GUIDELINES FOR FATIGUE AND STATIC ANALYSIS OF WELDED AND UN-WELDED STEEL STRUCTURES

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Summary

This report aims to present a guideline for; fatigue analysis of welded structures using nominal and structural hot spot stress methods according to International Institute of Welding (IIW) recommendations. The guideline also gives recommendations on fatigue assessment of cut edges for strip steel, structural steels according new recommendations for assessment presented by SSAB (Swedish Steel Ltd). Moreover, the guideline covers a section about static and ductile design of welded joints using different applicable standards, Eurocode 3 and BSK07. The different sections are described with detailed background and theory and later exemplified with different calculation examples.

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1. INTRODUCTION

1.1. Fatigue of welded structures

It is a well-known fact that material that is subjected to a fluctuating load may fail even though the magnitude of the load is such that the stresses produced are well below the yield strength. The fatigue life of a structure can be divided into three phases: initiation, propagation and final failure. The fatigue strength of welded structures is mainly reduced due to; local and global stress concentrations, welding residual stresses and weld defects and flaws. The local stress concentration in combination with defects will result in early crack initiation and the weld fatigue will be dominated by crack growth. The material strength in this case will only affect the crack initiation. The existence of welding residual stresses will influence the fatigue life, in many cases reducing it. Figure 1a illustrate the reduction of the fatigue strength for welded structures in comparison with base material due to; i) weld shape and joint geometry ii) stress concentration due to weld imperfections iii) high tensile residual stresses.

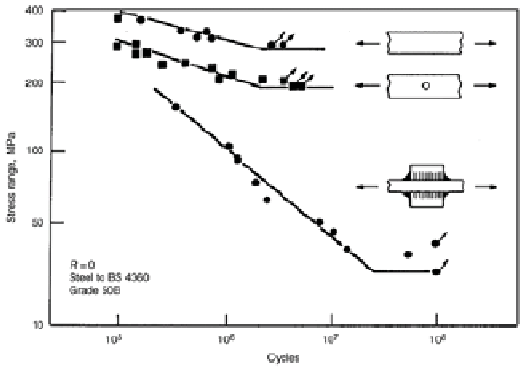


Figure 1a. Fatigue strength for base material, perforated base material and welded structure.

Figure 1b shows the different phases of the fatigue life and relevant factors that are assessed to estimate the fatigue life at the different phases. The fatigue phenomenon and the progressive damage due to the cyclic loading are governed by local quantities (defects, flaws, stress concentrations, etc…) and to develop proper design methods will estimate the fatigue life they also need to be based on local approaches.

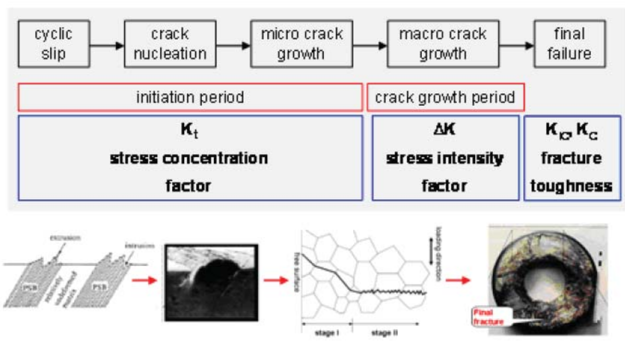


Figure 1b. Different phases in the fatigue life process.

Today there are mainly four methods to predict fatigue on welded components and they are defined in IIW Fatigue Design Recommendations, see Hobbacher [1]:

- Nominal stress approach
- Structural/Geometrical “hot-spot” stress approach
- Effective notch stress approach
- Linear elastic fracture mechanical crack growth approach

Fatigue resistance of complex welded components based on stress analysis performed with FEA can be assessed in many ways with varying degrees of time consumption and accuracy. A large model will increase both the model preparation and the computational time. Large and complex FEA models may include several critical locations and complex boundary conditions, see example in Figure 2a where the stress value is continually changing. Nominal stress values are in this case difficult or impossible to define. Even if a nominal stress can be defined, one must select from a catalogue of details, the geometry most closely resembling the actual welded detail. In many cases the actual weld has little similarity to one of the geometries shown in the standard. A schematic overview over complexity and work effort for different design methods are presented in Figure 2b.

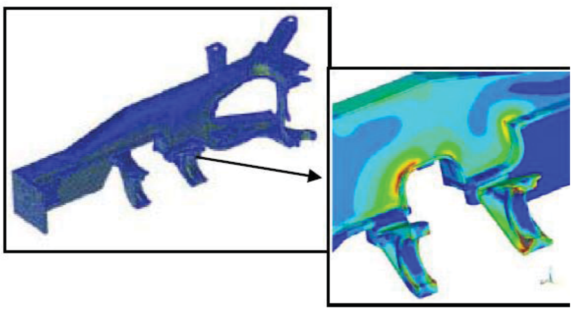


Figure 2a. Stresses in a construction machinery frame, near the attachment of the axle housing, red color corresponds to high and blue to low stresses.

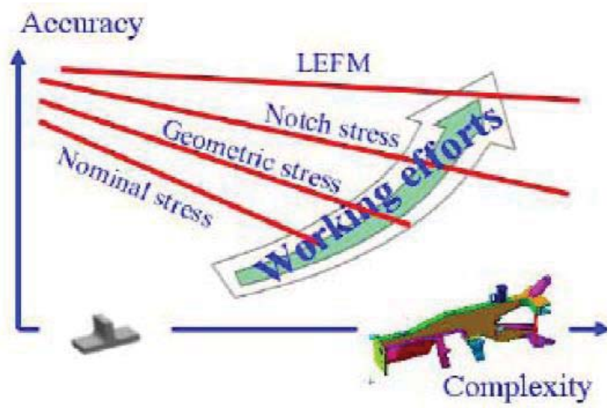


Figure 2b. Schematic overview pf accuracy, complexity and work effort associated with the different fatigue assessment methods for welded structures.

1.2. Fatigue of cut edges

In fatigue loaded applications it is important that the introduction of high strength steels goes hand in hand with the improvement of production quality. Since defects are commonly induced from the manufacturing processes such as welding and cutting, these will eventually delimit the service life of the structure if steels with increased strength are used. Post weld treatment methods or improved welding processes can be utilized to improve the weld quality end thereby enable design benefits when using high strength steels. However, when using high strength steel to reduce the plate thickness and thereby enable lightweight design, the overall stress levels in the structure increases. Thus, other locations such as the cut edges may become critical for fatigue failure unless they are not designed and manufactured with the same quality as the welded joint. The main governing factors of the fatigue strength in cut edges are the surface quality (surface roughness, hardness etc.), yield and ultimate strength of the material and residual stresses induced during the manufacturing, which must be taken into consideration in the fatigue design phase [2, 3].

From a design point of view, it is very convenient to utilize the quality level system on the drawing to communicate the necessary quality of a component feature, not only for the weld quality but also the cut edge quality. This is essential if to enable lightweight design of fatigue loaded welded structures, were the specified quality on the drawing reflects the fatigue strength. The international standard ISO 9013:2002 [4] provide quality acceptance limits of the surface roughness produced using thermal cutting, and classify the geometrical tolerances into four different ranges, where range 1 is the highest (smoothest surface) quality and range 4 is the lowest quality. Each quality range is defined as the maximum allowed surface roughness R_z as a function of the plate thickness.

Stenberg et al [2] conducted a study of whether the quality acceptance limits for surface roughness within ISO 9013:2002 [4] correlates to the fatigue strength of cut edges in plate thickness >12mm. Fatigue testing was conducted on material with different strength which were cut using various cutting processes. Surface roughness and residual stress measurements were also conducted. The fatigue strength was estimated by correlating the measured surface roughness with the quality acceptance limits within ISO9013:2002 along with the fatigue strength model developed by Sperle [3], see figure 3a. The testing proved a 15-70% increase of the fatigue strength compared to the estimation, see figure 3b. This proves a weak link to between the quality levels within ISO 9013:2002 and the resulting fatigue strength of cut edges.

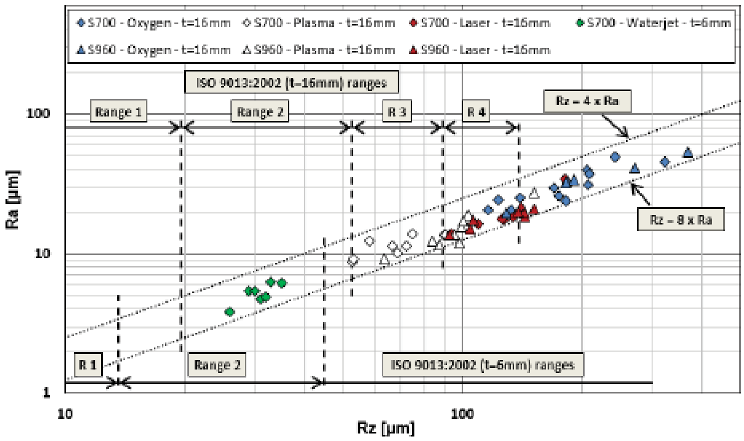


Figure 3a. Surface roughness measurement on cut edges.

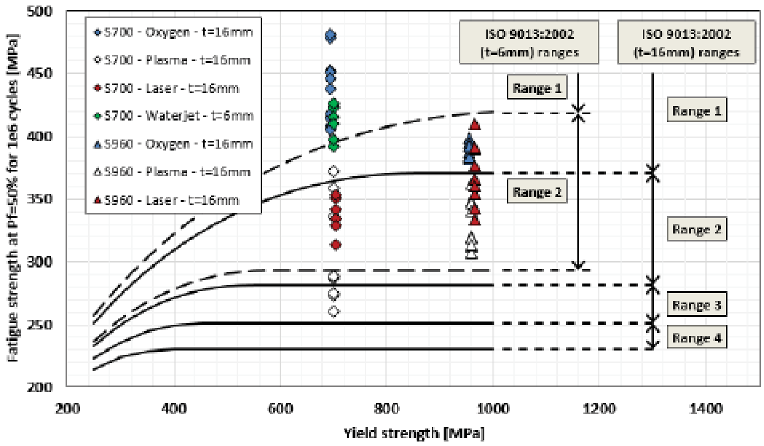


Figure 3b. atigue strength and limit lines using fatigue strength model developed by Sperle [3] and surface roughness acceptance limits in ISO 9013:2002.

2. STATIC JOINT DESIGN

2.1. Basic design

The design methods taken from EN 1993 assume that the standard of construction is as specified in the execution standards set designer and that the construction materials and products used are those specified in EN 1993 or in the relevant material and product specifications.

All joints shall have a design resistance such that the structure can satisfy all the basic design requirements provided by the designer according to specific codes, including in EN 1993 parts 1-1, 1-8 [5].

Local yielding can be accepted in areas with stress concentrations when designing against static loads, where two requirements must be assessed:

1) Based on the total cross-sectional area (A_{gr}) (with no deductions for holes), the capacity is appraised with the design strength value

$$f_{yd} = \frac{f_{yk}}{\gamma_{M0}}$$

2) Based on the net area (A_{net}) (with deduction for holes in the cross-sectional area), the load capacity is appraised with the design strength value:

$$f_{ud} = \frac{0.9 * f_{uk}}{\gamma_{M2}}$$

The lower of these two values should be used when determining the capacity of the cross-section.

f_{yk} = characteristic yield limit
f_{uk} = characteristic ultimate strength
f_{yd} = design yield limit
f_{ud} = design ultimate strength

γ_{M0} and γ_{M2} are partial coefficients and according to Eurocode 3, the partial coefficients can be chosen as follows:
γ_{M0} = 1.0 (for cross sections where the load carrying capacity is limited by the yield strength of the material)
γ_{M1} = 1.0 (for cross sections where the load carrying capacity is limited by the instability of the structure)
γ_{M2} = 1.25 (for cross sections in pure tension or when assessing joints)

When analyzing welded (and bolted joints it is sufficient to calculate the capacity of the joint based on f_{ud}. Fully formed plastic hinges can be accepted for joints under static load, but in this case the deformations of the structure should also be checked so that these do not become unacceptably large.

In case of joints subjected to fatigue which are assessed against maximum (static) loads, the analyses should follow the theory of elasticity, even if the load capacity is based on the ultimate strength of the material. If several stresses act simultaneously, von Mises criterion should be used for the assessment.

2.2. General

EN 1993 parts 1-1, 1-8 is valid for weldable structural steels according to EN 1993-1-1 with a yield strength is between 235 – 460 MPa. For materials with higher yield strength, S500 – S700 MPa EN 1993-1-12 gives recommendations on compensation of the strength with correlation factor β_w. The rules are valid for material with thickness ≥ 4 mm and for butt welds, fillet welds and plug welds. The filler material should at least have the same strength properties (yield) as the base material according to EN 1993-1-8, but undermatching filler material is allowed for S500-S700 MPa.

2.3. Butt welds

For full penetration butt welds, where welding has been carried out with filler material which gives a welded joint with at least the same strength as for the base material, then the weld resistance equal the resistance for the weakest part of the joined connection. That is, a butt weld with complete penetration can be assumed to be of equal strength to the lowest steel grade in the welded joint if the weld was produced using overmatching filler material. Figure 4 gives some examples of full penetrated butt welds.

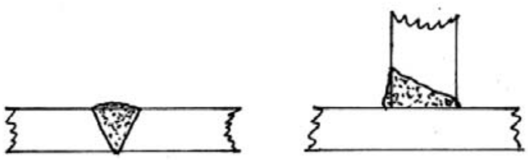


Figure 4. Full penetrated butt welds.

Partially penetrated butt welds are designed and analyzed as fillet welds. Even if the weld is centric in the plate, the weld is eccentric loaded. The welds designing cross section is affected by normal force and moment, see figure 5. If the plates are controlled or brought into force by a rigid structure the weld can be considered centrically loaded.

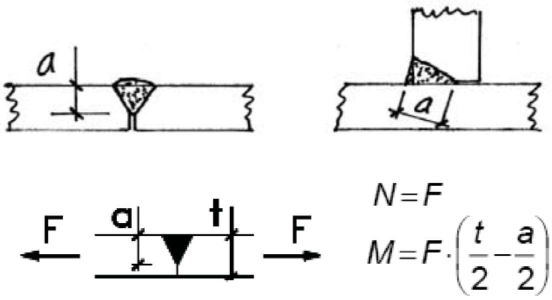


Figure 5. Partial penetrated butt welds.

The design resistance of a T-butt joint, consisting of a pair of partial penetration butt welds reinforced by superimposed fillet welds, may be determined as for a full penetration butt weld if the total nominal throat thickness, exclusive of the un-welded gap, is not less than the thickness t of the part forming the stem of the tee joint, provided that the un-welded gap is not more than (t / 5) or 3 mm, whichever is less, see figure 6.

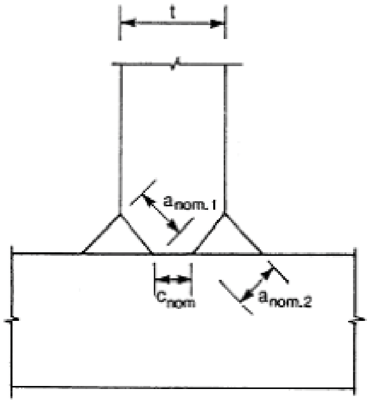


Figure 6. Effective penetration for T-butt welds.

The design resistance of a T-butt joint which does not meet the requirements should be determined using the method for a fillet weld or a deep penetration fillet weld, depending on the amount of penetration. The throat thickness should be determined in conformity with the provisions for both fillet welds and partial penetration butt welds.

2.4. Fillet welds

The rules for fillet welds are valid if the angle between the welded plates is 60° ≤ α ≤ 120°. If the angle is < 60° then the fillet weld should be designed as partial penetrated butt weld. If the angle is > 120°, then the fillet weld should also be designed as partial penetrated butt weld, see figure 7.

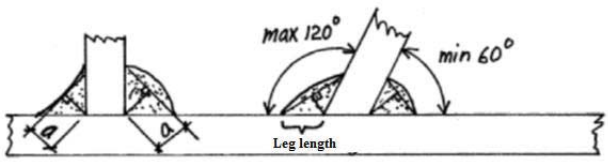
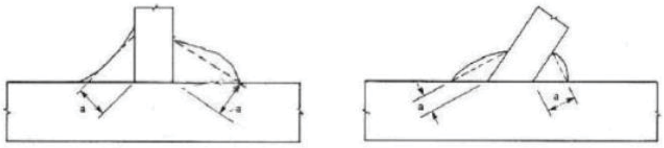
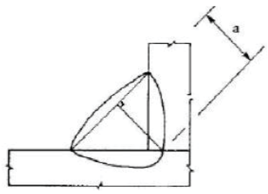


Figure 7. Angles for fillet welds.

The throat thickness should be ≥ 3 mm. The effective length of the weld, l_{eff}, is the effective length where the weld has full and even dimension. If the welding procedure assure full dimension also at start and stop; l_{eff} then equals the full weld length. Otherwise l_{eff} = full weld length – 2*throat thickness. Figure 8 illustrate how the throat thickness is defined for fillet welds and deep penetration.





Throat thickness of fillet welds *Throat thickness of deep penetration fillet weld*

Figure 8. Throat thickness for fillet welds.

One has to determine the smallest effective weld length for load carrying fillet welds which is sufficient. The effective weld length l_{eff} should be at least 30 mm and at least 6 times the throat thickness;

- For throat thickness < 5 mm: l_{eff} at least 30 mm
- For throat thickness > 5 mm: l_{eff} at least 6*throat thickness

2.5. Design resistance

The design resistance of a fillet weld should be determined using:
- Directional method
- Simplified method

Directional method

In directional method, the forces transmitted by a unit length of weld are resolved into components parallel and transverse to the longitudinal axis of the weld and normal and transverse to the plane of its throat.

The design throat area A_w should be taken as $A_w = \Sigma\ a*l_{eff.}$

The location of the design throat area should be assumed to be concentrated in the root. A uniform distribution of stress is assumed on the throat section of the weld, leading to the normal stresses and shear stresses (figure 9), as follows:
$\sigma_{\perp}$ - is the normal stress perpendicular to the throat
$\sigma_{||}$ - is the normal stress parallel to the axis of the weld
$\tau_{\perp}$ - is the shear stress (in the plane of the throat) perpendicular to the axis of the weld
$\tau_{||}$ - is the shear stress (in the plane of the throat) parallel to the axis of the weld

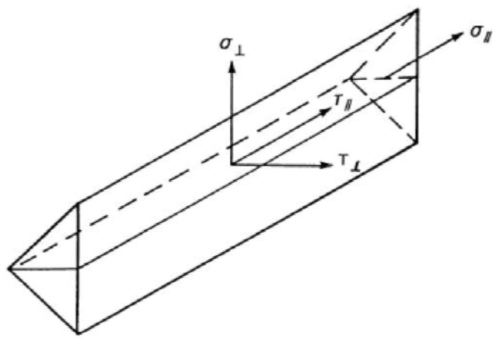


Figure 9. Stress components in a fillet weld.

