Chapter 3
Fatigue Resistance

3.1 Basic Principles

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

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

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

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

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

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

The original version of this chapter was revised. Belated correction has been updated. An erratum to this chapter is available at DOI 10.1007/978-3-319-23757-2_8

The original version of this chapter was revised. An erratum to this chapter can be found at DOI 10.1007/978-3-319-23757-2_7

A.F. Hobbacher, *Recommendations for Fatigue Design of Welded Joints and Components*, IIW Collection, DOI 10.1007/978-3-319-23757-2_3

All fatigue resistance data are given as characteristic values, which are assumed to represent a survival probability of at least 95 %, calculated from the mean value on the basis of two-sided 75 % tolerance limits of the mean, unless otherwise stated (see Sect. 3.7). Other existing definitions as e.g. a survival probability of 95 % on the basis of 95 % one-sided limit of the mean or mean minus two standard deviations corresponding to a survival probability of 97.7 % are practically equal for engineering applications.

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

The fatigue resistance of a welded joint is also limited by the fatigue resistance of the parent material.

3.2 Fatigue Resistance of Classified Structural Details

The fatigue assessment of classified structural details and welded joints is based on the nominal stress range. In most cases, structural details are assessed on the basis of the maximum principal stress range in the section where potential fatigue cracking is considered. However, guidance is also given for the assessment of shear loaded details, based on the maximum shear stress range. Separate S-N curves are provided for consideration of normal or shear stress ranges, as illustrated in Figs. 3.1, 3.2 and 3.3 respectively.

Care must be taken to ensure that the stress used for the fatigue assessment is the same as that given in the tables of the classified structural details. Macro-structural hot

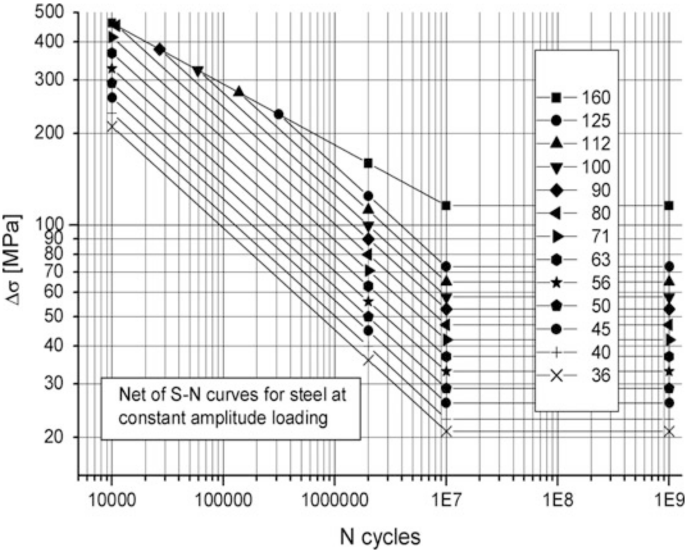


Fig. 3.1 Fatigue resistance S-N curves for steel, normal stress, standard applications

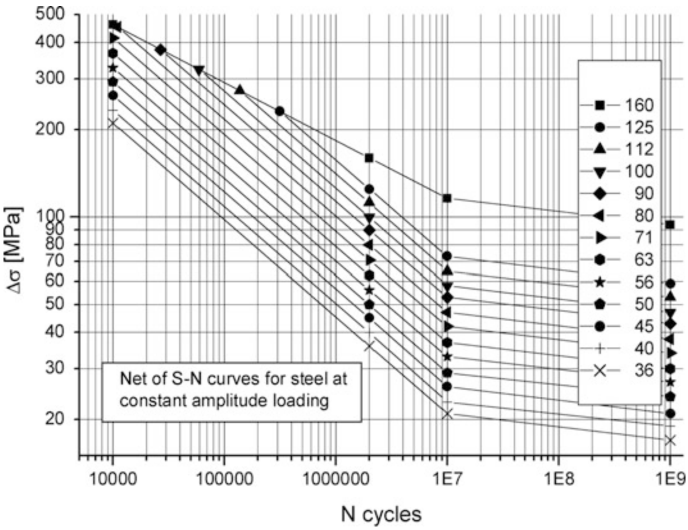


Fig. 3.2 Fatigue resistance S-N curves for steel, normal stress, very high cycles applications

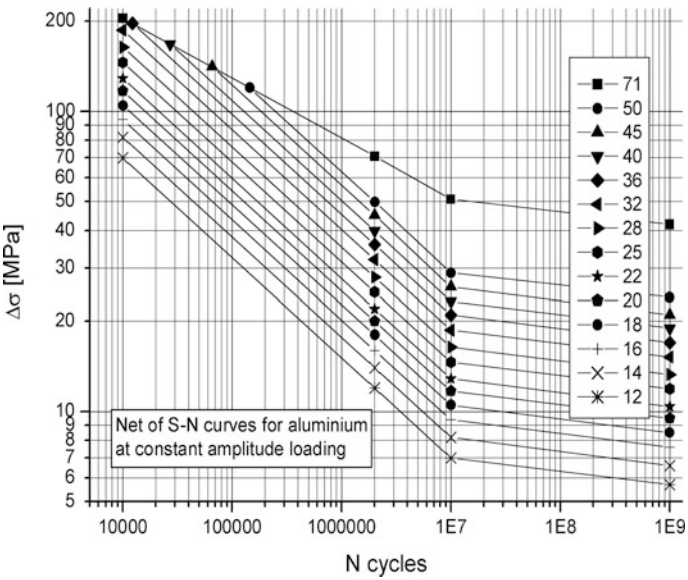


Fig. 3.3 Fatigue resistance S-N curves for aluminium, normal stress

spot stress concentrations not covered by the structural detail of the joint itself, e.g. large cut-outs in the vicinity of the joint, have to be accounted for by the use of a detailed stress analysis, e.g. finite element analysis, or appropriate stress concentration factors (see Sect. 2.2.2).

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

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

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

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

The slope of the fatigue strength S-N curves for details assessed on the basis of normal stresses (Fig. 3.1) is **m = 3.00** if not stated expressly otherwise. The constant amplitude knee point is assumed to correspond to **N = $\mathbf{10^7}$ cycles**.

The slope of the fatigue strength curves for details assessed on the basis of shear stresses (Figs. 3.2, 3.4, 3.5 and 3.6) is **m = 5.00**, but in this case the knee point is assumed to correspond to **N = $\mathbf{10^8}$ cycles**.

The conventional assumption is that the S-N curves terminate at a fatigue limit, below which failure will not occur, or in which case the S-N curve becomes a horizontal line. Traditionally, this constant amplitude fatigue limit (CAFL), also referred as ‘knee point’, is defined in terms of the corresponding fatigue endurance on the S-N curve, $N = 10^7$ being the most common assumption (see Fig. 3.1). However, new experimental data indicate that a CAFL does not exist and the S-N curve should continue on the basis of a further decline in stress range of about 10 % per decade in terms of cycles, which corresponds to a slope of **m = 22**.

This issue is only relevant if a design is expected to withstand very large numbers of stress cycles, such as for example at rotating welded machine parts. The matter is still under development and users should consult the latest relevant literature. Meanwhile, the nominal stress-based characteristic S-N curves are presented with the extrapolation beyond 10^7 cycles at a slope of m = 22 in Figs. 3.2 and 3.3.

