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RECOMMENDATIONS FOR FATIGUE DESIGN OF WELDED JOINTS AND COMPONENTS

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PREFACE

This document has been prepared as a result of an initiative by Commissions XIII and XV of the International Institute of Welding (IIW). The task has been transferred to the Joint Working Group XIII-XV, where it has been discussed and drafted in the years 1990 to 1996 and updated in the years 2002-2007. The document contains contributions from:

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1 GENERAL

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1.1 INTRODUCTION

The aim of these recommendations is to provide a basis for the design and analysis of welded components loaded by fluctuating forces, to avoid failure by fatigue. In addition they may assist other bodies who are establishing fatigue design codes. It is assumed that the user has a working knowlegde of the basics of fatigue and fracture mechanics.

The purpose of designing a structure against the limit state due to fatigue damage is to ensure, with an adequate survival probability, that the performance is satisfactory during the design life. The required survival probability is obtained by the use of appropriate partial safety factors.

1.2 SCOPE AND LIMITATIONS

The recommendations present general methods for the assessment of fatigue damage in welded components, which may affect the limit states of a structure, such as ultimate limit state and servicability limit state [1-1].

The recommendations give fatigue resistance data for welded components made of wrought or extruded products of ferritic/pearlitic or bainitic structural steels up to **f_y=960 MPa**, of austenitic stainless steels and of aluminium alloys commonly used for welded structures.

The recommendations are **not** applicable to low cycle fatigue, where $\mathbf{\Delta\sigma_{nom} > 1.5 \cdot fy}$, $\mathbf{max\sigma_{nom} > f_y}$, for corrosive conditions or for elevated temperature operation in the creep range.

1.3 DEFINITIONS

Characteristic value	Loads, forces or stresses, which vary statistically, at a specified fractile, here: 95% at a confidence level of the mean of 75% .
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 the recommendation. Also referred to as standard structural detail.
Concentrated load effect	A local stress field in the vicinity of a point load or reaction force, or membrane and shell bending stresses due to loads causing distortion of a cross section not sufficiently stiffened by a diaphragm.
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 tip propagation during one stress cycle.
Crack propagation threshold	Limiting value of stress intensity factor range below which crack propagation will not occur.
Cut off limit	Fatigue strength under variable amplitude loading, below which the stress cycles are considered to be non-damaging.
Design value	Characteristic value factored by a partial safety factor.
Effective notch stress	Notch stress calculated for a notch with a certain effective notch radius.
Equivalent stress range	Constant amplitude stress range which is equivalent in terms of fatigue damage to the variable amplitude loading under study, at the same number of cycles.
Fatigue	Detoriation of a component caused by crack initiation

	and/or by the growth of cracks.
Fatigue action	Load effect causing fatigue, i.e. fluctuation load.
Fatigue damage ratio	Ratio of fatigue damage sustained to fatigue damage required to cause failure, defined as the ratio of the number of applied stress cycles and the corresponding fatigue life at constant amplitude.
Fatigue life	Number of stress cycles of 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.
Hot spot	A point in a structure where a fatigue crack may initiate due to the combined effect of structural stress fluctuation and the weld geometry or a similar notch.
Local nominal stress	Nominal stress including macro-geometric effects, concentrated load effects and misalignments, disregarding the stress raising effects of the welded joint itself. Also referred to as modified nominal stress.
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 nonlinear 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 a large opening, a curved part in a beam, a bend in a flange not supported by diaphragms or stiffeners,

	discontinuities in pressure containing shells, eccentricity in a lap joint (see fig. (2.2)-3).
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	Summation of individual fatigue damage ratios caused by each stress cycle or stress range block above a certain cut-off limit according to the Palmgren-Miner rule.
Misalignment	Axial and angular misalignments caused either by detail design or by poor fabrication or welding distortion.
Modified nominal stress	See 'Local nominal stress'.
Nominal stress	A stress in a component, resolved using general theories, e.g. beam theory. See also local nominal stress.
Nonlinear stress peak	The stress component of a notch stress which exceeds the linearly distributed structural stress at a local notch.
Notch stress	Total stress at the root of a notch taking into account the stress concentration caused by the local notch, consisting of the sum of structural stress and nonlinear 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 a specified value.
Rainflow counting	A standardized procedure for stress range counting.
Range counting	A procedure of determining various stress cycles and their ranges from a stress history, preferably by rainflow counting method.
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** ($\Delta\sigma_R$ or $\Delta\tau_R$), also known as Wöhler curve.
Stress cycle	A part of a stress history containing a stress maximum and a stress minimum, determined usually by a range counting method.
Stress history	A time based presentation of a fluctuating stress, defined by sequential stress peaks and troughs (valleys), either for the total life or for a certain sample.
Stress intensity factor	Main parameter in fracture mechanics, the combined effect of stress and crack size at the crack tip region.
Stress range	The difference between stress maximum and stress minimum in a stress cycle, the most important parameter governing fatigue life.
Stress range block	A part of the 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 a stress history. Here, frequency is the number of occurrances. (Also referred to as "stress spectrum" or "cumulative frequency diagram").
Stress range occurrences	A tabular or graphical presentation of stress ranges, usually discretized in stress range blocks. See also "stress range exceedances".
Stress ratio	Ratio of minimum to maximum algebraic value of the stress in a particular stress cycle.
Stress intensity factor ratio	Ratio of minimum to maximum algebraic value of the stress intensity factor of a particular load cycle.
Structural discontinuity	A geometric discontinuity due to the type of welded joint, usually to be found in the tables of classified structural details. The effects of a structural discontinuity are (i) concentration of the membrane stress and (ii) formation of

	secondary shell bending stresses (see fig. (2.2)-6).
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.
Structural stress concentration factor	The ratio of structural (hot spot) stress to modified (local) nominal stress.
Structural hot spot stress	The value of structural stress on the surface at a hot spot.
Variable amplitude loading	A type of loading causing irregular stress fluctuation with stress ranges (and amplitudes) of variable magnitude.

1.4 SYMBOLS

$\mathbf{K}$	stress intensity factor
$\mathbf{K_{max}}$	stress intensity factor caused by $\boldsymbol{\sigma_{max}}$
$\mathbf{K_{min}}$	stress intensity factor caused by $\boldsymbol{\sigma_{min}}$
$\mathbf{M_k}$	magnification function for **K** due to nonlinear stress peak
$\mathbf{M_{k,m}}$	magnification function for **K**, concerning membrane stresses
$\mathbf{M_{k,b}}$	magnification function for **K**, concerning shell bending stresses
$\mathbf{R}$	stress ratio
$\mathbf{Y}$	correction function for **K**, taking into account crack form, aspect ratio, relative crack size etc.
$\mathbf{Y_m}$	correction function for **K**, concerning membrane stress
$\mathbf{Y_b}$	correction function for **K**, concerning shell bending stress
$\mathbf{a}$	depth of a surface crack or semi length of a through crack
$\mathbf{a_o}$	initial depth of a surface crack
$\mathbf{a_f}$	crack size at failure
$\mathbf{e}$	eccentricity, amount of offset misalignment
$\mathbf{f_y}$	actual or specified yield strength of the material
$\mathbf{k_m}$	stress magnification factor due to misalignment
$\mathbf{k_s}$	stress concentration factor due to structural discontinuity
$\mathbf{k_t}$	stress concentration factor due to local notch
$\mathbf{m}$	exponent of S-N curve or Paris power law
$\mathbf{t}$	plate thickness, thickness parameter (crack center to nearest surface)
$\mathbf{\Delta K}$	stress intensity factor range
$\mathbf{\Delta K_{S,d}}$	design value of stress intensity factor range caused by actions
$\mathbf{\Delta K_{th}}$	threshold stress intensity factor range
$\boldsymbol{\Delta\sigma}$	stress range
$\boldsymbol{\Delta\sigma_{S,d}}$	design value of stress range caused by actions
$\boldsymbol{\Delta\sigma_{R,L}}$	characteristic value of stress range at knee point of S-N curve
$\boldsymbol{\Delta\tau}$	shear stress range
$\boldsymbol{\gamma_M}$	partial safety factor for fatigue resistance in terms of stress
$\boldsymbol{\Gamma_M}$	partial safety factor for fatigue resistance in terms of cycles
$\boldsymbol{\sigma}$	normal stress
$\boldsymbol{\sigma_{ben}}$	shell bending stress
$\boldsymbol{\sigma_{en}}$	effective notch stress
$\boldsymbol{\sigma_{ln}}$	(local) notch stress
$\boldsymbol{\sigma_{max}}$	stress maximum in stress history
$\boldsymbol{\sigma_{mem}}$	membrane stress
$\boldsymbol{\sigma_{min}}$	stress minimum in stress history
$\boldsymbol{\sigma_{nlp}}$	nonlinear stress peak
$\boldsymbol{\sigma_{nom}}$	nominal stress
σ_{hs}	structural hot spot stress

Subscripts:

S	fatigue actions
R	fatigue resistance
d	design value
k	characteristic value
$\boldsymbol{\tau}$	shear stress

1.5 BASIC PRINCIPLES

According to the ISO format for verification of structures [1-1], fatigue action and fatigue resistance are clearly separated. Fatigue resistance is given in terms of tentative data. The representation of tentative data has also been separated from the assessment curves used for damage calculation, because different damage calculation methods may require special modifications to the resistance S-N curve, which is usually based on constant amplitude tests. Thus, the flexibility and possibility for continuous updating of the document is maintained. No recommendations are given for the fatigue load (action) side, nor for the partial safety factor on fatigue actions γ_F.

The different approaches for the fatigue assessment of welded joints and components considered are: nominal stress, structural hot-spot stress, effective notch stress, fracture mechanics method and component testing.

1.6 NECESSITY FOR FATIGUE ASSESSMENT

Fatigue assessment is generally required for components subject to fluctuating loads.
In the following cases, detailed fatigue assessment usually is **not** required:

a) The highest nominal design stress range satisfies

$$\textit{steel}: \quad \Delta\sigma_{S,d} \leq 36 \; [MPa] \; / \; \gamma_M$$
$$\textit{aluminium}: \quad \Delta\sigma_{S,d} \leq 12 \; [MPa] \; / \; \gamma_M$$

γ_M should be taken from an applicable design code. This paragraph is not applicable to tubular joints.

b) A Miner sum (4.3.1) equal or less to **D=0.5** using a FAT fatigue class according to (3.2) of FAT 36 for steel or FAT 12 for aluminium

c) For a detail for which a constant amplitude fatigue limit $\Delta\sigma_{R,L}$ is specified and all design stress ranges are under an assumed or specified design resistance fatigue limit (see 3.2 !)

$$\Delta\sigma_{S,d} \leq \Delta\sigma_{R,L} / \gamma_M$$

d) For a crack, at which all design stress intensity factors are under an assumed or specified threshold level ΔK_{th} for crack propagation.

$$\Delta K_{S,d} \leq \Delta K_{th} / \gamma_M$$

for steel $\Delta K_{th} = 2.0 \; MPa\sqrt{m} = 63 \; N \cdot mm^{-3/2}$
for aluminium $\Delta K_{th} = 0.7 \; MPa\sqrt{m} = 21 \; N \cdot mm^{-3/2}$

1.7 APPLICATION OF THE DOCUMENT

Based on the initial information about the welded joint and the loads, an assessment procedure has to be chosen. Then, the fatigue action data (e.g. stress type) and the fatigue resistance data have to be determined according to the assessment procedure. The corresponding types of fatigue action and resistance are:

Tab. {1}-1: Presentation of fatigue actions and resistances vs. assessment procedure

Fatigue action	Fatigue resistance	Assessment procedure
Forces on component	Resistance determined by test of component	Component testing
Nominal stress in section	Resistance given by tables of structural details in terms of a set of S-N curves	Summation of cumulative damage
Structural hot-spot stress at weld toe	Resistance against structural hot-spot stress in terms of S-N curves	
Effective notch stress in weld notch	Resistance against effective notch stress in terms of a universal S-N curve	
Stress intensity at crack tip	Resistance against crack propagation in terms of the material parameters of the crack propagation law	Summation of crack increments

The chosen procedure has to be performed using adequate safety factors.

Tab. {1}-3: General guidance for the application of the document

Item	**Initial Information**		**Fatigue Action**		**Fatigue Resistance**	
(1)	Does joint correpond to a tabulated structural detail?	yes →	determine nominal stress (2.2.2)	then →	look up fatigue resistance class (FAT) in tables (3.2)	go to (6)
	if no ↓					
(2)	Is hot-spot structural stress assess-ment ap-plicable?	yes →	determine hot-spot structural stress (2.2.3)	then →	look up re-sistance S-N curve for hot-spot structural stress (3.3)	go to (6)
	if no ↓					
(3)	Is effective notch stress assessment applicable?	yes →	determine effective notch stress (2.2.4)	then →	look up re-sistance S-N curve for effective notch stress (3.4)	go to (6)
	if no ↓					
(4)	Are cracks or cracklike imperfec-tions pre-sent?	yes →	determine stress intensity factor (2.2.5)	then →	look up resistance against crack pro-pagation (3.6 and 3.8)	go to (7)
	if no ↓					

(5)	Test entire component (4.5)	go to (8)			
	test structural detail (3.7)	go to (1)			
Modifications and Assessment Procedures					
(6)	Modify resistance S-N curve (3.5) for all effects not yet covered	is Miner rule adequate (4.3)? yes →	calculate design resistance S-N curve (4.3.1) using γ_M (8)	then →	perform summation (4.3.1) giving life cycles, assess if OK
		if no →	calc. dimensionless crack propagation param. from resistance S-N curve (4.3.2) using γ_M (8)		
			then ↓		
(7)	calc. design crack propagation resistance data using Γ_M (8)	then →	perform crack propagation calc. (4.4) giving life cycles		
			assess if OK		
Safety Considerations					
(8)	define γ_M according to safety considerations (chapter 5)				

2 FATIGUE ACTIONS (LOADING)

All types of fluctuating load acting on the component and the resulting stresses at potential sites for fatigue have to be considered. Stresses or stress intensity factors then have to be determined according to the fatigue assessment procedure applied.

The actions originate from live loads, dead weights, snow, wind, waves, pressure, accelerations, dynamic response etc. Actions due to transient temperature changes should be considered. Improper knowledge of fatigue actions is one of the major sources of fatigue damage.

Tensile residual stresses due to welding decrease the fatigue resistance, however, the influence of residual weld stresses is already included in the fatigue resistance data given in chapter 3.

2.1 BASIC PRINCIPLES

2.1.1 Determination of Actions

The actions in service have to be determined in terms of characteristic loads. Partial safety factors on actions γ_F have to be applied as specified in the application code giving the design values of the actions for fatigue assessment.

In this document, there is no guidance given for the establishing of design values for actions (loads), nor for partial safety factors γ_F for actions (loads).

2.1.2 Stress Range

Fatigue assessment is usually based on stress range or stress intensity factor range. Thus, the actions have to be given in these terms.

$$\Delta\sigma = \sigma_{max} - \sigma_{min}$$

$$\Delta K = K_{max} - K_{min}$$

The maximum and the minimum values of the stresses are to be calculated from a superposition of all non permanent, i.e. fluctuating, actions:

a) fluctuations in the magnitudes of loads
b) movement of loads on the structure
c) changes in loading directions
d) structural vibrations due to loads and dynamic response
e) temperature transients

Fatigue analysis is based on the cumulative effect of all stress range occurrences during the anticipated service life of the structure.

2.1.3 Types of Stress Raisers and Notch Effects

Different types of stress raisers and notch effects lead to the calculation of different types of stress. The choice of stress depends on the fatigue assessment procedure used.

Tab. {2}-1: Stress raisers and notch effects

Type	Stress raisers	Stress determined	Assessment procedure
A	General analysis of sectional forces using general theories e.g. beam theory, no stress risers considered	Gross average stress from sectional forces	Not applicable for fatigue analysis, only for component testing
B	A + macrogeometrical effects due to the design of the component, but excluding stress risers due to the welded joint itself.	Range of nominal stress (also modified or local nominal stress)	Nominal stress approach
C	A + B + structural discontinuities due to the structural detail of the welded joint, but excluding the notch effect of the weld toe transition	Range of structural hot-spot stress	Structural hot-spot stress approach
D	A + B + C + notch stress concentration due to the weld bead notches a) actual notch stress b) effective notch stress	Range of elastic notch stress (total stress)	a) Fracture mechanics approach b) effective notch stress approach

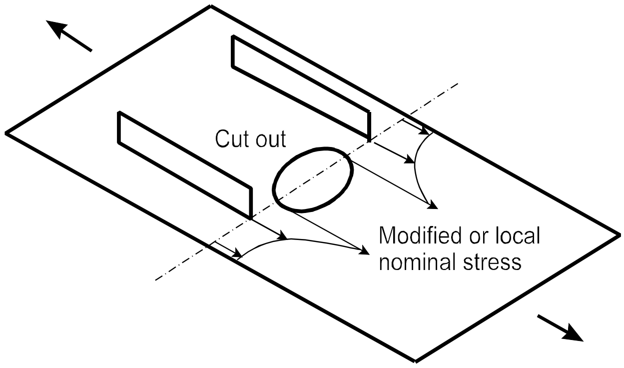


Fig. (2.1)-1 Modified or local nominal stress

Figure (2.1-1) shows an example of different stress definitions, such as gross nominal stress and modified or local nominal stress. Figure (2.1-2) shows the rise of stress in the vicinity of the notch, caused by the structural detail and the weld toe.

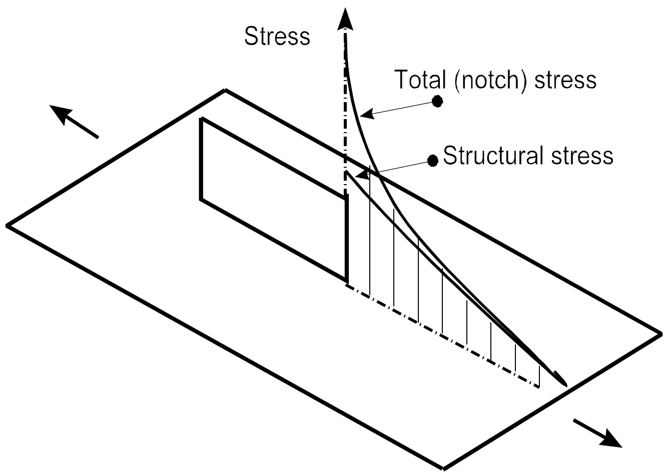


Fig. (2.1)-2 Notch stress and structural hot-spot stress

2.2 DETERMINATION OF STRESSES AND STRESS INTENSITY FACTORS

2.2.1 Definition of Stress Components

The stress distribution over the plate thickness is non-linear in the vicinity of notches.

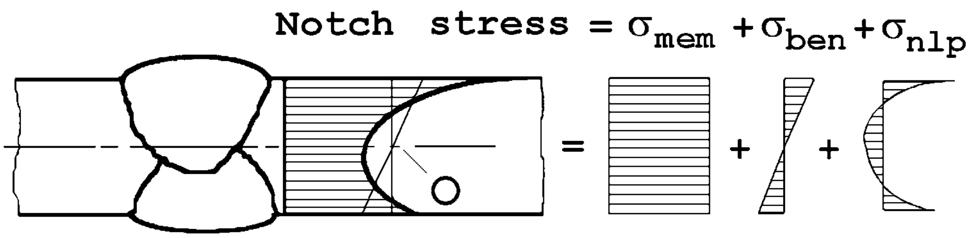


Fig. (2.2)-1 Non-linear stress distribution separated to stress components

The stress components of the notch stress $\boldsymbol{\sigma_{ln}}$ are [1-2]:

$\boldsymbol{\sigma_{mem}}$	membrane stress
$\boldsymbol{\sigma_{ben}}$	shell bending stress
$\boldsymbol{\sigma_{nlp}}$	non-linear stress peak

If a refined stress analysis method is used, which gives a non-linear stress distribution, the stress components can be separated by the following method:

The membrane stress $\boldsymbol{\sigma_{mem}}$ is equal to the average stress calculated through the thickness of the plate. It is constant through the thickness.

The shell bending stress $\boldsymbol{\sigma_{ben}}$ is linearly distributed through the thickness of the plate. It is found by drawing a straight line through the point **O** where the membrane stress intersects the mid-plane of the plate. The gradient of the shell bending stress is chosen such that the remaining non-linearly distributed component is in equilibrium.

The non-linear stress peak $\boldsymbol{\sigma_{nlp}}$ is the remaining component of the stress.

The stress components can be separated analytically for a given stress distribution **σ(x)** for **x=0** at surface to **x=t** at through thickness:

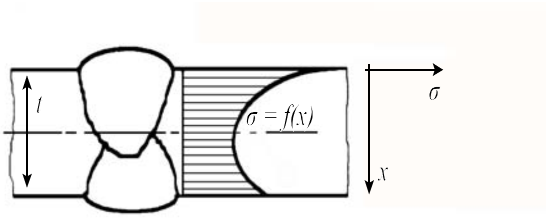


Fig. (2.2)-2 Position of coordinates

$$\sigma_{mem} = \frac{1}{t} \cdot \int_{x=0}^{x=t} \sigma(x) \cdot dx$$

$$\sigma_{ben} = \frac{6}{t^2} \cdot \int_{x=0}^{x=t} \sigma(x) \cdot \left(\frac{t}{2} - x\right) \cdot dx$$

$$\sigma_{nlp}(x) = \sigma(x) - \sigma_{mem} - \left(1 - \frac{2x}{t}\right) \cdot \sigma_{ben}$$

2.2.2 Nominal Stress

2.2.2.1 General

Nominal stress is the stress calculated in the sectional area under consideration, disregarding the local stress raising effects of the welded joint, but including the stress raising effects of the macrogeometric shape of the component in the vicinity of the joint, such as e.g. large cutouts. Overall elastic behaviour is assumed.

The nominal stress may vary over the section under consideration. E.g. at a beam-like component, the modified (also local) nominal stress and the variation over the section can be calculated using simple beam theory. Here, the effect of a welded on attachment is ignored.

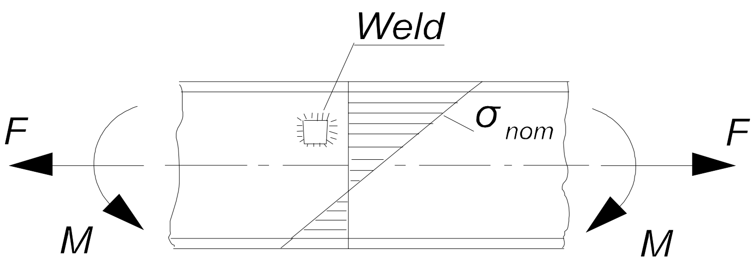


Fig. (2.2)-2 Nominal stress in a beam-like component

The effects of macrogeometric features of the component as well as stress fields in the vicinity of concentrated loads must be included in the nominal stress. Consequently, macrogeometric effects may cause a significant redistribution of the membrane stresses across the section. Similar effects occur in the vicinity of concentrated loads or reaction forces. Significant shell bending stress may also be generated, as in curling of a flange, or distortion of a box section.

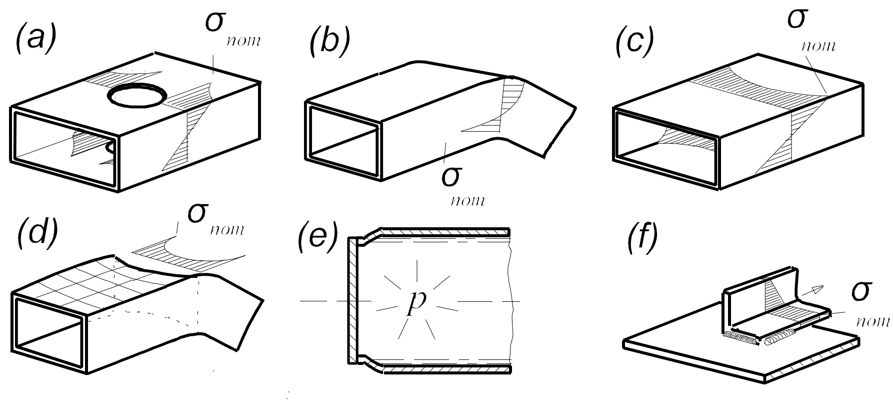


Fig. (2.2)-3 Examples of macrogeometric effects

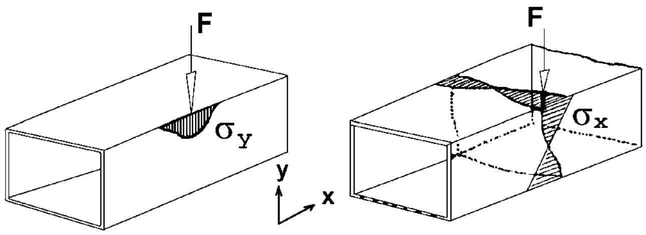


Fig. (2.2)-4 Modified (local) nominal stress near concentrated loads

The secondary bending stress caused by axial or angular **misalignment** needs to be considered if the misalignment exceeds the amount which is already covered by fatigue resistance S-N curves for the structural detail. This is done by the application of an additional stress raising factor $\mathbf{k_{m,eff}}$ (see 3.8.2). Intentional misalignment (e.g. offset of neutral axis in butt joint between plate of different thickness) is considered when assessing the fatigue actions (stress) by multiplying by the factor. If it is non-intentional, it is regarded as a weld imperfection which affects the fatigue resistance and has to be considered by dividing the fatigue resistance (stress) by the factor.

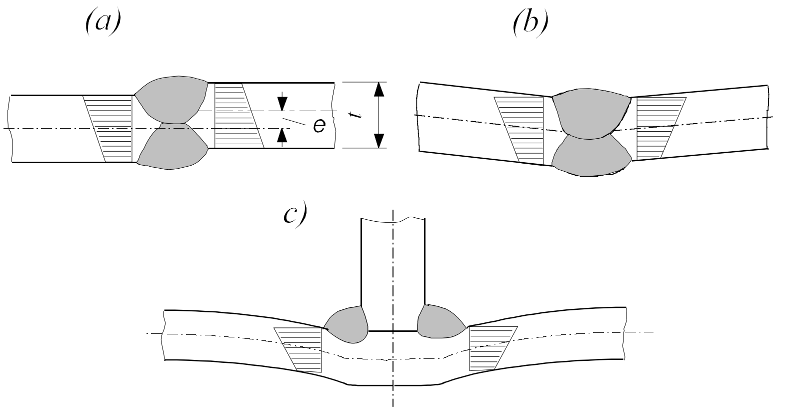


Fig. (2.2)-5 Axial and angular misalignement

2.2.2.2 Calculation of Nominal Stress

In simple components the nominal stress can be determined using elementary theories of structural mechanics based on linear-elastic behaviour. Nominal stress is the average stress in weld throat or in plate at weld toe as indicated in the tables of structural details. The stress $\boldsymbol{\sigma}_{\mathbf{w}}$ or $\boldsymbol{\tau}_{\mathbf{w}}$ in weld throat **a** at a weld length $\mathbf{l}_{\mathbf{w}}$ and a force in the weld **F** becomes

$$\sigma_W \ or \ \tau_W = \frac{F}{A_W} = \frac{F}{a \cdot l_W}$$

In other cases, finite element method (FEM) modelling may be used. This is primarily the case in:

a) complicated statically over-determined (hyperstatic) structures
b) structural components incorporating macrogeometric discontinuities, for which no analytical solutions are available

Using FEM, meshing can be simple and coarse. Care must be taken to ensure that all stress raising effects of the structural detail of the welded joint are excluded when calculating the **modified (local) nominal stress**.

If nominal stresses are calculated for fillet welds by a coarse finite element mesh, nodal forces should be used in a section through the weld instead of element stresses in order to avoid stress underestimation.

2.2.2.3 Measurement of Nominal Stress

The fatigue resistance S-N curves of classified structural details are based on nominal stress, disregarding the stress concentrations due to the welded joint. Therefore the measured nominal stress must exclude the stress or strain concentration due to the corresponding discontinuity in the structural component. Thus, strain gauges must be placed outside of the stress concentration field of the welded joint.

In practice, it may be necessary firstly to evaluate the extension and the stress gradient of the field of stress concentration (see 2.2.3.4) due to the welded joint. For further measurements, simple strain gauge application outside this field is sufficient.

2.2.3 Structural Hot Spot Stress

2.2.3.1 General

The structural or geometric stress σ_{hs} at the hot spot includes all stress raising effects of a structural detail excluding all stress concentrations due to the local weld profile itself. So, the non-linear peak stress σ_{nlp} caused by the local notch, i.e. the weld toe, is excluded from the structural stress. The structural stress is dependent on the global dimensional and loading parameters of the component in the vicinity of the joint (type **C** in 2.1.3 table **{2}-1)**. It is determined on the surface at the hot spot of the component which is to be assessed. Structural hot spot stresses σ_{hs} are generally defined at plate, shell and tubular structures. Figure (2.2)-6 shows examples of structural discontinuities and details together with the structural stress distribution.

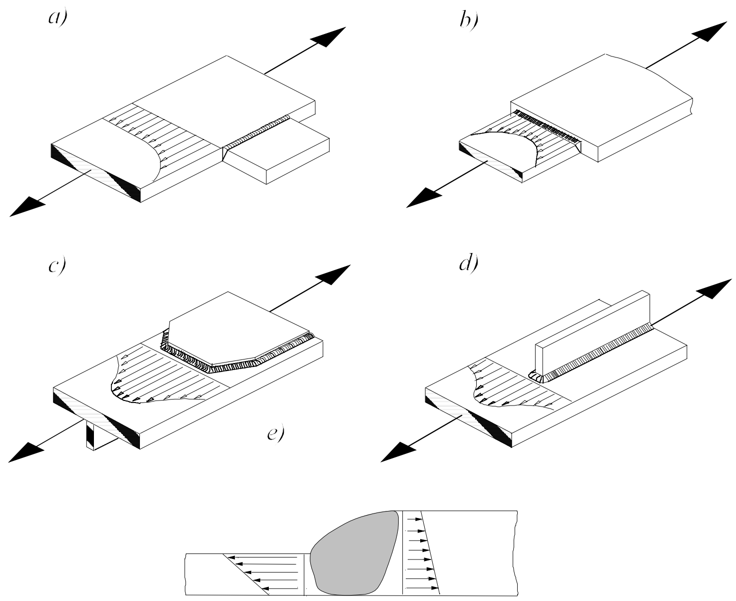


Fig. (2.2)-6 Structural details and structural stress

The structural hot spot stress approach is recommended for welded joints where there is no clearly defined nominal stress due to complicated geometric effects, and where the structural discontinuity is not comparable to a classified structural detail.

The structural hot-spot stress can be determined using reference points and extrapolation to the weld toe at the hot spot in consideration. The method as defined here is limited to the assessment of the weld toe, i.e. cases **a** to **e** in fig.(2.2)-8. It is not applicable in cases where crack will grow from the weld root and propagate through the weld metal, i.e. cases **f** to **i** in fig. (2.2)-8.

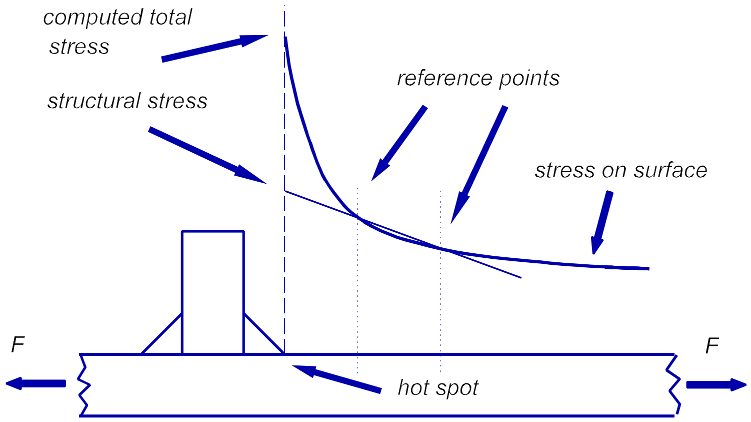


Fig. (2.2)-7 Definition of structural hot-spot stress

Note:
The method of structural hot spot stress may be extended to the assessment of spots of the welded joint suceptible to fatigue cracking other than on plate surface, e.g. on a fillet weld root. In this case, structural hot spot stress on surface is used as an indication and estimation of the stress for the spot in consideration. The S-N curves or structural hot spot stress concentration factors used for verification in this case depend largely on geometric and dimensional parameters and are only valid within the range of these parameters.

