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RECOMMENDATIONS FOR FATIGUE DESIGN OF WELDED JOINTS AND COMPONENTS

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PREFACE

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

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1 GENERAL

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1.1 INTRODUCTION

The aim of these recommendations is to provide a basis for the design and analysis of welded components loaded by fluctuating forces, to avoid failure by fatigue. In addition they may assist other bodies who are establishing fatigue design codes. It is assumed that the user has a working 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 ultimate limit state and serviceability limited state [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 $\Delta\sigma_{nom} > 1.5 \cdot f_y$, for corrosive conditions or for elevated temperature operation in the creep range.

1.3 DEFINITIONS

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

Fatigue	Detoriation of a component caused by crack initiation and/or by the growth of cracks.
Fatigue action	Load effect causing fatigue.
Fatigue damage ratio	Ratio of fatigue damage sustained to fatigue damage required to cause failure, defined as the ratio of the number of applied stress cycles and the corresponding fatigue life at constant amplitude.
Fatigue life	Number of stress cycles of a particular magnitude required to cause fatigue failure of the component.
Fatigue limit	Fatigue strength under constant amplitude loading corresponding to infinite fatigue life or a number of cycles large enough to be considered infinite by a design code.
Fatigue resistance	Structural detail's resistance against fatigue actions in terms of S-N curve or crack propagation properties.
Fatigue strength	Magnitude of stress range leading to a particular fatigue life.
Fracture mechanics	A branch of mechanics dealing with the behaviour and strength of components containing cracks.
Hot spot	A point in a structure where a fatigue crack may initiate due to the combined effect of structural stress fluctuation and the weld geometry or a similar notch.
Local nominal stress	Nominal stress including macro-geometric effects, concentrated load effects and misalignments, disregarding the stress raising effects of the welded joint itself. Also referred to as modified nominal stress.
Local notch	A notch such as the local geometry of the weld toe, including the toe radius and the angle between the base plate surface and weld reinforcement. The local notch does not alter the structural stress but generates nonlinear stress peaks.
Macro-geometric discontinuity	A global discontinuity, the effect of which is usually not taken into account in the collection of standard structural

	details, such as a large opening, a curved part in a beam, a bend in a flange not supported by diaphragms or stiffeners, discontinuities in pressure containing shells, eccentricity in a lap joint (see fig. (2.2)-3).
Macro-geometric effect	A stress raising effect due to macro-geometry in the vicinity of the welded joint, but not due to the welded joint itself.
Membrane stress	Average normal stress across the thickness of a plate or shell.
Miner sum	Summation of individual fatigue damage ratios caused by each stress cycle or stress range block above a certain cut-off limit according to the Palmgren-Miner rule.
Misalignment	Axial and angular misalignments caused either by detail design or by poor fabrication or welding distortion.
Modified nominal stress	See 'Local nominal stress'.
Nominal stress	A stress in a component, resolved using general theories, e.g. beam theory. See also local nominal stress.
Nonlinear stress peak	The stress component of a notch stress which exceeds the linearly distributed structural stress at a local notch.
Notch stress	Total stress at the root of a notch taking into account the stress concentration caused by the local notch, consisting of the sum of structural stress and nonlinear stress peak.
Notch stress concentration factor	The ratio of notch stress to structural stress.
Paris' law	An experimentally determined relation between crack growth rate and stress intensity factor range.
Palmgren-Miner rule	Fatigue failure is expected when the Miner sum reaches unity.
Rainflow counting	A standardized procedure for stress range counting.
Range counting	A procedure of determining various stress cycles and their ranges from a stress history, preferably by rainflow counting

	method.
Shell bending stress	Bending stress in a shell or plate-like part of a component, linearly distributed across the thickness as assumed in the theory of shells.
S-N curve	Graphical presentation of the dependence of fatigue life N on fatigue strength S ($\Delta\sigma_R$ or $\Delta\tau_R$), also known as Wöhler curve.
Stress cycle	A part of a stress history containing a stress maximum and a stress minimum, determined usually by a range counting method.
Stress history	A time based presentation of a fluctuating stress, defined by sequential stress peaks and troughs (valleys), either for the total life or for a certain sample.
Stress intensity factor	Main parameter in fracture mechanics, the combined effect of stress and crack size at the crack tip region.
Stress range	The difference between stress maximum and stress minimum in a stress cycle, the most important parameter governing fatigue life.
Stress range block	A part of the total spectrum of stress ranges which is discretized in a certain number of blocks.
Stress range exceedances	A tabular or graphical presentation of the cumulative frequency of stress range exceedances, i.e the number of ranges exceeding a particular magnitude of stress range in a stress history. Here, frequency is the number of occurrences. (Also referred to as "stress spectrum" or "cumulative frequency diagram").
Stress range occurrences	A tabular or graphical presentation of stress ranges, usually discretized in stress range blocks. See also "stress range exceedances".
Stress ratio	Ratio of minimum to maximum algebraic value of the stress in a particular stress cycle.
Stress intensity factor ratio	Ratio of minimum to maximum algebraic value of the stress

intensity factor of a particular load cycle.

Structural discontinuity	A geometric discontinuity due to the type of welded joint, usually to be found in the tables of classified structural details. The effects of a structural discontinuity are (i) concentration of the membrane stress and (ii) formation of secondary shell bending stresses (see fig. (2.2)-6).
Structural stress	A stress in a component, resolved taking into account the effects of a structural discontinuity, and consisting of membrane and shell bending stress components. Also referred to as geometric stress.
Structural stress concentration factor	The ratio of structural (hot spot) stress to modified (local) nominal stress.
Structural hot spot stress	The value of structural stress on the surface at a hot spot.
Variable amplitude loading	A type of loading causing irregular stress fluctuation with stress ranges (and amplitudes) of variable magnitude.

1.4 SYMBOLS

K	stress intensity factor	
K_{max}	stress intensity factor caused by $\sigma_{\max}$	
K_{min}	stress intensity factor caused by $\sigma_{\min}$	
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	
R	stress ratio	
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	depth of a surface crack or semi length of a through crack	
a_o	initial depth of a surface crack	
a_f	crack size at failure	
e	eccentricity, amount of offset misalignment	
f_y	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	
t	plate thickness, thickness parameter (crack center to nearest surface)	
ΔK	stress intensity factor range	
ΔK_{S,d}	design value of stress intensity factor range caused by actions	
ΔK_{th}	threshold stress intensity factor range	
Δσ	stress range	
Δσ_{S,d}	design value of stress range caused by actions	
Δσ_{R,L}	characteristic value of fatigue limit	
Δτ	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_{ben}	shell bending stress	
σ_{en}	effective notch stress	
σ_{ln}	(local) notch stress	
σ_{max}	stress maximum in stress history	
σ_{mem}	membrane stress	
σ_{min}	stress minimum in stress history	
σ_{nlp}	nonlinear stress peak	
σ_{nom}	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], fatigue action and fatigue resistance are clearly separated. Fatigue resistance is given in terms of tentative data. The representation of tentative data has also been separated from the assessment curves used for damage calculation, because different damage calculation methods may require special modifications to the resistance S-N curve, which is usually based on constant amplitude tests. Thus, the flexibility and possibility for continuous updating of the document is maintained.

No recommendations are given for the fatigue load (action) side, nor for the partial safety factor on fatigue actions γ_F .

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

1.6 NECESSITY FOR FATIGUE ASSESSMENT

Fatigue assessment is generally required for components subject to fluctuating loads.

In the following cases, detailed fatigue assessment is not required:

- a) The highest nominal design stress range satisfies

$$\begin{aligned} \text{steel} &: \Delta \sigma_{S,d} \leq 36 \text{ [MPa]} / \gamma_M \\ \text{aluminium} &: \Delta \sigma_{S,d} \leq 14 \text{ [MPa]} / \gamma_M \end{aligned}$$

γ_M should be taken from an applicable design code.

This paragraph is not applicable to tubular joints.

- b) A Miner sum (4.3.1) equal to **D=0.5** using a FAT fatigue class according to (3.2) of FAT 36 for steel or FAT 14 for aluminium corresponds to a fatigue life greater than 5 million cycles.
- c) For a detail for which a constant amplitude fatigue limit $\Delta \sigma_{R,L}$ is specified and all design stress ranges are under the design resistance fatigue limit

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

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

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

for steel	$\Delta K_{th}=2.0 \text{ MPa}\sqrt{\text{m}}$
for aluminium	$\Delta K_{th}=0.7 \text{ MPa}\sqrt{\text{m}}$

1.7 APPLICATION OF THE DOCUMENT

Based on the initial information about the welded joint, the stress type to be used in the fatigue assessment is defined and determined. The fatigue resistance data are then selected according to the stress type of the fatigue action. The corresponding types of fatigue action and resistance are:

Tab. {1}-1: Fatigue actions and resistances

Fatigue action	Fatigue resistance
Forces on component	Resistance determined by test at component
Nominal stress in section	Resistance given by tables of structural details in terms of a set of S-N curves
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

The fatigue assessment procedure depends on the presentation of fatigue resistance data. The chosen procedure has to be performed using adequate safety factors.

Tab. {1}-2: Assessment procedures

Presentation of fatigue resistance data	Assessment procedure
Forces at component	Component testing
S-N curves	Linear cumulative damage, (in special cases nonlinear damage calculation)
Parameters of crack propagation law	Crack propagation calculation

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

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

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

2 FATIGUE ACTIONS (LOADING)

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

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

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

2.1 BASIC PRINCIPLES

2.1.1 Determination of Actions

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

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

2.1.2 Stress Range

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

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

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

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

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

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

2.1.3 Types of Stress Raisers and Notch Effects

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

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

Type	Stress raisers	Stress determined	Assessment procedure
A	General stress analysis using general theories e.g. beam theory, no stress raisers applied	Elementary technical mechanics	not applicable for fatigue of welded structures
B	A + macrogeometrical effects due to the design of the component, but excluding stress raisers due to the welded joint itself.	Range of nominal stress (also modified or local nominal stress)	Nominal stress approach
C	A + B + structural discontinuities due to the structural detail of the welded joint, but excluding the notch effect of the weld toe transition	Range of structural Stress (hot spot stress)	Structural Stress (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

2.2 DETERMINATION OF STRESSES AND STRESS

INTENSITY FACTORS

2.2.1 Definition of Stress Components

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

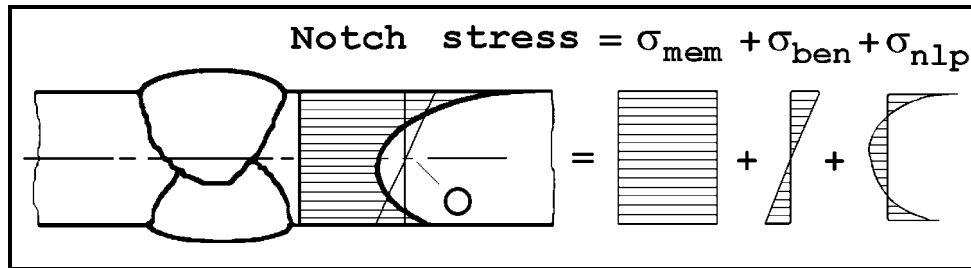


Fig. (2.2)-1 Non-linear stress distribution separated to stress components

The stress components of the notch stress σ_{ln} are [2]:

- σ_{mem} membrane stress
- σ_{ben} shell bending stress
- σ_{nlp} non-linear stress peak

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

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

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

The non-linear stress peak σ_{nlp} is the remaining component of the stress.

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

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

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

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

2.2.2 Nominal Stress

2.2.2.1 General

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

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

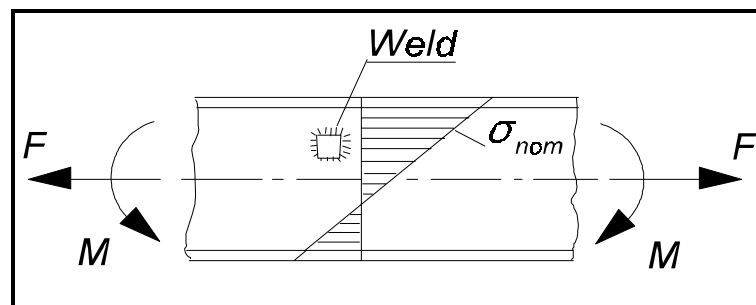


Fig. (2.2)-2 Nominal stress in a beam-like component

The effects of macrogeometric features of the component as well as stress fields in the vicinity of concentrated loads must be included in the nominal stress. Consequently, macrogeometric effects may cause a significant redistribution of the membrane stresses

across the section. Similar effects occur in the vicinity of concentrated loads or reaction forces. Significant shell bending stress may also be generated, as in curling of a flange, or distortion of a box section.

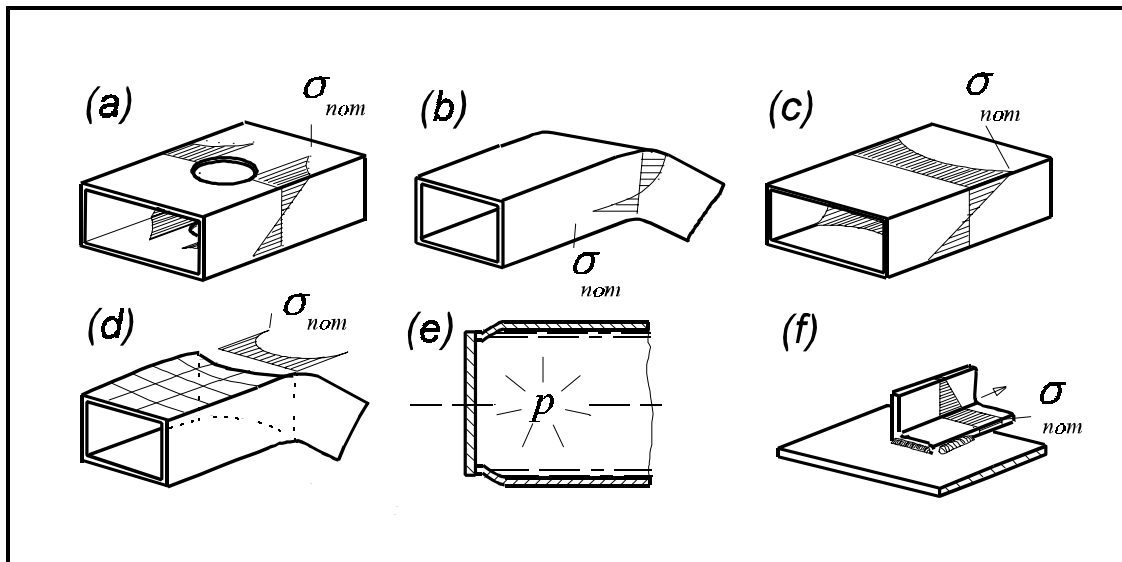


Fig. (2.2)-3 Examples of macrogeometric effects

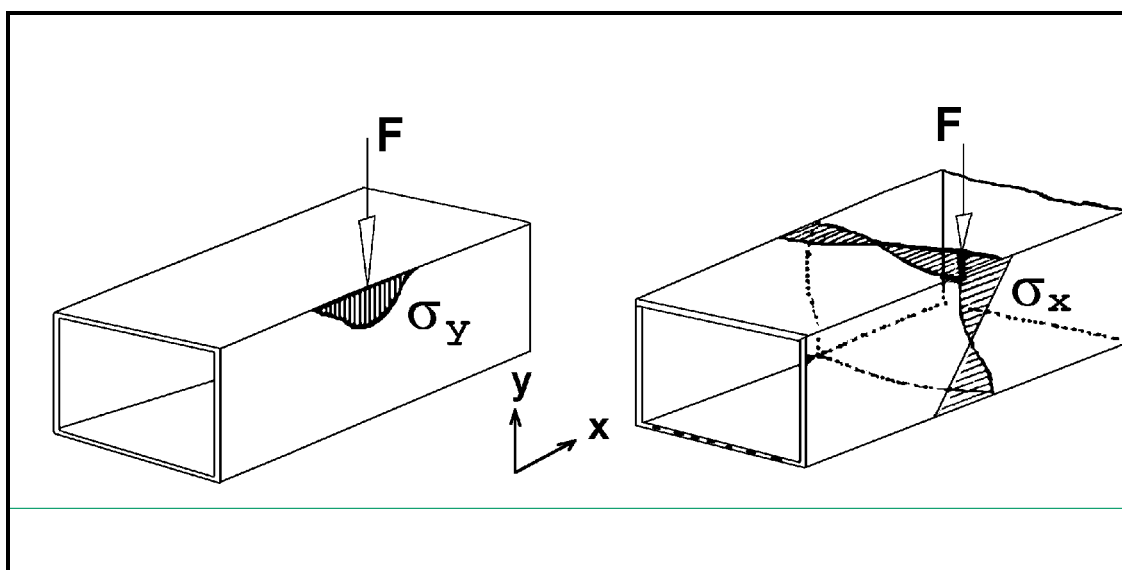


Fig. (2.2)-4 Modified (local) nominal stress near concentrated loads

The secondary bending stress caused by axial or angular **misalignment** needs to be considered if the misalignment exceeds the amount which is already covered by fatigue resistance S-N curves for the structural detail. This is done by the application of an additional stress raising factor $k_{m,eff}$ (see 3.8.2). Intentional misalignment (e.g. allowable misalignment specified in the design stage) is considered when assessing the fatigue actions (stress) by multiplying by the factor. If it is non-intentional, it is regarded as a weld

imperfection which affects the fatigue resistance and has to be considered by dividing the fatigue resistance (stress) by the factor.

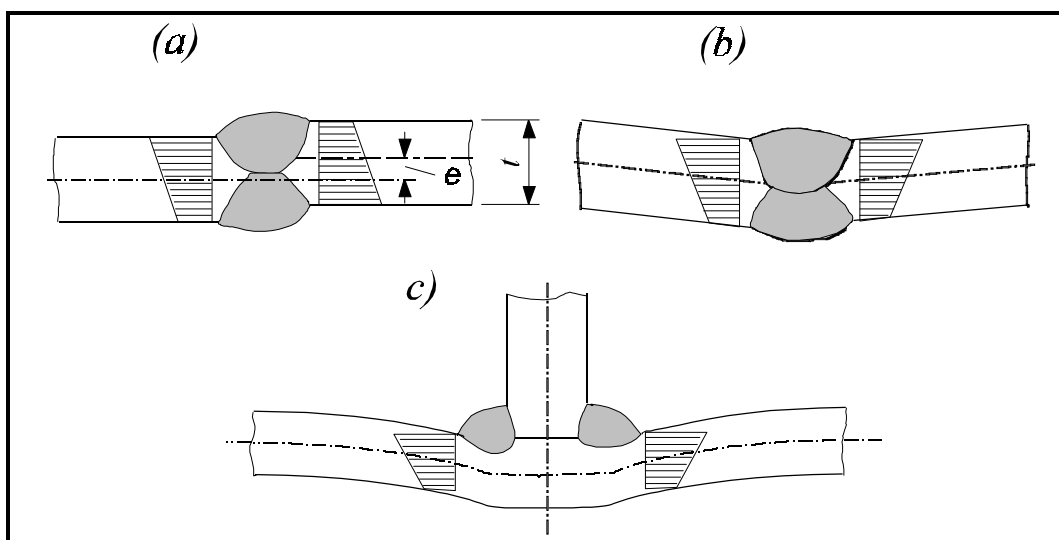


Fig. (2.2)-5 Axial and angular misalignment

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

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

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

2.2.2.3 Measurement of Nominal Stress

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

outside of the stress concentration field of the welded joint.