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

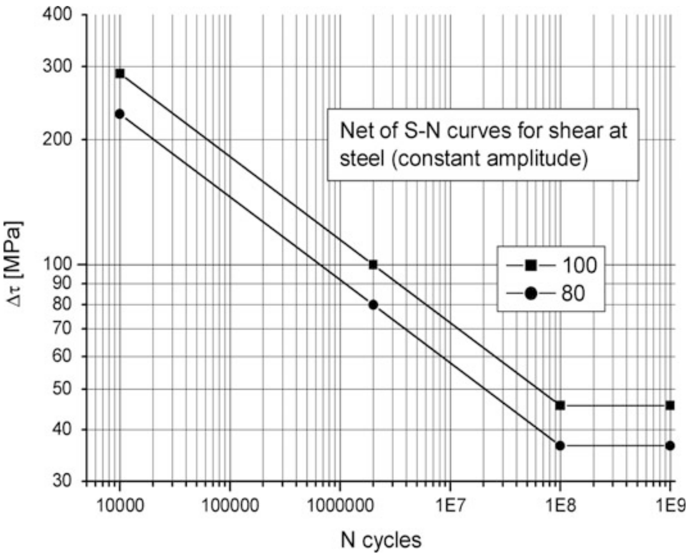


Fig. 3.4 Fatigue resistance S-N curve for shear at steel, standard applications

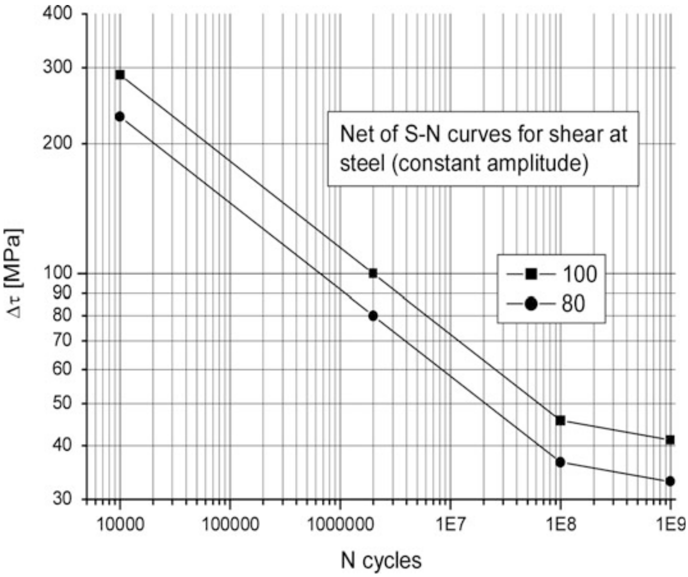


Fig. 3.5 Fatigue resistance S-N curves for shear at steel, very high cycle applications

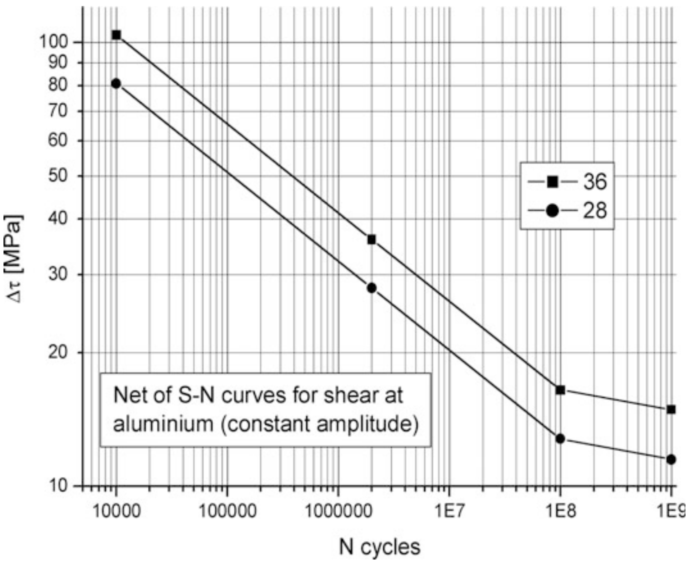


Fig. 3.6 Fatigue resistance S-N curve for shear at aluminium

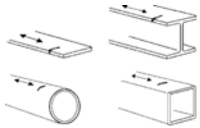
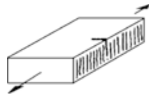
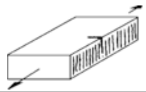
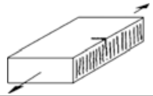
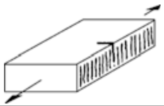
As appropriate, the fatigue classes given in Table 3.1 shall be modified according to Sect. 3.5. The limitations on weld imperfections shall be considered (Sect. 3.8).

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

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

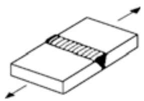
The S-N curves for weld details refer to specific failure modes, generally fatigue crack growth from the weld toe through the base material, from the weld root trough the weld throat, or from the weld surface through the weld and then into the base material. In an assessment of a given weld detail it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

Table 3.1 Fatigue resistance values for structural details in steel and aluminium assessed on the basis of nominal stresses

No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
100	Unwelded parts of a component				
111		Rolled or extruded products, components with machined edges, seamless hollow sections m = 5			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

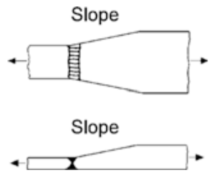
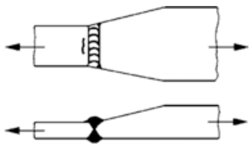
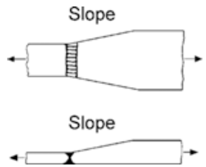
(continued)

Table 3.1 (continued)

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

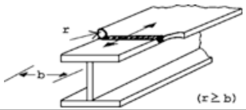
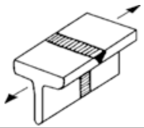
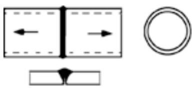
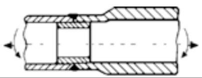
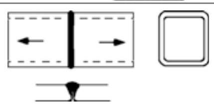
(continued)

Table 3.1 (continued)

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

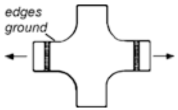
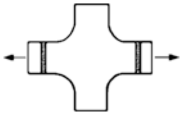
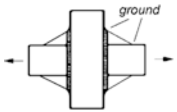
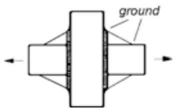
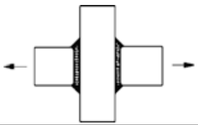
(continued)

Table 3.1 (continued)

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

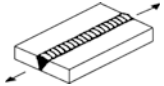
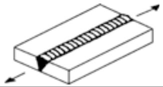
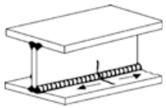
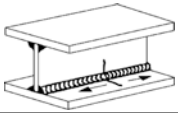
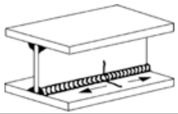
(continued)

Table 3.1 (continued)

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

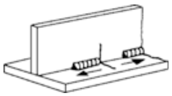
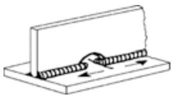
(continued)

Table 3.1 (continued)

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	

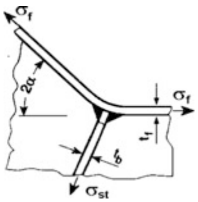
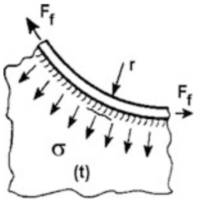
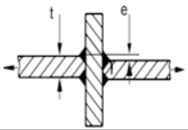
(continued)

Table 3.1 (continued)

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

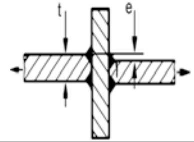
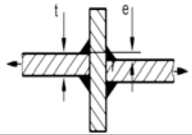
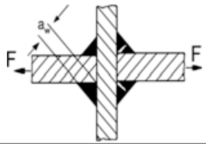
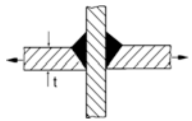
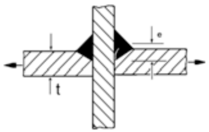
(continued)