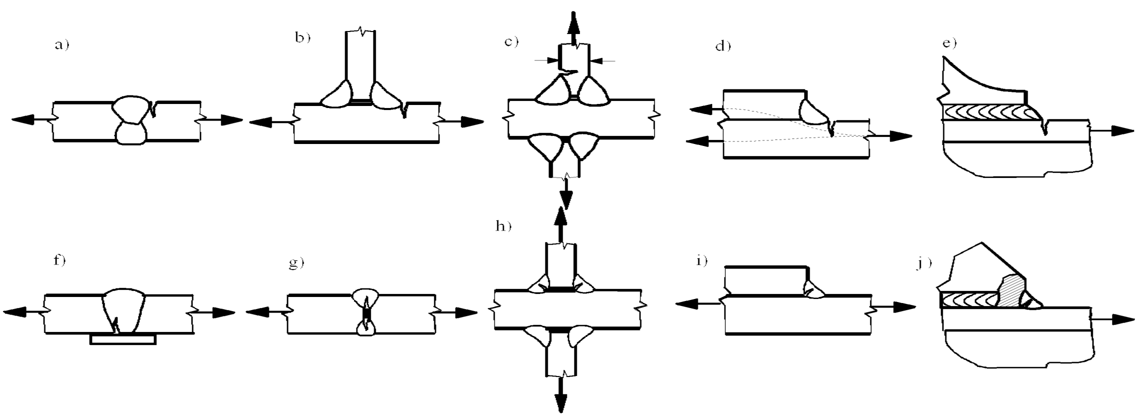


Fig. (2.2)-8: Various locations of crack propagation in welded joints.

In case of a biaxial stress state at the plate surface, it is recommeded to use the principal stress which is approximately in line with the perpendicular to the weld toe, i.e. within a deviation of ±60° (fig. 2.2-9). The other principal stress may be analysed, if necessary, using the fatigue class for parallel welds in the nominal stress approach.

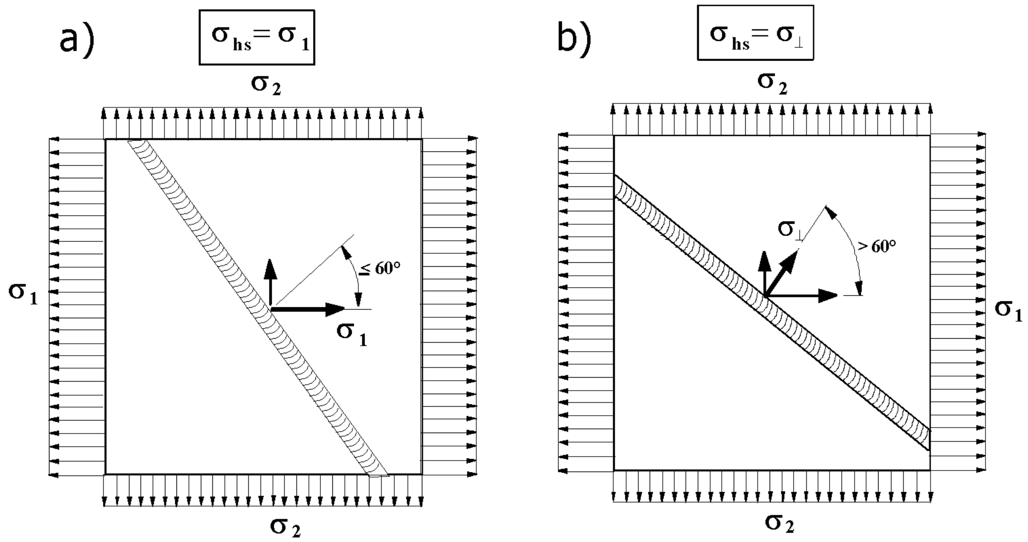


Fig. (2.2)-9 Biaxial stress at weld toe

2.2.3.2 Types of hot spots

Besides the definitions of structural hot spot stress as given above, two types of hot spots have to be distiguished according to their location on the plate and their orientation to the weld toe:

Tab. {2.2}-1: Types of hot spots

Type	Description	Determination
a	Structural hot spot stress transverse to weld toe on plate surface	Special FEA procedure or measurement and extrapolation
b	Structural hot spot stress transverse to weld toe at plate edge	Special FEA procedure or measurement and extrapolation

2.2.3.3 Determination of Structural Hot Spot Stress

Determination of structural hot spot stress can be done either by measurement or by calculation. Here the non-linear peak stress is eleminated by linearisation of the stress through the plate thickness (see 2.2.1) or by extrapolation of the stress at the surface to the weld toe. The following considerations focus on extrapolation procedures of the surface stress, which are nearly the same in measurement and calculation.

Firstly the stresses at the reference points, i.e. extrapolation points, have to be determined, secondly the structural hot spot stress has to be determined by extrapolation to the weld toe.

The structural hot spot stress may be determined using two or three stress or strain values at particular reference points apart from the weld toe in direction of stress. The closest position to the weld toe must be chosen to avoid any influence of the notch due to the weld itself (which leads to a non-linear stress peak). This is practically the case at a distance of **0.4 t** from the weld toe, where **t** is plate thickness. The structural hot spot stress at the weld toe is then obtained by extrapolation.

Identification of the critical points (hot spots) can be made by:

a) measuring several different points
b) analysing the results of a prior FEM analysis
c) experience of existing components, which failed

2.2.3.4 Calculation of Structural Hot Spot Stress

In general, analysis of structural discontinuities and details to obtain the structural hot spot stress is not possible using analytical methods. Parametric formulae are rarely available. Thus, finite element (FEM) analysis is mostly applied.

Usually, structural hot spot stress is calculated on the basis of an idealized, perfectly aligned welded joint. Consequently, any possible misalignment has to be taken explicitely into consideration by the FEA model or by an appropriate stress magnification factor k_m, see also 3.8.2. This applies particularly to butt welds, cruciform joints and one-sided transverse fillet welds at free, unsupported plates.
The extent of the finite element model has to be chosen such that constraining boundary effects of the structural detail analysed are comparable to the actual structure.

Models with thin plate or shell elements or alternatively with solid elements may be used. It should be noted that on the one hand the arrangement and the type of the elements have to allow for steep stress gradients as well as for the formation of plate bending, and on the other hand, only the linear stress distribution in the plate thickness direction needs to be

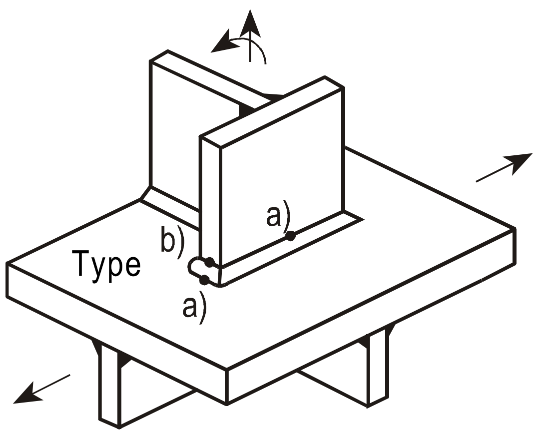


Fig. (2.2)-10: Types of Hot Spots

evaluated with respect to the definition of the structural hot spot stress. The stresses should be determined at the specified reference points.

For FEM analysis, sufficient expertise of the analyst is required. Guidance is given in [2-3]. In the following, only some rough recommendations are given:

In a **plate or shell element** model (Fig. (2.2)-11, left part), the elements have to be arranged in the mid-plane of the structural components. 8-noded elements are recommended particularly in case of steep stress gradients. In simplified models, the welds are not modelled, except for cases where the results are affected by local bending, e. g. due to an offset between plates or due to the small distance between adjacent welds. Here, the welds may be included by vertical or inclined plate elements having appropriate stiffness or by introducing constraint equations or rigid links to couple node displacements. Thin-shell elements naturally provide a linear stress distribution over the shell thickness, suppressing the notch stresses at weld toes. Nevertheless, the structural hot-spot stress is frequently determined by extrapolation from the reference points mentioned before, particularly at points showing an additional stress singularity such as stiffener ends.

An alternative particularly for complex cases is recommended using prismatic **solid elements** which have a displacement function allowing steep stress gradients as well as plate bending with linear stress distribution in the plate thickness direction. This is offered, e. g. by isoparametric 20-node elements with mid-side nodes at the edges, which allow only one element to be arranged in the plate thickness direction due to the quadratic displacement function and the linear stress distribution. At a reduced integration, the linear part of the stresses can be directly evaluated at the shell surface and extrapolated to the weld toe. Modelling of welds is generally recommended as shown in fig. (2.2)-11 (right part). The alternative with a multi-layer arrangement of solid elements allows to linearise the stresses over the plate thickness directly at the weld toe, using the stresses evaluated from the elements butting from the plate side.

If the structural hot-spot stress is determined by extrapolation, the **element lengths** are determined by the reference points selcted for stress evaluation. In order to avoid an influence of the stress singularity, the stress closest to the hot spot is usually evaluated at the first nodal point. Therefore, the length of the element at the hot spot corresponds to its distance from the first reference point. If finer meshes are used, the refinement should be inroduced in the thickness direction as well. Coarser meshes are also possible with higher-order elements and fixed lengths, as further explained below.

Appropriate element widths are important particularly in cases with steep stress gradients. The width of the solid element or the two shell elements in front of the attachment should not exceed the attachment width '**w**', i. e. the attachment thickness plus two weld leg lengths. See also figure (2.2)-11.

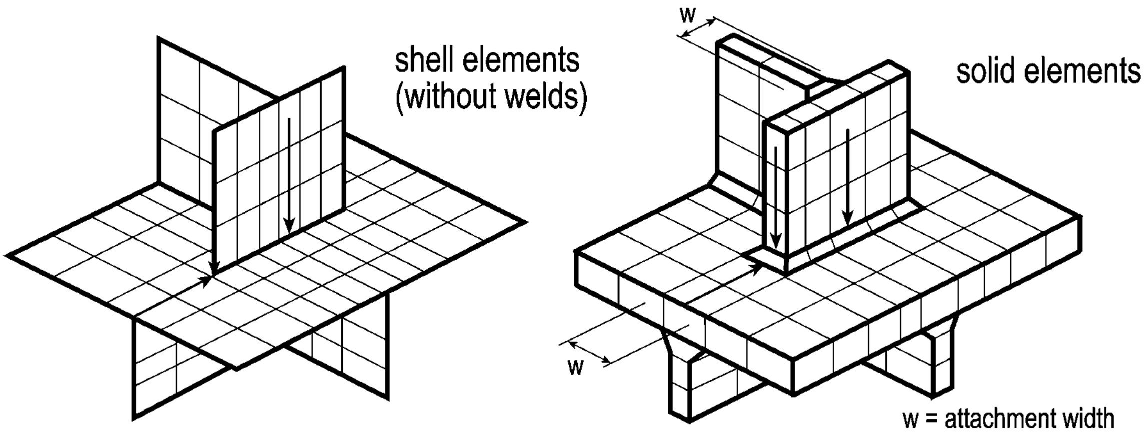


Fig. (2.2)-11: Typical meshes and stress evaluation paths for a welded detail

Usually, the structural hot spot stress components are evaluated on the plate surface or edge. Typical extrapolation paths are shown by arrows in fig. (2.2)-11. If the weld is not modelled, it is recommended to extrapolate the stress to the structural intersection point in order to avoid stress underestimation due to the missing stiffness of the weld.

Type "a" hot spots:

The structural hot spot stress $\boldsymbol{\sigma_{hs}}$ is determined using the reference points and extrapolation equations as given below (see also fig. (2.2)-12).

1) Fine mesh with element length not more than **0.4 t** at hot spot: Evaluation of nodal stresses at two reference points **0.4 t** and **1.0 t**, and linear extrapolation (eq. 1).

$$\sigma_{hs} = 1.67 \cdot \sigma_{0.4 \cdot t} - 0.67 \cdot \sigma_{1.0 \cdot t} \qquad (1)$$

2) Fine mesh as defined above: Evaluation of nodal stresses at three reference points **0.4 t**, **0.9 t** and **1.4 t**, and quadratic extrapolation (eq. 2). This method is recommended in cases with pronounced non-linear structural stress increase to the hot spot, at sharp diversions of force or at thickwalled structures.

$$\sigma_{hs} = 2.52 \cdot \sigma_{0.4 \cdot t} - 2.24 \cdot \sigma_{0.9 \cdot t} + 0.72 \cdot \sigma_{1.4 \cdot t} \qquad (2)$$

3) Coarse mesh with higher-order elements having lengths equal to plate thickness at the hot spot: Evaluation of stresses at mid-side points or surface centers respectively, i.e. at two reference points **0.5 t** and **1.5 t**, and linear extrapolation (eq. 3).

$$\sigma_{hs} = 1.50 \cdot \sigma_{0.5 \cdot t} - 0.50 \cdot \sigma_{1.5 \cdot t} \qquad (3)$$

At the extrapolation procedures for structural hot spot stress of type **"a"**, the usual wall thickness correction shall be applied as given in chapter 3.5.2. For circular tubular joints, a wall thickness correction exponent of **n=0.4** is recommended.

Type "b" hot spots:

The stress distribution is not dependent of plate thickness. So, the reference points are given at absolute distances from the weld toe, or from the weld end if the weld does not continue around the end of the attached plate.

4) Fine mesh with element length of not more than 4 mm at the hot spot: Evaluation of nodal stresses at three reference points **4 mm**, **8 mm** and **12 mm** and quadratic extrapolation (eq. 4).

$$\sigma_{hs} = 3 \cdot \sigma_{4\ mm} - 3 \cdot \sigma_{8\ mm} + \sigma_{12\ mm} \qquad (4)$$

5) Coarse mesh with higher-order elements having length of **10 mm** at the hot spot: Evaluation of stresses at the mid-side points of the first two elements and linear extrapolation (eq. 5).

$$\sigma_{hs} = 1.5 \cdot \sigma_{5\ mm} - 0.5 \cdot \sigma_{15\ mm} \qquad (5)$$

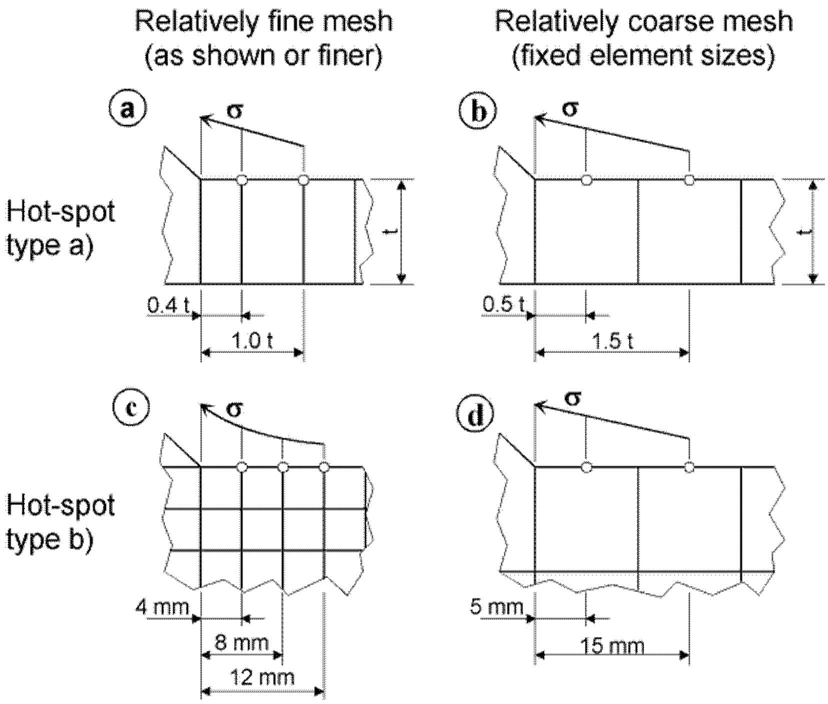


Fig. (2.2)-12: Reference points at different types of meshing

At the extrapolation procedures for structural hot spot stress of type **"b"**, a wall thickness correction exponent of **n=0.1** shall be applied.

Tab. 2.2.-2: Recommended meshing and extrapolation (see also fig. (2.2)-12)

Type of model and weld toe		Relatively coase models		Relatively fine models	
		Type a	Type b	Type a	Type b
Element size	Shells	t x t max t x w/2*)	10 x 10 mm	≤0.4 t x t or ≤0.4 t x w/2	≤ 4 x 4 mm
	Solids	t x t max t x w	10 x 10 mm	≤0.4 t x t or ≤0.4 t x w/2	≤ 4 x 4 mm
Extra-polation points	Shells	0.5 t and 1.5 t mid-side points**)	5 and 15 mm mid-side points	0.4 t and 1.0 t nodal points	4, 8 and 12 mm nodal points
	Solids	0.5 and 1.5 t surface center	5 and 15 mm surface center	0.4 t and 1.0 t nodal points	4, 8 and 12 mm nodal points

*) w = longitudinal attachment thickness + 2 weld leg lengths
**) surface center at transverse welds, if the weld below the plate is not modelled (see left part of fig. 2.2-11)

Alternative methods:

Alternative methods have been developed, which may be useful in special cases. In the method after Haibach [2-7], the stress on the surface 2 mm apart from the weld toe is determined. In the method after Xiao and Yamada [2-8], the stress 1 mm apart from the weld toe on the aticipated crack path is taken. Both methods are useful at sharp diversions of force or at thickwalled structures. In the latter method no correction of wall thickness shall be applied. A further alternative procedure after Dong [2-4] uses a special stress parameter with a consideration of wall thickness and stress gradient.

2.2.3.5 Measurement of Structural Hot Spot Stress

The recommended placement and number of strain gauges is dependent of the presence of higher shell bending stresses, the wall thickness and the type of strucutral stress.

The center point of the first gauge should be placed at a distance of **0.4 t** from the weld toe. The gauge length should not exceed **0.2 t**. If this is not possible due to a small plate thickness, the leading edge of the gauge should be placed at a distance **0.3 t** from the weld toe. The following extrapolation procedure and number of gauges are recommended:

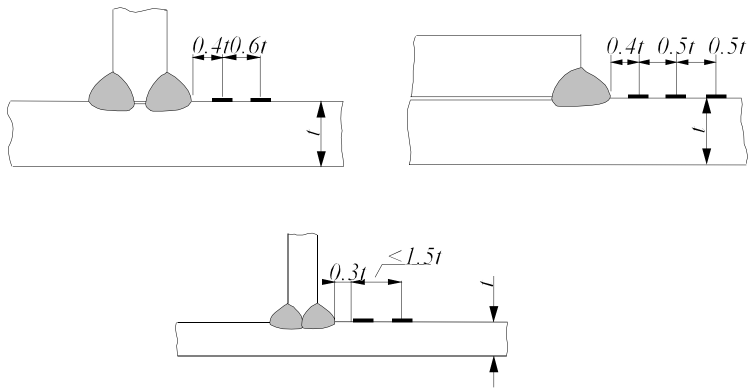


Fig. (2.2)-13: Examples of strain gauges in plate structures

Type "a" hot spots:

a) Two gauges at reference points **0.4 t** and **1.0 t** and linear extrapolation (eq. 6).

$$\varepsilon_{hs} = 1.67 \cdot \varepsilon_{0.4\ t} - 0.67 \cdot \varepsilon_{1.0\ t} \qquad (6)$$

b) Three gauges at reference points **0.4 t**, **0.9 t** and **1.4 t**, and quadratic extrapolation in cases of pronounced non-linear structural stress increase to the hot spot (eq. 7).

$$\varepsilon_{hs} = 2.52 \cdot \varepsilon_{0.4\ t} - 2.24 \cdot \varepsilon_{0.9\ t} + 0.72 \cdot \varepsilon_{1.4\ t} \qquad (7)$$

Often multi-grid strip gauges are used with fixed distances between the gauges. Then the gauges may not be located as recommended above. Then it is recommended to use e.g. four gauges and fit a curve through the results.

Type "b" hot spots:

Strain gauges are attached at the plate edge at 4, 8 and 12 mm distant from the weld toe. The hot spot strain is determined by quadratic extrapolation to the weld toe (eq. 8):

$$\varepsilon_{hs} = 3 \cdot \varepsilon_{4\ mm} - 3 \cdot \varepsilon_{8\ mm} + \varepsilon_{12\ mm} \qquad (8)$$

Tubular joints:

For tubular joints, there exist recommendations which allow the use of linear extrapolation using two strain gauges. Here, the measurement of simple uniaxial stress is sufficient. For additional details see ref. [2-6]

Determination of stress:

If the stress state is close to uniaxial, the structural hot spot stress is obtained approximately from eqn. (9).

$$\sigma_{hs} = E \cdot \varepsilon_{hs} \qquad (9)$$

At biaxial stress states, the actual stress may be up to 10% higher than obtained from eqn. (9). In this case, use of rosette strain gauges is recommended. If FEA results are available giving the ratio between longitudinal and transverse strains $\boldsymbol{\varepsilon_y/\varepsilon_x}$, the structural hot spot stress $\boldsymbol{\sigma_{hs}}$ can then be resolved from eqn. (10), assuming that this principal stress is about

$$\sigma_{hs} = E \cdot \varepsilon_x \frac{1 + \nu \frac{\varepsilon_y}{\varepsilon_x}}{1 - \nu^2} \qquad (10)$$

perpenticular to the weld toe.

Instead of absolute strains, strain ranges $\boldsymbol{\Delta\varepsilon_{max} = \varepsilon_{max} - \varepsilon_{min}}$ are usually measured and substituted in the above equations, producing the range of structural hot spot stress $\boldsymbol{\Delta\sigma_{hs}}$.

2.2.3.6 Structural Hot Spot Stress Concentration Factors and Parametric Formulae

For many joints between circular section tubes parametric formulae have been established for the stress concentration factor $\mathbf{k_{hs}}$ in terms of structural hot-spot stress at the critical points (hot spots), see ref. [2-6]. Hence the structural hot spot stress $\boldsymbol{\sigma_{hs}}$ becomes:

$$\sigma_{hs} = k_{hs} \cdot \sigma_{nom} \qquad (11)$$

where $\boldsymbol{\sigma_{nom}}$ is the nominal axial membrane stress in the braces, calculated by elementary stress analysis.

2.2.4 Effective Notch Stress

2.2.4.1 General

Effective notch stress is the total stress at the root of a notch, obtained assuming linear-elastic material behaviour. To take account of the statistical nature and scatter of weld shape parameters, as well as of the non-linear material behaviour at the notch root, the real weld contour is replaced by an effective one. For structural steels and aluminium an effective notch root radius of **r = 1 mm** has been verified to give consistent results. For fatigue assessment, the effective notch stress is compared with a common fatigue resistance curve.

The method is restricted to welded joints which are expected to fail from the weld toe or weld root. The fatigue assessment has to be additionally performed at the weld toes for the parent material using the structural hot-spot stress (see chapter 2.2.3) and the associated FAT class for parent material. Other causes of fatigue failure, e.g. from surface roughness or embedded defects, are not covered. Also it is also not applicable where considerable stress components parallel to the weld or parallel to the root gap exist.

The method is also restricted to assessment of naturally formed as-welded weld toes and roots. At weld toes, an effective notch stress of at least **1.6** times the structural hot-spot stress should be assumed.

The method is well suited to the comparison of alternative weld geometries. Unless otherwise specified, flank angles of 30° for butt welds and 45° for fillet welds are suggested.

The method is limited to thicknesses **t >= 5 mm**. For smaller wall thicknesses, the method has not yet been verified.

At machined or ground welds, toes or roots shall be assessed using the real notch stress and the nominal stress fatigue resistance value of a butt weld ground flush to plate. Here, the difference between k_t (geometric notch factor as calculated by FEA) and k_f (notch factor effective for fatigue) might be considered.

2.2.4.2 Calculation of Effective Notch Stress

Effective notch stresses or stress concentration factors can be calculated by parametric formulae, taken from diagrams or calculated from finite element or boundary element models. The effective notch radius is introduced such that the tip of the radius touches the root of the real notch, e.g. the end of an unwelded root gap.

For the determination of effective notch stress by FEA, element sizes of not more that 1/6 of the radius are recommended in case of linear elements, and 1/4 of the radius in case of higher order elements. These sizes have to be observed in the curved parts as well as in the beginning of the straight part of the notch surfaces in both directions, tangential and normal to the surface.

Possible misalignment has to be considered in the calculations.

2.2.4.3 Measurement of Effective Notch Stress

Because the effective notch radius is an idealization, the effective notch stress cannot be measured directly in the welded component. In contrast, the simple definition of the effective notch can be used for photo-elastic stress measurements in resin models.

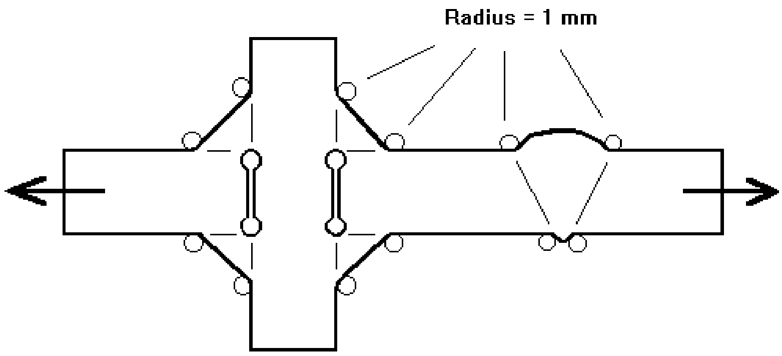


Fig. (2.2)-14 Fictitious rounding of of weld toes and roots

2.2.5 Stress Intensity Factors

2.2.5.1 General

Fracture mechanics assumes the existence of an initial crack $\mathbf{a_i}$. It can be used to predict the growth of the crack to a final size $\mathbf{a_f}$. Since for welds in structural metals, crack initiation occupies only a small portion of the life, this method is suitable for assessment of fatigue life, inspection intervals, crack-like weld imperfections and the effect of variable amplitude loading.

The parameter which describes the fatigue action at a crack tip in terms of crack propagation is the stress intensity factor (SIF) range $\mathbf{\Delta K}$.

Fracture mechanics calculations generally have to be based on total stress at the notch root, e.g. at the weld toe. For a variety of welded structural details, correction functions for the local notch effect and the nonlinear stress peak of the structural detail have been established. Using these correction functions, fracture mechanics analysis can be based on Structural hot spot stress or even on nominal stress. The correction function formulae may be based on different stress types. The correction function and the stress type have to correspond.

2.2.5.2 Calculation of Stress Intensity Factors by Parametric Formulae

First, the local nominal stress or the structural hot spot stress at the location of the crack has to be determined, assuming that no crack is present. The stress should be separated into membrane and shell bending stresses. The stress intensity factor (SIF) **K** results as a superposition of the effects of both stress components. The effect of the remaining stress raising discontinuity or notch (non-linear peak stress) has to be covered by additional factors $\mathbf{M_k}$.

$$K = \sqrt{\pi \cdot a} \cdot (\sigma_{mem} \cdot Y_{mem} \cdot M_{k,mem} + \sigma_{ben} \cdot Y_{ben} \cdot M_{k,ben})$$

where

$\mathbf{K}$	stress intensity factor
σ_{mem}	membrane stress
σ_{ben}	shell bending stress
$\mathbf{Y_{mem}}$	correction function for membrane stress intensity factor
$\mathbf{Y_{ben}}$	correction function for shell bending stress intensity factor
$\mathbf{M_{k,\,mem}}$	correction for non-linear stress peak in terms of membrane action
$\mathbf{M_{k,\,ben}}$	correction for non-linear stress peak in terms of shell bending

The correction functions $\mathbf{Y_{mem}}$ and $\mathbf{Y_{ben}}$ can be found in the literature. The solutions in ref. [4-1 to 4-6] are particularly recommended. For most cases, the formulae for stress intensity factors given in appendix 6.2 are adequate. $\mathbf{M_k}$-factors may be found in references [4-7] and [4-8].

2.2.5.3 Calculation of Stress Intensity Factors by Finite Elements

Stress intensity factor determination methods are usually based on FEA analyses. They may be directly calculated as described in the literature, or indirectly using the weight function approach. For more details see appendix 6.2

2.2.5.4 Assessment of Welded Joints without Detected Cracks

Fracture mechanics may be used to assess the fatigue properties of welded joints at which no cracks have been detected. For a conservative approach, it is recommended to calculate the number of life cycles according to chapters 3.8.5 and 4.4.

For cracks starting from weld toe, an initial crack depth of **a = 0.15 mm** and an aspect ratio of **a:c = 1:10** should be assumed. For root cracks e.g. at fillet welds, the root gap should be taken as an initial crack.

2.3 STRESS HISTORY

2.3.1 General

The fatigue design data presented in chapter 3 were obtained from tests performed under constant amplitude loading. However, loads and the resulting fatigue actions (i.e. stresses) on real structures usually fluctuate in an irregular manner and give rise to variable amplitude loading. The stress amplitude may vary in both magnitude and period from cycle to cycle.

The stress history is a record and/or a representation of the fluctuations of the fatigue actions in the anticipated service time of the component. It is described in terms of successive maxima and minima of the stress caused by the fatigue actions. It covers all loading events and the corresponding induced dynamic response.

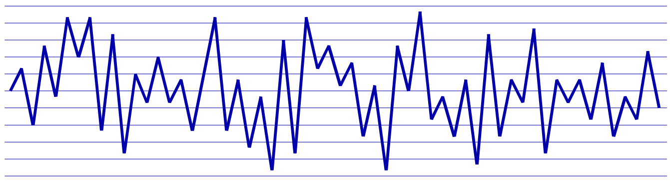


Fig. (2.3)-1 Stress time history illustration

In most cases, the stress-time history is stationary and ergodic, which allows the definition of a mean range and its variance, a statistical histogram and distribution, an energy spectrum and a maximum values probabilistic distribution from a representation of a limited length. Therefore, the data needed to perform a fatigue analysis can be determined from measurements conducted during a limited time.

A stress history may be given as

a) a record of successive maxima and minima of stress measured in a comparable structure with comparable loading and service life, or a typical sequence of load events.

b) a two dimensional transition matrix of the stress history derived from a).

c) a one- or two-dimensional stress range histogram (stress range occurrences) obtained from a) by a specified counting method.

d) a one-dimensional stress range histogram (stress range exceedances, stress range spectrum) specified by a design code.

The representations a) and b) may be used for component testing. c) and d) are most useful for fatigue analysis by calculation.

2.3.2 Cycle Counting Methods

Cycle counting is the process of converting a variable amplitude stress sequence into a spectrum. Different methods of counting are in use, e.g. zero crossing counting, peak counting, range pair counting or rainflow counting. For welded components, the reservoir or rainflow method is recommended for counting stress ranges [7-1 and 7-2].

2.3.3 Cumulative Frequency Diagram (Stress Spectrum)

The cumulative frequency diagram (stress spectrum) corresponds to the cumulative probability of stress range expressed in terms of stress range level exceedances versus the number of cycles. The curve is therefore continuous.

The spectrum may be discretized giving a table of discrete blocks. For damage calculations up to 20 stress levels may be appropriate. All cycles in a block should be assumed to be equal to the mean of the stress ranges in the block.