The components $\sigma_\perp$, $\tau_\perp$ and $\tau_{||}$ are due to external forces the weld will transfer and should considered in the design. Residual stresses are not considered. The component $\sigma_{||}$ do not transfer any load and should not be considered. The stress components due to the force transmitted through the weld is calculated and assembled into a effective comparison stress. The effective stress should not exceed the design value of the welded joints strength.

$$\sigma_j = \sqrt{\sigma_{\parallel}^2 + 3\left(\tau_{\perp}^2 + \tau_{\parallel}^2\right)}$$

Two design criteria's must be fulfilled in the calculation cross section:

1. The effective stress should maximum be the design value for the welded joints strength

$$\sqrt{\sigma_{\perp}^2 + 3\left(\tau_{\perp}^2 + \tau_{\parallel}^2\right)} \leq \frac{f_u}{\beta_w \gamma_{M2}}$$

   Where the right-hand side is the weld joint strength. The filler material strength is at least the base material strength.

2. The normal stress perpendicular to the design cross section should maximum be the design value for the base material strength

$$\sigma_{\perp} \leq \frac{0.9 f_u}{\gamma_{M2}}$$

f_u is the nominal ultimate tensile strength of the weaker part joined. β_w is the appropriate correlation factor taken from table 1.

Welds between parts with different material strength grades should be designed using the properies of the material with the lower strength grade. For undermatching filler material for S500-S700, the filler materia strength is used.

Table 1. Correlation factor β_w for fillet welds.

Standard and steel grade			Correlation factor β_w
EN 10025	EN 10210	EN 10219	
S 235 S 235 W	S 235 H	S 235 H	0.8
S 275 S 275 N/NL S 275 M/ML	S 275 H S 275 NH/NLH	S 275 H S 275 NH/NLH S 275 MH/MLH	0.85
S 355 S 355 N/NL S 355 M/ML S 355 W	S 355 H S 355 NH/NLH	S 355 H S 355 NH/NLH S 355 MH/MLH	0.9
S 420 N/NL S 420 M/ML		S 420 MH/MLH	1.0
S 460 N/NL S 420 M/ML S 420 Q/QI/QL1	S 460 NH/NLH	S 460 NH/NLH S 460 MH/MLH	1.0

The stresses $\sigma_\perp$ and $\tau_\perp$ can be determined according to figure 10.

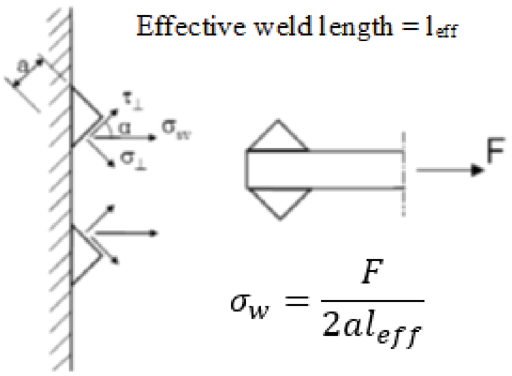


Figure 10. definition of stresses $\sigma_\perp$ and $\tau_\perp$.

If the fillet weld is symmetrical, then

$$\sigma_\perp = \frac{F}{2al_{eff}} \sin\alpha$$

$$\tau_\perp = \frac{F}{2al_{eff}} \cos\alpha$$

If the welds are also isosceles, $\alpha = 45^\circ$, and thus

$$\sigma_\perp = \tau_\perp = \frac{F}{2\sqrt{2} * a * l_{eff}}$$

Simplified method

In the simplified method, the design resistance of a fillet weld may be assumed to be adequate if, at every point along its length, the resultant of all the forces per unit length transmitted by the weld satisfy the following criterion;

$$F_{w,Ed} \leq F_{w,Rd}$$

Where:
$F_{w,Ed}$ is the design value of the weld force per unit length;
$F_{w,Rd}$ is the design weld resistance per unit length.

Independent of the orientation of the weld throat plane to the applied force, the design resistance per unit length $F_{w,Rd}$ should be determined from:

$$F_{w,Rd} = f_{vw.d} * a$$

where:
$f_{vw.d}$ is the design shear strength of the weld. The design shear strength $f_{vw.d}$ of the weld should be determined from:

$$\frac{f_u}{\sqrt{3} * \beta_w * \gamma_{M2}} \approx 0.6 * \frac{f_u}{\beta_w * \gamma_{M2}}$$

The weld joint strength is lowest in pure shear stress. To be on the safe side this strength value could be used independent of the load direction in the design cross section

Fillet welds – some special cases

The design value for the welded joint strength is described earlier as

$$\frac{f_u}{\beta_w \gamma_{M2}}$$

However, when the load is only in the welds longitudinal direction (only $\tau_{||}$), then the welded joints load capacity becomes

$$0.6 * a * l_{eff} \frac{f_u}{\beta_w \gamma_{M2}}$$

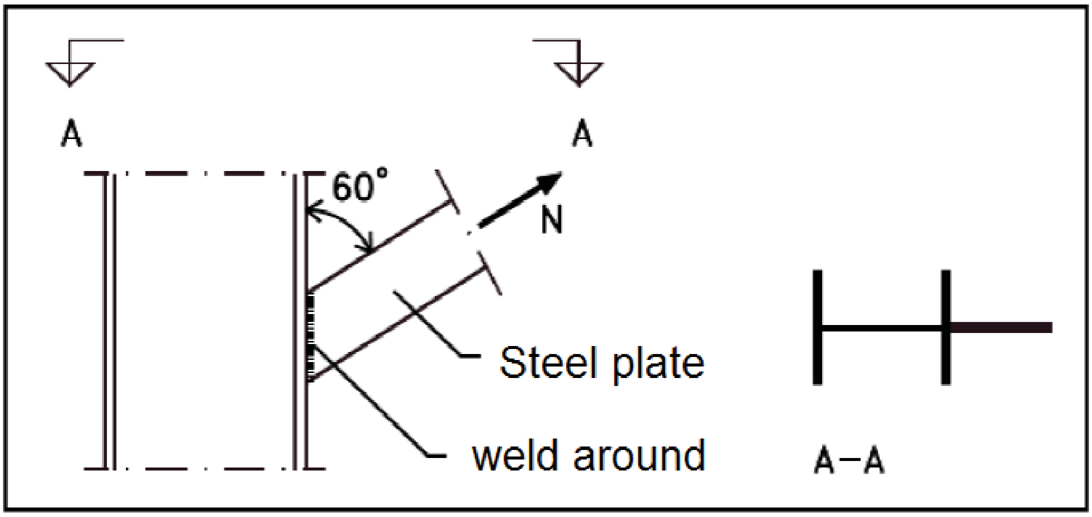
If the loads are only perpendicular to the welds length direction and in 45° angle to the design cross section, then the welded joints load capacity becomes

$$0.7 * a * l_{eff} \frac{f_u}{\beta_w \gamma_{M2}}$$

2.6. Examples – static joint design

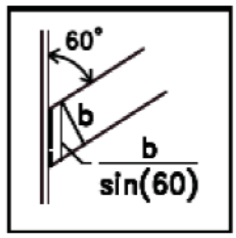
Example 1

A plate 10x120 mm is attached to a HEA column. The centric tensile load is N = 260 kN. The plate is welded with a fillet weld around with throat thickness of 4 mm. The material in the column and the plate is S275, f_u = 430 MPa. The correlation factor for the welded join strength β_w = 0.85 (EN 1993-1-8). Can the welded connection sustain this load?



Solution:

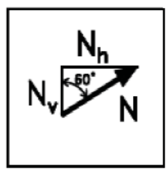
The weld at both sides of the weld is included and the plate is welded all around. The effective weld length, l_{eff}, becomes



$$l_{eff} = 2 * \frac{b}{\sin(60)} = 2 * \frac{120}{\sin(60)} = 2 * 138.5 = 277\ mm$$

The loads vertical component, N_v, results in shear stress $\tau_{||}$

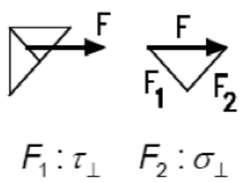
$$N_v = N * \cos(60) = 260 * \cos(60) = 130\ kN$$



$$\tau_{||} = \frac{N_v}{a * l_{eff}} = \frac{130 * 10^3}{4 * 277} = 117\ MPa$$

The loads horizontal component N_h results in the stress components $\sigma_\perp$ and $\tau_\perp$

$$N_h = N * \sin(60) = 260 * \sin(60) = 225\ kN$$



$$\sigma_\perp = \tau_\perp = \frac{N_h}{\sqrt{2} * a * l_{eff}} = \frac{225 * 10^3}{\sqrt{2} * 4 * 277} = 144\ MPa$$

Design criteria $\sigma_j \leq \frac{f_u}{\beta_w * \gamma_{M2}}$ *and* $\sigma_\perp \leq \frac{0.9 * f_u}{\gamma_{M2}}$

Design values for the weld joint strength $\frac{f_u}{\beta_w * \gamma_{M2}} = \frac{430}{0.85 * 1.2} = 422\ MPa$

Design value for the base material strength $\frac{0.9 * f_u}{\gamma_{M2}} = \frac{0.9 * 430}{1.2} = 322\ MPa$

$$\sigma_j = \sqrt{\sigma_\parallel^2 + 3\left(\tau_\perp^2 + \tau_\parallel^2\right)} = \sqrt{144^2 + 3 * (144^2 + 117^2)} = 352\ MPa =$$

$\sigma_j = 352\ MPa < 422\ MPa$ OK!

$\sigma_\perp = 144\ MPa < 322\ MPa$ OK!

Both criteria's are fulfilled. The weld strength is sufficient!

The load 260 kN gives the stress 352 MPa, the weld joint strength is 422 MPa

$\frac{422}{352} * 260 = 312\ kN$ = the weld strength calculated with the directional method

If we calculate the strength with the simplified method

$$a * l_{eff} \frac{\frac{f_u}{\sqrt{3}}}{\beta_w \gamma_{M2}} = 4 * 277 * \frac{\frac{430}{\sqrt{3}}}{0.85 * 1.2} = 270\ kN$$

$\frac{312}{270} = \mathbf{1.15}$ In this case the directional method gives a strength 15 % higher than the simplified method

Example 2

Overlap joint, plate with centric tensile load N. Fillet welds with throat thickness 4 mm along three edges. Material S275 (f_u = 430 MPa, β_w = 0.85), effective weld length l_{eff} = 100 mm, b_{eff} = 120 mm.

If the joint has enough deformation capability the resistance can be set equal to the sum of the individual weld resistance. Condition: $0.5 \leq l/b \leq 2$

Determine the joints total load resistance.

Solution:

The weld joint strength resistance: $\frac{f_u}{\beta_w * \gamma_{M2}} = \frac{430}{0.85*1.2} = 422\ MPa$

Strength for the different welds:

Longitudinal welds $0.6 * a * l_{eff} * 422 = 0.6 * 4 * 100 * 422 = 101\ kN$

Transversal weld $0.7 * a * b_{eff} * 422 = 0.7 * 4 * 120 * 422 = 142\ kN$

The joint total resistance $2 * 101 + 142 = 344\ kN$

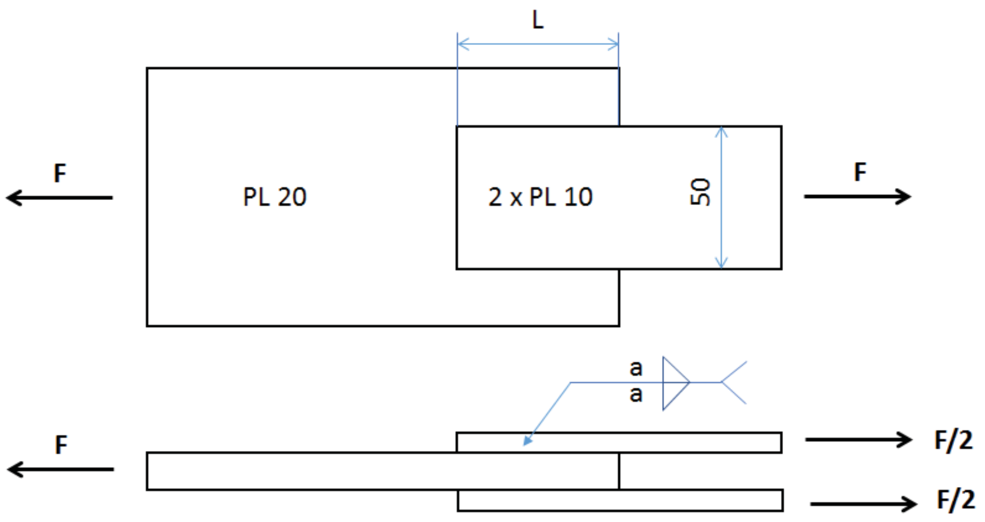
Example 3

Two flat steel bars 10x50 mm are welded onto a thicker sheet. They are subjected to static load with a tensile force F = 250 kN. Determine the required minimum length L and the throat a. Material S355J0 (f_{uk} = 490 MPa), overmatching electrodes are used. The following partial coefficients are assumed:

Material properties $\gamma_{M0} = 1.0$ $\gamma_{M2} = 1.25$

Load factor $\gamma_F = 1.1$

Consequence of failure $\gamma_n = 1.2$



Solution:

The maximum throat thickness for the fillet weld is $a_{max}=10/\sqrt{2} = 7$ mm

The joint has a total of 4 welds, the design throat area is $A_w = \sum a * l_{eff} = 4 * a * l_{eff}$

and the shear stress parallel to the weld is therefore $\tau_{||d} = \frac{F_{||k} * \gamma_F * \gamma_n}{A_w}$

The strength requirement is $\sqrt{3} * \tau_{||d} \leq \frac{f_{wuk}}{\beta_w * \gamma_{M2}}$

Where $\beta_w = 0.9$ and $f_{wuk} = f_{uk}$ for overmatching electrodes. With the values inserted;

$$\sqrt{3} * \frac{F_{||k} * \gamma_F * \gamma_n}{A_w} \leq \frac{f_{wuk}}{\beta_w * \gamma_{M2}} \quad or$$

$$F_{||k} \leq \frac{f_{uk} * A_w}{\beta_w * \gamma_{M2} * \sqrt{3} * \gamma_F * \gamma_n} = \frac{490 * 28 * l_{eff}}{0.9 * 1.25 * \sqrt{3} * 1.1 * 1.2} = 5334 * l_{eff}$$

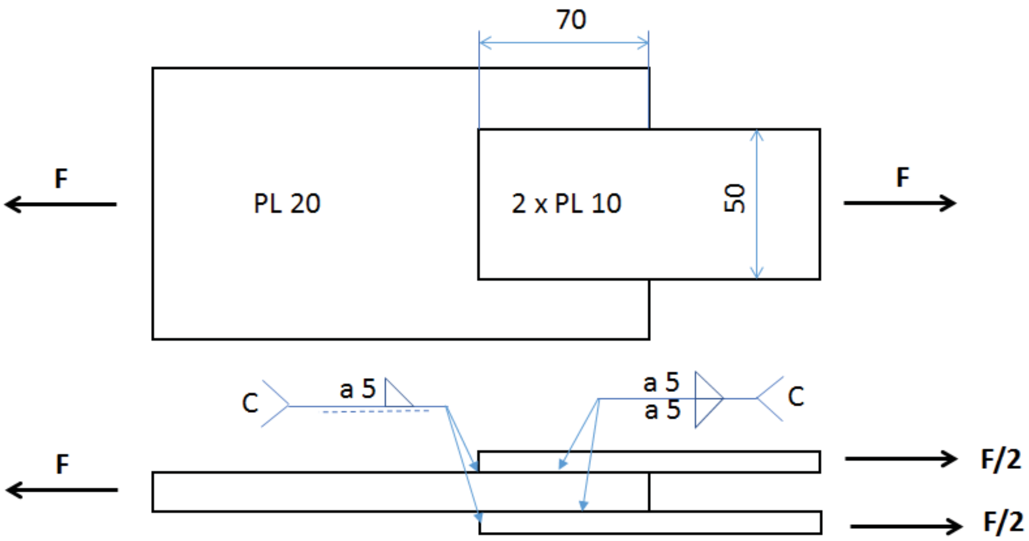
$$l_{eff} \geq \frac{F_{||k}}{5334} = \frac{250000}{5334} = 47\ mm$$

The length is to close to the requirement $l_{eff} > 6*a = 42$ mm. Instead select a = 5 mm which gives an effective length of $l_{eff} = 47*7/5 = 66$ mm. The weld length L should be at least 80 mm (66 mm + start and stop (2*5 mm) + rounding to the nearest higher even 5 mm. The weld throat need to be 5 mm with weld class C, EN-ISO 5817.

Example 4

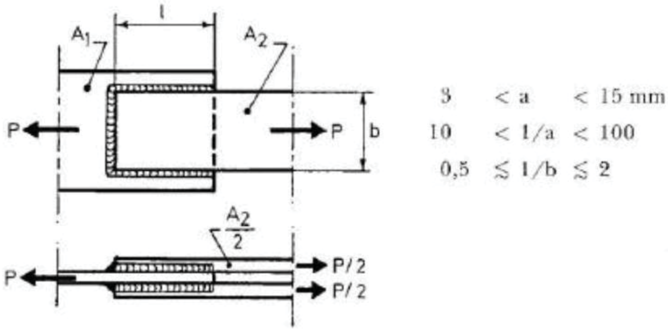
What force can the welded joint transfer if it is a weld class C joint produced with overmatching electrodes? Material S460QL (f_{uk} = 550 MPa, f_{yk} = 460 MPa). The following partial coefficients are assumed:

Material properties	$\gamma_{M0} = 1.0$	$\gamma_{M2} = 1.25$
Load factor	$\gamma_F = 1.1$	
Consequence of failure	$\gamma_n = 1.2$	



Solution

Interacting longitudinal and transverse welds can be calculated in accordance with plasticity theory if they are subjected only to static loads and if the requirements below are fulfilled. The condition for failure analysis



The stresses can be considered even distributed over the calculation cross section if; l > 10*a, l < 100*a (in static loading), l < 60*a (in fatigue loading), a > 3 mm and a < 15 mm.

