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***RECOMMENDATIONS FOR
FATIGUE DESIGN OF WELDED
JOINTS AND COMPONENTS***

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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 was transferred to the Joint Working Group XIII-XV, where it was discussed and drafted in the years 1990 to 1996 and then updated in the years 2002-2007. The main points of the update are: Revision of the chapter on structural hot spot stress, consideration of aluminium at the effective notch stress method, a new chapter on improvement techniques and a revision of the chapter on multiaxial loading. The document contains contributions from:

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1 GENERAL

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It is the user's responsibility to ensure that the recommendations given here are suitable for his/her intended purposes.

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 knowledge 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 the ultimate and servicability limit states [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 $\Delta\sigma_{nom} > 1.5 \cdot f_y$, $\max\sigma_{nom} > f_y$, 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% survival probability referred to a two sided confidence level of the mean of 75% .
Classified or standard 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 these fatigue design recommendations. Also referred to as standard structural detail.
Concentrated load effect	i) A local stress field in the vicinity of a point load or reaction force, ii) 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 between constant maximum and minimum stress limits.
Crack propagation rate	Amount of crack extension per stress cycle.
Crack propagation threshold	Limiting value of stress intensity factor range below which crack propagation can be considered as negligible.
Cut off limit	Fatigue strength under variable amplitude loading, below which the stress cycles are considered to be non-damaging.
Cycle counting	Procedure of converting the history of variable amplitude loading into an equivalent spectrum or transition matrix (e.g. 'Rainflow' or 'Reservior' methods).
Design value	Characteristic value factored by a partial safety factor.
Effective notch stress	Notch stress calculated for a notch with a certain assumed notch radius.
Equivalent stress range	Constant amplitude stress range which is equivalent in terms of fatigue damage to a variable stress history for the same number of applied stress cycles.
Fatigue	Deterioration of a component caused by the crack initiation and/or by the growth of a crack.

Fatigue action	Load effect causing fatigue, i.e. fluctuating 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 loading.
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.
Fatigue resistance	Structural detail's resistance to fatigue actions expressed in terms of a 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 or modified nominal stress	Nominal stress including macro-geometric effects, concentrated load effects and misalignments, disregarding the stress raising effects of the welded joint itself.
Local notch	A localised geometric feature, such as the toe of a weld, that causes stress concentration. The local notch does not alter the structural stress but generates a nonlinear stress peak.
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 Figure (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 fatigue crack growth rate and stress intensity factor range.
Palmgren-Miner rule	Method for estimating fatigue life under variable amplitude loading from the constant amplitude S-N curve (see 4.3.1). Often referred to as Miner's rule.
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 applied stress range 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, usually determined by cycle counting.

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 period of time.
Stress intensity factor	The fracture mechanics parameter, which is a function of applied stress, crack size and geometry.
Stress range	The difference between the maximum and minimum stresses in a cycle.
Stress range block	A part of the total spectrum of stress ranges which is discretized in a certain number of blocks.
Stress spectrum	A tabular or graphical presentation of the cumulative frequency of stress range exceedence (e.g. the number of stress ranges exceeding a particular magnitude of stress range in a stress history, where frequency is the number of occurrences).
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 Figure (2.2)-6).
Structural or geometric stress	A stress in a component, resolved to take into account the effects of a structural discontinuity, and consisting of membrane and shell bending stress components.
Structural stress concentration factor	The ratio of structural (hot spot) stress to local or modified 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

A	cross sectional area of loaded plate (a suffix may be added) or weld throat size
B	plate width
C	constant in equation of S-N curve with exponent m
CV	comparison value used in verification procedure for assessing combined loading
D	fatigue damage sum according to the Palmgren-Miner rule or mean diameter
D_{max}	maximum diameter
D_{min}	minimum diameter
E	elastic modulus
F	force or statistical safety factor
FAT_x	classification reference to S-N curve, in which x is the stress range in MPa at $2 \cdot 10^6$ cycles
H	fillet weld leg length
K	stress intensity factor
K_{max}	stress intensity factor caused by σ_{max}
K_{min}	stress intensity factor caused by σ_{min}
L	attachment length in direction of loading considered
M	bending moment
M_k	magnification function for K due to nonlinear stress peak
M_{k,m}	magnification function for K , concerning membrane stresses
M_{k,b}	magnification function for K , concerning shell bending stresses
N	fatigue life in cycles
N_i	constant amplitude fatigue life at the <i>i</i> th stress range
R	stress ratio
Stdv	standard deviation of logN
W	fillet weld leg length (see Table {6.2}-4)
Y	correction function for K , taking into account crack form, aspect ratio, relative crack size etc.
Y_m	correction function for K , concerning membrane stress
Y_b	correction function for K , concerning shell bending stress
a	weld throat size or depth of a surface crack or semi length of an embedded crack
a₀	initial depth of a surface crack
a_f	value of a at fatigue failure
b	distance between crack centre and nearest plate edge
c	half length of surface or embedded elliptical crack
d	deviation from the true circle due to angular misalignment
e	eccentricity, amount of offset misalignment
f_y	actual or specified yield strength of the material
k_m	stress magnification factor due to misalignment
k_s	stress concentration factor due to structural discontinuity

k_t	stress concentration factor due to local notch
m	exponent of S-N curve or Paris power law
n	exponent in thickness correction or number of data pairs
n_i	number of applied stress cycles at the i th stress range
t	plate thickness, thickness parameter (crack center to nearest surface)
ΔK	stress intensity factor range
$\Delta K_{s,d}$	design value of stress intensity factor range caused by actions
ΔK_{th}	threshold stress intensity factor range
$\Delta \sigma$	stress range
$\Delta \sigma_{s,d}$	design value of stress range caused by actions
$\Delta \sigma_{R,L}$	characteristic value of stress range at knee point of S-N curve
$\Delta \tau$	shear stress range
γ_M	partial safety factor for fatigue resistance in terms of stress
Γ_M	partial safety factor for fatigue resistance in terms of cycles
σ	normal stress
σ_b	shell bending stress
σ_{en}	effective notch stress
σ_{ln}	(local) notch stress
σ_{max}	stress maximum in stress history
σ_m	membrane stress
σ_{min}	stress minimum in stress history
σ_{nlp}	nonlinear stress peak
σ_{nom}	(modified) nominal stress
σ_{hs}	structural hot spot stress

Subscripts:

S	fatigue actions
R	fatigue resistance
d	design value
k	characteristic value
τ	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. The main fatigue resistance data provided in this document are in the form of S-N or fatigue crack growth curves, based on constant amplitude test results. No specific recommendations are given for the fatigue load (action) side, or for the partial safety factors on fatigue resistance γ_M or 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 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 is **not** usually required. If there is any doubt that these criteria apply, a fatigue assessment is recommended:

- a) The highest nominal design stress range satisfies

$$\text{steel} : \Delta\sigma_{S,d} \leq 36 \text{ [MPa]} / \gamma_M \quad (1.1)$$

$$\text{aluminium: } \Delta\sigma_{S,d} \leq 12 \text{ [MPa]} / \gamma_M \quad (1.2)$$

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

- b) The Miner sum **D** (Section 4.3.1) is less than or equal to **D=0.5** when evaluated using either fatigue class 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 (Section 3.2)

$$\Delta\sigma_{S,d} \leq \Delta\sigma_{R,L} / \gamma_M \quad (1.3)$$

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

$$\Delta K_{S,d} \leq \Delta K_{th} / \gamma_M \quad (1.4)$$

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

1.7 APPLICATION OF THE DOCUMENT

Various assessment procedures are presented of which the choice is depending on the initial information about the welded joint and the applied loading. Then, the fatigue action data (e.g. stress type) and the fatigue resistance data are determined according to the assessment procedure. The corresponding types of fatigue action and resistance are summarized in Tables {1}-1 and 2:

Table {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 may need to be performed using appropriate safety factors.

Table {1}-2: General guidance for the application of the document

Item	Initial Information	Fatigue Action	Fatigue Resistance
(1)	Does joint correspond to a tabulated structural detail? if no ↓	yes → determine nominal stress (2.2.2) then →	look up fatigue resistance class (FAT) in Tables (3.2) go to (6)
(2)	Is hot-spot structural stress assessment applicable? if no ↓	yes → determine hot-spot structural stress (2.2.3) then →	look up resistance S-N curve for hot-spot structural stress (3.3) go to (6)
(3)	Is effective notch stress assessment applicable? if no ↓	yes → determine effective notch stress (2.2.4) then →	look up resistance S-N curve for effective notch stress (3.4) go to (6)
(4)	Is there a risk that cracks or cracklike imperfections will be present? if no ↓	yes → determine stress intensity factor (2.2.5) then →	look up resistance against crack propagation (3.6 and 3.8) go to (7)

(5)	Test entire component (4.5)	go to (8)			
	Test structural detail (3.7)	go to (6)			
Modifications and Assessment Procedures					
(6)	Modify resistance S-N curve (3.5) for all effects not yet covered	Using Miner rule? yes → no ↓	calculate design resistance S-N curve (4.3.1) using γ_M (8)	then →	perform summation (4.3.1) to estimate life cycles, assess if OK
		Using fracture mechanics →	calc. dimensionless crack propagation parameter from resistance S-N curve (4.3.2) using γ_M (8)		
			then ↓		
(7)	Calculate design crack propagation resistance data using (8)	then →	Perform crack propagation calculation (4.4) and estimate 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 also be considered. Improper knowledge of fatigue actions is one of the major sources of fatigue damage.

Tensile residual stresses due to welding and other manufacturing processes decrease the fatigue resistance. However, the influence of high tensile residual stresses is already included in the fatigue resistance data given in Section 3.

2.1 BASIC PRINCIPLES

2.1.1 Determination of Fatigue Actions (Loading)

In assessing fatigue performance, a safe estimate of fatigue loading to be endured throughout the life of the structure or component under consideration is crucial. All types of varying loading should be considered. Fluctuating loading from different sources may be significant at different phases of the life, e.g. construction, transportation, installation, in-service, and may involve different frequencies. The design load spectrum should be selected on the basis that it is an upper bound estimate of the accumulated service conditions over the full design life of the structure or component concerned. If relevant, this may be based on characteristic load data and partial safety factors γ_F specified in the application code giving design values for the fatigue loading.

No guidance is given in this document for the establishing of design values for actions (loads), nor for partial safety factors γ_F on actions (loads).

2.1.2 Stress Range

Fatigue assessment is usually based on stress range or stress intensity factor range. Thus, the the fatigue loading (actions) needs to be expressed in these terms.

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} \quad (2.1)$$

$$\Delta K = K_{\max} - K_{\min} \quad (2.2)$$

The maximum and minimum stresses should be calculated from the superposition of all non permanent, i.e. fluctuating loads:

- 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 Concentrations and Notch Effects

The stress required to assess the fatigue resistance of a particular stress concentration feature depends on the type and the fatigue assessment procedure used.

Table {2}-1: Stress concentrations and notch effects considered

Type	Stress concentrations	Stress determined	Assessment procedure
A	None	Gross average stress from sectional forces, calculated using general theories, e.g. beam theory	Not applicable for fatigue analysis of joints, only for component testing
B	Macrogeometrical effects due to the design of the component, but excluding stress concentrations due to the welded joint itself.	Range of nominal stress (also modified or local nominal stress)	Nominal stress approach
C	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

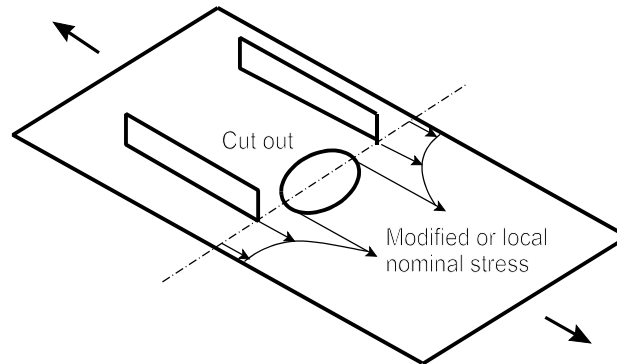


Figure (2.1)-1 Modified or local nominal stress

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 increase in stress in the vicinity of the notch, caused by the structural detail and the weld toe.

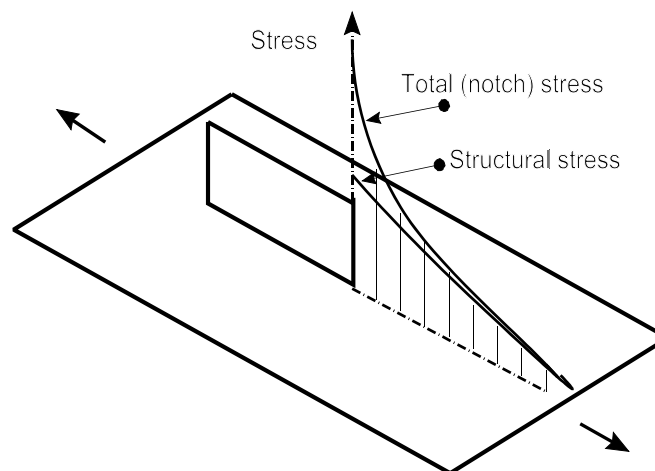


Figure (2.1)-2 Notch stress and structural hot-spot stress

2.2 DETERMINATION OF STRESSES AND STRESS INTENSITY FACTORS

2.2.1 Definition of Stress Components

In the vicinity of a notch the stress distribution over the plate thickness is non-linear.

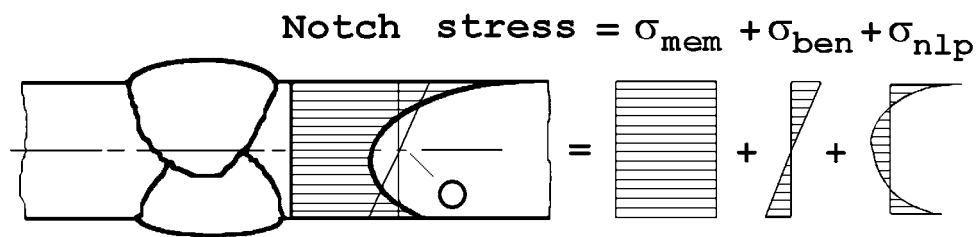


Fig. (2.2)-1a Non-linear stress distribution separated to stress components

The stress components of the notch stress σ_{in} are [1-2]:

σ_{m}	membrane stress
σ_{b}	shell bending stress
σ_{nl}	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:

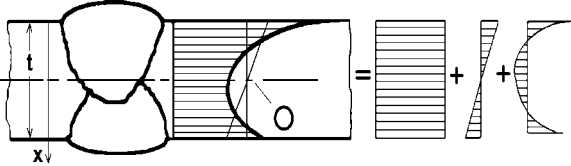
The membrane stress σ_{m} is equal to the average stress calculated through the thickness of the plate. It is constant through the thickness.

The shell bending stress σ_{b} is linearly distributed through the thickness of the plate. It is found by drawing a straight line through the point **O** in Figure (2.2)-1a 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 σ_{nl} is the remaining component of the stress.

The stress components can be separated analytically for a given through thickness stress distribution $\sigma(x)$ from $x=0$ at the surface to $x=t$:

Notch stress = $\sigma_m + \sigma_b + \sigma_{nl}$



$$\sigma_m = \frac{1}{t} \cdot \int_{x=0}^{x=t} \sigma(x) \cdot dx \quad (2.3)$$

Figure (2.2)-1b Position of coordinates

$$\sigma_b = \frac{6}{t^2} \cdot \int_{x=0}^{x=t} (\sigma(x) - \sigma_m) \cdot \left(\frac{t}{2} - x\right) \cdot dx \quad (2.4)$$

$$\sigma_{nl}(x) = \sigma(x) - \sigma_m - \left(1 - \frac{2x}{t}\right) \cdot \sigma_b \quad (2.5)$$

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. For example 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.

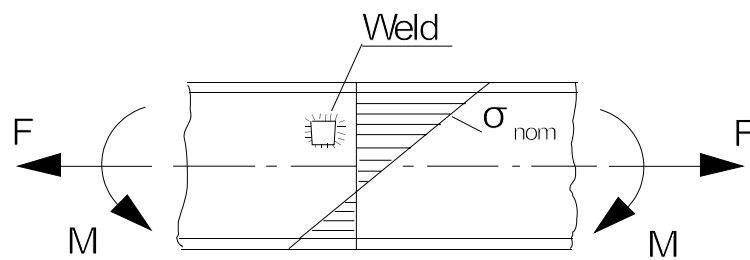


Figure (2.2)-2 Nominal stress in a beam-like component

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

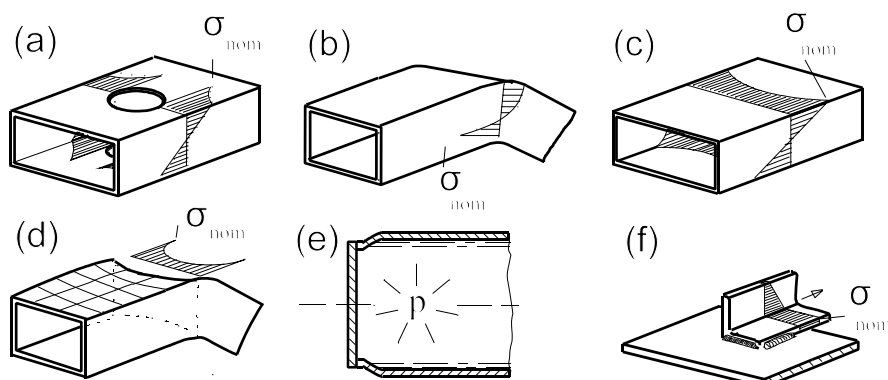


Figure (2.2)-3 Examples of macrogeometric effects

The secondary bending stress caused by axial or angular **misalignment** (e.g. as considered to be acceptable in the fabrication specification) needs to be considered if the misalignment exceeds the amount which is already covered by the fatigue resistance S-N curve for the structural detail. This is done by the application of an additional stress magnification factor $k_{m,eff}$ (see Section 3.8.2). Either the applied stress is multiplied by $k_{m,eff}$ or the fatigue resistance (stress) is divided by it.

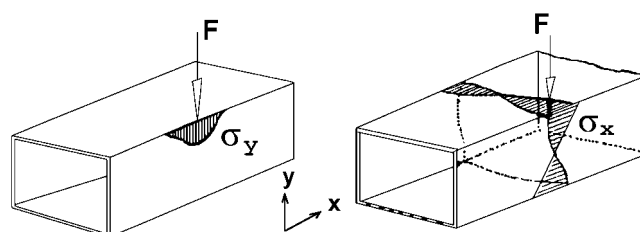


Figure (2.2)-4 Modified (local) nominal stress near concentrated loads

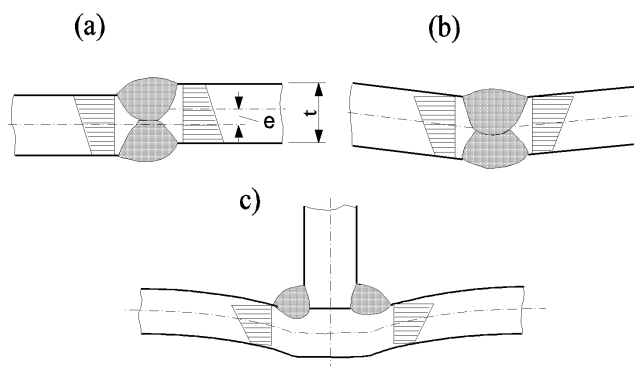


Figure (2.2)-5 Axial and angular misalignment

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 the weld throat or in the plate at the weld toe as indicated in the tables of structural details. The stress σ_w or τ_w in weld throat a for a weld of length l_w and a force in the weld F becomes

$$\sigma_w \text{ or } \tau_w = \frac{F}{A_w} = \frac{F}{a \cdot l_w} \quad (2.6)$$

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

If the finite element method is used, meshing can be simple and coarse. Care must be taken to ensure that all stress concentration effects from 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 coarse finite element meshes, nodal forces rather than element stresses should be used in a section through the weld 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 the stress concentration field of the welded joint.

In practice, it may be necessary first to evaluate the extent and the stress gradient of the field of stress concentration (see Section 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 that 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 Section 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 for plate, shell and tubular structures. Figure (2.2)-6 shows examples of structural discontinuities and details together with the structural stress distribution.

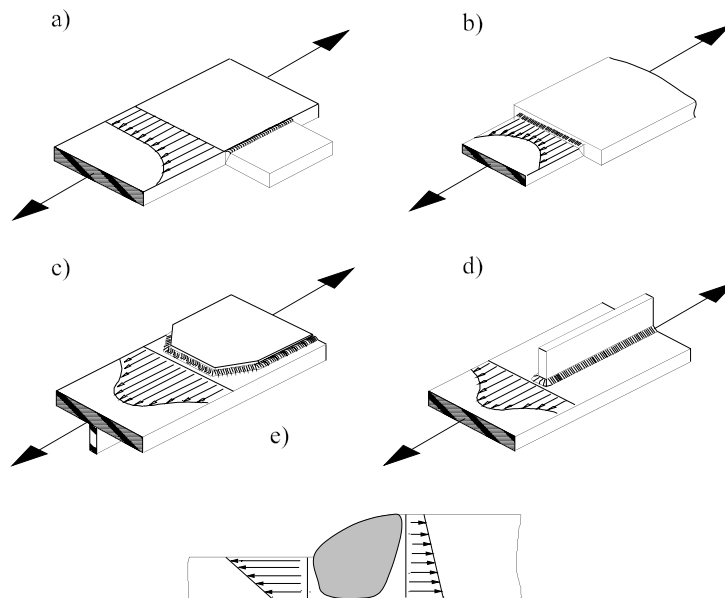


Figure (2.2)-6 Structural details and structural stress

The structural hot spot stress approach is typically used where there is no clearly defined nominal stress due to complicated geometric effects, or where the structural discontinuity is not comparable to a classified structural detail.