Besides the representation in probabilities, a presentation of the number of occurrences or exceedances in a given number of cycles, e.g. 1 million, is used. An example showing a Gaussian normal distribution is given below:

Tab. {2.3}-1: Example of a stress range occurrance table (stress histogram or frequency)

# of block	Relative stress range	Occurrence (frequency)
1	1.000	2
2	0.950	16
3	0.850	280
4	0.725	2720
5	0.575	20000
6	0.425	92000
7	0.275	280000
8	0.125	605000

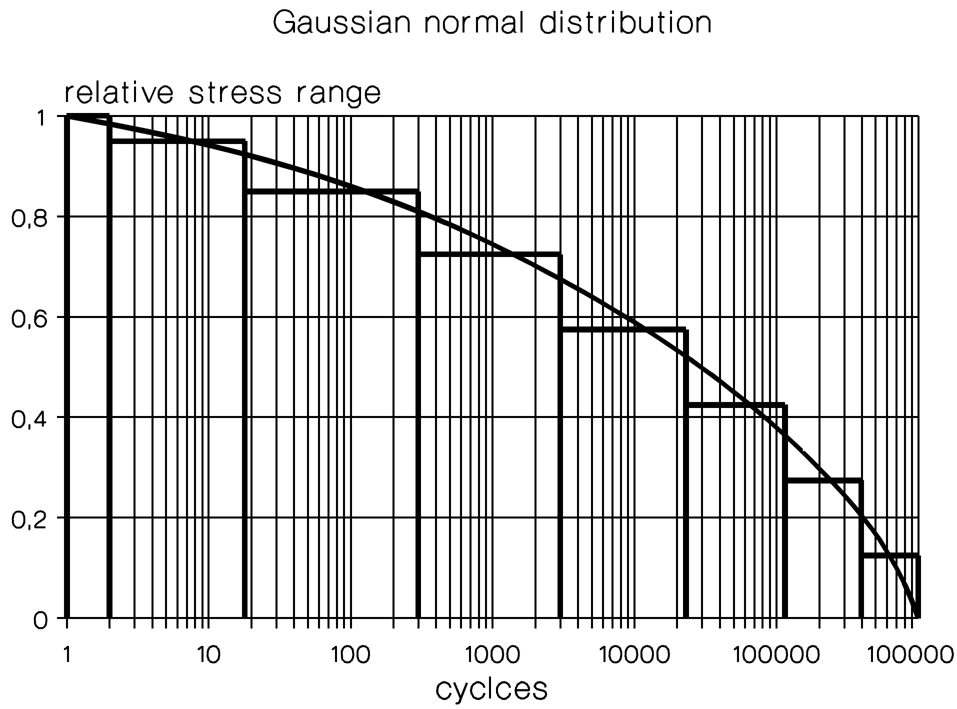


Fig. (2.3)-2 Example of a cumulative frequency diagram (stress spectrum)

3 FATIGUE RESISTANCE

3.1 BASIC PRINCIPLES

Fatigue resistance is usually derived from constant or variable amplitude tests. The fatigue resistance data given here are based on published results from constant amplitude tests. Guidance on the direct use of test data is given in section 3.7 and 4.5.

The fatigue resistance data must be expressed in terms of the same type of stress as used in controlling or determining at the generation of those data.

In conventional endurance testing, there are different definitions of failure. In general, small specimens are tested to complete rupture, while in large components the observation of a through wall crack is taken as a failure criterion. The fatigue resistance data are based on the number of cycles **N** to failure. The data are represented in S-N curves

$$N = \frac{C}{\Delta\sigma^m} \qquad or \qquad N = \frac{C}{\Delta\tau^m}$$

In fracture mechanics crack propagation testing, the crack growth rate data are derived from crack propagation monitoring.

All fatigue resistance data are given as characteristic values, which are assumed to have a survival probability of at least 95%, calculated from a mean value of a two-sided 75% confidence level, unless otherwise stated (see 3.7).

The (nominal) stress range should be within the limits of the elastic properties of the material. The range of the design values of the stress range shall not exceed $\mathbf{1.5 \cdot f_y}$ for nominal normal stresses or $\mathbf{1.5 \cdot f_y/\sqrt{3}}$ for nominal shear stresses.

The fatigue resistance of a weld is limited by the fatigue resistance of the base material.

3.2 FATIGUE RESISTANCE OF CLASSIFIED STRUCTURAL DETAILS

The fatigue assessment of classified structural details and welded joints is based on the nominal stress range. In most cases structural details are assessed on the basis of the maximum principal stress range in the section where potential fatigue cracking is considered. However, guidance is also given for the assessment of shear loaded details, based on the maximum shear stress range. Separate S-N curves are provided for consideration of normal or shear stress ranges, as illustrated in figures (3.2)-1 and (3.2)-2 respectively.

Care must be taken to ensure that the stress used for the fatigue assessment is the same as that given in the tables of the classified structural details. Macro-structural hot spot stress concentrations not covered by the structural detail of the joint itself, e.g. large cutouts in the vicinity of the joint, have to be accounted for by the use of a detailed stress analysis, e.g. finite element analysis, or appropriate stress concentration factors (see 2.2.2).

The fatigue curves are based on representative experimental investigations and thus include the effects of:

structural hot spot stress concentrations due to the detail shown
local stress concentrations due to the weld geometry
weld imperfections consistent with normal fabrication standards
stress direction
welding residual stresses
metallurgical conditions
welding process (fusion welding, unless otherwise stated)
inspection procedure (NDT), if specified
postweld treatment, if specified

Furthermore, within the limits imposed by static strength considerations, the fatigue curves of welded joints are practically independent of the tensile strength of the material.

Each fatigue strength curve is identified by the characteristic fatigue strength of the detail in MPa at 2 million cycles. This value is the fatigue class (FAT).

The slope of the fatigue strength curves for details assessed on the basis of normal stresses (fig. (3.2)-1...3) is **m=3.00** if not stated expressedly otherwise. The constant amplitude knee point is at **$1\cdot 10^7$ cycles**.

The slope of the fatigue strength curves for details assessed on the basis of shear stresses (fig. (3.2)-4..6) is **m=5.00**, but in this case the knee point is at **10^8 cycles**.

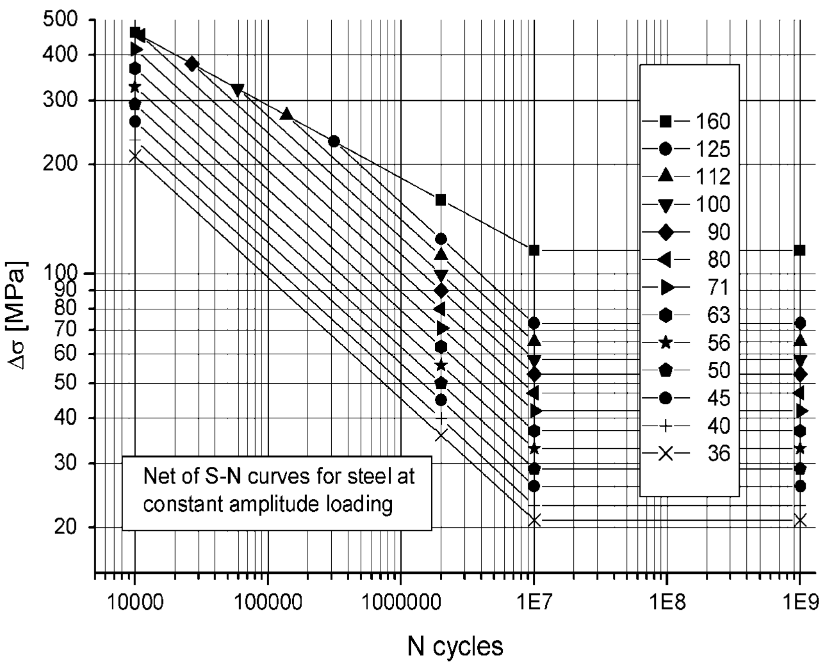


Fig. (3.2)-1: Fatige resistance S-N curves for steel, normal stress, standard applications

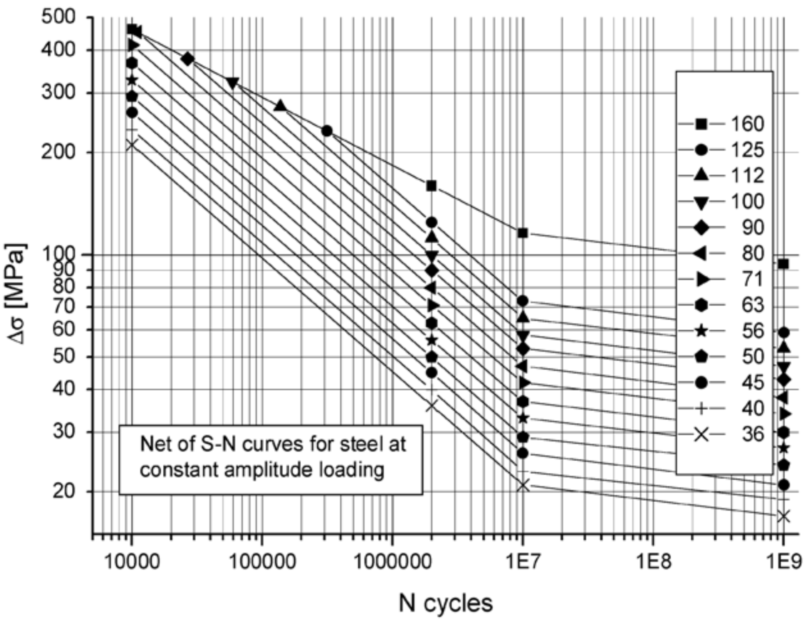


Fig. (3.2)-2: Fatigue resistance S-N curves for steel, normal stress, very high cycles applications

The fatigue resistance of welded steel components at higher cycles than the knee point isstill in discussion. New experimental data indicate a further decline of about 10% per decade in terms of cycles, which corresponds to a slope of **m=22**. This fact may be of interest at very high cycles as they are encountered in e.g. rotating engines. The user should consult the newest relevant literature. Here, two sets of SN curves are given representing the conventional design and the recommendations for the very high cycle regime.

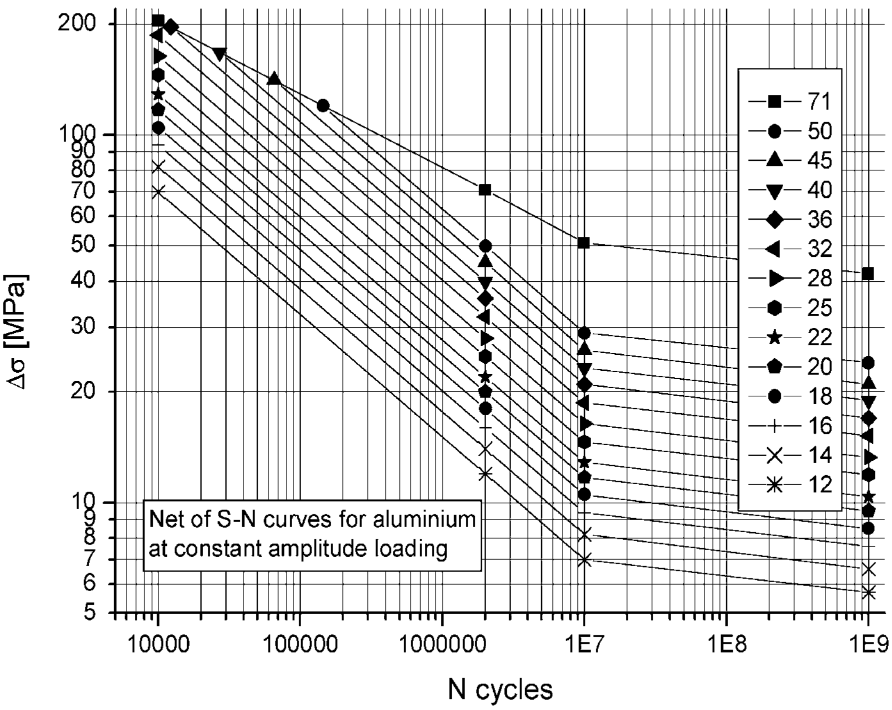


Fig. (3.2)-3: Fatigue resistance S-N curves for aluminium, normal stress

The fatigue resistance of welded aluminium components at higher cycles than the knee point is described by a further decline of about 10% per decade in terms of cycles, which corresponds to a slope of **m=22**.

The descriptions of the structural details only partially include information about the weld size, shape and quality. The data refer to a standard quality as given in codes and standard welding procedures. For higher or lower qualities, conditions of welding may be specified and verified by test (3.7).

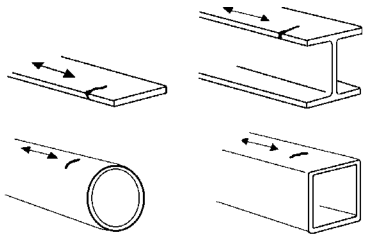
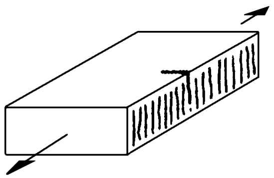
The fatigue classses given in table {3.2-1} shall be modified as given in 3.5. The limitations of weld imperfections shall be considered (3.8).

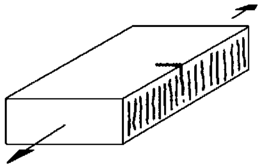
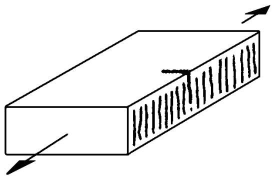
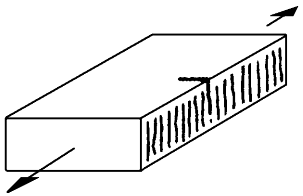
All butt welds shall be full penetration welds without lack of fusion, unless otherwise stated.

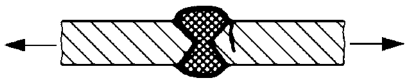
All S-N curves of details are limited by the material S-N curve, which may vary due to different strengths of the materials. A higher fatigue class for the material than 160 may be chosen if verified by test.

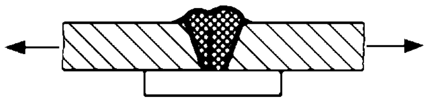
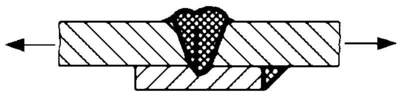
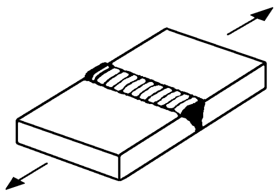
Disregarding major weld defects, fatigue cracks originate from the weld toe, and then propagate through the base material, or from the weld root, and then propagate through the weld throat. For potential toe cracks, the nominal stress in the base material has to be calculated and compared with the fatigue resistance given in the tables. For potential root cracks, the nominal stress in the weld throat has to be calculated. If both failure modes are possible, e.g. at cruciform joints with fillet welds, both potential failure modes have to be assessed.

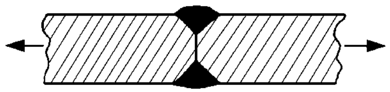
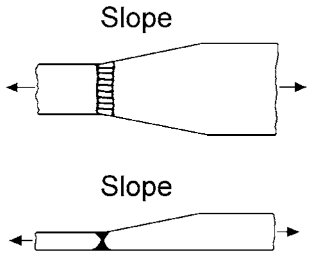
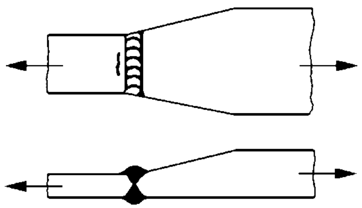
Tab. {3.2}-1: Fatigue resistance values for structural details in steel and aluminium assessed on the basis of nominal stresses.

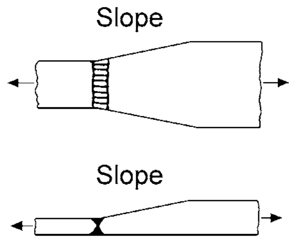
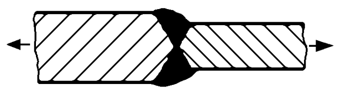
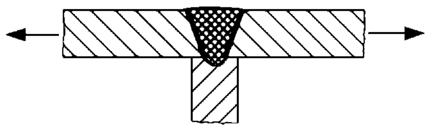
No.	**Structural Detail**	**Description (St.= steel; Al.= aluminium)**	**FAT St.**	**FAT Al.**	**Requirements and Remarks**
100	**Unwelded parts of a component**				
111		Rolled or extruded products, components with machined edges, seamless hollow sections. m = 5 St.: For high strength steels a higher FAT class may be used if verified by test. Al.: AA 5000/6000 alloys AA 7000 alloys	160	70 80	No fatigue resistance of any detail to be higher at any number of cycles! Sharp edges, surface and rolling flaws to be removed by grinding. Any machining lines or grooves to be parallel to stresses!
121		Machine gas cut or sheared material with subsequent dressing, no cracks by inspection, no visible imperfections m = 3	140	---	All visible signs of edge imperfections to be removed. The cut surfaces to be machined or ground, all burrs to be removed. No repair by welding refill! Notch effects due to shape of edges have to be considered.

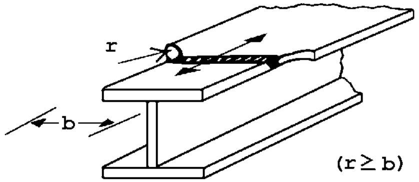
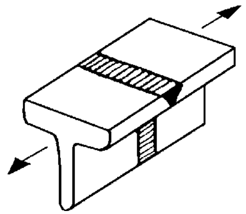
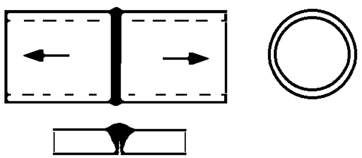
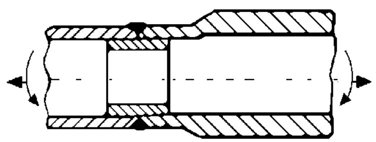
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
122		Machine thermally cut edges, corners removed, no cracks by inspection m = 3	125	40	Notch effects due to shape of edges have to be considered.
123		Manually thermally cut edges, free from cracks and severe notches m = 3	100	---	Notch effects due to shape of edges have to be considered.
124		Manually thermally cut edges, uncontrolled, no notch deeper than 0.5 mm m = 3	80	---	Notch effects due to shape of edges have to be considered.

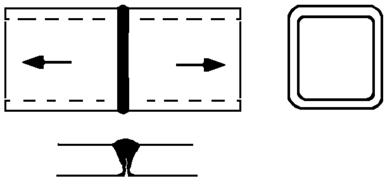
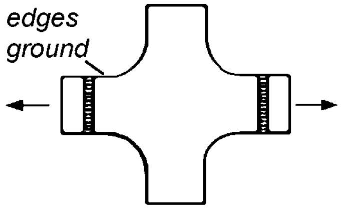
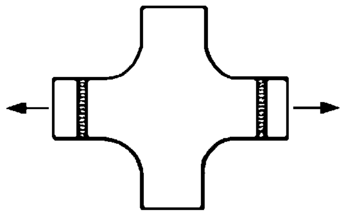
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
200	**Butt welds, transverse loaded**				
211		Transverse loaded butt weld (X-groove or V-groove) ground flush to plate, 100% NDT	112	45	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignement < 5% of plate thickness. Required quality cannot be inspected by NDT !
212		Transverse butt weld made in shop in flat position, NDT weld reinforcement < 0.1 · thickness	90	36	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignment <5% of plate thickness.
213		Transverse butt weld not satisfying conditions of 212, NDT Al.: Butt weld with toe angle ≤50° Butt welds with toe angle >50°	80	 32 25	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignment <10% of plate thickness.

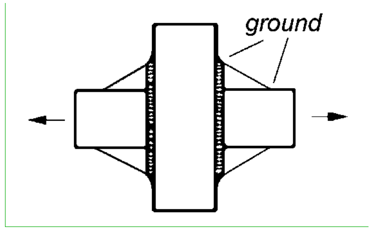
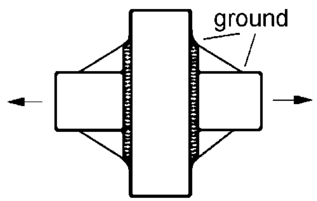
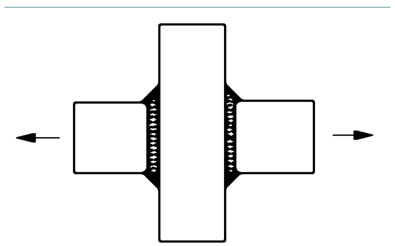
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
214		Transverse butt weld, welded on non-fusible backing, root crack	80	28	Backing removed, root visually inspected. Misalignment <10% of plate thickness.
215		Transverse butt weld on permanent backing bar terminating >10 mm from plate edge, else –>	71 63	25 22	Misalignment <10% of plate thickness.
216		Transverse butt welds welded from one side without backing bar, full penetration root controlled by NDT no NDT	 71 36	 28 12	Misalignment <10% of plate thickness.

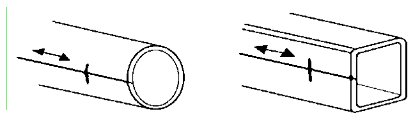
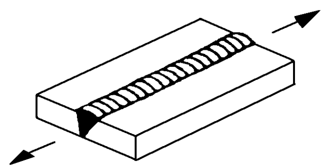
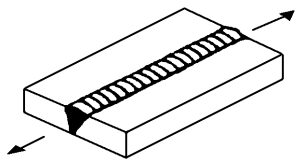
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
217		Transverse partial penetration butt weld, analysis based on stress in weld throat sectional area, weld overfill not to be taken into account.	36	12	The detail is not recommended for fatigue loaded members. Assessment by notch stress or fracture mechanics is preferred.
221	 	Transverse butt weld ground flush, NDT, with transition in thickness and width slope 1:5 slope 1:3 slope 1:2	 112 100 90	 45 40 32	All welds ground flush to surface, grinding paralell to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Misalignment due to thickness step by design to be considered, see chapter 3.8.2. Additional misalignment due to fabrication imperfection < 5% of plate thickness.
222		Transverse butt weld made in shop, welded in flat position, weld profile controlled, NDT, with transition in thickness and width: slope 1:5 slope 1:3 slope 1:2	 90 80 72	 32 28 25	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Misalignment due to thickness step by design to be considered, see chapter 3.8.2. Additional misalignment due to fabrication imperfection < 5% of plate thickness.

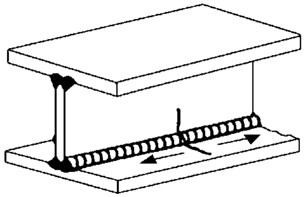
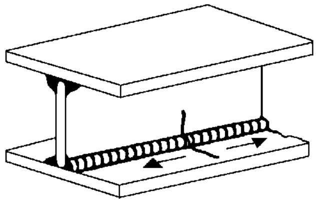
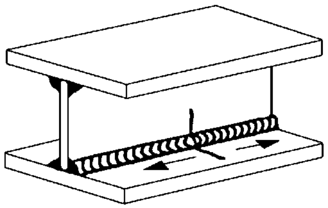
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
223		Transverse butt weld, NDT, with transition on thickness and width slope 1:5 slope 1:3 slope 1:2	 80 71 63	 25 22 20	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Misalignment due to thickness step by design to be considered, see chapter 3.8.2. Additional misalignment due to fabrication imperfection < 10% of plate thickness.
224		Transverse butt weld, different thicknesses without transition, centres aligned. In cases, where weld profile is equivalent to a moderate slope transition, see no. 222	71	22	Misalignment <10% of plate thickness. If centers are not aligned by design, this misalignment has to be considered, see chapter 3.8.2.
225		Three plate connection, root crack	71	22	Misalignment <10% of plate thickness.

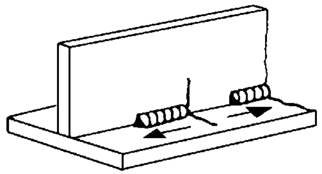
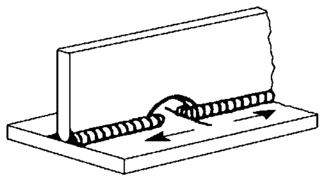
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
226		Transverse butt weld flange splice in built-up section welded prior to the assembly, ground flush, with radius transition, NDT	100	40	All welds ground flush to surface, grinding paralell to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress.
231		Transverse butt weld splice in rolled section or bar besides flats, ground flush, NDT	80	28	All welds ground flush to surface, grinding paralell to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress.
232		Transverse butt weld splice in circular hollow section, welded from one side, full penetration, root crack root inspected by NDT no NDT	 71 36	 28 12	Welded in flat position.
233		Tubular joint with permanent backing	71	28	Welded in flat position.

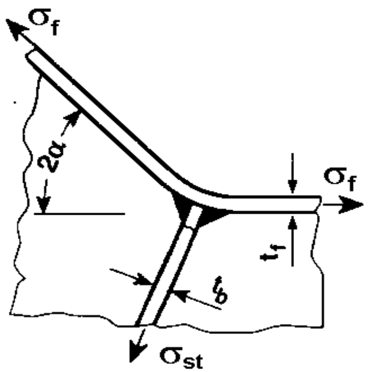
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
234		Transverse butt weld splice in rectangular hollow section, welded from one side, full penetration, root crack root inspected by NDT no NDT	 56 36	 25 12	Welded in flat position.
241		Transverse butt weld ground flush, weld ends and radius ground, 100% NDT at crossing flanges, radius transition.	100	40	All welds ground flush to surface, grinding paralell to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. No misalignment. Required weld quality cannot be inspected by NDT
242		Transverse butt weld made in shop at flat position, weld profile controlled, NDT, at crossing flanges, radius transition	90	36	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides.Misalignment <5% of plate thickness.

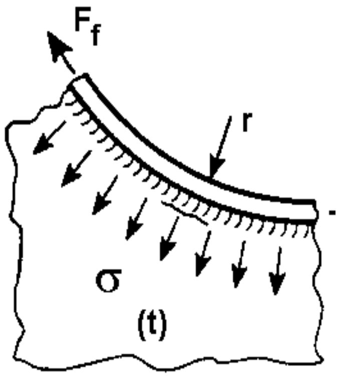
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
243		Transverse butt weld ground flush, NDT, at crossing flanges with welded triangular transition plates, weld ends ground. Crack starting at butt weld. For crack of throughgoing flange see details 525 and 526!	80	32	All welds ground flush to surface, grinding paralell to direction of stress. Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignment <10% of plate thickness.
244		Transverse butt weld, NDT, at crossing flanges, with welded triangular transition plates, weld ends ground. Crack starting at butt weld. For crack of throughgoing flange see details 525 and 526!	71	28	Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignment <10% of plate thickness.
245		Transverse butt weld at crossing flanges. Crack starting at butt weld. For crack of throughgoing flange see details 525 and 526!	50	20	Welded from both sides. Misalignment <10% of plate thickness.

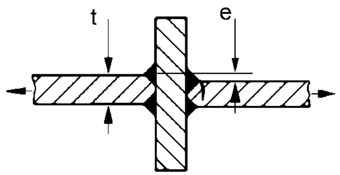
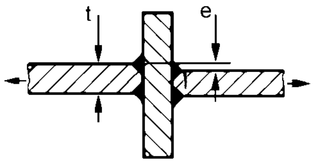
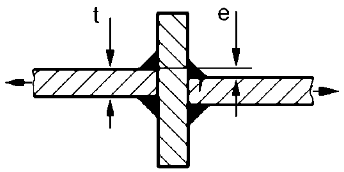
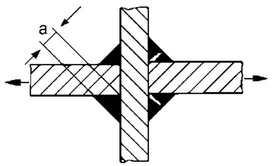
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
300	**Longitudinal load-carrying welds**				
311		Automatic longitudinal seam welds without stop/start positions in hollow sections with stop/start positions	125 90	50 36	
312		Longitudinal butt weld, both sides ground flush parallel to load direction	125	50	
313		Longitudinal butt weld, without stop/start positions, NDT with stop/start positions	125 90	50 36	

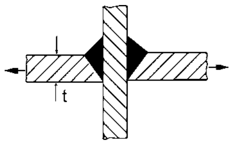
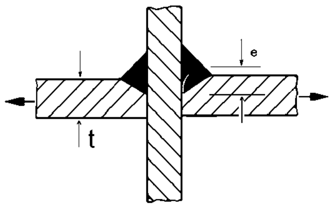
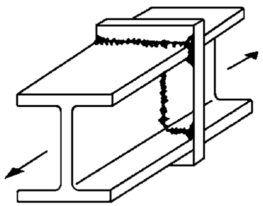
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
321		Continuous automatic longitudinal fully penetrated K-butt weld without stop/-start positions (based on stress range in flange) NDT	125	50	No start-Stop position is permitted except when the repair is performed by a specialist and inspection is carried out to verify the proper execution of the weld.
322		Continuous automatic longitudinal double sided fillet weld without stop/start positions (based on stress range in flange)	100	40	Discussion: EC3 has 112 ??
323		Continuous manual longitudinal fillet or butt weld (based on stress range in flange)	90	36	

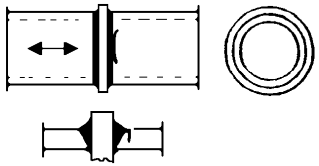
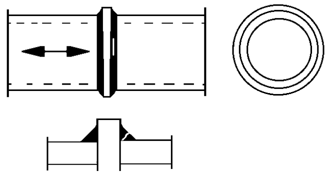
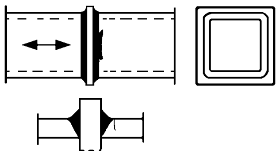
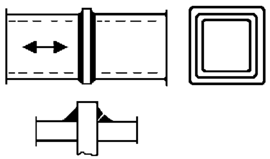
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
324		Intermittent longitudinal fillet weld (based on normal stress in flange **σ** and shear stress in web **τ** at weld ends). $\tau/\sigma =$ 0 0.0 - 0.2 0.2 - 0.3 0.3 - 0.4 0.4 - 0.5 0.5 - 0.6 0.6 - 0.7 > 0.7	 80 71 63 56 50 45 40 36	 32 28 25 22 20 18 16 14	Analysis based on normal stress in flange and shear stress in web at weld ends. Representation by formula: Steel: $FAT = 80 \cdot (1 - \Delta\tau/\Delta\sigma)$ but >=36 Alum.: $FAT = 32 \cdot (1 - \Delta\tau/\Delta\sigma)$ but >=14
325		Longitudinal butt weld, fillet weld or intermittent weld with cope holes (based on normal stress in flange **σ** and shear stress in web **τ** at weld ends), cope holes not higher than 40% of web. $\tau/\sigma =$ 0 0.0 - 0.2 0.2 - 0.3 0.3 - 0.4 0.4 - 0.5 0.5 - 0.6 > 0.6	 71 63 56 50 45 40 36	 28 25 22 20 18 16 14	Analysis based on normal stress in flange and shear stress in web at weld ends. Representation by formula: Steel: $FAT = 71 \cdot (1 - \Delta\tau/\Delta\sigma)$ but >=36 Alum.: $FAT = 28 \cdot (1 - \Delta\tau/\Delta\sigma)$ but >=14

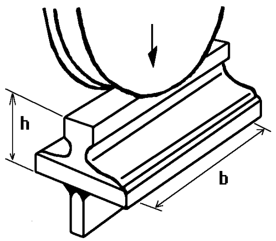
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
331		Joint at stiffened knuckle of a flange to be assessed according to no. 411 - 414, depending on type of joint. Stress in stiffener plate: $\sigma = \sigma_f \cdot \frac{A_f}{\sum A_{st}} \cdot 2 \cdot \sin\alpha$ A_f = area of flange A_{St} = area of stiffener Stress in weld throat: $\sigma = \sigma_f \cdot \frac{A_f}{\sum A_w} \cdot 2 \cdot \sin\alpha$ A_w = area of weld throat	---	---	