Table 3.1 (continued)

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: $\sigma = \frac{F_f}{r \cdot \Sigma a}$ $\mathbf{F_f}$ 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 Single sided T-joints	80 90	28 32	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing Misalignment < 15 % of primary plate thickness in cruciform joints

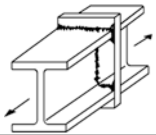
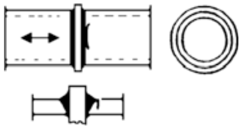
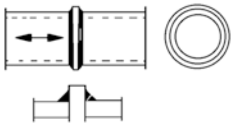
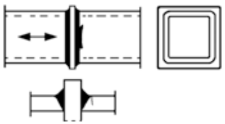
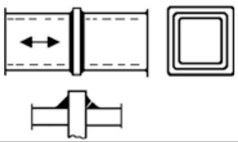
(continued)

Table 3.1 (continued)

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 $e < 0.15 \cdot t$, 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: $\boldsymbol{\Delta\sigma_{w,\,root} = \Delta\sigma_{w,\,nom} \cdot (1 + 6e/a)}$ **e** = excentricity between midpoints plate and weld throat **a** (inclusive penetration), rotated into vertical leg plane using root tip as pivot An analysis by effective notch stress procedure is recommended

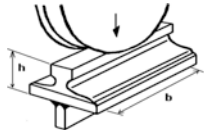
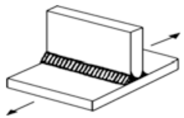
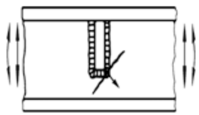
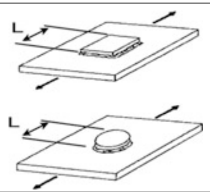
(continued)

Table 3.1 (continued)

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	

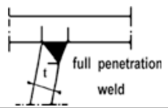
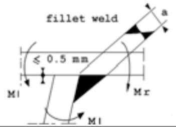
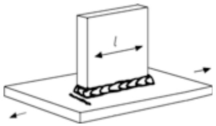
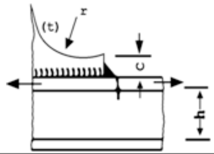
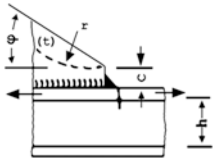
(continued)

Table 3.1 (continued)

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			71	25	

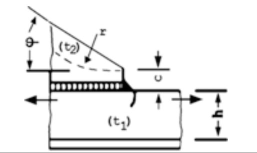
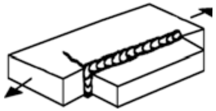
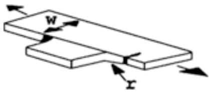
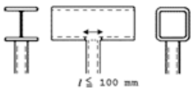
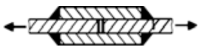
(continued)

Table 3.1 (continued)

No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
		Trapezoidal stiffener to deck plate, full penetration butt weld, calculated on basis of stiffener thickness, out of plane bending			
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 $\phi > 20°$	 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			**t** = thickness of attachment For $t_2 < 0.7\ t_1$, FAT rises 12 %

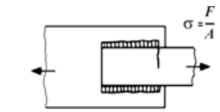
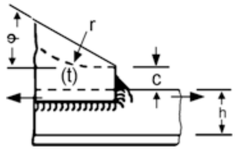
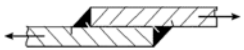
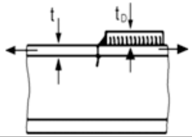
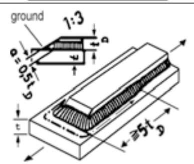
(continued)

Table 3.1 (continued)

No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
		(sniped end or radius), fillet weld around end. $c < 2t_2$, max. 25 mm $r > 0.5$ h $r < 0.5$ h or $\phi > 20°$	 50 45	 18 16	Particularly suitable for assessment on the basis of structural hot spot stress approach
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!

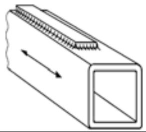
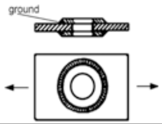
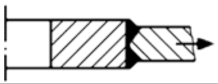
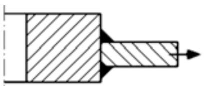
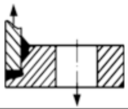
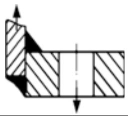
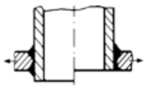
(continued)

Table 3.1 (continued)

No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
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
613		Lap joint gusset, fillet welded, non-load-carrying, with smooth transition (sniped end with $\phi < 20°$ or radius), welded to loaded element c < 2At, 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, eccenticity 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

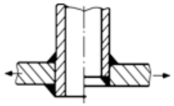
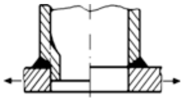
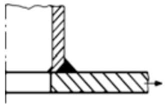
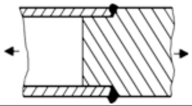
(continued)

Table 3.1 (continued)

No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
721		End of reinforcement plate on rectangular hollow section wall thickness: t < 25 mm	50	20	No undercut at transverse weld!
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

(continued)

Table 3.1 (continued)

No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
					Analysis based on modified nominal stress. However, structural hot spot stress recommended
832		Tubular branch or pipe penetrating a plate, fillet welds. Toe cracks Root cracks (analysis based on stress in weld throat)	71 36	25 12	If diameter > 50 mm, stress concentration of cutout has to be considered Analysis based on modified nominal stress. However, structural hot spot stress recommended
841		Nozzle welded on plate, root pass removed by drilling	71	25	If diameter >50 mm, stress concentration of cutout has to be considered Analysis based on modified nominal stress. However, structural hot spot stress recommended
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			63	22	Analysis based on stress in tube or pipe Full penetration of weld to solid bas is required

(continued)

Table 3.1 (continued)

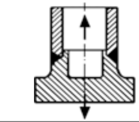
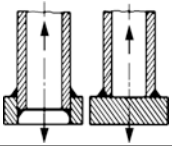
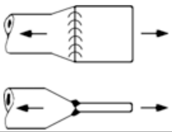
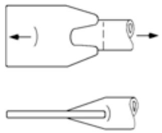
No.	Structural Detail	Description (St. = steel; Al. = aluminium)	FAT St.	FAT Al.	Requirements and remarks
		Butt welded joint between circular tube or pipe and flange with integral backing. Potential fatigue failure fromweld root			
913		Fillet or partial penetration welded joint between circular tube 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
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	

Table 3.2 Fatigue resistance values for structural details on the basis of shear stress

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

3.3 Fatigue Resistance Assessed on the Basis of Structural Hot Spot Stress

3.3.1 Fatigue Resistance Using Reference S-N Curve

The S-N curves for assessing the fatigue resistance of a detail on the basis of structural hot spot stress (Sect. 2.2.3) are given in the Table 3.3 for steel and aluminium, where the definition of the FAT class is given in Sect. 3.2. The resistance values refer to the as-welded condition unless stated otherwise. The effects of high tensile residual stress are included. Only small effects of misalignment are included, see also Sect. 3.8.2. The weld shape should be similar to that shown below (Table 3.3).

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

For hollow section joints, special hot-spot stress design *S-N* curves have been recommended by the IIW [14]. These tubular joint design curves should not be applied to other types of structure.