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

2.2.3 Structural Hot Spot Stress

2.2.3.1 General

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

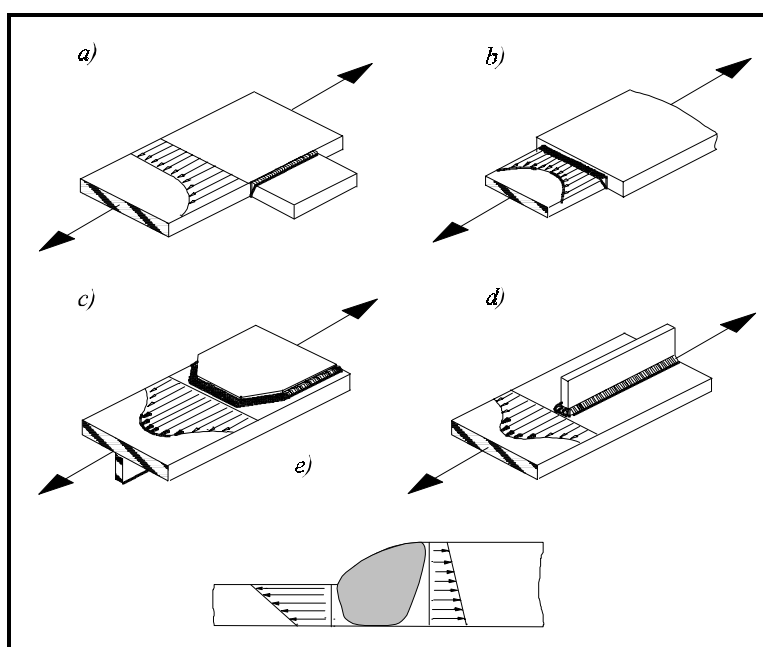


Fig. (2.2)-6 Structural details and structural stress

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

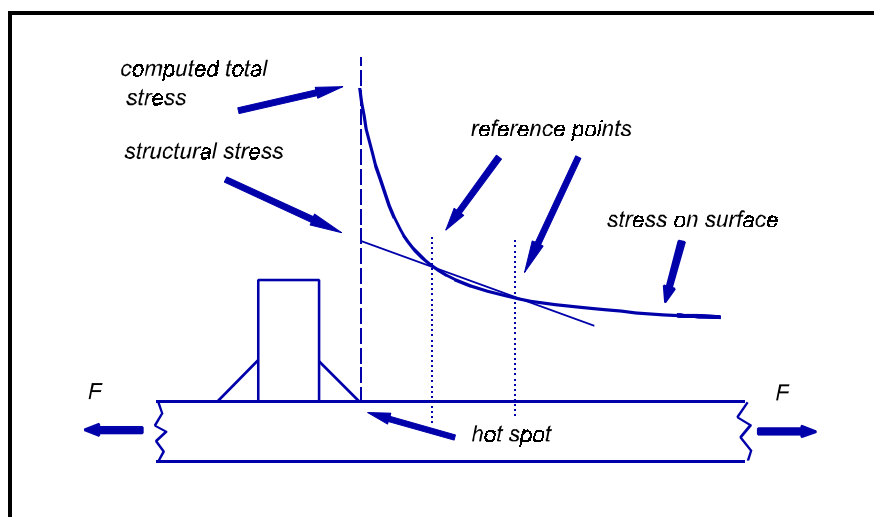


Fig. (2.2)-7 Definition of structural hot spot stress

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

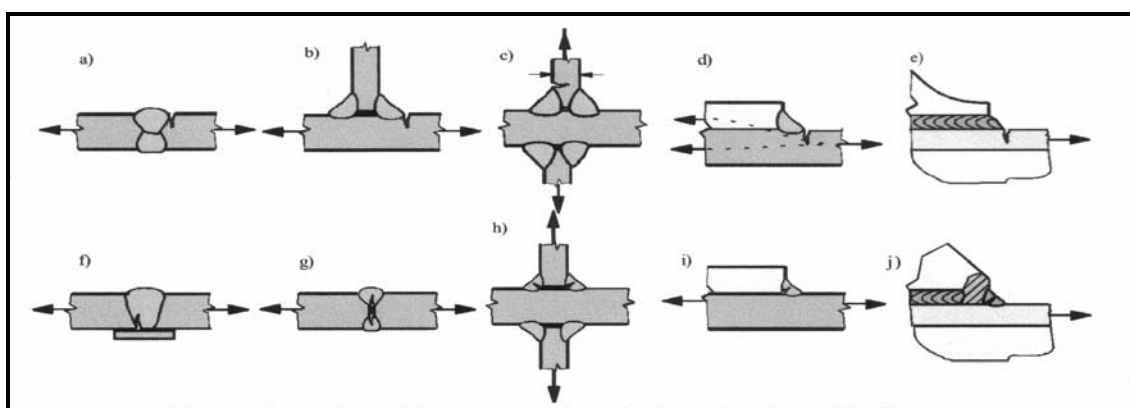


Fig. (2.2)-8: Various locations of crack propagation in welded joints.

Note:

The method of structural hot spot stress may be extended to the assessment of spots of the welded joint susceptible to fatigue cracking other than on plate surface, e.g. on a fillet weld root. In this case, structural hot spot stress on surface is used as an indication and

estimation of the stress for the spot in consideration. The S - N curves or structural hot spot stress concentration factors used for verification in this case depend largely on geometric and dimensional parameters and are only valid within the range of these parameters.

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

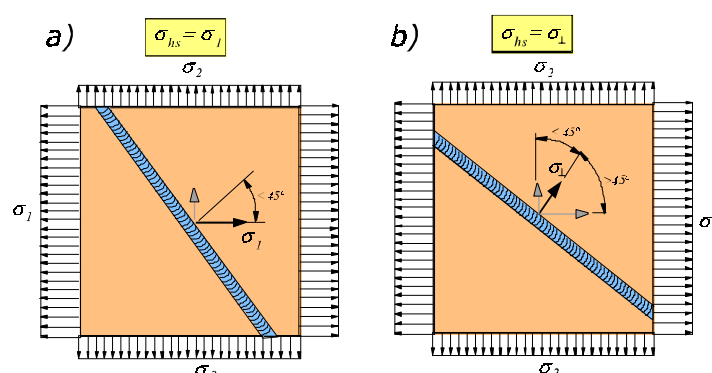


Fig. (2.2)-9 Biaxial stress at weld toe

2.2.3.2 Types of hot spots

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

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

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

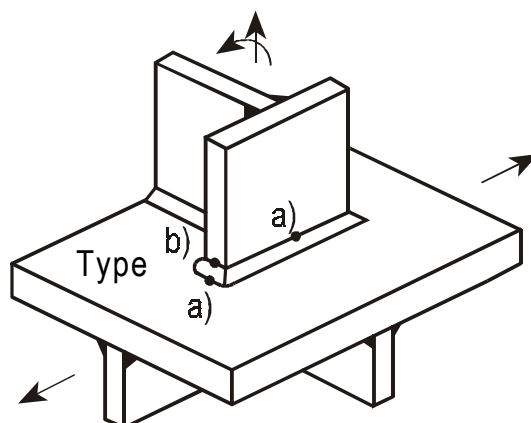


Fig. (2.2)-10: Types of Hot Spots

2.2.3.3 Determination of Structural Hot Spot Stress

Determination of structural hot spot stress can be done either by measurement or by calculation. The extrapolation procedures are nearly the same for both methods. Firstly the stresses at the reference points, i.e. extrapolation points, have to be determined, secondly the structural hot spot stress has to be determined by extrapolation.

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

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

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

2.2.3.4 Calculation of Structural Hot Spot Stress

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

Usually, structural hot spot stress is calculated on the basis of an idealized, perfectly aligned welded joint. Consequently, any possible misalignment has to be taken explicitly into consideration by the FEA model or by an appropriate stress magnification factor k_m ,

see also 3.8.2. This applies particularly to butt welds, cruciform joints and transverse fillet welds at free, unsupported plates.

The extent of the finite element model has to be chosen such that boundary effects on the structural detail considered are sufficiently small and reasonable boundary conditions can be formulated.

Models with thin plate or shell elements or alternatively with solid elements may be used. It should be noted that on the one hand the arrangement and the type of the elements have to allow for steep stress gradients as well as for the formation of plate bending, and on the other hand, only the linear stress distribution in the plate thickness direction needs to be evaluated with respect to the definition of the structural hot spot stress. The stresses should be determined at the specified reference points.

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

In a **plate or shell element** model (Fig. (2.2)-11), the elements have to be arranged in the mid-plane of the structural components. 8-noded elements are recommended particularly in case of steep stress gradients. In simplified models, the welds are not modelled, except for cases where the results are affected by local bending, e. g. due to an offset between plates or due to the small distance between adjacent welds. Here, the welds may be included by vertical or inclined plate elements having appropriate stiffness or by introducing constraint equations or rigid links to couple node displacements.

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

The **element lengths** are determined by the reference points for the subsequent extrapolation. In order to avoid an influence of the stress singularity, the stress closest to the hot spot is usually evaluated at the first or second nodal point. Therefore, the length of the element at the hot spot has to correspond at least to its distance from the first reference point. Coarser meshes are possible with higher-order elements and fixed lengths, as further explained below.

Appropriate element widths are important particularly in cases with steep stress gradients. The width of the solid element or the two shell elements in front of the attachment should not exceed the attachment width ' w ', i. e. the attachment thickness plus two weld leg

lengths. See also figure (2.2)-10.

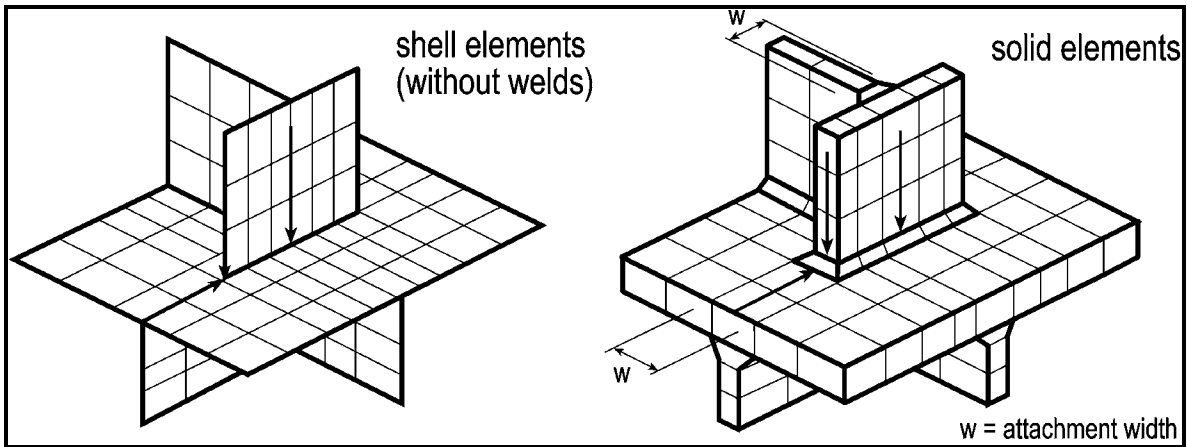


Fig. (2.2)-11: Typical meshes and stress evaluation paths for a welded detail

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

Type “a” hot spots:

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

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

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

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

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

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

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

Type “b” hot spots:

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

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

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

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

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

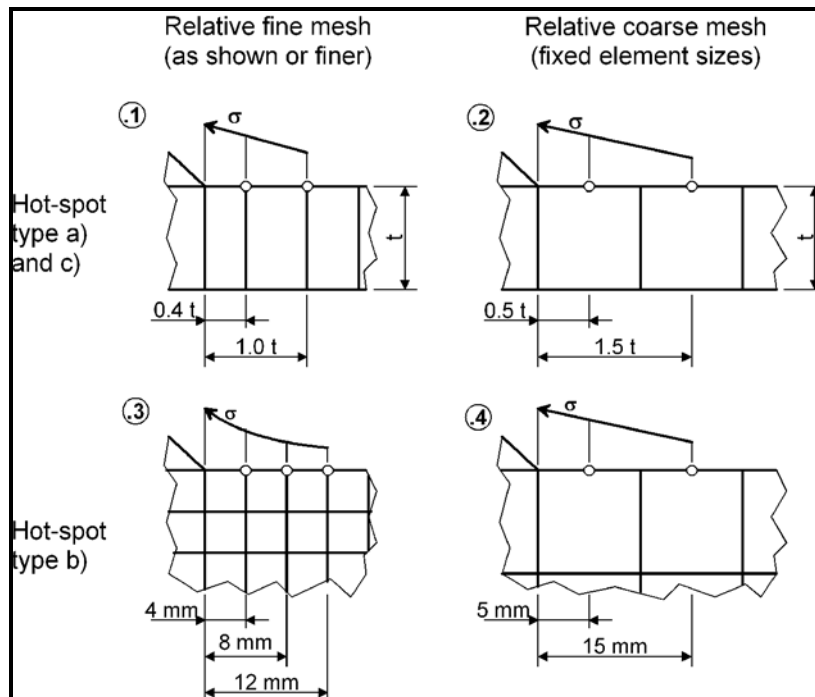


Fig. (2.2)-12: Reference points at different types of meshing

2.2.3.5 Measurement of Structural Hot Spot Stress

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

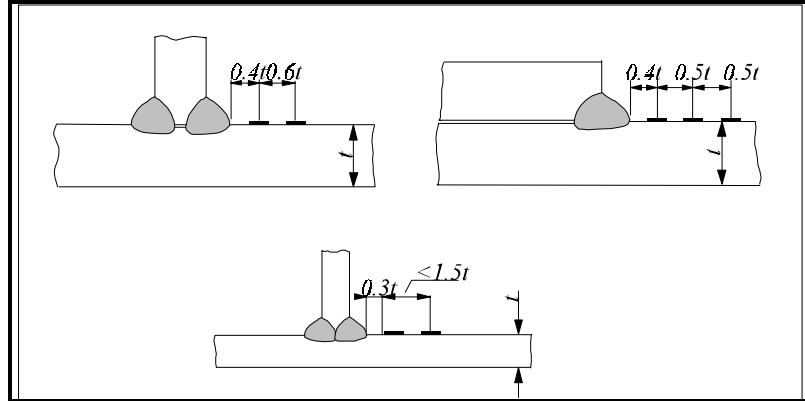


Fig. (2.2)-13: Examples of strain gauges in plate structures

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

Type “a” hot spots:

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

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

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

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

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

Type “b” hot spots:

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

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

Tubular joints:

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

Determination of stress:

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

$$\sigma_{hs} = E \cdot \epsilon_{hs} \quad (9)$$

At biaxial stress states, the actual stress may be up to 10% higher than obtained from eqn. (3). In this case, use of rosette strain gauges is recommended. If FEA results are available giving the ratio between longitudinal and transverse strains ϵ_y/ϵ_x , the structural hot spot stress σ_{hs} can then be resolved from eqn. (10), assuming that this principal stress is about perpendicular to the weld toe.

$$\sigma_{hs} = E \cdot \epsilon_x \frac{1 + \nu \frac{\epsilon_y}{\epsilon_x}}{1 - \nu^2} \quad (10)$$

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

2.2.3.6 Structural Hot Spot Stress Concentration Factors and Parametric Formulae

For many joints between circular section tubes parametric formulae have been established for the stress concentration factor k_{hs} in terms of structural stress at the critical points (hot spots). Hence the structural hot spot stress σ_{hs} becomes:

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

where σ_{nom} is the nominal axial membrane stress in the braces, calculated by elementary stress analysis.

2.2.4 Effective Notch Stress

2.2.4.1 General

Effective notch stress is the total stress at the root of a notch, obtained assuming linear-elastic material behaviour. To take account of the statistical nature and scatter of weld shape parameters, as well as of the non-linear material behaviour at the notch root, the real weld contour is replaced by an effective one. For structural steels 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 common fatigue resistance curve.

The method is restricted to welded joints which are expected to fail from the weld toe or weld root. Other causes of fatigue failure, e.g. from surface roughness or embedded defects, are not covered. Also it is also not applicable where considerable stress components parallel to the weld or parallel to the root gap exist.

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

In cases where a mean geometrical notch root radius can be defined, e.g. after certain post weld improvement procedures, this geometrical radius plus 1 mm may be used in the effective notch stress analysis.

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

Note:

The method does not consider benign effects of welding residual stresses, as widely observed at fillet welds roots which are not stress relieved. The results may be conservative in comparison with nominal stress fatigue data which consider these residual stresses by definition.

Discussion: Should this note be given ???

2.2.4.2 Calculation of Effective Notch Stress

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

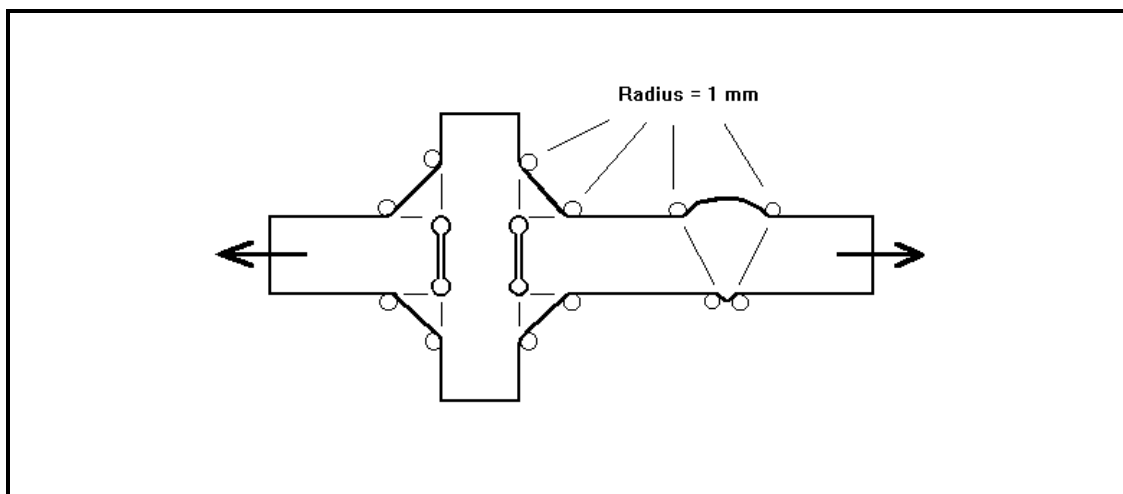


Fig. (2.2)-12 Effective notch stress concentration factors

Possible misalignment has to be considered in the calculations.

2.2.4.3 Measurement of Effective Notch Stress

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

2.2.5 Stress Intensity Factors

2.2.5.1 General

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

The parameter which describes the fatigue action at a crack tip in terms of crack propagation is the stress intensity factor (SIF) range ΔK .

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

2.2.5.2 Calculation of Stress Intensity Factors by Parametric Formulae

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

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

where

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

The correction functions Y_{mem} and Y_{ben} can be found in the literature. The solutions in ref. [14-16] 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 [19] and [20].

2.2.5.3 Calculation of Stress Intensity Factors by Finite Elements

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

2.3 STRESS HISTORY

2.3.1 General

The fatigue design data presented in chapter 3 were obtained from tests performed under constant amplitude loading. However, loads and the resulting fatigue actions (i.e. stresses) on real structures usually fluctuate in an irregular manner and give rise to variable amplitude loading. The stress amplitude may vary in both magnitude and periode from cycle to cycle. Because the physical phenomena implied in fatigue are not chaotic but random, the fluctuations can be characterized by mathematical functions and by a limited number of parameters.

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

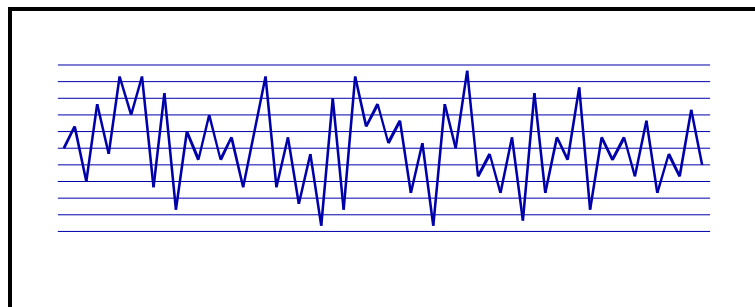


Fig. (2.3)-1 Stress time history illustration

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

A stress history may be given as

- a) a record of successive maxima and minima of stress measured in a comparable structure with comparable loading and service life, or a typical sequence of load events.
- b) a two dimensional transition matrix of the stress history derived from a).
- c) a one- or two-dimensional stress range histogram (stress range occurrences) obtained from a) by a specified counting method.

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

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

2.3.2 Cycle Counting Methods

Cycle counting is the process of converting a variable amplitude stress sequence into equivalent (in terms of fatigue damage) constant amplitude stress cycles. Different methods of counting are in use, e.g. zero crossing counting, peak counting, range pair counting or rainflow counting. For welded components, the reservoir or rainflow method is recommended for counting stress ranges [26 and 27].

2.3.3 Cumulative Frequency Diagram (Stress Spectrum)

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

The spectrum may be discretized giving a table of discrete blocks. For damage calculations 20 stress levels are recommended if more than 10^8 cycles are expected. Below this number of cycles, 8 or 10 stress levels may be sufficient. All cycles in a block should be assumed to be equal to the mean of the stress ranges in the block.

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

Tab. {2.3}-1: Stress range occurrence table (stress histogram or frequency)

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

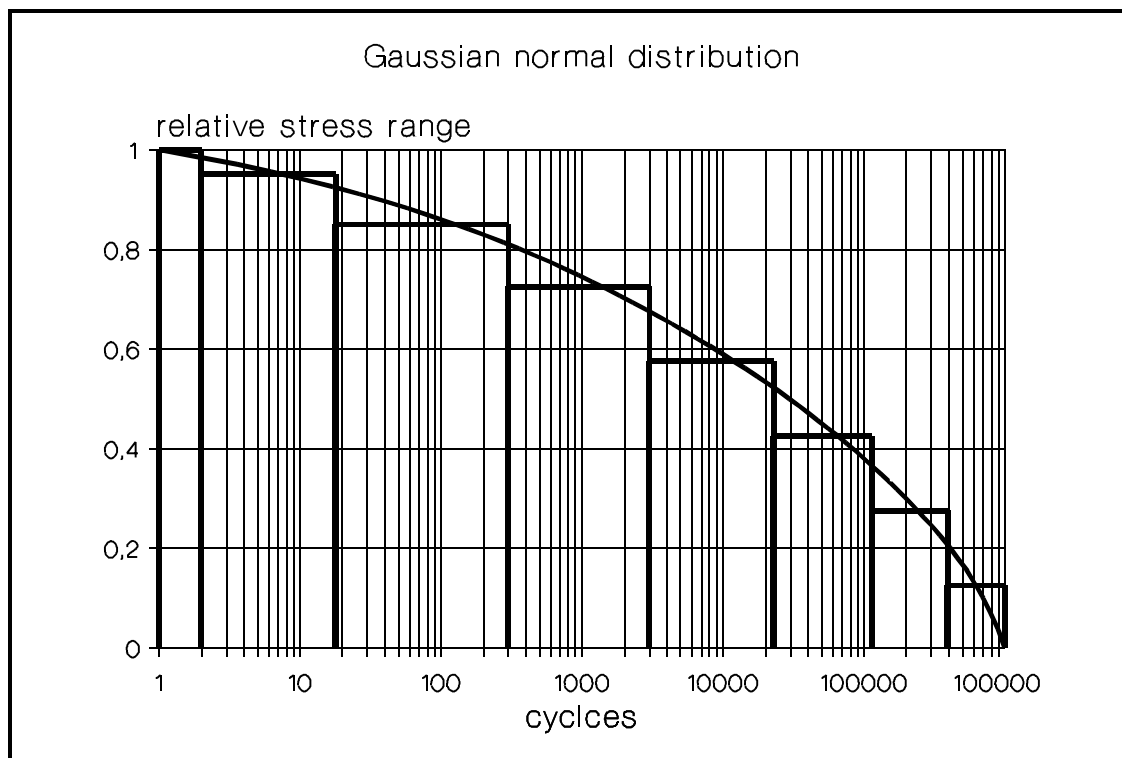


Fig. (2.3)-2 Cumulative frequency diagram (stress spectrum)

3 FATIGUE RESISTANCE

3.1 BASIC PRINCIPLES

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

The fatigue resistance data must be expressed in terms of the same stress as that controlled or determined during the generation of those data.