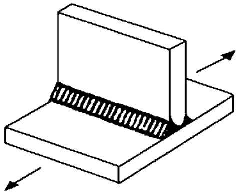
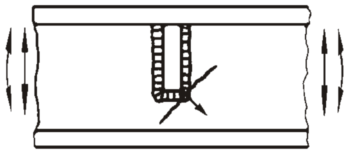
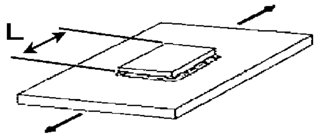
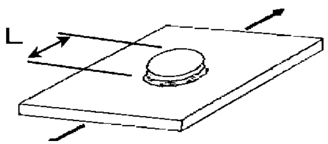
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
332		Unstiffened curved flange to web joint, to be assessed according to no. 411 - 414, depending on type of joint. Stress in web plate: $$\sigma = \frac{F_f}{r \cdot t}$$ Stress in weld throat: $$\sigma = \frac{F_f}{r \cdot \Sigma a}$$ **F_f** axial force in flange **t** thickness of web plate **a** weld throat	---	---	The resulting force of F_f-left and F_f-right will bend the flange perpendicular to the plane of main loading. In oder to minimize this additional stressing of the welds, it is recommended to minimize the width and to maximize the thickness of the flange. Stress parallel to the weld is to be considered. At additional shear, principal stress in web is to be consired (see 321 to 323)

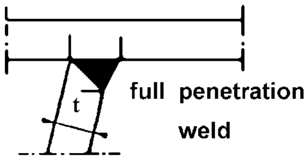
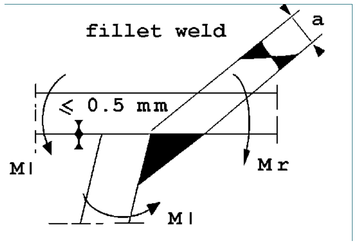
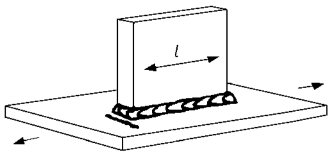
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
400	**Cruciform joints and/or T-joints**				
411		Cruciform joint or T-joint, K-butt welds, full penetration, no lamellar tearing, misalignment e<0.15·t, weld toes ground, toe crack. Single sided T-joints and cruciform joints without misalignment	80 90	28 32	Material quality of intermediate plate has to be checked against susceptibility of lamellar tearing. Misalignment <15% of primary plate.
412		Cruciform joint or T-joint, K-butt welds, full penetration, no lamellar tearing, misalignment e<0.15·t, toe crack. Single sided T-joints and cruciform joints without misalignment	71 80	25 28	Material quality of intermediate plate has to be checked against susceptibility of lamellar tearing. Misalignment <15% of loaded plate.
413		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds, no lamellar tearing, misalignment e<0.15·t, toe crack. Single sided T-joints and cruciform joints without misalignment	63 71	22 25	Material quality of intermediate plate has to be checked against susceptibility of lamellar tearing. Misalignment <15% of loaded plate. Also to be assessed as 414
414		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds including toe ground joints, weld root crack. For a/t<=1/3	36 40	12 14	Analysis based on stress in weld throat Also to bes assessed as 413. Ratio a/t is calculated from weld throat over wall thicknes

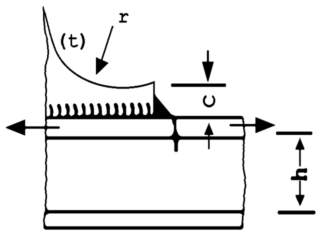
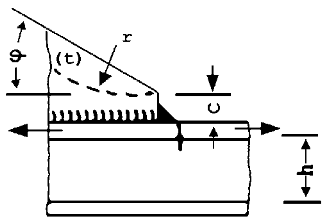
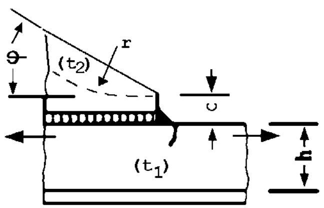
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
415		Cruciform joint or T-joint, single-sided arc or laser beam welded V-butt weld, full penetration, no lamellar tearing, misalignment e< 0.15·t, toe crack. Root inspected. If root is not inspected, then root crack	71 36	25 12	
416		Cruciform joint or T-joint, single-sided arc welded fillet or partial penetration Y-butt weld, no lamellar tearing, misalignment of plates e < 0.15·t, stress at weld root. Penetration verified.	71	25	Analysis based on axial and bending stress in weld throat. Excentricity **e** to be considered in analysis. Stress at weld root: $\boldsymbol{\Delta\sigma_{w,\,root} = \Delta\sigma_{w,\,nom} \cdot (1+6e/a)}$ **e** = excentricity between midpoints plate and weld throat **a** inclusive penetration, rotated into vertical leg plane. An analysis by effective notch stress procedure is recommended
421		Splice of rolled section with intermedia-te plate, fillet welds, weld root crack. Analysis base on stress in weld throat.	36	12	

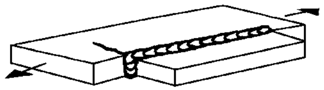
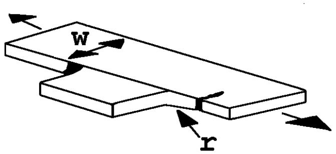
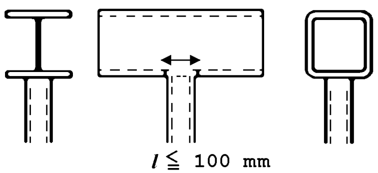
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
422		Splice of circular hollow section with intermediate plate, singlesided butt weld, toe crack wall thickness > 8 mm wall thickness < 8 mm	 56 50	 22 20	Welds NDT inspected in order to ensure full root penetration.
423		Splice of circular hollow section with intermediate plate, fillet weld, root crack. Analysis based on stress in weld throat. wall thickness > 8 mm wall thickness < 8 mm	 45 40	 16 14	
424		Splice of rectangular hollow section, single-sided butt weld, toe crack wall thickness > 8 mm wall thickness < 8 mm	 50 45	 20 18	Welds NDT inspected in order to ensure full root penetration.
425		Splice of rectangular hollow section with intermediate plate, fillet welds, root crack wall thickness > 8 mm wall thickness < 8 mm	 40 36	 16 14	

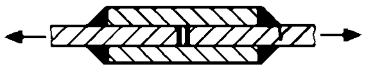
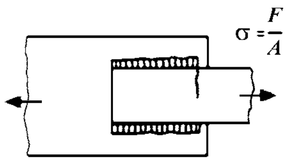
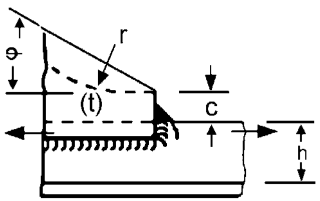
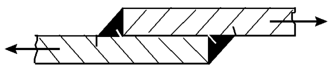
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
431		Weld connecting web and flange, loaded by a concentrated force in web plane perpendicular to weld. Force distributed on width **b = 2·h + 50 mm**. Assessment according to no. 411 - 414. A local bending due to eccentric load should be considered.	---	---	Full penetration butt weld.

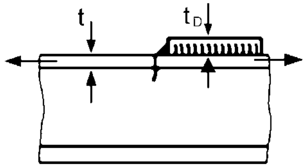
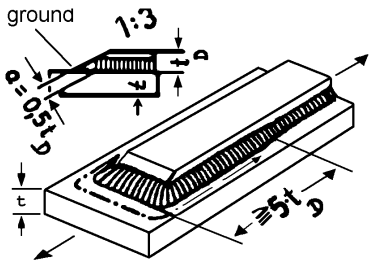
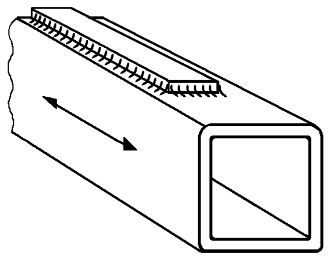
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
500	**Non-load-carrying attachments**				
511		Transverse non-load-carrying attachment, not thicker than main plate K-butt weld, toe ground Two sided fillets, toe ground Fillet weld(s), as welded thicker than main plate	 100 100- 80 71	 36 36 28 25	Grinding parallel to stress An angular misalignment corresponding to $\mathbf{k_m = 1.2}$ is already covered
512		Transverse stiffener welded on girder web or flange, not thicker than main plate. K-butt weld, toe ground Two-sided fillets, toe ground fillet weld(s): as welded thicker than main plate	 100 100 80 71	 36 36 28 25	For weld ends on web principal stress to be used
513		Non-loadcarrying rectangular or circular flat attachments or studs Non-loadcarrying studs, as welded $L \leq 50$ mm $L > 50$ and ≤ 150 mm $L > 150$ and ≤ 300 mm $L > 300$ mm	 80 71 63 50	 28 25 20 18	

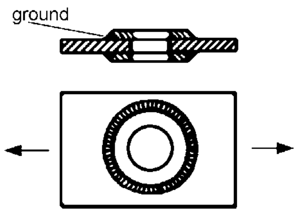
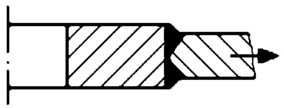
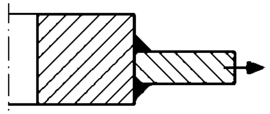
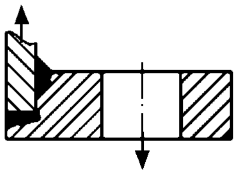
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
514		Trapezoidal stiffener to deck plate, full penetration butt weld, calculated on basis of stiffener thickness, out of plane bending	71	25	
515		Trapezoidal stiffener to deck plate, fillet or partial penetration weld, out of plane bending	50	16	Calculation on basis of stiffener thickness and weld throat, whichever is smaller
521		Longitudinal fillet welded gusset at length **l** l < 50 mm l < 150 mm l < 300 mm l > 300 mm	 80 71 63 50	 28 25 20 18	For gusset near edge: see 525 "flat side gusset"

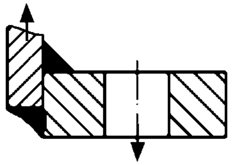
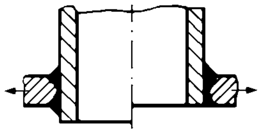
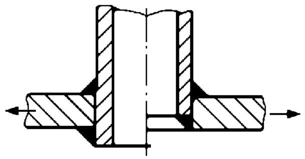
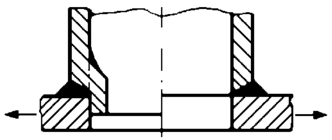
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
522		Longitudinal fillet welded gusset with radius transition, end of fillet weld reinforced and ground, $c < 2\ t$, max 25 mm $r > 150$ mm	90	32	**t** = thickness of attachment
523		Longitudinal fillet welded gusset with smooth transition (sniped end or radius) welded on beam flange or plate. $c < 2\ t$, max 25 mm $r > 0.5\ h$ $r < 0.5\ h$ or $\varphi < 20°$	 71 63	 25 20	**t** = thickness of attachment If attachement thickness < 1/2 of base plat thickness, then one step higher allowed (not for welded on profiles!)
524		Longitudinal flat side gusset welded on plate edge or beam flange edge, with smooth transition (sniped end or radius). $c < 2t_2$, max. 25 mm $r > 0.5\ h$ $r < 0.5\ h$ or $\varphi < 20°$	 50 45	 18 16	**t** = thickness of attachment For $t_2 < 0.7\ t_1$, FAT rises 12%

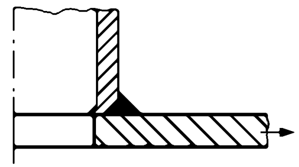
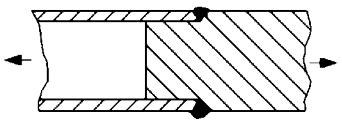
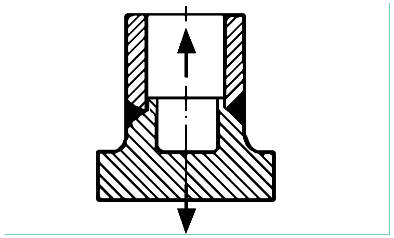
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
525		Longitudinal flat side gusset welded on plate or beam flange edge, gusset length **l**: l < 150 mm l < 300 mm l > 300 mm	 50 45 40	 18 16 14	For $t_2 < 0.7\ t_1$, FAT rises 12%
526		Longitudinal flat side gusset welded on edge of plate or beam flange, radius transition ground. r>150 or r/w > 1/3 1/6 < r/w < 1/3 r/w < 1/6	 90 71 50	 36 28 22	Smooth transition radius formed by grinding the weld area in transition in order to temove the weld toe completely. Grinding parallel to stress.
531		Circular or rectangular hollow section, fillet welded to another section. Section width parallel to stress direction < 100 mm, else like longitudinal attachment	71	28	Non load-carrying welds. Width parallel to stress direction < 100 mm.

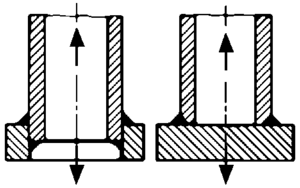
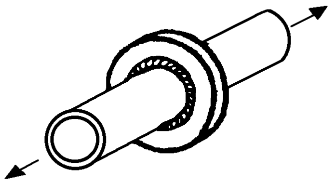
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
600	**Lap joints**				
611		Transverse loaded lap joint with fillet welds Fatigue of parent metal Fatigue of weld throat	 63 45	 22 16	Stresses to be calculated in the main plate using a plate width equalling the weld length. Buckling avoided by loading or design!
612		Longitudinally loaded lap joint with side fillet welds Fatigue of parent metal Fatigue of weld (calc. on max. weld length of 40 times the throat of the weld	 50 50	 18 18	Weld terminations more than 10 mm from plate edge. Buckling avoided by loading or design! For verification of parent metal, the higher stress of both members has to be taken.
613		Lap joint gusset, fillet welded, non-load-carrying, with smooth transition (sniped end with φ<20° or radius), welded to loaded element c<2·t, but c <= 25 mm to flat bar to bulb section to angle section	 63 56 50	 22 20 18	**t** = thickness of gusset plate
614		Transverse loaded overlap joint with fillet welds. Stress in plate at weld toe (toe crack) Stress in weld throat (root crack)	 63 36	 22 12	Stresses to be calculated using a plate width equalling the weld length. For stress in plate, excenticity to be considered, as given in chapters 3.8.2 and 6.3. Both failure modes have to be assessed separately.

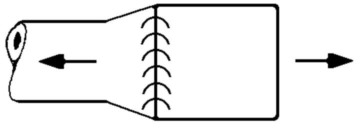
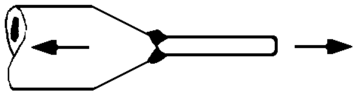
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
700	**Reinforcements**				
711		End of long doubling plate on I-beam, welded ends (based on stress range in flange at weld toe) $t_D \le 0.8$ t 0.8 t < $t_D \le 1.5$ t $t_D > 1.5$ t	 56 50 45	 20 18 16	End zones of single or multiple welded cover plates, with or without frontal welds. If the cover plate is wider than the flange, a frontal weld is needed. No undercut at frontal welds!
712		End of long doubling plate on beam, reinforced welded ends ground (based on stress range in flange at weld toe) $t_D \le 0.8$ t 0.8 t < $t_D \le 1.5$ t $t_D > 1.5$ t	 71 63 56	 28 25 22	Grinding parallel to stress direction.
721		End of reinforcement plate on rectangular hollow section. wall thickness: t < 25 mm	50	20	No undercut at frontal weld!

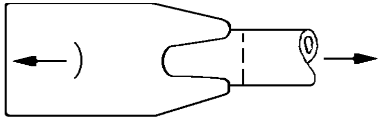
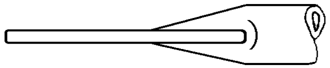
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
731		Reinforcements welded on with fillet welds, toe ground Toe as welded	 80 71	 32 25	Grinding in direction of stress! Analysis based on modified nominal stress, however, structural stress approach recommended.
800	**Flanges, branches and nozzles**				
811		Stiff block flange, full penetration weld	71	25	
812		Stiff block flange, partial penetration or fillet weld toe crack in plate root crack in weld throat	 63 36	 22 12	
821		Flat flange with > 80% full penetration butt welds, modified nominal stress in pipe, toe crack	71	25	Assessment by structural hot spot is recommended.

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
822		Flat flange with fillet welds, modified nominal stress in pipe, toe crack.	63	22	Assessment by structural hot spot is recommended.
831		Tubular branch or pipe penetrating a plate, K-butt welds.	80	28	If diameter > 50 mm, stress concentration of cutout has to be considered Assessment by structural hot spot is recommended.
832		Tubular branch or pipe penetrating a plate, fillet welds. Toe cracks. Root cracks (analysis based on stress in weld throat)	71 36	25 12	If diameter > 50 mm, stress concentration of cutout has to be considered Assessment by structural hot spot is recommended.
841		Nozzle welded on plate, root pass removed by drilling.	71	25	If diameter > 50 mm, stress concentration of cutout has to be considered Assessment by structural hot spot is recommended.

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
842		Nozzle welded on pipe, root pass as welded.	63	22	If diameter > 50 mm, stress concentration of cutout has to be considered Assessment by structural hot spot is recommended.
900	**Tubular joints**				
911		Circular hollow section butt joint to massive bar, as welded	63	22	Root of weld has to penetrate into the massive bar in order to avoid a gap perpenticular to the stress direction.
912		Circular hollow section welded to component with single side butt weld, backing provided. Root crack.	63	22	Root of weld has to penetrate into the backing area in order to avoid a gap perpenticular to the stress direction.

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
913		Circular hollow section welded to component single sided butt weld or double fillet welds. Root crack.	50	18	Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see chapter 5) or by downgrading down to 2 FAT classes.
921		Circular hollow section with welded on disk K-butt weld, toe ground Fillet weld, toe ground Fillet welds, as welded	 90 90 71	 32 32 25	Non load-carrying weld.

<table>
<tr><th>No.</th><th>Structural Detail</th><th>Description
(St.= steel; Al.= aluminium)</th><th>FAT St.</th><th>FAT Al.</th><th>Requirements and Remarks</th></tr>
<tr><td>931</td><td>
</td><td>Tube-plate joint, tubes flattened, butt weld (X-groove)

Tube diameter < 200 mm and plate thickness < 20 mm</td><td>63</td><td>18</td><td></td></tr>
<tr><td>932</td><td>
</td><td>Tube-plate joint, tube slitted and welded to plate

tube diameter < 200 mm and plate thickness < 20 mm
tube diameter > 200 mm or plate thickness > 20 mm</td><td>

63

45</td><td>

18

14</td><td></td></tr>
</table>

Tab. {3.2}-2: Fatigue resistance values for structural details on the basis of shear stress

No.	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.
1	Parent metal or full penetration butt weld; **m=5 down to 1E8** cycles	100	36
2	Fillet weld or partial penetration butt weld; **m=5 down to 1E8** cycles	80	28

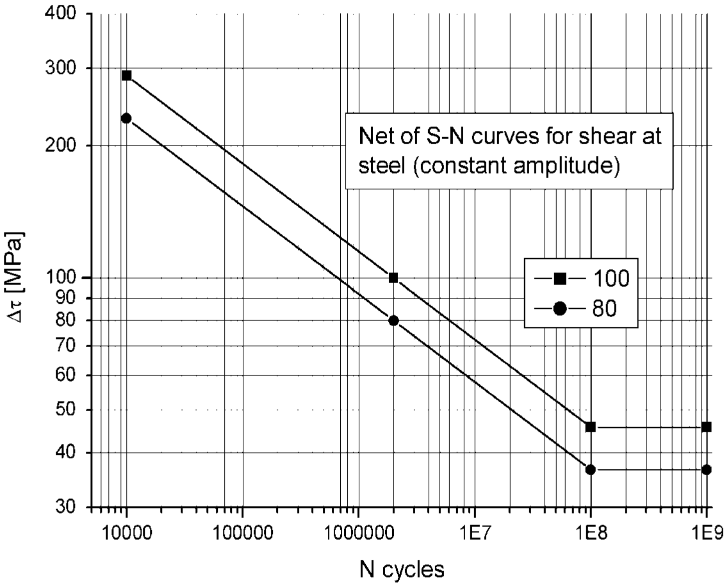


Fig. (3.2)-4: Fatigue resistance S-N curve for shear at steel, standard applications

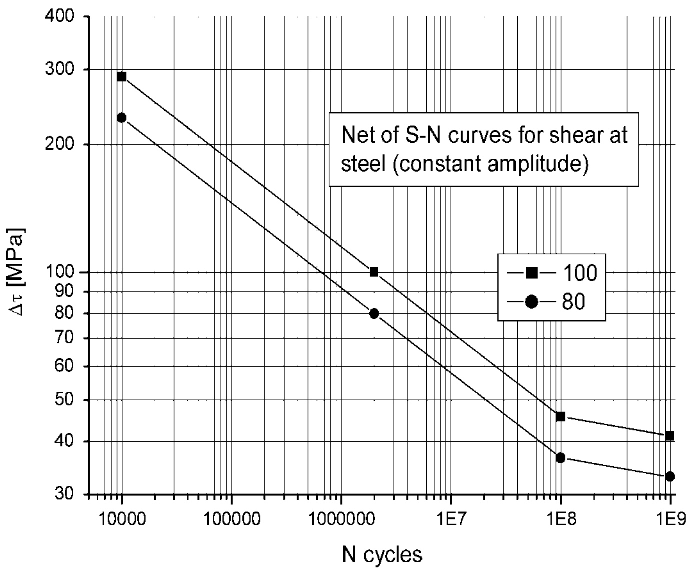


Fig. (3.2)-5: Fatigue resistance S-N curves for shear at steel, very high cycle applications

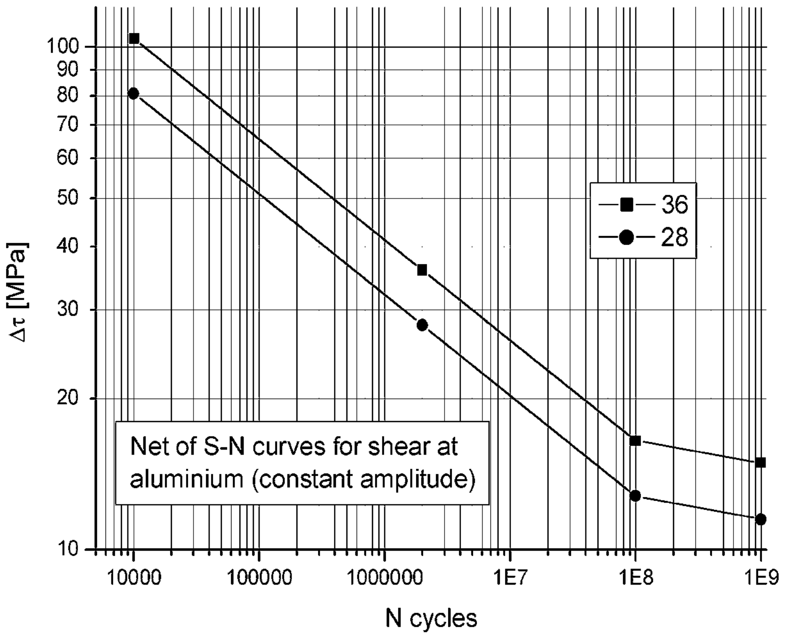


Fig. (3.2)-6: Fatigue resistance S-N curve for shear at aluminium

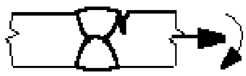
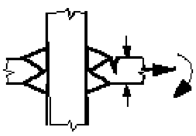
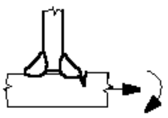
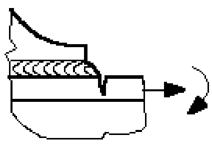
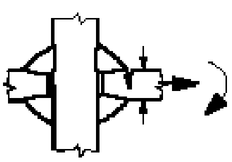
3.3 FATIGUE RESISTANCE AGAINST STRUCTURAL HOT SPOT STRESS

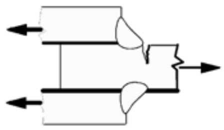
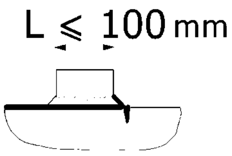
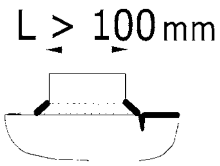
3.3.1 Fatigue Resistance Using Reference S-N Curve

The S-N curves for fatigue resistance against structural hot spot stress (2.2.3) are given in the table {3.3}-1 for steel and aluminium, where the definition of the FAT class is given in chapter 3.2. The resistance values refer to the as-welded condition unless stated otherwise. The effects of welding residual stress are included. Only small effects of misalignment are included, see also 3.8.2). The weld shape should be similar as shown below.

The design value of the structural hot spot stress range shall not exceed $\boldsymbol{\Delta\sigma_{hs} < 2\cdot f_y}$. The fatigue resistance of a weld is limited by the fatigue resistance of the base material.

Tab. {3.3}-1: Fatigue resistance against structural hot spot stress

No.	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
1		Butt joint	As welded, NDT	100	40
2		Cruciform or T-joint with full penetration K-butt welds	K-butt welds, no lamellar tearing	100	40
3		Non load-carrying fillet welds	Transverse non-load carrying attachment, not thicker than main plate, as welded	100	40
4		Bracket ends, ends of longitudinal stiffeners	Fillet welds welded around or not, as welded	100	40
5		Cover plate ends and similar joints	As welded	100	40
6		Cruciform joints with load-carrying fillet welds	Fillet welds, as welded	90	36

No.	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
7		Lap joint with load carrying fillt welds	Fillet welds, as welded	90	36
8		Type “b” joint with short attachment	Fillet or full penetration weld, as welded	100	40
9		Type “b” joint with long attachment	Fillet or full penetration weld, as welded	90	36

Note 1: Table does not cover larger effects of misalignment. They have to be considered explicitely in determination of stress range, see also 3.8.2.

Note 2: The nominally non- or partially load-carrying fillet welds shown under no. 3 and 5 in tab. {3.3}-1 may be load-carrying in reality in certain cases, e.g. if the bending of the base plate is restrained. In these cases load-carrying fillet welds should be assumed with FAT classes given under no. 6 and 7 in tab.{3.3}-1 . This may also apply to no. 4 without soft bracket end.

Note 3: A further reduction by one FAT class is recommended for fillet welds having throat thicknesses of less than one third of the thickness of the base plate.

For hollow section joints, special hot-spot stress design *S-N* curves have been recommended by the IIW [2-6]. The tubular joint design curves should not be applied to other types of structures.

3.3.2 Fatigue Resistance Using a Reference Detail

The tables of the fatigue resistance of structural details given in 3.2, or fatigue data from other sources which refer to a comparable detail, may be used. The reference detail should be chosen as similar as possible to the detail to be assessed.

Thus the procedure will be:

a) Select a reference detail with known fatigue resistance, which is as similar as possible to the detail being assessed with respect to geometric and loading parameters.

b) Identify the type of stress in which the fatigue resistance is expressed. This is usually nominal stress (as in tables in chapter 3.2).

c) Establish a FEM model of the reference detail and the detail to be assessed with the same type of meshing and elements following the recommendations given in 2.2.3.

d) Load the reference detail and the detail to be assessed with the stress identified in b).

e) Determine the structural hot spot stress $\boldsymbol{\sigma}_{\mathbf{hs, ref}}$ of the reference detail and the Structural hot spot stress $\boldsymbol{\sigma}_{\mathbf{hs, assess}}$ of the detail to be assessed.

f) The fatigue resistance for 2 million cyles of the detail to be assessed $\mathbf{FAT}_{\mathbf{assess}}$ is then calculated from fatigue class of the reference detail $\mathbf{FAT}_{\mathbf{ref}}$ by:

$$FAT_{assess} = \frac{\sigma_{hs,ref}}{\sigma_{hs,assess}} \cdot FAT_{ref}$$

3.4 FATIGUE RESISTANCE AGAINST EFFECTIVE NOTCH STRESS

3.4.1 Steel

The effective notch stress fatigue resistance against fatigue actions, as determined in 2.2.4 for steel, is given in table {3.4}-1. The definition of the FAT class is given in chapter 3.2. The fatigue resistance value refers to the as-welded condition. The effect of welding residual stresses is included. Possible misalignment is **not** included.

The fatigue resistance of a weld toe is additionally limited by the fatigue resistance of the parent material, which is determined by the use of the structural hot-spot stress and the FAT class of the non-welded parent material. This additional verification has to be performed according to chapter 2.2.3..

Tab. {3.4}-1: Effective notch fatigue resistance for steel

No.	Quality of weld notch	Description	FAT
1	Effective notch radius equalling **1 mm** replacing weld toe and weld root notch	Notch as-welded, normal welding quality m=3	225

3.4.2 Aluminium

The same regulations apply as for steel.

Tab. {3.4}-2: Effective notch fatigue resistance for aluminium

No.	Quality of weld notch	Description	FAT
1	Effective notch radius equalling **1 mm** replacing weld toe and weld root notch	Notch as-welded, normal welding quality m=3	71

3.5 FATIGUE STRENGTH MODIFICATIONS

3.5.1 Stress Ratio

3.5.1.1 Steel

For stress ratios **R<0.5** a fatigue enhancement factor **f(R)** may be considered by multiplying the fatigue class of classified details by **f(R)**. The fatigue enhancement factor depends on the level and direction of residual stresses. Here, all types of stress which are **not** considered in fatigue analysis and which are effective during service loading of the structure are regarded as residual stress. The ranking in categories I, II or III should be done and documented by the design office. If no reliable information on residual stress is available, an enhancement factor **f(R)=1** is recommended. Other factors should only be used if reliable informations or estimations of the residual stress level were present.

The following cases are to be distinguished:

I: Unwelded base material and wrought products with negligible residual stresses (**$<0.2 \cdot f_y$**), stress relieved welded components, in which the effects of constraints or secondary stresses have been considered in analysis. No constraints in assembly.

$f(R) = 1.6$	for $R < -1$
$f(R) = -0.4 \cdot R + 1.2$	for $-1 \leq R \leq 0.5$
$f(R) = 1$	for $R > 0.5$

II: Small scale thin-walled simple structural elements containing short welds. Parts or components containing thermally cut edges. No constraints in assembly.

$f(R) = 1.3$	for $R < -1$
$f(R) = -0.4 \cdot R + 0.9$	for $-1 \leq R \leq -0.25$
$f(R) = 1$	for $R > -0.25$

III: Complex two- or three-dimensional welded components, components with global residual stresses, thickwalled components. Normal case for welded components and structures.

$f(R) = 1$	no enhancement

It has to be noted in this respect that stress relief in welded joints is unlikely to be fully effective, and additional residual stresses may be introduced by lack of fit during assembly of prefabricated welded components, by displacements of abutments or by other reasons. For such reasons, it is recommended that values of **f(R)>1** should only be adopted for welded components in very special circumstances.

3.5.1.2 Aluminium

The same regulations as for steel are recommended.