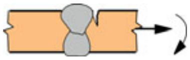
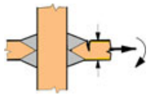
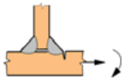
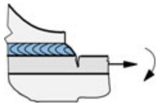
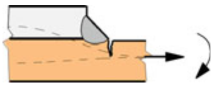
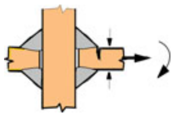
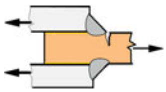
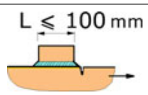
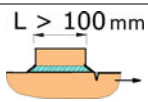
3.3.2 Fatigue Resistance Using a Reference Detail

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

Thus, the procedure will be:

(a) Select a reference detail with known fatigue resistance, which is as similar as possible to the detail being assessed with respect to geometric and loading parameters.
(b) Identify the type of stress in which the fatigue resistance is expressed. This is usually the nominal stress (as in the tables in Sect. 3.2).
(c) Establish a FEA model of the reference detail and the detail to be assessed with the same type of meshing and elements following the recommendations given in Sect. 2.2.3.

Table 3.3 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

Note 1 Table does not cover larger effects of misalignment than those specified in Sect. 3.8.2. They have to be considered explicitly in the determination of the hot spot stress range

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

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

(d) Load the reference detail and the detail to be assessed with the stress identified in b).
(e) Determine the structural hot spot stress $\boldsymbol{\sigma}_{\mathbf{hs,\ ref}}$ of the reference detail and the structural hot spot stress $\boldsymbol{\sigma}_{\mathbf{hs,\ assess}}$ of the detail to be assessed.
(f) The fatigue resistance for 2 million cycles of the detail to be assessed $\mathbf{FAT}_{\mathbf{assess}}$ is then calculated from fatigue class of the reference detail $\mathbf{FAT}_{\mathbf{ref}}$ by:

$$FAT_{assess} = \frac{\sigma_{hs,\ ref}}{\sigma_{hs,\ assess}} \cdot FAT_{ref} \tag{3.2}$$

3.4 Fatigue Resistance Assessed on the Basis of the Effective Notch Stress

3.4.1 Steel

The effective notch stress fatigue resistance against fatigue actions, as determined in Sect. 2.2.4 for steel [24], is given in Table 3.4. The definition of the FAT class is given in Sect. 3.2. The fatigue resistance value refers to the as-welded condition. The effect of high tensile residual stresses is included. The effect of possible misalignment is **not** included.

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

3.4.2 Aluminium

The same regulations apply as for steel (Table 3.5).

Table 3.4 Effective notch fatigue resistance for steel

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

Table 3.5 Effective notch fatigue resistance for aluminium

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

3.5 Fatigue Strength Modifications

3.5.1 Stress Ratio

3.5.1.1 Steel

For effective stress ratios, based on consideration of both applied and residual stresses, **R < 0.5** a fatigue enhancement factor **f(R)** may be considered by multiplying the fatigue class of classified details by **f(R)**. This factor depends on the level and direction of residual stresses. Here, all types of stress which are **not** considered in fatigue analysis and which are effective during service loading of the structure are regarded as residual stress. The ranking in categories I, II or III should be documented by the design office. If no reliable information on residual stress is available, an enhancement factor **f(R) = 1** is recommended. Other factors should only be used if reliable information or estimations of the residual stress level are available [47].

The following cases are to be distinguished (Fig. 3.7):

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

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

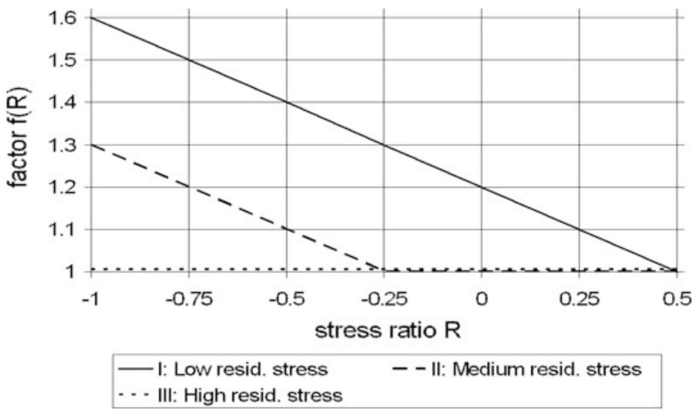


Fig. 3.7 Enhancement factor f(R)

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

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

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

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

It should be noted that stress relief in welded joints is unlikely to be fully effective, and additional residual stresses may be introduced by lack of fit during assembly of prefabricated welded components, by displacements of abutments or for other reasons. Consequently, it is recommended that values of **f(R) > 1** should only be adopted for welded components in very special circumstances. In several cases, stress relieving might reduce the fatigue properties as e.g. at TMCP steels by reduction of mechanical properties, or at weld roots in single sided butt welds or at fillet welds, by reduction of beneficial residual compressive stress.

Note: For unwelded or stress relieved steel structures, a simplified approach may be used, which consists in considering only 60 % of the stresses in compression.

3.5.1.2 Aluminium

The same regulations as for steel are recommended.

3.5.2 Wall Thickness

Fatigue resistance modifications are required at the nominal stress method (see Sect. 3.2) and the hot spot structural stress method of type "**a**" at surface extrapolation as described in Sect. 3.3. It is not required at the effective notch stress method and at the fracture mechanics method (see Sects. 3.4 and 3.6).

3.5.2.1 Steel

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

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

where the reference thickness $\mathbf{t_{ref} = 25\ mm}$. The thickness correction exponent **n** is dependent on the effective thickness $\mathbf{t_{eff}}$ and the joint category (see Table 3.6) [45]. In the same way a benign thinness effect might be considered, but this should be verified by component test.

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

For the determination of $\mathbf{t_{eff}}$, the following cases have to be distinguished (Fig. 3.8):

$$\text{if} \quad \mathbf{L/t > 2} \quad \text{then} \quad \mathbf{t_{eff} = t} \tag{3.6a}$$

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

Table 3.6 Thickness correction exponents

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

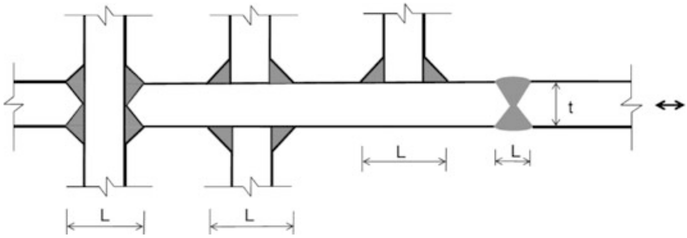


Fig. 3.8 Definition of toe distance L

3.5.2.2 Aluminium

The same rules as for steel are recommended.

3.5.3 Improvement Techniques

3.5.3.1 General

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

The main improvements techniques are:

(a) Methods for improvement of weld profile:

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

(b) Methods for improvement of residual stress conditions:

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

(c) Methods for improvement of environmental conditions:

Painting
Resin coating

The effects of all improvement techniques are sensitive to the method of application and the applied loading, being most effective in the low stress high cycle regime. They may also depend on the material, the structural detail, the applied stress ratio and the dimensions of the welded joint. Consequently, fatigue tests for the verification of the procedure in the endurance range of interest are recommended (Sects. 3.7 and 2.2.2).

Recommendations are given below for the following post-welding weld toe improvement methods: grinding, TIG dressing, hammer and needle peening.

3.5.3.2 Applicability of Improvement Methods

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

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

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

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

The improvement procedures described below, apply solely to the weld toe and hence to a potential fatigue crack growth starting from this point. Thus, weld details of the type illustrated in Fig. 3.9 are suitable for treatment. However, the benefit of an improvement technique could be reduced as a result of intervention of fatigue cracking from the weld root. Thus, details of the kind shown in Fig. 3.10 are less suitable. In general, all potential alternative sites for fatigue crack initiation (e.g. weld root or imperfections) in treated welded joints should be assessed in order to establish the fatigue life of the weld detail under consideration.