The structural hot-spot stress can be determined using reference points by extrapolation to the weld toe under consideration from stresses at reference points. Strictly speaking, the method as defined here is limited to the assessment of the weld toe, i.e. cases **a** to **e** in Figures (2.2)-8. However, the approach may be extended to the assessment of other potential fatigue crack initiation sites including the weld root, by using the structural hot spot stress on the surface as an indication of that in the region of interest. The S-N curves

or the stress concentration factors used for verification in such cases depend largely on the geometric and dimensional parameters and are only valid in the range of these parameters.

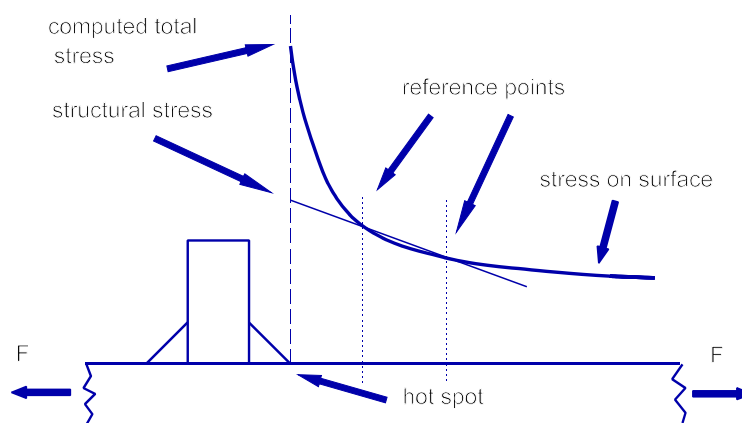


Figure (2.2)-7 Definition of structural hot-spot stress

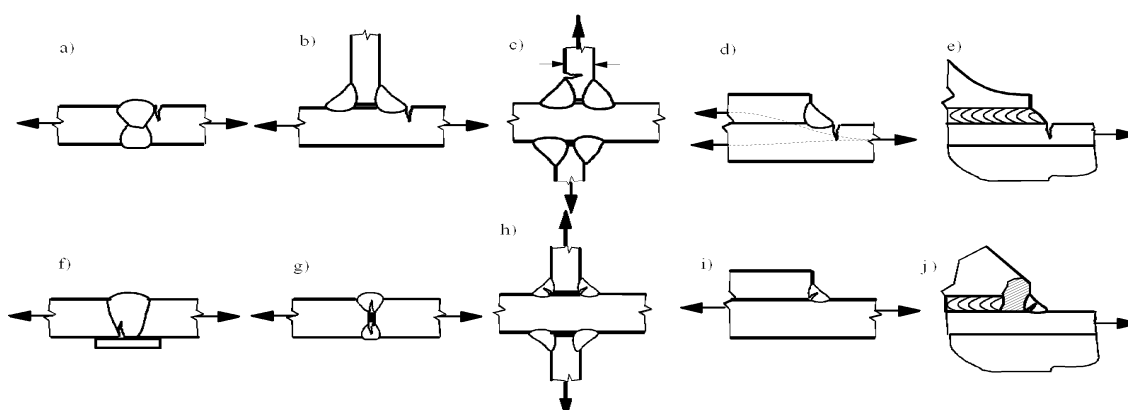


Figure (2.2)-8: Various locations of crack propagation in welded joints.

In the case of a biaxial stress state at the plate surface, it is recommended that the principal stress which acts approximately in line with the perpendicular to the weld toe, i.e. within $\pm 60^\circ$ (Figure 2.2-9) is used. The other principal stress may need to be analysed, if necessary, using the fatigue class in the nominal stress approach for welds parallel to the stress.

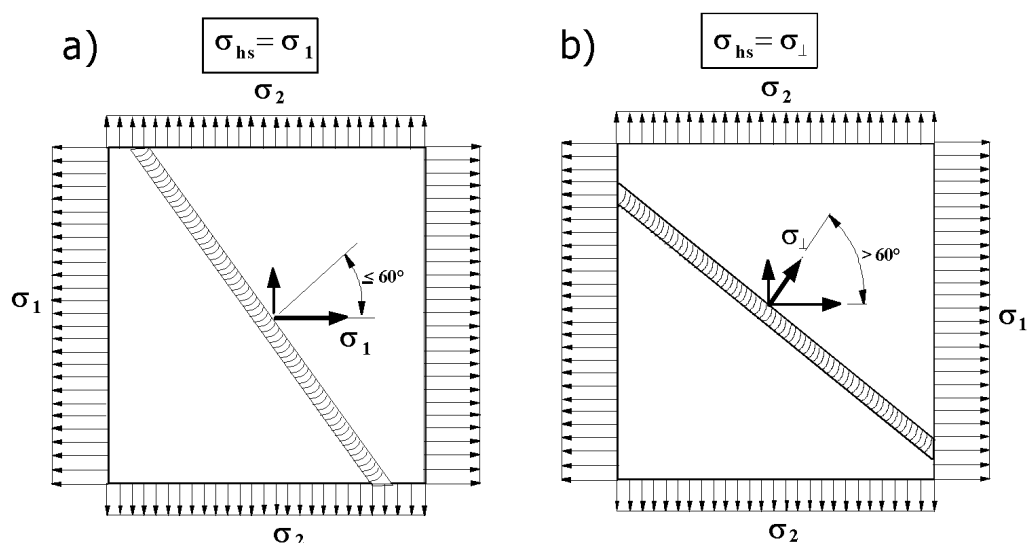


Figure (2.2)-9 Biaxial stresses at weld toe

2.2.3.2 Types of hot spots

Besides the definitions of structural hot spot stress as given above, two types of hot spots are defined according to their location on the plate and their orientation in respect to the weld toe as defined in Figure (2.2)-10:

Table {2.2}-1: Types of hot spots

Type	Description	Determination
a	Weld toe on plate surface	FEA or measurement and extrapolation
b	Weld toe at plate edge	FEA or measurement and extrapolation

The structural stress acts normal to the weld toe in each case and is determined either by a special FEA procedure or by extrapolation from measured stresses.

2.2.3.3 Determination of Structural Hot Spot Stress

The structural hot spot stress can be determined either by measurement or by calculation. Here the non-linear peak stress is eliminated by linearization of the stress through the plate thickness (see Section 2.2.1) or by extrapolation of the stress at the surface to the weld toe. The following considerations focus on surface stress extrapolation procedures of the surface stress, which are essentially the same for both measurement and calculation.

The procedure is first to establish the reference points and then to determine the structural hot spot stress by extrapolation to the weld toe from the stresses of those reference points. Depending on the method, there may be two or three reference points.

The reference point closest 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, especially if they 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 analysis (FEA) is generally 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 explicitly into consideration explicitly in the FEA model or by applying an appropriate stress magnification factor k_m , see also Section 3.8.2. This applies particularly to butt welds, cruciform joints and one-sided transverse fillet welded attachments on one side of a unsupported plate.

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

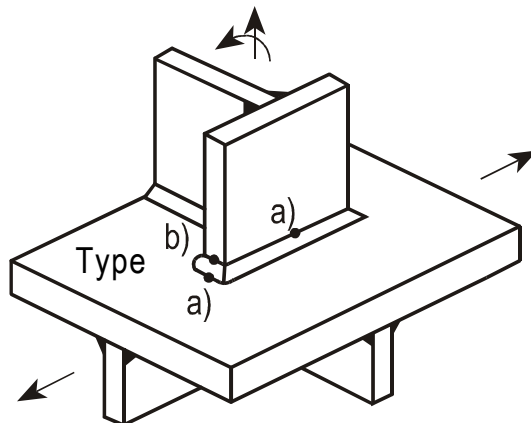


Fig. (2.2)-10: Types of Hot Spots

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

A reasonably high level of expertise is required on the part of the FEA analyst. Guidance is given in [2-3]. In the following, only some rough recommendations are given:

In a **plate or shell element** model (Figure (2.2)-11, left part), the elements are arranged in the mid-plane of the structural components. 8-noded elements are recommended particularly in regions 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 a 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 through the shell thickness, suppressing the notch stress 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.

Alternatively, particularly for complex cases, 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 may be used. An example is 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. By 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 Figure (2.2)-11 (right part). The alternative with a multi-layer arrangement of solid elements allows to linearize the stresses over the plate thickness directly at the weld toe.

Surface stress extrapolation methods:

If the structural hot-spot stress is determined by extrapolation, the **element lengths** are determined by the reference points selected 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 introduced in the thickness direction as well. Coarser meshes are also possible with higher-order elements and fixed lengths, as further explained further 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 as indicated in Figure (2.2)-11.

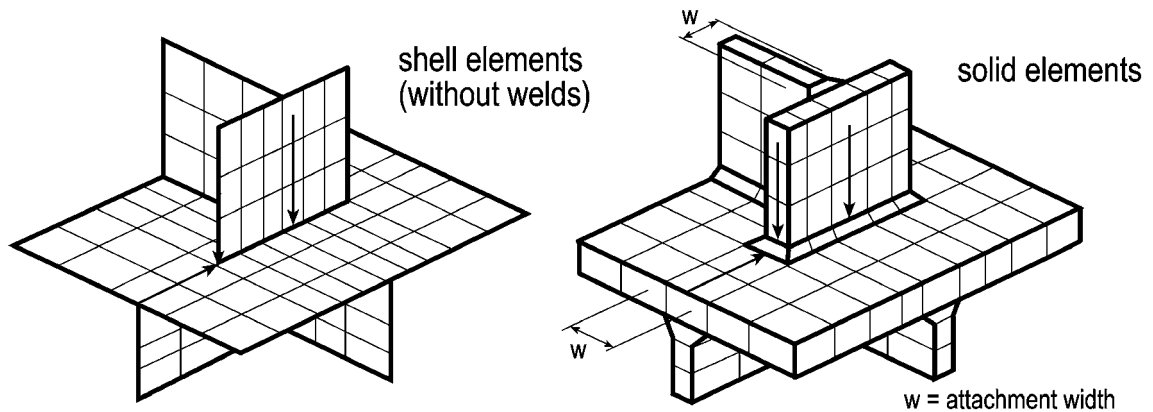


Figure (2.2)-11: Typical meshes and stress evaluation paths for a welded detail

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

Type “a” hot spots:

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

- 1) Fine mesh with element length not more than **0.4 t** at the hot spot: Evaluation of nodal stresses at two reference points **0.4 t** and **1.0 t**, and linear extrapolation (eq. 2.7).

$$\sigma_{hs} = 1.67 \cdot \sigma_{0.4 \cdot t} - 0.67 \cdot \sigma_{1.0 \cdot t} \quad (2.7)$$

- 2) Fine mesh as defined in 1) above: Evaluation of nodal stresses at three reference points **0.4 t**, **0.9 t** and **1.4 t**, and quadratic extrapolation (eq. 2.8). This method is recommended for cases of pronounced non-linear structural stress increase towards the hot spot, at sharp changes of direction of the applied force or for thickwalled structures.

$$\sigma_{hs} = 2.52 \cdot \sigma_{0.4 \cdot t} - 2.24 \cdot \sigma_{0.9 \cdot t} + 0.72 \cdot \sigma_{1.4 \cdot t} \quad (2.8)$$

- 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 centres respectively, i.e. at two reference points **0.5 t** and **1.5 t**, and linear extrapolation (eq. 2.9).

$$\sigma_{hs} = 1.50 \cdot \sigma_{0.5 \cdot t} - 0.50 \cdot \sigma_{1.5 \cdot t} \quad (2.9)$$

Application of the usual wall thickness correction, as given in Section 3.5.2 is required when the structural hot spot stress of type “a” is obtained by surface extrapolation. For circular tubular joints, the wall thickness correction exponent of **n=0.4** is recommended.

Type “b” hot spots:

The stress distribution is not dependent on plate thickness. Therefore, 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. 2.10).

$$\sigma_{hs} = 3 \cdot \sigma_{4 \text{ mm}} - 3 \cdot \sigma_{8 \text{ mm}} + \sigma_{12 \text{ mm}} \quad (2.10)$$

- 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. 2.11).

$$\sigma_{hs} = 1.5 \cdot \sigma_{5 \text{ mm}} - 0.5 \cdot \sigma_{15 \text{ mm}} \quad (2.11)$$

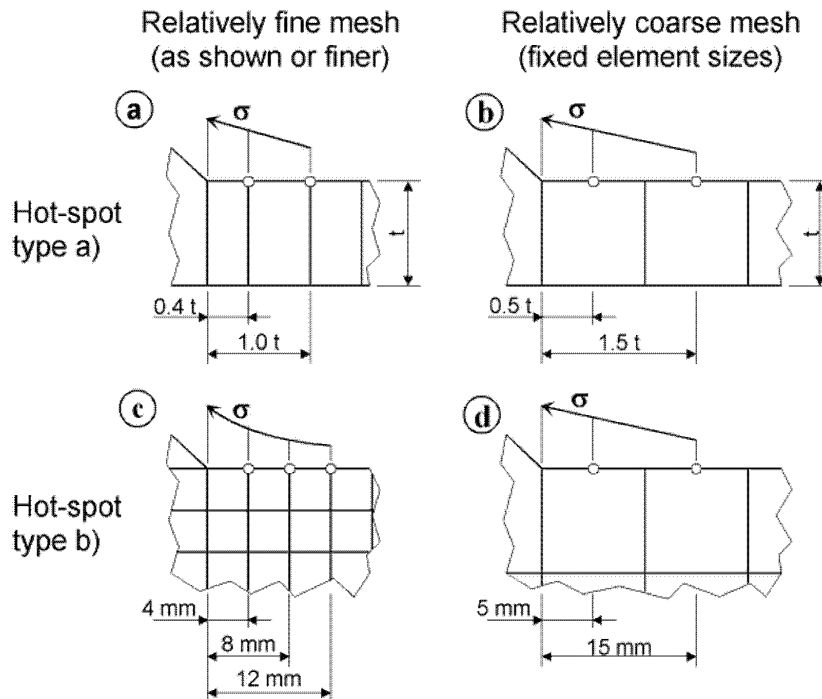


Figure (2.2)-12: Reference points at different types of meshing

In the case of type “b” hot spots obtained by surface stress extrapolation, the wall thickness correction (see Section 3.5.2) is applied with an exponent of **n=0.1**.

Table 2.2.-2: Recommended meshing and extrapolation (see also Figure (2.2)-12)

Type of model and weld toe		Relatively coarse models		Relatively fine models	
		Type a	Type b	Type a	Type b
Element size	Shells	$t \times t$ $\max t \times w/2^*)$	10 x 10 mm	$\leq 0.4 t \times t$ or $\leq 0.4 t \times w/2$	$\leq 4 \times 4$ mm
	Solids	$t \times t$ $\max t \times w$	10 x 10 mm	$\leq 0.4 t \times t$ or $\leq 0.4 t \times w/2$	$\leq 4 \times 4$ 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 of estimation the structural hot spot stress may be useful in special cases. However, care is needed to ensure that they are compatible with the fatigue design resistance data recommended in this document. In the method after Haibach [2-7], the stress on the surface 2 mm away from the weld toe is determined. In the method after Xiao and Yamada [2-8], the stress 1 mm below the weld toe on the anticipated crack path is taken. Both methods are useful at sharp changes in the direction of the applied force or at thickwalled structures. In both methods no correction is required for wall thickness. The results from FEA can also be evaluated using nodal forces or though thickness integration to estimate the structural hot spot stress.

A further alternative procedure after Dong [2-4] uses a special stress parameter based partly on structural hot spot stress and partly on fracture mechanics analysis, 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 depends on the extent of shell bending stresses, the wall thickness and the type of structural stress.

The center point of the first gauge, whose gauge length should not exceed **0.2 t**, is located at a distance of **0.4 t** from the weld toe. If this is not possible for example due to a small plate thickness, the leading edge of the gauge should be placed at a distance of **0.3 t** from

the weld toe. The following extrapolation procedure and number of gauges are recommended:

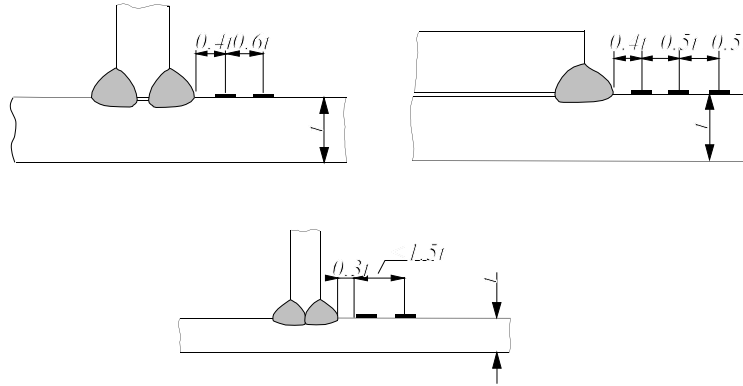


Figure (2.2)-13: Examples of strain gauges in plate structures

Type “a” hot spots:

- a) Two gauges at reference points **0.4 t** and **1.0 t** and linear extrapolation (eq. 2.12).

$$\epsilon_{hs} = 1.67 \cdot \epsilon_{0.4 t} - 0.67 \cdot \epsilon_{1.0 t} \quad (2.12)$$

- b) Three gauges at reference points **0.4 t**, **0.9 t** and **1.4 t**, and quadratic extrapolation. This method is particularly suitable for cases of pronounced non-linear structural stress increase towards the hot spot (eq. 2.13).

$$\epsilon_{hs} = 2.52 \cdot \epsilon_{0.4 t} - 2.24 \cdot \epsilon_{0.9 t} + 0.72 \cdot \epsilon_{1.4 t} \quad (2.13)$$

Precise positioning is not necessary if multi-grid strip gauges are used, since the results can be used to plot the stress distribution approaching the weld toe. The stresses at the required positions can then be read from the fitted curve.

Type “b” hot spots:

Three gauges are attached to the plate edge at reference points 4, 8 and 12 mm distant from the weld toe. The hot spot strain is determined by quadratic extrapolation to the weld toe (eq. 2.14):

$$\epsilon_{hs} = 3 \cdot \epsilon_{4 mm} - 3 \cdot \epsilon_{8 mm} + \epsilon_{12 mm} \quad (2.14)$$

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 approximation to the structural hot spot stress is obtained approximately from eqn. (2.15).

$$\sigma_{hs} = E \cdot \epsilon_{hs} \quad (2.15)$$

For biaxial stress states, the actual stress may be up to 10% higher than that obtained from eqn. (2.15). In this case, use of rosette strain gauges is recommended. If the ratio of longitudinal to transversal strains ϵ_y/ϵ_x is available, for example from FEA, the structural hot spot stress σ_{hs} can then be resolved from eqn. (2.16), assuming that this principal stress is approximately perpendicular to the weld toe.

$$\sigma_{hs} = E \cdot \epsilon_x \frac{1 + \nu \frac{\epsilon_y}{\epsilon_x}}{1 - \nu^2} \quad (2.16)$$

The above equations also apply if strain ranges are measured, producing the range of structural hot spot stress $\Delta\sigma_{hs}$.

2.2.3.6 Tubular joints

Special recommendations exist for determining the structural hot spot stress in tubular joints [2-6]. In general these allow the use of linear extrapolation from the measured or calculated stresses at two reference points. The measurement of simple uni-axial stress is sufficient.

Parametric formulae have been established for the stress concentration factor k_{hs} in many joints between circular and rectangular section tubes, see ref.[2-6]. Hence the structural hot spot stress σ_{hs} becomes:

$$\sigma_{hs} = k_{hs} \cdot \sigma_{nom} \quad (2.17)$$

where σ_{nom} is the nominal axial membrane or bending stress in the braces, calculated by elementary stress analysis or uni-axial measurement.

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 variation of the weld shape parameters, as well as of the non-linear material behaviour at the notch root, the actual weld contour is replaced by an effective one. For structural steels and aluminium alloys an effective notch root radius of $r = 1 \text{ mm}$ has been verified to give consistent results. For fatigue assessment, the effective notch stress is compared with a single fatigue resistance curve, although, as with other assessment methods, it is necessary to check that the fatigue resistance curve for parent metal is not exceeded.

The method is restricted to the assessment of welded joints with respect to potential fatigue failures from the weld toe or weld root. The fatigue assessment must be additionally performed at the weld toes for the parent material using structural hot-spot stress (see Section 2.2.3) and the associated fatigue class (FAT) for the base material. Other modes of fatigue failure, such as crack growth from surface roughness or embedded defects, are not covered. The method is also not applicable if there is a significant stress component parallel to the weld.

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. More details for practical application can be found in reference [3.6].

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

The method is limited to thicknesses $t \geq 5 \text{ mm}$, since the method has not yet been verified for smaller wall thicknesses.

At machined or ground welds toes shall be assessed using the notch stress of the actual profile in conjunction with the nominal stress based fatigue resistance curve for a butt weld ground flush to plate.

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 by finite element or boundary element models. The effective notch radius is introduced such that the tip of the radius coincides with 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 than $1/6$ 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, see also reference [3.6].

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, it 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.