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

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

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

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

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. 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 $1.5 \cdot f_y$ for nominal normal stresses or $1.5 \cdot f_y/\sqrt{3}$ for nominal shear stresses.

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

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

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

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

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

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

The slope of the fatigue strength curves for details assessed on the basis of normal stresses (fig. (3.2)-1) is **m=3.00**. The constant amplitude fatigue limit is **5 · 10⁶ cycles**. The slope of the fatigue strength curves for details assessed on the basis of shear stresses (fig. (3.2)-2) is **m=5.00**, but in this case the fatigue limit corresponds to an endurance of **10⁸ cycles**.

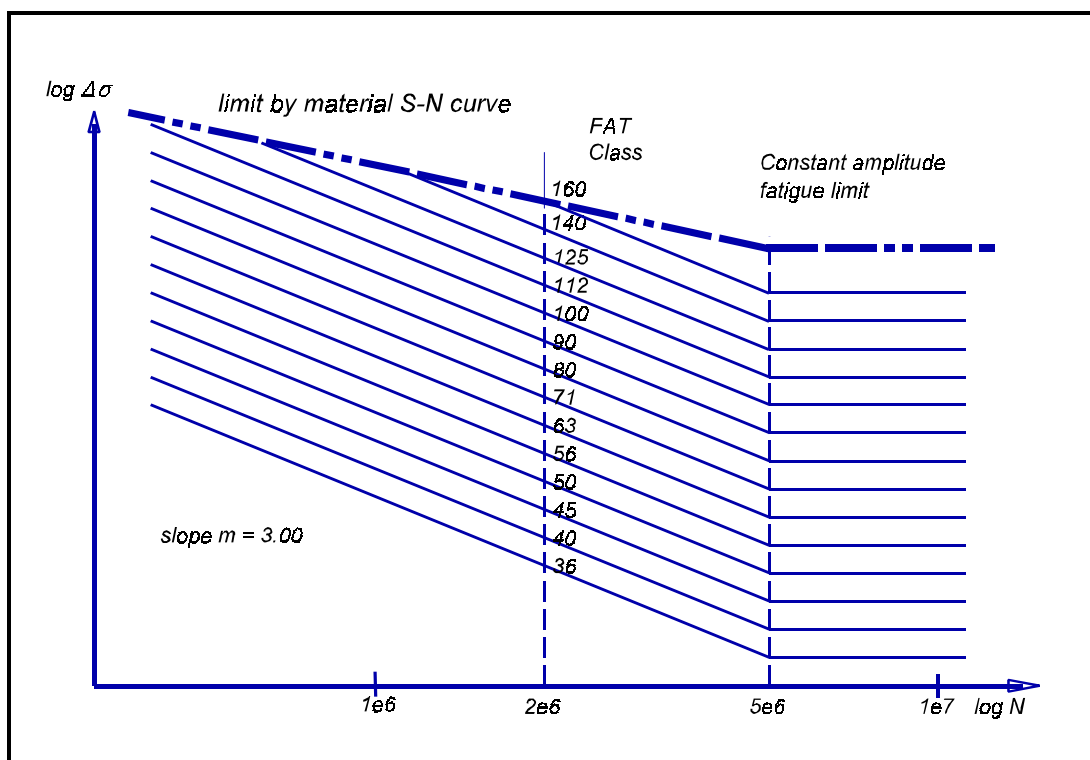


Fig. (3.2)-1: Fatigue resistance S-N curves for $m=3.00$, normal stress (steel)

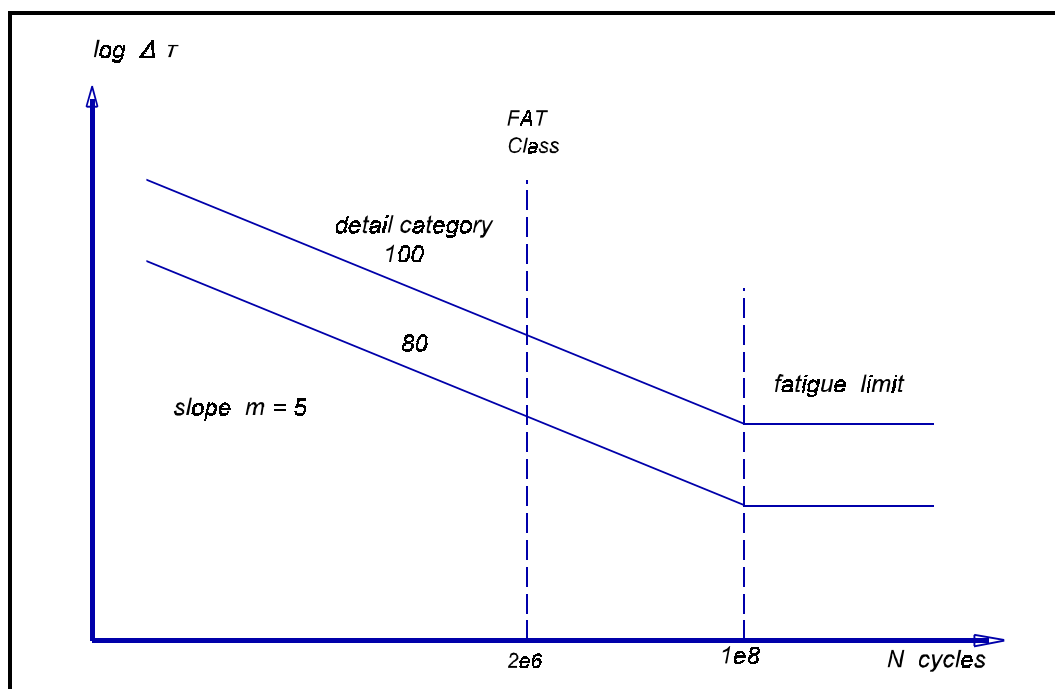


Fig. (3.2)-2 Fatigue resistance S-N curves for shear stress (steel)

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, modifications may be necessary as given in 3.5 and 3.8 . All butt welds shall be full penetration welds without lack of fusion, unless otherwise stated.

All S-N curves of details are limited by the material S-N curve, which may vary due to different strengths of the materials.

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

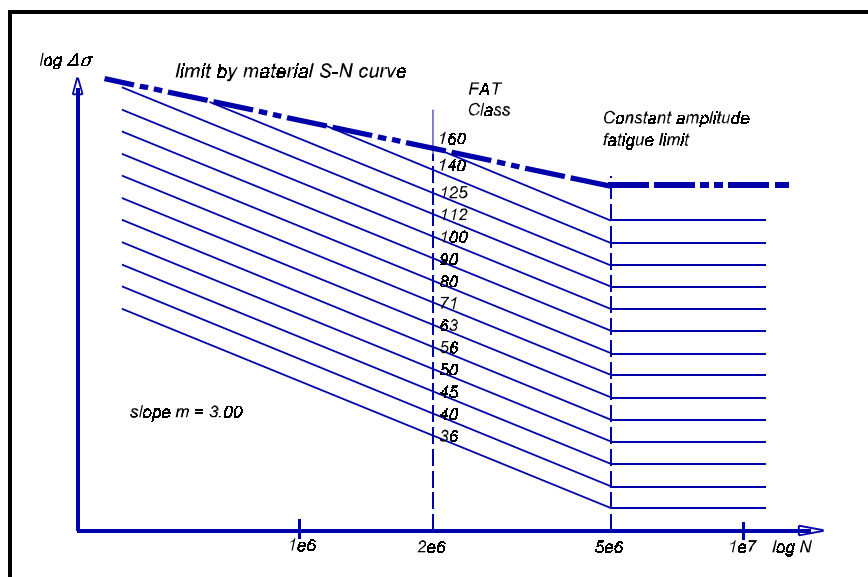


Fig. (3.2)-3: Fatigue resistance S-N curves for $m=3.00$, normal stress (steel)

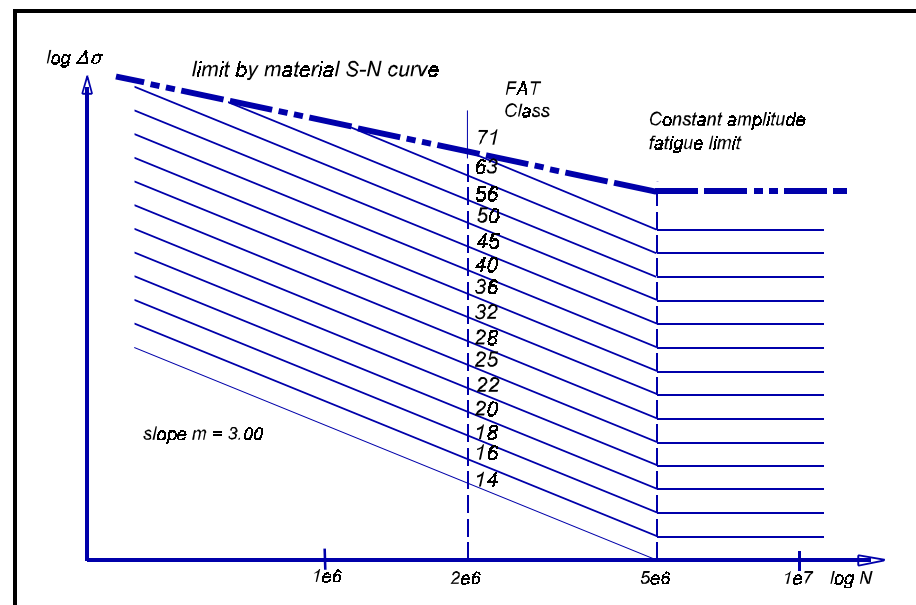
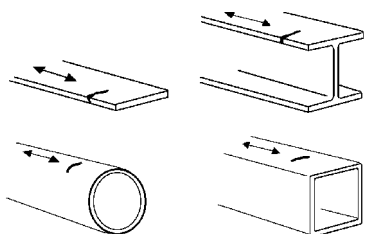
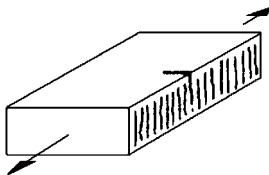
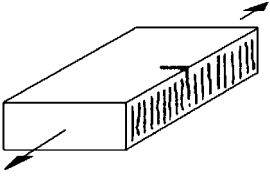


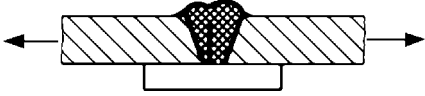
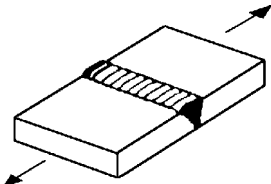
Fig. (3.2)-4 Fatigue resistance curves for aluminium (normal stress)

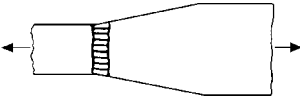
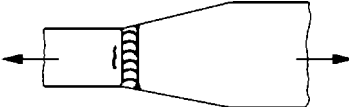
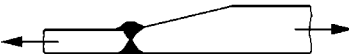
Tab. {3.2}-1: Fatigue resistance values for structural details in steel and aluminium assessed on the basis of nominal stresses.

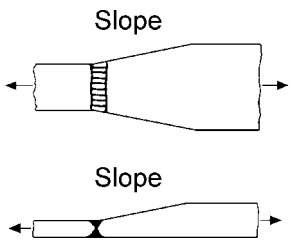
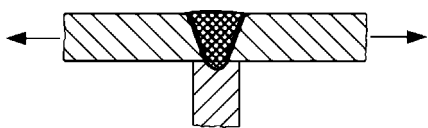
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
100	Unwelded parts of a component				
111		Rolled or extruded products, components with machined edges, seamless hollow sections. $m = 5$ St.: For high strength steels a higher FAT class may be used if verified by test. Al.: AA 5000/6000 alloys AA 7000 alloys	160	70 80	No fatigue resistance of any detail to be higher at any number of cycles! Sharp edges, surface and rolling flaws to be removed by grinding. Any machining lines or groves to be parallel to stresses! For high strength steels a higher FAT class may be used if verified by test.
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! Notcheffects due to shape of edges have to be considered.

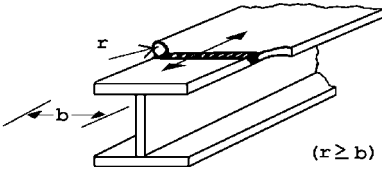
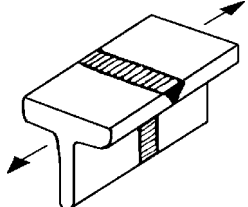
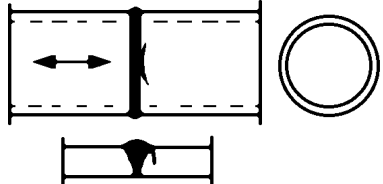
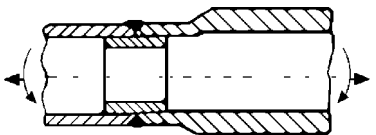
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
122		Machine thermally cut edges, corners removed, no cracks by inspection $m = 3$	125	40	Notcheffects due to shape of edges have to be considered.
123		Manually thermally cut edges, free from cracks and severe notches $m = 3$	100	---	Notcheffects due to shape of edges have to be considered.
124		Manually thermally cut edges, uncontrolled, no notch deeper than .5 mm $m = 3$	80	---	Notcheffects due to shape of edges have to be considered.
200	Butt welds, transverse loaded				

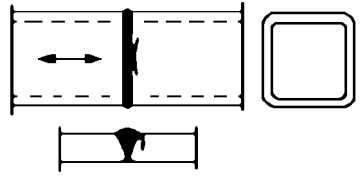
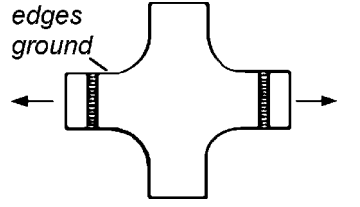
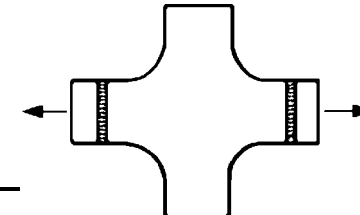
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
211		Transverse loaded butt weld (X-groove or V-groove) ground flush to plate, 100% NDT	125	50	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides.
212		Transverse butt weld made in shop in flat position, toe angle $\leq 30^\circ$, NDT	100	40	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignment $<10\%$
213		Transverse butt weld not satisfying conditions of 212, NDT Al.: Butt weld with toe angle $\leq 50^\circ$ Butt welds with toe angle $>50^\circ$	80	32 25	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignment $<10\%$

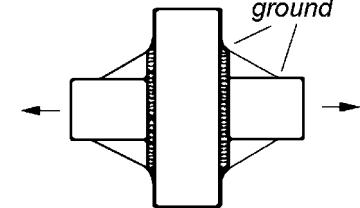
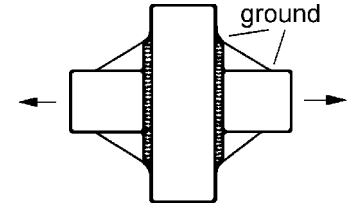
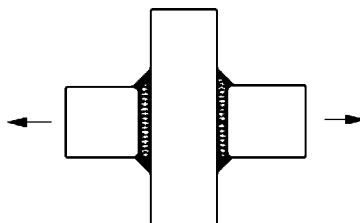
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
214		Transverse butt weld, welded on ceramic backing, root crack	80	---	Backing removed, root visually inspected. Arc welds: Misalignment <10% Laser beam welds: Misalignment < 5%
215		Transverse butt weld on permanent backing bar terminating >10 mm from plate edge, else	71 63	25	Arc welds: Misalignment <10% Laser beam welds: Misalignment < 5%
216		Transverse butt welds welded from one side without backing bar, full penetration root controlled by NDT no NDT	71 45	28 18	Arc welds: Misalignment <10% Laser beam welds: Misalignment < 5%

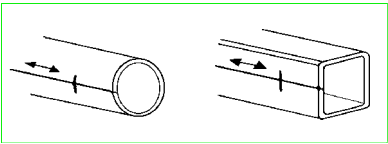
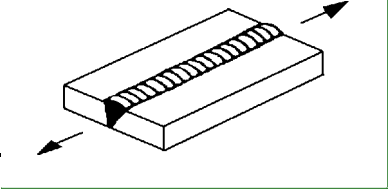
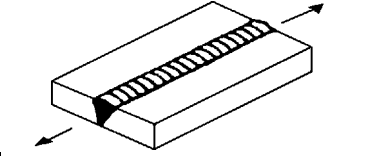
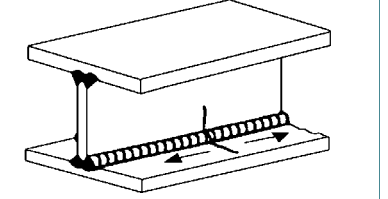
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
217		Transverse partial penetration butt weld, analysis based on stress in weld throat sectional area, weld overfill not to be taken into account.	45	16	The detail is not recommended for fatigue loaded members. Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see chapter 5) or by downgrading up to 2 FAT classes, e.g FAT 36 at steel and FAT 14 at aluminium
221	Slope  Slope 	Transverse butt weld ground flush, NDT, with transition in thickness and width slope 1:5 slope 1:3 slope 1:2	125 100 80	40 32 25	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Arc welds: Misalignment <10% Laser beam welds: Misalignment < 5% Exceeding misalignments to be considered, see chapter 3.8.2
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	100 90 80	32 28 25	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Arc welds: Misalignment <10% Laser beam welds: Misalignment < 5% Exceeding misalignments to be considered, see chapter 3.8.2

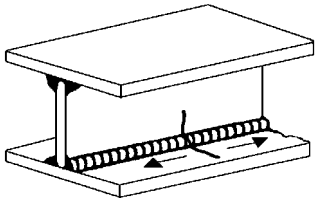
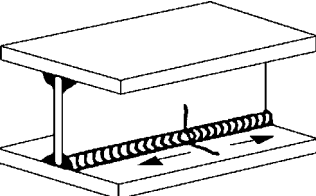
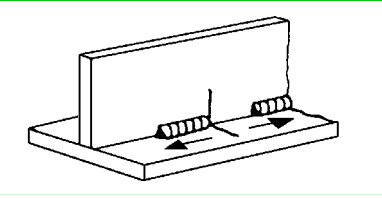
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
223		Transverse butt weld, NDT, with transition on thickness and width slope 1:5 slope 1:3 slope 1:2	80 71	25 22	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Arc welds: Misalignment <10% Laser beam welds: Misalignment < 5% Exceeding misalignments to be considered, see chapter 3.8.2
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 smaller plate thickness
225		Three plate connection, root crack	71	22	Arc welds: Misalignment <10% Laser beam welds: Misalignment < 5%

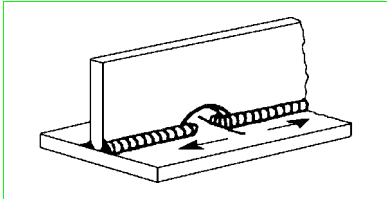
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
226		Transverse butt weld flange splice in built-up section welded prior to the assembly, ground flush, with radius transition, NDT	112	45	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress.
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 to be ground flush in direction of stress.
232		Transverse butt weld splice in circular hollow section, welded from one side, full penetration, root inspected by NDT no NDT	71 45	28 18	Welded in flat position. Weld toe angle <30°. discussion: one step higher because of tube???
233		Tubular joint with permanent backing	71	28	Welded in flat position. Weld toe angle <30°

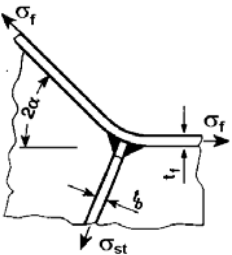
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
234		Transverse butt weld splice in rectangular hollow section, welded from one side, full penetration, root inspected by NDT no NDT	56 45	25 14	Welded in flat position. Weld toe angle <30°
241		Transverse butt weld ground flush, weld ends and radius ground, 100% NDT at crossing flanges, radius transition.	125	50	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignment <10%
242		Transverse butt weld made in shop at flat position, weld profile controlled, NDT, at crossing flanges, radius transition	100	40	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignment <10%

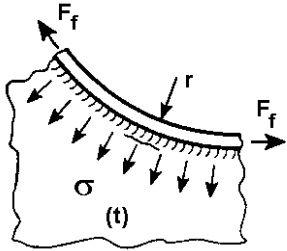
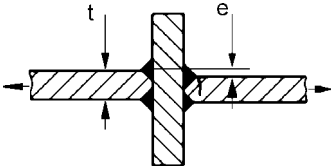
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
243		Transverse butt weld ground flush, NDT, at crossing flanges with welded triangular transition plates, weld ends ground. Crack starting at butt weld. For crack of throughgoing flange see details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

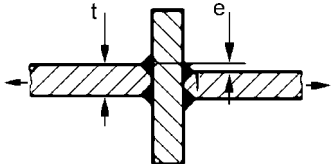
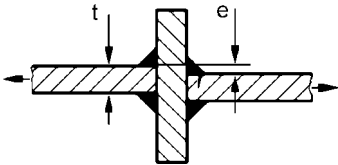
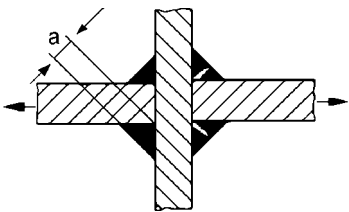
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
311		Automatic longitudinal seam welds without stop/start positions in hollow sections with stop/start positions	125 90	50 36	
312		Longitudinal butt weld, both sides ground flush parallel to load direction, 100% NDT	125	50	
313		Longitudinal butt weld, without stop/start positions, NDT with stop/start positions	125 90	50 36	
321		Continuous automatic longitudinal fully penetrated K-butt weld without stop/start positions (based on stress range in flange) NDT	125	50	No start-Stop position is permitted except when the repair is performed by a specialist and inspection is carried out to verify the proper execution of the weld. A very good fit between flange and web plates is essential.