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

A profile improvement can sometimes assist in the application of a residual stress technique and vice versa (e.g. grinding before peening in the case of a poor

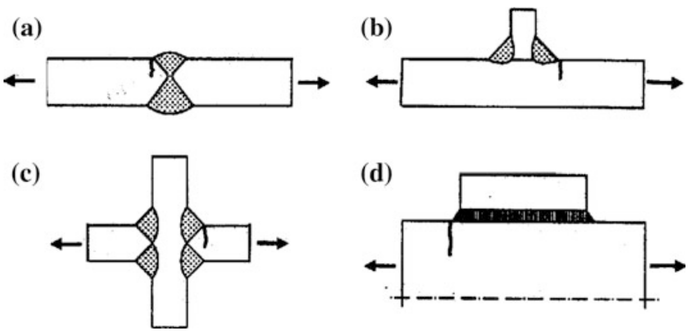


Fig. 3.9 Examples of joints suitable for improvement

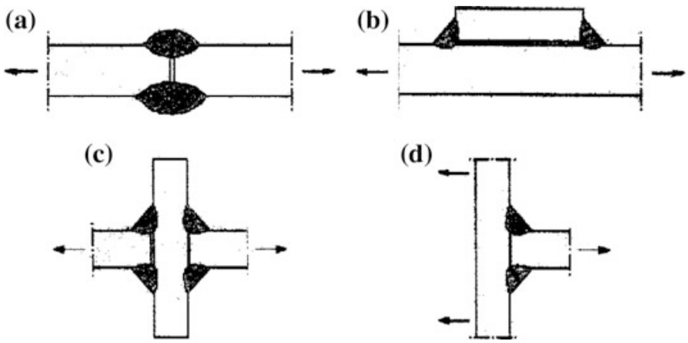


Fig. 3.10 Examples of joints, in which an improvement might be limited by a possible root crack

weld profile or shot peening a dirty surface before TIG dressing). However, a higher benefit factor than that applicable for the second technique alone can only be justified on the basis of special fatigue tests.

3.5.3.3 Grinding

Weld toe fatigue cracks initiate at undercut, cold laps or the sharp crack-like imperfections, just a few tenths of a millimetre deep, which are an inherent feature of most arc welds. The aim of grinding is firstly to remove these imperfections and secondly to create a smooth transition between weld and plate, thus, reducing the stress concentration. All embedded imperfections revealed by grinding must be repaired. For the details of the grinding procedure see Ref. [46].

The benefit of grinding is given as a factor on the stress range of the fatigue class of the non-improved joint, see Tables 3.7 and 3.8.

The thickness correction exponent according to Sect. 3.5.2 Table 3.6 is **n = 0.2**.

Table 3.7 FAT classes for use with nominal stress at joints improved by grinding

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

Table 3.8 FAT classes for use with structural hot-spot stress at joints improved by grinding

Material	Load-carrying fillet welds	Non-load-carrying fillet welds and butt welds
Mild steel, f_y < 355 MPa	112	125
Higher strength steel, f_y ≥ 355 MPa	112	125
Aluminium alloys	45	50

3.5.3.4 TIG Dressing

By TIG (tungsten inert gas) dressing, the weld toe is remolten in order to remove the weld toe imperfections and to produce a smooth transition from the weld to plate surface, thus reducing the stress concentration. The recommendations (Tables 3.9 and 3.10) apply to partial or full penetration arc welded in steels with a specified yield strength up to 900 MPa and to wall thicknesses ≥ 10 mm operating in a non-corrosive environment or under conditions of corrosion protection. The details of the procedure are described in Ref. [46].

The thickness correction exponent according to chapter 3.5.2 Table 3.6 is **n = 0.2**.

A possible interaction between heat treatment and TIG dressing at aluminium alloys should be considered.

3.5.3.5 Hammer Peening

By hammer peening, the material is plastically deformed at the weld toe in order to introduce beneficial compressive residual stresses. The recommendations are restricted to steels with specified yield strengths up to 900 MPa and structural aluminium alloys, both operating in non-corrosive environments or under conditions of corrosion protection. The recommendations apply for plate thicknesses from 10 to 50 mm in steel and 5 to 25 mm in aluminium and to arc welded fillet welds with a minimum weld leg length of 0.1 × t, where t is the thickness of the stressed plate (Tables 3.11 and 3.12). The details of the procedure are described in Ref. [46].

Special requirements apply when establishing the benefit of hammer peening:

Table 3.9 FAT classes for use with nominal stress at joints improved by TIG dressing

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

Table 3.10 FAT classes for use with structural hot-spot stress at joints improved by TIG dressing

Material	Load-carrying fillet welds	Non-load-carrying fillet welds and butt welds
Mild steel, f_y < 355 MPa	112	125
Higher strength steel, f_y > 355 MPa	112	125
Aluminium alloys	45	50

Table 3.11 FAT classes for use with nominal stress at joints improved by hammer peening

Area of application and maximum possible claim	Mild steel $f_y < 355$ MPa	Steel $f_y \geq 355$ MPa	Aluminium
Benefit at details with FAT ≤ 90 at steel or FAT ≤ 32 at aluminium, as welded	1.3	1.5	1.5
Max possible FAT after improvement	FAT 112	FAT 125	FAT 56

Table 3.12 FAT classes for use with structural hot-spot stress at joints improved by hammer peening

Material	Load-carrying fillet welds	Non-load-carrying fillet welds
Mild steel, $f_y < 355$ MPa	112	125
Higher strength steel, $f_y \geq 355$ MPa	125	140
Aluminium alloys	50	56

(a) Maximum amount of nominal compressive stress in load spectrum including proof loading <0.25 f_y (for aluminium, use f_y of heat affected zone)
(b) The S-N curve for the hammer peened weld is is used in conjunction with an effective stress range that depends on applied stress ratio R = minσ/maxσ as follows:

if $R < 0$	The S-N resistance curve is used with full stress range $\Delta\sigma$
if $0 < R \leq 0.4$	The S-N resistance curve is used with the maximum stress σ_{max}
if $R > 0.4$	Then there is no benefit

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

3.5.3.6 Needle Peening

By needle peening, the material is plastically deformed at the weld toe in order to introduce beneficial compressive residual stresses. The details of the procedure are described in [46].

Special requirements apply when establishing the benefit of needle peening:

(a) Maximum amount of nominal compressive stress in load spectrum including proof loading ≤ 0.25 f_y (for aluminium, use f_y of heat affected zone), see Tables 3.13 and 3.14.
(b) The S-N curve for needle peened weld is expressed in terms of an effective stress range that depends on applied R ratio as follows:

Table 3.13 FAT classes for use with nominal stress at joints improved by needle peening

Area of application and maximum possible claim	Mild steel fy < 355 MPa	Steel fy ≥ 355 MPa	Aluminium
Benefit at details with FAT ≤ 90 at steel or FAT ≤ 32 at aluminium, as welded	1.3	1.5	1.5
Max possible FAT after improvement	FAT 112	FAT 125	FAT 56

Table 3.14 FAT classes for structural hot-spot stress at joints improved by needle peening

Material	Load-carrying fillet welds	Non-load-carrying fillet welds
Mild steel, $f_y < 355$ MPa	112	125
Higher strength steel, $f_y > 355$ MPa	125	140
Aluminium alloys	50	56

if $R < 0$	The S-N resistance curve is used with full stress range $\Delta\sigma$
if $0 < R \leq 0.4$	The S-N resistance curve is used with the maximum stress σ_{max}
If $R > 0.4$	Then there is no benefit

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

3.5.4 *Effect of Elevated Temperatures*

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

$$FAT_{HT} = FAT_{20^\circ C} \cdot \frac{E_{HT}}{E_{20^\circ C}} \tag{3.7}$$

3.5.4.1 Steel

For higher temperatures, the fatigue resistance data may be modified by the reduction factor given in Fig. 3.11. This fatigue reduction factor is a conservative approach and might be relaxed according to test evidence or applicable codes. Creep effects are not covered here.