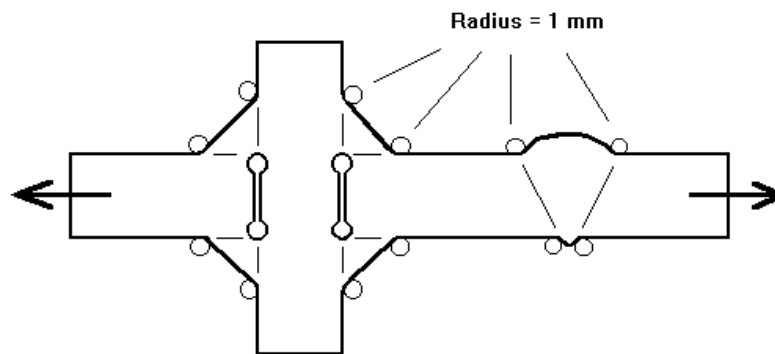


Figure (2.2)-14 Fictitious rounding of weld toes and roots

2.2.5 Stress Intensity Factors

2.2.5.1 General

Fracture mechanics is used to assess the behaviour of cracks. It can be used to calculate the growth of an initial crack a_i to a final size a_f . Since crack initiation occupies only a small proportion of the lives of welded joints in structural metals, the 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 ΔK .

Fracture mechanics calculations related to welded joints are generally based on the total stress at the notch root, e.g. at the weld toe. For a variety of welded structural details, correction functions that allow for the stress concentration effect have been established. In addition, further correction functions may be required dependent on the size and shape of the crack compared with the size of the component containing the crack. These correction functions are based on different applied stress types (e.g. membrane, bending, structural hot spot stress, nominal stress). The one used must correspond to the stress type under consideration.

2.2.5.2 Calculation of Stress Intensity Factors by Parametric Formulae

First, the relevant applied stress (usually the local nominal or the structural hot spot stress) at the location of the crack is determined, assuming that no crack is present. Ideally, the stress should be separated into membrane and shell bending stress components. The stress intensity factor (SIF) K results as a superposition of the effects of both stress components. The effects of the crack shape and size are covered by the correction function Y . The effects of the any remaining stress raising discontinuity or notch (non-linear peak stress) can to be covered by additional factors M_k [4-8 and 4-10], while

$$K = \sqrt{\pi \cdot a} \cdot (\sigma_m \cdot Y_m \cdot M_{k,m} + \sigma_b \cdot Y_b \cdot M_{k,b}) \quad (2.18)$$

where

K	stress intensity factor
σ_m	membrane stress
σ_b	shell bending stress
Y_m	correction function for membrane stress intensity factor
Y_b	correction function for shell bending stress intensity factor
$M_{k,m}$	correction for non-linear stress peak in terms of membrane action
$M_{k,b}$	correction for non-linear stress peak in terms of shell bending

The correction functions Y_m and Y_b 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. 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 factors can be determined directly by FEA 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 in which no flaws have been detected. In such cases it is necessary to assume the presence of a crack, for example based on prior metallurgical evidence or the detection limit of the used inspection method, and then to calculate the SIF as above. For cracks starting from a weld toe, in absence of other evidence, it is recommended that an initial crack depth of at least **$a = 0.15 \text{ mm}$** and an aspect ratio of **$a:2c = 0.1$** should be assumed. For root cracks in load-carrying fillet welded cruciform joints, the actual root gap should be taken as the initial crack.

2.3 STRESS HISTORY

2.3.1 General

The fatigue design data presented in Section 3 were obtained from tests performed under constant amplitude loading. However, loads and the resulting fatigue actions (i.e. stresses) in real structures usually fluctuate in an irregular manner and give rise to variable amplitude loading. The stress range 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 should aim to cover all loading events and the corresponding induced dynamic response in a conservative way.

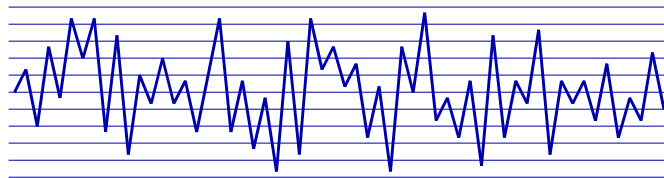


Figure (2.3)-1 Stress time history illustration

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 covering a limited period of operation. Therefore, the data needed to perform a fatigue analysis can be determined from service load measurements or observations conducted over a limited time, as long as it is reasonably representative of the loading to be experienced during the whole fatigue life.

A stress history may be given as

- a) a record of successive maxima and minima of stress measured in a comparable structure for 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 exceedences, stress range spectrum) specified by a design code.

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

2.3.2 Cycle Counting Methods

Cycle counting is the process of converting a variable amplitude stress sequence into a series of constant amplitude stress range cycles that are equivalent in terms of damage to the original sequence. Various methods are available including zero crossing counting, peak counting, range pair counting and rainflow counting. For welded components, the 'rainflow' or similar 'reservoir' methods are 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 exceedences versus the number of cycles. The curve is therefore continuous.

It is usually more convenient to represent the spectrum by a table of discrete blocks of cycles of constant amplitude stress range, typically up to 20 different stress levels. The assumed magnitude of the stress range in a given block would then depend on the conservatism required. Typical values would be the maximum or the mean of the stress range in the block.

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

Table {2.3}-1: Example of a stress range occurrence table (stress histogram or frequency)

Block No.	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

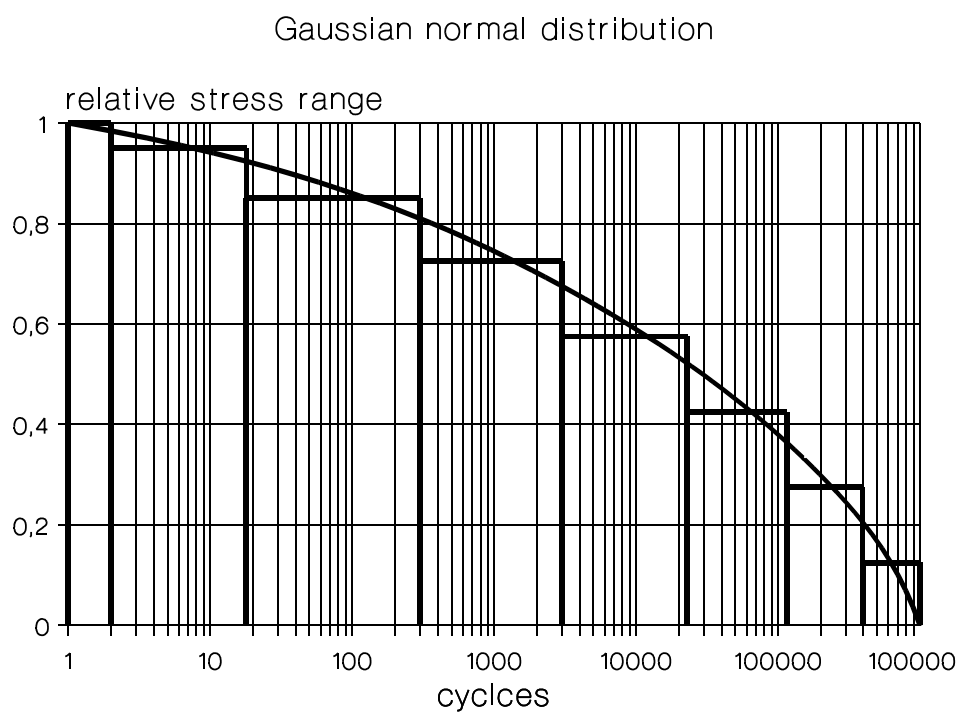


Figure (2.3)-2 Example of a cumulative frequency diagram (stress spectrum)

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 fatigue test data is given in Section 3.7 and 4.5.

As generally required, the fatigue resistance data presented here are expressed in terms of the same type of stress as that used to determine test data upon which they are based.

The present fatigue endurance resistance data for welded joints are expressed as S-N curves. However, there are different definitions of failure in conventional fatigue endurance testing. In general, small welded specimens are tested to complete rupture, which is usually very close to through-thickness cracking. In large components or vessels, the observation of a larger or through-wall crack is usually taken as a failure. The fatigue failure according to the present S-N curves effectively corresponds to through-section cracking. The S-N curves are of the form:

$$N = \frac{C}{\Delta\sigma^m} \quad \text{or} \quad N = \frac{C}{\Delta\tau^m} \quad (3.1)$$

where the slope **m** may adopt different values over the range of possible fatigue lives, from the low endurance to the high cycle regime (see Section 3.2).

For fracture mechanics analyses, the fatigue resistance data are in the form of relationships between **ΔK** and the rate of fatigue crack propagation (**da/dN**). The fatigue crack growth rate data are derived by monitoring crack propagation in tests.

All fatigue resistance data are given as characteristic values, which are assumed to represent a survival probability of at least 95%, calculated from the mean value on the basis of two-sided 75% tolerance limits of the mean, unless otherwise stated (see Section 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 **1.5 · f_y** for nominal normal stresses or **1.5 · f_y/√3** for nominal shear stresses.

The fatigue resistance of a welded joint is limited by the fatigue resistance of the parent 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 cut-outs 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 Section 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
- direction of loading
- high residual stresses
- metallurgical conditions
- welding process (fusion welding, unless otherwise stated)
- inspection procedure (NDT), if specified
- post weld treatment, if specified

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

Each fatigue strength S-N 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 S-N curves for details assessed on the basis of normal stresses (Figure (3.2)-1...3) is **m=3.00** if not stated expressly otherwise. The constant amplitude knee point is assumed to correspond to **N = 10⁷ cycles**.

The slope of the fatigue strength curves for details assessed on the basis of shear stresses (Figure (3.2)-4 to 6) is **m=5.00**, but in this case the knee point is assumed to correspond to **N = 10⁸ cycles**.

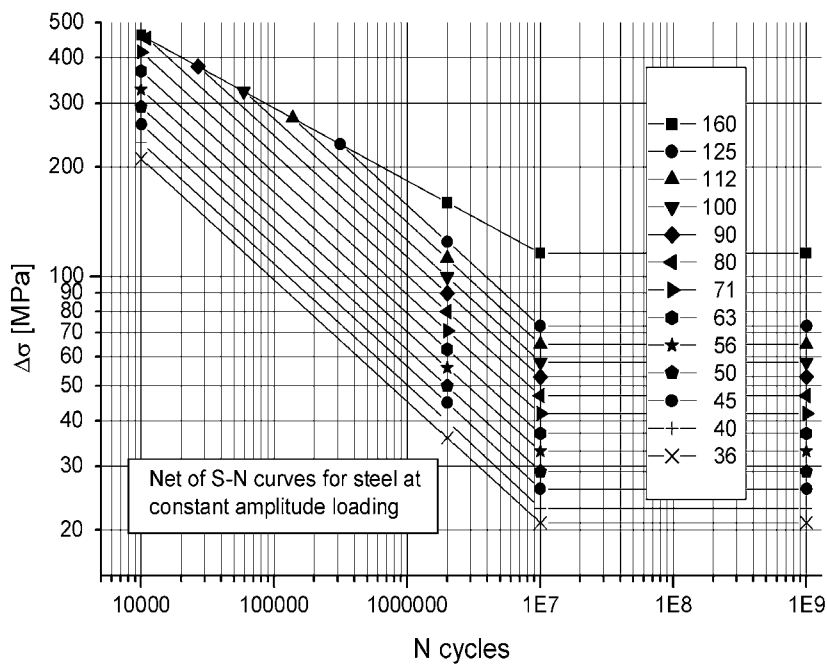


Figure (3.2)-1: Fatigue resistance S-N curves for steel, normal stress, standard applications

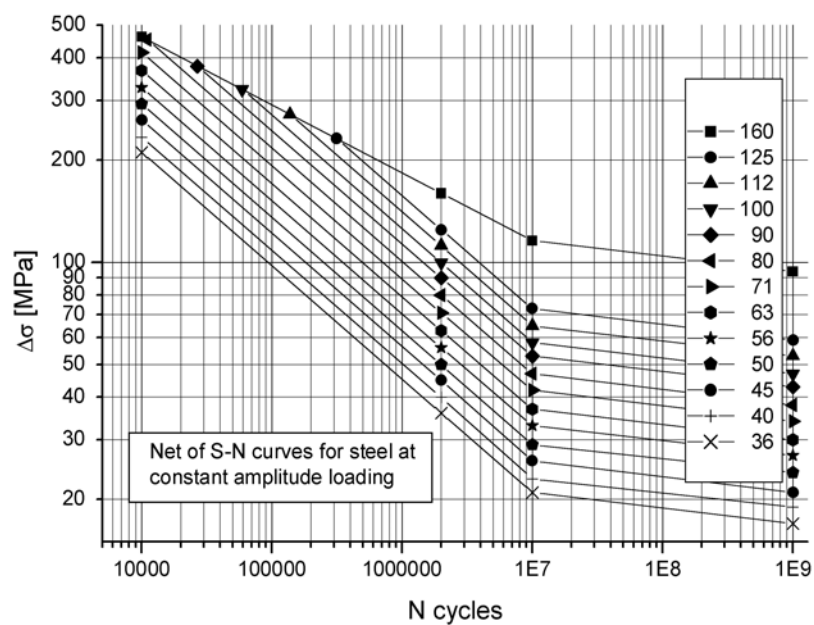


Figure (3.2)-2: Fatigue resistance S-N curves for steel, normal stress, very high cycles applications

The conventional assumption is that the S-N curves terminate at a fatigue limit, below which failure will not occur, or in which case the S-N curve becomes a horizontal line. Traditionally, this constant amplitude fatigue limit (CAFL), also referred as ‘knee point’, is defined in terms of the corresponding fatigue endurance on the S-N curve, $N=10^7$ being the most common assumption (see Figure (3.2)-1). However, new experimental data indicate that a CAFL does not exist and the S-N curve should continue on the basis of a further decline in stress range of about 10% per decade in terms of cycles, which corresponds to a slope of $m=22$. This issue is only relevant if a design relies on a CAFL to establish maximum allowable stresses to achieve effectively a so called ‘infinite life’, such as for example at rotating parts that experience very large numbers of stress cycles. The matter is still under development and users should consult the latest relevant literature. Meanwhile, the nominal stress-based characteristic S-N curves are presented with the extrapolation beyond 10^7 cycles at a slope of $m=22$ in Figures (3.2)-2 and 3.

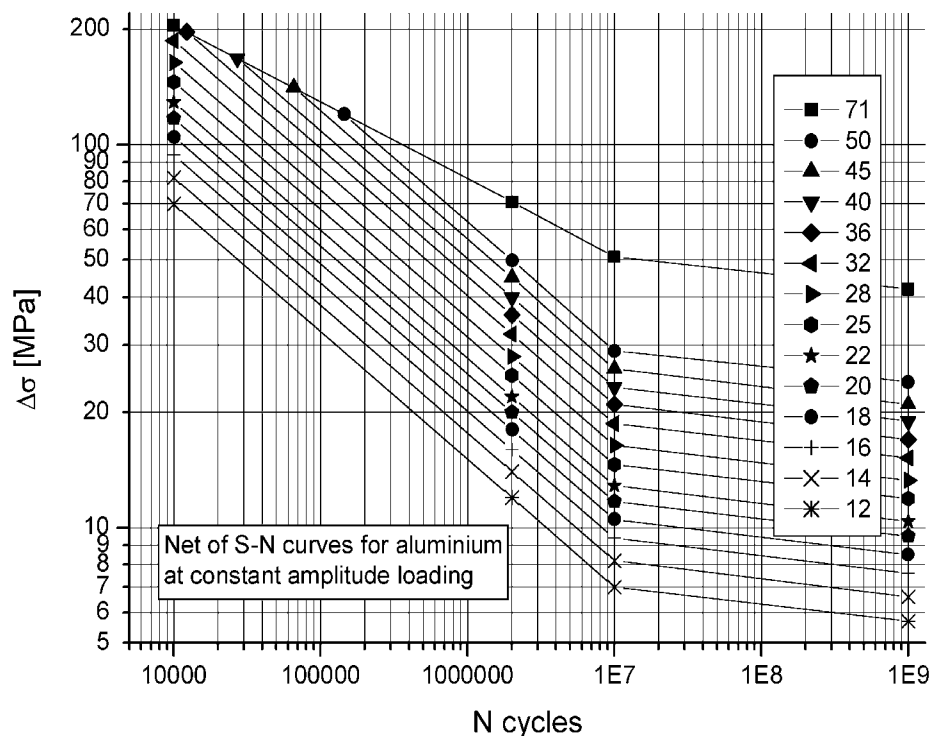


Figure (3.2)-3: Fatigue resistance S-N curves for aluminium, normal stress

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 (Section 3.7).

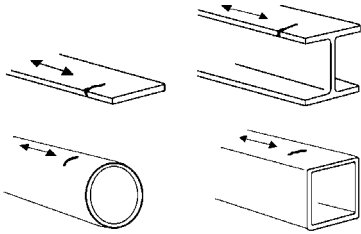
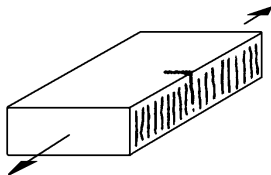
As appropriate, the fatigue classes given in Table {3.2-1} shall be modified according to Section 3.5. The limitations on weld imperfections shall be considered (Section 3.8).

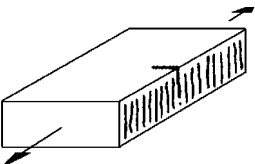
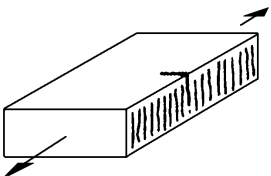
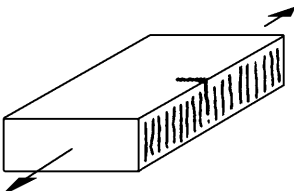
All butt weld joints shall be fully fused and have full penetration welds, unless otherwise stated.

All the S-N curves for weld details are limited by the S-N curve for the parent metal, which may vary with material tensile strength. It is recommended that a higher fatigue class for the material than stated (i.e. FAT 160 for steel or FAT 71 for aluminium alloys) should only be assumed if verified by test.

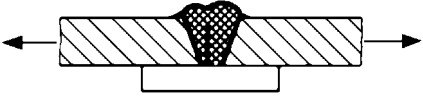
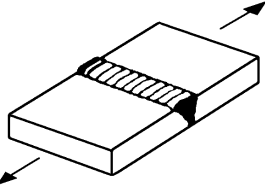
The S-N curves for weld details refer to specific failure modes, generally fatigue crack growth from the weld toe through the base material, from the weld root through the weld throat, or from the weld surface through the weld and then into the base material. In an assessment of a given weld detail it is important to consider all possible potential failure modes for the direction of loading. E.g. at cruciform joints with fillet welds, both potential failure modes, such as toe crack through plate and root crack through weld throat, have to be assessed.

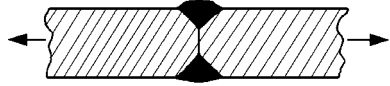
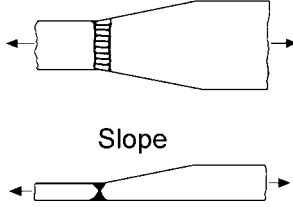
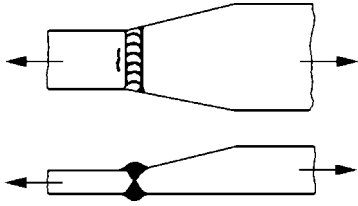
Tab. {3.2}-1: Fatigue resistance values for structural details in steel and aluminium assessed on the basis of nominal stresses.

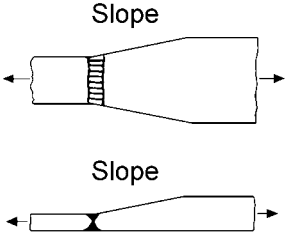
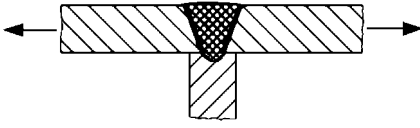
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
100	Unwelded parts of a component				
111		Rolled or extruded products, components with machined edges, seamless hollow sections. $m = 5$ St.: For high strength steels a higher FAT class may be used if verified by test. Al.: AA 5000/6000 alloys AA 7000 alloys	160	71 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 shall be considered.

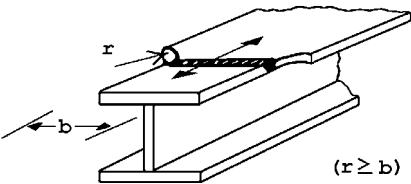
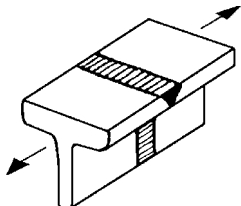
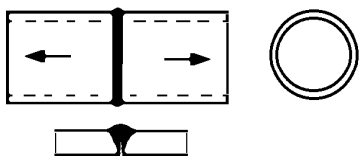
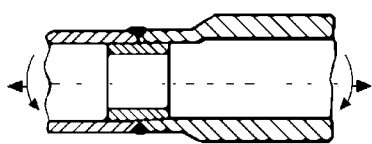
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
122		Machine thermally cut edges, corners removed, no cracks by inspection $m = 3$	125	40	Notch effects due to shape of edges shall be considered.
123		Manually thermally cut edges, free from cracks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

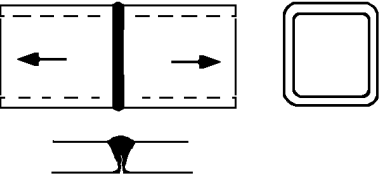
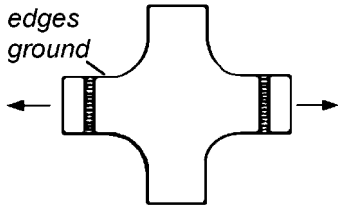
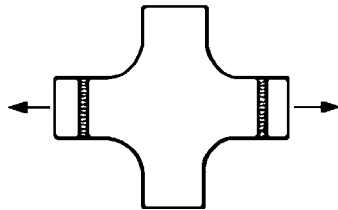
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
200	Butt welds, transverse loaded				
211		Transverse loaded butt weld (X-groove or V-groove) ground flush to plate, 100% NDT	112	45	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress. Welded from both sides. Misalignment < 5% of plate thickness. Proved free from significant defects by appropriate 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 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 ground flush in direction of stress. Welded from both sides. Misalignment < 10% of plate thickness.