The load carrying capacity of the longitudinal welds

There is totally four longitudinal welds. Their effective length is l_{eff} = 70 – 5 = 65 mm (reduction for the start, free ends, but not stop where the longitudinal and transverse welds meet)

The following equation should apply

$$\sqrt{\sigma_\perp^2 + 3\left(\tau_\perp^2 + \tau_\parallel^2\right)} \leq \frac{f_{wuk}}{\beta_w \gamma_{M2}}$$

With $\sigma_\perp = \tau_\perp = 0$, $\tau_{||} = F_{||k} * \gamma_F * \gamma_n / a * l_{eff}$ and $f_{wuk} = f_{uk}$ (overmatching electrodes)

$$\sqrt{3} * \frac{F_{||k} * \gamma_F * \gamma_n}{a * l_{eff}} \leq \frac{f_{uk}}{\beta_w * \gamma_{M2}}$$

$\beta_w = 1.0$ for S460 and $F_{||k} = \frac{5*65*550}{\sqrt{3}*1.1*1.2*1.0*1.25} = 62.5\ kN$

The force capacity in one longitudinal weld is $F_{||k} = 62.5\ kN$

The load carrying capacity of the transverse welds

There are two transverse welds. Their effective length is l_{eff} = 50 mm, so no start/stop is considered.

$$\sqrt{\sigma_\perp^2 + 3\left(\tau_\perp^2 + \tau_\parallel^2\right)} \leq \frac{f_{wuk}}{\beta_w \gamma_{M2}}$$

With $\tau_{||} = 0$ and $\sigma_\perp = \tau_\perp = \frac{1}{\sqrt{2}} * \frac{F_{\perp k} * \gamma_F * \gamma_n}{a * l_{eff}}$ then

$$\sqrt{2} * \frac{F_{\perp k} * \gamma_F * \gamma_n}{a * l_{eff}} \leq \frac{f_{uk}}{\beta_w * \gamma_{M2}}$$

or if $f_{wuk} = f_{uk}$ and $\beta_w = 1.0$

$$F_{\perp k} = \frac{5 * 50 * 550}{\sqrt{2} * 1.1 * 1.2 * 1.0 * 1.25} = 58.9\ kN$$

The force capacity in one transverse weld is $F_{\perp k}$ = 58.9 kN

As there are 4 longitudinal and 2 transverse welds, the total load carrying capacity is:

$F_{tot,k} = 4*F_{||k} + 2*F_{\perp k}$ = 4*62.5 + 2*58.9 =368 kN

Assessment of the two sheets PL10x50,

Designing strength $f_{yd} = \frac{f_{yk}}{\gamma_{M0}} = \frac{460}{1.0}$ = 460 MPa

$f_{ud} = \frac{0.9*f_{uk}}{\gamma_{M2}} = \frac{0.9*550}{1.25}$ = 396 MPa which is lower thatn f_{yd}

The force capacity of the sheets is

$$F_{Rk} = \frac{f_{ud} * A_{pl}}{\gamma_F * \gamma_n} = \frac{396 * 2 * 50 * 10}{1.1 * 1.2} = 300kN$$

The welds are able to withstand a force of 368 kN, but the two sheets PL50x10 can only transfer the force 300 kN

3. FATIGUE ASSESSMENT OF WELDED STRUCTURES

Fatigue assessment and the utilization of reliable and accurate design methods is challenging for the design analysist in two ways. The fatigue damage mechanisms itself is a local phenomenon, which require a very dense finite element mesh. However, welded structures are in general large geometrically complex components with varying loading and complex boundary conditions, which may be difficult to define accurately. Such demands are satisfied using large and complex finite element models, which in turn makes the fatigue assessment process very time consuming.

The IIW recommendations for fatigue assessment of welded structures [1] provides a comprehensive description of the common fatigue assessment methods for welded structures:

- Nominal stress approach
- Structural "hot spot" stress approach
- Effective notch stress approach
- Linear elastic fracture mechanics approach (LEFM)

The fatigue assessment of both simple and complex welded structures using finite element analysis can be assessed using the above-mentioned methods. These methods vary in accuracy and time consumption depending on the required accuracy, which is illustrated in figure 12. A large and complex model will increase the total assessment time in terms of preparation, solving and post processing.

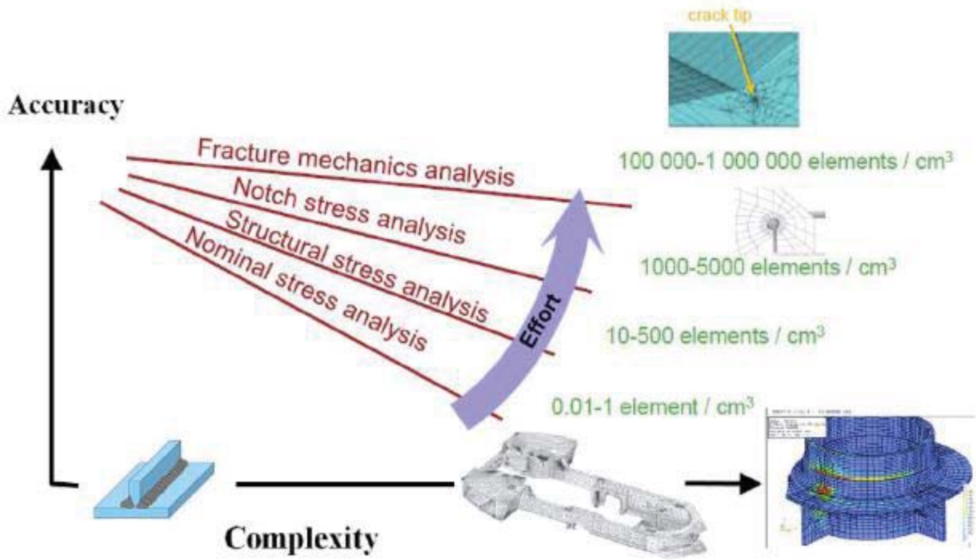


Figure 12. Schematic overview of the accuracy, complexity and work effort associated with the different fatigue assessment methods, reproduction of [6].

3.1. Nominal stress method

3.1.1. Definition of stress components

The stress distribution over the plate thickness is non-linear in the vicinity of notches. The stress components of the notch stress are (Figure 12):
σ_{mem} membrane stress,
σ_{ben} shell bending stress,
σ_{nlp} non-linear stress peak

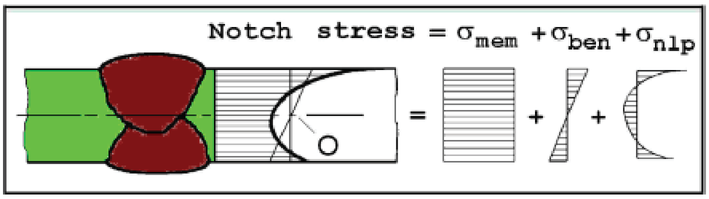


Figure 12. the stress distribution over the plate thickness

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, and it is constant through the thickness,
- the shell bending stress σ_{ben} is linearly distributed through the thickness of the plate, and it is found by drawing a straight line through the point "0" 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 σ(x) for x=0 at surface to x=t at through thickness.

3.1.2. Nominal stress

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 macro-geometric shape of the component near the joint, such as e.g. large cutouts. Overall elastic behavior is assumed. The nominal stress may vary over the section under consideration. For example, at a beam-like component, the modified (also local) nominal stress and the variation over the section can be calculated using simple beam theory. Here, the effect of a welded on attachment is ignored (Figure 13).

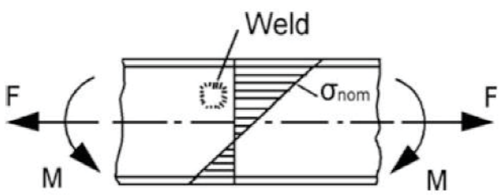


Figure 13. Nominal stress in a beam-like structure.

The effects of macro-geometric features of the component and stress fields in the vicinity of concentrated loads must be included in the nominal stress. Both may cause significant redistribution of the membrane stresses across the section. Significant shell bending stress may also be generated, as in curling of a flange, or distortion of a box section (Figures. 14, 15a, b).
The secondary bending stress caused by axial or angular misalignment (e.g. as considered to be acceptable in the fabrication specification) needs to be considered if the misalignment exceeds the amount which is already covered by the fatigue resistance S-N curve for the structural detail.

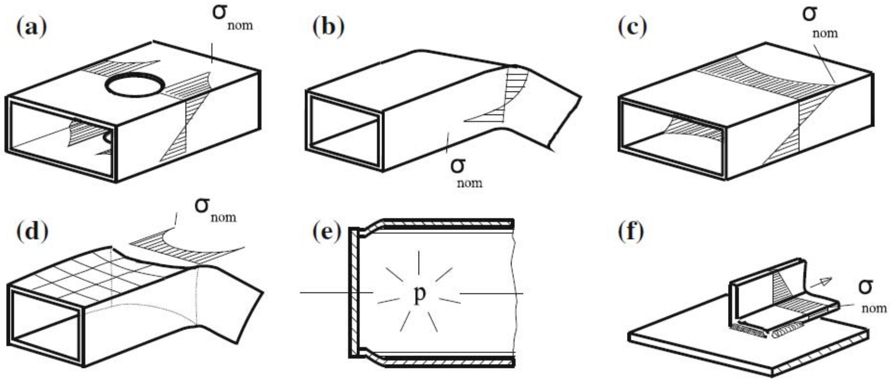


Figure 14. Examples of macrogeometric effects. Stress concentrations at **a)** cut-outs, **b**) curved beams, **c**) wide plates, **d)** curved flanges, **e)** concentrated loads, **f)** eccentricities.

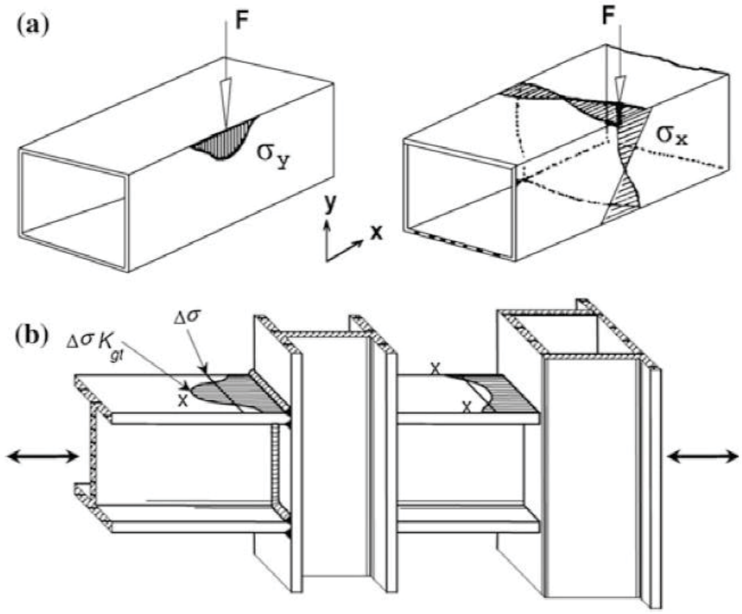


Figure 15. **a)** Modified (local) nominal stress near concentrated loads. **b)** Modified (local) nominal stress at hard spots

3.1.3. Calculation of nominal stress

In simple components the nominal stress can be determined using elementary theories of structural mechanics based on linear-elastic behavior. Nominal stress is the average stress in the weld throat or in the plate at the weld toe as indicated in the tables of structural details. A possible misalignment shall be considered either in analysis or in resistance data (Figure 16a). The weld throat is determined at (Figure 16b).

Butt welds: Wall thickness of the plates, at dissimilar wall thicknesses, the smaller wall thickness has to be taken
Fillet welds: The smallest distance from the root or deepest point of penetration to the surface of the fillet weld bead

The stress σ_w or τ_w in weld throat a for a weld of length l_w and a force in the weld F becomes

$$\sigma_w \quad or \quad \tau_w = \frac{F}{A_w} = \frac{F}{a \cdot l_w}$$

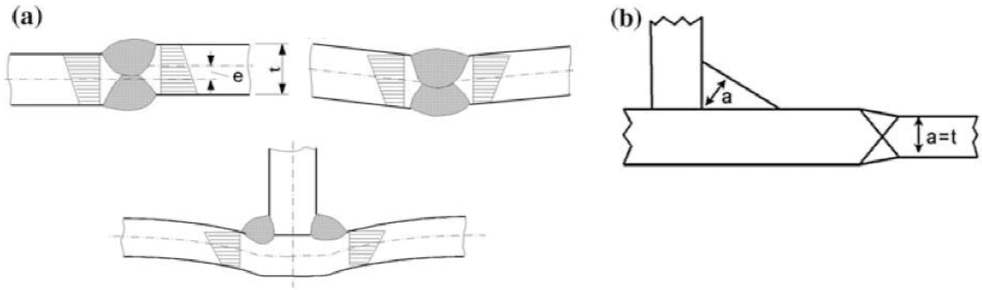


Figure 16. **a)** Axial and angular misalignment. **b)** Weld throat

In other cases, finite element method (FEM) modelling may be used. This is primarily the case in
(a) complex statically over-determined (hyper static) structures
(b) structural components incorporating macro-geometric discontinuities, for which no analytical solutions are available

If the finite element method is used, meshing can be simple and coarse. Care must be taken to ensure that all stress concentration effects from the structural detail of the welded joint are excluded when calculating the modified (local) nominal stress.
If nominal stresses are calculated for fillet welds by coarse finite element meshes, nodal forces rather than element stresses should be used in a section through the weld in order to avoid stress underestimation.
When a nominal stress is intended to be calculated by finite elements, the more precise option of the structural hot spot stress determination should be considered.

3.1.4. Nominal stress at weld toe

To find the nominal stress in a FE model a plot is created of the stress along a path approaching the weld. The FE model often has a gradient near the weld that corresponds to the geometric stress. A simple rule to obtain the nominal stress is to extrapolate the linear part of the stress on the surface inwards against the weld, see Figure 17. In the example below the nominal stress could easily be determined but in most cases the reality never looks like in the fatigue codes.

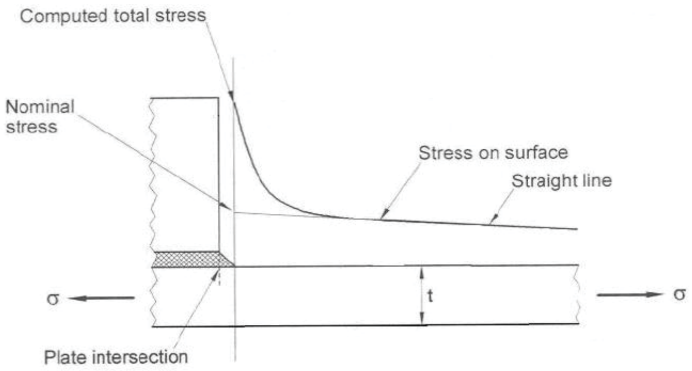


Figure 17. Extrapolated nominal stress in welded joint.

3.1.5. Nominal stress at weld root /throat

When the weld is sensitive to fatigue root cracking the analysis should be based on stresses at weld throat by calculating the weld weld stress $\sigma_{n,w}$. The weld stress is based on average stress components in the weld throat (similar to static design), see figure 18;

$$\sigma_{n,w} = \sqrt{\sigma_\perp^{\ 2} + \tau_\perp^{\ 2}}$$

the stress $\sigma\perp$ is the normal stress to the weld throat section, the stress $\tau\perp$ is the normal stress to the weld throat section.

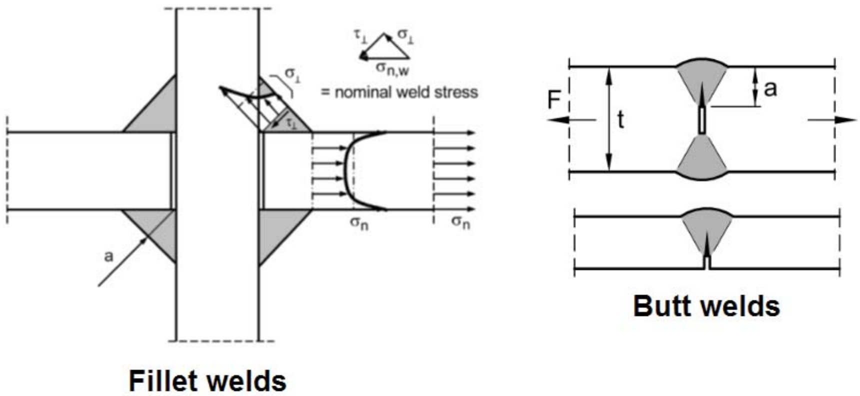


Figure 18. weld stress, for assessment of weld root cracking.

For cruciform joints and T-joints the weld stress can be calculated according to the following equation:

$$\sigma_{n,w} = \sigma_n \frac{t}{2a}$$

$(\sigma_n t)$ is the axial force in the plate and (2a) is the weld throat.

3.1.6. K_m modification due to 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 km given in Table 2.

Table 2. stress magnification factor due to misalignment.

Type of k_m analysis	Nominal stress approach
Type of welded joint	k_m already covered in FAT class
Butt joint made in shop in flat position	1.15
Other butt joints	1.30
Cruciform joints	1.45
Fillet welds on one plate surface	1.25
Fillet welds on both plate surfaces	1.25

3.1.7. Fatigue strength (FAT) – IIW

The fatigue strength is given at $2*10^6$ cycles and is defined as the FAT value for the actual geometry, see figure 19 as an example. The slope is 3 (5 in shear) before and 22 after 10^7 cycles. The FAT value is given at 97.7 % probability of survival. The IIW design rules, [1], denote the design curves as FAT71, which means fatigue strength of 71 MPa at 2 million cycles with 97.7 % probability of survival. Figure 20 shows the collection of S-N curve (FAT) according to IIW for nominal stress. The FAT values are given for a R-ratio of 0.5 (R = 0.5) which is at a high mean stress with an assumption of high tensile residual stresses in the weld.
Appendix A give the complete list of FAT values for all structural details according to IIW for nominal stress.