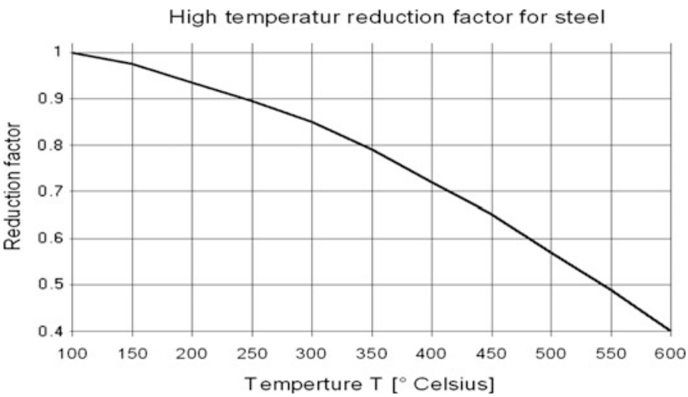


Fig. 3.11 Fatigue strength reduction factor for steel at elevated temperatures

3.5.4.2 Aluminium

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

3.5.5 Effect of Corrosion

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

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

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

3.6 Fatigue Resistance Assessed on the Basis of Crack Propagation Analysis

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

$$\frac{da}{dN} = C_0 \cdot \Delta K^m \quad if \quad \Delta K < K_{th} \quad else \quad \frac{da}{dN} = 0 \tag{3.8}$$

where the material parameters are

C_0 Constant of the power law
m Exponent of the power law
ΔK Range of cyclic stress intensity factor
ΔK_{th} Threshold value of stress intensity, under which no crack propagation is assumed
R **K_{min}/K_{max}**, taking all stresses including residual stresses into account (see Sect. 3.5.1)

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

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

$$C = C_{0,\,steel} \cdot \left(\frac{E_{steel}}{E}\right)^m \tag{3.9}$$

$$\Delta K_{th} = \Delta K_{th,\,steel} \cdot \left(\frac{E}{E_{steel}}\right) \tag{3.10}$$

3.6.1 Steel

See Table 3.15

Table 3.15 Parameters of the Paris power law and threshold data for steel

Units	Paris power law parameters	Threshold values ΔK_{th}			
		R ≥ 0.5	0 ≤ R≤0.5	R < 0	Surface crack depth < 1 mm
K [$N \cdot mm^{-3/2}$] da/dN [mm/cycle]	$C_0 = 5.21 \cdot 10^{-13}$ m = 3.0	63	170–214 · R	170	≤63
K [$MPa\sqrt{m}$] da/dN [m/cycle]	$C_0 = 1.65 \cdot 10^{-11}$ m = 3.0	2.0	5.4–6.8 · R	5.4	≤2.0

3.6.2 Aluminium

See Table 3.16

Table 3.16 Parameters of the Paris power law and threshold data for aluminium

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

3.6.3 Correlation of Fracture Mechanics to Other Verification Methods

The biggest portion of service life of welded joints is spent in crack propagation. So, estimates of fatigue life or the fatigue class FAT can be made by fracture mechanics calculations using appropriate parameters. The calculations should be verified at known structural details. A possible example of a set of parameters could be:

$a_i = 0.1$ mm	Initial crack size parameter (fitted value)
$a_i{:}c_i = 1$	Initial aspect ratio (at butt welds ground flush $a_i{:}c_i = 0.1$)
$a_f = \min(t/2;\ 12.5\ mm)$	Final crack size parameter (t is wall thickness)
$r = t/25$	Toe radius for most cases
$\theta = 45°$	Weld angle for most cases, 30° for butt welds
$m = 3.0$	Exponent of the Paris-Erdogan power law

At cruciform joints or butt welds with partial penetration, the one half of the root gap shall be taken as the initial crack size parameter. Since the existence of a high stress concentration at the root gaps and a rapid growth in "c"-direction, a through-going crack or at least an initial aspect ratio $a_i{:}c_i = 0.1$ may be assumed and a two-dimensional analysis may be adequate.

At butt welds ground flush, the point of a possible crack initiation may be located in the weld metal. Thus the constant for weld metal shall be taken, and $a_i{:}c_i = 0.1$ is recommended. For material parameters see Table 3.17.

Misalignment shall be considered either in determination of the stress distribution by finite element analysis or by modification of the results of fracture mechanics calculations. See chapter 3.8.2.

Table 3.17 Constants Co of the power law for correlation (units in N and mm)

	Weld metal (root cracks)	Weld toes (base metal)
Steel	$5.21 \cdot 10^{-13}$	$3.00 \cdot 10^{-13}$
Aluminium	$1.41 \cdot 10^{-10}$	$0.81 \cdot 10^{-10}$

3.7 Fatigue Resistance Determination by Testing

3.7.1 General Considerations

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

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

Experimental fatigue data are scattered, with the extent of scatter tending to be greatest in the low stress/low crack propagation regime (e.g. see Fig. 3.12). For statistical evaluation, a Gaussian log-normal distribution should be assumed. If possible, at least 10 specimens should be tested.

Many methods of statistical evaluation are available. However, the most common approach for analysing fatigue data is to fit S-N or crack propagation curves by regression analysis, taking **log(N)** or **log(da/dN)** as the dependent variable.

Test results should be analysed to produce **characteristic** values (subscript **k**). These are values that represent 95 % survival probability (i.e. 5 % failure probability) calculated from the mean on the basis of a two-sided confidence of 75 %. More details on the use of the confidence level and formulae are given below.

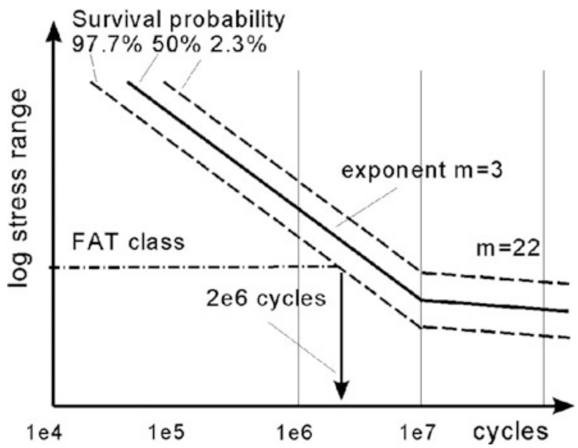


Fig. 3.12 Scatter band in S-N curve

At higher test cycles than about two or ten million cycles, the staircase method is recommended for testing and evaluation [70]. For a combined evaluation of failed and run-out specimens, maximum likelihood method is recommmended [71].

3.7.2 Evaluation of Test Data

Different methods for fatigue testing exist. For the derivation of S-N curves, testing at two stress range levels (**Δσ**) to give fatigue lives within the range of 5×10^4 to 10^6 cycles is preferred. For obtaining fracture mechanics crack propagation parameters, the range of stress intensity factor (**ΔK**) should be varied between the threshold and the critical level for fracture.

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

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

(b) Calculate exponents **m** and constant **logC** (or $\mathbf{logC_0}$ respectively) of the formulae:

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

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

by linear regression taking stress or stress intensity factor range as the independent variable, i.e. **logN = f(log Δσ)** or **log(da/dN) = f(log ΔK).**
The number and the spread of the data pairs should be critically assessed. If the number of pairs of test data **n < 10**, or if the data are not sufficiently evenly distributed to determine **m** accurately, a fixed value of **m** should be taken, as derived from other tests under comparable conditions, e.g. **m = 3** for steel and aluminium welded joints at stiff and thick-walled components. In all cases, the standard deviation of the exponent **m** shall be determined for a subsequent check if the pre-fixed exponent, e.g. **m = 3**, is still reasonable. For other conditions other slopes might be also adequate.
Values $\mathbf{x_i}$ equal to **logC** or $\mathbf{logC_0}$ are calculated from the $\mathbf{(N, \Delta\sigma)_i}$ or $\mathbf{(da/dN, \Delta K)_i}$ test results using the above equations.