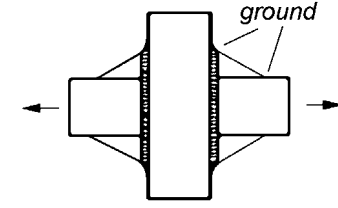
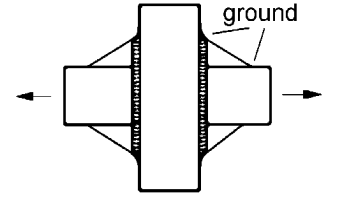
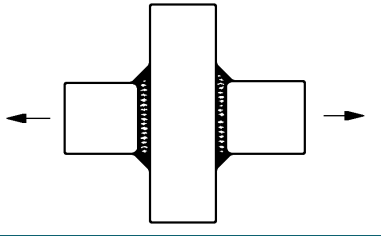
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
214		Transverse butt weld, welded on non-fusible temporary backing, root crack	80	28	Backing removed, root visually inspected. Misalignment <10% of plate thickness.
215		Transverse butt weld on permanent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

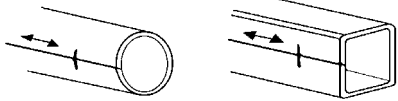
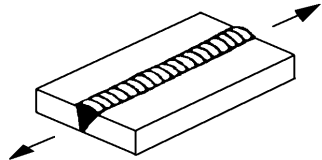
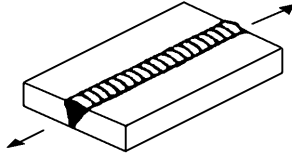
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
217		Transverse partial penetration butt weld, analysis based on stress in weld throat sectional area, weld overfill not to be taken into account.	36	12	The detail is not recommended for fatigue loaded 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 parallel to direction of loading. 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 deliberate thickness step to be considered, see Section 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 ground flush in direction of stress. Misalignment due to deliberate thickness step to be considered, see Section 3.8.2. Additional misalignment due to fabrication imperfection < 5% of plate thickness.

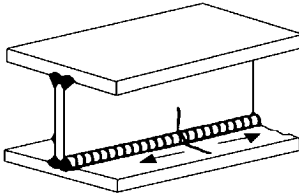
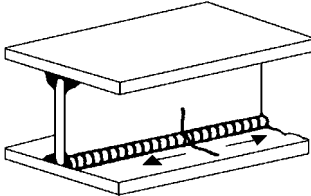
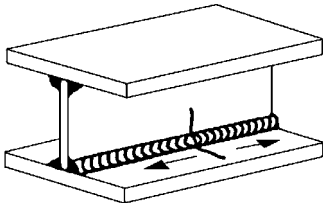
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
223		Transverse butt weld, NDT, with transition on thickness and width slope 1:5 slope 1:3 slope 1:2	80 71 63	25 22 20	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress. Misalignment due to deliberate thickness step to be considered, see Section 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 deliberately misaligned, this misalignment has to be considered, see Section 3.8.2.
225		Three plate connection, potential cracking from root	71	22	Misalignment <10% of plate thickness.

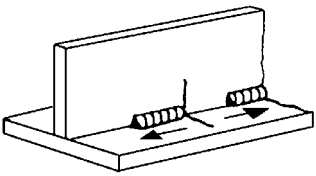
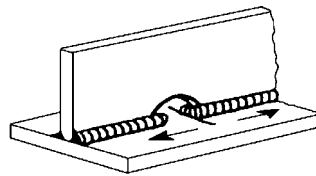
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
226		Transverse butt weld flange splice in built-up section welded prior to the assembly, ground flush, with radius transition, NDT	100	40	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges 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 parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress.
232		Transverse butt weld splice in circular hollow section, welded from one side, full penetration, potential failure from root . root inspected by NDT no NDT	71 36	28 12	Welded in flat position. Axial misalignment < 5% of wall thickness
233		Tubular joint with permanent backing	71	28	Full penetration weld

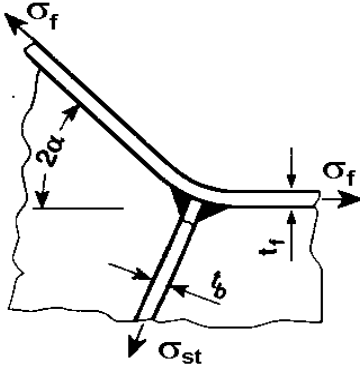
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
234		Transverse butt weld splice in rectangular hollow section, welded from one side, full penetration, root crack root inspected by NDT no NDT	56 36	25 12	Welded in flat position.
241		Transverse 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 parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges 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 ground flush in direction of stress. Welded from both sides. Misalignment <5% of plate thickness.

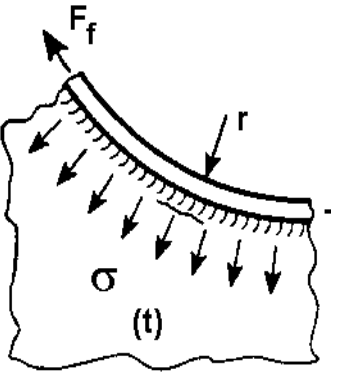
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
243		Transverse butt weld at intersecting flange, weld ground flush, NDT, at crossing flanges with welded triangular transition plates, weld ends ground. Crack starting at butt weld. For crack of continuous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

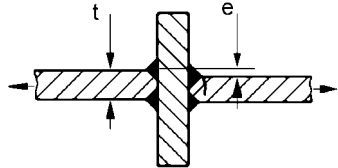
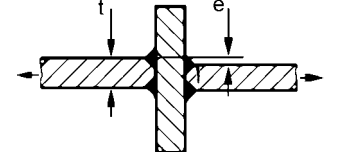
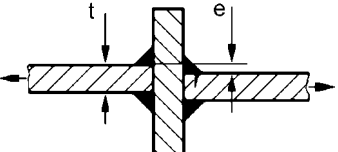
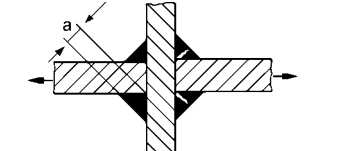
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
300	Longitudinal load-carrying welds				
311		Automatic longitudinal seam welds without stop/start positions in hollow sections	125	50	
		with stop/start positions	90	36	
312		Longitudinal butt weld, both sides ground flush parallel to load direction, proved free from significant defects by appropriate NDT	125	50	
313		Longitudinal butt weld, without stop/start positions, NDT	100	40	
		with stop/start positions	90	36	

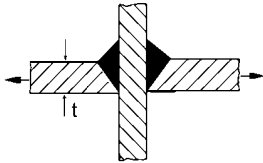
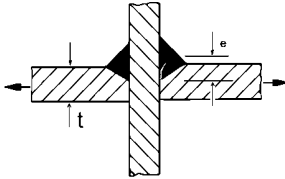
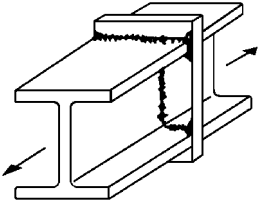
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
321		Continuous automatic longitudinal fully penetrated K-butt weld without stop/start positions (based on stress range in flange) NDT	125	50	No stop-start position is permitted except when the repair 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	
323		Continuous manual longitudinal fillet or butt weld (based on stress range in flange)	90	36	

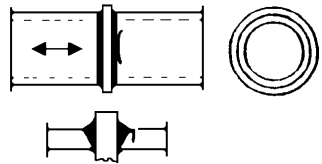
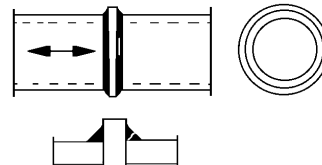
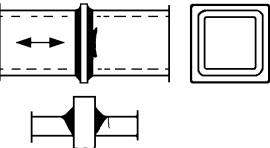
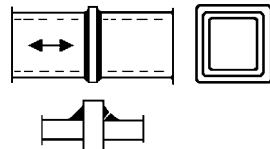
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
324		Intermittent longitudinal fillet weld (based on normal stress in flange σ and shear stress in web τ at weld ends). $\tau/\sigma =$ 0 0.0 - 0.2 0.2 - 0.3 0.3 - 0.4 0.4 - 0.5 0.5 - 0.6 0.6 - 0.7 > 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 not lower than 36 Alum.: $FAT = 32 \cdot (1 - \Delta\tau/\Delta\sigma)$ but not lower than 14
325		Longitudinal butt weld, fillet weld or intermittent weld with cope holes (bas- ed 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 not lower than 36 Alum.: $FAT = 28 \cdot (1 - \Delta\tau/\Delta\sigma)$ but not lower than 14

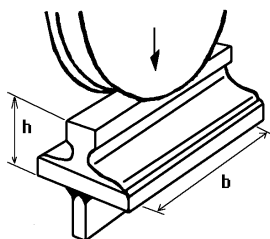
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
331		Joint at stiffened knuckle of a flange to be assessed according to no. 411 - 414, depending on type of joint. Stress in stiffener plate: $\sigma = \sigma_f \cdot \frac{A_f}{\sum A_{st}} \cdot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

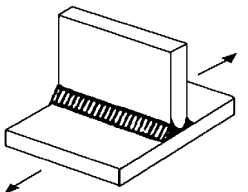
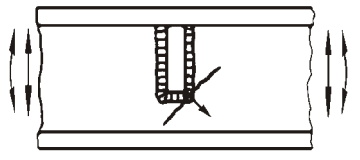
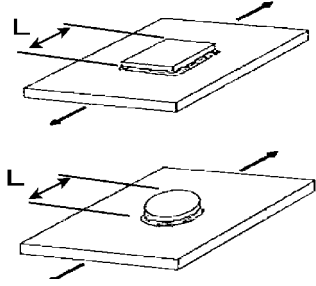
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
332		Unstiffened curved flange to web joint, to be assessed according to no. 411 - 414, depending on type of joint. Stress in web plate: $\sigma = \frac{F_f}{r \cdot t}$ Stress in weld throat: $\sigma = \frac{F_f}{r \cdot \sum a}$ 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 order 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. For additional shear, principal stress in web is to be considered (see 321 to 323)

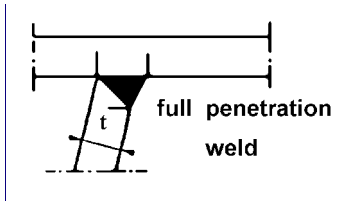
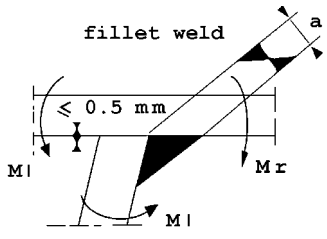
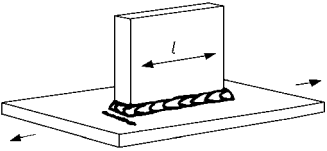
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
400	Cruciform joints and/or T-joints				
411		Cruciform joint or T-joint, K-butt welds, full penetration, weld toes ground, potential failure from weld toe. Single sided T-joints and cruciform joints without misalignment	80 90	28 32	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing. Misalignment <15% of primary plate thickness in cruciform joints.
412		Cruciform joint or T-joint, K-butt welds, full penetration, potential failure from weld toe. Single sided T-joints and cruciform joints without misalignment	71 80	25 28	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing. Misalignment <15% of primary plate thickness in cruciform joints.
413		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds, potential failure from weld toe. Single sided T-joints and cruciform joints without misalignment	63 71	22 25	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing. Misalignment <15% of primary plate thickness in cruciform joints. 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 $a/t \leq 1/3$	36 40	12 14	Analysis based on stress in weld throat $\sigma_w = F / \sum (a_w \cdot l)$ l = length of weld Also to be assessed as 412 or 413.

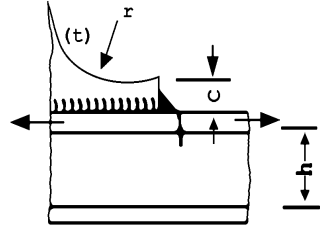
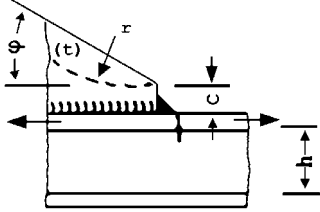
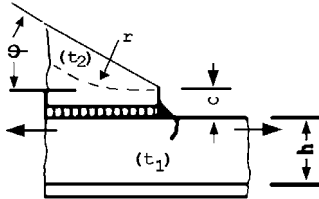
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
415		Cruciform joint or T-joint, single-sided arc or laser beam welded V-butt weld, full penetration, potential failure from weld toe. Full penetration checked by inspection of root. If root is not inspected, then root crack	71 36	25 12	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing. Misalignment <15% of primary plate thickness in cruciform joints. .
416		Cruciform joint or T-joint, single-sided arc welded fillet or partial penetration Y-butt weld, no lamellar tearing, misalignment of plates $e < 0.15 \cdot t$, stress at weld root. Penetration verified. Attention: Bending by excentricity e must be consired!	71	25	Analysis based on axial and bending stress in weld throat. Excentricity e to be considered in analysis. Stress at weld root: $\Delta\sigma_{w, root} = \Delta\sigma_{w, nom} \cdot (1+6e/a)$ e = excentricity between midpoints plate and weld throat a (inclusive penetration), rotated into vertical leg plane using root tip as pivot. An analysis by effective notch stress procedure is recommended
421		Splice of rolled section with intermediate plate, fillet welds, potential failure from weld root.	36	12	Analysis based on stress in weld throat.

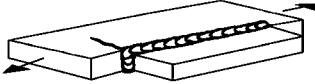
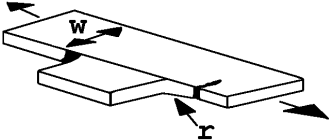
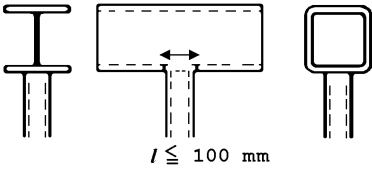
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
422		Splice of circular hollow section with intermediate plate, singelsided butt weld, potential failure from toe wall thickness > 8 mm wall thickness < 8 mm	56 50	22 20	NDT of welds in order to ensure full root penetration.
423		Splice of circular hollow section with intermediate plate, fillet weld, potential failure from root. 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, potential fairure from toe wall thickness > 8 mm wall thickness < 8 mm	50 45	20 18	NDT of welds in order to ensure full root penetration.
425		Splice of rectangular hollow section with intermediate plate, fillet welds, potential failure from root wall thickness > 8 mm wall thickness < 8 mm	40 36	16 14	

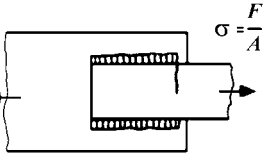
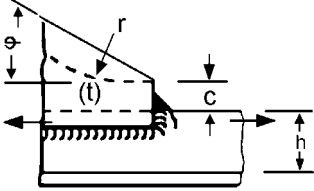
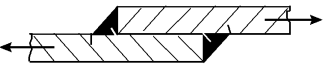
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
431		Weld connecting web and flange, loaded by a concentrated force in web plane perpendicular to weld. Force distributed on width $b = 2 \cdot h + 50 \text{ mm}$. Assessment according to no. 411 -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

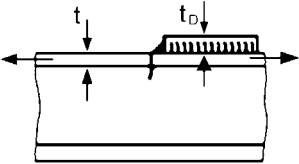
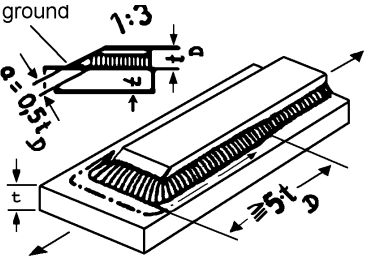
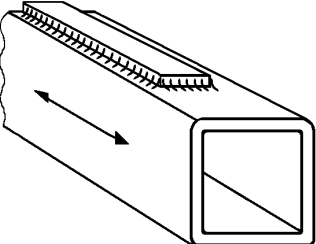
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
500	Non-load-carrying attachments				
511		Transverse non-load-carrying attachment, not thicker than main plate K-butt weld, toe ground Two sided fillets, toe ground Fillet weld(s), as welded thicker than main plate	100 100 80 71	36 36 28 25	Grinding marks normal to weld toe An angular misalignment corresponding to $k_m = 1.2$ 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	
513		Non-load-carrying rectangular or circular flat studs, pads or plates. $L \leq 50$ mm $L > 50$ and ≤ 150 mm $L > 150$ and ≤ 300 mm $L > 300$ mm	80 71 63 50	28 25 20 18	

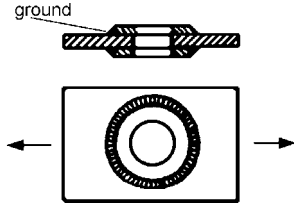
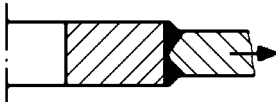
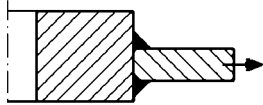
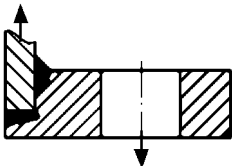
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
514		Trapezoidal stiffener to deck plate, full penetration butt weld, calculated on basis of stiffener thickness, out of plane bending	71	25	
515		Trapezoidal stiffener to deck plate, fillet or partial penetration weld, out of plane bending	71	25	Calculation based on maximum out-of-plane bending stress range in weld throat or stiffener.
521		Longitudinal fillet welded gusset of length l . Fillet weld around end. $l < 50 \text{ mm}$ $l < 150 \text{ mm}$ $l < 300 \text{ mm}$ $l > 300 \text{ mm}$	80 71 63 50	28 25 20 18	For gusset on edge: see detail 525. Particularly suitable for assessment on the basis of structural hot spot stress approach.

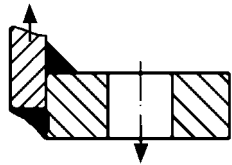
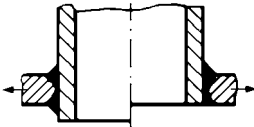
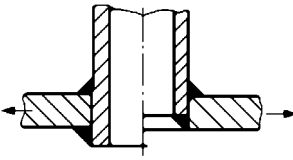
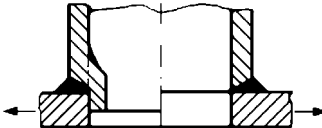
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
522		Longitudinal fillet welded gusset with radius transition, fillet weld around end and toe ground, $c < 2t$, max 25 mm $r > 150$ mm	90	32	t = thickness of attachment Particularly suitable for assessment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

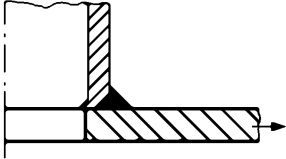
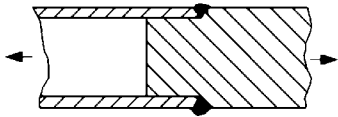
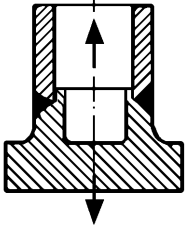
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
525		In-plane or out-of-plane longitudinal gusset welded to plate or beam flange edge, gusset length l: $l < 150 \text{ mm}$ $150 \leq l < 300 \text{ mm}$ $l \geq 300 \text{ mm}$	50 45 40	18 16 14	For $t_2 < 0.7 t_1$, FAT rises 12% t_1 is main plate thickness t_2 is gusset thickness
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 remove 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 $< 100 \text{ mm}$, else like longitudinal attachment	71	28	Non load-carrying welds. Width parallel to stress direction $< 100 \text{ mm}$.

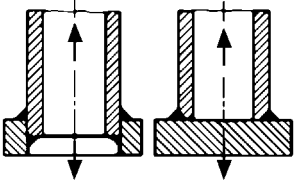
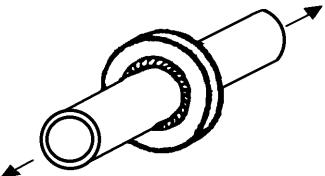
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
600	Lap joints				
611		Transverse loaded lap joint with fillet welds Fatigue of parent metal Fatigue of weld throat	63 45	22 16	Stresses to be calculated in the main plate using a plate width equal to 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 main plate edge. Buckling avoided by loading or design. For verification of parent metal, the higher stresses of the two members must be taken.
613		Lap joint gusset, fillet welded, non-load-carrying, with smooth transition (sniped end with $\phi < 20^\circ$ or radius), welded to loaded element $c < 2 \cdot t$, but $c \leq 25$ 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, eccentricity to be considered, as given in chapters 3.8.2 and 6.3. <u>Both failure modes have to be assessed separately</u>

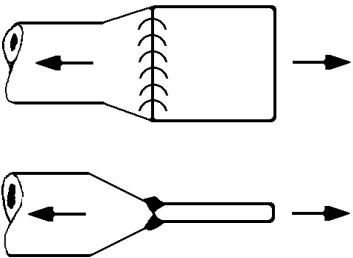
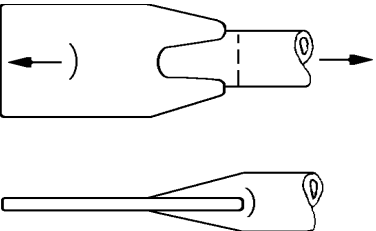
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
700	Reinforcements				
711		End of long doubling plate on I-beam, welded ends (based on stress range in flange at weld toe) $t_D \leq 0.8 t$ $0.8 t < t_D \leq 1.5 t$ $t_D > 1.5 t$	56 50 45	20 18 16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

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
731		Fillet welded reinforcements Toe ground As welded	80 71	32 25	Grinding in direction of stress! Analysis based on modified nominal stress, however, structural hot spot 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		Fillet welded pipe to flat flange joint. Potential fatigue failure from weld toe in pipe.	63	22	Analysis based on modified nominal stress. However, structural hot spot stress 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 Analysis based on modified nominal stress. However, structural hot spot stress 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 Analysis based on modified nominal stress. However, structural hot spot stress 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 Analysis based on modified nominal stress. However, structural hot spot stress recommended.