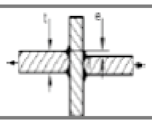
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
412		Cruciform joint or T-joint, K-butt welds, full penetration, potential failure from weld toe Single sided T-joints	71 80	25 28	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing Misalignment < 15 % of primary plate thickness in cruciform joints

Figure 19. example of FAT for structural details.

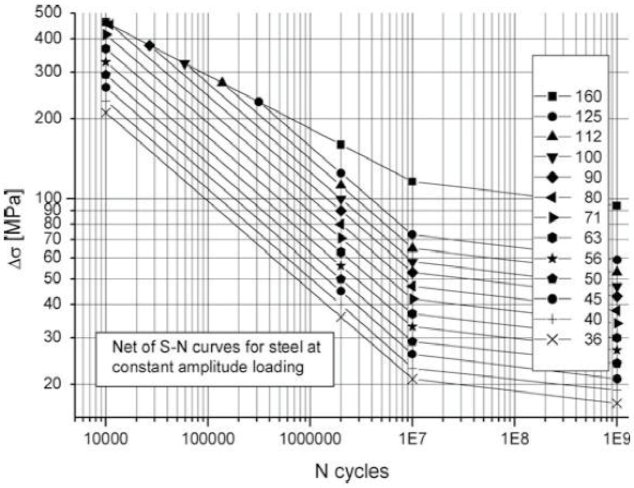


Figure 20. Fatigue resistance S-N curves for steel, normal stress, very high cycles applications

3.1.8. Limitations

The nominal stress method could be used if the stress is well defined, FAT class and loading are consistent with the fatigue class (structural detail). Also the magnitude of distortion and eccentricity have to be moderate. The method is mostly applicable to weld toe failure and in most cases the actual weld has little similarity to the geometries tabulated in the standards and recommendations. When a nominal stress is intended to be calculated by finite elements, the more precise option of the structural hot spot stress determination should be considered.

For complex welded structures with many attachments and loading locations the stress value is continually changing. A nominal stress value is difficult or impossible to define. Even if a nominal stress can be defined, one must select from a catalogue of details, the geometry most closely resembling the actual welded detail. In many cases the actual weld has little similarity to one of the geometries shown in the standard. Experience and engineering judgement must then be used. Figure 21 illustrate the challenge of finding the nominal stress in a complex structure and loading and structural detail which resembles the welds analyzed.

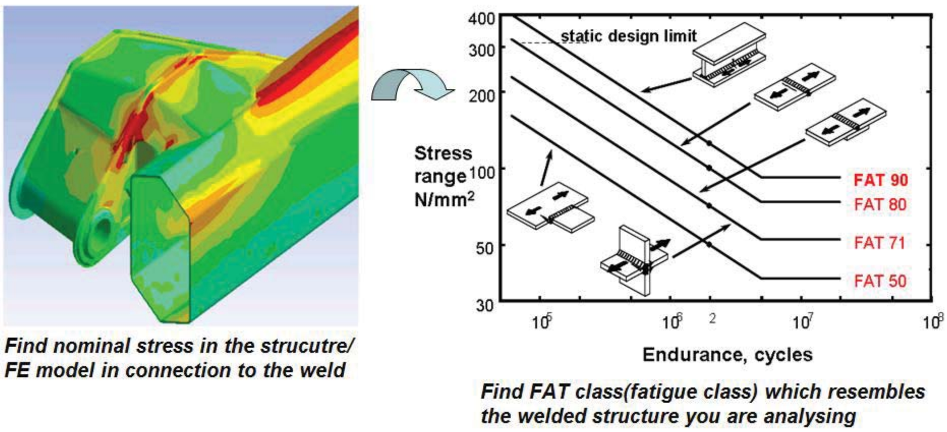


Figure 21. Example illustrating limitation with nominal stress method.

3.1.9. Examples – Nominal stress method

Example 1

The following simple example illustrate how the extrapolation of the nominal stress is carried out along the surface of the plate (weld toe assessment) for a plate with two welded longitudinal attachments. The stress applied is 80 MPa in the plate and the corresponding structural detail (521, non-load carrying attachment) gives a FAT 80 (fillet welds, as welded). Figure 22 shows the structural detail suitable for this example.

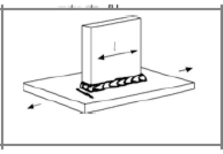
521		Longitudinal fillet welded gusset of length l. Fillet weld around end l < 50 mm l < 150 mm l < 300 mm l > 300 mm	 80 71 63 50	 28 25 20 18	For gusset on edge: see detail 525 Particularly suitable for assessment on the basis of structural hot spot stress approach

Figure 22. Structural detail 521.

Figure 23 shows the finite element representation of the structural detail analyzed where a quarter of the geometry is modeled considering the double symmetry of the geometry.

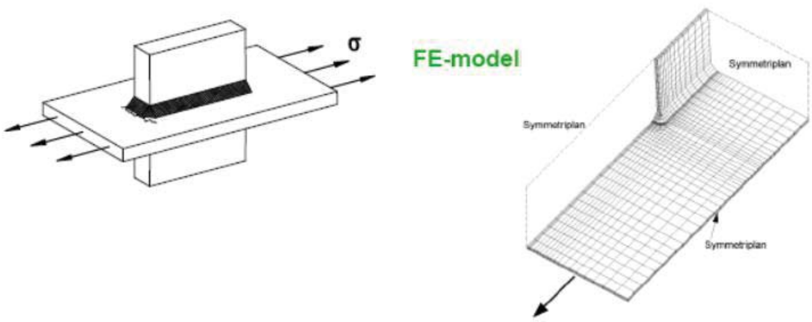
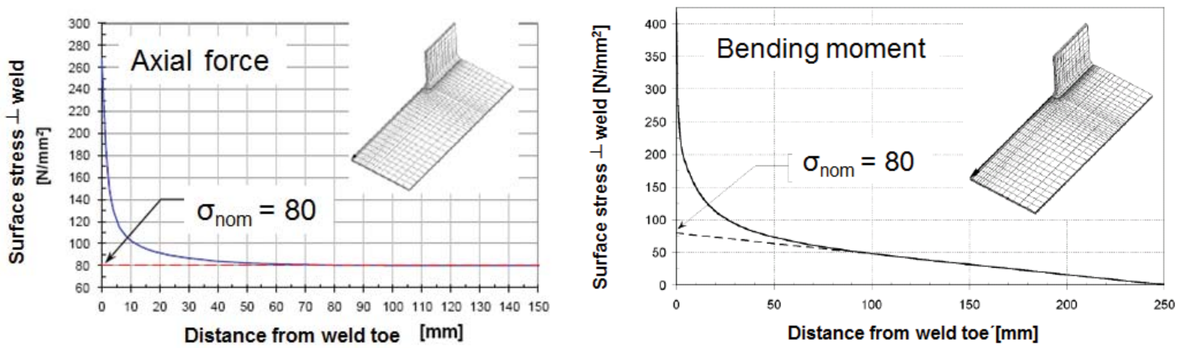


Figure 23. FE model, example 1.

Figure 24a shows the stress extrapolation along the surface of the plate (from weld toe and outward) which defines the nominal stress in this case for axial loading. Figure 24b shows the stress along the path if the load would have been in bending and how the extrapolation of the nominal stress should be carried out.



a) b)

Figure 24. nominal stress for example 1.

Example 2

The following example illustrate the fatigue life assessment of welded component with welded stiffener attachments to the main plate using the nominal stress method. Figure 25 shows the component with dimensions and the loading (axial, 80 MPa) and the finite element representation using shell elements.

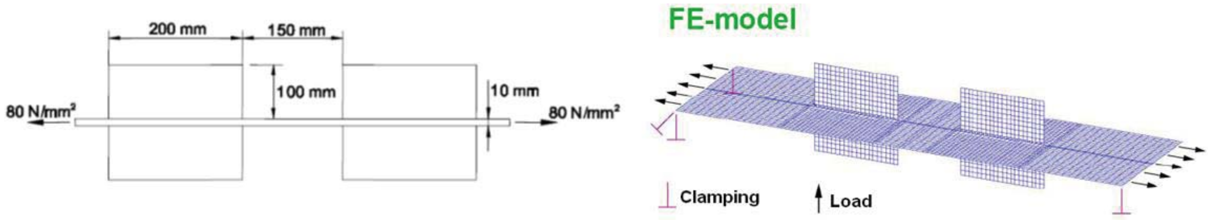


Figure 25. Geometry, dimensions and FE model, example 2.

The component is critical for weld toe cracking in 8 different locations where the stress concentration is high. However, considering double symmetry, it is only two locations; inner weld toe and outer weld toe. There is no geometry that identically match this geometry in the list of structural details. However, structural detail 512 is the closest, figure 26, which gives FAT values for longitudinal fillet welded guest as function of the length of the gusset plate. The length in this example is 200 mm which gives a FAT value of 63.

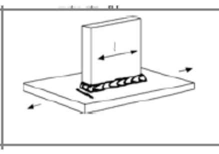
521		Longitudinal fillet welded gusset of length l. Fillet weld around end l < 50 mm l < 150 mm l < 300 mm l > 300 mm	 80 71 63 50	 28 25 20 18	For gusset on edge: see detail 525 Particularly suitable for assessment on the basis of structural hot spot stress approach

Figure 26. Structural detail 521.

The nominal stress in the outer welds is 80 MPa and does not require an extrapolation since this is the load applied. However, for the inner welds an extrapolation is required to determine the nominal stress. This extrapolation is illustrated in figure 27. The nominal stress for the inner welds is 90 MPa.

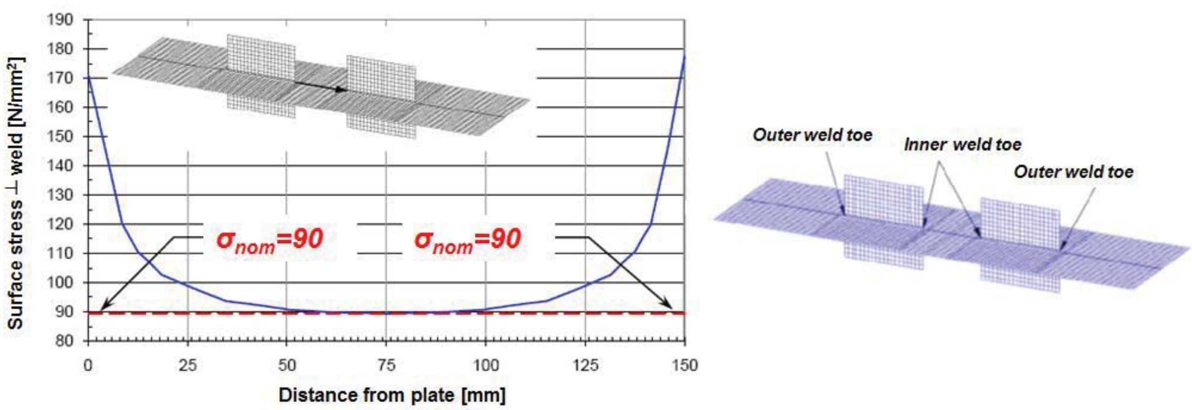


Figure 27. extrapolation to determine the nominal stresses for the inner welds.

Now the fatigue life's for the different failure locations can be estimated based on the nominal stresses and the FAT value.

Outer weld:
FAT 63, σ_{nom} = 80 MPa

$$N = 2 * 10^6 * \left(\frac{FAT}{\sigma_{nom}}\right)^3 = 2 * 10^6 * \left(\frac{63}{80}\right)^3 = 977 * 10^3\ cycles$$

Inner weld:
FAT 63, σ_{nom} = 90 MPa

$$N = 2 * 10^6 * \left(\frac{FAT}{\sigma_{nom}}\right)^3 = 2 * 10^6 * \left(\frac{63}{90}\right)^3 = 686 * 10^3\ cycles$$

The failure will occur at the inner weld toe after approximately $700*10^3$ cycles.

Note: The fatigue life estimated here is at a low failure probability of 2.3 %. Furthermore, the FAT values are given at a R =0.5 which corresponds to high mean stress. These will result in that the estimation in this example is on the conservative side.

Example 3
The following example, Figure 28, illustrate fatigue life assessment using nominal stress of load carrying weld in a cruciform joint with leg length of 7 mm and a weld throat thickness of 7 mm. The joint is sensitive to weld toe and weld root cracking and both should be evaluated. The joint is loaded with a force resulting in a nominal stress of 120 MPa.

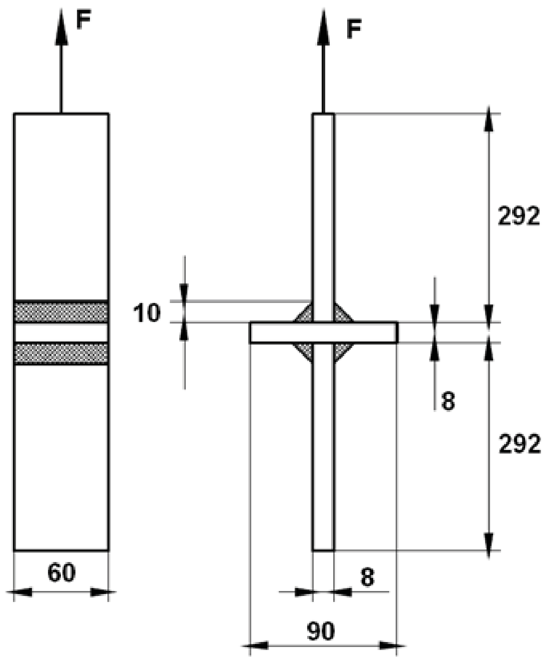


Figure 28. Example 3, load carrying cruciform joint.

First, the structural details and the corresponding FAT values for weld toe and root cracking should be determined. Figure 29 shows detail 413 (weld toe crack) and 414 (weld root crack) which represent this example well.

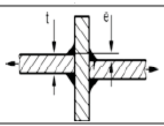
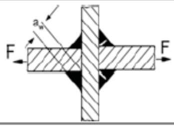
413		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds, potential failure from weld toe Single sided T-joints	63 71	22 25	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing Misalignment < 15 % of primary plate thickness in cruciform joints Also to be assessed as 414
414		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds including toe ground joints, potential failure from weld root For a/t <=1/3	36 40	12 14	Analysis based on stress in weld throat $\sigma_w = F/\sum(a_w \cdot l)$ l = length of weld, a_w = load carrying weld throat. Also to be assessed as 413

Figure 29. Structural detail 413 (toe cracking) and 414 (root cracking).

For weld toe cracking FAT 63 is suitable here. In this FAT a misalignment of < 15% is incorporated in the fatigue resistance. For more accurate assessment (if misalignment is not present in the analyzed component) a correction of the FAT value (increased) could be made. For weld root cracking FAT 40 is suitable since a/t = 7/8 = 87% which is ≤ 33 %. The analysis should be based on the stress in the weld throat.

Nominal stress in plate, weld toe: σ_{nom} =120 MPa

Nominal stress in weld throat, weld root: $\sigma_w = \frac{\sigma_{nom} * t}{2 * a} = \frac{120*8}{2*\frac{10}{\sqrt{2}}} = 68\ MPa$

Fatigue life at weld toe: $2 * 10^6 * \left(\frac{FAT}{\sigma_{nom}}\right)^3 = 2 * 10^6 * \left(\frac{63}{120}\right)^3 = 289\ 000\ cycles$

Fatigue life at weld root: $2 * 10^6 * \left(\frac{FAT}{\sigma_w}\right)^3 = 2 * 10^6 * \left(\frac{40}{68}\right)^3 = 407\ 000\ cycles$

The failure will occur at the weld toe after approximately $289*10^3$ cycles.

3.2. Structural "hot spot" stress method

The structural or geometric stress σ_{hs} at the hot spot includes all stress raising effects of a structural detail excluding that due to the local weld profile itself. So, the non-linear peak stress σ_{nl} 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 near the joint. Figure 30 illustrates the definition of structural stress according to IIW.

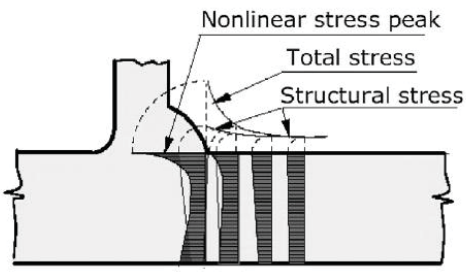


Figure 30. Definition of structural stress.

It is determined on the surface at the hot spot of the component which is to be assessed. Structural hot spot stresses σ_{hs} are generally defined for plate, shell and tubular structures. Figure 31 shows examples of structural discontinuities and details together with the structural stress distribution.

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

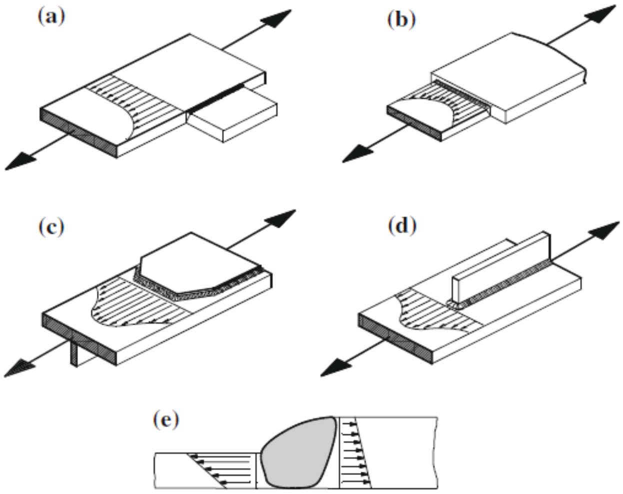


Figure 31. Structural details and structural stress, e.g. at **a)** end of longitudinal lateral attachment, **b)** joint of plates with unequal width, **c)** end of cover plate, **d)** end of longitudinal attachment, **e)** joint with unequal thickness

The structural hot-spot stress can be determined using reference points by extrapolation to the weld toe under consideration from stresses at reference points, figure 32.

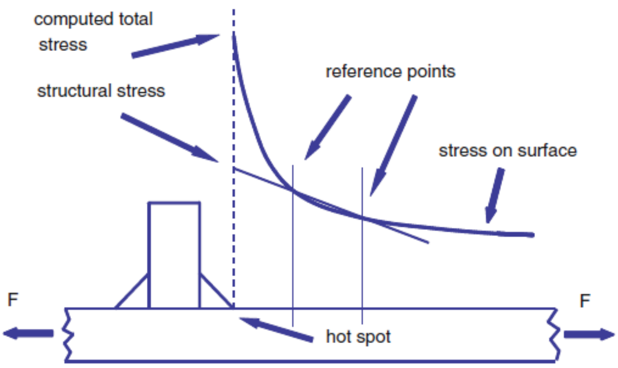


Figure 32. Definition of structural hot-spot stress.