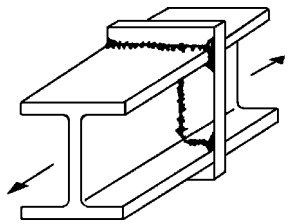
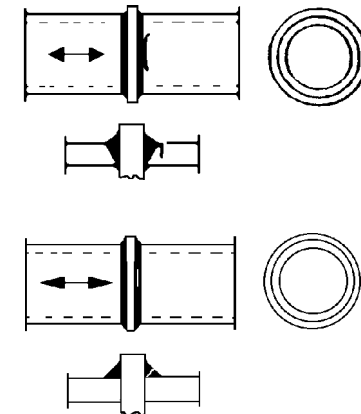
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
322		Continuous automatic longitudinal double sided fillet weld without stop/start positions (based on stress range in flange)	100	40	A very good fit between flange and web plates is essential.
323		Continuous manual longitudinal fillet or butt weld (based on stress range in flange)	90	36	A very good fit between flange and web plates is essential.
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 $80 \cdot \left(1 - \frac{\Delta \tau}{\Delta \sigma}\right)$ but ≥ 36 alum. $36 \cdot \left(1 - \frac{\Delta \tau}{\Delta \sigma}\right)$ but ≥ 14

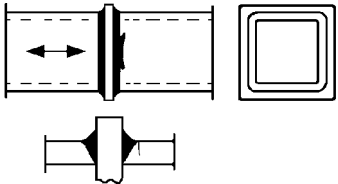
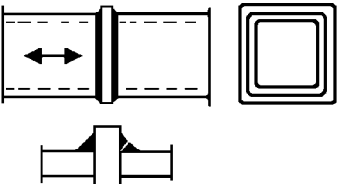
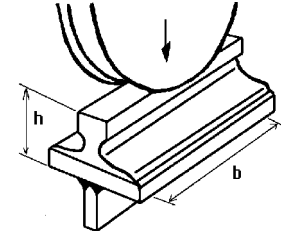
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks																					
325		Longitudinal butt weld, fillet weld or intermittent weld with cope holes (based on normal stress in flange σ and shear stress in web τ at weld ends), cope holes not higher than 40% of web. $\tau/\sigma =$ <table><tr><td>0</td><td>71</td><td>28</td></tr><tr><td>0.0 - 0.2</td><td>63</td><td>25</td></tr><tr><td>0.2 - 0.3</td><td>56</td><td>22</td></tr><tr><td>0.3 - 0.4</td><td>50</td><td>20</td></tr><tr><td>0.4 - 0.5</td><td>45</td><td>18</td></tr><tr><td>0.5 - 0.6</td><td>40</td><td>16</td></tr><tr><td>> 0.6</td><td>36</td><td>14</td></tr></table>	0	71	28	0.0 - 0.2	63	25	0.2 - 0.3	56	22	0.3 - 0.4	50	20	0.4 - 0.5	45	18	0.5 - 0.6	40	16	> 0.6	36	14			Analysis based on normal stress in flange and shear stress in web at weld ends. representation by formula?? steel $80 \cdot \left(1 - \frac{\Delta \tau}{\Delta \sigma}\right)$ but ≥ 36 alum. $36 \cdot \left(1 - \frac{\Delta \tau}{\Delta \sigma}\right)$ but ≥ 14
0	71	28																								
0.0 - 0.2	63	25																								
0.2 - 0.3	56	22																								
0.3 - 0.4	50	20																								
0.4 - 0.5	45	18																								
0.5 - 0.6	40	16																								
> 0.6	36	14																								

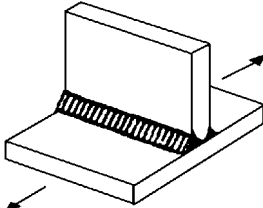
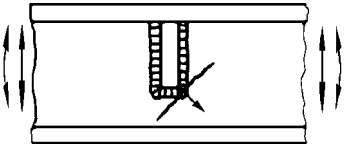
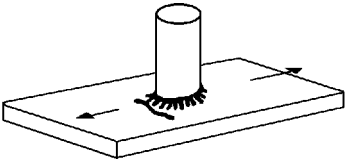
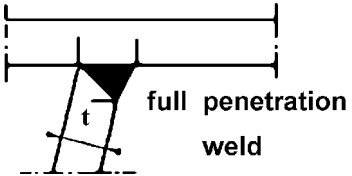
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
331		Joint at stiffened knuckle of a flange to be assessed according to no. 411 - 414, depending on type of joint. Stress in stiffener plate: $\sigma = \sigma_f \cdot \frac{A_f}{\sum A_{st}} \cdot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

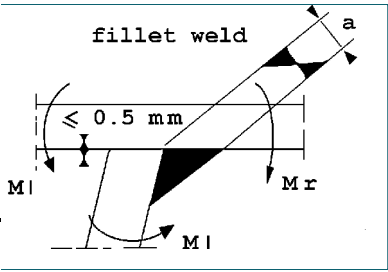
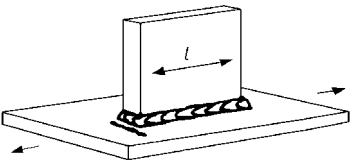
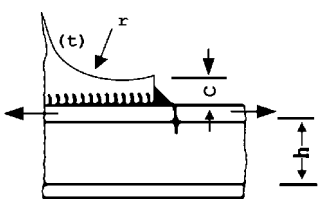
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
332		Unstiffened curved flange to web joint, to be assessed according to no. 411 - 414, depending on type of joint. Stress in web plate: $\sigma = \frac{F_g}{r \cdot t}$ Stress in weld throat: $\sigma_w = \frac{F_f}{r \cdot \sum a}$ 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 longitudinally to the weld is to be considered. At additional shear, principle stress in web is to be considered (see 321 to 323)
400	Cruciform joints and/or T-joints				
411		Cruciform joint or T-joint, K-butt welds, full penetration, no lamellar tearing, misalignment $e < 0.15 \cdot t$, weld toes ground, toe crack	80	28	Material quality of intermediate plate has to be checked against susceptibility of lamellar tearing. Misalignment $< 15\%$ of primary plate.

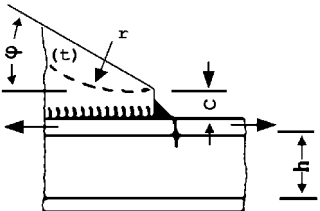
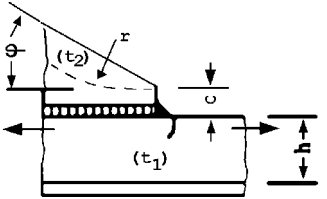
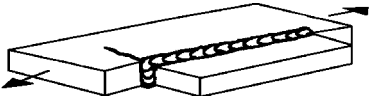
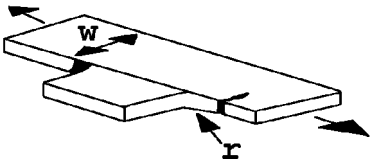
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
412		Cruciform joint or T-joint, K-butt welds, full penetration, no lamellar tearing, misalignment $e < 0.15t$, toe crack	71	25	Material quality of intermediate plate has to be checked against susceptibility of lamellar tearing. Misalignment <15% of primary plate.
413		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds, no lamellar tearing, misalignment $e < 0.15t$, toe crack	63	22	Material quality of intermediate plate has to be checked against susceptibility of lamellar tearing. Misalignment <15% of primary plate.
414		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds including toe ground joints, weld root crack. Analysis based on stress in weld throat.	45	16	Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see chapter 5) or by downgrading up to 2 FAT classes, e.g FAT 36 at steel and FAT 14 at aluminium.
414b	picture needed!	Cruciform joint or T-joint, single-sided arc or laser beam welded V-butt weld, full penetration, no lamellar tearing, misalignment $e < 0.15t$, toe crack. Root inspected Root not inspected, root crack	71 45	25 16	Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see chapter 5) or by downgrading up to 2 FAT classes, e.g FAT 36 at steel and FAT 14 at aluminium.

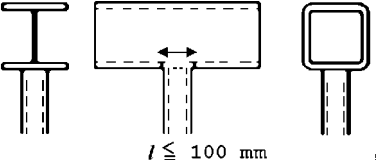
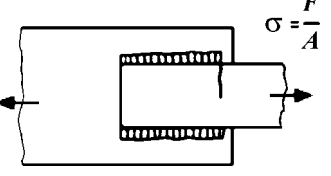
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
421		Splice of rolled section with intermediate plate, fillet welds, weld root crack. Analysis base on stress in weld throat.	45	16	Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see chapter 5) or by downgrading down to 2 FAT classes, e.g FAT 36
422		Splice of circular hollow section with intermediate plate, singlesided butt weld, toe crack wall thickness > 8 mm wall thickness < 8 mm	56 50	22 20	Welds NDT inspected in order to ensure full root penetration.
423		Splice of circular hollow section with intermediate plate, fillet weld, root crack. Analysis based on stress in weld throat. wall thickness > 8 mm wall thickness < 8 mm	45 40	16 14	

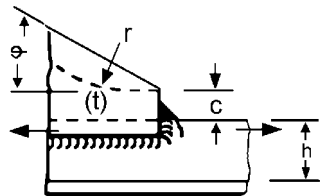
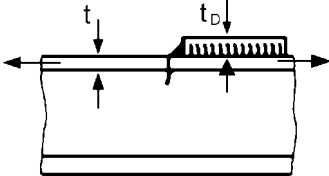
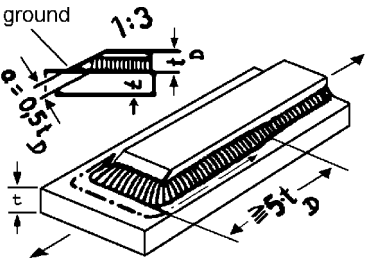
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
424		Splice of rectangular hollow section, single-sided butt weld, toe crack wall thickness > 8 mm wall thickness < 8 mm	50 45	20 18	Welds NDT inspected in order to ensure full root penetration.
425		Splice of rectangular hollow section with intermediate plate, fillet welds, root crack wall thickness > 8 mm wall thickness < 8 mm	40 36	16 14	
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.	---	---	Full penetration butt weld.
500	Non-load-carrying attachments				

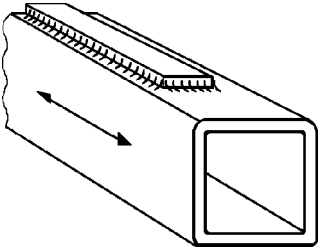
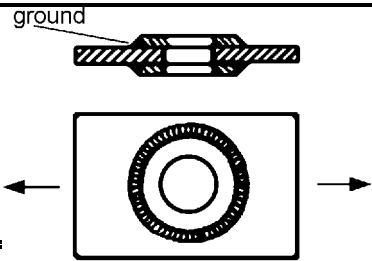
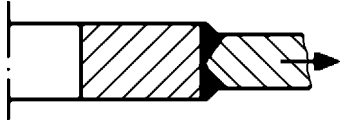
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
511		Transverse non-load-carrying attachment, not thicker than main plate K-butt weld, toe ground Two-sided fillets, toe ground Fillet weld(s), as welded thicker than main plate	100 100 80 71	36 36 28 25	Grinding parallel to stress At one sided fillet welds, 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	For weld ends on web principle stress to be used
513		Non-load-carrying stud as welded	80	28	
514		Trapezoidal stiffener to deck plate, full penetration butt weld, calculated on basis of stiffener thickness, out of plane bending	71	25	

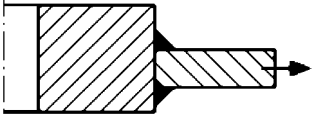
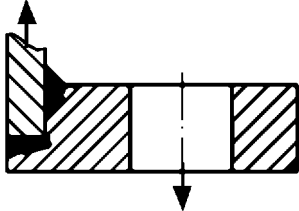
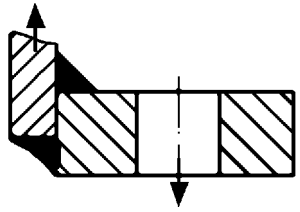
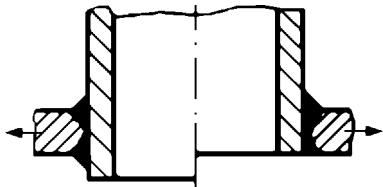
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
515		Trapezoidal stiffener to deck plate, fillet or partial penetration weld, calculated on basis of stiffener thickness and weld throat, whichever is smaller	45	16	
521		Longitudinal fillet welded gusset at length l $l < 50 \text{ mm}$ $l < 150 \text{ mm}$ $l < 300 \text{ mm}$ $l > 300 \text{ mm}$	80 71 63 50	28 25 20 18	For gusset near edge: see 525 "flat side gusset" If attachment thickness $< 1/2$ of base plate thickness, then one step higher allowed (not for welded on profiles!)
522		Longitudinal fillet welded gusset with radius transition, end of fillet weld reinforced and ground, $c < 2 t$, max 25 mm $r > 150 \text{ mm}$	90	32	t = thickness of attachment

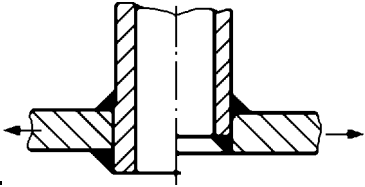
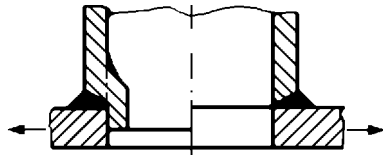
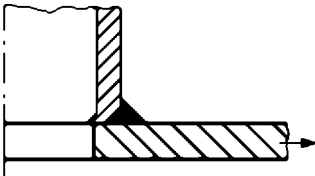
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
523		Longitudinal fillet welded gusset with smooth transition (sniped end or radius) welded on beam flange or plate. $c < 2t$, max 25 mm $r > 0.5h$ $r < 0.5h$ or $\varphi < 20^\circ$	71 63	25 20	t = thickness of attachment If attachment thickness $< 1/2$ of base plate thickness, then one step higher allowed (not for welded on profiles!)
524		Longitudinal flat side gusset welded on plate edge or beam flange edge, with smooth transition (sniped end or radius). $c < 2t_2$, max. 25 mm $r > 0.5h$ $r < 0.5h$ or $\varphi < 20^\circ$	50 45	18 16	t = thickness of attachment For $t_2 < 0.7 t_1$, FAT rises 12%
525		Longitudinal flat side gusset welded on plate or beam flange edge, gusset length l: $l < 150 \text{ mm}$ $l < 300 \text{ mm}$ $l > 300 \text{ mm}$	50 45 40	18 16 14	For $t_2 < 0.7 t_1$, FAT rises 12%
526		Longitudinal flat side gusset welded on edge of plate or beam flange, radius transition ground. $r > 150$ or $r/w > 1/3$ $1/6 < r/w < 1/3$ $r/w < 1/6$	90 71 50	36 28 22	Smooth transition radius formed by grinding the weld area in transition in order to remove the weld toe completely. Grinding parallel to stress.

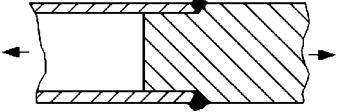
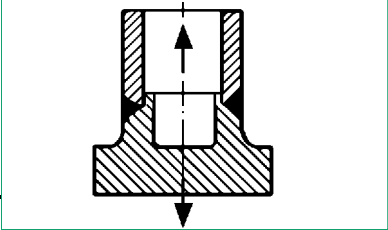
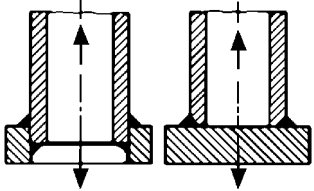
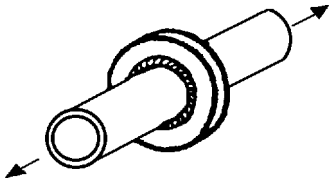
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
531	 $l \leq 100 \text{ mm}$	Circular or rectangular hollow section, fillet welded to another section. Section width parallel to stress direction < 100 mm, else like longitudinal attachment	71	28	Non load-carrying welds. Width parallel to stress direction < 100 mm.
600	Lap joints				
611		Transverse loaded lap joint with fillet welds Fatigue of parent metal Fatigue of weld throat Stress ratio must be $0 < R < 1$!	63 45	22 16	Stresses to be calculated in the main plate using a plate width equalling the weld length. Root crack of welds to be verified separately as detail 712.
612	 $\sigma = \frac{F}{A}$	Longitudinally loaded lap joint with side fillet welds Fatigue of parent metal Fatigue of weld (calc. on max. weld length of 40 times the throat of the weld)	50 50	18 18	Weld terminations more than 10 mm from plate edge.

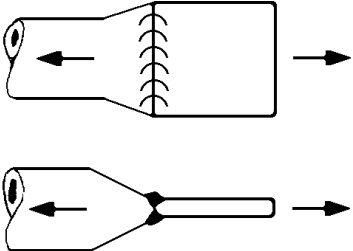
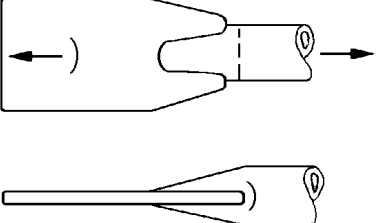
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
613		Lap joint gusset, fillet welded, non-load-carrying, with smooth transition (sniped end with $\phi < 20^\circ$ or radius), welded to loaded element $c < 2 \cdot t$, but $c \leq 25$ mm to flat bar to bulb section to angle section	63 56 50	22 20 18	t = thickness of gusset plate
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 frontal welds. If the cover plate is wider than the flange, a frontal weld is needed. No undercut at frontal welds!
712		End of long doubling plate on beam, reinforced welded ends ground (based on stress range in flange at weld toe) $t_D \leq 0.8 t$ $0.8 t < t_D \leq 1.5 t$ $t_D > 1.5 t$	71 63 56	28 25 22	Grinding parallel to stress direction.

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
721		End of reinforcement plate on rectangular hollow section. wall thickness: $t < 25 \text{ mm}$	50	20	No undercut at frontal weld!
731		Reinforcements welded on with fillet welds, toe ground Toe as welded Analysis based on modified nominal stress	80 71	32 25	Grinding in direction of stress!
800	Flanges, branches and nozzles				
811		Stiff block flange, full penetration weld	71	25	

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
812		Stiff block flange, partial penetration or fillet weld toe crack in plate root crack in weld throat	63 45	22 16	Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see chapter 5) or by downgrading down to 2 FAT classes, e.g FAT 36 at steel and FAT 14 at aluminium
821		Flat flange with > 80% full penetration butt welds, modified nominal stress in pipe, toe crack	71	25	
822		Flat flange with fillet welds, modified nominal stress in pipe, toe crack.	63	22	
831		Tubular branch or pipe penetrating a plate, K-butt welds. If diameter > 50 mm, stress concen- tration of cutout has to be considered	80	28	

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
832		Tubular branch or pipe penetrating a plate, fillet welds. If diameter > 50 mm, stress concentration of cutout has to be considered	71	25	Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see chapter 5) or by downgrading down to 2 FAT classes.
841		Nozzle welded on plate, root pass removed by drilling. If diameter > 50 mm, stress concentration of cutout has to be considered	71	25	
842		Nozzle welded on pipe, root pass as welded. If diameter > 50 mm, stress concentration of cutout has to be considered	63	22	
900	Tubular joints				

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
911		Circular hollow section butt joint to massive bar, as welded	63	22	Root of weld has to penetrate into the massive bar in order to avoid a gap perpendicular to the stress direction.
912		Circular hollow section welded to component with single side butt weld, backing provided. Root crack.	63	22	Root of weld has to penetrate into the backing area in order to avoid a gap perpendicular to the stress direction.
913		Circular hollow section welded to component single sided butt weld or double fillet welds. Root crack.	50	18	Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see chapter 5) or by downgrading down to 2 FAT classes.
921		Circular hollow section with welded on disk K-butt weld, toe ground Fillet weld, toe ground Fillet welds, as welded	90 90 71	32 32 25	Non load-carrying weld.

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	71	---	
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. xx: 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

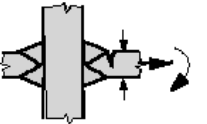
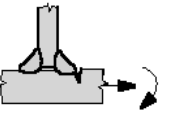
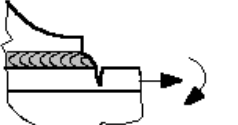
3.3 FATIGUE RESISTANCE AGAINST STRUCTURAL HOT SPOT STRESS

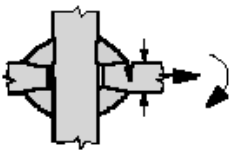
3.3.1 Fatigue Resistance using Reference S-N Curve

The S-N curves for fatigue resistance against structural hot spot stress (2.2.3) are given in the table {3.3}-1 for steel and aluminium, where the definition of the FAT class is given in chapter 3.2. The resistance values refer to the as-welded condition unless stated otherwise. The effects of welding residual stress are included. Effects of misalignment are not included.