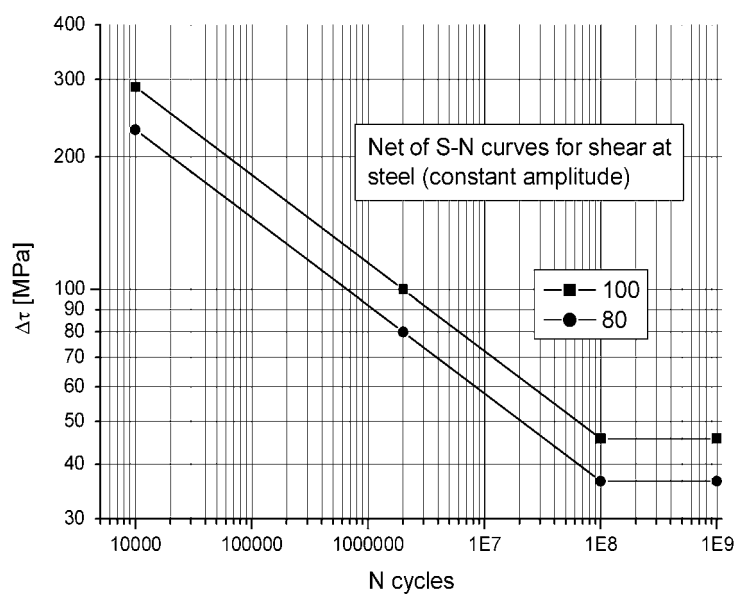
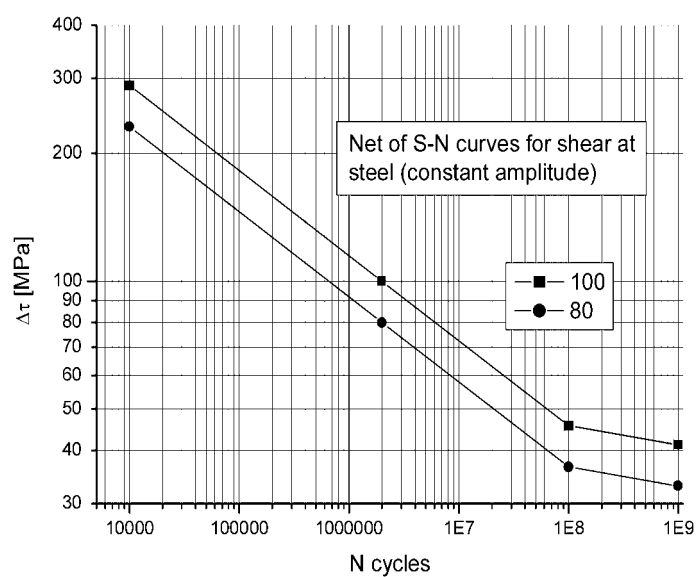
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
842		Nozzle welded on pipe, root pass as welded.	63	22	If diameter > 50 mm, stress concentration of cutout has to be considered Analysis based on modified nominal stress. However, structural hot spot stress recommended.
900	Tubular joints				
911		Butt welded circular tube or pipe to solid bar joint. Potential fatigue failure from weld toe or root in tube or pipe.	63	22	Analysis based on stress in tube or pipe. Full penetration of weld to solid bar is required.
912		Butt welded joint between circular tube or pipe and flange with integral backing. Potential fatigue failure from weld root.	63	22	Analysis based on stress in tube or pipe. Full penetration of weld to solid bar is required.

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
913		Fillet or partial penetration welded joint between circular tube or pipe and flange. Potential fatigue failure from weld root.	50	18	Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see Section 5) or by downgrading by two FAT classes.
921		Circular hollow section with welded on disc, potential fatigue failure from toe in hollow section K-butt weld, toe ground 90 Fillet weld, toe ground 90 Fillet welds, as welded 71			

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
931		Tube-plate joint, tubes flattened, butt weld (X-groove) Tube diameter < 200 mm and plate thickness < 20 mm	63	18	
932		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	63 45	18 14	

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


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

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

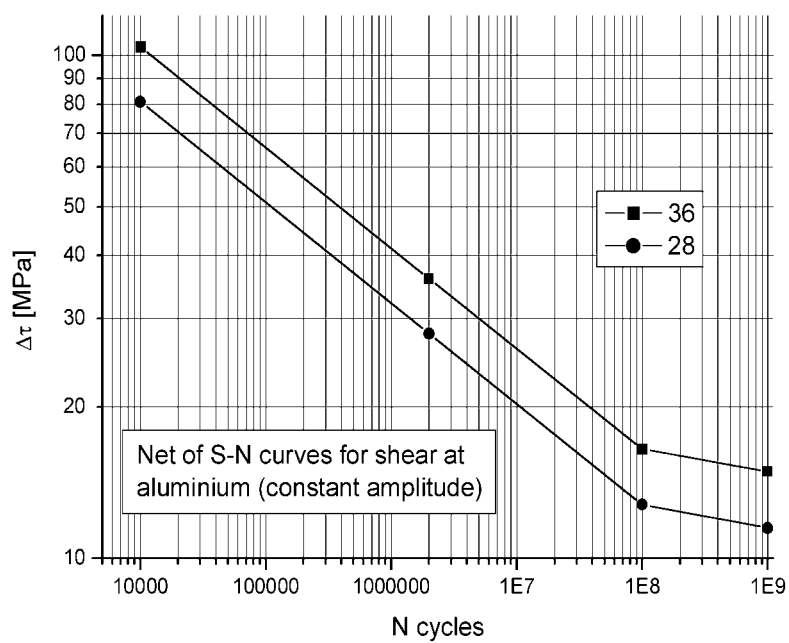


Figure (3.2)-6: Fatigue resistance S-N curve for shear at aluminium

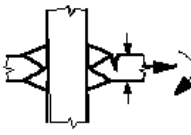
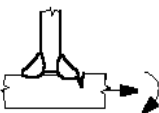
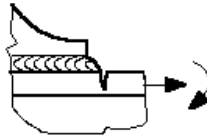
3.3 FATIGUE RESISTANCE ASSESSED ON THE BASIS OF STRUCTURAL HOT SPOT STRESS

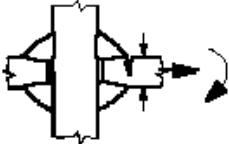
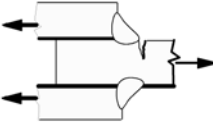
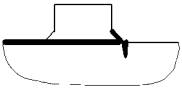
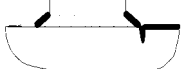
3.3.1 Fatigue Resistance Using Reference S-N Curve

The S-N curves for assessing the fatigue resistance of a detail on the basis of structural hot spot stress (Section 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 Section 3.2. The resistance values refer to the as-welded condition unless stated otherwise. The effects of high tensile residual stress are included. Only small effects of misalignment are included, see also Section 3.8.2. The weld shape should be similar to that shown below.

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

Table {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

No	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
6		Cruciform joints with load-carrying fillet welds	Fillet welds, as welded	90	36
7		Lap joint with load carrying fillet welds	Fillet welds, as welded	90	36
8	$L \leq 100 \text{ mm}$ 	Type "b" joint with short attachment	Fillet or full penetration weld, as welded	100	40
9	$L > 100 \text{ mm}$ 	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 than those specified in Section 3.8.2. They have to be considered explicitly in the determination of the hot spot stress range.

Note 2: The nominally non- or partially load-carrying fillet welds shown under no. 3 and 5 in Table {3.3}-1 may actually be load-carrying, in certain cases, e.g. for very large attachments or 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]. These tubular joint design curves should not be applied to other types of structure.

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 to be 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 the nominal stress (as in the tables in Section 3.2).
- c) Establish a FEA model of the reference detail and the detail to be assessed with the same type of meshing and elements following the recommendations given in Section 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 $\sigma_{hs, ref}$ of the reference detail and the structural hot spot stress $\sigma_{hs, assess}$ of the detail to be assessed.
- f) The fatigue resistance for 2 million cycles of the detail to be assessed FAT_{assess} is then calculated from fatigue class of the reference detail FAT_{ref} by:

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

3.4 FATIGUE RESISTANCE ASSESSED ON THE BASIS OF THE EFFECTIVE NOTCH STRESS

3.4.1 Steel

The effective notch stress fatigue resistance against fatigue actions, as determined in Section 2.2.4 for steel, is given in Table {3.4}-1. The definition of the FAT class is given in Section 3.2. The fatigue resistance value refers to the as-welded condition. The effect of high tensile residual stresses is included. The effect of 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 check shall be performed according to Section 2.2.3..

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

No.	Quality of weld notch	Description	FAT
1	Effective notch radius equal to 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.

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

No.	Quality of weld notch	Description	FAT
1	Effective notch radius equal to 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 effective stress ratios, based on consideration of both applied and residual stresses, $R < 0.5$ a fatigue enhancement factor $f(R)$ may be considered by multiplying the fatigue class of classified details by $f(R)$. This 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 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 information or estimations of the residual stress level are available.

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.

$$\begin{aligned} f(R) &= 1.6 && \text{for } R < -1 \text{ or completely in compression} \\ f(R) &= -0.4 \cdot R + 1.2 && \text{for } -1 \leq R \leq 0.5 \\ f(R) &= 1 && \text{for } R > 0.5 \end{aligned} \quad (3.3)$$

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

$$\begin{aligned} f(R) &= 1.3 && \text{for } R < -1 \text{ or completely in compression} \\ f(R) &= -0.4 \cdot R + 0.9 && \text{for } -1 \leq R \leq -0.25 \\ f(R) &= 1 && \text{for } R > -0.25 \end{aligned} \quad (3.4)$$

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

$$f(R) = 1 \quad \text{no enhancement} \quad (3.5)$$

It should 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 for other reasons. Consequently, 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.

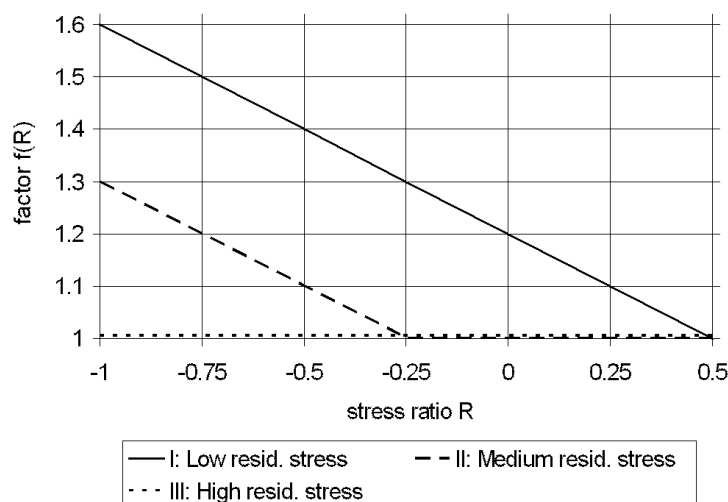


Figure (3.5)-1 Enhancement factor $f(R)$

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 the site for potential fatigue cracking is the weld toe. The fatigue resistance values here given for steel refer to a wall thickness up to 25 mm. The lower fatigue strength for thicker members is taken into consideration by multiplying the FAT class of the structural detail by the thickness reduction factor $f(t)$:

$$f(t) = \left(\frac{t_{ref}}{t_{eff}} \right)^n \quad (3.6)$$

where the reference thickness $t_{ref}=25$ mm. The thickness correction exponent n is dependent on the effective thickness t_{eff} and the joint category (see Table {3.5}-1) [5-1]. In the same way a benign thinness effect might be considered, but this should be verified by component test.

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

Table {3.5}-1: Thickness correction exponents

Joint category	Condition	n
Cruciform joints, transverse T-joints, plates with transverse attachments, ends of longitudinal stiffeners	as-welded	0.3
Cruciform joints, transverse T-joints, plates with transverse attachments, Ends of longitudinal stiffeners	toe ground	0.2
Transverse butt welds	as-welded	0.2
Butt welds ground flush, base material, longitudinal welds or attachments to plate edges	any	0.1

For the determination of t_{eff} , the following cases have to be distinguished:

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

if $L/t \leq 2$ then $t_{\text{eff}} = 0.5 \cdot L$ or $t_{\text{eff}} = t$ whichever is the larger

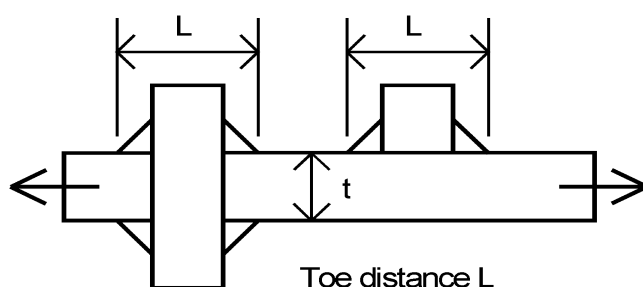


Figure. (3.5)-2: Definition of toe distance

3.5.2.2 Aluminium

The same rules as for steel are recommended.

3.5.3 Improvement Techniques

3.5.3.1 General

Post weld improvement techniques may increase the fatigue resistance, generally as a result of an improvement in the weld profile, the residual stress conditions or the environmental conditions of the welded joint. They may be used to increase the fatigue strength of new structures, notably if a weld detail is found to be critical, or as a part of repair or upgrading of an existing structure.

The main improvements techniques are:

a) Methods for improvement of weld profile:

Machining or grinding of but weld cap flush to the 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 relief

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, the structural detail, the applied stress ratio and the dimensions of the welded joint. Consequently, fatigue tests for the verification of the procedure in the endurance range of interest are recommended (Sections 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.

3.5.3.2 Applicability of Improvement Methods

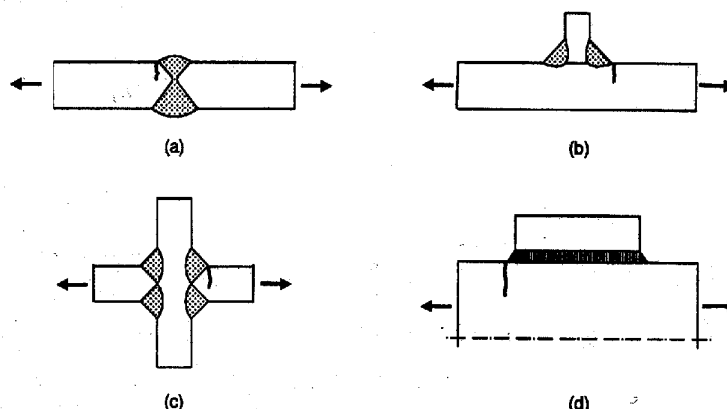


Figure (3.5)-3: Examples of joints suitable for improvement

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 with specified yield strengths up to 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 method. They do not apply to the effective notch stress or fracture mechanics method.

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 crack growth starting from this point. Thus, weld details of the type illustrated in Figure (3.5)-3 are suitable for treatment. However, the benefit of an improvement technique could be reduced as a result of intervention of fatigue cracking from the weld root. Thus, details of the kind shown in Figure (3.5)-4 are less suitable. In general, all potential alternative sites for fatigue crack initiation (e.g. weld root or imperfections) in treated welded joints should be assessed in order to establish the fatigue life of the weld detail under consideration.

The benefit factors due to the improvement techniques 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 Section 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 recommended improvement benefit factors do not apply to materials operating under free corrosion.

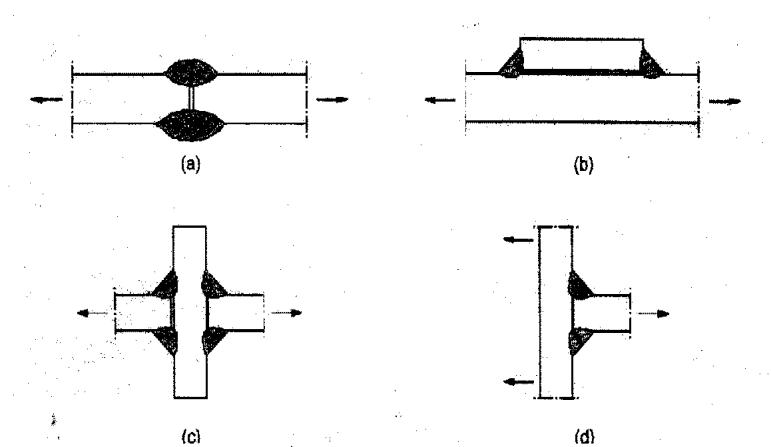


Fig: (3.5)-4: Examples of joints, in which an improvement might be limited by a possible root crack

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.

Table 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 $FAT \leq 90$ for steel or $FAT \leq 32$ for aluminium	1.3	1.3
Max possible FAT class after improvement	FAT 112	FAT 45

Table 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, $f_y < 355$ MPa	112	125
Higher strength steel, $f_y \geq 355$ MPa	112	125
Aluminium alloys	45	50

The thickness correction exponent according to Section 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 ≥ 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, $f_y < 355$ MPa	112	125
Higher strength steel, $f_y \geq 355$ 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 protection. 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 $0.1 \cdot t$, 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:

- 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)
- The S-N curve for the hammer peened weld 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 $FAT \leq 90$ for steel or $FAT \leq 32$ for aluminium	1.3	1.5	1.5
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, $f_y < 355$ MPa	112	125
Higher strength steel, $f_y \geq 355$ MPa	125	140
Aluminium alloys	50	56

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:

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

if $R < 0$ then the effective stress range = benefit factor $\cdot \Delta\sigma$

if $0 < R \leq 0.4$ then the effective stress range = benefit factor $\cdot$ 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 $f_y < 355$ MPa	Steel $f_y \geq 355$ MPa	Aluminium
Benefit at details with FAT ≤ 90 at steel or FAT ≤ 32 at aluminium, as welded	1.3	1.5	1.5
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, $f_y < 355$ MPa	112	125
Higher strength steel, $f_y > 355$ MPa	125	140
Aluminium alloys	50	56

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

$$FAT_{HT} = FAT_{20^\circ C} \cdot \frac{E_{HT}}{E_{20^\circ C}} \quad (3.7)$$

3.5.4.1 Steel

For higher temperatures, the fatigue resistance data may be modified by the reduction factor given in Figure (3.5)-13. This fatigue reduction factor is a conservative approach and might be relaxed according to test evidence or applicable codes. Creep effects are not covered here.

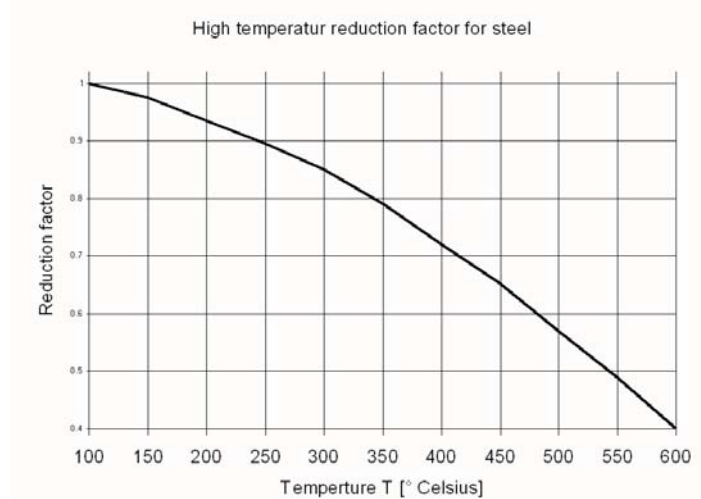


Figure (3.5)-5 Fatigue strength reduction factor for steel at elevated temperatures

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 corresponding constant amplitude fatigue limit (CAFL or 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 C_0 in the Paris power law shall be multiplied by a factor of 3.0. A threshold ΔK value shall not be considered.

No further specific recommendations are given for corrosion fatigue assessment. If no service experience is available, monitoring of the structure in service is recommended.

3.6 FATIGUE RESISTANCE ASSESSED ON THE BASIS OF CRACK PROPAGATION ANALYSIS

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

$$\frac{da}{dN} = C_0 \cdot \Delta K^m \quad \text{if} \quad \Delta K < \Delta K_{th} \quad \text{then} \quad \frac{da}{dN} = 0 \quad (3.8)$$

where the material parameters are

- C_0 constant of the power law
- m exponent of the power law
- ΔK range of cyclic stress intensity factor
- ΔK_{th} threshold value of stress intensity, under which no crack propagation is assumed
- R K_{min}/K_{max} , taking all stresses including residual stresses into account (see Section 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.

$$C = C_{0, steel} \cdot \left(\frac{E_{steel}}{E} \right)^m \quad (3.9) \quad \Delta K_{th} = \Delta K_{th, steel} \cdot \left(\frac{E}{E_{steel}} \right) \quad (3.10)$$

3.6.1 Steel

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

Units	Paris power law parameters	Threshold values ΔK_{th}			
		$R \geq 0.5$	$0 \leq R < 0.5$	$R < 0$	surface crack depth < 1 mm
K [N·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]	$C_0 = 1.65 \cdot 10^{-11}$ $m = 3.0$	2.0	5.4-6.8·R	5.4	≤ 2.0

3.6.2 Aluminium

Table 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·mm ^{-2/3}] da/dN [mm/cycle]	$C_0 = 1.41 \cdot 10^{-11}$ m = 3.0	21	56.7-72.3·R	567	≤ 21
K [MPa√m] da/dN [m/cycle]	$C_0 = 4.46 \cdot 10^{-10}$ m = 3.0	0.7	1.8-2.3·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. All specimens to failure
2. First specimen to failure
3. **p** amongst **n** specimens to failure

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) the ordinate.