Strictly speaking, the method as defined here is limited to the assessment of the weld toe, i.e. cases **a** to **d** in Figure 33. In the case of a biaxial stress state at the plate surface, it is recommended that the principal stress which acts approximately in line with the perpendicular to the weld toe, i.e. within ±60° (Figure 34) is used.

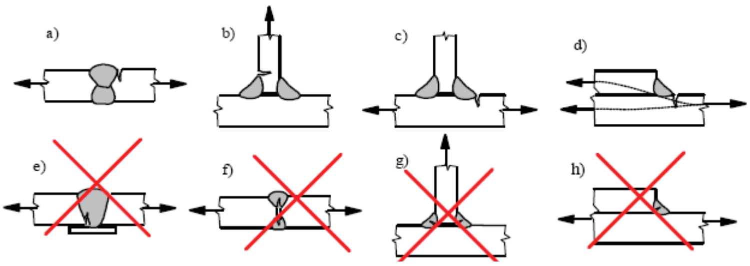


Figure 33. Various locations of crack propagation in welded joints. **a–d)** with weld toe cracks, **e–h)** with weld root cracks.

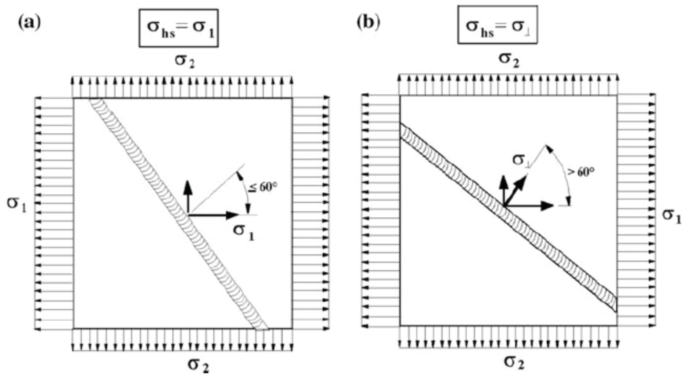
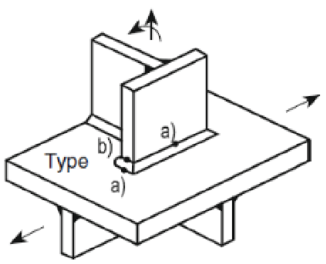


Figure 34. Biaxial stresses at weld toe, principle stress within **a)** and without **b)** an angle of 60°perpendicular to the weld.

3.2.1. Types of hot spots

Besides the definitions of structural hot spot stress as given above, two types of hot spots are defined according to their location on the plate and their orientation in respect to the weld toe as defined in figure 35. Figure 36 shows some examples of hot spot type b.



Type	Description
a	Structural hot spot stress transverse to weld toe on plate surface
b	Structural hot spot stress transverse to weld toe at plate edge

Figure 35. Types of hot spots.

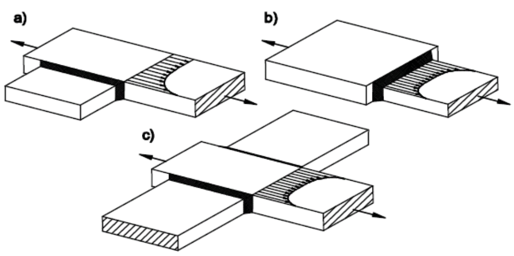


Figure 36. Examples of hot spots type b.

3.2.2. Determination of structural hot spot stress

The structural hot spot stress can be determined either by measurement or by calculation. Here the non-linear peak stress is eliminated by extrapolation of the stress at the surface to the weld toe. The following considerations focus on surface stress extrapolation procedures of the surface stress, which are essentially the same for both measurement and calculation. The procedure is first to establish the reference points and then to determine the structural hot spot stress by extrapolation to the weld toe from the stresses of those reference points. Depending on the method, there may be two or three reference points. The reference point closest to the weld toe must be chosen to avoid any influence of the notch due to the weld itself (which leads to a non-linear stress peak). This is practically the case at a distance of 0.4 t from the weld toe, where t is plate thickness. The structural hot spot stress at the weld toe is then obtained by extrapolation.

3.2.3. Calculation of structural hot spot stress

The extent of the finite element model must be chosen such that constraining boundary effects of the structural detail analysed are comparable to the actual structure.
Models with either thin plate or shell elements or with solid elements may be used. It should be noted that on the one hand the arrangement and the type of the elements must allow for steep stress gradients and for the formation of plate bending, but on the other hand, only the linear stress distribution in the plate thickness direction needs to be evaluated with respect to the definition of the structural hot spot stress. The stresses should be determined at the specified reference points.
A reasonably high level of expertise is required on the part of the FEA analyst. In the following, only some rough recommendations are given:
In a plate or shell element model (Figure 37), the elements are arranged in the mid-plane of the structural components. 8-noded elements are recommended particularly in regions of steep stress gradients. In simplified models, the welds are not modelled, except for cases where the results are affected by local bending, e. g. due to an offset between plates or due to a small distance between adjacent welds. Here, the welds may be included by vertical or inclined plate elements having appropriate stiffness or by introducing constraint equations or rigid links to couple node displacements. Thin-shell elements naturally provide a linear stress distribution through the shell thickness, suppressing the notch stress at weld toes. Nevertheless, the structural hot-spot stress is frequently determined by extrapolation from the reference points mentioned before, particularly at points showing an additional stress singularity such as stiffener ends.

Alternatively, particularly for complex cases, prismatic solid elements which have a displacement function allowing steep stress gradients as well as plate bending with linear stress distribution in the plate thickness direction may be used. An example is isoparametric 20-node elements with mid-side nodes at the edges, which allow only one element to be arranged in the plate thickness direction due to the quadratic displacement function and the linear stress distribution. By reduced integration, the linear part of the stresses can be directly evaluated at the shell surface and extrapolated to the weld toe. Modelling of welds is generally recommended as shown in Figure 37.

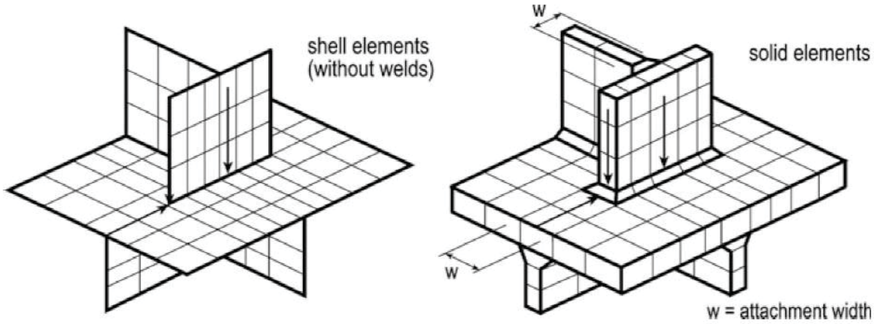


Figure 37. Typical meshes and stress evaluation paths for a welded detail.

Surface extrapolation methods:

If the structural hot-spot stress is determined by extrapolation, the element lengths are determined by the reference points selected for stress evaluation. In order to avoid an influence of the stress singularity, the stress closest to the hot spot is usually evaluated at the first nodal point. Therefore, the length of the element at the hot spot corresponds to its distance from the first reference point. If finer meshes are used, the refinement should be introduced in the thickness direction as well. Coarser meshes are also possible with higher-order elements and fixed lengths, as explained further below. Figure 38 shows how the stressers at the reference points should be extracted and evaluated for different types of meshing.

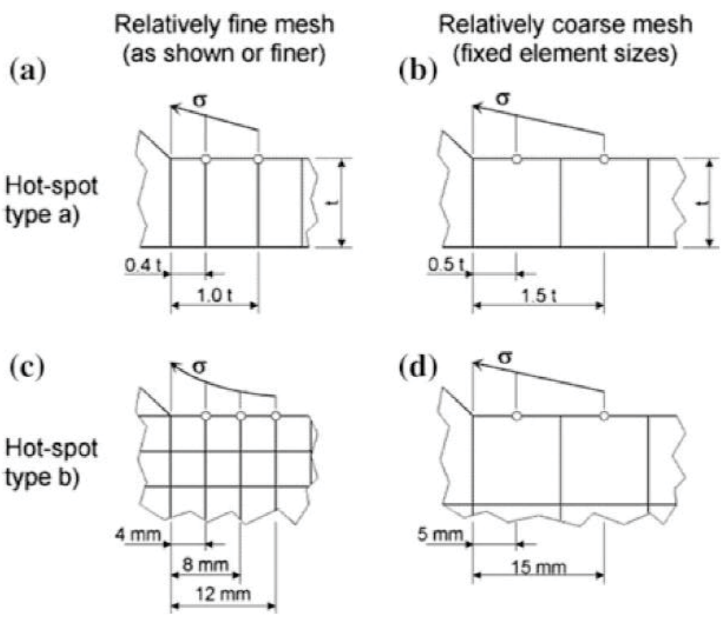


Figure 38. Reference points at different types of meshing. Stress **type "a"** (a, b), **type "b"** (c, d)

Type "a" hot spots (dependent on plate thickness):

1) Fine mesh element length < 0.4t at hot spot. Nodal stresses at two reference points **0.4 t** and **1.0 t**, and linear extrapolation

$$\sigma_{hs} = 1.67\sigma_{0.4t} - 0.67\sigma_{1.0t}$$

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. Pronounced non-linear structural stress

$$\sigma_{hs} = 2.52\sigma_{0.4t} - 2.24\sigma_{0.9t} + 0.72\sigma_{1.4t}$$

3) Coarse mesh with higher-order elements having lengths equal to plate thickness. Two reference points **0.5 t** and **1.5 t**, and linear extrapolation

$$\sigma_{hs} = 1.5\sigma_{0.5t} - 0.5\sigma_{1.5t}$$

Type "b" hot spots (independent on plate thickness):
The stress distribution is not dependent on plate thickness. Therefore, the reference points are given at absolute distances from the weld toe, or from the weld end if the weld does not continue around the end of the attached plate.

1) 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.

$$\sigma_{hs} = 3\sigma_{4\,mm} - 3\sigma_{8\,mm} + \sigma_{12\,mm}$$

2) 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

$$\sigma_{hs} = 1.5\sigma_{5\,mm} - 0.5\sigma_{15\,mm}$$

Table 3 below summarizes the meshing and extrapolation procedure.

Table 3. recommended meshing and extrapolation.

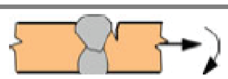
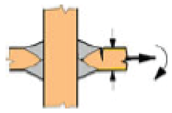
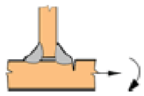
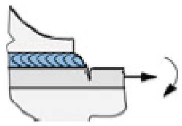
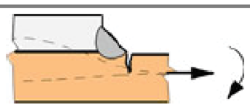
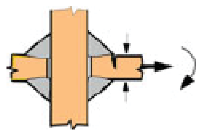
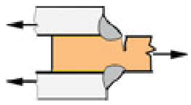
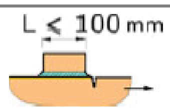
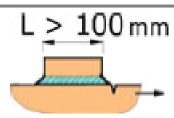
Type of model and weld toe		Relatively coarse models		Relatively fine models	
		Type a	Type b	Type a	Type b
Element size	Shells	t x t max t x w/2[a]	10 × 10 mm	≤0.4 t x t or ≤0.4 t x w/2	≤4 × 4 mm
	Solids	t x t max t x w	10 × 10 mm	≤0.4 t x t or ≤0.4 t x w/2	≤4 × 4 mm
Extra-polation points	Shells	0.5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

[a]w = longitudinal attachment thickness +2 weld leg lengths

3.2.4. Fatigue strength (FAT) – IIW

The fatigue strength is given at $2*10^6$ cycles and is defined as the FAT value for the actual geometry. The slope is 3 before and 22 after 10^7 cycles. The FAT value is given at 97.7 % probability of survival. The FAT values are given for a R-ratio of 0.5 (R = 0.5) which is at a high mean stress with an assumption of high tensile residual stresses in the weld. For structural "hot spot" stress assessment only two FAT values are applicable; FAT 90 and FAT 100, depending on weld shape and geometry analyzed. These FAT values are presented in table 4 below.

Table 4. Fatigue resistance against structural "hot spot" stress.

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

3.2.5. Limitations

The method is only applicable to weld toe failure, no weld root failures can be assessed with method as presented here. The method is typically used where there is no clearly defined nominal stress due to complex geometric effects, or where the structural discontinuity is not comparable to a classified structural detail.

3.2.6. Examples – Structural "hot spot" stress method

Example 1

The following example illustrate how the structural hot spot stress can be used for evaluation on a simple fillet weld in longitudinal attachment. The geometry has been analyzed with nominal stress method and the results will be compared here. Figure 39 shows the geometry and the corresponding FE model.

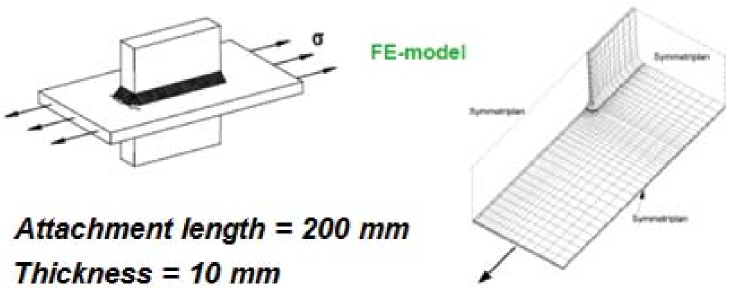
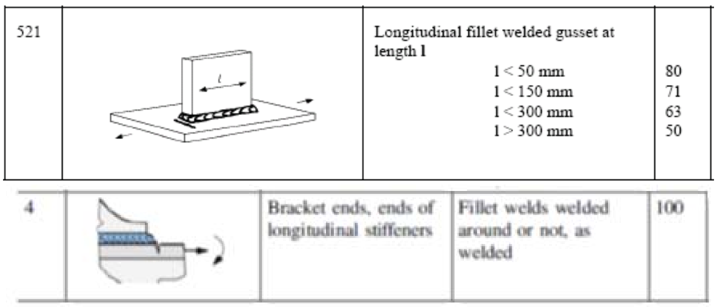


Figure 39. FE model, example 1.

The FAT value in the nominal stress method is dependent on the attachment length, which in this particular case is FAT 63. In the structural hot spot stress method, the corresponding FAT value is FAT 100. Figure 40 shows the FAT values and structural detail categories for nominal stress method, No. 521, and structural hot spot stress method, No. 4.



521		Longitudinal fillet welded gusset at length l l < 50 mm l < 150 mm l < 300 mm l > 300 mm		80 71 63 50
4		Bracket ends, ends of longitudinal stiffeners	Fillet welds welded around or not, as welded	100

Figure 40. Fatigue resistance nominal and structural hot spot stress, example 1.

Figure xx shows the stress distribution along the surface of the plate towards the weld toe, hot spot type "a". The nominal stress is 80 MPa. For the structural hot spot stress, the reference stress at point 0.4t (t =10 mm) is 120 MPa and at reference point 1.0t is 110 MPa. The elements are quadratic shape function and a linear extrapolation is carried out to evaluate the hot spot stress;

$$\sigma_{hs} = 1.67\sigma_{0.4t} - 0.67\sigma_{1.0t} = 1.67 * 120 - 0.67 * 110 = 127\ MPa$$

Similar results are received if the linearized stress distribution is extrapolated to the weld toe based on the two reference point stresses, as can be seen in figure 41.

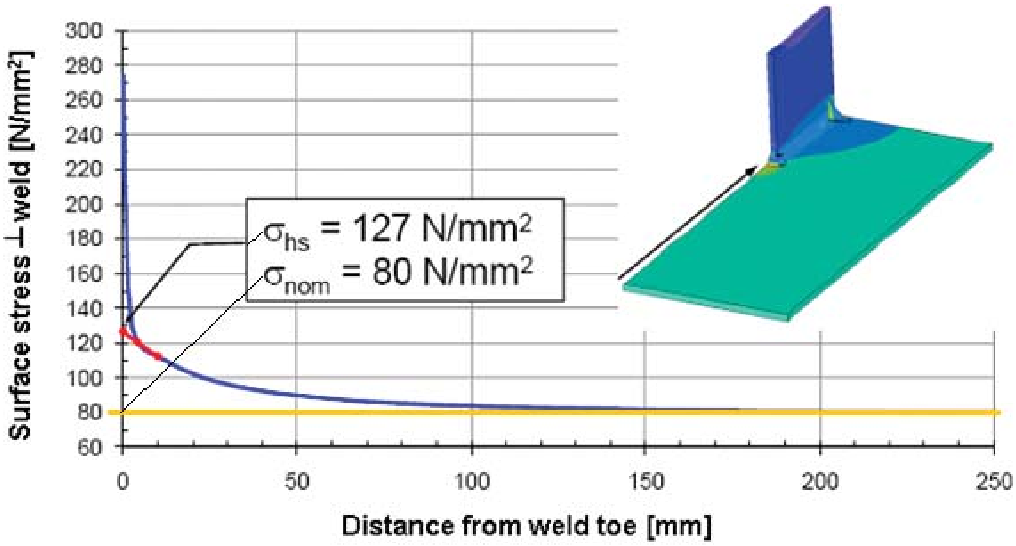


Figure 41. Stress distribution and evaluation of nominal and hot spot stress.

Figure 42 shows the stress distribution through the thickness at hot spot reference point 0.4t and 1.0t. The variation can be negligible which is also an indication of small bending and linear extrapolation is applicable.

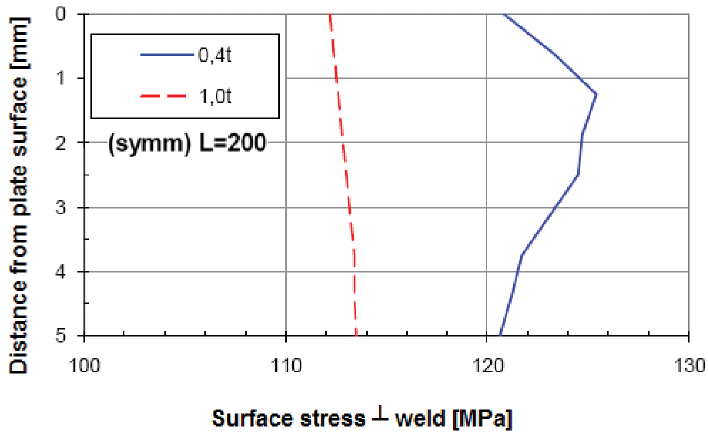


Figure 42. through thickness distribution example 1.