(c) Calculate mean $\mathbf{x_m}$ and the standard deviation **Stdv** of **logC** (or $\mathbf{logC_0}$ respectively) using **m** obtained in b).

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

d) Calculate the characteristic values $\mathbf{x_k}$ by the formulae
The values of **k** are given in Table 3.18.

Table 3.18 Values of **k** for the calculation of characteristic values

n	6	8	10	15	20	30	50	100
k	2.32	2.23	2.17	2.07	2.01	1.95	1.88	1.81

Note: In several areas of applications, the codes refer to mean minus two standard deviations, which corresponds to a survival probability of 97.7 %. Referring to survival probability of 95 % at two-sided confidence level of the mean of 75 % (one-sided 87.5 %, sometimes also 95 %) and considering the usual scatter of fatigue tests as shown in Fig. 3.12, the difference in terms of stress is less than 2 % and thus may be neglected. The method proposed above is equal to about mean minus two standard deviations at about 20 specimens.

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

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

$$\text{Values of } \mathbf{k}: \quad k = 1.645 \cdot \left(1 + \frac{1}{\sqrt{n}}\right) \tag{3.16}$$

For more details and information, see Appendix 6.4 and Refs. [68–72, 75].

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

3.7.3 Evaluation of Data Collections

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

The evaluation procedure should consist of the following steps:

1. Calculate the constant **log C** of the S-N Wöhler curve for each data point (see Sect. 3.7.2.) using anticipated knowledge of the slope exponent from comparable test series, e.g. slope **m = 3.00** for steel or aluminium.
2. Plot all values **log C** in a Gaussian probability chart, showing the values of **log C** on the abscissa and the cumulative survival probability on the ordinate.
3. Check the probability plot for heterogeneity of the population. If it is heterogeneous, separate the portion of the population which is of interest (see illustration on Figs. 3.13 and 3.14).
4. Evaluate the interesting portion of population according to Sect. 3.7.2., which is the portion of the lowest values of **log C**.

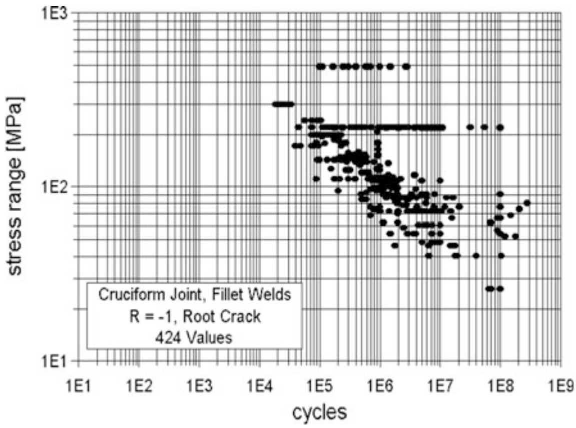


Fig. 3.13 Example of scatter in data collections

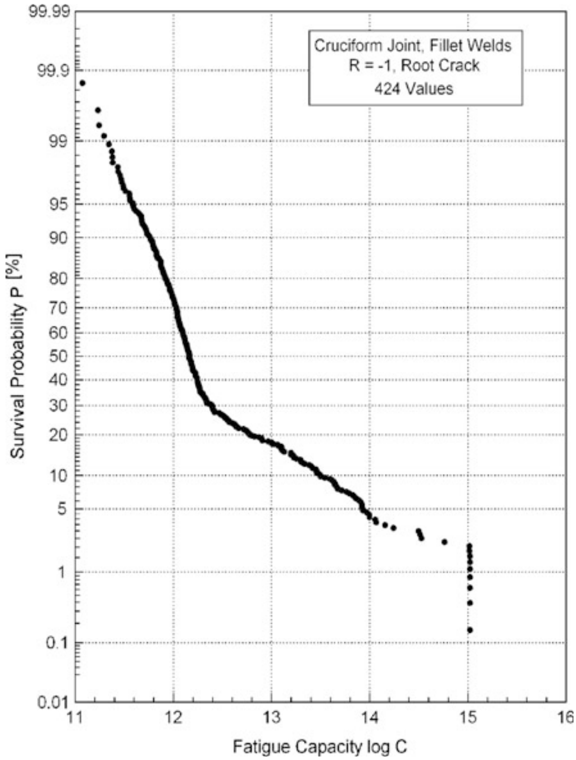


Fig. 3.14 Example of a heterogeneous population

3.8 Fatigue Resistance of Joints with Weld Imperfections

3.8.1 General

3.8.1.1 Types of Imperfections

The types of imperfections covered in this document are listed below. Other imperfections, not yet covered, may be assessed by assuming similar imperfections with comparable notch effect. Definitions are given in Ref. [48–50].

Imperfect shape

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

Undercut

Volumetric discontinuities

Gas pores and cavities of any shape.

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

Planar discontinuities

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

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

3.8.1.2 Effects and Assessment of Imperfections

Three effects of geometrical imperfections can be distinguished, as summarized in Table 3.19.

Increase of general stress level

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

Local notch effect

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

Additive notch effect

If the location of the notch due to the weld imperfection coincides with a structural discontinuity associated with the geometry of the weld shape (e.g. weld

Table 3.19 Categorization and assessment procedure for weld imperfections

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

toe), then the fatigue resistance of the welded joint is decreased by the additive notch effect. This may be the case at weld shape imperfections.

Competitive notch effect

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

Crack-like imperfections

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

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

If a weld imperfection cannot be clearly identified as a type or an effect of the types listed here, it is recommended that it is assumed to be crack-like [54, 57].

3.8.2 Misalignment

Misalignment in axially loaded joints leads to an increase of stress in the welded joint due to the occurrence of secondary shell bending stresses [55, 56]. The resulting stress is calculated by stress analysis or by using the formulae for the stress magnification factor $\mathbf{k_m}$ given in Table (3.20) and in Appendix 6.3.

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

Table 3.20 Consideration of stress magnification factors due to misalignment

Type of k_m analysis	Nominal stress approach	Structural hot spot, effective notch and fracture mechanics appoach	
Type of welded joint	k_m already covered in FAT class	k_m already covered in SN curves	Default value of effective k_m to be considered in stress
Butt joint made in shop in flat position	1.15	1.05	1.10*
Other butt joints	1.30	1.05	1.25*
Cruciform joints	1.45	1.05	1.40*
Fillet welds on one plate surface	1.25	1.05	1.20**
Fillet welds on both plate surfaces	1.25	1.05	1.10***

* but not more than $(1 + 2.5 \cdot e_{max}/t)$, where e_{max} = permissible misalignment and t = wall thickness of loaded plate
** but not more than $(1 + 0.2 \cdot t_{ref}/t)$, where t_{ref} = reference wall thickness of fatigue resistance curves
*** but not more than $(1 + 0.1 \cdot t_{ref}/t)$, where t_{ref} = reference wall thickness of fatigue resistance curves

Some allowance for misalignment is already included in the tables of classified structural details (3.2). In particular, the data for transverse butt welds are directly applicable for misalignment which results in an increase of stress up to 30 %, while for the cruciform joints the increase can be up to 45 %. In the case of the structural hot spot stress and the effective notch stress assessment methods, a small but inevitable amount of misalignment corresponding to a stress magnification factor of $\mathbf{k_m = 1.05}$ is already included in the fatigue resistance S-N curves (Table 3.20).