The design value of the structural hot spot stress range shall not exceed $\Delta\sigma_{hs} < 2 \cdot f_y$.

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

No.	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
1		Butt joint, special quality	See details 1) to 3) in table 8.3, for misalignment see note below.	112	45
2		Butt joint, standard quality	See detail 7) in table 8.3, for misalignment see note below.	100	40
3		Cruciform joint with full penetration K-butt welds	Weld toe angle $\leq 60^\circ$, for misalignment see note below.	100	40
4		Non load-carrying fillet welds	Weld toe angle $\leq 60^\circ$, for misalignment see note below	100	40
5		Bracket ends, ends of longitudinal stiffeners	Weld toe angle $\leq 60^\circ$	100	40
6		Cover plate ends and similar joints	Weld toe angle $\leq 60^\circ$	100	40

No.	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
7		Cruciform joints with load-carrying fillet welds	Weld toe angle $\leq 60^\circ$, for misalignment see note below.	90	36

Note: Table does not cover effects of misalignment. They have to be considered explicitly in determination of stress

3.3.2 Fatigue Resistance Using a Reference Detail

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

- 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.
- Identify the type of stress in which the fatigue resistance is expressed. This is usually nominal stress (as in tables in chapter 3.2).
- Establish a FEM model of the reference detail and the detail to be assessed with the same type of meshing and elements following the recommendations given in 2.2.3.
- Load the reference detail and the detail to be assessed with the stress identified in b).
- 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.
- 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 AGAINST EFFECTIVE NOTCH STRESS

3.4.1 Steel

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

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

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

3.4.2 Aluminium

At present, no commonly accepted data can be given.

3.5 FATIGUE STRENGTH MODIFICATIONS

3.5.1 Stress Ratio

3.5.1.1 Steel

For stress ratios $R < 0.5$ a fatigue enhancement factor $f(R)$ may be considered by multiplying the fatigue class of classified details by $f(R)$. The fatigue enhancement factor depends on the level and direction of residual stresses. It should only be used if reliable information or estimation of the residual stress level was present. The following cases are to be distinguished:

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

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

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

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

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

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

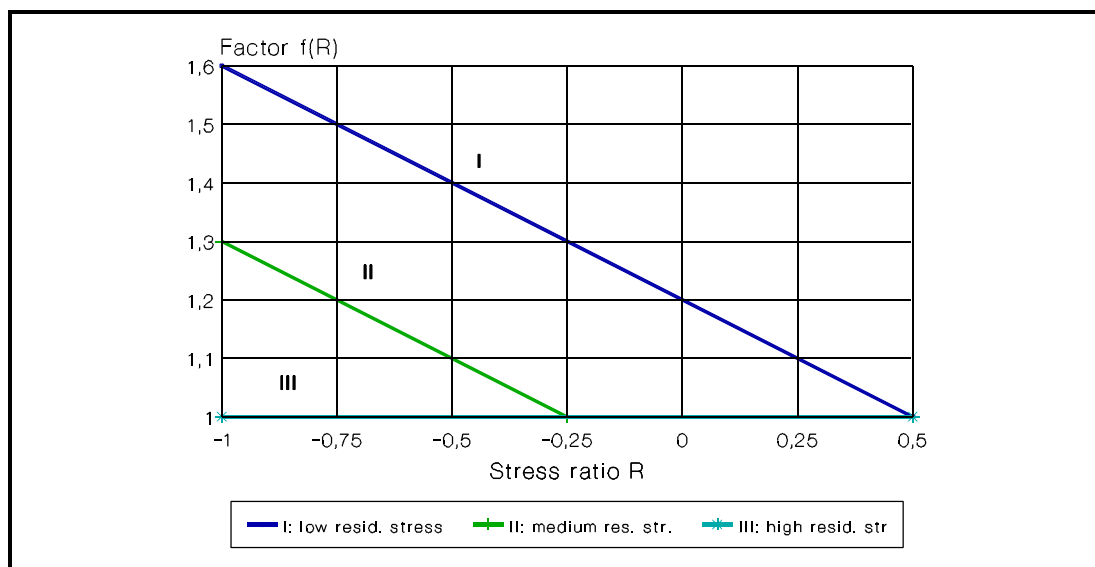


Fig. (3.5)-1 Enhancement factor $f(R)$

The ranking in categories I, II or III should be done and documented by the design office. If no reliable information on residual stress is available, $f(R)=1$.

It has to be noted in this respect that stress relief in welded joints is unlikely to be fully effective, and long range residual stresses may be introduced during assembly of pre-fabricated welded components. For such reasons, it is recommended that values of $f(R)>1$ should only be adopted for welded components in very special circumstances.

3.5.1.2 Aluminium

The same regulations as for steel are recommended.

3.5.2 Wall Thickness

3.5.2.1 Steel

The influence of plate thickness on fatigue strength should be taken into account in cases where cracks start from the weld toe on plates thicker than 25 mm. The reduced strength is taken in consideration by multiplying the fatigue class of the structural detail by the thickness reduction factor $f(t)$. The thickness correction exponent n is dependent on the effective thickness t_{eff} and the joint category (see table {3.5}-1) [21].

Tab. {3.5}-1: Thickness correction exponents

Joint category	Condition	n
----------------	-----------	-----

Cruciform joints, transverse T-joints, plates with transverse attachments	as-welded	0.3
Cruciform joints, transverse T-joints, plates with transverse attachments	toe ground	0.2
Transverse butt welds	as-welded	0.2
Butt welds ground flush, base material, longitudinal welds or attachments	any	0.1

$$f(t) = \left(\frac{25}{t_{eff}} \right)^n \quad \text{where } t > 25 \text{ mm}$$

$$\text{If } L/t \leq 2 \quad \text{then } t_{eff} = 0.5 \cdot L$$

$$\text{else } t_{eff} = t$$

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

3.5.2.2 Aluminium

The same regulations as for steel are recommended.

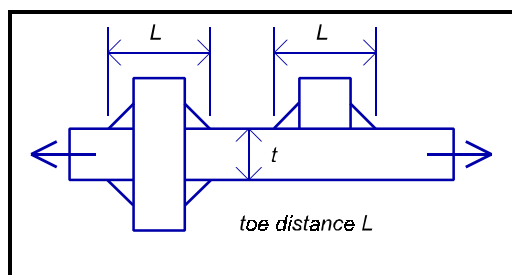


Fig. (3.5)-2 Toe distance

3.5.3 Improvement Techniques

3.5.3.1 General

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

- a) Methods of improvement of weld profile:

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

- b) Methods for improvement of residual stress conditions:

Peening (hammer-, needle-, shot- or brush-peening)
 Coining
 Overstressing

Stress relieving thermal treatment

c) Methods for improvement of environmental conditions:

Painting
Resin coating

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

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

For some post welding improvement procedures, direct recommendations are given below. They may be used in connection with repair or upgrading of existing structures, not for general use in design in order to obtain a longer fatigue life than the use of standard design S-N curves would give. The recommendations apply to nominal stress and structural hot spot stress method, they do not apply to effective notch stress and fracture mechanics method.

3.5.3.2 Applicability of Improvement Methods

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

The recommendations apply to welded joints of plates, of sections built up of plates or similar rolled or extruded shapes, and hollow sections. If not specified else, the plate thickness range for steel is from 6 to 150 mm, for aluminium from 4 to 50 mm.

The application is limited to joints operating at temperatures below the creep range. In general, the recommendations do not apply at low cycle fatigue conditions, so the nominal stress range is limited to $\Delta\sigma < 1.5 \cdot f_y$. For the special improvement procedures additional restrictions may be given.

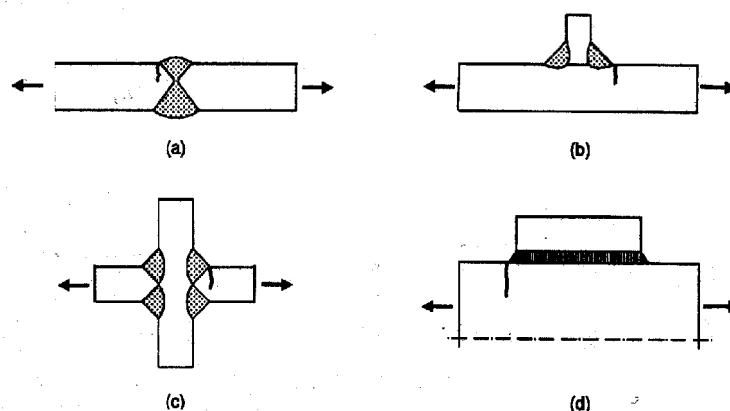


Fig: (3.5)-3: Examples of joint suitable for improvement

The improvement procedures described below, apply solely to the weld toe and to cracks starting from this point. All other points of a possible start of fatigue cracks therefore should be carefully considered as e.g. the weld root or weld imperfections.

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

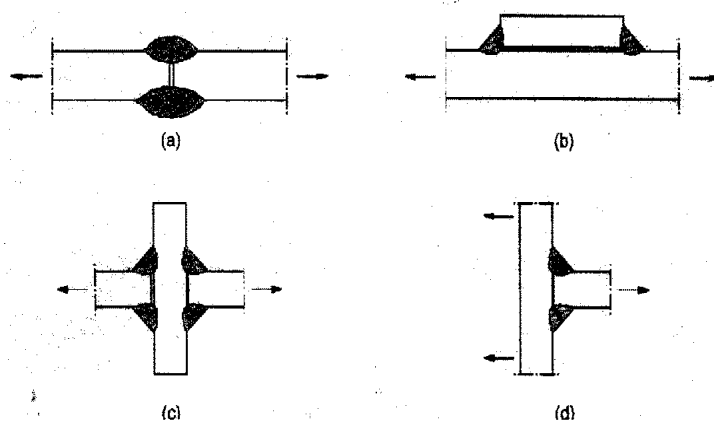


Fig: (3.5)-4: Examples of joints, at which an improvement might be limited by a possible root crack

3.5.3.3 Burr Grinding

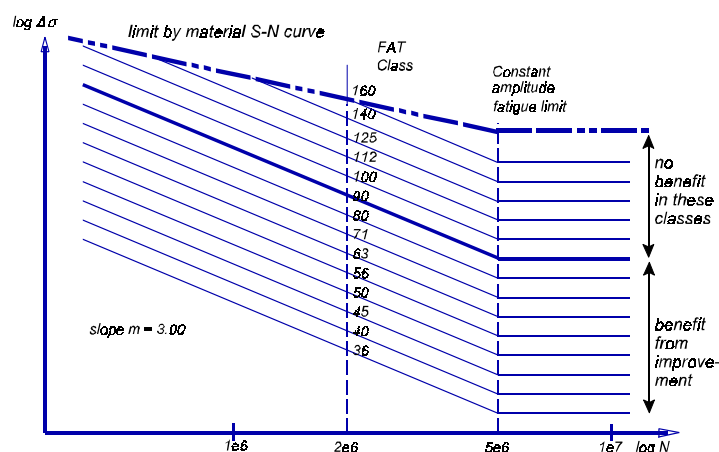
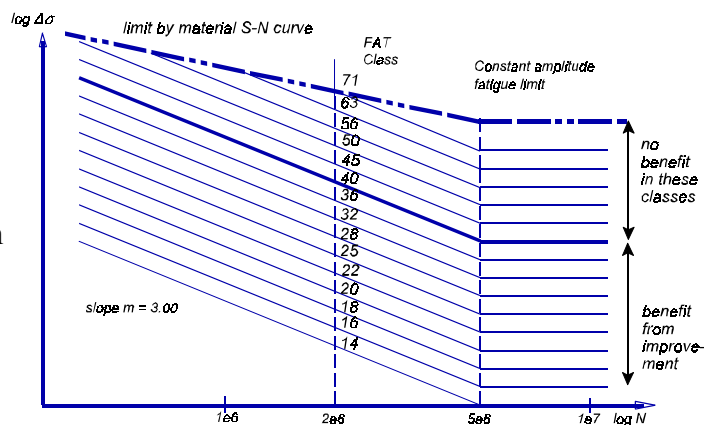
Fatigue cracks initiate at the weld toe at points of cold fusion or other sharp crack-like defects of a few tenth of a millimeter. The grinding has firstly to remove these defects and secondly to create a smooth weld transition and thus to reduce the stress concentration. All embedded imperfection which emerge to the surface at grinding must be repaired. For the details of application see ref. [xx].

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

Tab. 3.5-1: Benefit factors on stress of burr grinding

Area of application	Mild steel $f_y < 355 \text{ MPa}$	Steel $f_y > 355 \text{ MPa}$ & aluminium alloys
All structural details leading to a IIW fatigue class of 90 at steel or 32 at aluminium or lower as applicable	1.3	1.5 (1.3*)
All S-N curves and fatigue classes for assessment by structural hot spot stress, but not higher than 100 at steel and 40 at aluminium. Butt joints to be assessed by the nominal stress fatigue class.	1.3	1.5 (1.3*)

* For transverse fillet welds at continuous plates, corresponding to FAT 80 at steel and FAT 28 at aluminium in the catalogue of details

Fig. (3.5)-5: Benefit of burr grinding at steel**Fig. (3.5)-6:** Benefit of burr grinding at aluminium

3.5.3.4 TIG Dressing

By TIG (tungsten inert gas) dressing, the weld toe is remolten in order to remove the weld toe undercut or other irregularities and to smoothen the stress concentration of the weld transition. The recommendations apply to partial or full penetration arc welded fillet welds in steels with a specified yield strength up to 900 MPa and to wall thicknesses ≥ 10 mm operating non-corrosive environment or under conditions of corrosion protection. The details of the procedure are described in ref. [xx].

Tab. 3.5-2: Benefit factors on stress of TIG dressing

Area of application	Mild steel $f_y < 355$ MPa	Steel $f_y > 355$ MPa & aluminium alloys
All structural details leading to a IIW fatigue class of 90 at steel or lower	1.3	1.5 (1.3*)
All S-N curves and fatigue classes for assessment by structural hot spot stress, but not higher than 100 at steel and 40 at aluminium. Butt joints to be assessed by the nominal stress fatigue class.	1.3	1.5 (1.3*)

* For transverse fillet welds at continuous plates, corresponding to FAT 80 at steel and FAT 28 at aluminium in the catalogue of details

Fig. (3.5)-7: Benefits of by TIG dressing at steel

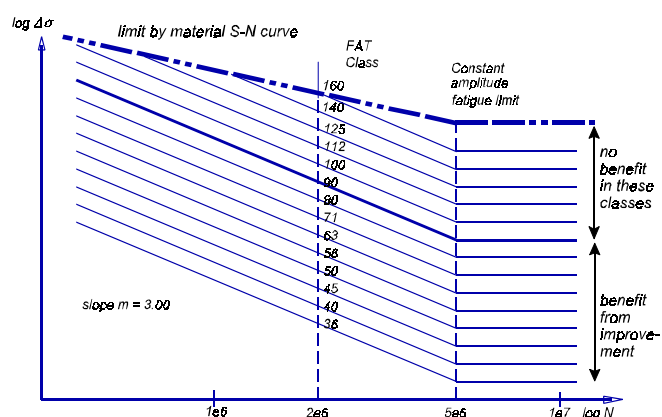
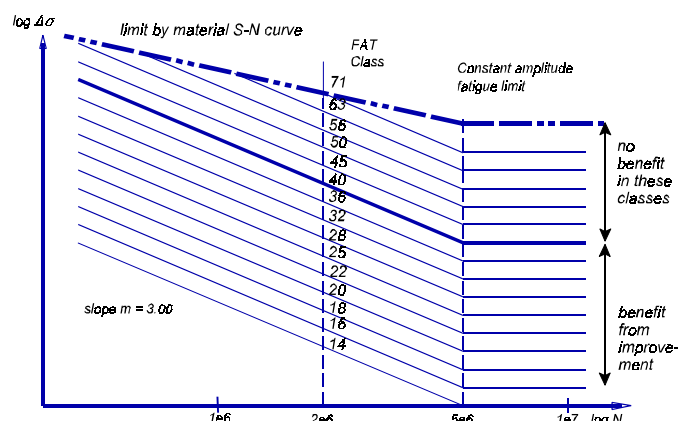


Fig. (3.5)-8: Benefit of TIG dressing at aluminium



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 recommendation is restricted to steels with a specified yield strength up to 900 MPa and structural aluminium alloys, both operating non-corrosive environment or under conditions of corrosion protection. The recommendations apply for plate thicknesses from 10 to 50 mm at steel and 5 to 25 mm at aluminium (?) and to arc welded fillet welds with a minimum weld leg length of $0.1 \cdot t$, where t is the wall thickness of the stressed plate. The details of the procedure are described in ref. [xx].

Tab. 3.5-3: Benefit on stress of hammer peening (nominal stress)

Area of application	Benefit	Requirements
All structural details leading to a IIW fatigue class of 90 at steel or 40 at aluminium or lower	Upgrade for steel to FAT 125 for aluminium to FAT 56	Max. amount of nominal compressive stress in load spectrum $< 0.25 \cdot f_y$ if $R < 0$ then use $\Delta \sigma$ if $R \geq 0$ then use max σ instead of $\Delta \sigma$ (for aluminium use f_y of HAZ!)

For structural hot spot stress see recommendations for needle peening

Fig. (3.5)-9: Benefits of hammer peening at steel

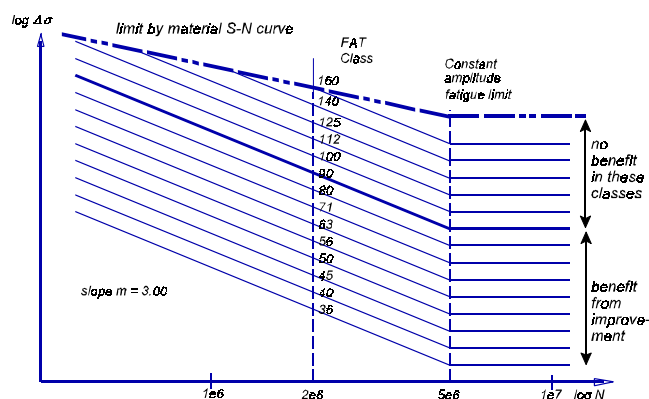
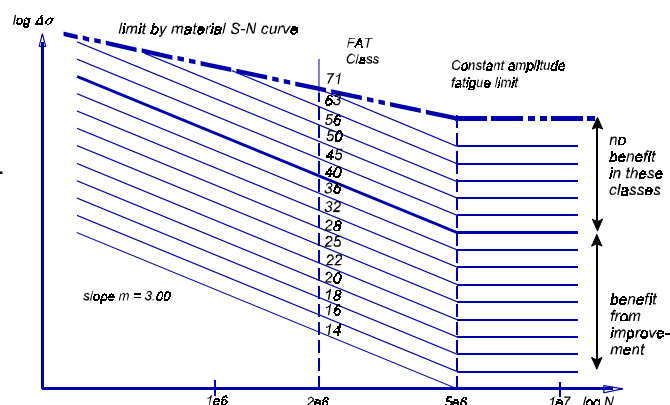


Fig. (3.5)-10: Benefits of improvement by hammer peening at aluminium



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. Before any application, it is recommended to grind the weld toe in order to remove undercut and weld toe irregularities and subsequently to finish with a sandpaper tool for a glossy surface. The details of the procedure are described in [xx].

Tab. 3.5-4: Benefit on stress of needle peening (nominal stress)

Area of application	Benefit	Requirements
All structural details leading to a IIW fatigue class of 90 at steel or 40 at aluminium or lower	Upgrade for steel to FAT 125 for aluminium to FAT 56	Max. amount of nominal compressive stress in load spectrum $< 0.25 \cdot f_y$ if $R < 0$ then use $\Delta \sigma$ if $R \geq 0$ then use $\max \sigma$ instead of $\Delta \sigma$ (for aluminium use f_y of HAZ!)

Fig. (3.5)-11: Benefits of by needle peening at steel

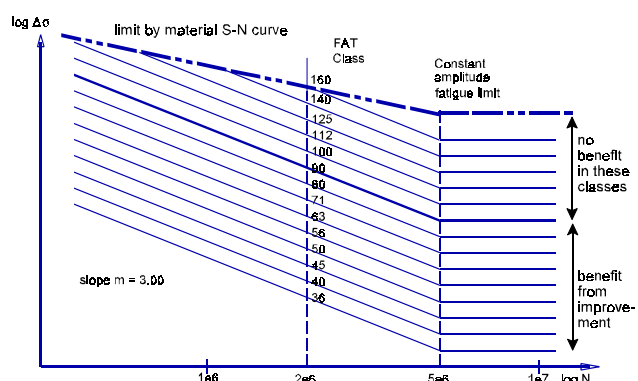
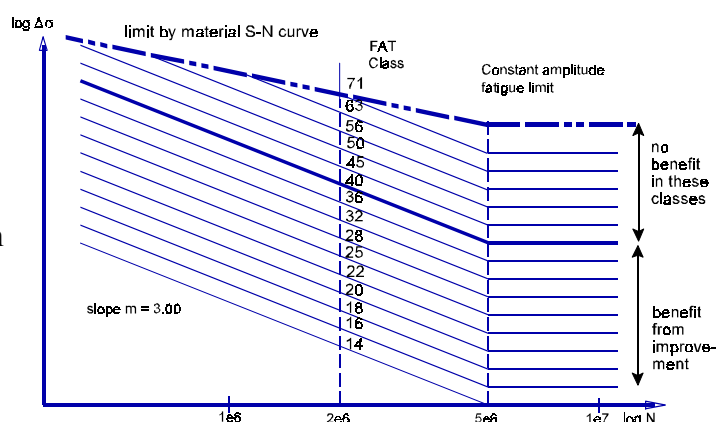


Fig. (3.5)-12: Benefits of needle peening at aluminium



At all peening techniques, the structural hot spot stress approach should be applied only to joints with fillet welds (with any penetration) and not to butt joints. The structural hot spot stress, which includes the stress increase due to the structural geometry and possible

misalignments can be assessed by the corresponding material S-N curve, e.g. FAT 160 for steel and FAT 71 for aluminium alloys in conjunction with the slope exponent $m=5.0$. In this way, the base metal at the weld toe is assumed to have a lower fatigue strength than the peened weld.

