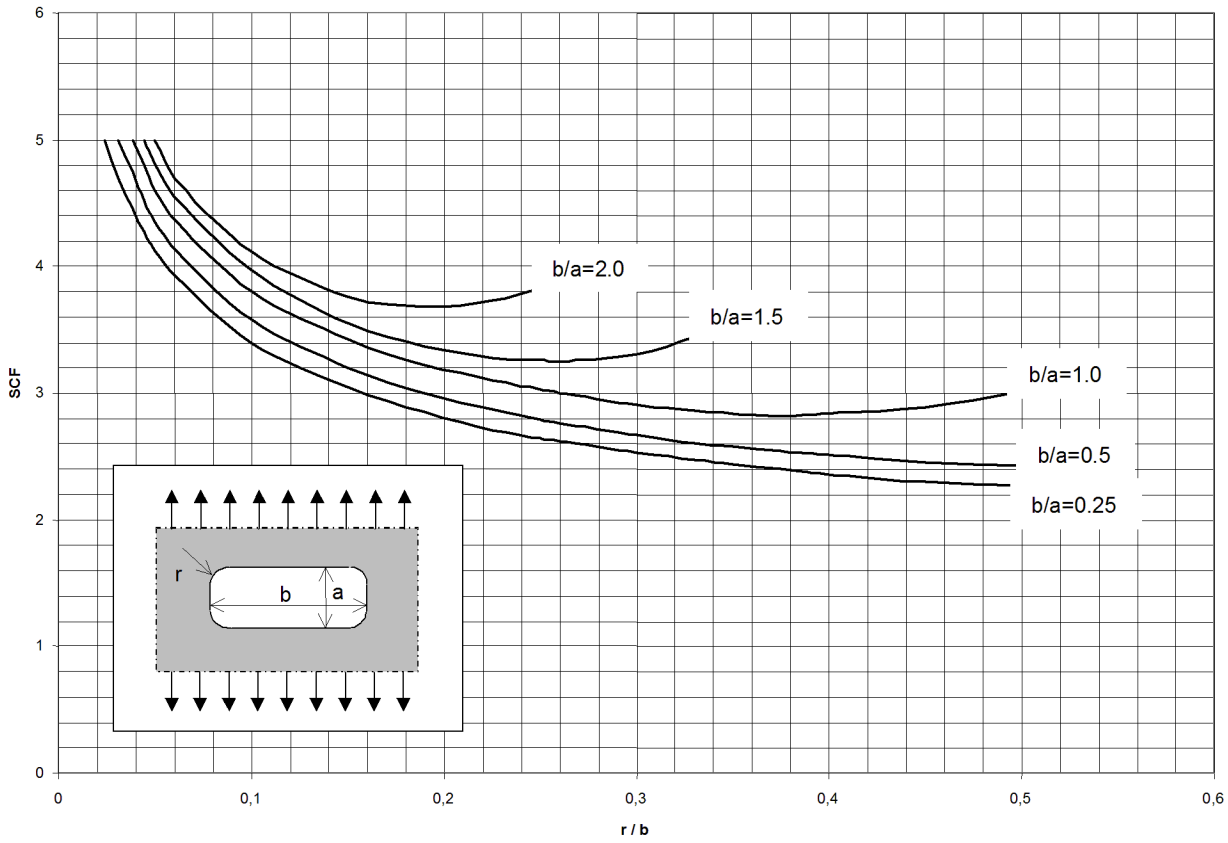


Figure 3-2 Stress concentration factors for rounded rectangular holes

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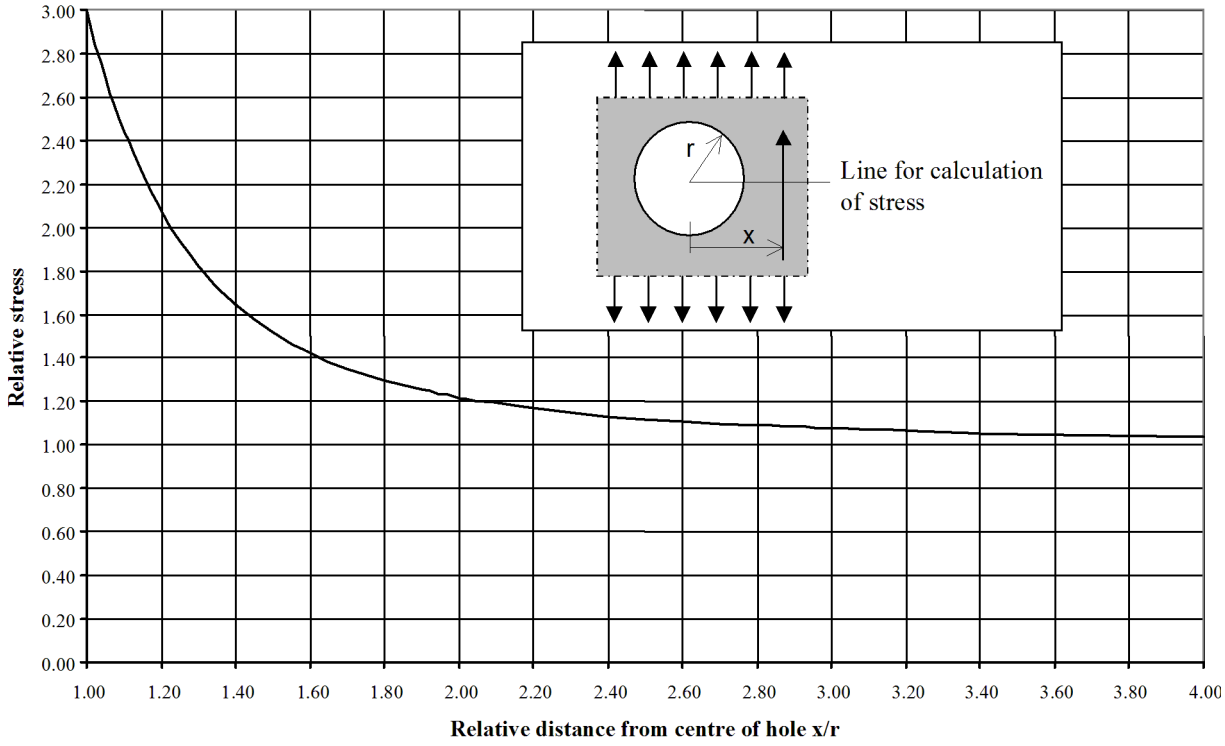


Figure 3-3 Stress distribution at a hole

3.1.5 Stress concentration factors for holes with edge reinforcement

Stress concentration factors for holes with reinforcement are given in App.C.

Fatigue cracking around a circumferential weld may occur at several locations at reinforced rings in plates depending on geometry of ring and weld size.

1) Fatigue cracking transverse to the weld toe in a region with a large stress concentration giving large stress parallel to the weld (flexible reinforcement), see Figure 3-4 a). Then $\sigma_{hot\ spot} = \sigma_p$ which includes the stress concentration due to the detail (σ_p = SCF ·σ_n).
2) Fatigue cracking parallel to the weld toe (stiff reinforcement with full penetration weld or large fillet weld size), see Figure 3-4 b). Fatigue crack initiating from the weld toe. The principal stress σ_1 is the crack driving stress.

   Then $\sigma_{hot\ spot} = \sigma_1$.

   Also the region at the top position needs to be checked.

   Then $\sigma_{hot\ spot} = \sigma_n$.

   As an alternative to using the principal stress as hot spot stress at 45° position in Figure 3-4 b) one may use the concept of effective hot spot stress as described in [4.3.4]. See also [4.3.9].
3) Fatigue cracking from the weld root (stiff reinforcement with small fillet weld size), see Figure 3-4 c).

Fillet welds at positions θ = 45° and θ = 0° should be assessed with respect to fatigue.

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