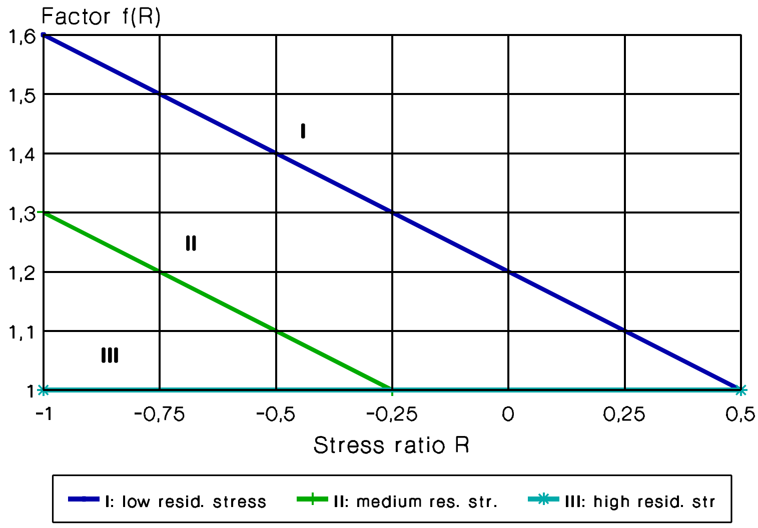


Fig. (3.5)-1 Enhancement factor f(R)

3.5.2 Wall Thickness

3.5.2.1 Steel

The influence of plate thickness on fatigue strength should be taken into account in cases where cracks start from the weld toe. The fatigue resistance values here given refer to a wall thickness up to 25 mm at steel. The reduced strength is taken in consideration by multiplying the fatigue class of the structural detail by the thickness reduction factor **f(t)**. The thickness correction exponent **n** is dependent on the effective thickness $\mathbf{t_{eff}}$ and the joint category (see table {3.5}-1) [5-1]. The same way a benign thinness effect might be considered, but should be verified by component test.

Tab. {3.5}-1: Thickness correction exponents

Joint category	Condition	**n**
Cruciform joints, transverse T-joints, plates with transverse attachments, longitudinal stiffeners	as-welded	0.3
Cruciform joints, transverse T-joints, plates with transverse attachments, longitudinal stiffeners	toe ground	0.2
Transverse butt welds	as-welded	0.2
Butt welds ground flush, base material, longitudinal welds or attachements	any	0.1

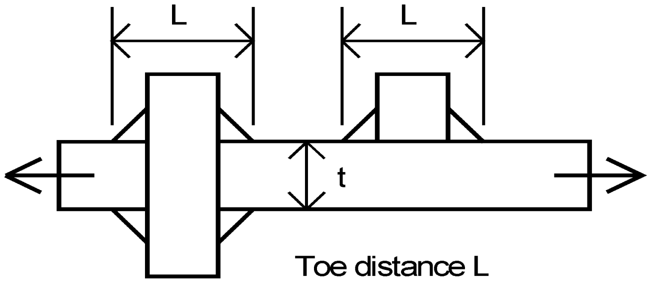
$$f(t) = \left(\frac{t_{ref}}{t_{eff}} \right)^n$$ Reference thickness $\mathbf{t_{ref}}$ = 25 mm

The plate thickness correction factor is not required in the case of assessment based on effective notch stress procedure or fracture mechanics.

At determination of $\mathbf{t_{eff}}$, the following cases have to be distinguished:

if **L/t > 2** then $\mathbf{t_{eff} = t}$

if **L/t ≤ 2** then $\mathbf{t_{eff} = 0.5 \cdot L}$ or $\mathbf{t_{eff} = t_{ref}}$ whichever is larger



Fif. (3.5)-2: Definition of toe distance

3.5.2.2 Aluminium

The same regulations as for steel are recommended.

3.5.3 Improvement Techniques

3.5.3.1 General

Post weld improvement techniques may raise the fatigue resistance. These techniques improve the weld profile, the residual stress conditions or the environmental conditions of the welded joint. The improvements methods are:

a) Methods for improvement of weld profile:

Machining or grinding of weld seam flush to surface
Machining or grinding of the weld transition at the toe
Remelting of the weld toe by TIG-, plasma or laser dressing

b) Methods for improvement of residual stress conditions:

Peening (hammer-, needle-, shot-, brush-peening or ultrasonic treatment)
Overstressing (proof testing)
Stress relieving thermal treatment

c) Methods for improvement of environmental conditions:

Painting
Resin coating

The effects of all improvement techniques are sensitive to the method of application and the applied loading, being most effective in the low stress high cycle regime. They may also depend on the material, structural detail and dimensions of the welded joint. Consequently, fatigue tests for the verification of the procedure in the endurance range of interest are recommended (chapters 3.7 and 4.5).

Recommendations are given below for the following post-welding weld toe improvement methods: Grinding, TIG dressing, hammer and needle peening. They may be used under the following circumstances:

a) Increasing the fatigue strength of new structures.
b) Repair or upgrading of existing structures

3.5.3.2 Applicabiliy of Improvement Methods

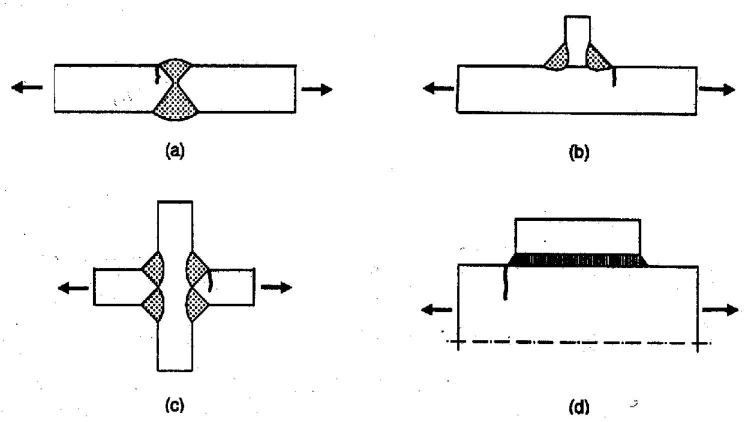


Fig: (3.5)-3: Examples of joint suitable for improvement

The recommendations apply to all arc welded steel or aluminium components subjected to fluctuating or cyclic stress and designed to a fatigue limit state criterion. They are limited to structural steels up to a specified yield strength of 900 MPa and to weldable structural aluminium alloys commonly used in welded structures, primarily of the AA 5000 and AA 6000 series but including weldable Al-Zn-Mg alloys.

The recommendations apply to welded joints in plates, sections built up of plates or similar rolled or extruded shapes, and hollow sections. Unless otherwise specified, the plate thickness range for steel is 6 to 150 mm, while that for aluminium is 4 to 50 mm.

The recommended levels of improvement in fatigue strength only apply when used in conjunction with the nominal stress or structural hot spot stress verification methods. They do not apply to effective notch stress or fracture mechanics verification methods.

The application is limited to joints operating at temperatures below the creep range. In general, the recommendations do not apply for low cycle fatigue conditions, so the nominal stress range is limited to $\Delta\sigma < 1.5 \cdot f_y$. Additional restrictions may apply for specific improvement procedures. It is important to note that the fatigue resistance of an improved weld is limited by the fatigue resistance S-N curve of the base material.

The improvement procedures described below, apply solely to the weld toe and hence to a potential fatigue cracks growth starting from this point. All other potential fatigue crack initiation sites (e.g. weld root or imperfections) should, therefore, be carefully considered.

The benefit factors are presented as upgrades to the FAT class that applies to the as-welded joint. Alternative factors, including a possible change to a shallower, more favourable, slope of S-N curve for the improved weld, may be derived on the basis of special fatigue tests (see 4.5).

A profile improvement can sometimes assist in the application of a residual stress technique and vice versa (e.g. grinding before peening in the case of a poor weld profile or shot peening a dirty surface before TIG dressing). However, a higher benefit factor than that applicable for the second technique alone can only be justified on the basis of special fatigue tests.

The recommendations do not apply to joints operating under free corrosion.

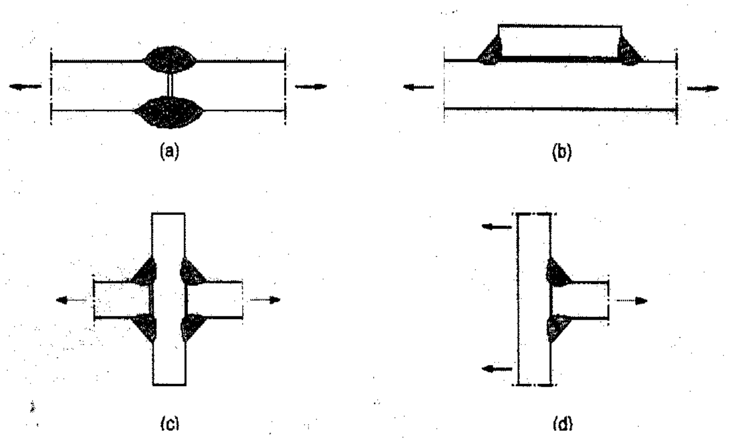


Fig: (3.5)-4: Examples of joints, in which an improvement might be limited by a possible root crack

3.5.3.3 Grinding

Weld toe fatigue cracks initiate at undercut, cold laps or the sharp crack-like imperfections, just a few tenths of a millimetre deep, which are an inherent feature of most arc welds. The aim of grinding is firstly to remove these imperfections and secondly to create a smooth transition between weld and plate, thus, reducing the stress concentration. All embedded imperfections revealed by grinding must be repaired. For the details of the grinding procedure see ref. [5-2].

The benefit of grinding is given as a factor on the stress range of the fatigue class of the non-improved joint.

Tab. 3.5-2a: FAT classes for use with nominal stress at joints improved by grinding

Area of application and maximum possible claim	Steel	Aluminium
Benefit at details classified in as-welded condition as FAT≤90 for steel or FAT≤32 for aluminium	1.3	1.3
Max possible FAT class after improvement	FAT 112	FAT 45

Tab. 3.5-2b: FAT classes for use with structural hot-spot stress at joints improved by grinding

Material	Load-carrying fillet welds	Non-load-carrying fillet welds and butt welds
Mild steel, $f_y < 350$ MPa	90	112
Higher strength steel, $f_y \geq 350$ MPa	112	125
Aluminium alloys	45	50

The thickness correction exponent according to chapter 3.5.2 table {3.5}-1 is **n=0.2** .

3.5.3.4 TIG Dressing

By TIG (tungsten inert gas) dressing, the weld toe is remelted in order to remove the weld toe imperfections and to produce a smooth transition from the weld to plate surface, thus reducing the stress concentration. The recommendations apply to partial or full penetration arc welded welds in steels with a specified yield strength up to 900 MPa and to wall thicknesses $\geq$10 mm operating in a non-corrosive environment or under conditions of corrosion protection. The details of the procedure are described in ref. [5-2].

Tab. 3.5-3a: FAT classes for use with nominal stress at joints improved by TIG dressing

Area of application and maximum possible claim	Steel	Aluminium
Benefit at details classified in as-welded condition as FAT$\leq$90 for steel or FAT$\leq$32 for aluminium	1.3	1.3
Max possible FAT class after improvement	FAT 112	FAT 45

Tab. 3.5-3b: FAT classes for use with structural hot-spot stress at joints improved by TIG dressing

Material	Load-carrying fillet welds	Non-load-carrying fillet welds and butt welds
Mild steel, $f_y < 350$ MPa	90	112
Higher strength steel, $f_y > 350$ MPa	112	125
Aluminium alloys	45	50

The thickness correction exponent according to chapter 3.5.2 table {3.5}-1 is **n=0.2** .

3.5.3.5 Hammer Peening

By hammer peening, the material is plastically deformed at the weld toe in order to introduce beneficial compressive residual stresses. The recommendations are restricted to steels with specified yield strengths up to 900 MPa and structural aluminium alloys, both operating in non-corrosive environments or under conditions of corrosion potection. The recommendations apply for plate thicknesses from 10 to 50 mm in steel and 5 to 25 mm in aluminium and to arc welded fillet welds with a minimum weld leg length of 0.1·t, where t is the thickness of the stressed plate. The details of the procedure are described in ref. [5-2].

Special requirements apply when establishing the benefit of hammer peening:

a) Maximum amount of nominal compressive stress in load spectrum including proof loading $< 0.25 \cdot f_y$ (for aluminium, use f_y of heat affected zone)

b) The S-N curve for the hammer peened weld is is used in conjunction with an effective stress range that depends on applied stress ratio (R) as follows:

   if R<0 then the effective stress range = applied $\Delta\sigma$
   if $0 < R \leq 0.4$ then the effective stress range = maximum applied σ
   If R> 0.4 then there is no benefit

Tab. 3.5-4a: FAT classes for use with nominal stress at joints improved by hammer peening

Area of application and maximum possible claim	Mild steel $f_y < 355$ MPa	Steel $f_y \geq 355$ MPa	Aluminium
Benefit at details classified in as-welded condition as FAT≤90 for steel or FAT≤32 for aluminium	1.3	1.6	1.6
Max possible FAT after improvement	FAT 112	FAT 125	FAT 56

Tab. 3.5-4b: FAT classes for use with structural hot-spot stress at joints improved by hammer peening

Material	Load-carrying fillet welds	Non-load-carrying fillet welds
Mild steel, $f_y < 350$ MPa	112	125
Higher strength steel, $f_y \geq 350$ MPa	125	160
Aluminium alloys	56	63

For wall thicknesses bigger than 25 mm, the thickness correction for as-welded joints still applies (see 3.5).

3.5.3.6 Needle Peening

By needle peening, the material is plastically deformed at the weld toe in order to introduce beneficial compressive residual stresses. The details of the procedure are described in [5-2]. Special requirements apply when establishing the benefit of hammer peening:

a) Maximum amount of nominal compressive stress in load spectrum including proof loading $< 0.25 \cdot f_y$ (for aluminium, use f_y of heat affected zone)

b) The S-N curve for hammer peened weld is expressed in terms of an effective stress rane that depends on applied R ratio as follows:

if R<0 then the effective stress range = benefit factor · $\Delta\sigma$
if $0 < R \leq 0.4$ then the effective stress range = benefit factor · maximum σ
If R> 0.4 then there is no benefit

Tab. 3.5-5a: FAT classes for use with nominal stress at joints improved by needle peening

Area of application and maximum possible claim	Mild steel fy <355 MPa	Steel fy ≥355 MPa	Aluminium
Benefit at details with FAT≤90 at steel or FAT≤32 at aluminium, as welded	1.3	1.6	1.6
Max possible FAT after improvement	FAT 112	FAT 125	FAT 56

Tab. 3.5-5b: FAT classes for use with structural hot-spot stress at joints improved by needle peening

Material	Load-carrying fillet welds	Non-load-carrying fillet welds
Mild steel, f_y < 350 MPa	112	125
Higher strength steel, f_y > 350 MPa	125	160
Aluminium alloys	56	63

For wall thicknesses bigger than 25 mm, the thickness correction for as-welded joints still applies (see 3.5).

3.5.4 Effect of Elevated Temperatures

One of the main material parameters governing the fatigue resistance is the modulus of elasticity **E** which decreases with increase in temperature. So the fatigue resistance at elevated temperatures (HT) may be calculated as

$$FAT_{HT} = FAT_{20^\circ C} \cdot \frac{E_{HT}}{E_{20^\circ C}}$$

3.5.4.1 Steel

For higher temperatures, the fatigue resistance data may be modified with a reduction factor given in fig. (3.5)-13. The fatigue reduction factor is a conservative approach and might be raised according to test evidence or application codes. Creep effects are not covered here.

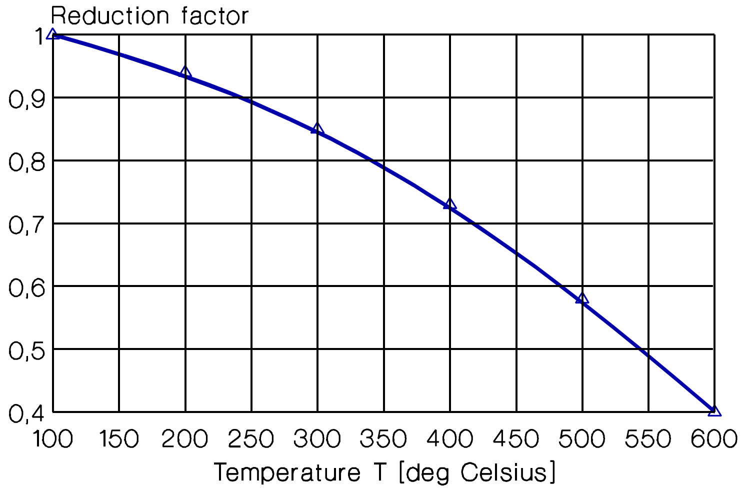


Fig. (3.5)-5 Fatigue strength reduction factor for steel at elevated temperatures

3.5.4.2 Aluminium

The fatigue data given here refer to operation temperatures lower than 70 °C. This value is a conservative approach. It may be raised according to test evidence or an applicable code.

3.5.5 Effect of Corrosion

The fatigue resistance data given here refer to non-corrosive environments. Normal protection against atmospheric corrosion is assumed. A corrosive environment or unprotected exposure to atmospheric conditions may reduce the fatigue class. The position of the knee point of the SN curve (traditionally the fatigue limit) may also be reduced considerably. The effect depends on the spectrum of fatigue actions **and** on the time of exposure.

For steel, except stainless steel, in marine environment not more than 70% of the fatigue resistance values in terms of stress range shall be applied and no fatigue limit or knee point of the S-N curve shall be considered. In fracture mechanics crack propagation calculations the constant $\mathbf{C_0}$ of the Paris Power Law shall be multiplied by a factor of 3.0 . A threshold value shall not be considered.

No further specific recommendations are given for corrosion fatigue assessment. It is recommended to monitor in service, if no service experience is available.

3.6 FATIGUE RESISTANCE AGAINST CRACK PROPAGATION

The resistance of a material against cyclic crack propagation is characterized by the material parameters of the "Paris" power law of crack propagation

$$\frac{da}{dN} = C_0 \cdot \Delta K^m \quad if \quad \Delta K < \Delta K_{th} \quad then \quad \frac{da}{dN} = 0$$

where the material parameters are

$\mathbf{C_0}$	constant of the power law
m	exponent of the power law
ΔK	range of cyclic stress intensity factor
$\mathbf{\Delta K_{th}}$	threshold value of stress intensity, under which no crack propagation is assumed
R	ratio $\mathbf{K_{min}/K_{max}}$, taking all stresses including residual stresses into account (see 3.5.1)

In the absence of specified or measured material parameters, the values given below are recommended. They are characteristic values.

For elevated temperatures other than room temperature or for metallic materials other than steel, the crack propagation parameters vary with the modulus of elasticity **E** and may be determined accordingly.

$$C = C_{0,\,steel} \cdot \left(\frac{E_{steel}}{E} \right)^m \qquad \Delta K_{th} = \Delta K_{th,\,steel} \cdot \left(\frac{E}{E_{steel}} \right)$$

3.6.1 Steel

Tab. 3.6-1: Parameters of the Paris power law and threshold data for steel

Units	Paris power law parameters	Threshold values ΔK_{th}			
		R≥0.5	0≤R≤0.5	R<0	surface crack depth <1 mm
K [$N \cdot mm^{-2/3}$] da/dN [mm/cycle]	$C_0 = 5.21 \cdot 10^{-13}$ m = 3.0	63	170-214·R	170	≤63
K [MPa√m] da/dN [m/cycle]	$C_0 = 1.65 \cdot 10^{-11}$ m = 3.0	2	5.4-6.8·R	54	≤2

3.6.2 Aluminium

Tab. 3.6-2: Parameters of the Paris power law and threshold data for aluminium

Units	Paris power law parameters	Threshold values ΔK_{th}			
		$R \geq 0.5$	$0 \leq R \leq 0.5$	$R<0$	surface crack depth <1 mm
K [$N \cdot mm^{-2/3}$] da/dN [mm/cycle]	$C_0 = 1.41 \cdot 10^{-11}$ $m = 3.0$	21	$56.7 - 72.3 \cdot R$	567	≤ 21
K [$MPa\sqrt{m}$] da/dN [m/cycle]	$C_0 = 4.46 \cdot 10^{-10}$ $m = 3.0$	0.7	$1.8 - 2.3 \cdot R$	18	≤ 0.7

3.7 FATIGUE RESISTANCE DETERMINATION BY TESTING

3.7.1 General Considerations

Fatigue tests may be used to establish a fatigue resistance curve for a component or a structural detail, or the resistance of a material against (non critical) cyclic crack propagation.

Statistical methods offer three ways of testing a limited number of samples from a larger population:

1. a specimen to failure
2. first specimen to failure
3. **p** specimens to failure amongst **n** specimens

It is recommended that test results are obtained at constant stress ratios **R**. The S-N data should be presented in a graph showing log(endurance in cycles) as the abscissa and log(range of fatigue actions) as the ordinate. For crack propagation data, the log(stress intensity factor range) should be the abscissa and the log(crack propagation rate per cycle) the ordinate.

Experimental fatigue data are scattered, the extent of scatter tends to be greatest in the low stress/low crack propagation regime (e.g. see fig. (3.7)-1). For statistical evaluation, a Gaussian log-normal distribution should be assumed. The number of failed test specimens should be equal or greater than 10. For other conditions, special statistical considerations are required.

Many methods of statistical evaluation are available. However, the most common approach for analysing fatigue data is to fit S-N or crack propagation curves by regression analysis, taking **log(N)** or **log(da/dN)** as the dependent variable. Then, characteristic values are established by adopting curves lying **k** standard deviations of the dependent variable from the mean (values are given in 6.4.1). In the case of S-N data, this would be below the mean, while the curve above the mean would be appropriate in case of crack propagation data.

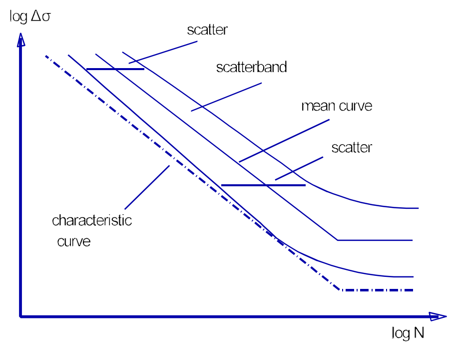


Fig. (3.7)-1 Scatterband in SN curve

Thus, more precisely, test results should analysed to produce **characteristic** values (subscript **k**). These are values at a 95% survival probability (i.e. 5% failure probability) associated with a two-sided 75% confidence level of the mean.

More details on the use of the confidence level and formulae are given in appendix 6.4.

3.7.2 Evaluation of Test Data

Different methods for testing exist. For the derivation of S-N curves, testing at two levels of the stress range **Δσ** within the range of 10^5 to 10^6 cycles is preferred. For fracture mechanics crack propagation parameters, the range of stress intensity factor **ΔK** should be distributed between threshold and brittle fracture levels.

For the evaluation of test data originating from a test series, the characteristic values are calculated by the following procedure:

a) Calculate $\log_{10}$ of all data: Stress range **Δσ** and number of cycles **N**, or stress intensity factor range **ΔK** and crack propagation rate **da/dN**.

b) Calculate exponents **m** and constant **logC** (or **logC$_0$** resp.) of the formulae:

$$\text{for S-N curve} \quad \log N = \log C - m \cdot \log \Delta\sigma$$

$$\text{for crack propag.} \quad \log \frac{da}{dN} = \log C_0 - m \cdot \log \Delta K$$

by linear regression taking stress or stress intensity factor range as the independent variable, i.e. **logN=f(log Δσ)** or **log(da/dN)=f(log ΔK).**

If the number of pairs of test data **n<10**, or if the data are not sufficiently evenly distributed to determine **m** accurately, a fixed value of **m** should be taken, as derived from other tests under comparable conditions, e.g. **m=3** for steel and alumunium welded joints.

If a fixed value of **m** is used, the values **x$_i$** equalling **logC** or **logC$_0$** are calculated from the **(N, Δσ)$_i$** or **(N, da/dN)$_i$** test results using the equations above.

c) Calculate mean **x$_m$** and standard deviation **Stdv** of **logC** (or **logC$_0$** resp.) using **m** obtained in b).

$$x_m = \frac{\sum x_i}{n} \qquad Stdv = \sqrt{\frac{\sum (x_m - x_i)^2}{n-1}}$$

d) Calculate the characteristc values **x$_k$** by the formula

$$\text{S-N data:} \quad x_k = x_m - k \cdot Stdv$$
$$\text{Crack propagation rate:} \quad x_k = x_m + k \cdot Stdv$$

The values of **k** are given in table {3.7}-1.

Tab. {3.7}-1: Values of **k** for the calculation of characteristic values

n	10	15	20	25	30	40	50	100
k	2.7	2,4	2.3	2.2	2.15	2.05	2.0	1.9

For **n<10** and more details and information, see appendix 6.4.1 and ref. [10-3].

In case of S-N data, proper account should be taken of the fact that residual stresses are usually low in small-scale specimens. The results should be corrected to allow for the greater effects of residual stresses in real components and structures. This may be achieved either by testing at high **R**-ratios, e.g. **R=0.5**, or by testing at **R=0** and lowering the fatigue strength at 2 million cycles (FAT) by 20% .

3.7.3 Evaluation of Data Collections

Usually data collections do not origin from a single statistical population. These heterogeneous populations of data require a special consideration in order to avoid an excessive and unnecessary calculative scatter.

The evaluation procedure should consist of the following steps:

1. To calculate the constant **C** of the SN Wöhler curve for each data point (eq.1) using the anticipated knowledge of the slope exponent of comparable test series, e.g slope **m=3.00** for steel or aluminium.

2. To plot all values **C** into a Gaussian probability chart, showing the values of **C** on the abscissa and the cumulative survival probability on the ordinate.

3. To check the probability plot for heterogeneity of the population. If it is heterogeneous, separate the portion of the population which is of interest (see illustration on figures (3.7)-2 and (3.7-3)).

4. To evaluate the interesting portion of population according to chapter 3.7.2.

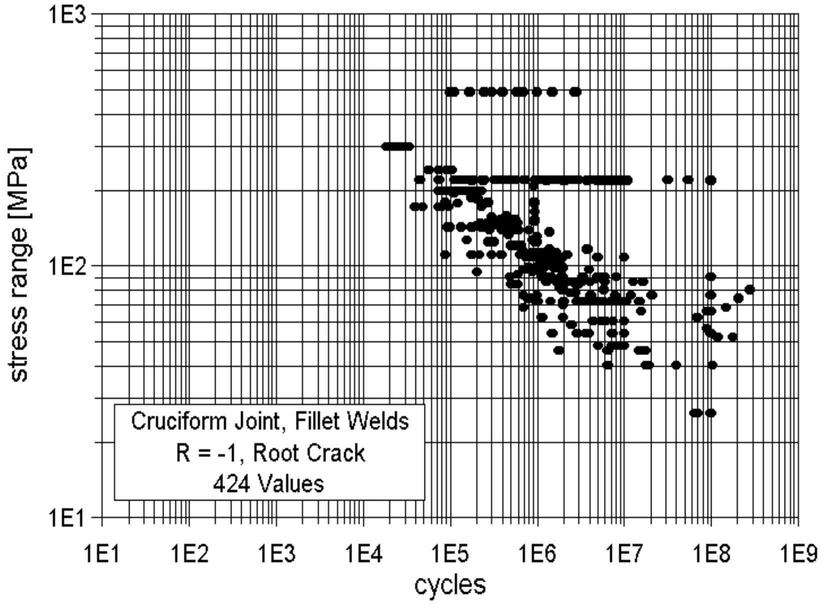


Fig. (3.7)-2: Example of scatter in data collections

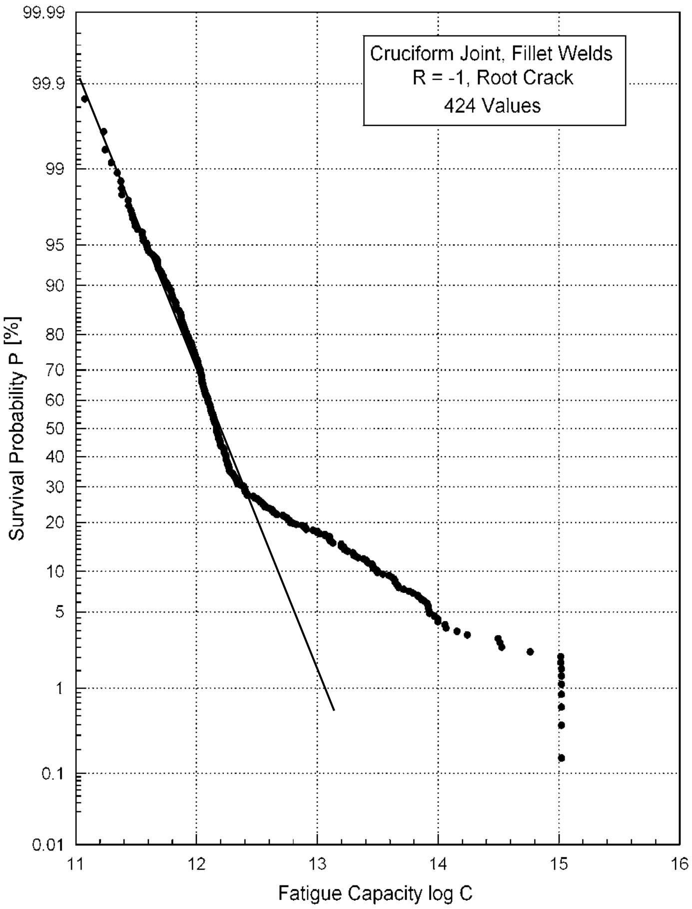


Fig. (3.7)-3: Example of a heterogeneous population

3.8 FATIGUE RESISTANCE OF JOINTS WITH WELD IMPERFECTIONS

3.8.1 General

3.8.1.1 Types of Imperfections

The types of imperfections covered in this document are listed below. Other imperfections, not yet covered, may be assessed by assuming similar imperfections with comparable notch effect.

Imperfect shape

All types of misalignment including centre-line mismatch (linear misalignment) and angular misalignment (angular distortions, roofing, peaking).

Undercut

Volumetric discontinuities

Gas pores and cavities of any shape.

Solid inclusions, such as isolated slag, slag lines, flux, oxides and metallic inclusions.

Planar discontinuities

All types of cracks or cracklike imperfections, such as lack of fusion or lack of penetration (Note that for certain structural details intentional lack of penetration is already covered, e.g. at partial penetration butt welds or cruciform joints with fillet welds)

If a volumetric discontinuity is surface breaking or near the surface, or if there is any doubt about the type of an embedded discontinuity, it shall be assessed like a planar discontinuity.

3.8.1.2 Effects and Assessment of Imperfections

At geometrical imperfections, three effects affecting fatigue resistance can be distiguished, as summarized in table {3.8}-1.

Increase of general stress level

This is the effect of all types of misalignment due to secondary bending. The additional effective stress concentration factor can be calculated by appropriate formulae. The fatigue resistance of the structural detail under consideration is to be lowered by division by this factor.

Local notch effect

Here, interaction with other notches present in the welded joint is decisive. Two cases are to be distinguished:

Additive notch effect

If the location of the notch due to the the weld imperfection coincides with a structural discontinuity associated with the geometry of the weld shape (e.g. weld toe), then the fatigue resistance of the welded joint is decreased by the additive notch effect. This may be the case at weld shape imperfections.

Competitive notch effect

If the location of the notch due to the weld imperfection does not coincide with a structural geometry associated with the shape geometry of the weld, the notches are in competition. Both notches are assessed separately. The notch giving the lowest fatigue resistance is governing.

Cracklike imperfections

Planar discontinuities, such as cracks or cracklike imperfections, which require only a short period for crack initiation, are assessed using fracture mechanics on the basis that their fatigue lives consist entirely of crack propagation.

After inspection and detection of a weld imperfection, the first step of the assessment procedure is to determine the type and the effect of the imperfection as given here.

If a weld imperfection cannot be clearly associated to a type or an effect of imperfections listed here, it is recommended that it is assumed to be cracklike.