3.5.4 Effect of Elevated Temperatures

3.5.4.1 Steel

For higher temperatures, the fatigue resistance data may be modified with a reduction factor given in fig. (3.5)-13. The fatigue reduction factor is a conservative approach and might be raised according to test evidence or application codes.

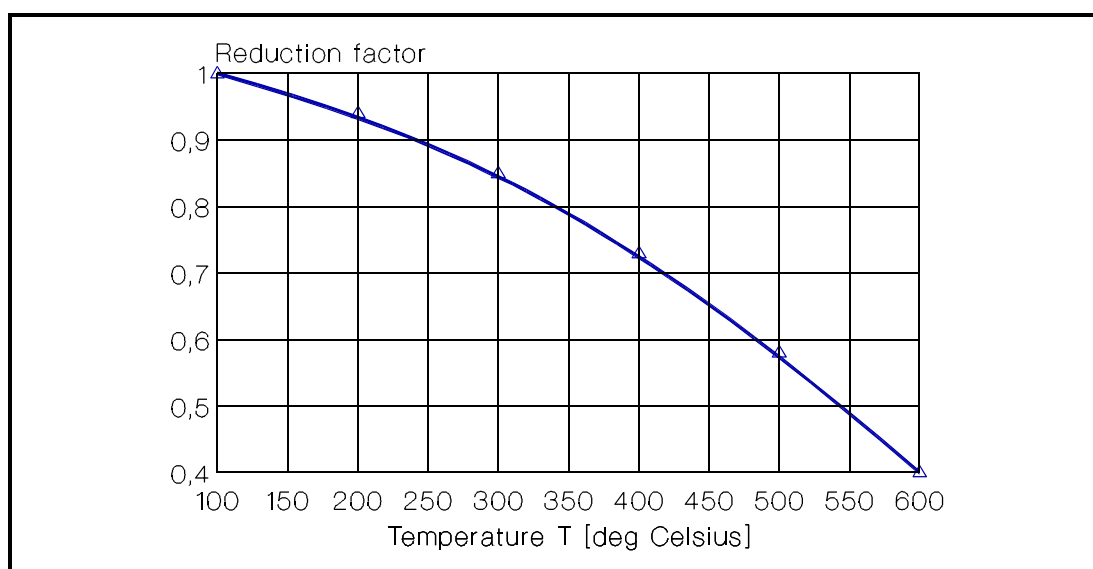


Fig. (3.5)-13 Fatigue strength reduction factor for steel at elevated temperatures

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 fatigue limit may also be reduced considerably. The effect depends on the spectrum of fatigue actions **and** on the time of exposure. **No** specific recommendations are given for corrosion fatigue assessment.

3.6 FATIGUE RESISTANCE AGAINST CRACK PROPAGATION

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

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

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
R	ratio K_{min}/K_{max} , taking all stresses including residual stresses into account (see 3.5.1)

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

3.6.1 Steel

check numbers!!

$$C_0 = 1.58 \cdot 10^{-11} \quad (\text{units in MPa}\sqrt{\text{m}} \text{ and m}) \text{ or}$$

$$C_0 = 5.0 \cdot 10^{-13} \quad (\text{units in N}\cdot\text{mm}^{-3/2} \text{ and mm})$$

$$m = 3$$

$$\Delta K_{th} = 6.0 - 4.56 \cdot R \quad \text{but not lower than 2} \quad (\text{units in MPa}\sqrt{\text{m}}) \text{ or}$$

$$\Delta K_{th} = 190 - 144 \cdot R \quad \text{but not lower than 62} \quad (\text{units in N}\cdot\text{mm}^{-3/2})$$

3.6.2 Aluminium

$$C_0 = 4.28 \cdot 10^{-9} \quad (\text{units in MPa}\sqrt{\text{m}} \text{ and m}) \text{ or}$$

$$C_0 = 1.35 \cdot 10^{-11} \quad (\text{units in N}\cdot\text{mm}^{-3/2} \text{ and mm})$$

$$m = 3$$

$$\Delta K_{th} = 2.0 - 1.5 \cdot R \quad \text{but not lower than 0.7} \quad (\text{units in MPa}\sqrt{\text{m}}) \text{ or}$$

$$\Delta K_{th} = 63 - 48 \cdot R \quad \text{but not lower than 21} \quad (\text{units in N}\cdot\text{mm}^{-3/2})$$

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:

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

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

Many methods of statistical evaluation are available. However, the most common approach for analysing fatigue data is to fit S-N or crack propagation curves by regression analysis, taking $\log(N)$ or $\log(da/dN)$ as the dependent variable. Then, characteristic values are established by adopting curves lying **k** standard deviations (2 Stdv at a number of specimens bigger than 40) of the dependent variable from the mean. In the case of S-N data, this would be below the mean, while the curve above the mean would be appropriate in case of crack propagation data.

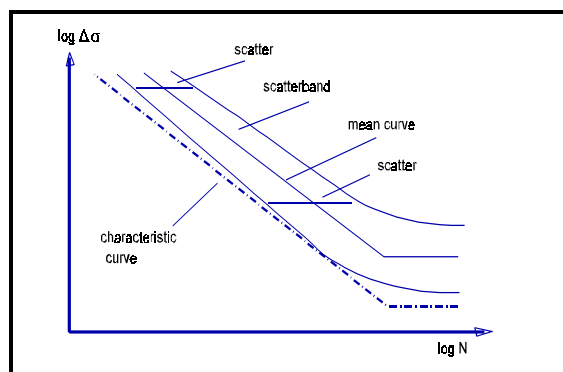


Fig. (3.7)-1 Scatterband in SN curve

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

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

3.7.2 Evaluation of Test Data

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

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

- a) Calculate $\log_{10}$ of all data: Stress range $\Delta\sigma$ 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 $\log C_0$ resp.) of the formulae:

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

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

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

Calculate the values x_i equalling $\log C$ or $\log C_0$ from the $(N, \Delta\sigma)_i$ or $(N, da/dN)_i$ test results.

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

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

- d) Calculate the characteristic values x_k by the formula

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

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

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

n	10	15	20	25	30	40	50	100
k	2.7	2.4	2.3	2.2	2.15	2.05	2.0	1.9

For **n**<10 and more details and information, see appendix 6.4.1 and ref. [35, xx].

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

3.7.3 Evaluation of Data Collections

Usually data collections do not origin from a single statistical population. These heterogeneous populations of data require a special consideration in order to avoid an excessive and unnecessary calculative scatter.. The evaluation procedure should consist of the following steps:

1. Calculate the constant **C** of the SN Wöhler curve for each data point (eq.1) using the anticipated knowledge of the slope exponent of comparable test series, e.g slope **m=3.00** for steel or aluminium.
2. Plot all values **C** into a Gaussian probability chart, showing the values of **C** on the abscissa and the cumulative survival probability on the ordinate.
3. Check the probability plot for heterogeneity of the population. If it is heterogeneous, separate the portion of the population which is of interest.
4. Evaluate the interesting portion of population according to chapter 3.7.2.

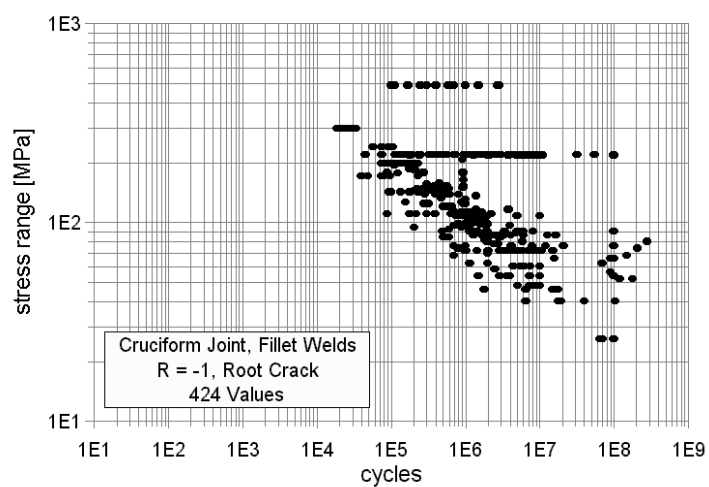


Fig. (3.7)-2: Example of scatter in data collections

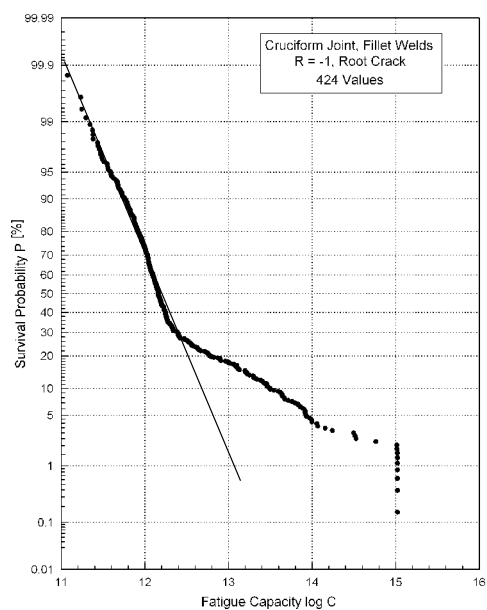


Fig. (3.7)-3: Example of a heterogeneous population

3.8 FATIGUE RESISTANCE OF JOINTS WITH WELD IMPERFECTIONS

3.8.1 General

3.8.1.1 Types of Imperfections

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

Imperfect shape

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

Undercut

Volumetric discontinuities

Gas pores and cavities of any shape.

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

Planar discontinuities

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

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

3.8.1.2 Effects and Assessment of Imperfections

At geometrical imperfections, three effects affecting fatigue resistance can be 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 effective stress concentration factor can be calculated by appropriate formulae. The fatigue resistance of the structural detail under consideration is to be lowered by division by this factor.

Local notch effect

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

Additive notch effect

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

Competitive notch effect

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

Cracklike imperfections

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

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

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

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

Effect of imperfection		Type of imperfection	Assessment
Rise of general stress level		Misalignment	Formulae for effective stress concentration
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 appendix 6.3.

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

Some allowance for misalignment is already included in the tables of classified structural details (3.2). In particular, the data for transverse butt welds are directly applicable for misalignment which results in an increase of stress up to 30%, while for the cruciform joints the increase can be up to 45%. In these cases the effective stress magnification factor $k_{m,eff}$ should be calculated as given below.

Tab. {3.8}-2: Effective stress magnification

Type of welded joint	k_m already covered	$k_{m,eff}$
butt welds, transverse	1.30	$k_m/1.3$ at least 1.0
cruciform joints	1.45	$k_m/1.45$ at least 1.0

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

$$k_m = 1 + (k_{m,axial} - 1) + (k_{m,angular} - 1) \quad (42)$$

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

3.8.3 Undercut

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

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

3.8.3.1 Steel

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

Fatigue class	Allowable undercut u/t	
	butt welds	fillet welds
100	0.025	not applicable
90	0.05	not applicable
80	0.075	0.05
71	0.10	0.075
63	0.10	0.10
56 and lower	0.10	0.10
Notes: a) undercut deeper than 1 mm shall be assessed as a crack-like imperfection. b) the table is only applicable for plate thicknesses from 10 to 20 mm		

3.8.3.2 Aluminium

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

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

3.8.4 Porosity and Inclusions

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

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

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

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

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

3.8.4.1 Steel

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

Fatigue class	Max. length of an inclusion in mm		Limits of porosity in % of area * **
	as-welded	stress relieved +	
100	1.5	7.5	3
90	2.5	19	3
80	4	58	3
71	10	no limit	5
63	35	no limit	5
56 and lower	no limit	no limit	5
* Area of radiograph used is length of weld affected by porosity multiplied by width of weld ** Maximum pore diameter or width of an inclusion less than 1/4 plate thickness or 6 mm + Stress relieved by post weld heat treatment			

3.8.4.2 Aluminium

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

Fatigue class	Max. length of an inclusion in mm **	Limits of porosity in % of area * **
	as-welded	
40 and higher	1.5	0 +)
36	2.5	3
32	4	3
28	10	5
25	35	5
15 and lower	no limit	5
* Area of radiograph used is length of weld affected by porosity multiplied by width of weld ** Maximum pore diameter or width of an inclusion less than 1/4 plate thickness or 6 mm +) Single pores up to 1.5 mm allowed		

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

3.8.5 Cracklike Imperfections

3.8.5.1 General Procedure

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

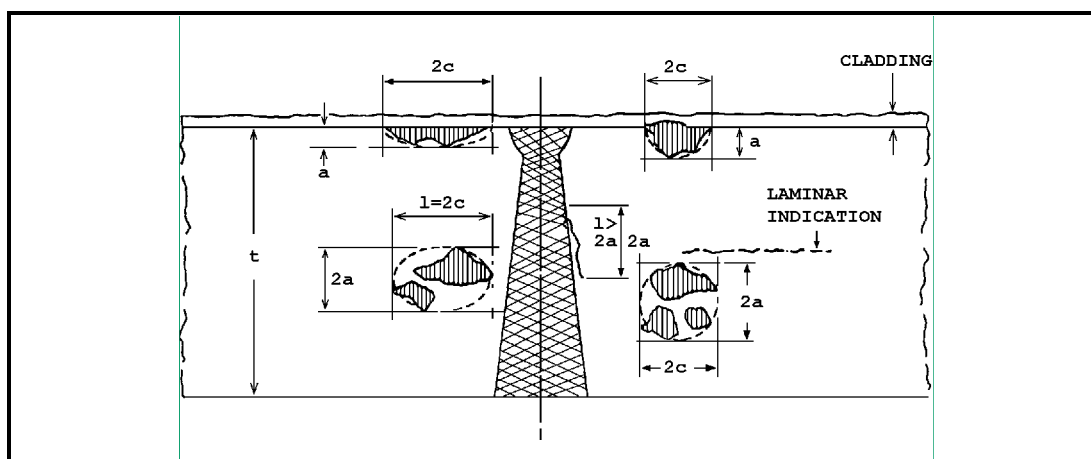


Fig. (3.8)-1 Transformation of NDT indications to an elliptic or semi-elliptic

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

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

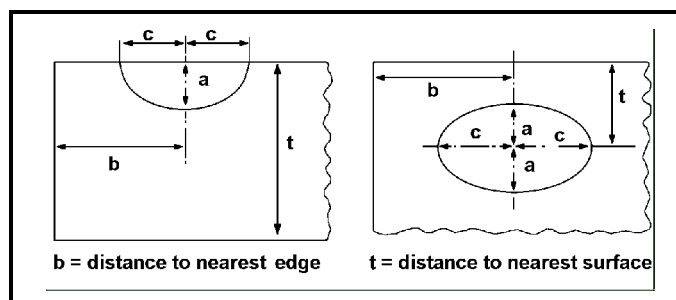


Fig. (3.8)-2 Crack dimensions for assessment

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

3.8.5.2 Simplified Procedure

The simplified procedure is based on the integration of the crack propagation law (4.4) from an initial defect size a_i to defect size of 0.75% of wall thickness using the material

resistance against crack propagation as given in 3.6.1 for steel. For cracks near the plate edge, the distance **b** from the center of crack ellipsis to the plate edge was constantly assumed equalling **c**. This ensures conservative results.

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

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

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

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

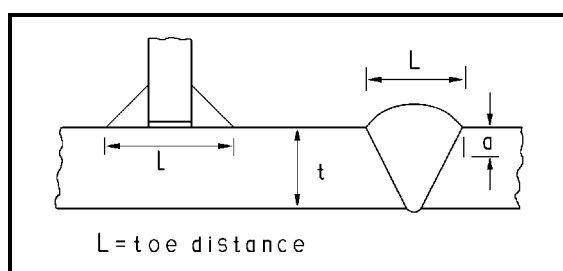


Fig. (3.8)-3 Toe distance **L** for simplified procedure

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	4	7	16
20.0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	8	11
16.0	0	0	0	0	0	0	0	0	0	0	0	4	7	9	11	15
12.0	0	0	0	0	0	0	0	0	0	0	6	9	12	14	16	19
10.0	0	0	0	0	0	0	0	0	0	5	9	12	15	17	19	22
8.0	0	0	0	0	0	0	4	7	9	13	16	19	21	22	25	30
6.0	0	0	0	0	0	6	9	12	15	18	21	23	25	26	28	33
5.0	0	0	0	0	6	10	13	16	18	21	24	26	28	29	31	35
4.0	0	0	0	5	10	14	18	20	22	25	28	29	31	32	33	37
3.0	0	0	7	11	16	20	23	25	27	30	32	33	34	35	37	39
2.0	5	11	16	20	25	28	31	32	34	36	37	39	40	40	41	43
1.0	22	28	32	34	38	40	42	43	44	45	46	47	48	48	48	48
0.5	38	42	45	47	49	51	52	53	53	54	54	54	54	54	54	52
0.2	57	59	61	61	63	63	63	63	63	63	63	62	61	61	60	56
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100
a_i	long surface crack apart from edge, fillet welds $l/t=2.5$ $a/c=0.1$															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	13	22
20.0	0	0	0	0	0	0	0	0	0	0	0	7	11	13	17	25
16.0	0	0	0	0	0	0	0	0	0	0	9	12	15	18	21	28
12.0	0	0	0	0	0	0	0	0	0	11	15	18	21	23	26	32
10.0	0	0	0	0	0	0	0	0	10	15	19	22	24	26	28	34
8.0	0	0	0	0	0	0	8	12	15	20	24	26	28	29	32	37
6.0	0	0	0	0	0	12	16	19	22	26	29	31	33	34	36	40
5.0	0	0	0	0	11	17	20	24	26	29	32	34	35	36	38	42
4.0	0	0	0	9	17	22	26	28	30	33	36	37	39	40	41	44
3.0	0	0	13	18	25	29	32	34	36	38	40	42	43	44	45	47
2.0	11	19	25	29	34	37	39	41	42	44	46	47	48	49	50	51
1.0	32	38	42	44	48	50	52	53	54	55	56	57	57	57	57	56
0.5	50	53	56	58	60	62	63	63	64	64	64	64	63	63	62	59
0.2	70	72	73	74	75	75	74	74	74	73	72	71	70	69	67	62
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100
a_i	short surface crack apart from edge, fillet welds $l/t=2.5$ $a/c=.5$															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	23	35
20.0	0	0	0	0	0	0	0	0	0	0	0	15	21	24	29	38
16.0	0	0	0	0	0	0	0	0	0	0	18	23	27	30	34	42
12.0	0	0	0	0	0	0	0	0	0	21	27	32	35	37	40	45
10.0	0	0	0	0	0	0	0	0	20	27	33	36	39	41	43	47
8.0	0	0	0	0	0	0	18	24	28	34	39	41	43	45	47	49
6.0	0	0	0	0	0	23	30	34	37	42	45	47	48	49	51	52
5.0	0	0	0	0	22	31	36	39	42	46	48	50	51	52	53	53
4.0	0	0	0	20	32	38	42	45	47	50	52	54	54	55	55	55
3.0	0	0	26	33	42	47	50	52	53	55	57	58	58	58	58	57
2.0	22	36	43	48	53	56	58	60	61	62	62	62	62	62	62	59
1.0	53	60	63	66	68	69	70	70	70	70	69	69	68	67	66	62
0.5	74	76	78	78	79	78	78	77	77	76	74	73	72	71	69	64
0.2	92	91	91	90	88	86	85	84	83	81	79	77	75	74	72	65
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100
Surface cracks at butt weld toes																
a_i	long surface crack near plate edge, butt welds $l/t=1$ $a/c=0.1$															