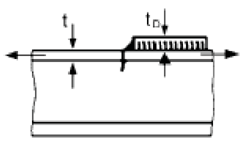
Table 5 presents the fatigue life estimation results and compares the nominal stress method with hot spot stress method. The estimations are also carried out for different attachment length, however, the current case with L = 200 mm gives an identical fatigue life with both methods, approx. $1*10^6$ cycles. For other attachment length the analysis shows a quite large difference between the two methods. The main reason is that in the nominal stress method the FAT value is determined based on an interval of attachment length, whereas for structural hot spot stress method, different stresses are calculated for different geometrical shapes, which captures the global stiffness changes, and one fixed FAT value is used.

Table 5. Example 1; comparison between nominal and structural “hot spot” stress method.

Length of attachm. L	75 (FAT=71)	150 (FAT=71)	150 (FAT=63)	200 (FAT=63)	300 (FAT=63)	300 (FAT=50)
Nominal stress fatigue life	$1398 \cdot 10^3$	$1398 \cdot 10^3$	$977 \cdot 10^3$	$977 \cdot 10^3$	$977 \cdot 10^3$	$488 \cdot 10^3$
Hot spot stress fatigue life	$1549 \cdot 10^3$	$1144 \cdot 10^3$	$1144 10^3$	$976 \cdot 10^3$	$824 \cdot 10^3$	$824 \cdot 10^3$
Difference (%)	11%	-18%	17%	0%	-16%	69%

Example 2

The following example illustrate how the structural hot spot stress can be used for evaluation on a wide flange I beam with a welded doubling plate. The structure is also analyzed with nominal stress method. The weld is non-load carrying and among the structural detail categories for hot spot stress method, No. 4, is suitable with a FAT 100. In the nominal stress method the FAT values are dependent on the flange and doubling plate thickness relation (t_D/t); the larger relation the lower FAT value. In this example the plate is 160 mm wide on a HEA 200 beam, t_D = 11.5 mm and t = 10 mm. The structure is subjected to a axial stress of 80 MPa. This result in a FAT 50 in the nominal stress system. Figure 43 shows the different structural detail categories for nominal and structural hot spot stress method.

711		End of long doubling plate on I-beam, welded ends (based on stress range in flange at weld toe) $t_D \le 0.8\,t$ $0.8\,t < t_D \le 1.5\,t$ $t_D > 1.5\,t$	 56 50 45

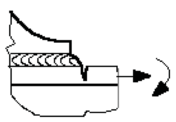
4		Bracket ends, ends of longitudinal stiff-eners	Fillet welds welded around or not, as welded	100

Figure 43. example 2, structural details for nominal and hot spot stress method.

Figure 44 shows the FE model (considering symmetry) and 1st principal stress contour plot showing that the highest stress occurs at the weld in the doubling plate.

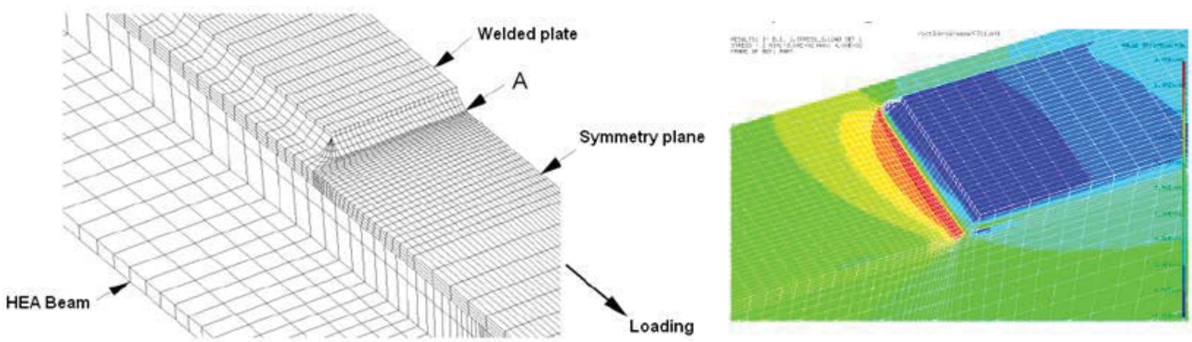


Figure 44. FE model and stress counter, example 2.

Figure 45 shows the stress distribution along the surface of the plate towards the weld toe, hot spot type “a”. The nominal stress is 80 MPa. The elements are quadratic shape function and a linear extrapolation is carried out to evaluate the hot spot stress. The stresses at the reference points 0.4t and 1.0t are plotted along the weld and the structural hot spot stress is calculated based on these, also along the entire weld. It is observed that the highest hot spot stress occurs at approximately 12 mm from the center of the weld.

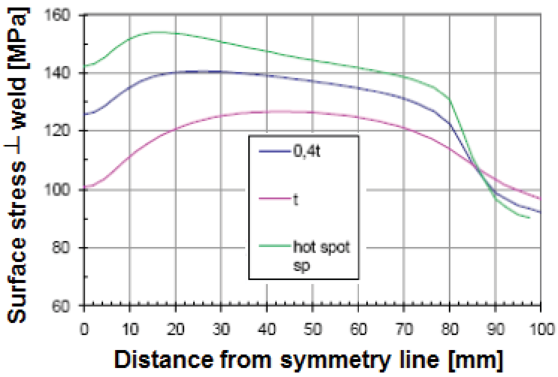


Figure 45. hot spot stress along weld in example 2.

Figure 46 shows the stress distribution along the surface, towards the weld toe, at 12 mm from the center of the weld. The nominal stress is 80 MPa. The hot spot stress is evaluated with linear extrapolation and quadratic extrapolation (in order to evaluate any high stress gradients). Quadratic extrapolation requires 3 hot spot point to be evaluated.

$$\sigma_{hs} = 1.67\sigma_{0.4t} - 0.67\sigma_{1.0t} \text{ (linear extrapolation)}$$

$$\sigma_{hs} = 2.52\sigma_{0.4t} - 2.24\sigma_{0.9t} + 0.72\sigma_{1.4t} \text{ (quadratic extrapolation)}$$

$\sigma_{0.4t}$ = 140 MPa, $\sigma_{0.9t}$ = 122 MPa, $\sigma_{1.0t}$ = 119 MPa and $\sigma_{1.4t}$ = 108 MPa; σ_{hs}^{lin} = 154 MPa and σ_{hs}^{quad} = 157 MPa.

Similar results are received if graphical extrapolation is carried out to the weld toe based on the reference point stresses, as can be seen in figure 46. The difference between liner and quadratic extrapolated hot spot stresses is negligible which is an indication of moderate stress gradients.

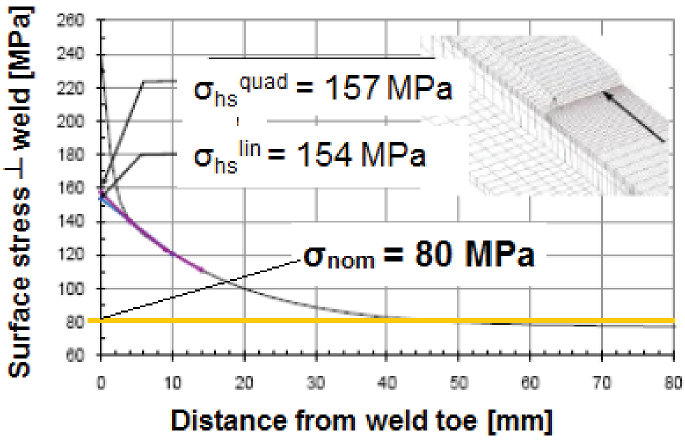


Figure 46. Example 2, stress distribution and evaluation of nominal and hot spot stress.

Table xx presents the fatigue life estimation results and compares the nominal stress method with hot spot stress method. The estimations are also carried out for different doubling plate thickness t_D, however, the current case with t_D = 11.5 mm a fatigue life of 488*10^3 cycles using the nominal stress method and 517*10^3 cycles using the structural hot spot stress method.

Table 6. Example 2; comparison between nominal and structural “hot spot” stress method.

Thickness of welded plate	8 (FAT = 56)	8 (FAT = 50)	11,5 (FAT = 50)	15 (FAT = 50)	15 (FAT = 45)	25 (FAT = 45)
Nominal stress fatigue life	$686 \cdot 10^3$	$488 \cdot 10^3$	$488 \cdot 10^3$	$488 \cdot 10^3$	$355 \cdot 10^3$	$355 \cdot 10^3$
Hot spot stress fatigue life	$617 \cdot 10^3$	$617 \cdot 10^3$	$517 \cdot 10^3$	$453 \cdot 10^3$	$453 \cdot 10^3$	$380 \cdot 10^3$
Difference (%)	-10%	21%	6%	-7%	28%	7%

4. FATIGUE OF UN-WELDED BASE MATERIAL

4.1. General

Parent material which has not been welded can be fully utilized if the structural design has been successful. The fatigue strength of high strength steels is higher than mild steels [7]. How much higher is dependent on the steel's strength, the roughness of the plate surface, the quality of the edges and notches such as holes, indentations or screwed or riveted joints.

4.2. Material effect and surface condition

The rate of this increase depends, among other things, on the surface condition of the material. The fatigue strength is better in cold-rolled than in hot-rolled surfaces due to the surface quality. The notch effect from a fatigue point of view can be described by the surface roughness (Rz or Ra value). These are assessed during surface topography measurements and defined according to figure 47. Rz is usually assessed as the mean value of five measurements and is designated Rz_5. Herein Rz here refers to this value.

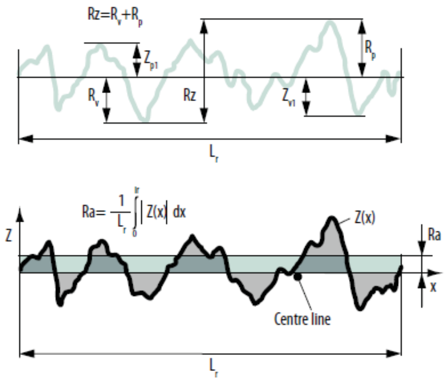


Figure 47. Definition of surface roughness and mean surface deviation.

The surface roughness, Rz, for base material mainly depend on the cutting process used and if any post treatment has been carried out. Figure 48 shows typical roughness ranges for different steel grades and cutting processes. Figure 49 shows typical roughness ranges for rolled, ground and blast surfaces.

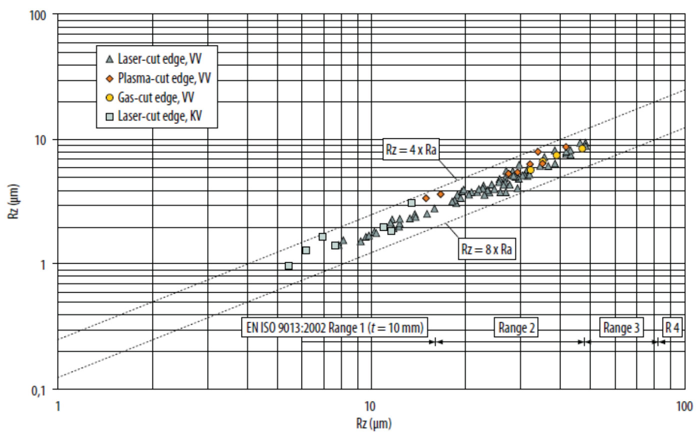


Figure 48. Surface roughness measurement on cut edges, different cutting processes.

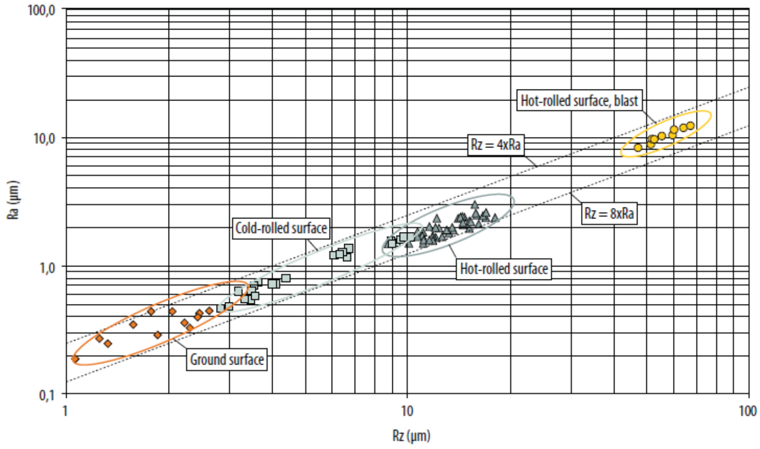


Figure 49. Surface roughness measurement of rolled, ground and blast surfaces.

4.3. Calculation procedure – Base plate with surface condition

$\Delta\sigma^*$ refers to the fatigue strength value at 50% failure probability, 10^6 load cycles and a stress ratio R=0. Based on the correlation to roughness, the fatigue strength can be calculated using the respective steel's strength values and the surface condition (Rz value) as input. The fatigue strength $\Delta\sigma$ is then calculated in accordance with the following:

$$\Delta\sigma = \frac{\Delta\sigma^*}{K_r}$$

where

$\Delta\sigma^*$ is the fatigue strength of a fictitious smooth test specimen and K_r the surface factor

$$\Delta\sigma^* = 9.8989 * R_e^{0.6071}$$

$$K_r = \frac{1}{1 - 0.000254 * R_m * \ln\left(\frac{Rz}{6} + 1\right)}$$

where R_e is the yield strength (MPa) and R_m the tensile strength (MPa).

The correlation for K_r applies when the fatigue life is dominated by crack initiation. When the formula $\Delta\sigma = \Delta\sigma^*/K_r$ above gives a falling curve in figure 50, $\Delta\sigma$ is chosen equal to the maximum value and the curve continues horizontally, which represents a fatigue life dominated by crack growth. The correlation above is illustrated in figure xx where the fatigue strength as function of the yield strength has been calculated for a number of Rz values. To calculate the fatigue strength for other than $N=10^6$, the following equation is used;

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

where N is the number of load cycles to failure, $\Delta\sigma$ stress range, C and m material constants. The exponent is m=5. Figure 50 indicates that the increase in fatigue strength with the increase in the yield strength diminishes if the surface condition is impaired. The increase stops completely at a certain yield strength which, in turn, gets lower with increased Rz value. At this yield strength the fatigue life switches from initiation domination to crack growth type. Measurements of shot-blast surfaces gives Rz values of 35 to 50 without corresponding decreases in fatigue strength due to the "better" surface topography and the presence of a compressive stress state due to the cold working during blasting.

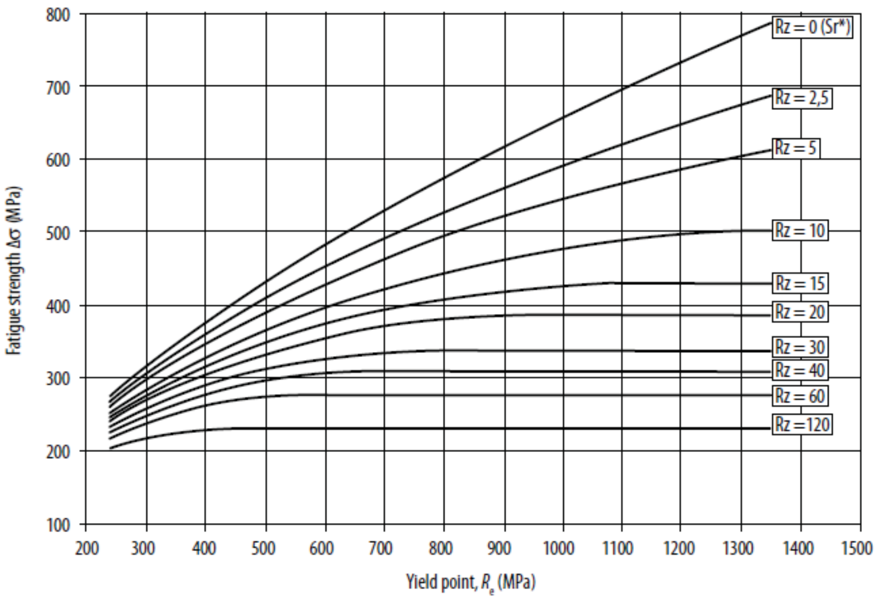


Figure 50. Fatigue strength at $N=10^6$ load cycles and R=0, failure probability 50%, for non-welded parent material with different surface condition (Rz value).

4.4. Material factor

The material factor is calculated as a function of yield strength and surface conditions. The curves with designation A-K in figure 51 correspond to Rz values from 3 to 120 (Ra=0.5-20). The L curve corresponds to φ_m =1, i.e., no material dependence and applies to parent material with crack-like imperfections or welded joints. The fatigue strength of parent material is calculated by multiplying FAT for actual the structural detail with the material factor, φ_m. To be able to associate the different curves in figure xx with different surface and edge conditions in practice, table 7 should be used to estimate the surface and edge conditions for different cutting processes and quality levels. **Appendix B** presents the structural details of parent material and their corresponding FAT values. These are given for failure probability of 2.3 % at $2*10^6$ cycles at R =0.5. To determine the fatigue strength at 50 % failure probability the FAT value have to be multiplied with φ_Q = 1.3.

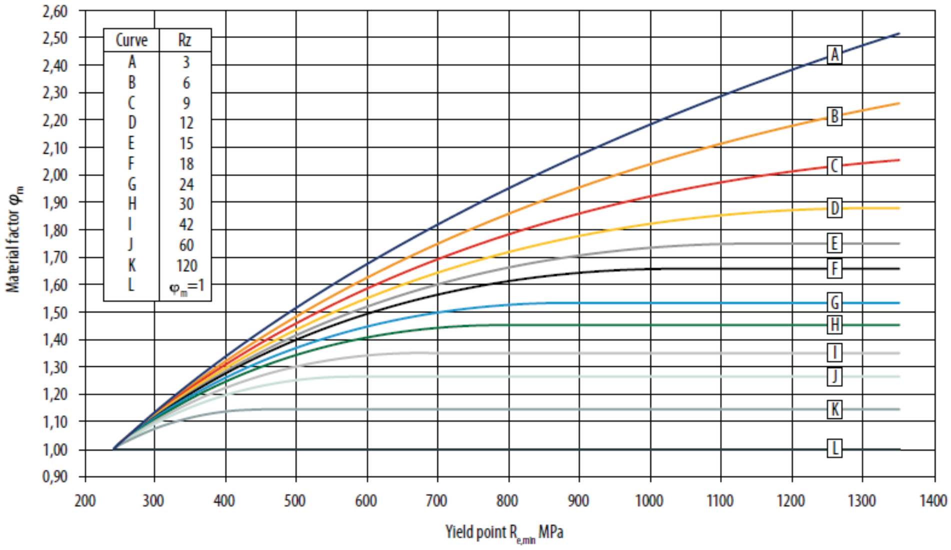


Figure 51. The material factor as a function of yield strength and surface condition.