Tab. {3.8}-1: Categorization and assessment procedure for weld imperfections

<table>
<tr><th colspan="2">Effect of imperfection</th><th>Type of imperfection</th><th>Assessment</th></tr>
<tr><td colspan="2">Rise of general stress level</td><td>Misalignment</td><td>Formulae for effective stress concentration</td></tr>
<tr><td rowspan="2">Local notch effect</td><td>additive</td><td>Weld shape imperfections, undercut</td><td>Tables given</td></tr>
<tr><td>competitive</td><td>Porosity and inclusions not near the surface</td><td>Tables given</td></tr>
<tr><td colspan="2">Cracklike imperfection</td><td>Cracks, lack of fusion and penetration, all types of imperfections other than given here</td><td>Fracture mechanics</td></tr>
</table>

3.8.2 Misalignment

Misalignment in axially loaded joints leads to an increase of stress in the welded joint due to the occurrence of secondary shell bending stresses. The resulting stress is calculated by stress analysis or by using the formulae for the stress magnification factor $\mathbf{k_m}$ given in table (3.8)-2 and in appendix 6.3.

Secondary shell bending stresses do not occur in continuous welds longitudinally loaded or in joints loaded in pure bending, and so misalignment will not reduce the fatigue resistance. However, misalignment in components, e.g. beams, subject to overall bending may cause secondary bending stresses in parts of the component, where the through thickness stress gradient is small, e.g. in a flange of a beam, where the stress is effectively axial. Such cases should be assessed.

Some allowance for misalignment is already included in the tables of classified structural details (3.2). In particular, the data for transverse butt welds are directly applicable for misalignment which results in an increase of stress up to 30%, while for the cruciform joints the increase can be up to 45% . In local concepts of fatigue analysis, a small but unevitable amount of misalignment according to a stress manification factor of $\mathbf{k_m=1.05}$ is already included in the fatigue resistance S-N curves.

In special joints, i.e. all listed in table 3.8-2, the effect of a larger misalignment has to be additionally considered in the local stress (structural hot spot stress or effective notch stress). The misalignement effect may be present even in the vicinity of supporting structures. A corresponding stress increase has to be taken into account also in crack propagation analyses. In all those cases, where the stress magnification factor is directly calculated, the effective stress magnification factor $\mathbf{k_{m,\,eff}}$ should be calculated as given below.

$$K_{m,\ eff} = \frac{k_{m,\ calculated}}{k_{m,\ already\ covered}}$$

For the simultaneous occurrence of linear and angular misalignment, both stress magnification factors should be applied simultaneously using the formula:

$$k_m = 1 + (k_{m,axial} - 1) + (k_{m,angular} - 1)$$

As misalignment reduces the fatigue resistance, the fatigue resistance of the classified structural detail (3.2) has to be divided by the effective stress magnification factor.

Tab. {3.8}-2: Consideration of stress magnification factors due to misalignment

Type of k_m analysis	Nominal stress approach	Structural hot spot and effective notch approach	
Type of welded joint	k_m already covered in FAT class	k_m already covered in SN curves	Default value of effective k_m to be considered in stress
Butt joint made in shop in flat position	1,15	1,05	1.10*
Other butt joints	1.30	1,05	1.25*
cruciform joints	1.45	1,05	1.40*
Fillet welds on one plate surface	1,25	1,05	1.20**

*) but not more than $(1 + 2.5 \cdot e_{max}/t)$, where e_{max} = permissible misalignment and t = wall thickness of loaded plate
**) but not more than $(1 + 0.2 \cdot t_{ref}/t)$, where t_{ref} = reference wall thickness of fatigue resistance curves

3.8.3 Undercut

The basis for the assessment of undercut is the ratio **u/t**, i.e. depth of undercut to plate thickness. Though undercut is an additive notch, it is already considered to a limited extent in the tables of fatigue resistance of classified structural details (3.2).

Undercut does not reduce fatigue resistance of welds which are only longitudinally loaded.

3.8.3.1 Steel

Tab. {3.8}-3: Acceptance levels for weld toe undercut in steel

Fatigue class	Allowable undercut u/t	
	butt welds	fillet welds
100	0.025	not applicable
90	0.05	not applicable
80	0.075	0.05
71	0.10	0.075
63	0.10	0.10
56 and lower	0.10	0.10

Notes: a) undercut deeper than 1 mm shall be assessed as a crack-like imperfection.
b) the table is only applicable for plate thicknesses from 10 to 20 mm

3.8.3.2 Aluminium

Tab. {3.8}-4: Acceptance levels for weld toe undercut in aluminium

Fatigue class	Allowable undercut u/t	
	butt welds	fillet welds
50	0.025	not applicable
45	0.05	not applicable
40	0.075	0.05
36	0.10	0.075
32	0.10	0.10
28 and lower	0.10	0.10
Notes: a) undercut deeper than 1 mm shall be assessed as a crack-like imperfection. b) the table is only applicable for plate thicknesses from 10 to 20 mm		

3.8.4 Porosity and Inclusions

Embedded volumetric discontinuities, such as porosity and inclusions, are considered as competitive weld imperfections which can provide alternative sites for fatigue crack initiation than those covered by the fatigue resistance tables of classified structural details (3.2).

Before assessing the imperfections with respect to fatigue, it should be verified that the conditions apply for competitive notches, i.e. that the anticipated sites of crack initiation in the fatigue resistance tables do not coincide with the porosity and inclusions to be assessed and no interaction is expected.

It is important to ensure that there is no interaction between multiple weld imperfections, be it from the same or different type. Combined porosity or inclusions shall be treated as a single large one. The defect interaction criteria given in (3.8.5) for the assessment of cracks also apply for adjacent inclusions. Worm holes shall be assessed as slag inclusions.

If there is any doubt about the coalescence of porosity or inclusions in the wall thickness direction or about the distance from the surface, the imperfections shall be assessed as cracks. It has to be verified by NDT that the porosity or inclusions are embedded and volumetric. If there is any doubt, they are to be treated as cracks.

The parameter for assessing porosity is the maximum percentage of projected area of porosity in the radiograph; for inclusions, it is the maximum length. Directly adjacent inclusions are regarded as a single one.

3.8.4.1 Steel

Tab. {3.8}-5: Acceptance levels for porosity and inclusions in welds in steel

Fatigue class	Max. length of an inclusion in mm		Limits of porosity in % of area * **
	as-welded	stress relieved +	
100	1.5	7.5	3
90	2.5	19	3
80	4	58	3
71	10	no limit	5
63	35	no limit	5
56 and lower	no limit	no limit	5

* Area of radiograph used is length of weld affected by porosity multiplied by width of weld
** Maximum pore diameter or width of an inclusion less than 1/4 plate thickness or 6 mm
\+ Stress relieved by post weld heat treatment

3.8.4.2 Aluminium

Tab. {3.8}-6: Acceptance levels for porosity and inclusions in welds in aluminium

Fatigue class	Max. length of an inclusion in mm **	Limits of porosity in % of area * **
	as-welded	
40 and higher	1.5	0 +)
36	2.5	3
32	4	3
28	10	5
25	35	5
15 and lower	no limit	5

* Area of radiograph used is length of weld affected by porosity multiplied by width of weld
** Maximum pore diameter or width of an inclusion less than 1/4 plate thickness or 6 mm
+) Single pores up to 1.5 mm allowed

Tungsten inclusions have no effect on fatigue behaviour and therefore do not need to be assessed.

3.8.5 Cracklike Imperfections

3.8.5.1 General Procedure

Planar discontinuities, cracks or cracklike defects are identified by non-destructive testing and inspection. NDT indications are idealized as elliptical cracks for which the stress intensity factor is calculated according to 2.2.5.

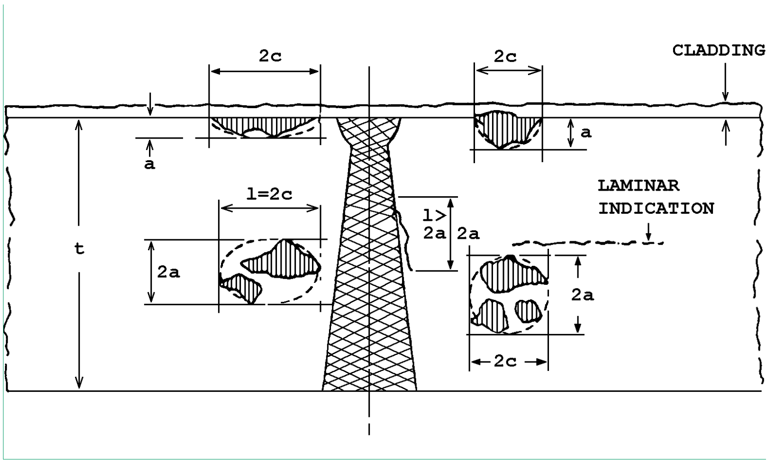


Fig. (3.8)-1 Transformation of NDT indications to an elliptic or semi-elliptic

For **embedded cracks**, the shape is idealized by a circumscribing ellipse, which is measured by its two half-axes **a** and **c**. The crack parameter **a** (crack depth) is the half-axis of the ellipse in the direction of the crack growth to be assessed. The remaining perpendicular half-axis is the half length of the crack **c**. The wall thickness parameter **t** is the distance from the center of the ellipse to the nearest surface. If the ratio **a/t > 0.75**, the defect is to be recategorized as a surface defect.

Surface cracks are described in terms of a circumscribing halfellipse. The wall thickness parameter is wall thickness **t**. If the ratio of **a/t>0.75**, the defect is regarded as being fully penetrating and is to be recategorized as a centre crack or an edge crack, whichever is applicable.

For details of dimensions of cracks and recategorization see appendix 6.2.

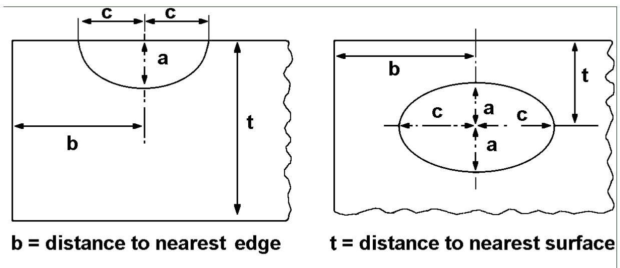


Fig. (3.8)-2 Crack dimensions for assessment

3.8.5.2 Simplified Procedure

The simplified procedure is based on the integration of the crack propagation law (4.4) from an initial defect size $\mathbf{a_i}$ to defect size of 0.75% of wall thickness using the material resistance against crack propagation as given in 3.6.1 for steel. For cracks near the plate edge, the distance **b** from the center of crack ellipsis to the plate edge was constantly assumed equalling **c**. This ensures conservative results.

In the tables the stress ranges at $2*10^6$ cycles corresponding to the definition of the fatigue classes (FAT) of classified structural details (3.2) are shown. The tables have been calculated using the correction functions and the weld joint local geometry correction given in 6.2.4. (see tab. {6.2}-1 and tab. {6.2}-3).

In assessing a defect by the simplified procedure, the stress range $\mathbf{\Delta\sigma_i}$ for the initial crack size parameter $\mathbf{a_i}$ and the stress range $\mathbf{\Delta\sigma_c}$ for the critical crack size parameter $\mathbf{a_c}$ are taken. The stress range $\mathbf{\Delta\sigma}$ or the FAT class belonging to a crack propagation from $\mathbf{a_i}$ to $\mathbf{a_c}$ at $2\cdot10^6$ cycles is then calculated by:

$$\Delta\sigma = \sqrt[3]{\Delta\sigma_i^3 - \Delta\sigma_c^3}$$

For aluminium, the tables may be used by dividing the resistance stress ranges at $2\cdot 10^6$ cycles (FAT classes) for steel by **3**.

Tables {3.8}-7: Stress ranges at $2\cdot10^6$ cycles (FAT classes in N/mm^2) of welds containing cracks for the simplified procedure (following 3 pages)

Surface cracks at fillet weld toes

a_i	long surface crack near plate edge, fillet welds l/t=2.5 a/c=0.1															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	7	16
20.0	0	0	0	0	0	0	0	0	0	0	0	4	6	8	11	19
16.0	0	0	0	0	0	0	0	0	0	0	4	7	9	11	15	22
12.0	0	0	0	0	0	0	0	0	0	6	9	12	14	16	19	25
10.0	0	0	0	0	0	0	0	0	5	9	12	15	17	19	22	27
8.0	0	0	0	0	0	0	4	7	9	13	16	19	21	22	25	30
6.0	0	0	0	0	0	6	9	12	15	18	21	23	25	26	28	33
5.0	0	0	0	0	6	10	13	16	18	21	24	26	28	29	31	35
4.0	0	0	0	5	10	14	18	20	22	25	28	29	31	32	33	37
3.0	0	0	7	11	16	20	23	25	27	30	32	33	34	35	37	39
2.0	5	11	16	20	25	28	31	32	34	36	37	39	40	40	41	43
1.0	22	28	32	34	38	40	42	43	44	45	46	47	48	48	48	48
0.5	38	42	45	47	49	51	52	53	53	54	54	54	54	54	54	52
0.2	57	59	61	61	63	63	63	63	63	63	63	62	61	61	60	56
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

a_i	long surface crack apart from edge, fillet welds l/t=2.5 a/c=0.1															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	13	22
20.0	0	0	0	0	0	0	0	0	0	0	0	7	11	13	17	25
16.0	0	0	0	0	0	0	0	0	0	0	9	12	15	18	21	28
12.0	0	0	0	0	0	0	0	0	0	11	15	18	21	23	26	32
10.0	0	0	0	0	0	0	0	0	10	15	19	22	24	26	28	34
8.0	0	0	0	0	0	0	8	12	15	20	24	26	28	29	32	37
6.0	0	0	0	0	0	12	16	19	22	26	29	31	33	34	36	40
5.0	0	0	0	0	11	17	20	24	26	29	32	34	35	36	38	42
4.0	0	0	0	9	17	22	26	28	30	33	36	37	39	40	41	44
3.0	0	0	13	18	25	29	32	34	36	38	40	42	43	44	45	47
2.0	11	19	25	29	34	37	39	41	42	44	46	47	48	49	50	51
1.0	32	38	42	44	48	50	52	53	54	55	56	57	57	57	57	56
0.5	50	53	56	58	60	62	63	63	64	64	64	64	63	63	62	59
0.2	70	72	73	74	75	75	74	74	74	73	72	71	70	69	67	62
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

a_i	short surface crack apart from edge, fillet welds l/t=2.5 a/c=.5															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	23	35
20.0	0	0	0	0	0	0	0	0	0	0	0	15	21	24	29	38
16.0	0	0	0	0	0	0	0	0	0	0	18	23	27	30	34	42
12.0	0	0	0	0	0	0	0	0	0	21	27	32	35	37	40	45
10.0	0	0	0	0	0	0	0	0	20	27	33	36	39	41	43	47
8.0	0	0	0	0	0	0	18	24	28	34	39	41	43	45	47	49
6.0	0	0	0	0	0	23	30	34	37	42	45	47	48	49	51	52
5.0	0	0	0	0	22	31	36	39	42	46	48	50	51	52	53	53
4.0	0	0	0	20	32	38	42	45	47	50	52	54	54	55	55	55
3.0	0	0	26	33	42	47	50	52	53	55	57	58	58	58	58	57
2.0	22	36	43	48	53	56	58	60	61	62	62	62	62	62	62	59
1.0	53	60	63	66	68	69	70	70	70	70	69	69	68	67	66	62
0.5	74	76	78	78	79	78	78	77	77	76	74	73	72	71	69	64
0.2	92	91	91	90	88	86	85	84	83	81	79	77	75	74	72	65
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

Surface cracks at butt weld toes

a_i	long surface crack near plate edge, butt welds l/t=1 a/c=0.1															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	7	17
20.0	0	0	0	0	0	0	0	0	0	0	0	4	6	8	11	20
16.0	0	0	0	0	0	0	0	0	0	0	4	7	9	11	15	23
12.0	0	0	0	0	0	0	0	0	0	6	9	12	14	16	20	27
10.0	0	0	0	0	0	0	0	0	5	9	12	15	18	20	23	29
8.0	0	0	0	0	0	0	4	7	9	13	17	19	22	23	26	32
6.0	0	0	0	0	0	6	9	12	15	18	22	25	26	28	30	35
5.0	0	0	0	0	6	10	13	16	18	22	25	28	29	31	33	38
4.0	0	0	0	5	10	14	18	21	23	26	29	31	33	34	36	40
3.0	0	0	7	11	16	21	24	27	29	31	34	36	37	38	40	43
2.0	5	11	16	20	26	30	32	34	36	38	40	42	43	44	45	48
1.0	22	29	33	36	40	43	45	46	47	49	51	52	52	53	53	54
0.5	41	45	48	50	53	55	57	58	58	59	60	60	60	60	60	59
0.2	61	64	66	68	69	70	70	70	70	70	70	70	69	69	68	64
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

a_i	long surface crack apart from edge, butt welds l/t=1 a/c=0.1															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	13	23
20.0	0	0	0	0	0	0	0	0	0	0	0	7	11	13	17	26
16.0	0	0	0	0	0	0	0	0	0	0	9	12	15	18	21	29
12.0	0	0	0	0	0	0	0	0	0	11	15	18	21	23	26	33
10.0	0	0	0	0	0	0	0	0	10	15	19	22	25	27	29	36
8.0	0	0	0	0	0	0	8	12	15	20	24	27	29	31	33	39
6.0	0	0	0	0	0	12	16	19	22	26	30	32	34	35	37	43
5.0	0	0	0	0	11	17	20	24	26	30	33	35	37	38	40	45
4.0	0	0	0	9	17	22	26	29	31	34	37	39	41	42	44	48
3.0	0	0	13	18	25	29	32	35	37	40	42	44	45	46	48	51
2.0	11	19	25	29	35	38	41	43	45	47	49	50	51	52	53	55
1.0	33	39	43	46	50	53	54	56	57	59	60	61	61	61	62	61
0.5	52	56	59	61	64	66	67	68	68	69	69	69	69	69	68	66
0.2	74	77	78	79	80	81	81	80	80	80	79	78	77	76	75	70
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

a_i	short surface crack apart from edge, butt welds l/t=1 a/c=0.5															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	23	36
20.0	0	0	0	0	0	0	0	0	0	0	0	15	21	24	29	40
16.0	0	0	0	0	0	0	0	0	0	0	18	23	27	30	34	43
12.0	0	0	0	0	0	0	0	0	0	21	27	32	35	37	41	47
10.0	0	0	0	0	0	0	0	0	20	27	33	37	39	41	44	50
8.0	0	0	0	0	0	0	18	24	28	34	39	42	44	46	48	52
6.0	0	0	0	0	0	23	30	34	37	42	46	48	50	51	53	56
5.0	0	0	0	0	22	31	36	39	42	47	50	52	53	54	56	57
4.0	0	0	0	20	32	38	43	46	48	52	54	56	57	58	59	60
3.0	0	0	26	33	42	47	51	53	55	58	59	61	61	62	62	62
2.0	22	36	43	48	54	58	60	62	63	65	66	67	67	67	67	65
1.0	54	61	65	68	71	73	74	74	75	75	75	75	74	74	73	69
0.5	76	80	82	83	84	84	84	84	84	83	82	81	80	79	77	71
0.2	98	98	98	98	97	95	94	93	92	90	88	86	85	83	81	74
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

Embedded cracks

a_i	embedded long crack near plate edge a/c=0.1															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	7	17
20.0	0	0	0	0	0	0	0	0	0	0	0	3	5	7	11	20
16.0	0	0	0	0	0	0	0	0	0	0	4	6	9	11	14	24
12.0	0	0	0	0	0	0	0	0	0	5	8	11	14	16	19	28
10.0	0	0	0	0	0	0	0	0	4	8	12	15	17	19	23	31
8.0	0	0	0	0	0	0	3	6	8	12	16	19	22	24	27	35
6.0	0	0	0	0	0	5	9	12	14	18	22	25	27	29	32	40
5.0	0	0	0	0	5	9	12	15	18	22	26	28	31	32	35	43
4.0	0	0	0	4	9	14	17	20	23	26	30	33	35	37	39	47
3.0	0	0	6	10	16	20	24	27	29	32	36	38	40	42	45	52
2.0	4	10	15	19	25	30	33	36	38	41	44	46	48	50	52	59
1.0	22	29	33	37	42	46	49	51	53	56	59	61	63	64	67	73
0.5	42	47	52	55	60	63	66	68	69	72	75	77	79	80	82	88
0.2	68	73	77	80	84	87	90	92	93	96	98	100	101	103	105	110
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

a_i	embedded long crack apart from plate edge a/c=0.1															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	19	30
20.0	0	0	0	0	0	0	0	0	0	0	0	12	17	20	24	33
16.0	0	0	0	0	0	0	0	0	0	0	14	19	22	25	29	37
12.0	0	0	0	0	0	0	0	0	0	17	22	26	29	31	34	41
10.0	0	0	0	0	0	0	0	0	16	22	27	30	33	35	37	44
8.0	0	0	0	0	0	0	14	19	23	28	32	35	37	39	41	48
6.0	0	0	0	0	0	19	24	28	31	35	38	41	42	44	46	53
5.0	0	0	0	0	18	25	29	33	35	39	42	44	46	47	49	56
4.0	0	0	0	15	26	31	35	38	40	43	46	48	50	51	54	59
3.0	0	0	21	27	35	39	42	45	46	49	52	54	56	57	59	64
2.0	17	29	35	40	45	49	51	53	55	58	60	62	64	65	67	71
1.0	44	51	55	58	62	65	67	69	70	73	75	77	78	79	80	84
0.5	65	69	73	75	79	82	84	85	86	88	90	91	92	93	94	97
0.2	91	95	98	100	103	105	106	107	108	110	111	112	112	113	114	117
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

a_i	embedded short crack apart from plate edge a/c=0.5															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	27	41
20.0	0	0	0	0	0	0	0	0	0	0	0	17	24	28	34	46
16.0	0	0	0	0	0	0	0	0	0	0	20	27	32	35	40	50
12.0	0	0	0	0	0	0	0	0	0	24	32	37	41	43	47	55
10.0	0	0	0	0	0	0	0	0	23	32	38	42	45	48	51	58
8.0	0	0	0	0	0	0	20	28	33	40	45	48	51	53	56	62
6.0	0	0	0	0	0	27	35	40	43	48	53	56	58	59	62	67
5.0	0	0	0	0	26	36	42	46	49	54	57	60	62	63	66	71
4.0	0	0	0	23	37	44	49	53	56	60	63	65	67	68	70	75
3.0	0	0	31	39	49	54	58	61	64	67	70	71	73	74	76	80
2.0	26	42	50	55	62	67	70	72	74	76	79	80	81	82	84	87
1.0	62	70	75	78	83	86	88	89	91	92	94	95	96	97	98	100
0.5	88	93	96	99	102	104	105	106	107	108	110	110	111	112	112	115
0.2	118	121	123	124	126	128	129	129	130	131	132	133	133	134	135	137
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

4 FATIGUE ASSESSMENT

4.1 GENERAL PRINCIPLES

In fatigue assessment, the fatigue actions and the fatigue resistance are related by means of an appropriate assessment procedure. It must be ensured that all three elements (actions, resistance and assessment procedure) correspond. Three procedures may be distinguished:

a) Procedures based on S-N curves, such as

nominal stress approach
Structural hot spot stress approach
effective notch stress approach

b) Procedures based on crack propagation considerations

c) Direct experimental approach by fatigue testing of components or entire structures

4.2 COMBINATION OF NORMAL AND SHEAR STRESS

If normal and shear stress occur simultaneously, their combined effect shall be considered. Three cases may be distinguished:

a) If the equivalent nominal shear stress range is less than 15% of the equivalent normal stress range or if the damage sum due to shear stress range is lower than 10% of that due to normal stress range, the effect of shear stress may be neclected.

b) If the normal and shear stress vary simultaneously in phase, or if the plane of maximum principal stress is not changed significantly, e.g. not more that 20°, the maximum principal stress range should be used, elswise the damage sums of normal and shear stress shall be calculated separately and finally added.

c) If normal and shear stress vary independently out of phase, in damage calculation the multiaxial damage sums shall be calculated separately and finally added. The usage of only **1/2** of the calculated life cycles is recommended for steel. This reduction does not apply for aluminium.

Fracture mechanics crack propagation calculations should be based on maximum principal stress range.

4.3 FATIGUE ASSESSMENT USING S-N CURVES

Fatigue verification is carried out using

the design spectrum of fatigue actions in terms of stress ranges $\Delta\sigma_{i,S,d}$, in which the stresses of the characteristic spectrum $\Delta\sigma_{i,S,k}$ have been multiplied by the partial safety factor γ_F for fatigue actions.

and

the design resistance S-N curve based on design resistance stresses $\Delta\sigma_{R,d}$, in which the characteristic resistance stress ranges $\Delta\sigma_{R,k}$ have been divided by the partial safety factor γ_M for fatigue resistance.

The design resistance S-N curve may be modified further according to the needs of the damage calculation procedure.

For **constant amplitude loading**, the characteristic stress range $\Delta\sigma_{R,k}$ at the required number of stress cycles is firstly determined. Secondly the fatigue criterion is checked:

$$\Delta\sigma_{S,d} = \Delta\sigma_{S,k}\cdot\gamma_F \le \Delta\sigma_{R,d} = \frac{\Delta\sigma_{R,k}}{\gamma_M}$$

At **constant amplitude loading** by normal and shear stress, the maximum principal stress shall be taken, if the direction of maximum pricipal stress is within ±60° to the normal of the weld. Otherwise the following formula has to be verified:

$$\left(\frac{\Delta\sigma_{S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{S,d}}{\Delta\tau_{R,d}}\right)^2 \le CV$$

where the comparison value CV is dependend of material and type of loading. See table {4-1}.

At **variable amplitude loading**, cumulative damage calculation procedure is applied. Usually a modified "Palmgren-Miner"-rule, as described in 4.3.1, is appropriate. For load spectra which are sensitive to the position of the knee point of the S-N curve, or in which the spectrum changes during the service time, additional assessment using the nonlinear damage calculation method described in 4.3.2 is recommended.

In all fields of application, where no test data nor service experience exist and the shape of the stress spectrum is not close to constant amplitude, it is recommended to proceed according to the calculation given in in 4.3.1.

4.3.1 Linear Damage Calculation by "Palmgren-Miner" Summation

Firstly the required number of cycles shall be specified and the design resistance S-N curve shall be determined. If the maximum design stress range $\Delta\sigma_{max,S,d}$ of the load spectrum is lower than the design knee point $\boldsymbol{\Delta\sigma_{L,R,d}}$ of the design resistance S-N curve, the life of the welded joint can be assumed as verified and no further damage calculation is necessary. This procedure is only recommended for steel in cases where a sufficient experience exists. It is **not** recommended for other cases as e.g. for aluminium and for steel under very high cycles (see chapter 3.2)

For a damage calculation at variable amplitude, the fatigue resistance curve has to be modified according to fig. (4)-1 and (4)-2. Then the slope $\mathbf{m_2}$ of the S-N curve at higher cycles than the knee point is assumed to be $\mathbf{m_2 = 2 \cdot m_1 - 1}$ [30] . For fatigue verification, it has to be shown that:

$$D = \sum_{1}^{i} \frac{n_i}{N_i} \leq 0.5...1.0$$

where D damage by summation (note restrictions in 4.2 and 4.3)
i index for block number in load spectrum of required design life
n_i number of cycles of design load stress range $\boldsymbol{\Delta\sigma_{i,S,d}}$ in load spectrum block **i**
N_i number of cycles at which design stress range $\boldsymbol{\Delta\sigma_{i,S,d}}$ causes failure in the modified design fatigue resistance S-N curve.

The order of sequence of the blocks has no effect on the results of this calculation.

It is accepted that the stresses below the assumed constant amplitude fatigue limit or below the knee point must be included in cumulative damage calculation relating to welded joints. There are currently different opinions how this should be achieved. The method presented here (fig. (4)-1) appears in a number of codes, including Eurocode 3. However, recent research indicates that a Miner sum of D=1 can be unconservative. Here, this question is partially solved by recommending a Miner sum of D=0.5 .

Note: It has been observed that for spectra with high mean stress fluctuations, the damage sum may be even lower, i.e. D=0.2 .

In some cases an equivalent constant amplitude stress range $\boldsymbol{\Delta\sigma_{eq,S}}$ has to be determined and compared directly with the constant amplitude resistance S-N curve. It is calculated as:

$$\Delta\sigma_{eq,S,d} = \sqrt[m_1]{\frac{1}{D} \cdot \frac{\Sigma(n_i \cdot \Delta\sigma_{i,S,d}^{m_1}) + \Delta\sigma_{L,d}^{(m_1 - m_2)} \cdot \Sigma(n_j \cdot \Delta\sigma_{j,S,d}^{m_2})}{\Sigma n_i + \Sigma n_j}}$$

where: D specified Miner sum
$\Delta\sigma_{eq,S,d}$ design value of characteristic equivalent stress range (loads)
m_1 slope above the knee point of the SN curve
m_2 slope below the knee point of the SN curve
$\Delta\sigma_{i,S,d}$ design values of stress ranges (loads) above the knee point
$\Delta\sigma_{j,S,d}$ design values of stress ranges (loads) below the knee point
$\Delta\sigma_{L,d}$ design value of stress range (resistance) at the knee point of S-N curve
n_i number of cycles belonging to $\Delta\sigma_i$
n_j number of cycles belonging to $\Delta\sigma_j$

For calculation of equivalent shear stress $\Delta\tau_{eq,S,d}$, the same formula applies respectively. If $\Delta\sigma_{eq,S,d}$ or $\Delta\tau_{eq,S,d}$ are below the knee point $\Delta\sigma_{L,d}$ or $\Delta\tau_{L,d}$, the FAT class and the slope $\mathbf{m_2}$ shall be used for following calculations. If all stress ranges are below the knee point and a further decline

$$\Delta\sigma_{eq,S,d} = \sqrt[m_2]{\frac{1}{D} \cdot \frac{\Sigma(n_j \cdot \Delta\sigma_{j,S,d}^{m_2})}{\Sigma n_j}}$$

of the S-N curve is given, the formula simplifies to:

The effects of combination of normal and shear stress shall be verified by:

$$\left(\frac{\Delta\sigma_{eq,S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{eq,S,d}}{\Delta\tau_{R,d}}\right)^2 \leq CV$$

where $\mathbf{\Delta\sigma_{R,d}}$ or $\mathbf{\Delta\tau_{R,d}}$ respectively is the design resistance stress range for the specified number of cycles and the appropriate FAT class. CV is a comparison value, which is given in table 4.1.

In cases where the stresses for different directions to the weld are verified by different methods, e.g. nominal stress, structural hot-spot stress or effective notch stress method, the verification by the above given formulae has to be performed with the fatigue resistance data of the correspon-ding method.

For load spectra near a constant amplitude loading, the usable number of load cycles $\mathbf{N_{use}}$ may be calculated as

$$\mathbf{N_{use} = (1 - D \cdot CV) \cdot N_{const} + N_{var}}$$

where N_{const} is the calculated number of load cycles using the maximum stress in spectrum and assuming a constant amplitude load, and N_{var} is the calculated number of load cycles at the variable amplitude loading. For D and CV see table {4-1}.

Note: The verification procedures for multiaxial and non-proportional loading are in development. The procedures given in table {4-1} describe a conservative approach. In cases of special interest, the user may consult the relevant literature.