25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	7	17
20.0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	8	20
16.0	0	0	0	0	0	0	0	0	0	0	0	4	7	9	11	23
12.0	0	0	0	0	0	0	0	0	0	0	6	9	12	14	16	27
10.0	0	0	0	0	0	0	0	0	0	5	9	12	15	18	20	29
8.0	0	0	0	0	0	0	4	7	9	13	17	19	22	23	26	32
6.0	0	0	0	0	0	6	9	12	15	18	22	25	26	28	30	35
5.0	0	0	0	0	6	10	13	16	18	22	25	28	29	31	33	38
4.0	0	0	0	5	10	14	18	21	23	26	29	31	33	34	36	40
3.0	0	0	7	11	16	21	24	27	29	31	34	36	37	38	40	43
2.0	5	11	16	20	26	30	32	34	36	38	40	42	43	44	45	48
1.0	22	29	33	36	40	43	45	46	47	49	51	52	52	53	53	54
0.5	41	45	48	50	53	55	57	58	58	59	60	60	60	60	60	59
0.2	61	64	66	68	69	70	70	70	70	70	70	70	69	69	68	64
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100
a _i	long surface crack apart from edge, butt welds l/t=1 a/c=0.1															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	13	23
20.0	0	0	0	0	0	0	0	0	0	0	0	0	7	11	13	26
16.0	0	0	0	0	0	0	0	0	0	0	0	9	12	15	18	29
12.0	0	0	0	0	0	0	0	0	0	0	11	15	18	21	23	33
10.0	0	0	0	0	0	0	0	0	0	10	15	19	22	25	27	36
8.0	0	0	0	0	0	0	8	12	15	20	24	27	29	31	33	39
6.0	0	0	0	0	0	12	16	19	22	26	30	32	34	35	37	43
5.0	0	0	0	0	11	17	20	24	26	30	33	35	37	38	40	45
4.0	0	0	0	9	17	22	26	29	31	34	37	39	41	42	44	48
3.0	0	0	13	18	25	29	32	35	37	40	42	44	45	46	48	51
2.0	11	19	25	29	35	38	41	43	45	47	49	50	51	52	53	55
1.0	33	39	43	46	50	53	54	56	57	59	60	61	61	61	62	61
0.5	52	56	59	61	64	66	67	68	68	69	69	69	69	69	68	66
0.2	74	77	78	79	80	81	81	80	80	80	79	78	77	76	75	70
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100
a _i	short surface crack apart from edge, butt welds l/t=1 a/c=0.5															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	23	36
20.0	0	0	0	0	0	0	0	0	0	0	0	0	15	21	24	40
16.0	0	0	0	0	0	0	0	0	0	0	0	18	23	27	30	43
12.0	0	0	0	0	0	0	0	0	0	0	21	27	32	35	37	47
10.0	0	0	0	0	0	0	0	0	0	20	27	33	37	39	41	50
8.0	0	0	0	0	0	0	18	24	28	34	39	42	44	46	48	52
6.0	0	0	0	0	0	23	30	34	37	42	46	48	50	51	53	56
5.0	0	0	0	0	22	31	36	39	42	47	50	52	53	54	56	57
4.0	0	0	0	20	32	38	43	46	48	52	54	56	57	58	59	60
3.0	0	0	26	33	42	47	51	53	55	58	59	61	61	62	62	62
2.0	22	36	43	48	54	58	60	62	63	65	66	67	67	67	67	65
1.0	54	61	65	68	71	73	74	74	75	75	75	75	74	74	73	69
0.5	76	80	82	83	84	84	84	84	84	83	82	81	80	79	77	71
0.2	98	98	98	98	97	95	94	93	92	90	88	86	85	83	81	74
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100
Embedded cracks																
a _i	embedded long crack near plate edge a/c=0.1															

25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	7	17
20.0	0	0	0	0	0	0	0	0	0	0	0	3	5	7	11	20
16.0	0	0	0	0	0	0	0	0	0	0	4	6	9	11	14	24
12.0	0	0	0	0	0	0	0	0	0	5	8	11	14	16	19	28
10.0	0	0	0	0	0	0	0	0	4	8	12	15	17	19	23	31
8.0	0	0	0	0	0	0	3	6	8	12	16	19	22	24	27	35
6.0	0	0	0	0	0	5	9	12	14	18	22	25	27	29	32	40
5.0	0	0	0	0	5	9	12	15	18	22	26	28	31	32	35	43
4.0	0	0	0	4	9	14	17	20	23	26	30	33	35	37	39	47
3.0	0	0	6	10	16	20	24	27	29	32	36	38	40	42	45	52
2.0	4	10	15	19	25	30	33	36	38	41	44	46	48	50	52	59
1.0	22	29	33	37	42	46	49	51	53	56	59	61	63	64	67	73
0.5	42	47	52	55	60	63	66	68	69	72	75	77	79	80	82	88
0.2	68	73	77	80	84	87	90	92	93	96	98	100	101	103	105	110
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100
a _i	embedded long crack apart from plate edge a/c=0.1															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	19	30
20.0	0	0	0	0	0	0	0	0	0	0	0	12	17	20	24	33
16.0	0	0	0	0	0	0	0	0	0	0	14	19	22	25	29	37
12.0	0	0	0	0	0	0	0	0	0	17	22	26	29	31	34	41
10.0	0	0	0	0	0	0	0	0	16	22	27	30	33	35	37	44
8.0	0	0	0	0	0	0	14	19	23	28	32	35	37	39	41	48
6.0	0	0	0	0	0	19	24	28	31	35	38	41	42	44	46	53
5.0	0	0	0	0	18	25	29	33	35	39	42	44	46	47	49	56
4.0	0	0	0	15	26	31	35	38	40	43	46	48	50	51	54	59
3.0	0	0	21	27	35	39	42	45	46	49	52	54	56	57	59	64
2.0	17	29	35	40	45	49	51	53	55	58	60	62	64	65	67	71
1.0	44	51	55	58	62	65	67	69	70	73	75	77	78	79	80	84
0.5	65	69	73	75	79	82	84	85	86	88	90	91	92	93	94	97
0.2	91	95	98	100	103	105	106	107	108	110	111	112	112	113	114	117
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100
a _i	embedded short crack apart from plate edge a/c=0.5															
25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	27	41
20.0	0	0	0	0	0	0	0	0	0	0	0	17	24	28	34	46
16.0	0	0	0	0	0	0	0	0	0	0	20	27	32	35	40	50
12.0	0	0	0	0	0	0	0	0	0	24	32	37	41	43	47	55
10.0	0	0	0	0	0	0	0	0	23	32	38	42	45	48	51	58
8.0	0	0	0	0	0	0	20	28	33	40	45	48	51	53	56	62
6.0	0	0	0	0	0	27	35	40	43	48	53	56	58	59	62	67
5.0	0	0	0	0	26	36	42	46	49	54	57	60	62	63	66	71
4.0	0	0	0	23	37	44	49	53	56	60	63	65	67	68	70	75
3.0	0	0	31	39	49	54	58	61	64	67	70	71	73	74	76	80
2.0	26	42	50	55	62	67	70	72	74	76	79	80	81	82	84	87
1.0	62	70	75	78	83	86	88	89	91	92	94	95	96	97	98	100
0.5	88	93	96	99	102	104	105	106	107	108	110	110	111	112	112	115
0.2	118	121	123	124	126	128	129	129	130	131	132	133	133	134	135	137
t =	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50	100

4 FATIGUE ASSESSMENT

4.1 GENERAL PRINCIPLES

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

- a) Procedures based on S-N curves, such as
 - nominal stress approach
 - Structural hot spot stress approach
 - effective notch stress approach
- b) Procedures based on crack propagation considerations
- c) Direct experimental approach by fatigue testing of components or entire structures

4.2 COMBINATION OF NORMAL AND SHEAR STRESS

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

- a) If the equivalent nominal shear stress range is less than 15% of the equivalent normal stress range or if the damage sum due to shear stress range is lower than 10% of that due to normal stress range, the effect of shear stress may be neglected.
- b) If the normal and shear stress vary simultaneously in phase, or if the plane of maximum principal stress is not changed significantly, the maximum principal stress range may be used.
- c) If normal and shear stress vary independently out of phase, in damage calculation the damage sums shall be calculated separately and finally added. The usage of $1/2$ of the calculated life cycles is recommended.

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

4.3 FATIGUE ASSESSMENT USING S-N CURVES

Fatigue verification is carried out using

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

and

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

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

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

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

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

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

4.3.1 Linear Damage Calculation by "Palmgren-Miner" Summation

If the maximum design stress range $\Delta\sigma_{\max,S,d}$ of the load spectrum is lower than the design fatigue limit $\Delta\sigma_{L,R,d}$ of the design fatigue resistance S-N curve, or if it is lower than the design cut-off limit $\Delta\sigma_{\text{cut},R,d}$ in cases where no fatigue limit is given, the life of the welded joint can be assumed to be **infinite** and no further damage calculation is necessary.

If the constant amplitude fatigue limit of the resistance S-N curve corresponds to an endurance less than 10^8 cycles, the fatigue resistance curve has to be modified according

to fig. (4)-1. Then the slope m_2 of the S-N curve from the constant amplitude fatigue limit ($5 \cdot 10^6$ cycles) up to 10^8 cycles is assumed to be $m_2 = 2 \cdot m_1 - 1$ [30]¹.

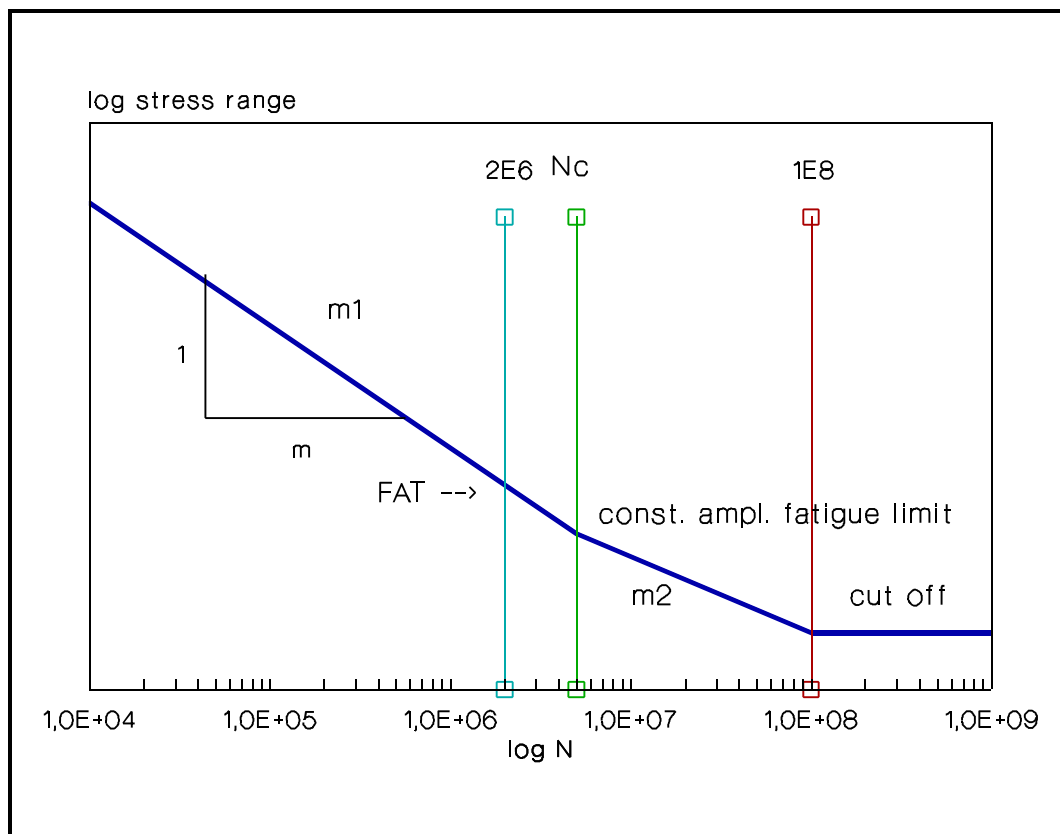


Fig. (4)-1 Modification of fatigue resistance Wöhler S-N curve for Palmgren-Miner summation

For fatigue verification it has to be shown that the calculated usable cycles are larger than the anticipated number of cycles occurring in service of the structure:

¹Although it is accepted that the stresses below the constant amplitude fatigue limit must be included in cumulative damage calculation relating to welded joints, there are currently different opinions how this should be achieved. The method presented here (fig. (4)-1) appears in a number of codes, including Eurocode 3. However, recent research indicates that it can be unconservative. Here, this question is partially solved by recommending a Miner sum of $\Sigma D = 0.5 \dots 1.0$ depending on shape of the spectrum. Other suggestions recommend that the S-N curve should be extrapolated further down before the slope change is introduced. For critical cases or areas of doubt, the user should consult relevant published literature.

$$\Sigma D_d = \sum_1^i \frac{n_i}{N_i} = 1$$

$$N_{usable} = \frac{N_{const} + N_{var}}{2}$$

- where ΣD_d damage by summation (note restrictions in 4.2 and 4.3)
 i index for block number in load spectrum of required design life
 n_i number of cycles of stress range $\Delta\sigma_{i,s,d}$ in load spectrum block i
 N_i number of cycles at which design stress range $\Delta\sigma_{i,s,d}$ causes failure in the modified design fatigue resistance S-N curve.
 N_{var} number of cycles calculated at variable amplitude load by use of damage summation ΣD_d
 N_{const} number of cycles calculated at constant amplitude load of maximum stress range in spectrum
 N_{usable} number of calculative usable cycles

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

In some cases it might be convenient to calculate an equivalent constant amplitude stress range $\Delta\sigma_E$ and to compare it directly to the constant amplitude resistance S-N curve neglecting the constant amplitude fatigue limit.

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

Tab. {4}-1: Constants, constant amplitude fatigue limit and cut-off limits

Values of modified characteristic fatigue resistance S-N curves for Palmgren-Miner summation. Initial slope $m_1=3.0$, constant amplitude fatigue limit $\Delta\sigma_{L,k}$ at $5 \cdot 10^6$ cycles, second slope $m_2=5.0$, cut-off at 10^8 cycles.				
Class	Constant C for S-N curve at $N < 5e6$ cycles, $m_1=3$	constant ampl. fat. limit	Constant C for S-N curve at $N > 5e6$ cycles, $m_2=5$	cut-off limit
225	2.278e13	166	6.261e17	91.1
200	1.600e13	147	3.474e17	80.9
180	1.166e13	133	2.052e17	72.8
160	8.192e12	118	1.139e17	64.8
140	5.488e12	103	5.840e16	56.7
125	3.906e12	92.1	3.313e16	50.6
112	2.810e12	82.5	1.913e16	45.3
100	2.000e12	73.7	1.086e16	40.5
90	1.458e12	66.3	6.411e15	36.4
80	1.012e12	58.9	3.558e15	32.4
71	7.158e11	52.3	1.959e15	28.7
63	5.001e11	46.4	1.078e15	25.5
56	3.512e11	41.3	5.980e14	22.7
50	2.500e11	36.8	3.393e14	20.2
45	1.823e11	33.2	2.004e14	18.2
40	1.280e11	29.5	1.112e14	16.2
36	9.331e10	26.5	6.565e13	14.6
32	6.554e10	23.6	3.643e13	13.0
28	4.390e10	20.6	1.869e13	11.3
25	3.125e10	18.4	1.060e13	10.1
22	2.130e10	16.2	5.596e12	8.9
20	1.600e10	14.7	3.474e12	8.1
18	1.166e10	13.3	2.052e12	7.3
16	8.192e9	11.8	1.139e12	6.5
14	5.488e9	10.3	5.840e11	5.7

4.3.2 Nonlinear Damage Calculation

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

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

Where the parameters for a fracture mechanics fatigue assessment are not known and only the resistance S-N curve is known, the S-N curve can be used to derive dimensionless fracture mechanics parameters, which allow a damage calculation [31]. The procedure is based on the "Paris" power law of crack propagation

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

where **a** crack parameter, damage parameter (dimensionless)
N Number of cycles
ΔK range of stress intensity factor
ΔK_{th} threshold value of stress intensity factor range
C₀, m material constants

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

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

The characteristic resistance parameters can be derived from the characteristic constant amplitude fatigue resistance S-N curve: The threshold value corresponds to the fatigue limit, **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

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

The fatigue verification is executed according to 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 4.3 are to be considered.

The actual fatigue class of a pre-damaged component is **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

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

is verified by the material resistance design parameters against crack propagation

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

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

using the "Paris" power law

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

where **a** crack parameter, damage parameter
N Number of cycles
ΔK range of stress intensity factor
ΔK_{th} threshold value of stress intensity factor range
C₀, m material constants

At 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.

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

where

K_c fracture toughness
R stress ratio

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

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

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

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 blockwise by summing the increments of a and the number of cycles of the blocks. The entire size of the spectrum in terms of cycles should be adjusted by multiplying the block cycles by an appropriate factor in order to ensure at least 20 loops over the whole spectrum in the integration procedure.

4.5 FATIGUE ASSESSMENT BY SERVICE TESTING

4.5.1 General

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

- Existence of a new design with no or not sufficient knowledge or experience of 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 in respect of weight, safety and economy after pre-dimensioning. Predimensioning may be done by the use of higher fatigue resistance data, according to a lower survival probability in comparison with the

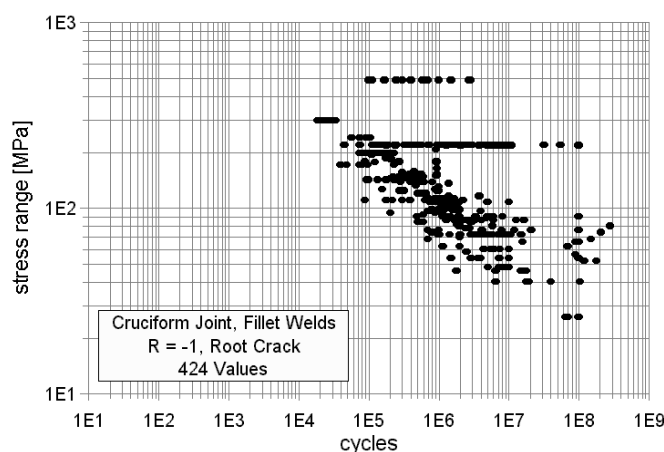


Fig. (4.5)-1: Scatter of test data showing possibilities of optimization

resistance data given here. Then the verification is achieved by a subsequent component testing. A predimensioning leading to the mean values of the the resistance data may be done by multiplying the resistance values in terms of stress by a factor of 1.3.

The verification or assessment depends of the safety strategy considered (see 5.2). Safe life, fail safe and damage tolerant strategy have to be distinguished.

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

Tab. {4.5}-1 : Testing approaches

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

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

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

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

This chapter considers the most common **all failed** approach. Other approaches and details of statistical analysis are considered in appendix 6.4.

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

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

The tests should be performed according to well established and appropriate procedures or standards [32].

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

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

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

- **0.178** for geometrically simple structures at a number of cycles between 10^4 and 10^5
- **0.25** for complex structures at cycles up to 10^6
- ----- no estimate can be given for higher cycles near the endurance limit. Here special verification procedures are recommended, see ref [32yy]

4.5.2 Acceptance Criteria

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

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

where

- N_T number of test life cycles of the test specimens corresponding to the log mean value or number of cycles of the first test specimen to fail, whichever is applicable.
- F factor dependent of the number of test results available as defined in tables {4.5}-1 and {4.5}-2. The F -factors refer to a 95% survival probability at a two sided confidence level of 75% of the mean (see also 6.4)
- N_d number of design life cycles, up to which the component or structure may be used in service

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

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

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

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

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

Stdv. \ n	2	4	6	8	10
0.178	2.72	2.07	1.83	1.69	1.55

0.200	3.08	2.26	1.98	1.80	1.64
0.250	4.07	2.77	2.34	2.09	1.85

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

4.5.3 Safe Life Verification

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

The partial safety factors γ_F and γ_M may be selected from appendix 6.4.3.

4.5.4 Fail Safe Verification

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

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

The partial safety factors γ_F and γ_M may be selected from appendix 6.4.3.

4.5.5 Damage Tolerant Verification

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

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

The partial safety factors γ_F and γ_M may be selected from appendix 6.4.3.

5 SAFETY CONSIDERATIONS

5.1 BASIC PRINCIPLES

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

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

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

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

These uncertainties are covered by an appropriate partial safety factor for the fatigue actions γ_F , which is **not considered here**.

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

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

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

5.2 FATIGUE DESIGN STRATEGIES

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

5.2.1 Infinite Life Design

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

5.2.2 Safe Life Design

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

5.2.3 Fail Safe Design

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

5.2.4 Damage Tolerant Design

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

5.3 PARTIAL SAFETY FACTORS

The required partial safety factor γ_M depends largely on circumstances such as

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

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

The safety factors are given in terms of stress. If safety factors are needed in terms of cycles, Γ_M may be calculated using the slope m of the resistance S-N curve

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

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

5.4 QUALITY ASSURANCE

Weld quality is assured preferably by the application of an ISO 9000 quality management system or a comparable system.

The weld quality should be equal to quality class **B** according to ISO 5817. However, some exceptions may be allowed in the tables given in chapter 3.2.

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

5.5 REPAIR OF COMPONENTS

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

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

- accident, e.g. collision

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

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

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

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

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

6 APPENDICES

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

6.1 LOAD CYCLE COUNTING

6.1.1 Transition Matrix

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

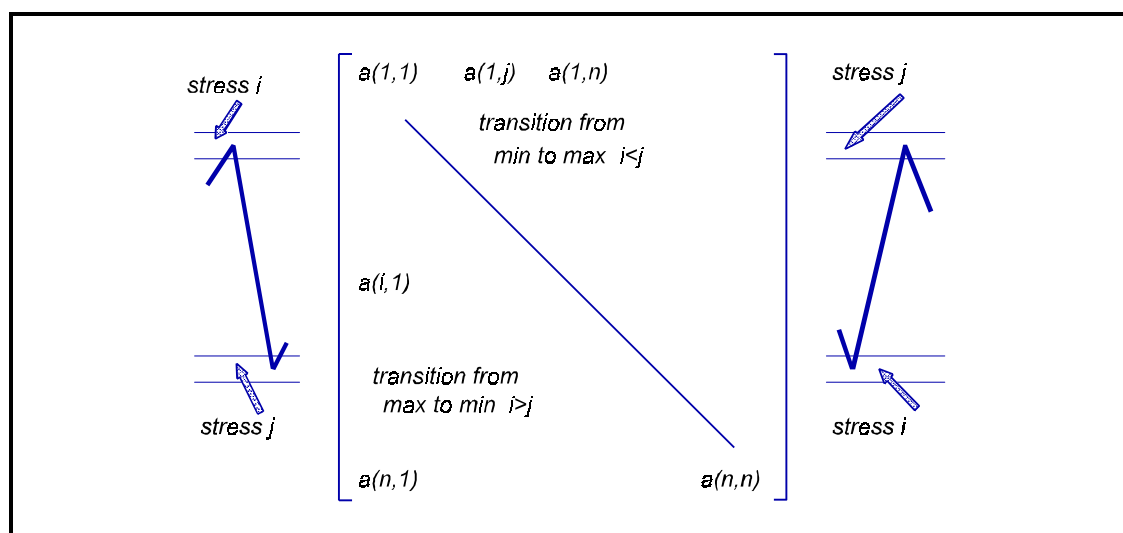


Fig. (6.1)-1 Principle of the transition matrix

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

6.1.2 Rainflow or Reservoir Counting Method

The algorithm of rainflow counting method is well explained by using the analogy of the flow of water on a pagoda roof. The stress signal, looked at vertically, is regarded as the pagoda roof. A cycle is obtained, when a contour is closed by the drop of the flow from a peak to a slope of the roof [26 and 27]. The range is then equal to the difference between the extreme values of the contour. Later the smaller included cycles can be determined the

same way. The non closed contour from the extreme of the entire signal leads to a half cycle. Reservoir counting is similar.