Table 7. Correlation between surface/edge condition and the material factor.

Type of surface or edge	Comment/quality specification	Surface condition Rz	ISO Range[1]	φ_m - curve
Ground	Corners deburred	3		A
Machined	Corners deburred	6		B
Surface of cold-rolled or continuously hot-dip galvanized strip material		6	(1)	B
Surface of hot-rolled strip material	High quality	12	(1)	D
	Good quality	15	(1)	E
	Moderate quality	18	(1–2)	F
Blasted surface of quenched and tempered plate material		42	–	I
Punched edge in cold-rolled strip material[2]	Good	15	–	D
Slitted edge in hot-rolled strip material[2]	Good quality, all visible imperfections are remedied	30	–	H
Laser-cut edge[2]	Very high quality, only cold-rolled strip material	9	1	C
Laser-cut edge in hot-rolled strip material[2]	High quality	15	1	E
	Good quality	18	2	F
	Moderate quality	24	2	G
		30	2	H
Plasma-cut edge in hot-rolled strip material[2]	High quality	15	2	E
	Good quality	18	2	F
	Moderate quality	24	2	G
		30	2	H
Gas-cut edge	Good quality	40	2–3	L
	Moderate quality	50	3	L

[1] SS-EN-ISO 9013 (t = 10 mm) [5.10]
[2] Free from crack-like imperfections

4.5. Examples – un-welded base material

Example 1

The following example illustrate how the above calculation procedure is used for a base plate with a certain surface condition. The procedure is valid for assessing cracking on the plate surface and not the edge. A load carrying structure is sensitive base material cracking, the structure is made of steel Domex 355 MC. The finite element analysis shows that the nominal stress (σ_{nom}) in the base material cut section is 200 MPa. Evaluate the fatigue life if the cutting procedure would be

a) Oxygen flame cutting
b) Laser beam cutting

R_e = 410 MPa, R_m = 470 MPa (data sheet from SSAB for Domex 355 MC)

The fatigue strength, Δσ* (reference strength) is:

$$\Delta\sigma^* = 9.8989 * R_e^{0.6071} = 9.898 * 410^{0.6071} = 382\ MPa$$

The difference between oxygen flame cutting and laser beam cutting is the different surface roughness's, Ra and Rz, which the cutting processes will achieve, and this will result in different surface factors K_f.
Typical surface conditions for oxygen flame cutting can be determined from figure 48, which gives Rz ≈ 20-40 μm (chose 30 μm). Note the large scatter which is typically for surface roughness measurements. For Laser beam cutting, from figure 48 we can read Rz ≈ 6-15 μm (chose 10 μm), again the measurements demonstrate large scatter.

Insertion of values in surface factor

$$K_r = \frac{1}{1 - 0.000254 * R_m * \ln\left(\frac{Rz}{6} + 1\right)}$$

Oxygen flame cutting

K_r^{oxygen} (Rz ≈ 30 μm) = 1.272 $\Delta\sigma = \frac{\Delta\sigma^*}{K_r} = \frac{382}{1.272} = 300\ MPa$

Fatigue life: $N_f = 10^6\left(\frac{\Delta\sigma}{\sigma_{nom}}\right)^5 = 10^6\left(\frac{300}{200}\right)^5 = 7.6 * 10^6\ cycles$

Laser beam cutting

K_r^{laser} (Rz ≈ 10 μm) = 1.105 $\Delta\sigma = \frac{\Delta\sigma^*}{K_r} = \frac{382}{1.105} = 346\ MPa$

Fatigue life: $N_f = 10^6\left(\frac{\Delta\sigma}{\sigma_{nom}}\right)^5 = 10^6\left(\frac{346}{200}\right)^5 = 15.5 * 10^6\ cycles$

The laser beam cutting gives 2x longer fatigue life due to smoother surface (smaller Rz) compared with oxygen cutting.

Example 2
The following example illustrate how the procedure is used for a cut edge with a certain surface condition of the edge. The procedure is valid for assessing cracking on the plate edge surface and not the plate surface. The following example will be solved graphically by using figure xx, relation between material factor (φ_m) and yield stress (R_m), table xx, correlation between surface condition and φ_m. The fatigue strength for the parent material is presented in **Appendix B**.

Domex 355 MC: R_e = 410 MPa, R_m = 470 MPa

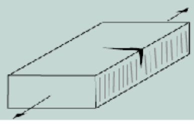
Nominal stress, σ_{nom} = 200 MPa

a) Oxygen flame cutting

Table 7 gives the type of surface, in this case gas-cut edge, and the material factor curve that should be used for a certain quality. We assume in this case a moderate quality (Rz = 50 µm), which corresponds to φ_m-curve L. curve L gives, for R_e = 410 MPa, φ_m = 1.0, see figure 51.

Type of surface or edge	Comment/quality specification	Surface condition Rz	ISO Range[1]	φ_m- curve
Gas-cut edge	Good quality	40	2–3	L
	Moderate quality	50	3	L

Structural detail, No. 11, for parent material in Appendix B gives the fatigue strength: FAT 140 (m = 3), φ_m = 1.0 (curve L).

No	Structural detail	Description of design surface or edge	Comment/ quality specification	Surface finish Rz	FAT (MPa)	Slope S-N, m	φ_m-curve
11		Machine gas-cut edges with subsequent machining, no cracks or visible defects.	All visible signs of defects to be removed. Cut surfaces to be milled or grinded, all burrs to be removed. No repairs by welding permitted! Rz not determined.	-	140	3	L

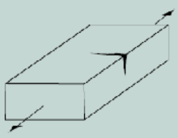
Fatigue life: $N_f = 2 * 10^6 \left(\frac{\varphi_m * \varphi_Q * \text{FAT}}{\sigma_{nom}}\right)^3 = 2 * 10^6 \left(\frac{1*1.3*140}{200}\right)^3 = 1.5 * 10^6\ cycles$

b) Laser beam cutting

Table 7 gives the type of surface, in this laser-cut edge in hot rolled strip material. We assume in this case a moderate quality (Rz = 24 µm), which corresponds to φ_m-curve G. Curve G gives, for R_e = 410 MPa, φ_m = 1.3, see figure 51.

Type of surface or edge	Comment/quality specification	Surface condition Rz	ISO Range[1]	φ_m- curve
Laser-cut edge in hot-rolled strip material[2]	High quality	15	1	E
	Good quality	18	2	F
	Moderate quality	24	2	G

Structural detail, No. 11, for parent material in Appendix B gives the fatigue strength: FAT 150 (m = 5), φ_m = 1.0 (curve G).

No	Structural detail	Description of design surface or edge	Comment/ quality specification	Surface finish Rz	FAT (MPa)	Slope S-N, m	φ_m-curve
09		Laser-cut edge	Very high quality. Only cold-rolled strip material.	9	190	5	C
		Laser-cut edge hot-rolled strip material.	High quality.	15	170	5	E
			Good quality.	18	160	5	F
			Moderate quality.	24	150	5	G
				30	150	5	H

Fatigue life: $N_f = 2 * 10^6 \left(\frac{\varphi_m * \varphi_Q * \text{FAT}}{\sigma_{nom}}\right)^5 = 2 * 10^6 \left(\frac{1.3*1.3*150}{200}\right)^5 = 4.07 * 10^6\ cycles$

The laser beam cutting gives 2.7x longer fatigue life due to smoother surface (smaller Rz) compared with oxygen cutting.

5. REFERENCES

[1] A. Hobbacher. Recommendation for fatigue design of welded joints and components. IIW document XIII-2151-07 / XV-1254-07

[2] T. Stenberg, E. Lindgren, Z. Barsoum, I. Barmicho, Fatigue assessment of cut edges in high strength steel – Influence of surface quality, Mat.-wiss. u. Werkstofftech. 2017, 48, 1–14.

[3] J.-O. Sperle, Influence of Parent Metal Strength on the Fatigue Strength of Parent Material with Machined and Thermally Cut Edges, Welding in the World, vol. 52, no. 7, pp. 79-92, 2008.

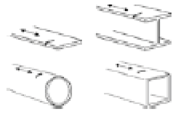
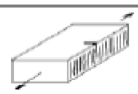
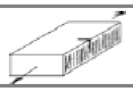
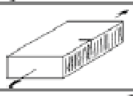
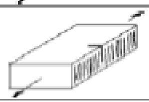
[4] International Standard: ISO 9013 Thermal cutting – Classification of thermal cuts – Geometrical product specification and quality tolerances, second edition ISO 9013:2002, Geneva, Switzerland, 2002

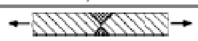
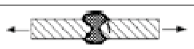
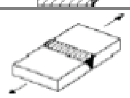
[5] Eurocode 3-Design of steel structures, Part 1.8 Joints, EN 1993-1-8.

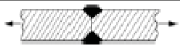
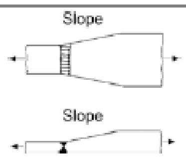
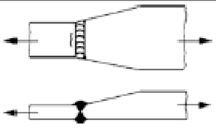
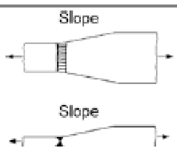
[6] Barsoum Z., Samuelsson J., Jonsson B., Björkblad A., Fatigue design of lightweight welded vehicle structures - Influence of material and production procedures, IMechE, Part B: Journal of Engineering Manufacture, Vol. 226, 10, pp.1736-1744, 2012.

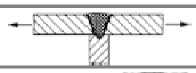
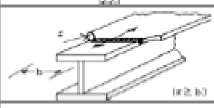
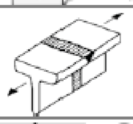
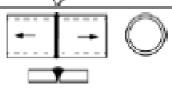
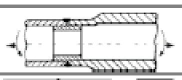
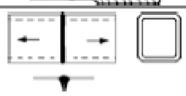
[7] Design handbook. Structural designing and manufacturing in high strength steels. Edition 1. SSAB.

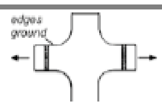
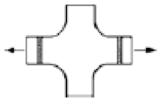
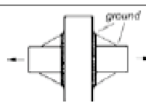
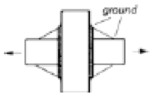
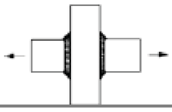
Appendix A: FAT nominal stress method (according to IIW)

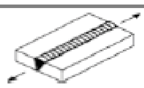
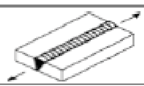
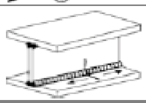
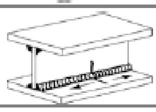
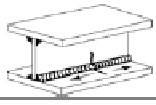
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
100	Unwelded parts of a component				
111		Rolled or extruded products, components with machined edges, seamless hollow sections m = 5			No fatigue resistance of any detail to be higher at any number of cycles Sharp edges, surface and rolling flaws to be removed by grinding. Any machining lines or grooves to be parallel to stresses
		Steel: A higher FAT class may be used if verified by test or specified by applicable code	160		
		Al.: AA 5000/6000 alloys		71	
		AA 7000 alloys		80	
121		Machine gas cut or sheared material with subsequent dressing, no cracks by inspection, no visible imperfections m = 3	140	—	All visible signs of edge imperfections to be removed. The cut surfaces to be machined or ground, all burrs to be removed No repair by welding refill Notch effects due to shape of edges shall be considered
122		Machine thermally cut edges, corners removed, no cracks by inspection m = 3	125	40	Notch effects due to shape of edges shall be considered
123		Manually thermally cut edges, free from cracks and severe notches m = 3	100	–	Notch effects due to shape of edges shall be considered
124		Manually thermally cut edges, uncontrolled, no notch deeper than 0.5 mm m = 3	80	–	Notch effects due to shape of edges shall be considered

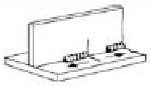
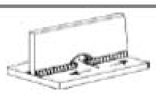
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
200	**Butt welds, transverse loaded**				
211		Transverse loaded butt weld (X-groove or V-groove) ground flush to plate, 100 % NDT	112	45	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress. Welded from both sides. Misalignment <5 % of plate thickness Proved free from significant defects by appropriate NDT
212		Transverse butt weld made in shop in flat position, NDT weld reinforcement <0.1 A thickness	90	36	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress. Welded from both sides. Misalignment <5 % of plate thickness
213		Transverse butt weld not satisfying conditions of 212, NDT Al.: Butt weld with toe angle ≤ 50° Butt welds with toe angle > 50°	80	 32 25	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress. Welded from both sides. Misalignment <10 % of plate thickness
214		Transverse butt weld, welded on non-fusible temporary backing, root crack	80	28	Backing removed, root visually inspected Misalignment <10 % of plate thickness
215		Transverse butt weld on permanent backing bar	71	25	Misalignment <10 % of plate thickness
216		Transverse butt welds welded from one side without backing bar, full penetration Root checked by appropriate NDT including visual inspection NDT without visual inspection No NDT	 71 63 36	 28 20 12	Misalignment <10 % of plate thickness

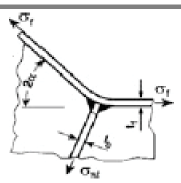
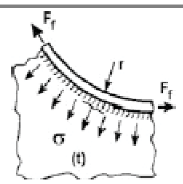
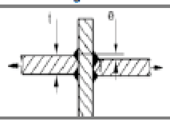
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
217		Transverse partial penetration butt weld, analysis based on stress in weld throat sectional area, weld overfill not to be taken into account	36	12	The detail is not recommended for fatigue loaded members Assessment by notch stress or fracture mechanics is preferred
221		Transverse butt weld ground flush, NDT, with transition in thickness and width Slope 1:5 Slope 1:3 Slope 1:2	 112 100 90	 45 40 32	All welds ground flush to surface, grinding parallel to direction of loading. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress Misalignment due to deliberate thickness step to be considered, see Sect. 3.8.2. Additional misalignment due to fabrication imperfection < 5 % of plate thickness
222		Transverse butt weld made in shop, welded in flat position, weld profile controlled, NDT, with transition in thickness and width: Slope 1:5 Slope 1:3 Slope 1:2	90 80 72	32 28 25	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress Misalignment due to deliberate thickness step to be considered, see Sect. 3.8.2. Additional misalignment due to fabrication imperfection < 5 % of plate thickness
223		Transverse butt weld, NDT, with transition on thickness and width Slope 1:5 Slope 1:3 Slope 1:2	 80 71 63	 25 22 20	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress Misalignment due to deliberate thickness step to be considered, see Sect. 3.8.2. Additional misalignment due to fabrication imperfection < 10 % of plate thickness

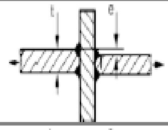
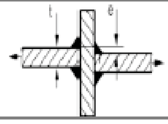
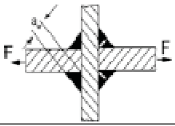
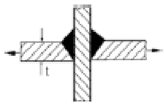
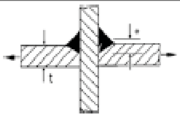
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
224		Transverse butt weld, different thicknesses without transition, centres aligned In cases, where weld profile is equivalent to a moderate slope transition, see no. 222	71	22	Misalignment < 10 % of plate thickness If centers are deliberately misaligned, this misalignment has to be considered, see Sect. 3.8.2
225		Three plate connection, potential cracking from root	71	22	Misalignment < 10 % of plate thickness
226		Transverse butt weld flange splice in built-up section welded prior to the assembly, ground flush, with radius transition, NDT	100	40	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress
231		Transverse butt weld splice in rolled section or bar besides flats, ground flush, NDT	80	28	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress
232		Transverse butt weld splice in circular hollow section, welded from one side, full penetration, potential failure from root root inspected by NDT no NDT	 71 36	 28 12	Welded in flat position Axial misalignment < 5 % of wall thickness
233		Tubular joint with permanent backing	71	28	Full peneration weld
234		Transverse butt weld splice in rectangular hollow section, welded from one side, full penetration, root crack root inspected by NDT, t >=8 mm root inspected by NDT, t < 8 mm no NDT	 71 56 36	 28 25 12	Welded in flat position

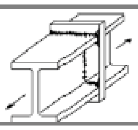
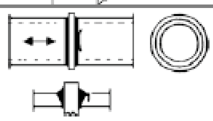
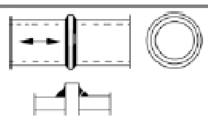
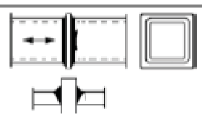
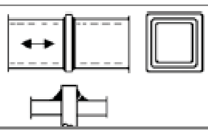
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
241		Transverse butt weld ground flush, weld ends and radius ground, 100 % NDT at crossing flanges, radius transition	100	40	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress Welded from both sides. No misalignment
242		Transverse butt weld made in shop at flat position, weld profile controlled, NDT, at crossing flanges, radius transition	90	36	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress Welded from both sides.Misalignment < 5 % of plate thickness
243		Transverse butt weld at intersecting flange, weld ground flush, NDT, at crossing flanges with welded triangular transition plates, weld ends ground Crack starting at butt weld For crack of continuous flange see details 525 and 526	80	32	All welds ground flush to surface, grinding parallel to direction of stress. Plate edges ground flush in direction of stress Welded from both sides. Misalignment < 10 % of plate thickness
244		Transverse butt weld at intersecting flange, NDT, at crossing flanges, with welded triangular transition plates, weld ends ground Crack starting at butt weld For crack of continuous flange see details 525 and 526	71	28	Plate edges ground flush in direction of stress Welded from both sides. Misalignment < 10 % of plate thickness
245		Transverse butt weld at intersecting flange Crack starting at butt weld For crack of continuous flange see details 525 and 526	50	20	Welded from both sides. Misalignment < 10 % of plate thickness