Tab. {4-1}: Verification procedures for combined normal and shear stress using S-N curves

Type of load	Phase of stresses	Verification procedure	Miner-sum D or comparison value CV	
Constant amplitude	proportional	verification of maximum principal stress or $\left(\frac{\Delta\sigma_{S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{S,d}}{\Delta\tau_{R,d}}\right)^2 \le CV$	CV=1.0	
	non-proportional	$\left(\frac{\Delta\sigma_{S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{S,d}}{\Delta\tau_{R,d}}\right)^2 \le CV$	steel	CV=0.5
			aluminium	CV=1.0
Variable amplitude	proportional	Verification of maximum principal stress and Miner sum D, or $\left(\frac{\Delta\sigma_{eq,S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{eq,S,d}}{\Delta\tau_{R,d}}\right)^2 \le CV$	D=0.5 CV = 1.0	
	non-proportional	$\left(\frac{\Delta\sigma_{eq,S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{eq,S,d}}{\Delta\tau_{R,d}}\right)^2 \le CV$	steel	D=0.5 CV=0.5
			aluminium	D=0.5 CV=1.0

Note: For fluctuating mean stress, a Palmgren-Miner sum of D=0.2 is recommended.

For the grid of fatigue resistance classes and an initial slope of **m=3** predominantly used in 3.2, the values of the modified characteristic fatigue resistance S-N curves have been calculated. Stepping down one class corresponds to a division by **1.12**. So different levels of safety γ_M of an applied S-N curve may be considered (see 6.4.3).

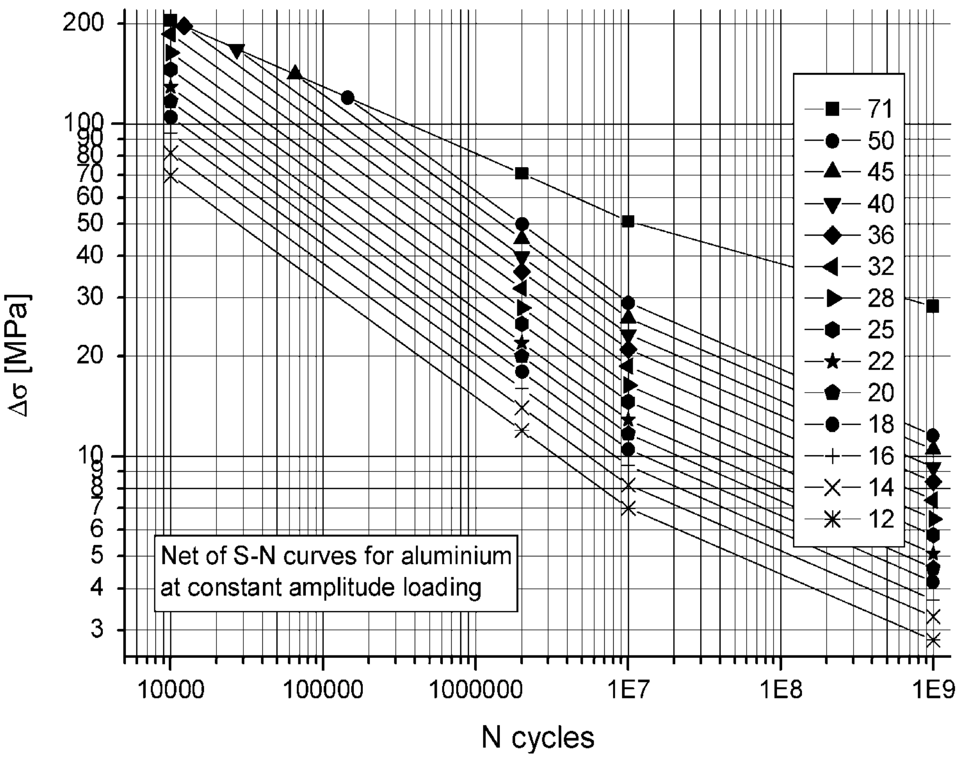


Fig. (4)-2: Modified resistance S-N curves of aluminium for Palmgren-Miner summation

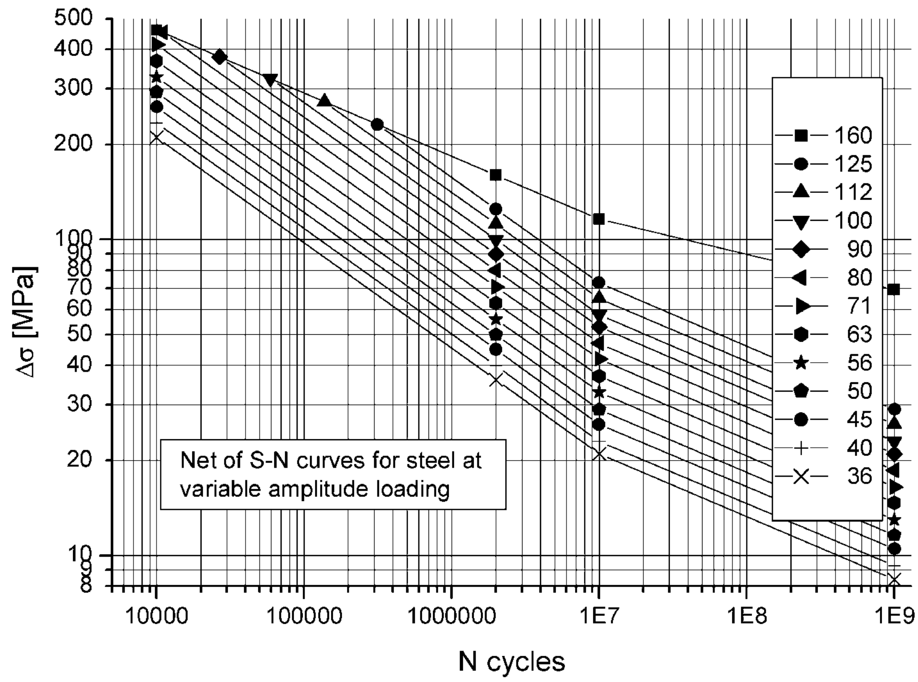


Fig. (4)-1: Modified resistance S-N curves of steel for Palmgren-Miner summation

Tab. {4}-2: FAT data, stress at kneepoint of S-N curve, constants of tentative S-N curves and constants for Palmgren-Miner summation

Stress ranges		Values of constant C: **N=C/Δσ^m** or **N=C/Δτ^m**		
FAT class [MPa]	stress at knee point [MPa]	# of cycles lower than knee point of S-N curve	# of cycles higher than knee point of S-N curve Constant C: **N=C/Δσ^m**	
Δσ at **2e6 c.**	**Δσ** at **1e7 c.**	**m=3**	constant ampl. **m=22**	variable ampl. **m=5**
125	73.1	3.906E+12	1,014E+48	2,091e+16
112	65.5	2.810E+12	9.064E+46	1.207E+16
100	58,5	2.000E+12	7.541E+45	6.851E+15
90	52.7	1.458E+12	7,583E+44	4.046E+15
80	46.8	1.024E+12	5,564E+43	2.245E+15
71	41.5	7.158E+11	3,954E+42	1.236E+15
63	36.9	5.001E+11	2,983E+41	6.800E+14
56	32.8	3.512E+11	2,235E+40	3.773E+14
50	29.3	2.500E+11	1,867E+39	2.141E+14
45	26.3	1.823E+11	1,734E+38	1,264E+14
40	23.4	1.280E+11	1,327E+37	7.016E+13
36	21.1	9.331E+10	1,362E+36	4.143E+13
32	18.7	6.554E+10	9,561E+34	2.299E+13
28	16.4	4.390E+10	5,328E+33	1.179E+13
25	14.6	3.125E+10	4,128E+32	6.691E+12
22	12.9	2.130E+10	2,710E+31	3.531E+12
20	11.7	1.600E+10	3,163E+30	2.192E+12
18	10.5	1.166E+10	2,925E+29	1.295E+12
16	9.4	8.192E+09	2,563E+28	7.184E+11
14	8.2	5.488E+09	1,270E+27	3.685E+11
12	7.0	3.456E+09	3,910E+25	1.705E+11
		m=5		
160	116.0	2.097E+17	2,619E+52	2.100E+17
80	58.0	6.554E+15	6,243E+45	6,564E+15
70	50.8	3.361E+15	3,381E+44	3,367E+15
Δτ at 2e6 c.	**Δτ at 1e8 c.**	**m=5**		
100	45,7	2,000E+16	3,297E+44	2,000E+16
80	36,6	3,277E+15	2,492E+42	3,277E+15
36	16,5	1,209E+14	6,090E+34	1,209E+14
28	12,8	3,442E+13	2,284E+32	3,442E+13

4.3.2 Nonlinear Damage Calculation

A nonlinear fracture mechanics damage calculation according to 4.4 is recommended in cases, where

a) the Miner summation is sensitive to the exact location of the knee point of the fatigue resistance S-N curve,
b) the spectrum of fatigue actions (loads) varies in service or is changed, and so the sequence of loads becomes significant or
c) the resistance S-N curve of a pre-damaged component has to be estimated.

Where the parameters for a fracture mechanics fatigue assessment are not known and only the resistance S-N curve is known, the S-N curve can be used to derive dimensionless fracture mechanics parameters, which allow a damage calculation [8-4]. The procedure is based on the "Paris" power law of crack propagation

$$\frac{da}{dN} = C_0 \cdot \Delta K^m \qquad if \quad \Delta K < \Delta K_{th} \quad then \quad \frac{da}{dN} = 0$$

where **a** crack parameter, damage parameter (dimensionless)
N Number of cycles
ΔK range of stress intensity factor
$\mathbf{\Delta K_{th}}$ threshold value of stress intensity factor range below which no crack propagation is assumed
$\mathbf{C_0}$, **m** material constants

The characteristic stress intensity factor range $\mathbf{\Delta K_{S,k}}$ of the fatigue action is calculated with the stresses of the spectrum $\mathbf{\Delta\sigma_{i,S,k}}$ and the crack parameter **a**

$$\Delta K_{S,k} = \Delta\sigma_{S,k} \cdot \sqrt{a}$$

The characteristic resistance parameters can be derived from the characteristic constant amplitude fatigue resistance S-N curve: The threshold value corresponds to the fatigue limit, $\mathbf{\Delta K_{th,k}=\Delta\sigma_{L,R,k}}$, **m** equals the slope of the S-N curve, and the constant $\mathbf{C_{0,k}}$ can be calculated from a data point ($\mathbf{\Delta\sigma_{S-N}}$ and $\mathbf{N_{S-N}}$) on the S-N curve, preferably from the fatigue class at $2 \cdot 10^6$ cycles

$$C_{0,k} = \frac{2}{(m-2) \cdot N_{S-N} \cdot \Delta\sigma_{S-N}^m}$$

The fatigue verification is executed according to 4.4, using an initial crack parameter $\mathbf{a_i=1}$ and a final one $\mathbf{a_f}=\infty$ or a large number e.g. $\mathbf{a_f=10^9}$. The restrictions on life cycles given in 4.3 are to be considered.

The actual fatigue class of a pre-damaged component thus becomes $\mathbf{FAT_{act.} = FAT/\sqrt{a}}$.

4.4 FATIGUE ASSESSMENT BY CRACK PROPAGATION CALCULATION

The fatigue action represented by the design spectrum of stress intensity factor ranges

$$\Delta K_{i,S,d} = \Delta K_{i,S,k} \cdot \gamma_F$$

is verified by the material resistance design parameters against crack propagation

$$C_{0,d} = C_{0,k} \cdot \gamma_M^m = C_{0,k} \cdot \Gamma_M$$

$$\Delta K_{th,d} = \frac{\Delta K_{th,k}}{\gamma_M}$$

using the "Paris" power law

$$\frac{da}{dN} = C_0 \cdot \Delta K^m \ , \quad \textit{if} \quad \Delta K < \Delta K_{th} \quad \textit{then} \quad \frac{da}{dN} = 0$$

where **a** crack parameter, damage parameter
N Number of cycles
ΔK range of stress intensity factor
$\mathbf{\Delta K_{th}}$ threshold value of stress intensity factor range below which no crack propagation is assumed
$\mathbf{C_0}$**, m** material constants

At stress intensity factors which are high compared with the fracture toughness of the material, $\mathbf{K_c}$, an acceleration of crack propagation will occur. In these cases, the following extension of the "Paris" power law of crack propagation is recommended. In the absence of an accurate value of the fracture toughness, a conservative estimate should be made.

$$\frac{da}{dN} = \frac{C_o \cdot \Delta K^m}{(1-R) - \frac{\Delta K}{K_c}}$$

where
$\mathbf{K_c}$ fracture toughness
R stress ratio

The number of life cycles **N** is determined by integration starting from an initial crack parameter $\mathbf{a_i}$ to a final one $\mathbf{a_f}$. The calculated number of life cycles **N** has to be greater or equal to the required number of cycles.

In general, the integration has to be carried out numerically. The increment for one cycle is

$$da = C_{0,d} \cdot \Delta K_d^m \;, \quad if \;\; \Delta K_d < K_{th,d} \;\; then \;\; da = 0$$

It is recommended that a continous spectrum is subdivided to an adequate number of stress range blocks, e.g. 8 or 10 blocks, and the integration performed blockwise by summing the increments of **a** and the number of cycles of the blocks. The entire size of the spectrum in terms of cycles should be adjusted by multiplying the block cycles by an appropriate factor in order to ensure at least 20 loops over the whole spectrum in the integration procedure.

4.5 FATIGUE ASSESSMENT BY SERVICE TESTING

4.5.1 General

Components or structures may be tested or verified in respect to fatigue for different reasons:

a) Existence of a new design with no or not sufficient knowledge or experience of fatigue behaviour.

b) Verification of a component or structure for a specified survival probability under a special fatigue action (stress) history.

c) Optimization of design and/or fabrication in respect of weight, safety and economy after pre-dimensioning. Predimensioning may be done by the use of higher fatigue resistance data, according to a lower survival probability in comparison with the resistance data given here. Then the verification is achieved by a subsequent component testing.

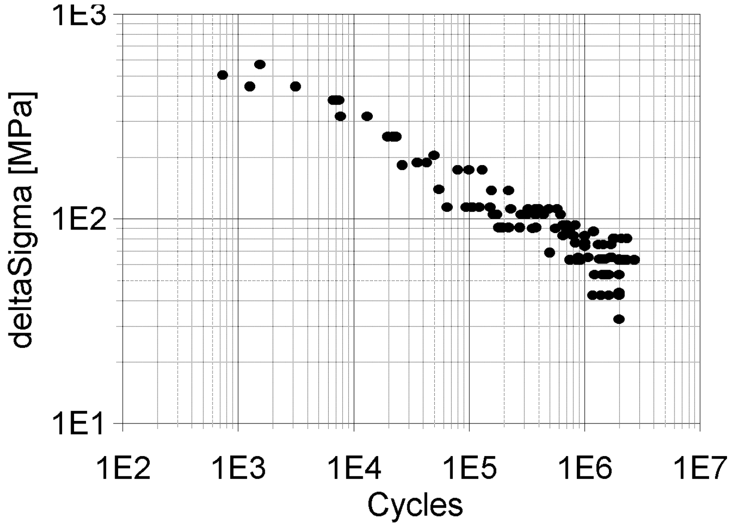


Fig. (4.5)-1: Example of scatter of test data

A predimesioning leading to the mean values of the resistance data may be done by multiplying the resistance values in terms of stress by a factor of **1.5**, which is based on a standard deviation of log cycles of 0.25 and an exponent of m=3.00 .

At component testing, the statistical nature of fatigue has to be considered. It has also be taken into account that the produced quality in fabrication may differ from the tested component. The system of quality assurance should be documented. The verification or assessment depends of the safety strategy considered (see 5.2). Safe life, fail safe and damage tolerant strategy have to be distinguished.

The fatigue tests should be performed using the data of the fatigue action history (see 3.7), factored by the partial safety factors γ_F and γ_M, i.e., the stress levels of the action history have to be multiplied by $\gamma_F \cdot \gamma_M$ for testing.

Tab. {4.5}-1 : Testing approaches

#	Testing procedure	Approach
1	all specimens of the samples are tested until failure	all failed
2	testing is stopped at failure of first specimen of the sample	first to fail
3	testing is stopped when **p** specimens of the **n** samples fail	**p** to fail

The **all failed** approach is the normal way of testing at small size samples of which each specimen represents the same weld details. The statistical analysis uses the data of the failed specimens disregarding the non-failed ones.

The **first to fail** approach may be used at a large scale sample with the same weld details and loading. The test is stopped at the first failure of a specimen.

The **n to fail** approach is used in similar conditions as the “first to fail” one, when repairs of crack details can be performed during the test. Each time when a detail fails, the test is stopped and the failed detail is repaired. Repairs are stopped depending of test conditions. At the end possibbly all details have failed and thus the “all failed” approach is applied. If only **p** specimens out of the **n** size of the sample failed, the “p to fail” approach is used.

This chapter considers the **all failed** and **first to fail** approaches. Other approaches and details of statistical analysis are considered in appendix 6.4.

The following test result data should be documented according to the selected approach:

- The mean of the log of number of cycles at failure of all **n** failed samples or details.
- The number of cycles of the first failed detail within **n** tested details.
- The number of cycles of the first **p** failed details within **n** tested details.

The tests should be performed according to well established and appropriate procedures or standards [9-1].

For the evaluation of service tests, an estimate of the standard deviation of **logN** has to be made, taking into account that the standard deviation varies with the life cycle of the component to be assessed, see fig. (3.7)-1.

For the number of test results being **n>10**, the standard deviation has to be calculated as given in 3.7-c.

For the number of test results being **n<10**, or if the procedure of first failure or **p** failures in **n** specimens is used, the standard deviation can be estimated as follows:

- **0.178** for geometrically simple structures at a number of cycles between 10^4 and 10^5
- **0.25** for complex structures at cycles up to 10^6
- ----- no estimate can be given for higher cycles near the endurance limit. Here special verification procedures are recommended, see ref. [8-1]

4.5.2 Acceptance Criteria

The number of design life cycles of the component or structure should be less than the minimum probable number of the test life cycles.

$$N_d < \frac{N_T}{F}$$

where

N_T number of test life cycles of the test specimens corresponding to the log mean value or number of cycles of the first test specimen to fail, whichever is applicable.

F factor dependent of the number of test results available as defined in tables {4.5}-1 and {4.5}-2. The **F**-factors refer to a 95% survival probability at a two sided confidence level of 75% of the mean (see also 6.4)

N_d number of design life cycles, up to which the component or structure may be used in service

If all components or test specimens are tested to failure, table {4.5}-1 shall be used.

Tab. {4.5}-1: **F**-factors for failure of all test specimens

Stdv. \ n	2	4	6	8	10
0.178	3.93	2.64	2.45	2.36	2.30
0.200	4.67	2.97	2.73	2.55	2.52
0.250	6.86	3.90	3.52	3.23	3.18

If the tests are carried out until failure of the first test specimen, table {4.5}-2 shall be used (see also 6.4).

The factor **F** may be further modified according to safety requirements as given in chapter 5.3. For more details see appendix 6.4.

Tab. {4.5}-2: F-factors for the first test specimen to fail

Stdv. \ n	2	4	6	8	10
0.178	2.72	2.07	1.83	1.69	1.55
0.200	3.08	2.26	1.98	1.80	1.64
0.250	4.07	2.77	2.34	2.09	1.85

4.5.3 Safe Life Verification

Safe life verification considers each structural element and detail as independent. Each element has to fulfill the acceptance criteria as defined in 4.5.2.

The partial safety factors γ_F applied to fatigue actions (loads) and γ_M applied to fatigue resistance may be selected from appendix 6.4.3.

4.5.4 Fail Safe Verification

Fatigue life verification of fail safe structures depends largely on the design and operation parameters of a structure. The effectiveness of statically over-determined (hyperstatic) behaviour or redundancy of structural components, the possibility of detection of failures in individual structural parts and the possibility of repair determine the level of safety required in the individual structural parts. So, no general recommendation can be given.

It is recommended that the factor **F** given in 4.5.2 is used as a general guidance and to establish agreement.

The partial safety factors γ_F applied to fatigue actions (loads) and γ_M applied to fatigue resistance may be selected from appendix 6.4.3.

4.5.5 Damage Tolerant Verification

The verification is based on crack growth measurements, starting from a crack size, which can be detected in inspection up to a critical crack size, at which the limit state of critical safety against brittle or plastic fracture or other modes of failure of the remaining sectional area is attained.

The criteria for factoring the observed life cycles for the test depend of the application. It is recommended to establish agreement on the factor **F.**

The partial safety factors γ_F applied to fatigue actions (loads) and γ_M applied to fatigue resistance may be selected from appendix 6.4.3.

5 SAFETY CONSIDERATIONS

5.1 BASIC PRINCIPLES

A component has to be designed for an adequate survival probability. The required survival probability is dependent on the

a) uncertainties and scatter in the fatigue assessment data,
b) safety strategy and
c) consequences of failure.

The uncertainties of fatigue assessment data may arise from **fatigue actions**, such as

1. determination of loads and load history,
2. determination of stresses or stress intensity factors from the model used for analysis, and
3. dynamic response problems.

These uncertainties are covered by an appropriate partial safety factor for the fatigue actions $\boldsymbol{\gamma_F}$, which is **not considered here**.

Uncertainties of fatigue assessment data arising from **fatigue resistance** and damage calculation are:

4. scatter of fatigue resistance data,
5. scatter of verification results of damage calculations.

The sources of uncertainty numbered 4. and 5. are considered here. For normal applications, they are already covered in the fatigue resistance data given here. For special applications, the data may be modified by the selection of an adequate partial safety factor $\boldsymbol{\gamma_M}$.

5.2 FATIGUE DESIGN STRATEGIES

Different ways of operation in service require different fatigue design strategies. The definition of a fatigue strategy refers predominantly to the method of fatigue analysis, inspection and monitoring in service.

5.2.1 Infinite Life Design

This strategy is based on keeping all fatigue actions under a assumed resistance fatigue limit or threshold value. No regular monitoring in service is specified. So, a high survival probability has to be provided. For fatigue actions which are almost uniform and act at very high cycles this strategy may be adequate.

Several design codes specify a fatigue limit for stresses lower than the knee point of the S-N resistance curve. It has to be checked, if the conditions for this regulations are applicable. It is recommeded for all other cases to consider a further decline of fatigue resistance beyond the knee point and to proceed according to 5.2.2.

5.2.2 Safe Life Design

This design strategy is based on the assumption that initially the welded joint is free of imperfections. No regular monitoring in service is specified, so a high survival probability has to be provided.

5.2.3 Fail Safe Design

This design strategy is based on statically over-determined (hyperstatic) or redundant structures. No regular monitoring in service is provided. In case of a fatigue failure, redistribution of forces provides an emergency life, so that the failure can be detected and repaired. The welded joints can be designed for a normal survival probability.

5.2.4 Damage Tolerant Design

This design strategy is based on the assumption of the presence of cracks as large as the detection level of the non-destuctive testing method applied. Fracture mechanics is used to calculate the life cycles until failure. From the number of life cycles, regular inspection intervals are derived. A normal probability of survival is adequate.

5.3 PARTIAL SAFETY FACTORS

The required partial safety factor $\boldsymbol{\gamma_M}$ depends largely on circumstances such as

a) fatigue design strategy
b) consequences of failure
c) practical experience in fields of application.

Thus, no general recommendation can be given. In most cases for normal fabrication quality and regular inspections in service, $\boldsymbol{\gamma_M=1}$ might be adequate.

The safety factors are given in terms of stress. If safety factors are needed in terms of cycles, $\boldsymbol{\Gamma_M}$ may be calculated using the slope **m** of the resistance S-N curve

$$\Gamma_{M,cycles} = (\gamma_M)^m$$

It should be recognized that the slope **m** of the S-N curve varies with the number of cycles, see fig. (3.7)-1. An example of a possible table of partial safety factors is given in appendix 6.4.

5.4 QUALITY ASSURANCE

Weld quality assurance is based on adequate organization of work flow in fabrication, on destructive and non-destructive inspection of materials and welds, and on individual acceptance levels of the different types of weld imperfections, which are related to the required fatigue resistance. The acceptable levels of of different types of weld imperfections may be found in chapter 3.8. or other fatigue based weld quality codes [6.6].

For practical fabrication in shop, general quality levels are needed, which are related to existing standards of description of weld imperfections. These standards are ISO 5817 for steel and ISO 10042 for aluminium. The quality levels given there, **B C D**, are not completely consistent in terms of their effect on fatigue properties. So, only general a recommendation can be given for a quality level of **B** . For several types of imperfections, this requirement may be relaxed according to the acceptance levels given in chapter 3.8 .

Note: There is a tendency in ISO 5817:2006 to specify **D** for static loaded structures, **C** for fatigue loaded ones and **B** for special requirements. Several inconsistencies in terms of fatigue properties still remain. In application of ISO 5817, a special consideration should be given to all types of misalingment and distortion.

Besides regulations and quality codes, the general standards of good workmanship have to be maintained.

5.5 REPAIR OF COMPONENTS

The most common cause of damage of welded structures and components is fatigue. Before any start of repair actions, it is vitally important to establish the reason for the damage.This will influence the decisions to be made about the need for repair and for the repair methods. Possible reasons for fatigue damage may be:

- inadequate load assumption with regard to stress range, number of cycles and shape of load spectrum
- inadequate stress analysis
- inadequate structural design, especially of weld details
- inadequate material e.g. regarding toughness and weldability
- inadequate workmanship (parts missing or not properly positioned, unsatisfactory application of thermal cutting processes, excessive weld imperfections as e.g. poor penetration, severe undercut, severe misalignment, unauthorized welding e.g. of fabrication aids)
- resonant or non-resonant forced vibrations or dynamic response not expected or not considered in design
- environmental influences enhancing fatigue such as corrosion or elevated temperature
- faulty operation, e.g. overload or fretting

- accident, e.g. collision

In most cases of damage, design, loads and imperfections are the governing parameters of the failure, material properties are often secondary.

The actions to be taken should be based on the results of the investigations. Possible actions are:

- no repair
- delayed repair
- immediate repair
- more frequent or contonuous crack monitoring, in-service inspection or vibration monitoring
- change in operation conditions

A large variety of repair methods exist. They may generally include the following aspects:

- removal of crack
- modification of detail design
- modification of service loads
- selection of adequate material and repair welding procedure
- weld toe improvements techniques
- quality control of the repair weld

6 APPENDICES

The appendices are intended to give special guidances, background information and additional explanations. They are not normative.

6.1 LOAD CYCLE COUNTING

6.1.1 Transition Matrix

To establish a transition matrix, first the number of different stess levels or classes has to be defined. 32 stress levels are sufficient. Then the numbers (occurrence) of transitions (reversals) from one extreme value (peak or through) to another are counted and summarized in the matrix. A number in the matrix element $\mathbf{a}_{\mathbf{i},\,\mathbf{j}}$ indicates the number of transitions from a stress belonging to class **i** to a stress belonging to class **j**.

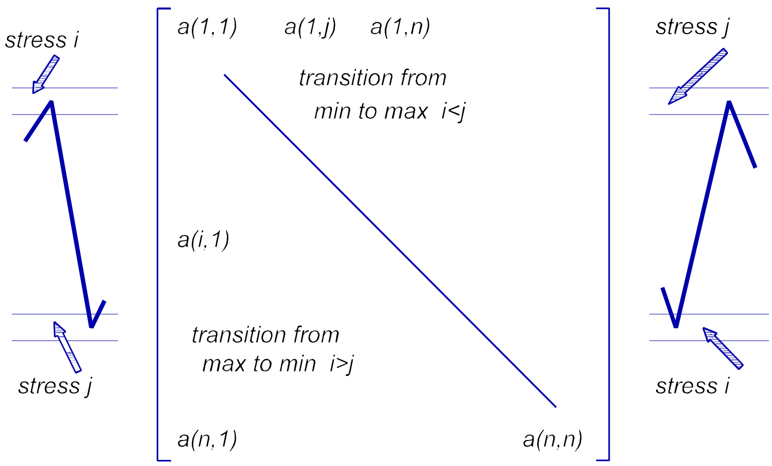


Fig. (6.1)-1 Principle of the transition matrix

The data for the transition matrix can be obtained by measurement or by time simulation computations. A time signal for fatigue tests or crack propagation simulations or cumulative frequency diagrams (stress spectra) for damage calculations can be generated from the transition matrix by a Markov random draw.

6.1.2 Rainflow or Reservoir Counting Method

The algorithm of rainflow counting method is well explained by using the analogy of the flow of water on a pagoda roof. The stress signal, looked at vertically, is regarded as the pagoda roof. A cycle is obtained, when a contour is closed by the drop of the flow from a peak to a slope of the roof [7-1 and 7-2]. The range is then equal to the difference between the extreme values of the contour. Later the smaller included cycles can be determined the same way. The non closed contour from the extreme of the entire signal leads to a half cycle. Reservoir counting is similar.

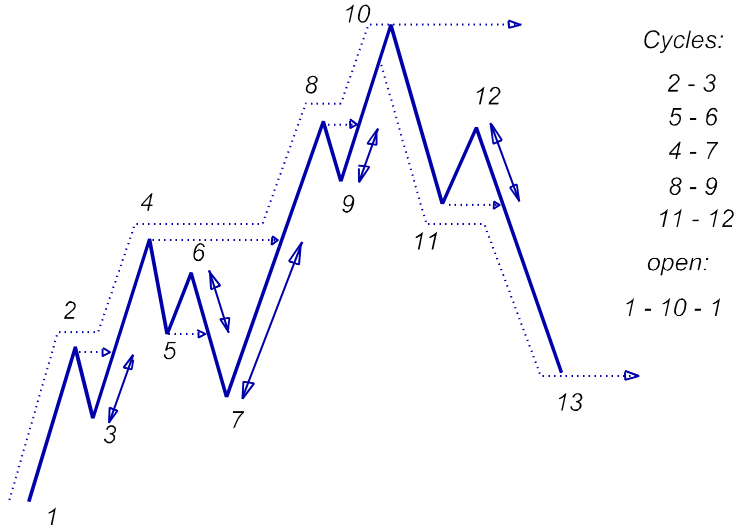


Fig. (6.1)-2 Illustration of rainflow counting

6.2 FRACTURE MECHANICS

6.2.1 Rapid Calculation of Stress Intensity Factors

A simplified method may be used to determine $\mathbf{M_k}$-factors [4-7]. Here, the $\mathbf{M_k}$-factors are derived from the non-linear stress peak distribution $\boldsymbol{\sigma_{nlp}(x)}$ along the anticipated crack path $\mathbf{x}$ assuming no crack being present. Hence, the function of the stress concentration factor $\mathbf{k_{t,nlp}(x)}$ can be calculated. The integration for a certain crack length $\mathbf{a}$ yields:

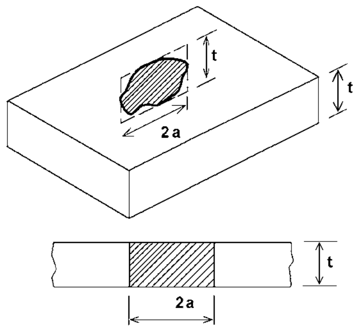
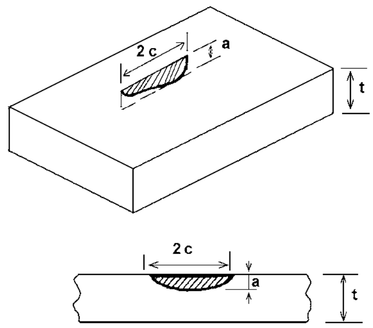
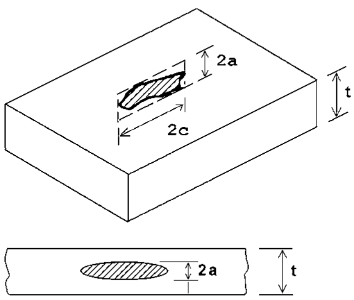
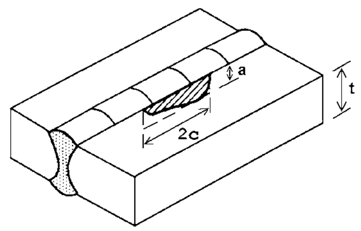
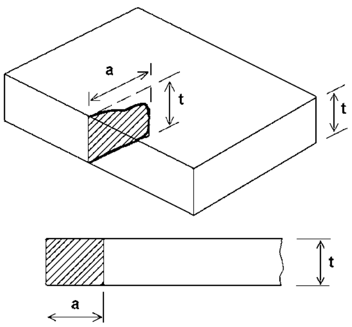
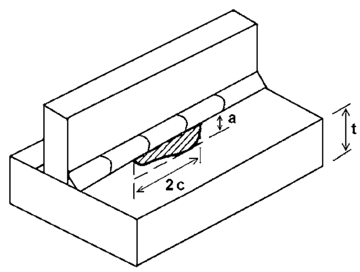
$$M_k = \frac{2}{\pi} \cdot \int_{x=0}^{x=a} \frac{k_{t,nlp}(x)}{\sqrt{a^2 - x^2}} dx$$

For different crack lengths $\mathbf{a}$, a function $\mathbf{M_k(a)}$ can be established, which is preferably presented in the form:

$$M_k(a) = \frac{const}{a^{\exp}} \qquad M_k(a) > 1$$

6.2.2 Dimensions of Cracks

Tab. {6.2}-1: Dimensions for assessment of crack-like imperfections (example)

Idealizations and dimensions of crack-like imperfection for fracture mechanics assessment procedure (t = wall thickness).	
	