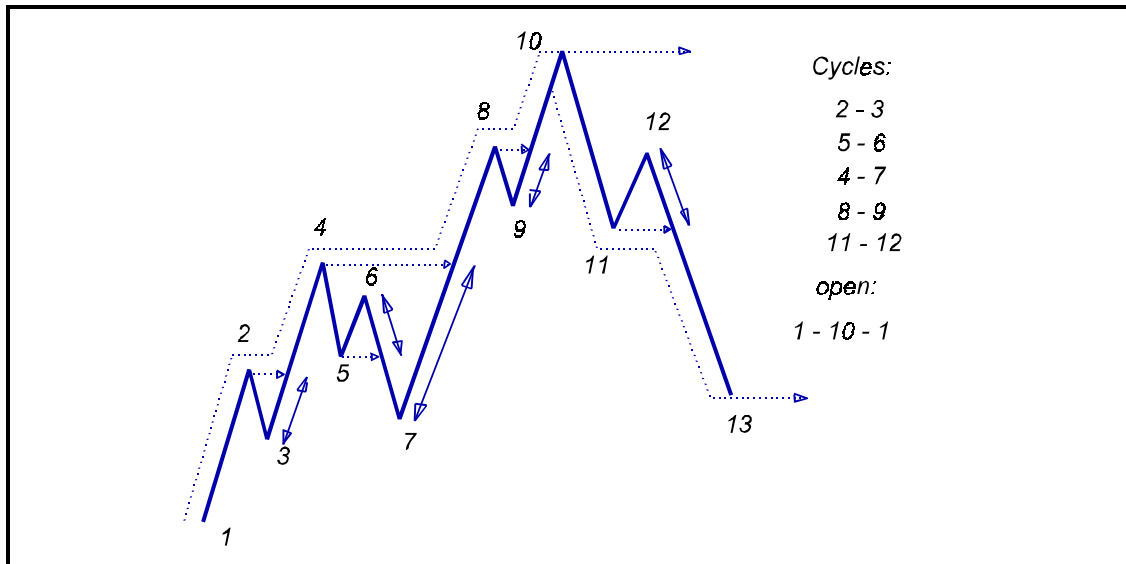


Fig. (6.1)-2 Illustration of rainflow counting

6.2 FRACTURE MECHANICS

6.2.1 Rapid Calculation of Stress Intensity Factors

A simplified method may be used to determine M_k -factors [19]. 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. The integration for a certain crack length a yields:

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

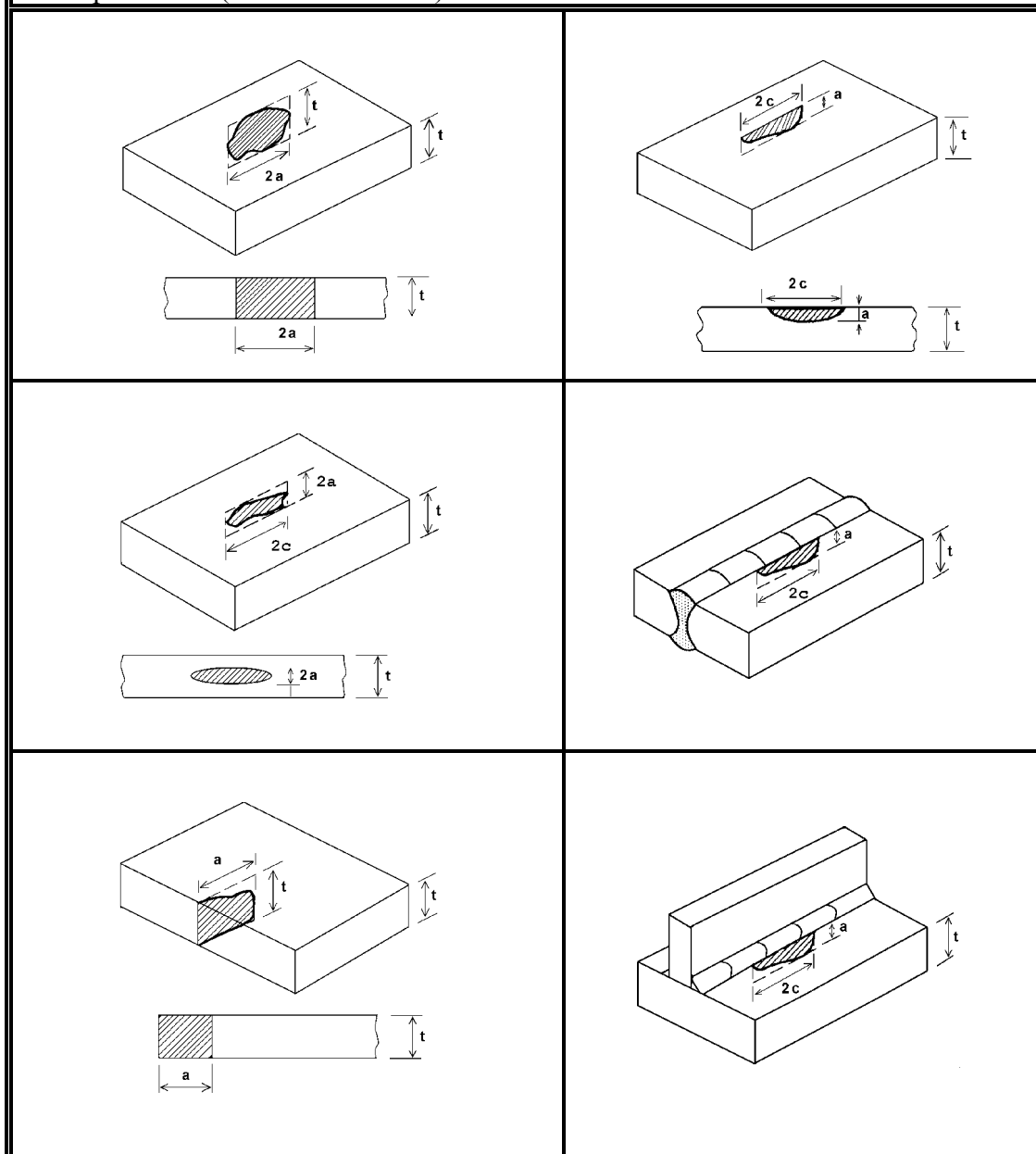
For different crack lengths a , a function $M_k(a)$ can be established, which is preferably presented in the form:

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

6.2.2 Dimensions of Cracks

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

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



6.2.3 Interaction of Cracks

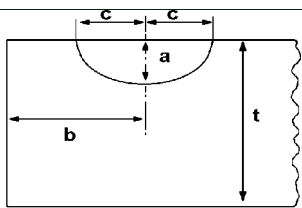
Adjacent cracks may interact and behave like a single large one. The interaction between adjacent cracks should be checked according to an interaction criterion.

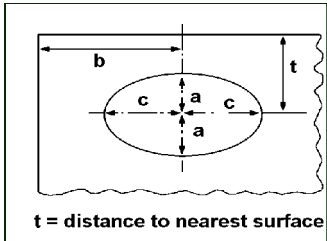
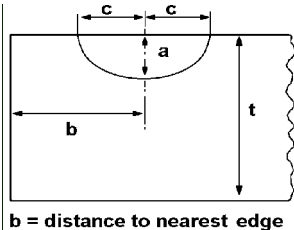
There are different interaction criteria, and in consequence no strict recommendation can be given. It is recommended to proceed according to an accepted code, e.g. [24].

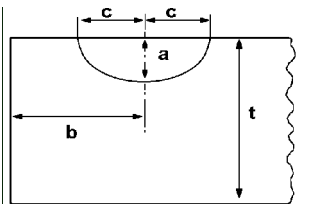
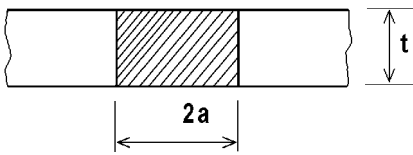
6.2.4 Formulae for Stress Intensity Factors

Stress intensity factor formulae may be taken from literature, see references [13] to [20]. For the majority of cases, the formulae given below are sufficient.

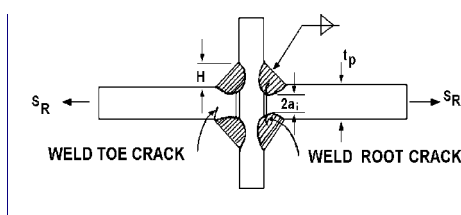
Tab. {6.2}-2: Stress intensity factors at welds

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

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. [14]
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. [14].
$K_1 = (\sigma_{mem} + H \cdot \sigma_{ben}) \sqrt{(\pi \cdot a / Q)} \cdot F_s$ $Q = 1 + 1.464 (a/c)^{1.65}$ $F_s = [M_1 + M_2 \cdot (a/t)^2 + M_3 \cdot (a/t)^4] \cdot g \cdot f \cdot f_w$ $M_1 = 1.13 - 0.09 (a/c)$ $M_2 = -0.54 - 0.89 / (0.2 + a/c)$ $M_3 = 0.5 - 1 / (0.65 + a/c) + 14 (1 - a/c)^{24}$ $f_w = [\sec(\pi \cdot c \sqrt{a/t} / (2 \cdot b))]^{1/2}$ 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. [15], where D is the diameter in mm and P is the internal pressure in N/mm^2.
$K_1 = \sigma \sqrt{(\pi \cdot a / Q)} \cdot F_s$ $S = p \cdot D_{inner} / (2t)$ $Q = 1 + 1.464 (a/c)^{1.65}$ $F_s = 0.97 \cdot [M_1 + M_2 \cdot (a/t)^2 + M_3 \cdot (a/t)^4] \cdot C \cdot g \cdot f \cdot f_w$ $M_1 = 1.13 - 0.09 (a/c)$ $M_2 = -0.54 - 0.89 / (0.2 + a/c)$ $M_3 = 0.5 - 1 / (0.65 + a/c) + 14 (1 - a/c)^{24}$ $f_w = [\sec(\pi \cdot c \sqrt{(a/t) / (2 \cdot b)})]^{1/2}$ $C = [(D_{out}^2 + D_{in}^2) / (D_{out}^2 - D_{in}^2) + 1 - 0.5 \sqrt{a/t}] \cdot 2t / D_{in}$ 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. [15,18].
$K = \sigma_{mem} \cdot \sqrt{(\pi \cdot a)} \cdot M_k$ 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. [17].

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

where $w = H + t/2$

σ = nominal stress range in the longitudinal plates

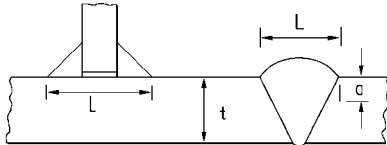
and with $x = H/t$

$$A_1 = 0.528 + 3.287 \cdot x - 4.361 \cdot x^2 + 3.696 \cdot x^3 - 1.875 \cdot x^4 + 0.415 \cdot x^5$$

$$A_2 = 0.218 + 2.717 \cdot x - 10.171 \cdot x^2 + 13.122 \cdot x^3 - 7.755 \cdot x^4 + 1.783 \cdot x^5$$

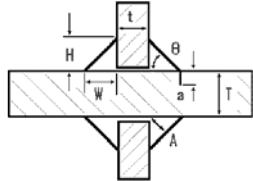
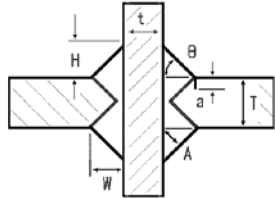
For a variety of welded joints parametric formulae of the M_k functions have been established and published [18,19]. For the majority of cases, the formulae given below are sufficient [20].

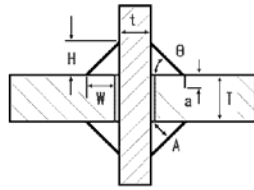
Tab. {6.2}-3:

Weld local geometry correction for crack at weld toe	
 L = 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. [20].
Stress intensity magnification factor $M_k > 1$ for <u>membrane stress</u>: for $l/t \leq 2$: $M_k = 0.51 \cdot (l/t)^{0.27} \cdot (a/t)^{-0.31}, \text{ for } (a/t) \leq 0.05 \cdot (l/t)^{0.55}$ $M_k = 0.83 \cdot (a/t)^{-0.15} \cdot (l/t)^{0.46}, \text{ for } (a/t) > 0.05 \cdot (l/t)^{0.55}$ 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 $l/t \leq 1$: $M_k = 0.45 \cdot (l/t)^{0.21} \cdot (a/t)^{-0.31}, \text{ for } (a/t) \leq 0.03 \cdot (l/t)^{0.55}$ $M_k = 0.68 \cdot (a/t)^{-0.19} \cdot (l/t)^{0.21}, \text{ for } (a/t) > 0.03 \cdot (l/t)^{0.55}$ for $l/t > 1$: $M_k = 0.45 \cdot (a/t)^{-0.31}, \text{ for } (a/t) \leq 0.03$ $M_k = 0.68 \cdot (a/t)^{-0.19}, \text{ for } (a/t) > 0.03$	

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

Tab. {6.2.4}: Formulae for 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:

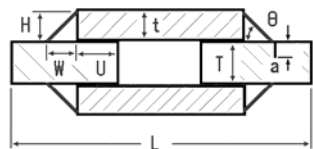
$$C = 0.2916 - 0.0620 \left(\frac{H}{T} \right) + 0.69421 \left(\frac{W}{T} \right) \quad (4)$$

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

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

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

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

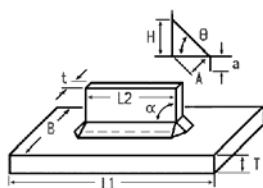
Lap joint

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

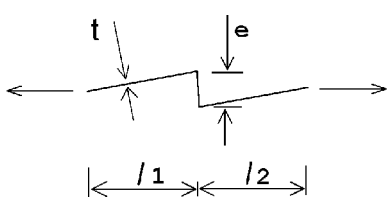
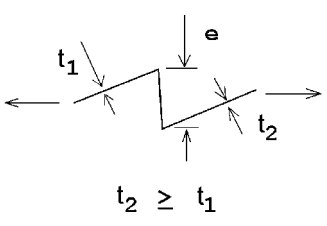
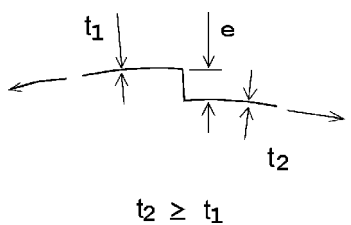
$$M_k = C \cdot \left(\frac{a}{T} \right)^k \quad M_k = \geq 1 \quad (7)$$

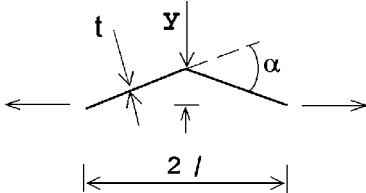
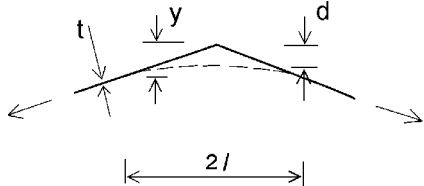
$$C = 0.9089 - 0.2357 \left(\frac{t}{T} \right) + 0.0249 \left(\frac{L}{T} \right) - 0.00038 \left(\frac{L}{T} \right)^2 + 0.0186 \left(\frac{B}{T} \right) - 1.1414 \left(\frac{\theta}{45} \right)$$

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

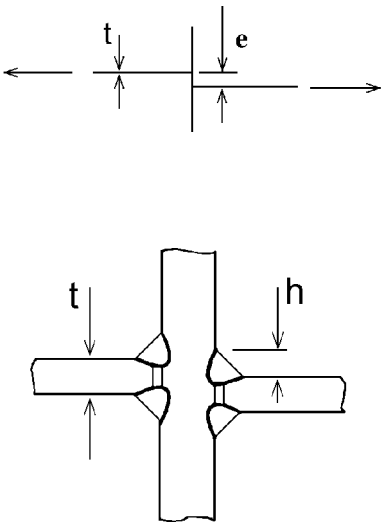
6.3 FORMULAE FOR MISALIGNMENT

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

#	TYPE OF MISALIGNMENT	
1	Axial misalignment between flat plates	
		$k_m = 1 + \lambda \cdot \frac{e \cdot l_1}{t(l_1 + l_2)}$
	λ is dependent on restraint, $\lambda=6$ 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	
		$k_m = 1 + \frac{6e}{t_1(1 - \nu y^2)} \cdot \frac{t_1^n}{t_1^n + t_2^n}$
	$n=1.5$ 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.
5	Angular misalignment at longitudinal joints in cylindrical shells  Assuming fixed ends: $\text{with } \beta = \frac{2l}{t} \sqrt{\frac{3(1-\nu y^2) \cdot \sigma}{E}}$ $k_m = 1 + \frac{3d}{t(1-\nu y^2)} \cdot \frac{\tanh(\beta/2)}{\beta/2}$ assuming pinned ends: $k_m = 1 + \frac{6d}{t(1-\nu y^2)} \cdot \frac{\tanh(\beta)}{\beta}$ d is the deviation from the idealized geometry

6	Ovality in pressurized cylindrical pipes and shells $k_m = 1 + \frac{1.5(D_{\max} - D_{\min}) \cdot \cos(2\Phi)}{t \left(1 + \frac{0.5 p_{\max}(1 - \nu^2)}{E} \cdot \left(\frac{\bar{D}}{t} \right)^2 \right)}$
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
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 different methods as described in 3.7 consider different statistical effects, when evaluating a set of fatigue data. Ideally, all effects have to be considered, e.g.

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

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

These characteristic values are, in principle, values at a **$\alpha=95\%$** survival probability (5% probability of failure) associated to a two sided confidence interval of 75% of the mean x_m and of the standard deviation **Stdv** of **$\beta=75\%$** (12.5% probability of being above or below the extreme value of the confidence interval):

$$x_k = x_m - k \text{ Stdv}$$

The factor **k_i** considers the effects a) to d) and corresponds to:

- the minimum value of the mean confidence interval
- the minimum value of the variance confidence interval

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

$$k_i = \frac{t_{(p, n-1)}}{\sqrt{n}} + \phi_{(alpa)}^{-1} \cdot \sqrt{\frac{n-1}{\chi^2_{(\frac{1+\beta}{2}, n-1)}}}$$

- 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 data (test specimens of details)
 - 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:

$$k_2 = \frac{t_{(0.875, n-1)}}{\sqrt{n}} + \Phi_{(0.95)}^{-1} = \frac{t_{(0.875, n-1)}}{\sqrt{n}} + 1.645$$

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

n	t	χ^2	k ₁	k ₂
2	251	28	1161	341
3	1.61	0.270	5.41	2.57
4	1.44	0.69	4.15	2.36
5	1.36	1.21	3.60	2.25
10	1.24	4.47	2.73	2.04
15	1.21	8.21	2.46	1.96
20	1.20	12.17	2.32	1.91
25	1.19	16.26	2.24	1.88
30	1.18	20.45	2.17	1.86
40	1.18	29.07	2.09	1.83
50	1.17	37.84	2.04	1.81
100	1.16	83.02	1.91	1.76

6.4.2 Statistical Evaluation at Component Testing

Testing all test specimens to failure

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

Starting from the formula in 4.5.2, there is

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

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

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

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

$$\log F = k \text{ Std}v$$

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

Testing all test specimens simultaneously until first failure

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

Starting from the formula in 4.5.2, there is

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

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

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

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

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

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

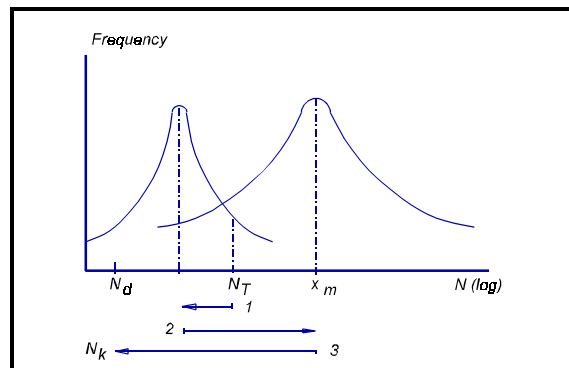


Fig. (6.4)-1 Distribution of action and resistance

$\log N_T$ 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:

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

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

Taking the acceptance criterion from chapter 3.7, $x_m - k_1 \text{Stdv} > x_k$, the factor **F** can be received:

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

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

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

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

For more details see ref. [35, 36].

Testing all specimens simultaneously until n failures amongst m specimens

Under development from IIW doc. XIII-1822-2000.

6.4.3 Statistical Considerations for Partial Safety Factors

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

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

Partial safety factor $\gamma_M \rightarrow$ 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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