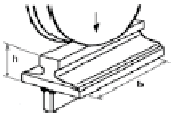
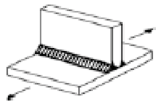
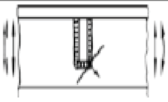
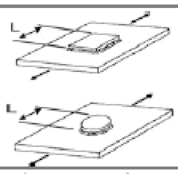
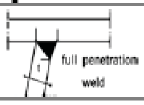
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
300	**Longitudinal load-carrying welds**				
311		Automatic longitudinal seam welds without stop/start positions in hollow sections with stop/start positions	125 90	50 36	
312		Longitudinal butt weld, both sides ground flush parallel to load direction, or continuous automatic longitudinal butt weld without start/stop positions proved free from significant defects by appropriate NDT	125	50	
313		Longitudinal butt weld, without stop/start positions, NDT with stop/start positions	112 90	45 36	
321		Continuous automatic longitudinal fully penetrated K-butt weld without stop/start positions (based on stress range in flange) NDT	125	50	No stop-start position is permitted except when the repair is performed by a specialist and inspection is carried out to verify the proper execution of the weld
322		Continuous automatic longitudinal double sided fillet weld without stop/start positions (based on stress range in flange)	112	45	
323		Continuous manual longitudinal fillet or butt weld (based on stress range in flange)	90	36	

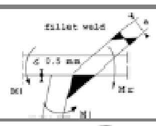
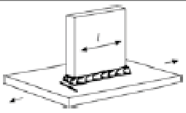
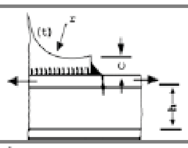
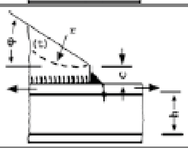
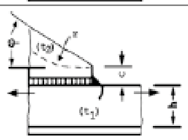
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
324		Intermittent longitudinal fillet weld (based on normal stress in flange **σ** and shear stress in web **τ** at weld ends)			Analysis based on normal stress in flange and shear stress in web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

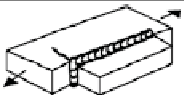
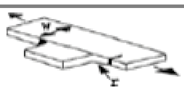
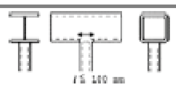
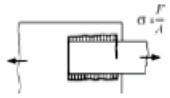
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
331		Joint at stiffened knuckle of a flange to be assessed according to no. 411–414, depending on type of joint Stress in stiffener plate: $\sigma = \sigma_f \cdot \frac{A_f}{\sum A_{st}} \cdot 2 \cdot \sin\alpha$ A_f = area of flange A_{st} = area of stiffener Stress in weld throat: $\sigma = \sigma_f \cdot \frac{A_f}{\sum A_w} \cdot 2 \cdot \sin\alpha$ A_w = area of weld throat	—	—	
332		Unstiffened curved flange to web joint, to be assessed according to no. 411–414, depending on type of joint Stress in web plate: $\sigma = \frac{F_f}{r \cdot t}$ Stress in weld throat: $\sigma = \frac{F_f}{r \cdot \Sigma a}$ F_f axial force in flange **t** thickness of web plate **a** weld throat	—	—	The resulting force of F_f-left and F_f-right will bend the flange perpendicular to the plane of main loading. In order to minimize this additional stressing of the welds, it is recommended to minimize the width and to maximize the thickness of the flange Stress parallel to the weld is to be considered. For additional shear, principal stress in web is to be consired (see 321–323)
400	**Cruciform joints and/or T-joints**				
411		Cruciform joint or T-joint, K-butt welds, full penetration, weld toes ground, potential failure from weld toe	80	28	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing Misalignment < 15 % of primary plate thickness in cruciform joints
		Single sided T-joints	90	32	

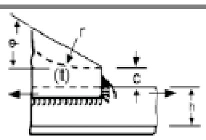
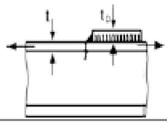
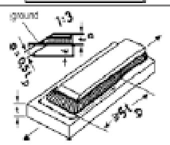
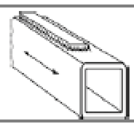
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
412		Cruciform joint or T-joint, K-butt welds, full penetration, potential failure from weld toe Single sided T-joints	71 80	25 28	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing Misalignment < 15 % of primary plate thickness in cruciform joints
413		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds, potential failure from weld toe Single sided T-joints	63 71	22 25	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing Misalignment < 15 % of primary plate thickness in cruciform joints Also to be assessed as 414
414		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds including toe ground joints, potential failure from weld root For a/t <=1/3	36 40	12 14	Analysis based on stress in weld throat $\sigma_w = F/\sum(a_w \cdot l)$ l = length of weld, a_w = load carrying weld throat. Also to be assessed as 413
415		Cruciform joint or T-joint, single-sided arc or laser beam welded V-butt weld, full penetration, potential failure from weld toe. Full penetration checked by inspection of root If root is not inspected, then root crack	71 36	25 12	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing Misalignment < 15 % of primary plate thickness in cruciform joints
416		Cruciform joint or T-joint, single-sided arc welded fillet or partial penetration Y-butt weld, no lamellar tearing, misalignment of plates e < 0.15 · t, stress at weld root. Penetration verified **Attention:** Bending by excenricity **e** must be consired!	71	25	Analysis based on axial and bending stress in weld throat. Excentricity **e** to be considered in analysis. Stress at weld root: $\Delta\sigma_{w,\,root} = \Delta\sigma_{w,\,nom} \cdot (1 + 6e/a)$ e = excentricity between midpoints plate and weld throat **a** (inclusive penetration), rotated into vertical leg plane using root tip as pivot An analysis by effective notch stress procedure is recommended

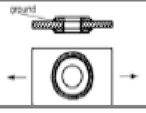
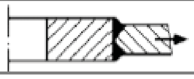
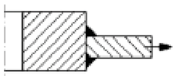
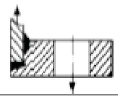
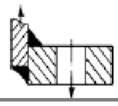
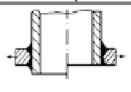
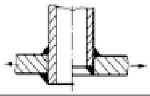
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
421		Splice of rolled section with intermediate plate, fillet welds, potential failure from weld root	36	12	Analysis based on stress in weld throat
422		Splice of circular hollow section with intermediate plate, singlesided butt weld, potential failure from toe wall thickness > 8 mm wall thickness < 8 mm	56 50	22 20	NDT of welds in order to ensure full root penetration
423		Splice of circular hollow section with intermediate plate, fillet weld, potential failure from root. Analysis based on stress in weld throat wall thickness >8 mm wall thickness <8 mm	45 40	16 14	
424		Splice of rectangular hollow section, single-sided butt weld, potential fairure from toe wall thickness > 8 mm wall thickness < 8 mm	50 45	20 18	NDT of welds in order to ensure full root penetration
425		Splice of rectangular hollow section with intermediate plate, fillet welds, potential failure from root wall thickness > 8 mm wall thickness < 8 mm	40 36	16 14	

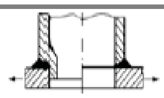
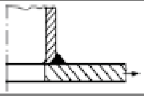
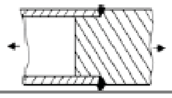
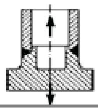
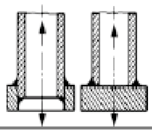
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
431		Weld connecting web and flange, loaded by a concentrated force in web plane perpendicular to weld. Force distributed on width **b = 2 · h + 50 mm** Assessment according to no. 411–414. A local bending due to eccentric load should be considered	–	–	
500	**Non-load-carrying attachments**				
511		Transverse non-load-carrying attachment, not thicker than main plate K-butt weld, toe ground Two sided fillets, toe ground Fillet weld(s), as welded thicker than main plate	 100 100 80 71	 36 36 28 25	Grinding marks normal to weld toe An angular misalignment corresponding to $\mathbf{k_m = 1.2}$ is already covered
512		Transverse stiffener welded on girder web or flange, not thicker than main plate K-butt weld, toe ground Two-sided fillets, toe ground fillet weld(s): as welded thicker than main plate	 100 100 80 71	 36 36 28 25	
513		Non-loadcarrying rectangular or circular flat studs, pads or plates L ≤ 50 mm L > 50 and ≤ 150 mm L > 150 and ≤ 300 mm L > 300 mm	 80 71 63 50	 28 25 20 18	
514		Trapezoidal stiffener to deck plate, full penetration butt weld, calculated on basis of stiffener thickness, out of plane bending	71	25	

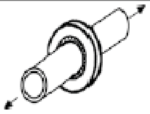
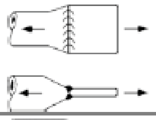
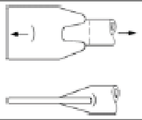
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
515		Trapezoidal stiffener to deck plate, fillet or partial penetration weld, out of plane bending	71	25	Calculation based on maximum out-of-plane bending stress range in weld throat or stiffener
521		Longitudinal fillet welded gusset of length l. Fillet weld around end l < 50 mm l < 150 mm l < 300 mm l > 300 mm	 80 71 63 50	 28 25 20 18	For gusset on edge: see detail 525 Particularly suitable for assessment on the basis of structural hot spot stress approach
522		Longitudinal fillet welded gusset with radius transition, fillet weld around end and toe ground, c < 2 t, max 25 mm r > 150 mm	90	32	t = thickness of attachment Particularly suitable for assessment on the basis of structural hot spot stress approach
523		Longitudinal fillet welded gusset with smooth transition (sniped end or radius) welded on beam flange or plate, fillet weld around end. c < 2 t, max 25 mm r > 0.5 h r < 0.5 h or ϕ > 20°	 71 63	 25 20	t = thickness of attachment If attachement thickness < 1/2 of base plat thickness, then one step higher allowed (not for welded on profiles!) Particularly suitable for assessment on the basis of structural hot spot stress approach
524		Longitudinal flat side gusset welded on plate edge or beam flange edge, with smooth transition (sniped end or radius), fillet weld around end. $c < 2t_2$, max. 25 mm r > 0.5 h r < 0.5 h or ϕ > 20°	 50 45	 18 16	t = thickness of attachment For $t_2 < 0.7\ t_1$, FAT rises 12 % Particularly suitable for assessment on the basis of structural hot spot stress approach

No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
525		In-plane or out-of-plane longitudinal gusset welded to plate or beam flange edge, gusset length l: l < 150 mm l < 300 mm l > 300 mm	 50 45 40	 18 16 14	For $t_2 < 0.7\ t_1$, FAT rises 12 % t_1 is main plate thkcness t_2 is gusset thickness
526		Longitudinal flat side gusset welded on edge of plate or beam flange, radius transition ground r > 150 or r/w > 1/3 1/6 < r/w < 1/3 r/w < 1/6	 90 71 50	 36 28 22	Smooth transition radius formed by grinding the weld area in transition in order to remove the weld toe completely. Grinding parallel to stress
531		Circular or rectangular hollow section, fillet welded to another section. Section width parallel to stress direction < 100 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	 63 45	 22 16	Stresses to be calculated in the main plate using a plate width equal to the weld length Buckling avoided by loading or design!
612		Longitudinally loaded lap joint with side fillet welds Fatigue of parent metal Fatigue of weld (calc. on max. weld length of 40 times the throat of the weld)	 50 50	 18 18	Buckling avoided by loading or design For verification of parent metal, the higher stresses of the two members must be taken

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 $\phi < 20°$ or radius), welded to loaded element c < 2Δt, but c <= 25 mm to flat bar to bulb section to angle section	 63 56 50	 22 20 18	**t** = thickness of gusset plate
614		Transverse loaded overlap joint with fillet welds Stress in plate at weld toe (toe crack) Stress in weld throat (root crack)	 63 36	 22 12	Stresses to be calculated using a plate width equalling the weld length For stress in plate, eccentricity to be considered, as given in chapters 3.8.2 and 6.3 Both failure modes have to be assessed separately
700	**Reinforcements**				
711		End of long doubling plate on I-beam, welded ends (based on stress range in flange at weld toe) $t_D \leq 0.8\ t$ $0.8\ t < t_D \leq 1.5\ t$ $t_D > 1.5\ t$	 56 50 45	 20 18 16	End zones of single or multiple welded cover plates, with or without transverse welds If the cover plate is wider than the flange, a transverse weld is needed. No undercut at transverse welds
712		End of long doubling plate on beam, reinforced welded ends ground (based on stress range in flange at weld toe) $t_D \leq 0.8\ t$ $0.8\ t < t_D \leq 1.5\ t$ $t_D > 1.5\ t$	 71 63 56	 28 25 22	Grinding parallel to stress direction
721		End of reinforcement plate on rectangular hollow section wall thickness: t < 25 mm	50	20	No undercut at transverse weld!

No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
731		Fillet welded reinforcements Toe ground As welded	 80 71	 32 25	Grinding in direction of stress! Analysis based on modified nominal stress, however, structural hot spot stress approach recommended
800	**Flanges, branches and nozzles**				
811		Stiff block flange, full penetration weld	71	25	
812		Stiff block flange, partial penetration or fillet weld toe crack in plate root crack in weld throat	 63 36	 22 12	
821		Flat flange with > 80 % full penetration butt welds, modified nominal stress in pipe, toe crack	71	25	Assessment by structural hot spot is recommended
822		Fillet welded pipe to flat flange joint. Potential fatigue failure from weld toe in pipe	63	22	Analysis based on modified nominal stress. However, structural hot spot stress recommended
831		Tubular branch or pipe penetrating a plate, K-butt welds	80	28	If diameter > 50 mm, stress concentration of cutout has to be considered Analysis based on modified nominal stress. However, structural hot spot stress recommended
832		Tubular branch or pipe penetrating a plate, fillet welds. Toe cracks Root cracks (analysis based on stress in weld throat)	71 36	25 12	If diameter > 50 mm, stress concentration of cutout has to be considered Analysis based on modified nominal stress. However, structural hot spot stress recommended

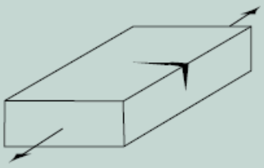
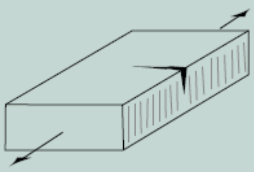
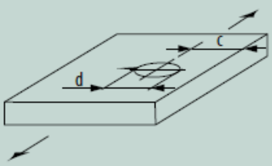
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
841		Nozzle welded on plate, root pass removed by drilling	71	25	If diameter >50 mm, stress concentration of cutout has to be considered Analysis based on modified nominal stress. However, structural hot spot stress recommended
842		Nozzle welded on pipe, root pass as welded	63	22	If diameter > 50 mm, stress concentration of cutout has to be considered Analysis based on modified nominal stress. However, structural hot spot stress recommended
900	**Tubular joints**				
911		But welded circular tube or pipe to solid bar joint. Potential fatigue failure from weld toe or root in tube or pipe	63	22	Analysis based on stress in tube or pipe Full penetration of weld to solid bas is required
912		Butt welded joint between circular tube or pipe and flange with integral backing. Potential fatigue failure fromweld root	63	22	Analysis based on stress in tube or pipe Full penetration of weld to solid bas is required
913		Fillet or partial penetration welded joint between circular tube or pipe and flange. Potential fatigue failure from weld root	50	18	Impairment of inspection of root cracks by NDT may be compensated by adequate safety considerations (see Sect. 3.5) or by downgrading by two FAT classes

No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
921		Circular hollow section with welded on disc, potential fatigue failure from toe in hollow section K-butt weld, toe ground Fillet weld, toe ground Fillet welds, as welded	 90 90 71	 32 32 25	
931		Tube-plate joint, tubes flattened, butt weld (X-groove) Tube diameter < 200 mm and plate thickness < 20 mm	63	18	
932		Tube-plate joint, tube slitted and welded to plate tube diameter < 200 mm and plate thickness < 20 mm tube diameter > 200 mm or plate thickness > 20 mm	 63 45	 18 14	

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

Appendix B: Structural details of parent material

No	Structural detail	Description of design surface or edge	Comment/ quality specification	Surface finish Rz	FAT (MPa)	Slope S-N, m	φ_m-curve
01		Ground	Corners deburred.	3	220	5	A
02		Machined	Corners deburred.	6	210	5	B
03		Surface of cold-rolled or continuously hot-dip galvanized strip material.		6	200	5	B
		Surface of hot-rolled strip material.	High quality.	12	180	5	D
			Good quality.	15	170	5	E
			Moderate quality.	18	160	5	F
			Exposed surface of weathering steel.	-	150	5	I
			Blasted surface.[1)]	70	170	5	E
		Blasted surface of quenched and tempered plate material.		42	180	5	I
04		Batch hot-dip galvanized surface.	Good quality.	-	170	5	J
05		Punched edge, cold-rolled strip material.	Good quality.	15	170	5	D
06		Slitted edge, hot-rolled strip material.	Good quality. All visible signs of defects to be removed. Edge corner rolling or blasting can increase FAT by 30%.	30	180	5	H
07		Punched edge, hot-rolled material.		-	140	3	L
08		Cut edge (power-shearing).		-	140	3	L
09		Laser-cut edge	Very high quality. Only cold-rolled strip material.	9	190	5	C
		Laser-cut edge hot-rolled strip material.	High quality.	15	170	5	E
			Good quality.	18	160	5	F
			Moderate quality.	24	150	5	G
				30	150	5	H
10		Plasma-cut edge hot-rolled strip material.	High quality.	15	170	5	E
			Good quality.	18	160	5	F
			Moderate quality.	24	150	5	G
				30	150	5	H
11		Machine gas-cut edges with subsequent machining, no cracks or visible defects.	All visible signs of defects to be removed. Cut surfaces to be milled or grinded, all burrs to be removed. No repairs by welding permitted! Rz not determined.	-	140	3	L
12		Machine thermally cut, corners removed, no cracks or notches by inspection.	Rz not determined.	-	125	3	L
13		Machine thermally cut, without cracks and sharp notches.	Rz not determined.	-	100	3	L
14		Machine thermally cut, uninspected, no notches deeper than 0.5 mm.	Rz not determined.	-	80	3	L
15		Circular open holes If $1.5d < c < 3d$, FAT is reduced by one step. The stress range can be calculated on the gross area if $A_{hole}/A_{gross}<0.1$. Reamed holes with deburred edges, allows the FAT class to be raised one step. FAT class can be raised two steps for holes with tightened screws.	Drilled and punched hole, cold-rolled plate	15	112	5	E
			Drilled hole, hot-rolled plate.	15	100	5	E
			Punched hole, hot-rolled plate.	-	80	3	L