	
	

6.2.3 Interaction of Cracks

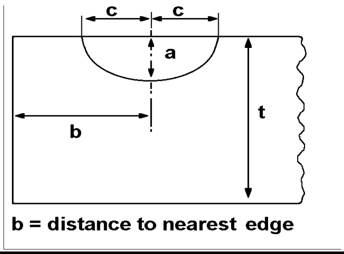
Adjacent cracks may interact and behave like a single large one. The interaction between adjacent cracks should be checked according to an interaction criterion.

There are different interaction criteria, and in consequence no strict recommendation can be given. It is recommended to proceed according to an accepted code, e.g. [6-3].

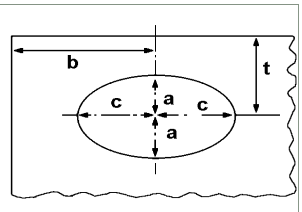
6.2.4 Formulae for Stress Intensity Factors

Stress intensity factor formulae may be taken from literature, see references [4-1 to 4-8]. For the majority of cases, the formulae given below are sufficient.

Tab. {6.2}-2: Stress intensity factors at welds

Surface cracks under membrane stress	
	The formula for the stress intensity factor K_1 is valid for $a/c < 1$, for more details see ref. [4-2]
$K_1 = \sigma \sqrt{(\pi \cdot a / Q)} \cdot F_s$ $Q = 1 + 1.464\ (a/c)^{1.65}$ $F_s = [M_1 + M_2 \cdot (a/t)^2 + M_3 \cdot (a/t)^4] \cdot g \cdot f \cdot f_w$ $M_1 = 1.13 - 0.09\ (a/c)$ $M_2 = -0.54 + 0.89 / (0.2 + a/c)$ $M_3 = 0.5 - 1 / (0.65 + a/c) + 14\ (1 - a/c)^{24}$ $f_w = [\sec(\pi \cdot c \sqrt{(a/t)} / (2 \cdot b))]^{1/2}$ g and f are dependent to direction "a"-direction: $g = 1$ $f = 1$ "c"-direction: $g = 1 + [0.1 + 0.35\ (a/t)^2]$ $f = \sqrt{(a/c)}$	

Embedded cracks under membrane stress



t = distance to nearest surface

The formula for the stress intensity factor K_1 is valid for $a/c < 1$, for more details see ref. [4-2]

K_1, Q, F_s, f_w as given before for surface cracks, but:

$M_1 = 1$

$M_2 = 0.05 / (0.11 + (a/c)^{3/2})$

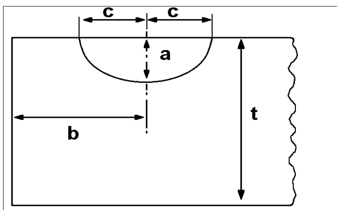
$M_3 = 0.29 / (0.23 + (a/c)^{3/2})$

g and f are dependent to direction

"a"-direction: $g = 1$ $\quad f = 1$

"c"-direction: $g = 1 - (a/t)^4 / (1 + 4a/c)$ $\quad f = \sqrt{(a/c)}$

Surface cracks under shell bending and membrane stress



b = distance to nearest edge

The formula for the stress intensity factor K_1 is valid for $a/c < 1$, for more details see ref.[4-2].

$K_1 = (\sigma_{mem} + H\cdot\sigma_{ben}) \sqrt{(\pi\cdot a / Q)} \cdot F_s$

$Q = 1 + 1.464 (a/c)^{1.65}$

$F_s = [M_1 + M_2\cdot(a/t)^2 + M_3\cdot(a/t)^4]\cdot g\cdot f\cdot f_w$

$M_1 = 1.13 - 0.09 (a/c)$

$M_2 = -0.54 - 0.89 / (0.2 + a/c)$

$M_3 = 0.5 - 1 / (0.65 + a/c) + 14 (1 - a/c)^{24}$

$f_w = [\sec(\pi\cdot c \sqrt{(a/t)} / (2\cdot b))]^{1/2}$

g and f are dependent to direction

"a"-direction: $g = 1$ $\quad f = 1$

"c"-direction: $g = 1 + [0.1 + 0.35 (a/t)^2]$ $\quad f = \sqrt{(a/c)}$

The function H is given by the formulae:

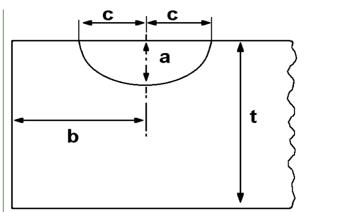
"a"-direction: $H = 1 + G_1(a/t) + G_2(a/t)^2$

where $G_1 = -1.22 - 0.12\cdot(a/c)$

$G_2 = 0.55 - 1.05\cdot(a/c)^{0.75} + 0.47(a/c)^{1.5}$

"c"-direction: $H = 1 - 0.34 (a/t) - 0.11 (a/c) (a/t)$

Surface crack in cylinder under internal pressure



b = distance to nearest edge

The formula for the stress intensity factor K_1 is valid for $a/c < 1$, for more details see ref.[4-3], where D is the diameter in mm and P is the internal pressure in N/mm^2.

$$K_1 = \sigma \sqrt{(\pi \cdot a / Q)} \cdot F_s$$

$$S = p \cdot D_{inner} / (2t)$$

$$Q = 1 + 1.464 (a/c)^{1.65}$$

$$F_s = 0.97 \cdot [M_1 + M_2 \cdot (a/t)^2 + M_3 \cdot (a/t)^4] \cdot C \cdot g \cdot f \cdot f_w$$

$$M_1 = 1.13 - 0.09 (a/c)$$
$$M_2 = -0.54 - 0.89 / (0.2 + a/c)$$
$$M_3 = 0.5 - 1 / (0.65 + a/c) + 14 (1 - a/c)^{24}$$

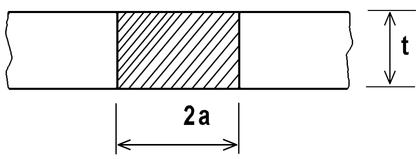
$$f_w = [\sec(\pi \cdot c \sqrt{(a/t)} / (2 \cdot b))]^{1/2}$$

$$C = [(D_{out}^2 + D_{in}^2) / (D_{out}^2 - D_{in}^2) + 1 - 0.5 \cdot \sqrt{a/t}] \cdot 2t/D_{in}$$

g and f are dependent to direction

"a"-direction: $g = 1$ $f = 1$
"c"-direction: $g = 1 + [0.1 + 0.35 (a/t)^2]$ $f = \sqrt{(a/c)}$

Through the wall cracks in curved shells under internal pressure



In sphere and longitudinal cracks in cylinder loaded by internal pressure. M_k covers increase of stress concentration factor due to bulging effect of shell. For details see ref. [4-3,4-6].

$$K = \sigma_{mem} \cdot \sqrt{(\pi \cdot a)} \cdot M_k$$

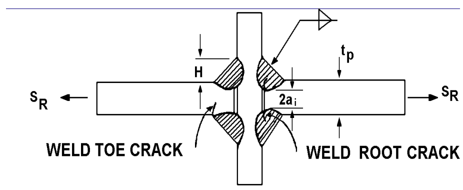
where $M_k = 1.0$ for $x < 0.8$

and $M_k = \sqrt{(0.95 + 0.65 \cdot x - 0.035 \cdot x^{1.6})}$ for $x > 0.8$ and $x < 50$

with $x = a / \sqrt{(r \cdot t)}$

a half distance between crack tips of through the wall crack
r radius of curvature perpenticular to the crack plane
t wall thickness

Root gap crack in a fillet welded cruciform joint



The formula for the stress intensity factor K is valid for H/t from 0.2 to 1.2 and for a/w from 0.0 to 0.7. For more details see ref. [4-5].

$$K = \frac{\sigma \cdot (A_1 + A_2 \cdot a/w) \cdot \sqrt{\pi a \cdot \sec(\pi a/2w)}}{1 + 2 \cdot H/t}$$

where $w = H + t/2$
σ = nominal stress range in the longitudinal plates

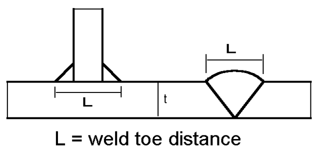
and with $x = H/t$

$$A_1 = 0.528 + 3.287 \cdot x - 4.361 \cdot x^2 + 3.696 \cdot x^3 - 1.875 \cdot x^4 + 0.415 \cdot x^5$$
$$A_2 = 0.218 + 2.717 \cdot x - 10.171 \cdot x^2 + 13.122 \cdot x^3 - 7.755 \cdot x^4 + 1.783 \cdot x^5$$

For a variety of welded joints parametric formulae of the $\mathbf{M_k}$ functions have been established and published [4-7, 4-8]. For the majority of cases, the formulae given below are sufficient [4-8].

Tab. {6.2}-3:

Weld local geometry correction for crack at weld toe



Applicable for transverse full penetrating or non-loadcarrying welds, e.g. butt weld, transverse attachment, cruciform joint K-butt weld. For more details see ref. [4-8].

Stress intensity magnification factor $M_k > 1$ for <u>membrane stress:</u>

for $l/t \le 2$:

$$M_k = 0.51 \cdot (l/t)^{0.27} \cdot (a/t)^{-0.31}, \quad \text{for } (a/t) \le 0.05 \cdot (l/t)^{0.55}$$
$$M_k = 0.83 \cdot (a/t)^{-0.15 (l/t)^{0.46}}, \quad \text{for } (a/t) > 0.05 \cdot (l/t)^{0.55}$$

for $l/t > 2$:

$$M_k = 0.615 \cdot (a/t)^{-0.31}, \quad \text{for } (a/t) \le 0.073$$
$$M_k = 0.83 \cdot (a/t)^{-0.2}, \quad \text{for } (a/t) > 0.073$$

Stress intensity magnification factor $M_k > 1$ for <u>bending stress:</u>

for $l/t \le 1$:

$$M_k = 0.45 \cdot (l/t)^{0.21} \cdot (a/t)^{-0.31}, \quad \text{for } (a/t) \le 0.03 \cdot (l/t)^{0.55}$$
$$M_k = 0.68 \cdot (a/t)^{-0.19 (l/t)^{0.21}}, \quad \text{for } (a/t) > 0.03 \cdot (l/t)^{0.55}$$

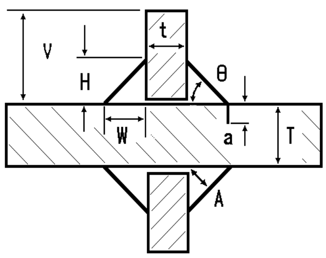
for $l/t > 1$:

$$M_k = 0.45 \cdot (a/t)^{-0.31}, \quad \text{for } (a/t) \le 0.03$$
$$M_k = 0.68 \cdot (a/t)^{-0.19}, \quad \text{for } (a/t) > 0.03$$

A systematic set of formulae was also developed in [4-7] using the procedure outlined in chapter 6.2.1. The formulae are valid within the given dimensional validity ranges.

Tab. {6.2.4}: Formulae for $\mathbf{M_k}$ values for different welded joints

Transverse non-loadcarrying attachment



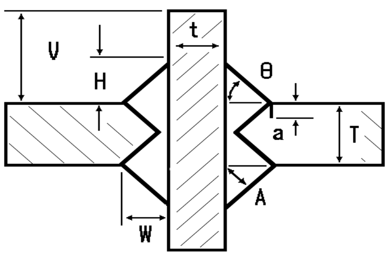
Dim.	**min**	**max**
H/T	0.2	1
W/T	0.2	1
θ	15°	60°
A/T	0.175	0.72
t/T	0.125	2 (4)

$$M_k = C \cdot \left(\frac{a}{T}\right)^k \qquad M_k = \leq 1$$

$$C = 0.8068 - 0.1554\left(\frac{H}{T}\right) + 0.0429\left(\frac{H}{T}\right)^2 + 0.0794\left(\frac{W}{T}\right) \tag{1}$$

$$k = -0.1993 - 0.1839\left(\frac{H}{T}\right) + 0.0495\left(\frac{H}{T}\right)^2 + 0.0815\left(\frac{W}{T}\right)$$

Cruciform joint K-butt weld



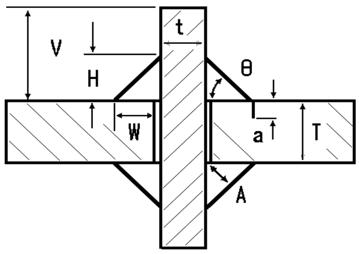
Dim.	**min**	**max**
H/T	0.2	1
W/T	0.2	1
θ	15°	60°
A/T	0.175	1.3
t/T	0.5	20

$$M_k = C \cdot \left(\frac{a}{T}\right)^k \qquad M_k \leq 1$$

$$C = 0.7061 - 0.4091\left(\frac{H}{T}\right) + 0.1596\left(\frac{H}{T}\right)^2 + 0.3739\left(\frac{W}{T}\right) - 0.1329\left(\frac{W}{T}\right)^2 \tag{2}$$

$$k = -0.2434 - 0.3939\left(\frac{H}{T}\right) + 0.1536\left(\frac{H}{T}\right)^2 + 0.3004\left(\frac{W}{T}\right) - 0.0995\left(\frac{W}{T}\right)^2$$

Cruciform joint fillet welds



Dim.	**min**	**max**
H/T	0.2	1
W/T	0.2	1
θ	15°	60°
A/T	0.175	0.8
t/T	0.5	10

$$M_k = C \cdot \left(\frac{a}{T}\right)^k \qquad M_k \geq 1$$

If 0.2 < H/T < 0.5 and 0.2 < W/T < 0.5 and a/T < 0.07 then:

$$C = 2.0175 - 0.8056\left(\frac{H}{T}\right) - 1.2856\left(\frac{W}{T}\right)$$

$$k = -0.3586 - 0.4062\left(\frac{H}{T}\right) + 0.4654\left(\frac{W}{T}\right) \qquad \textbf{(3)}$$

If 0.2 < H/T < 0.5 and 0.2 < W/T < 0.5 and a/T > 0.07 then:

$$C = 0.2916 - 0.0620\left(\frac{H}{T}\right) + 0.69421\left(\frac{W}{T}\right)$$

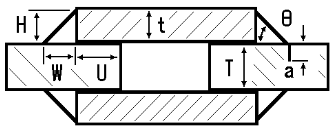
$$k = -1.1146 - 0.2132\left(\frac{H}{T}\right) + 1.4319\left(\frac{W}{T}\right) \qquad \textbf{(4)}$$

If 0.5 < H/T < 1.5 or 0.5 < W/T < 1.5 then:

$$C = 0.9055 - 0.4369\left(\frac{H}{T}\right) + 0.1753\left(\frac{H}{T}\right)^2 + 0.0665\left(\frac{W}{T}\right)^2$$

$$k = -0.2307 - 0.5470\left(\frac{H}{T}\right) + 0.2167\left(\frac{H}{T}\right)^2 + 0.2223\left(\frac{W}{T}\right) \qquad \textbf{(5)}$$

Lap joint



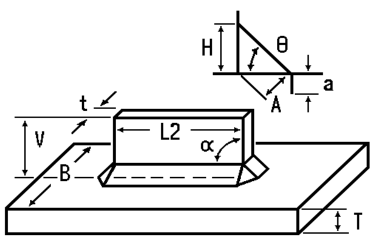
Dim.	**min**	**max**
H/T	0.25	1
W/T	0.25	2
U/T	0	1.5
θ	15°	70°
A/T	0.175	0.7
t/T	0.3	1

$$M_k = C \cdot \left(\frac{a}{T}\right)^k \qquad M_k \geq 1 \qquad \textbf{(6)}$$

$$C = 1.0210 - 0.3772\left(\frac{H}{T}\right) + 0.1844\left(\frac{H}{T}\right)^2 + 0.0187\left(\frac{W}{T}\right)^2 - 0.1856\left(\frac{U}{T}\right) + 0.1362\left(\frac{U}{T}\right)$$

$$k = -0.4535 - 0.1121\left(\frac{H}{T}\right) + 0.3409\left(\frac{W}{T}\right) - 0.0824\left(\frac{W}{T}\right)^2 + 0.0877\left(\frac{U}{T}\right) - 0.0417\left(\frac{U}{T}\right)$$

Longitudinal non-loadcarrying attachment



Dim.	**min**	**max**
L/T	5	40
B/T	2.5	40
θ/45°	0.670	1.33
t/T	0.25	2
A = 0.7 · t		

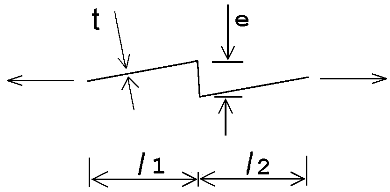
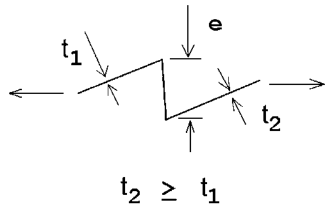
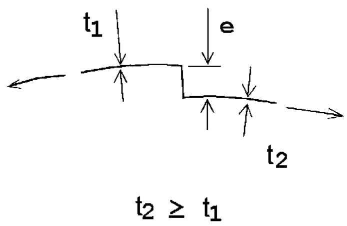
$$M_k = C \cdot \left(\frac{a}{T}\right)^k \qquad M_k = \geq 1 \qquad \textbf{(7)}$$

$$C = 0.9089 - 0.2357\left(\frac{t}{T}\right) + 0.0249\left(\frac{L}{T}\right) - 0.00038\left(\frac{L}{T}\right)^2 + 0.0186\left(\frac{B}{T}\right) - 0.1414\left(\frac{\theta}{45^\circ}\right)$$

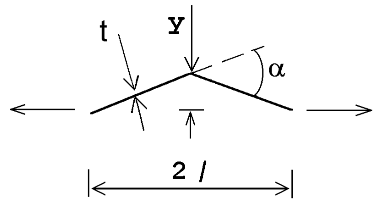
$$k = -0.02285 + 0.0167\left(\frac{t}{T}\right) - 0.3863\left(\frac{\theta}{45^\circ}\right) + 0.1230\left(\frac{\theta}{45^\circ}\right)^2$$

6.3 FORMULAE FOR MISALIGNMENT

Tab. {6.3}-1: Formulae for assessment of misalignment

#	**TYPE OF MISALIGNMENT**	
1	**Axial misalignment between flat plates**	
		$k_m = 1 + \lambda \cdot \frac{e \cdot l_1}{t(l_1 + l_2)}$
	λ is dependent on restraint, **λ=6** for unrestrained joints. For remotely loaded joints assume $\mathbf{l_1 = l_2}$.	
2	**Axial misalignment between flat plates of differing thickness**	
		$k_m = 1 + \frac{6e}{t_1} \cdot \frac{t_1^n}{t_1^n + t_2^n}$
	Relates to remotely loaded unrestraint joints. The use of **n=1.5** is supported by tests.	
3	**Axial misalignment at joints in cylindrical shells with thickness change**	
		$k_m = 1 + \frac{6e}{t_1(1 - \nu^2)} \cdot \frac{t_1^n}{t_1^n + t_2^n}$
	n=1.5 in circumferential joints and joints in spheres. **n=0.6** for longitudinal joints.	

4	**Angular misalignment between flat plates**



Assuming fixed ends:

$$with \quad \beta = \frac{2l}{t}\sqrt{\frac{3\sigma_m}{E}}$$

$$k_m = 1 + \frac{3y}{t} \cdot \frac{\tanh(\beta/2)}{\beta/2}$$

$$altern.: \quad k_m = 1 + \frac{3}{2} \cdot \frac{\alpha \cdot l}{t} \cdot \frac{\tanh(\beta/2)}{\beta/2}$$

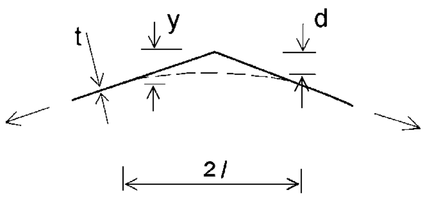
assuming pinned ends:

$$k_m = 1 + \frac{6y}{t} \cdot \frac{\tanh(\beta)}{\beta}$$

$$altern.: \quad k_m = 1 + \frac{3\alpha \cdot l}{t} \cdot \frac{\tanh(\beta)}{\beta}$$

The **tanh** correction allows for reduction of angular misalignement due to the straightening of the joint under tensile loading. It is always ≤**1** and it is conservative to ignore it.

5	**Angular misalignment at longitudinal joints in cylindrical shells**



Assuming fixed ends:

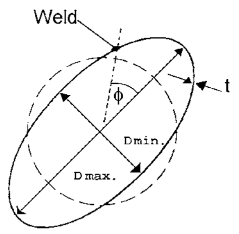
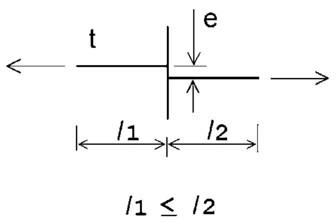
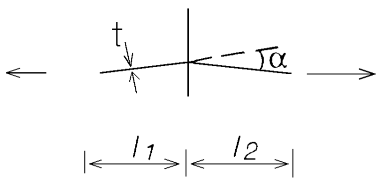
$$with \quad \beta = \frac{2l}{t}\sqrt{\frac{3(1-\nu^2)\cdot\sigma}{E}}$$

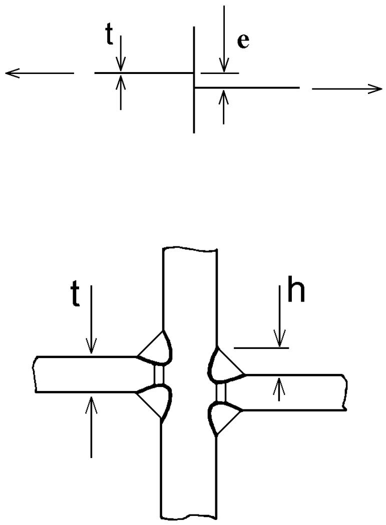
$$k_m = 1 + \frac{3d}{t(1-\nu^2)} \cdot \frac{\tanh(\beta/2)}{\beta/2}$$

assuming pinned ends:

$$k_m = 1 + \frac{6d}{t(1-\nu^2)} \cdot \frac{\tanh(\beta)}{\beta}$$

d is the deviation from the idealized geometry

6	**Ovality in pressurized cylindrical pipes and shells**	
		$k_m = 1 + \frac{1.5\,(D_{max} - D_{min}) \cdot \cos(2\Phi)}{t\left(1 + \frac{0.5\,p_{max}(1-\nu^2)}{E} \cdot \left(\frac{\bar{D}}{t}\right)^3\right)}$
7	**Axial misalignment of cruciform joints (toe cracks)**	
		$k_m = \lambda \cdot \frac{e \cdot l_1}{t(l_1 + l_2)}$ λ is dependent on restraint
	λ varies from **λ=3** (fully restrained) to **λ=6** (unrestraint). For unrestrained remotely loaded joints assume: **l_1=l_2** and **λ=6**	
8	**Angular misalignment of cruciform joints (toe cracks)**	
		$k_m = 1 + \lambda \cdot \alpha \cdot \frac{l_1 \cdot l_2}{t(l_1 + l_2)}$ λ is dependent on restraint
	If the inplane displacement of the transverse plate is restricted, λ varies from λ=0.02 to **λ=0.04**. If not, **λ** varies from **λ=3** to **λ=6**.	

9	**Axial misalignment in fillet welded cruciform joints (root cracks)**	
		$k_m = 1 + \frac{e}{t+h}$
	$\mathbf{k_m}$ refers to the stress range in weld throat.	

6.4 STATISTICAL CONSIDERATIONS ON SAFETY

6.4.1 Statistical Evaluation of Fatigue Test Data

The different methods as described in 3.7 consider different statistical effects, when evaluating a set of fatigue data. Ideally, all effects have to be considered, e.g.

a) Variance of data
b) Probability distribution of the mean value by its confidence interval
c) Probability distribution of the variance by its confidence interval
c) Difference of the distribution of the whole set of data (population) and the distribution of the sample (Gaussian versus t-distribution)
d) Deviation from the assumed Gaussian distribution which can be evaluated by a likelihood or a χ^2 test

For design, a safety margin is considered, which is applied to the mean values. The values used for design are the so called **characteristic** values (index **k**).

These charactreristic values are, in principle, values at a **α=95%** survival probability (5% probability of failure) associated to a two sided confidence interval of 75% of the mean $\mathbf{x_m}$ and of the standard deviation **Stdv**, i.e. **β=75%** (12.5% probability of being above or below the extreme value of the confidence interval):

$$x_k = x_m - k \cdot Stdv$$

The factor $\mathbf{k_i}$ considers the effects a) to d) and corresponds to:

- the minimun value of the mean confidence interval
- the maximum value of the variance confidence interval

Taking into account that the probability distribution of the mean corresponds to a Student law (t-distribution) and the probability distribution of the variance corresponds to a Chi-square law (χ^2), the general formula for $\mathbf{k_i}$ is given by:

$$k_1 = \frac{t_{(p,\, n-1)}}{\sqrt{n}} + \varphi^{-1}_{(alpa)} \cdot \sqrt{\frac{n-1}{\chi^2_{\left(\frac{1+\beta}{2},\, n-1\right)}}}$$

where **t** value of the two sided t-distribution (Student's law) for p=β=0.75, or of the one sided t-distribution for a probability of p=(1+β)/2=0.875 at **n-1** degrees of freedom
n number of data (test specimens of details)
φ distribution function of the Gaussian normal distribution probability of exceedence of α=95% (superscript **-1** indicates inverse function)
χ^2 Chi-sqare for a probability of (1+β)/2=0.875 at **n-1** degrees of freedom

If the variance is fixed from other tests or standard values, no confidence interval has to be considered and so the factor is given by:

$$k_2 = \frac{t(0.875,\ n-1)}{\sqrt{n}} + \varphi^{-1}_{(0.95)} = \frac{t(0.875,\ n-1)}{\sqrt{n}} + 1.645$$

Tab. {6.4}-1: k-values for the different methods

n	t	χ^2	k_1	k_2
2	2,51	28	11,61	3,41
3	1.61	0,27	5.41	2.57
4	1.44	0,69	4,15	2,36
5	1,36	1,21	3,6	2,25
10	1,24	4.47	2.73	2.04
15	1,21	8.21	2.46	1,96
20	1.20	12.17	2.32	1.91
25	1.19	16.26	2.24	1.88
30	1.18	20.45	2.17	1.86
40	1.18	29.07	2.09	1.83
50	1.17	37.84	2.04	1.81
100	1.16	83.02	1.91	1.76

6.4.2 Statistical Evaluation at Component Testing

Testing all test specimens to failure

When all specimens are tested to failure, the procedure is to estimate the mean log N_T of the S-N curve and the associated standard deviation.

Starting from the formula in 4.5.2, there is

$$N_d < \frac{N_T}{F}$$

which defines the safety factor **F** by:

$$\log N_T - \log F > \log N_d$$

Taking the acceptance criterion from chapter 3.7 $\mathbf{x_m - k\ Stdv > x_k}$ the factor **F** can be received:

$$\log F = k \cdot Stdv$$

With the formula for **k** the different values of **F** can be calculated, depending on number of test specimens **n** and on the assumed standard deviation **Stdv** of the test specimens in terms of **logN**.

Testing all test specimens simultaneously until first failure

When all test specimens are tested simultaneously until the first to fail, only one value of log N_T is obtained and no standard deviation can be derived from test results.

Starting from the formula in 4.5.2, there is

$$N_d < \frac{N_T}{F}$$

which defines the safety factor **F** by:

$$\log N_T - \log F > \log N_d$$

When considering statistical evaluation, account must be taken of additional effects as illustrated in fig. (6.4)-1:

1) Distribution of the 1/n-th extreme value
2) Distribution of the sample between 1/n-th extreme and mean
3) Safety margin for the characteristic value

where **N_T** first failure
x_m mean of the sample
N_k charactristic value
N_d design value

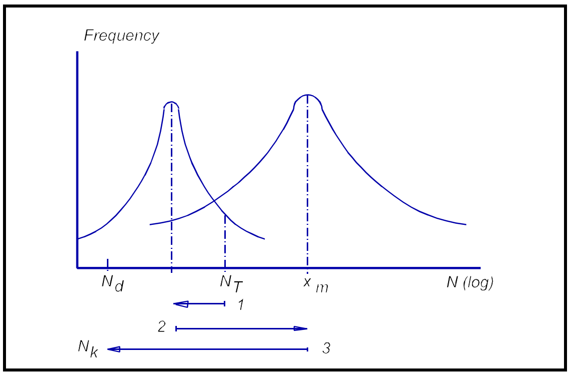


Fig. (6.4)-1 Distribution of action and re-sistance

log N_T is considered as the probable maximum (safe side) of the distribution of the minimum value of the log N distribution. The mean sample **x_m** is therefore given by:

$$x_m = \log N_T - k_a \cdot \alpha \cdot Stdv + k_b \cdot Stdv$$

with **Stdv** standard deviation of the sample
α from table of variance order statistics
k_a, k_b from table of expected values of normal order statistics

Taking the acceptance criterion from chapter 3.7, **x_m - k_1 Stdv > x_k** , the factor **F** can be recei-ved:

$$\log F = (k_a \cdot \alpha - k_b + k_1) \cdot Stdv = k \cdot Stdv$$

The different values of **F** can be calculated, depending on number of test specimens **n** and on the assumed standard deviation **Stdv** of the test specimens in terms of **log N**.

Tab. {6.4}-3: Values **k** for testing until first failure

n	2	4	6	8	10
k	2.44	1.77	1.48	1.28	1.07

For more details see ref. [10-3, 10-4].

Testing all specimens simultaneously until p failures amongst n specimens

Values of k may be taken from the relevant literature or from IIW doc. XIII-1822-2000 (under development).

6.4.3 Statistical Considerations for Partial Safety Factors

No general recommendations on partial safety factors are given. For special fields of application, tables of safety factors on load actions γ_F and on fatigue resistance γ_M may be established. Table {6.4}-4 shows a possible example for γ_M which may be adjusted according to the special requirements of the individual application.

Tab. {6.4}-4: Possible example for partial safety factors γ_M for fatigue resistance

Partial safety factor γ_M → Consequence of failure	Fail safe and damage tolerant strategy	Safe life and infinite life strategy
Loss of secondary structural parts	1.0	1.15
Loss of the entire structure	1.15	1.30
Loss of human life	1.30	1.40

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