Experimental fatigue data are scattered, with the extent of scatter tending to be greatest in the low stress/low crack propagation regime (e.g. see figure (3.7)-1). For statistical evaluation, a Gaussian log-normal distribution should be assumed. Ideally, there should be at least 10 failed specimens. 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 the case of crack propagation data.

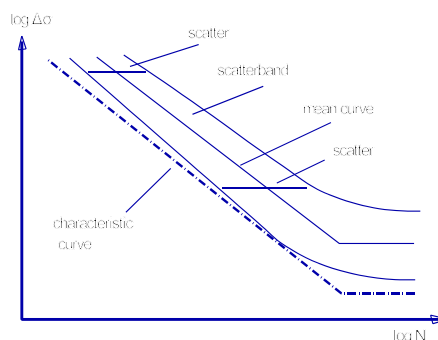


Figure (3.7)-1 Scatterband in SN curve

Thus, more precisely, test results should be analysed to produce **characteristic** values (subscript **k**). These are values that represent 95% survival probability (i.e. 5% failure probability) calculated from the mean on the basis of two-sided tolerance limits at the 75% level.

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 fatigue testing exist. For the derivation of S-N curves, testing at two stress range levels ($\Delta\sigma$) to give fatigue lives within the range of 10^5 to 10^6 cycles is preferred. For obtaining fracture mechanics crack propagation parameters, the range of stress intensity factor (ΔK) should be varied between the threshold and the critical level for fracture.

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 $\Delta\sigma$ and number of cycles N , or stress intensity factor range ΔK and crack propagation rate da/dN .
- b) Calculate exponents m and constant $\log C$ (or $\log C_0$ respectively) of the formulae:

$$\text{for } S-N \text{ curve} \quad \log N = \log C - m \cdot \log \Delta\sigma \quad (3.11)$$

$$\text{for crack propagation} \quad \log \frac{da}{dN} = \log C_0 - m \cdot \log \Delta K \quad (3.12)$$

by linear regression taking stress or stress intensity factor range as the independent variable, i.e. $\log N = f(\log \Delta\sigma)$ or $\log(da/dN) = f(\log \Delta K)$.

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 aluminium welded joints.

Values x_i equal to $\log C$ or $\log C_0$ are calculated from the $(N, \Delta\sigma)_i$ or $(da/dN, \Delta K)_i$ test results using the above equations.

- c) Calculate mean x_m and the standard deviation $Stdv$ of $\log C$ (or $\log C_0$ respectively) using m obtained in b).

$$x_m = \frac{\sum x_i}{n} \quad Stdv = \sqrt{\frac{\sum (x_m - x_i)^2}{n-1}} \quad (3.13)$$

- d) Calculate the characteristic values x_k by the formulae

$$S-N \text{ data:} \quad x_k = x_m - k \cdot Stdv \quad (3.14)$$

$$Crack \text{ propagation rate: } x_k = x_m + k \cdot Stdv \quad (3.15)$$

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

Table {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**, or for more details and information, see appendix 6.4.1 and ref. [10-3].

In the 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. Examples of ways to achieve this are by testing at high **R** values, e.g. **R=0.5**, or by testing at **R=0** and lowering the fatigue strength at 2 million cycles (FAT) by 20% to make the S-N curve steeper.

3.7.3 Evaluation of Data Collections

Usually data collections do not originate from a single statistical population. These heterogeneous populations of data require special consideration in order to avoid problems arising from the wide scatter, which are likely to display.

The evaluation procedure should consist of the following steps:

1. Calculate the constant **C** of the S-N Wöhler curve for each data point (see Section 3.7.2.) using anticipated knowledge of the slope exponent from comparable test series, e.g slope **m=3.00** for steel or aluminium.
2. Plot all values **C** in a Gaussian probability chart, showing the values of **C** on the abscissa and the cumulative survival probability on the ordinate.
3. 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. Evaluate the interesting portion of population according to Section 3.7.2.

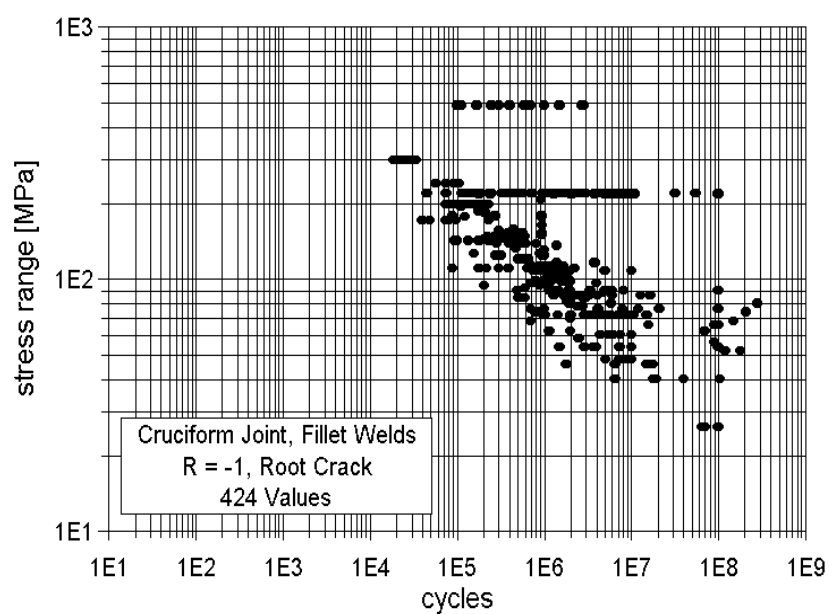


Figure (3.7)-2: Example of scatter in data collections

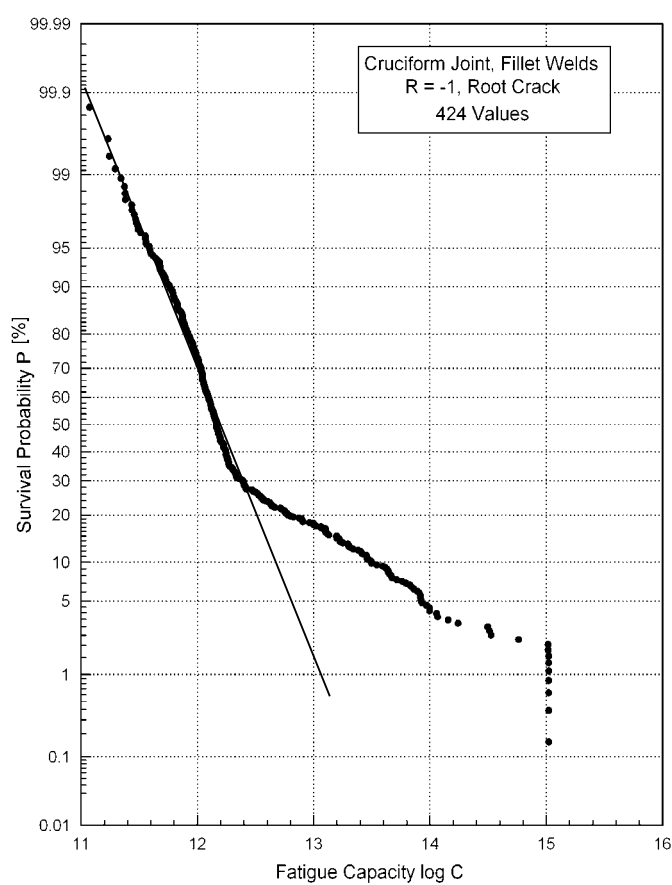


Figure (3.7)-3: Example of a heterogeneous population

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 distortion, 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. partial penetration butt welds or fillet welded cruciform joints).

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

Three effects of geometrical imperfections can be distinguished, 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 stress magnification 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 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.

Crack-like 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 identified as a type or an effect of the types listed here, it is recommended that it is assumed to be crack-like.

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

Effect of imperfection		Type of imperfection	Assessment
Increase of general stress level		Misalignment	Formulae for stress magnification factors
Local notch effect	additive	Weld shape imperfections, undercut	Tables given
	competitive	Porosity and inclusions not near the surface	Tables given
Cracklike imperfection		Cracks, lack of fusion and penetration, all types of imperfections other than given here	Fracture mechanics

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 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 the 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 the case of the structural hot spot stress and the effective notch stress assessment methods, a small but inevitable amount of misalignment corresponding to a stress magnification factor of $k_m=1.05$ is already included in the fatigue resistance S-N curves.

Additional requirements apply for the joints 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 misalignment effect may be present even in the vicinity of supporting structures. A corresponding stress increase must be taken into account also in crack propagation analyses. In all those cases where the stress magnification factor is calculated directly, use is made of an effective stress magnification factor $k_{m, eff}$.

$$k_{m, eff} = \frac{k_{m, calculated}}{k_{m, already covered}} \quad (3.16)$$

For joints containing both linear and angular misalignment, both stress magnification factors should be applied using the formula:

$$k_m = 1 + (k_{m, axial} - 1) + (k_{m, angular} - 1) \quad (3.17)$$

Since misalignment reduces the fatigue resistance, either the calculated applied stress is multiplied by $k_{m, eff}$ or the allowable stress range obtained from the relevant resistance S-N curve is divided by $k_{m, eff}$.

Table {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 $(1 + 0.2 \cdot t_{\text{ref}}/t)$, 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 (Section 3.2).

Undercut does not reduce the fatigue resistance of welds which are only loaded in the longitudinal direction /i.e. parallel to the undercut.

3.8.3.1 Steel

Table {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

Table {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 to 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 or inclusions to be assessed and that there is no interaction between them.

It is important to ensure that there is no interaction between multiple weld imperfections, be they of the same or different type. Combined porosity or inclusions shall be treated as a single large imperfection. 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 must 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

Table {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

Table {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 crack-like 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 Section 2.2.5.

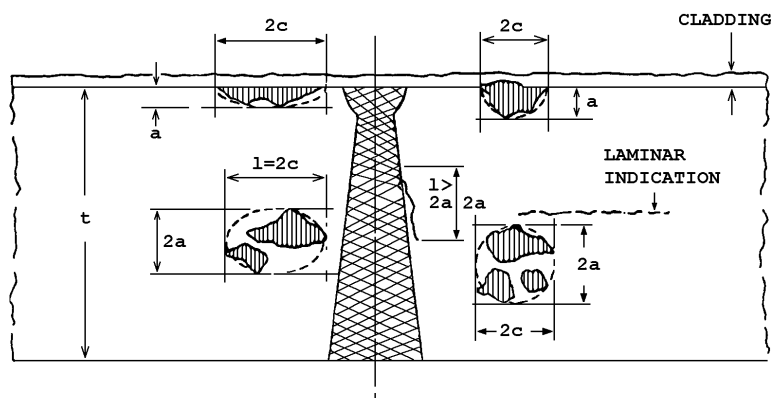
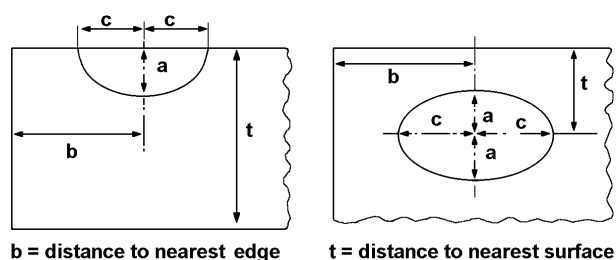


Figure (3.8)-1 Transformation of NDT indications to elliptic or semi-elliptic cracks

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 centre of the ellipse to the nearest surface. If $a/t > 0.75$, the defect should be recategorized as a surface crack.

Surface cracks are described in terms of a circumscribing half-ellipse. The thickness parameter is wall thickness t . If $a/t > 0.75$, 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.

Figure (3.8)-2 Crack dimensions for assessment

3.8.5.2 Simplified Procedure

The simplified procedure makes use of the fatigue resistance at $2 \cdot 10^6$ cycles (analogous to FAT classes for the classified structural details) for a ranges of crack types, sizes and shapes, of which the data are presented in Tables {3.8}-7. These were obtained by integration of the crack propagation law for steel, given in Section 3.6.1, between the limits of an initial crack size a_i and a final crack size of 0.75% of the wall thickness. In addition, use was made of the correction functions and the local weld geometry correction given in Section 6.2.4. (See Tables {6.2}-1 and {6.2}-3).

In assessing a defect by the simplified procedure, the stress range $\Delta\sigma_i$ corresponding to the initial crack size parameter a_i and the stress range $\Delta\sigma_c$ for the critical crack size parameter a_c are identified. The stress range $\Delta\sigma$ or the FAT class corresponding to a crack propagation from a_i to a_c in $2 \cdot 10^6$ cycles is then calculated by:

$$\Delta\sigma = \sqrt[3]{\Delta\sigma_i^3 - \Delta\sigma_c^3} \quad (3.18)$$

The tables may be used for aluminium 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 $2 \cdot 10^6$ cycles (FAT classes in N/mm²) 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	0	4	7	16
20.0	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	0	4	7	9	11	15	22
12.0	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	0	5	9	12	15	17	19	22	27
8.0	0	0	0	0	0	0	0	4	7	9	13	16	19	21	22	25	30
6.0	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	54	
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	0	8	13	22
20.0	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	0	17	23	35
20.0	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	0	4	7	17
20.0	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	0	4	7	9	11	15	23
12.0	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	0	5	9	12	15	18	20	23	29
8.0	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	8	12	15	20	24	27	29	31	33	39		
6.0	0	0	0	0	12	16	19	22	26	30	32	34	35	37	43		
5.0	0	0	0	11	17	20	24	26	30	33	35	37	38	40	45		
4.0	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	51		
2.0	11	19	25	29	35	38	41	43	45	47	49	50	51	52	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	18	24	28	34	39	42	44	46	48	52		
6.0	0	0	0	0	23	30	34	37	42	46	48	50	51	53	56		
5.0	0	0	0	22	31	36	39	42	47	50	52	53	54	56	57		
4.0	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	74	74	74	73	69	
0.5	76	80	82	83	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	0	4	7	17
20.0	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	0	4	6	9	11	14	24
12.0	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	0	4	8	12	15	17	19	23	31
8.0	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	14	19	23	28	32	35	37	39	41	48		
6.0	0	0	0	0	19	24	28	31	35	38	41	42	44	46	53		
5.0	0	0	0	18	25	29	33	35	39	42	44	46	47	49	56		
4.0	0	0	15	26	31	35	38	40	43	46	48	50	51	54	59		
3.0	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	71		
1.0	44	51	55	58	62	65	67	69	70	73	75	77	78	79	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	20	28	33	40	45	48	51	53	56	62		
6.0	0	0	0	0	27	35	40	43	48	53	56	58	59	62	67		
5.0	0	0	0	26	36	42	46	49	54	57	60	62	63	66	71		
4.0	0	0	23	37	44	49	53	56	60	63	65	67	68	70	75		
3.0	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 a 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 fatigue crack propagation considerations
- c) Direct experimental approach by the fatigue testing of components or entire structures

4.2 COMBINATION OF NORMAL AND SHEAR STRESS

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

- a) If the nominal shear stress range is less than 15% of the normal stress range or if the fatigue damage sum due to the shear stress range is lower than 10% of that due to the normal stress range, the effect of shear stress may be neglected.
- b) If the normal and shear stresses vary simultaneously in-phase, or if the plane of maximum principal stress does not change significantly ($< 20^\circ$) during cycling, the maximum principal stress range should be used, otherwise the procedure as given in Section 4.3.1 is recommended.
- c) If the normal and shear stresses vary independently out-of-phase (i.e. non-proportional loading), the procedure given in Section 4.3.1 is recommended.

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

4.3 FATIGUE ASSESSMENT USING S-N CURVES

The fatigue assessment 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 requirements of the damage calculation procedure.

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

$$\Delta\sigma_{S,d} = \Delta\sigma_{S,k} \cdot \gamma_F \leq \Delta\sigma_{R,d} = \frac{\Delta\sigma_{R,k}}{\gamma_M} \quad (4.1)$$

For **constant amplitude loading** that produces both normal and shear stresses, the maximum principal stress shall be used, provided its direction is within $\pm 60^\circ$ of normal to the weld. Otherwise the following criterion must be met, where the comparison value CV depends on the material and type of loading. See Table {4.3-1}.

$$\left(\frac{\Delta\sigma_{S,d}}{\Delta\sigma_{R,d}} \right)^2 + \left(\frac{\Delta\tau_{S,d}}{\Delta\tau_{R,d}} \right)^2 \leq CV \quad (4.2)$$

For **variable amplitude loading**, a cumulative damage calculation procedure should be applied. Usually a modified "Palmgren-Miner"-rule, as described in Section 4.3.1, is appropriate. Relevant data associated with their resistance S-N curves that are used to apply the rule are given in Table {4.3}-2. For load spectra which are sensitive to the position of the constant amplitude fatigue limit (CAFL) or knee point on the S-N curve, or in which the spectrum changes during the service life, an additional assessment using fracture mechanics, as described in Section 4.4 is recommended referring also to Sections 2.2.5 and 3.6..

In any field of application, for which there are no test data, or no service experience exist and the shape of the stress spectrum is not close to constant amplitude, the assessment procedure as detailed in Section 4.3.1 is recommended.

4.3.1 Linear Damage Calculation by the "Palmgren-Miner" Rule

First, the required number of cycles shall be specified and the design resistance S-N curve shall be determined. If the maximum design stress range $\Delta\sigma_{\max,S,d}$ in the load spectrum is lower than

the assumed design fatigue limit $\Delta\sigma_{L,R,d}$ for the design fatigue resistance S-N curve, the life of the welded joint can be assumed to be infinite and no further damage calculation is necessary. However, this procedure is not recommended for aluminium or for steels required to survive for very high numbers of load (see Section 3.2)

For other situations, the assumed constant amplitude fatigue limit (CAFL) or knee point is ignored. The S-N curve must be extrapolated beyond it at the shallower slope of $m_2 = 2 \cdot m_1 - 1$ [30] as shown in Figure (4.3)-1 and (4.3)-2. For fatigue verification, it has to be shown that:

$$D = \sum_{i=1}^i \frac{n_i}{N_i} \leq 0.5 \dots 1.0 \quad (4.3)$$

where D = damage sum or fatigue damage ratio (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 $\Delta\sigma_{i,S,d}$ in load spectrum block i
 N_i = number of cycles to failure at design stress range $\Delta\sigma_{i,S,d}$ obtained from 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 about how this should be achieved. The method presented here (Figure (4.3)-1 and -2) appears in a number of codes. However, recent research indicates that assuming a damage sum or fatigue damage ratio of $D=1$ can be non-conservative. Here, this question is partially solved by recommending a value of $D=0.5$.

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

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

$$\Delta\sigma_{eq,S,d} = \sqrt[m_1]{\frac{1}{D} \cdot \frac{\sum (n_i \cdot \Delta\sigma_{i,S,d}^{m_1}) + \Delta\sigma_{L,d}^{(m_1-m_2)} \cdot \sum (n_j \cdot \Delta\sigma_{j,S,d}^{m_2})}{\sum n_i + \sum n_j}} \quad (4.4)$$

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 at applied stress range $\Delta\sigma_i$
 n_j = number of cycles at applied stress range $\Delta\sigma_j$

For calculation of equivalent shear stress $\Delta\tau_{eq,S,d}$, the same formula applies expressed in terms of the corresponding shear stress ranges. If $\Delta\sigma_{eq,S,d}$ or $\Delta\tau_{eq,S,d}$ are below the knee points $\Delta\sigma_{L,d}$ or $\Delta\tau_{L,d}$, the corresponding constant amplitude fatigue lives are obtained from the S-N curves for the relevant FAT class extrapolated beyond the knee point at slope m_2 . If all stress ranges are below the knee point, the formula simplifies to:

$$\Delta\sigma_{eq,S,d} = \sqrt[m_2]{\frac{1}{D} \cdot \frac{\sum (n_j \cdot \Delta\sigma_{j,S,d}^{m_2})}{\sum n_j}} \quad (4.5)$$

The effects of combination of normal and shear stresses shall be assessed on the basis of the following criterion:

$$\left(\frac{\Delta\sigma_{eq,S,d}}{\Delta\sigma_{R,d}} \right)^2 + \left(\frac{\Delta\tau_{eq,S,d}}{\Delta\tau_{R,d}} \right)^2 \leq CV \quad (4.6)$$

where $\Delta\sigma_{R,d}$ and $\Delta\tau_{R,d}$ are the design resistance normal and shear stress ranges respectively for the specified number of cycles and the appropriate FAT class. CV is a comparison value, which is given in Table {4.3}-1.

In cases where the stresses acting in different directions with respect to the weld are assessed by different methods, e.g. nominal stress, structural hot-spot stress or effective notch stress method, the verification by the above given formulae must be performed with the fatigue resistance data for the same method.

For load spectra that are close to constant amplitude loading, the usable number of load cycles N_{use} may be calculated as

$$N_{use} = (1 - D \cdot CV) \cdot N_{const} + N_{var} \quad (4.7)$$

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 {4.3}-1.

Note: The verification procedures for multi-axial and non-proportional loading are in development. The procedures given in Table {4.3}-1 describe a conservative approach. In cases of special interest, the user may consult the relevant literature.

Table {4.3}-1: Assessment procedures for combined normal and shear stress using S-N curves

Type of load	Phase of stresses	Assessment procedure	Damage sum D or comparison value CV	
Constant amplitude	proportional	Assessment on the basis of the maximum principal stress or $\left(\frac{\Delta \sigma_{S,d}}{\Delta \sigma_{R,d}} \right)^2 + \left(\frac{\Delta \tau_{S,d}}{\Delta \tau_{R,d}} \right)^2 \leq CV$	CV=1.0	
	non-proportional	$\left(\frac{\Delta \sigma_{S,d}}{\Delta \sigma_{R,d}} \right)^2 + \left(\frac{\Delta \tau_{S,d}}{\Delta \tau_{R,d}} \right)^2 \leq CV$	steel	CV=0.5
			aluminium	CV=1.0
Variable amplitude	proportional	Assessment on the basis of maximum principal stress and Miner's rule, or $\left(\frac{\Delta \sigma_{eq,S,d}}{\Delta \sigma_{R,d}} \right)^2 + \left(\frac{\Delta \tau_{eq,S,d}}{\Delta \tau_{R,d}} \right)^2 \leq CV$	D=0.5 CV = 1.0	
	non-proportional	$\left(\frac{\Delta \sigma_{eq,S,d}}{\Delta \sigma_{R,d}} \right)^2 + \left(\frac{\Delta \tau_{eq,S,d}}{\Delta \tau_{R,d}} \right)^2 \leq CV$	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 S-N curves with the initial slope of **m=3** predominantly used in Section 3.2, stepping down one class corresponds to a division of the stress range by **1.12**. So, different levels of safety γ_M of an applied S-N curve may be considered (see Section 6.4.3).

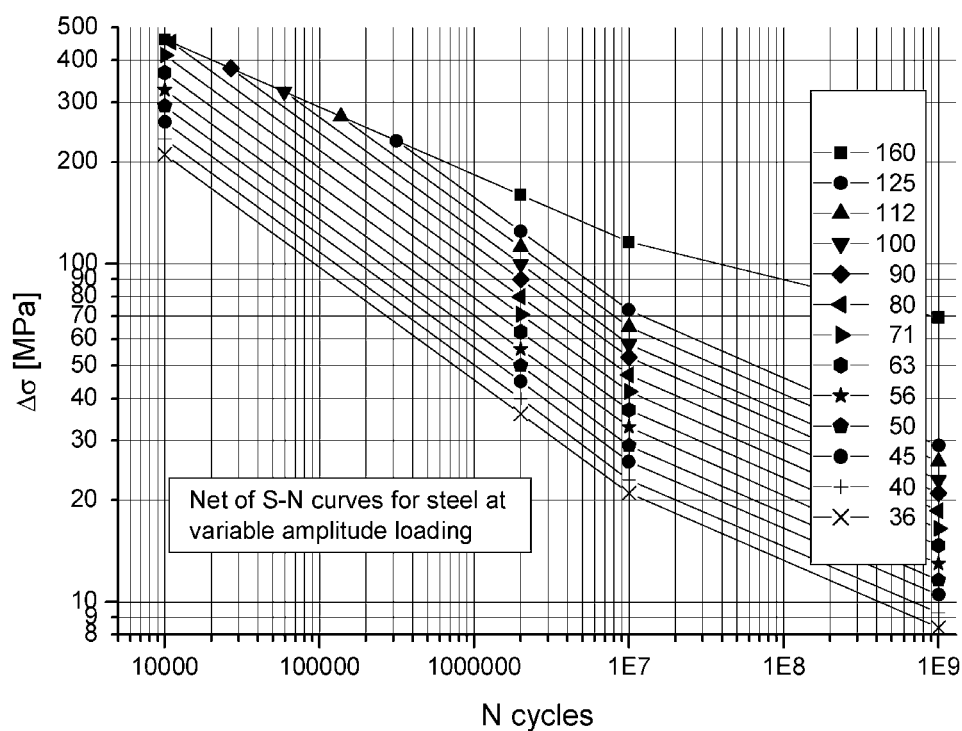


Figure (4.3)-1: Modified resistance S-N curves of steel for Palmgren-Miner summation

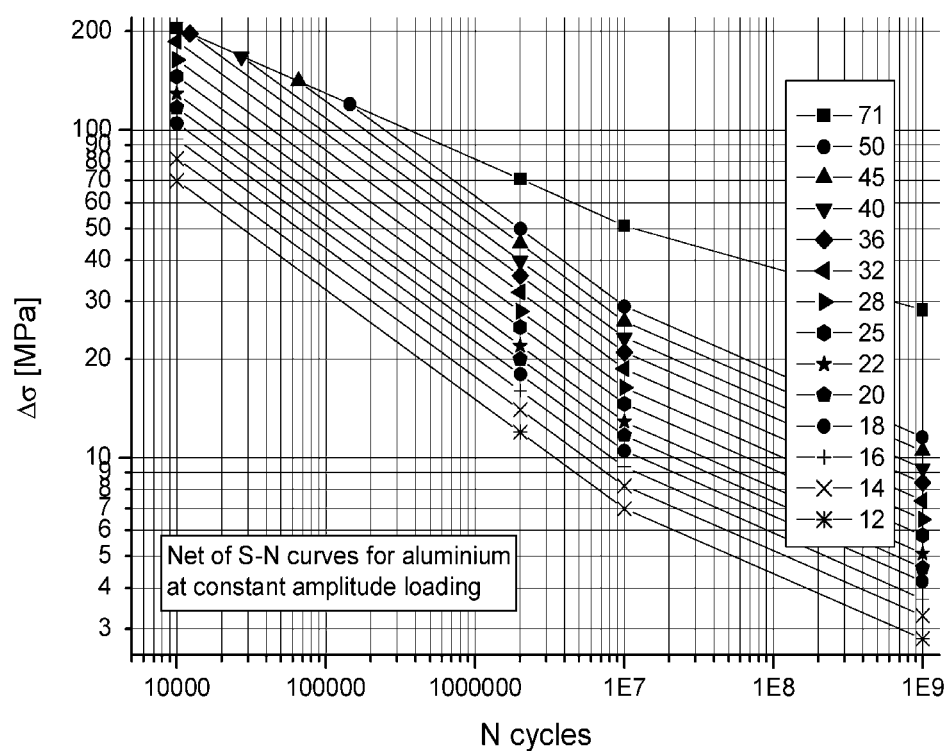


Figure (4.3)-2: Modified resistance S-N curves of aluminium for Palmgren-Miner summation

Tab. {4.3}-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: $N=C/\Delta\sigma^m$ or $N=C/\Delta\tau^m$		
FAT class [MPa]	Stress at knee point $\Delta\sigma_{i,R,k}$ [MPa]	For stress ranges above knee point	For stress ranges below knee point	
$\Delta\sigma$ at 2E+6 cycles	$\Delta\sigma$ at 1E+7 cycles		Constant C: $N=C/\Delta\sigma^m$	
		m=3	constant amplitude m=22	variable amplitude 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
$\Delta\tau$ at 2E+6 cycles	$\Delta\tau$ at 1E+8 cycles	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 Section 4.4 is recommended in cases, where

- The Miner summation is sensitive to the exact location of the knee point of the fatigue resistance S-N curve,
- The spectrum of fatigue actions (loads) varies in service or is changed, and so the sequence of loads becomes significant or
- 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

$$\frac{da}{dN} = C_0 \cdot \Delta K^m \quad \text{if } \Delta K > \Delta K_{th} \quad (4.8)$$

$$\text{but } \frac{da}{dN} = 0 \quad \text{if } \Delta K < \Delta K_{th} \quad (4.9)$$

where **a** = dimensionless crack parameter
N = Number of cycles
ΔK = Stress intensity factor range
ΔK_{th} = Threshold stress intensity factor range below which no crack propagation is assumed
C₀, m = material constants

The characteristic stress intensity factor range **ΔK_{S,k}** of the fatigue action is calculated with the stresses in the spectrum **Δσ_{i,s,k}** and the crack parameter **a**.

$$\Delta K_{S,k} = \Delta \sigma_{S,k} \cdot \sqrt{a} \quad (4.10)$$

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, **ΔK_{th,k} = Δσ_{L,R,k}**, **m** equals the slope of the S-N curve, and the constant **C_{0,k}** can be calculated from a data point (**Δσ_{S-N}** and **N_{S-N}**) on the S-N curve, preferably from the fatigue class at $2 \cdot 10^6$ cycles

$$C_{0,k} = \frac{2}{(m-2) \cdot N_{S-N} \cdot \Delta \sigma_{S-N}^m} \quad (4.11)$$

The fatigue assessment is carried out according to Section 4.4, using an initial crack parameter **a_i = 1** and a final one **a_f = ∞** or a large number e.g. **a_f = 10⁹**. The restrictions on life cycles given in Section 4.3 are to be considered.

The actual fatigue class of a pre-damaged component thus becomes **FAT_{act.} = FAT/√a**.

4.4 FATIGUE ASSESSMENT BY CRACK PROPAGATION CALCULATION

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

$$\Delta K_{i,S,d} = \Delta K_{i,S,k} \cdot \gamma_F \quad (4.12)$$

is verified by the material resistance design parameters against crack propagation

$$C_{0,d} = C_{0,k} \cdot \gamma_M^m = C_{0,k} \cdot \Gamma_M \quad (4.13)$$

$$\Delta K_{th,d} = \frac{\Delta K_{th,k}}{\gamma_M} \quad (4.14)$$

using the "Paris" power law

$$\frac{da}{dN} = C_0 \cdot \Delta K^m, \quad \text{if } \Delta K < \Delta K_{th} \quad \text{then} \quad \frac{da}{dN} = 0 \quad (4.15)$$

where **a** = Crack size
N = Number of cycles
ΔK = Stress intensity factor range
ΔK_{th} = Threshold value of stress intensity factor range below which no crack propagation is assumed
C₀, m = material constants

For applied stress intensity factors which are high compared with the fracture toughness of the material, **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.

$$\frac{da}{dN} = \frac{C_0 \cdot \Delta K^m}{(1-R) - \frac{\Delta K}{K_c}} \quad (4.16)$$

where

K_c = Fracture toughness
R = Stress ratio

The fatigue life **N** is determined by integration starting from an initial crack parameter **a_i** to a final one **a_f** [6.4 - 6.6]. The calculated number of life cycles **N** must be greater or equal to the required number of life cycles.

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

$$da = C_{0,d} \cdot \Delta K_d^m, \quad \text{if } \Delta K_d < K_{th,d} \text{ then } da = 0 \quad (4.17)$$

It is recommended that a continuous spectrum is subdivided to an adequate number of stress range blocks, e.g. 8 or 10 blocks, and the integration performed block-wise 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. If the sequence of loading is not known, the highest stresses in spectrum should be processed first.

4.5 FATIGUE ASSESSMENT ON THE BASIS OF SERVICE TESTING

4.5.1 General

An experimental fatigue assessment of a components or structures may be required for different reasons:

- Existence of a new design with no or insufficient knowledge or experience of its fatigue behaviour.
- Verification of a component or structure for a specified survival probability under a special fatigue action (stress) history.
- Optimization of design and/or fabrication with respect to weight, safety and economy after initial design. For example, the selected dimensions may be justified on the basis of higher fatigue resistance data than those presented here. Support for this might require component testing.

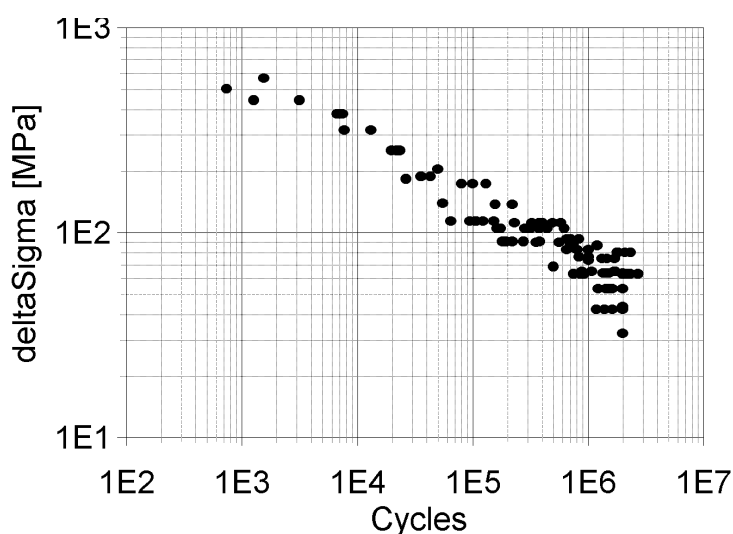


Figure (4.5)-1: Example of scatter of test data

Preliminary design corresponding to the mean values of the presented resistance S-N data could be done by assuming a 50% higher FAT value, which is based on a standard deviation of log N of 0.25 and an exponent of $m=3.00$.

In component testing, the statistical nature of fatigue must be considered. It might also be necessary to take into account differences in fabrication quality between the tested component and the actual structure. The system of quality assurance should be documented. The verification or assessment might also depend on the safety strategy considered (see Section 5.2), with some distinction between safe-life, fail-safe and damage tolerant strategies.

Ideally, the fatigue tests should be performed under loading conditions that represent the service fatigue action history (see Section 3.7), factored if necessary 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).

Table {4.5}-1 : Testing approaches

No	Testing procedure	Approach
1	All specimens from the samples are tested to failure	all failed
2	Testing is stopped at failure of first specimen from the sample	first to fail
3	Testing is stopped when p specimens of the n samples have failed	p to fail

The **all failed** approach is the normal way of testing a small sample of which each specimen represents the same weld details. The test data may be suitable for producing a S-N curve in which case their statistical analysis uses considers only the data of the failed specimens disregarding the results from the non-failed ones. However, there are techniques for including those as well, if necessary (e.g. [10.5]).

The **first to fail** approach is usually used to save time when a large number of identical specimens are tested. The results could be used to establish a safe fatigue life for the component, but only at the level of the test.

The **n to fail** approach is used in similar way to the “first to fail” one. A common situation would be one, in which the test specimen contains many potential sites of fatigue cracking, and when repair of cracks allow to continue the test. Each time when a detail fails, the test is stopped and the failed detail is repaired. At the end, possibly all details have failed and thus the “all failed” approach could be applied. If only **p** specimens out of the **n** possible ones failed, the “p to fail” approach may be used.

This section 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 to failure of all **n** failed samples or details.
- The number of cycles to failure of the first failed detail within **n** tested details.
- The number of cycles to failure 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].

In order to relate the results of the fatigue test to service operation, an estimate of the standard deviation of **log N** is required, possibly taking into account the fact that this can vary along the S-N curve, see Figure (3.7)-1.

If the number of test results **n**>**10**, the standard deviation should be calculated as detailed in Section 3.7-2c.

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

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

4.5.2 Acceptance Criteria

The required or usable fatigue life of the component or structure should be less than the minimum probable fatigue life estimated on the basis of the tests, such that

$$N_d < \frac{N_T}{F} \quad (4.18)$$

where **N_T** = The log mean fatigue life in cycles of the test specimens, or the life 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 as appropriate. The **F**-factors refer to a 95% survival probability at a two sided confidence level of 75% of the mean (see also appendix 6.4)

N_d = Number of cycles, up to which the component or structure may be used in service

If all components or test specimens are tested to failure, values of **F** from Table {4.5}-1 shall be used.

Table {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, values of **F** from Table {4.5}-2 shall be used (see also appendix 6.4).

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

Table {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 Assessment

Safe life assessment considers each structural element and detail as independent. Each element should fulfill the acceptance criteria defined in Section 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 Assessment

Fatigue life assessment of fail safe structures depends largely on the design and service operation parameters of the 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. Consequently, no general recommendation can be given.

The factor **F** given in Section 4.5.2 can be used for 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 Assessment

The verification that a structure is damage tolerant requires the demonstration that the structure can sustain fatigue cracking without failure until such time as the cracking is detected. When fatigue testing is employed as a part of the verification procedure, the failure criterion of the tests should be chosen to reflect the influence of the type of loading and the operation conditions of the actual structure.

The criteria for factoring the observed lives obtained in the tests depend of the application. It is recommended to establish agreement on the choice of the factor **F** between the relevant parties.

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 depends on the

- Uncertainties and scatter in the fatigue assessment data
- Safety strategy
- Consequences of failure.

Uncertainties in the fatigue assessment data may also origin from the **fatigue actions**, such as

- Determination of loads and load history
- Determination of stresses or stress intensity factors from the model used for analysis
- Dynamic response problems.

These uncertainties can be covered by an appropriate partial safety factor for the fatigue actions γ_F , which is **not considered here**. However, it is emphasized that assumptions made at the design stage should be conservative and ideally checked during early stages of service operation.

Uncertainties in a fatigue assessment arising from the **fatigue resistance** data and damage calculation methods include:

- Scatter in fatigue resistance data,
- Scatter of verification results from damage calculations.

The last two sources of uncertainty 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 γ_M .

5.2 FATIGUE DESIGN STRATEGIES

Different service operation conditions require different fatigue design strategies. The definition of a fatigue design 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 an assumed resistance fatigue limit or threshold value. If regular in-service monitoring is **not** specified, the survival probability must be high. This strategy is most suited to components that experience very high numbers of cycles, which are uniform or preferably close to constant amplitude.

The strategy often relies on the assumption that there is always a fatigue limit below which

infinite life can be expected. However, there are increasing doubts that this is the case for welded components. It is recommended that due consideration should be given to the adoption of an S-N curve that does not become horizontal at the CAFL or 'knee' point, but continues at a very shallow slope, as indicated in Section 5.2.2.

5.2.2 Safe Life Design

This design strategy is used in situations where regular inspection in service is not possible or the consequences of failure are very high. Consequently a very high survival probability is required.

5.2.3 Fail Safe Design

This design strategy is based on the assumption that the component or structure can tolerate extensive fatigue cracking without failing, possibly because it is statically over-determined (hyper-static) or there is an adequate redundancy. Regular monitoring in service is not usually provided. It is relied on the redistribution of forces if cracking does occur, which can be readily detected and repaired. Welded joints in such structures can be designed for a normal survival probability.

5.2.4 Damage Tolerant Design

This design strategy is based on the assumption that fatigue cracks will form but they will be readily detectable in service before they become critical. Fracture mechanics can be used to calculate suitable inspection intervals. However, apart from fatigue considerations it may also be necessary to ensure that the material is sufficiently tough to tolerate the largest fatigue crack that could be present before it has been detected. A normal probability of survival is adequate.

5.3 PARTIAL SAFETY FACTORS

The requirement for a partial safety factor to be applied to the fatigue resistance data γ_M depends largely on such circumstances as

- Fatigue design strategy
- Consequences of failure
- Practical experience in fields of application.

Examples of possible values for partial safety factors are given in Table {6.4}-4, but no general recommendations can be given. In most cases of the use of conservative fatigue resistance data given in the present Recommendations in design or assessment of components or structures of normal fabrication quality that will be regularly inspected in service, $\gamma_M=1$ should be adequate.

The safety factors $\gamma_M=1$ are given in terms of stress. If safety factors are needed in terms of cycles, Γ_M may be calculated using the exponent m of the resistance S-N curve or Paris power law of crack propagation.

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

It should be noted that the slope **m** of the S-N resistance curves may vary over the range of application (e.g. see Figure (3.7)-1).

5.4 QUALITY ASSURANCE

Weld quality assurance is based on adequate organization of work flow in fabrication, destructive and non-destructive inspection of materials and welds, and the individual acceptance levels for the different types of weld imperfections. Acceptable levels for different types of weld imperfections, that are related specifically to fatigue resistance may be found in Section 3.8 or in other fatigue based weld quality codes [e.g. 6.6].

More general weld quality acceptance criteria are needed for practical shop fabrication. The standards ISO 5817 for steel and ISO 10042 for aluminium are widely used. However, it should be noted that these are based more on traditional perceptions of what constitutes good workmanship than objective criteria related specifically to the influence of the imperfection on the strength including fatigue strength of the welded joint. Consequently they can be irrelevant, over-conservative and even potentially unsafe from the fatigue viewpoint. Nevertheless, there is a growing tendency to relate them to strength requirements. For example, ISO 5817:2006 quality level **D** might be specified for statically loaded structures, **C** for fatigue loaded ones and **B** for special requirements, even though these levels are not completely consistent in terms of their effect on fatigue properties. Besides regulations and quality codes, the general standards of good workmanship should be maintained. For conservative reasons, an ISO 5817:2006 level **B** may be specified or modified in conjunction with Section 3.8 or other fatigue based weld quality codes [e.g. 6.6].

5.5 REPAIR OF COMPONENTS

The most common cause of damage in welded structures and components is fatigue. Before the start of any repair of such damage, it is vitally important to establish the reasons for its occurrence since these will influence decisions to be made about the need for repair and for the repair method [11.1 - 11.4]. Possible reasons for fatigue damage include:

- Under-estimation of service loading, number of cycles and shape of load spectrum
- Unexpected sources of fatigue loading
- Inadequate stress analysis
- Inadequate structural design, especially of weld details
- Unsuitable material e.g. regarding toughness, corrosion resistance or weldability
- Poor workmanship (e.g. parts missing or not properly positioned, unsatisfactory application of thermal cutting, significant weld imperfections such as poor penetration, severe undercut, severe misalignment, unauthorized welding of fabrication aids)
- Unexpected dynamic response leading to vibrations not considered in design

- Environmental influences detrimental to fatigue e.g. 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 continuous crack monitoring, in-service inspection or vibration monitoring
- Change in operating 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 loading
- Selection of adequate material and repair welding procedure
- Application of a weld toe improvements technique (see Section 5.2)
- 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 LOADING HISTORY

6.1.1 Markov Transition Matrix

A Markov transition matrix is a method for recording the numbers of half-cycles of each particular stress range in a fatigue loading stress-time history and the number of 'transitions' from one extreme level (peak or trough) to another. Its general form is illustrated in Figure (6.1)-1. The actual spectrum is broken down into a number of equally spaced stress levels $a_1, a_2, a_3 \dots a_n$. 32 stress levels are sufficient. The two axes define the starting and the finishing level of each half-cycle, and each individual cell $a_{i,j}$ of the matrix defines the number of transitions from a level i to a level j stress. Falling stress half-ranges (from the peak in the stress-time history) appear in the cells below the diagonal, while rising stress half-cycles (from troughs in the stress-time history) appear in those above it, as indicated in Figure (6.1)-1.

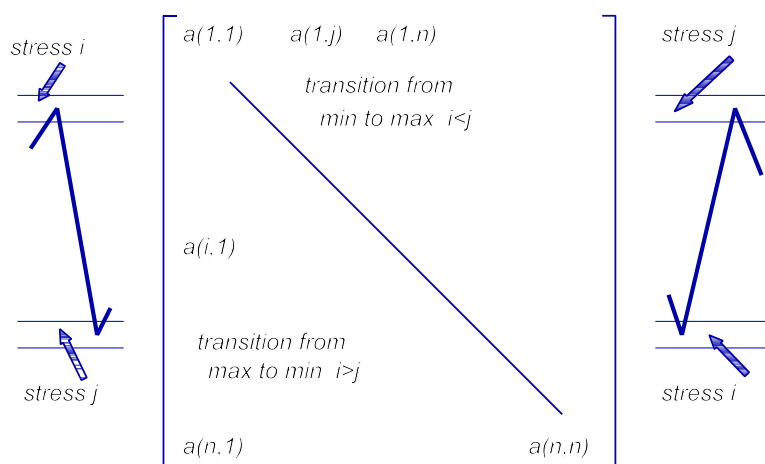


Figure (6.1)-1 Principle of the transition matrix

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

6.1.2 'Rainflow' or 'Reservoir' Counting Method

The algorithm of reservoir counting method is well explained by using the analogy of the flow of water from a reservoir, the boundary of which is the stress-time history, as illustrated in figure

(6.1)-2. Water is drained from the troughs in the stress-time history and the stress range is the largest drop before emptying that part of the reservoir.

Rainflow counting is similar but in this case, the stress-time history is visualized as a pagoda roof and stress cycles are defined in terms of the distances travelled by water flowing down the roof [7-1 and 7-2]. The same results are obtained from each method.

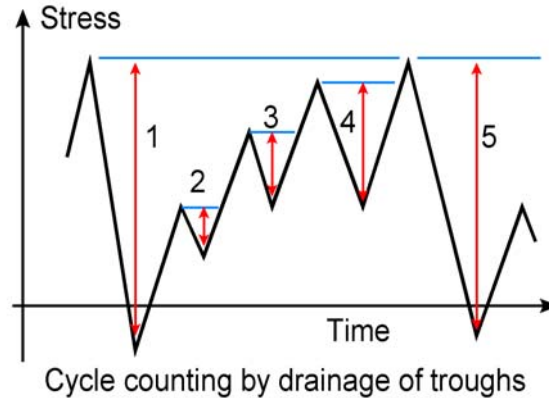


Figure (6.1)-2 Illustration of reservoir counting

6.2 FRACTURE MECHANICS

6.2.1 Rapid Calculation of Stress Intensity Factors

A simplified method may be used to determine M_k -factors [4-7]. Here, the M_k -factors are derived from the non-linear stress peak distribution $\sigma_{nlp}(x)$ along the anticipated crack path x assuming no crack being present. Hence, the function of the stress concentration factor $k_{t,nlp}(x)$ can be calculated [4.9]. The integration for a certain crack length 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 a , a function $M_k(a)$ can be established, which is preferably presented in the form:

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

6.2.2 Dimensions of Cracks

Table {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

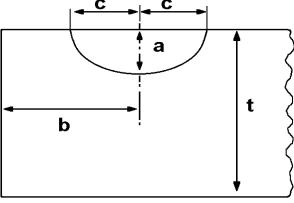
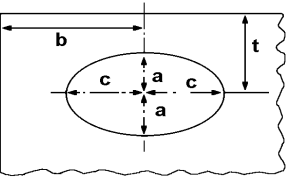
Adjacent cracks may interact and behave like a single large one. The interaction between adjacent cracks should be checked according to an interaction criterion.

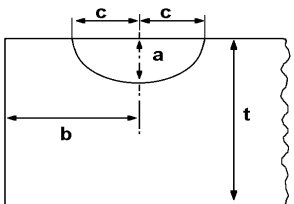
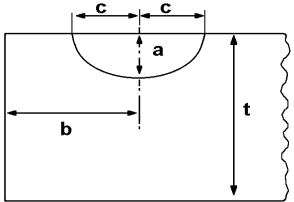
There are different interaction criteria, and in consequence no strict recommendation can be given. It is recommended to proceed according to an accepted code, e.g. [6-6].

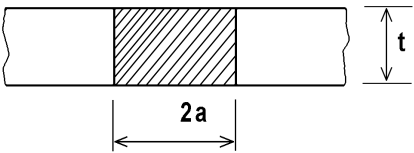
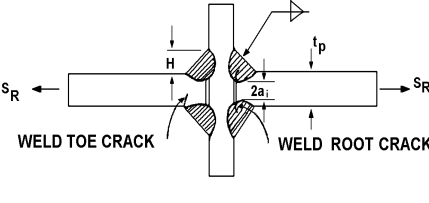
6.2.4 Formulae for Stress Intensity Factors

Stress intensity factor formulae may be taken from literature, see references [4-1 to 4-8]. The formulae given below address most of the cases relevant to welded joints.

Table {6.2}-2: Stress intensity factors at welds

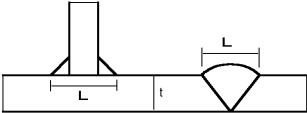
Surface cracks under membrane stress	
 b = distance to nearest edge	The formula for the stress intensity factor K_1 is valid for $a/c < 1$, for more details see ref. [4-2]
$K_1 = \sigma \sqrt{(\pi \cdot a / Q)} \cdot F_s$ $Q = 1 + 1.464 (a/c)^{1.65}$ $F_s = [M_1 + M_2 \cdot (a/t)^2 + M_3 \cdot (a/t)^4]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

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: $g = 1$ $f = 1$ "c"-direction: $g = 1 + [0.1 + 0.35 (a/t)^2]$ $f = \sqrt{(a/c)}$ 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/mm².
$K_1 = \sigma \sqrt{(\pi \cdot a / Q)} \cdot F_s$ $S = p \cdot D_{inner} / (2t)$ $Q = 1 + 1.464 (a/c)^{1.65}$ $F_s = 0.97 \cdot [M_1 + M_2 \cdot (a/t)^2 + M_3 \cdot (a/t)^4] \cdot C \cdot g \cdot f \cdot f_w$ $M_1 = 1.13 - 0.09 (a/c)$ $M_2 = -0.54 + 0.89 / (0.2 + a/c)$ $M_3 = 0.5 - 1 / (0.65 + a/c) + 14 (1 - a/c)^{24}$ $f_w = [\sec(\pi \cdot c \sqrt{(a/t) / (2 \cdot b)})]^{1/2}$ $C = [(D_{out}^2 + D_{in}^2) / (D_{out}^2 - D_{in}^2) + 1 - 0.5 \sqrt{a/t}] \cdot 2t / D_{in}$ 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 perpendicular 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].
$K = \frac{\sigma \cdot (A_1 + A_2 \cdot a/w) \cdot \sqrt{(\pi \cdot a \cdot \sec(\pi \cdot a/2w))}}{1 + 2 \cdot H/t}$ where $w = H + t/2$ σ = nominal stress range in the longitudinal plates and with $x = H/t$ $A_1 = 0.528 + 3.287 \cdot x - 4.361 \cdot x^2 + 3.696 \cdot x^3 - 1.875 \cdot x^4 + 0.415 \cdot x^5$ $A_2 = 0.218 + 2.717 \cdot x - 10.171 \cdot x^2 + 13.122 \cdot x^3 - 7.755 \cdot x^4 + 1.783 \cdot x^5$	

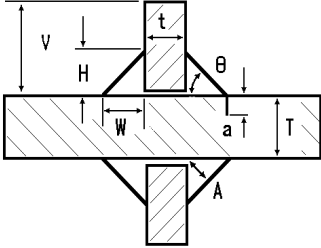
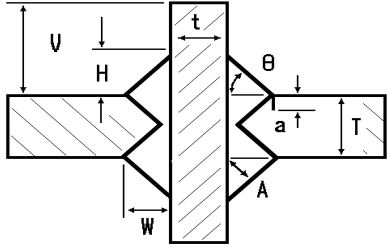
For a variety of welded joints parametric formulae of the M_k functions have been established and published [4-7, 4-8]. For the majority of cases, the formulae given below are sufficient [4-8].

Table {6.2}-3:

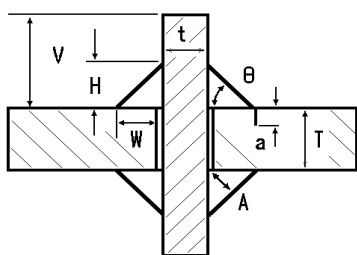
Weld local geometry correction for crack at weld toe	
 L = weld toe distance	Applicable for transverse full penetrating or non-loadcarrying welds, e.g. butt weld, transverse attachment, cruciform joint K-butt weld. For more details see ref. [4-8].
Stress intensity magnification factor $M_k > 1$ for <u>membrane stress</u>: for $l/t \leq 2$: $M_k = 0.51 \cdot (l/t)^{0.27} \cdot (a/t)^{-0.31}, \text{ for } (a/t) \leq 0.05 \cdot (l/t)^{0.55}$ $M_k = 0.83 \cdot (a/t)^{-0.15(l/t)^{0.46}}, \text{ for } (a/t) > 0.05 \cdot (l/t)^{0.55}$ for $l/t > 2$: $M_k = 0.615 \cdot (a/t)^{-0.31}, \text{ for } (a/t) \leq 0.073$ $M_k = 0.83 \cdot (a/t)^{-0.2}, \text{ for } (a/t) > 0.073$	
Stress intensity magnification factor $M_k > 1$ for <u>bending stress</u>: for $l/t \leq 1$: $M_k = 0.45 \cdot (l/t)^{0.21} \cdot (a/t)^{-0.31}, \text{ for } (a/t) \leq 0.03 \cdot (l/t)^{0.55}$ $M_k = 0.68 \cdot (a/t)^{-0.19(l/t)^{0.21}}, \text{ for } (a/t) > 0.03 \cdot (l/t)^{0.55}$ for $l/t > 1$: $M_k = 0.45 \cdot (a/t)^{-0.31}, \text{ for } (a/t) \leq 0.03$ $M_k = 0.68 \cdot (a/t)^{-0.19}, \text{ for } (a/t) > 0.03$	

Parametric formulae for M_k functions have been established for a variety of welded joints [4-7, 4.8].

Table {6.2}-4: Formulae for 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)
$M_k = C \cdot \left(\frac{a}{T} \right)^k \quad M_k \leq 1$ $C = 0.8068 - 0.1554 \left(\frac{H}{T} \right) + 0.0429 \left(\frac{H}{T} \right)^2 + 0.0794 \left(\frac{W}{T} \right) \quad (1)$ $k = -0.1993 - 0.1839 \left(\frac{H}{T} \right) + 0.0495 \left(\frac{H}{T} \right)^2 + 0.0815 \left(\frac{W}{T} \right)$			
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
$M_k = C \cdot \left(\frac{a}{T} \right)^k \quad M_k \leq 1$ $C = 0.7061 - 0.4091 \left(\frac{H}{T} \right) + 0.1596 \left(\frac{H}{T} \right)^2 + 0.3739 \left(\frac{W}{T} \right) - 0.1329 \left(\frac{W}{T} \right)^2 \quad (2)$ $k = -0.2434 - 0.3939 \left(\frac{H}{T} \right) + 0.1536 \left(\frac{H}{T} \right)^2 + 0.3004 \left(\frac{W}{T} \right) - 0.0995 \left(\frac{W}{T} \right)^2$			

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

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

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

$$C = 2.0175 - 0.8056 \left(\frac{H}{T} \right) - 1.2856 \left(\frac{W}{T} \right) \quad (3)$$

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

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

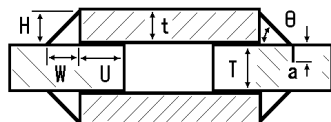
$$C = 0.2916 - 0.0620 \left(\frac{H}{T} \right) + 0.69421 \left(\frac{W}{T} \right) \quad (4)$$

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

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

$$C = 0.9055 - 0.4369 \left(\frac{H}{T} \right) + 0.1753 \left(\frac{H}{T} \right)^2 + 0.0665 \left(\frac{W}{T} \right)^2 \quad (5)$$

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

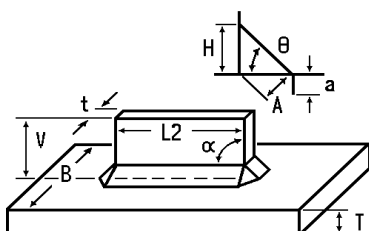
Lap joint


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

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

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

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

Longitudinal non-loadcarrying attachment


Dim.	min	max
L/T	5	40
B/T	2.5	40
$\theta/45^\circ$	0.670	1.33
t/T	0.25	2
$A = 0.7 \cdot t$		

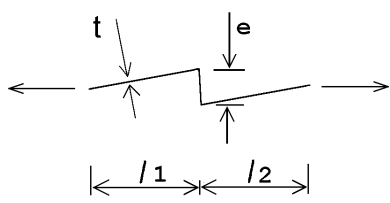
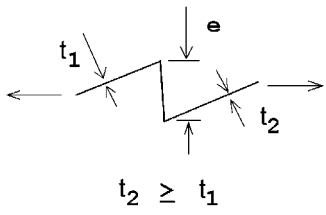
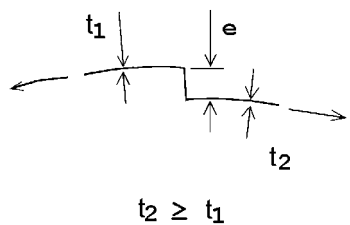
$$M_k = C \cdot \left(\frac{a}{T} \right)^k \quad M_k = \geq 1 \quad (7)$$

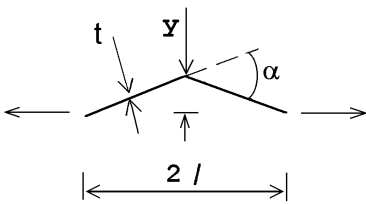
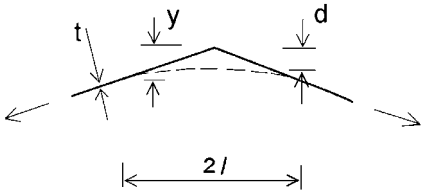
$$C = 0.9089 - 0.2357 \left(\frac{t}{T} \right) + 0.0249 \left(\frac{L}{T} \right) - 0.00038 \left(\frac{L}{T} \right)^2 + 0.0186 \left(\frac{B}{T} \right) - 0.1414 \left(\frac{\theta}{45^\circ} \right)$$

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

6.3 FORMULAE FOR MISALIGNMENT

Table {6.3}-1: Formulae for assessment of misalignment

No	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, $\lambda=6$ for unrestrained joints. For remotely loaded joints assume $l_1=l_2$.	
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: $\text{with } \beta = \frac{2l}{t} \sqrt{\frac{3\sigma_m}{E}}$ $k_m = 1 + \frac{3y}{t} \cdot \frac{\tanh(\beta/2)}{\beta/2}$ $\text{altern.: } k_m = 1 + \frac{3}{2} \cdot \frac{\alpha \cdot l}{t} \cdot \frac{\tanh(\beta/2)}{\beta/2}$ assuming pinned ends: $k_m = 1 + \frac{6y}{t} \cdot \frac{\tanh(\beta)}{\beta}$ $\text{altern.: } k_m = 1 + \frac{3\alpha \cdot l}{t} \cdot \frac{\tanh(\beta)}{\beta}$ The tanh correction allows for reduction of angular misalignment due to the straightening of the joint under tensile loading. It is always ≤ 1 and it is conservative to ignore it. σ_m is membrane stress range.
5	Angular misalignment at longitudinal joints in cylindrical shells  Assuming fixed ends: $\text{with } \beta = \frac{2l}{t} \sqrt{\frac{3(1-\nu^2) \cdot \sigma}{E}}$ $k_m = 1 + \frac{3d}{t(1-\nu^2)} \cdot \frac{\tanh(\beta/2)}{\beta/2}$ 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 $k_m = 1 + \frac{1.5(D_{\max} - D_{\min}) \cdot \cos(2\Phi)}{t \left(1 + \frac{0.5 p_{\max}(1 - \nu^2)}{E} \cdot \left(\frac{D}{t} \right)^3 \right)}$
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 $\lambda=3$ (fully restrained) to $\lambda=6$ (unrestrained). For unrestrained remotely loaded joints assume: $l_1=l_2$ and $\lambda=6$
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 $\lambda=0.02$ to $\lambda=0.04$. If not, λ varies from $\lambda=3$ to $\lambda=6$.

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

6.4.1 Statistical Evaluation of Fatigue Test Data

The methods for evaluating of fatigue test data as described in Section 3.7 consider different statistical effects, when evaluating a set of fatigue data. Ideally, all the following effects should be considered, e.g.

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

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 characteristic values are, in principle, values at a $\alpha=95\%$ survival probability (5% probability of failure) calculated from the mean value x_m on the basis of two sided tolerance limits of the 75% confidence level of the mean x_m :

$$x_k = x_m - k \cdot Stdv \quad (6.3)$$

The factor **k_i** considers the first four (as described above) and corresponds to:

- the minimum 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's law (t-distribution) and the probability distribution of the variance corresponds to a Chi-square law (χ^2), the general formula for **k_i** is given by:

$$k_1 = \frac{t(p, n-1)}{\sqrt{n}} + \varphi(\alpha)^{-1} \cdot \sqrt{\frac{n-1}{\chi^2(\frac{1+\beta}{2}, n-1)}}$$

where **t** = value of the two sided t-distribution (Student's law) for $p=\beta=0.75$, or of the one sided t-distribution for a probability of $p=(1+\beta)/2=0.875$ at **n-1** degrees of freedom

n = number of test results

φ = distribution function of the Gaussian normal distribution probability of exceedence of $\alpha=95\%$ (superscript **-1** indicates inverse function)

χ^2 = Chi-square for a probability of $(1+\beta)/2=0.875$ 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:

$$k_2 = \frac{t(0.875, n-1)}{\sqrt{n}} + \varphi^{-1}(0.95) = \frac{t(0.875, n-1)}{\sqrt{n}} + 1.645 \quad (6.5)$$

Table {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 of Results from 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 Section 4.5.2, there is

$$N_d < \frac{N_T}{F} \quad (6.6)$$

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

$$\log N_T - \log F > \log N_d \quad (6.7)$$

Taking the acceptance criterion $\mathbf{x}_m - \mathbf{k} \cdot \mathbf{Stdv} > \mathbf{x}_k$ from Section 3.7 the factor **F** can be deduced:

$$\log F = k \cdot \text{Stdv} \quad (6.8)$$

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

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 the standard deviation cannot be derived from test results.

Starting from the formula in Section 4.5.2, there is

$$N_d < \frac{N_T}{F} \quad (6.9)$$

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

$$\log N_T - \log F > \log N_d \quad (6.10)$$

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

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

where N_T = Life of first specimen to fail

x_m = Mean of the sample

N_k = Characteristic value

N_d = Design value

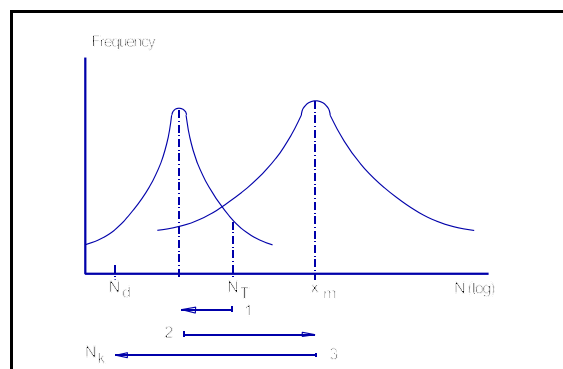


Figure. (6.4)-1 Distribution of action and resistance

$\log N_T$ 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:

$$x_m = \log N_T - k_a \cdot \alpha \cdot \text{Stdv} + k_b \cdot \text{Stdv} \quad (6.11)$$

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 $x_m - k_1 \text{Stdv} > x_k$ from Section 3.7, the factor **F** can be deduced:

$$\log F = (k_a \cdot \alpha - k_b + k_1) \cdot \text{Stdv} = k \cdot \text{Stdv} \quad (6.12)$$

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

Table {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 the relevant literature or ref. [10.5].

6.4.3 Statistical Considerations for Partial Safety Factors

No general recommendations on partial safety factors are given. For special fields of application, 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.

Table {6.4}-4: Possible examples of partial safety factors γ_M for fatigue resistance

Partial safety factor $\gamma_M \rightarrow$ 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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