Additional requirements apply for the joints listed in Table 3.20. The effect of a larger misalignment has to be additionally considered in the local stress (structural hot spot stress or effective notch stress). The misalignment effect may be present even in the vicinity of supporting structures. A corresponding stress increase must be taken into account also in crack propagation analyses. In all those cases where the stress magnification factor is calculated directly, use is made of an effective stress magnification factor $\mathbf{k_{m,eff}}$.

$$k_{m,\,eff} = \frac{k_{m,\,calculated}}{k_{m,\,\text{alreadycovered}}} \tag{3.17}$$

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

$$k_m = 1 + (k_{m,\,axial} - 1) + (k_{m,\,angular} - 1) \tag{3.18}$$

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

Table 3.20 tabulates the factors $\mathbf{k_m}$ which are already covered in the different verification methods. Actual or specified fabrication tolerances may be assessed by the formulae given in Sect. 6.3.

3.8.3 Undercut

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

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

3.8.3.1 Steel

See Table 3.21

Table 3.21 Acceptance levels for weld toe undercut in steel

Fatigue class	Allowable undercut u/t	
	Butt welds	Fillet welds
100	0.025	Not applicable
90	0.05	Not applicable
80	0.075	0.05
71	0.10	0.075
63	0.10	0.10
56 and lower	0.10	0.10

Notes
[a]Undercut deeper than 1 mm shall be assessed as a crack-like imperfection
[b]The table is only applicable for plate thicknesses from 10–20 mm

3.8.3.2 Aluminium

See Table 3.22

Table 3.22 Acceptance levels for weld toe undercut in aluminium

Fatigue class	Allowable undercut u/t	
	Butt welds	Fillet welds
50	0.025	Not applicable
45	0.05	Not applicable
40	0.075	0.05
36	0.10	0.075
32	0.10	0.10
28 and lower	0.10	0.10

Notes
[a]Undercut deeper than 1 mm shall be assessed as a crack-like imperfection
[b]The table is only applicable for plate thicknesses from 10–20 mm

3.8.4 Porosity and Inclusions

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

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

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

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

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

3.8.4.1 Steel

See Table 3.23

Table 3.23 Acceptance levels for porosity and inclusions in welds in steel

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

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

Table 3.24 Acceptance levels for porosity and inclusions in welds in aluminium

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

* Area of radiograph used is length of weld affected by porosity multiplied by width of weld
** Maximum pore diameter or width of an inclusion less than ¼ plate thickness or 6 mm
+ Single pores up to 1.5 mm allowed

3.8.4.2 Aluminium

Tungsten inclusions have no effect on fatigue behaviour and therefore do not need to be assessed (Table 3.24).

3.8.5 Crack-like Imperfections

3.8.5.1 General Procedure

Planar discontinuities, cracks or crack-like defects are identified by non-destructive testing and inspection. NDT indications are idealized as elliptical cracks (Fig. 3.15) for which the stress intensity factor is calculated according to Sect. 2.2.5.

For **embedded cracks**, the shape is idealized by a circumscribing ellipse, which is measured by its two half-axes **a** and **c**. The crack parameter **a** (crack depth) is the half-axis of the ellipse in the direction of the crack growth to be assessed. The remaining perpendicular half-axis is the half length of the crack **c**. The wall thickness parameter **t** is the distance from the centre of the ellipse to the nearest surface (Fig. 3.16). If **a/t > 0.75**, the defect should be re-categorized as a surface crack.

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

For details of dimensions of cracks and re-categorization see Appendix 6.2.

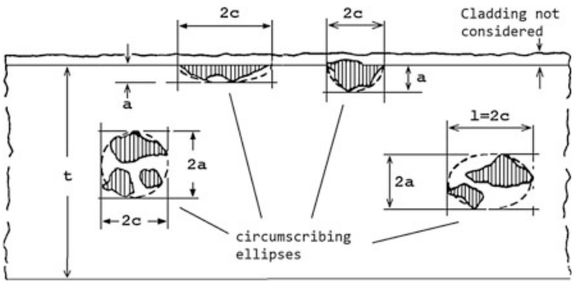


Fig. 3.15 Transformation of NDT indications into elliptic or semi-elliptic cracks

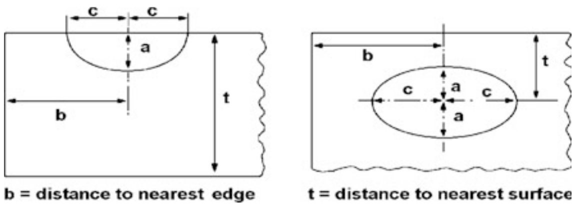


Fig. 3.16 Crack dimensions for assessment

3.8.5.2 Simplified Procedure

The simplified procedure makes use of the fatigue resistance at $2 \cdot 10^6$ cycles (analogous to FAT classes for the classified structural details) for ranges of crack types, sizes and shapes, of which the data are presented in Tables 3.25. These were obtained by integration of the crack propagation law for steel, given in Sect. 3.6.1, between the limits of an initial crack size $\mathbf{a_i}$ and a final crack size of 50 % of the wall thickness. In addition, use was made of the correction functions and the local weld geometry correction given in Sect. 6.2.4. (See Tables 6.1 and 6.3, also 6.14).

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

$$\Delta\sigma = \sqrt[3]{\Delta\sigma_i^3 - \Delta\sigma_c^3} \tag{3.19}$$

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

The tables have been calculated using Ref. [40, 42] with a constant of Co = 5.21e-13 [N; mm] and an exponent of m = 3.0 in order to cover the worst case under normal operation and environmental conditions. Corrosion is not considered. A possible misalignment has to be considered explicitly according to Table 3.20.

Note: The different definition of **t** for surface and embedded cracks in Table 3.25 shall be considered according to Fig. 3.16.

Table 3.25 Stress ranges at $2 \cdot 10^6$ cycles (FAT classes in N/mm^2) of welds containing cracks for the simplified procedure (following 3 pages)

Long crack at fillet weld toe, L/t = 2.5, a:c = 0.1														
a\ t	5	6	8	10	12	14	16	20	25	30	35	40	50	100
25	0	0	0	0	0	0	0	0	0	0	0	8	12	22
20	0	0	0	0	0	0	0	0	0	7	11	13	17	26
16	0	0	0	0	0	0	0	0	9	12	15	17	21	29
12	0	0	0	0	0	0	0	10	15	18	21	23	26	34
10	0	0	0	0	0	0	10	15	19	22	24	26	29	36
8	0	0	0	0	8	12	15	19	23	26	28	30	33	39
6	0	0	0	12	16	19	22	26	29	32	34	35	38	42
5	0	0	11	16	20	23	26	29	33	35	37	38	40	44
4	0	10	17	22	26	28	31	34	37	39	41	42	44	46
3	13	18	24	29	32	35	37	40	42	44	45	46	47	48
2	25	29	35	38	41	43	45	47	49	50	51	51	52	51
1	44	47	51	53	55	56	57	58	58	58	58	58	57	55
0.5	61	62	64	65	65	66	66	65	65	64	64	63	62	58
0.2	77	77	77	76	75	74	74	72	71	69	68	67	66	60
0.1	85	85	83	81	80	79	78	76	74	72	71	69	67	61
Short crack at fillet weld toe, L/t = 2.5, a:c = 0.5														
a\ t	5	6	8	10	12	14	16	20	25	30	35	40	50	100
25	0	0	0	0	0	0	0	0	0	0	0	17	22	31
20	0	0	0	0	0	0	0	0	0	15	20	23	27	35
16	0	0	0	0	0	0	0	0	17	22	26	28	31	37
12	0	0	0	0	0	0	0	20	26	29	32	34	36	41
10	0	0	0	0	0	0	19	26	30	33	35	37	39	43
8	0	0	0	0	17	23	27	31	35	37	39	40	42	45
6	0	0	0	23	28	32	34	38	41	42	44	45	46	48
5	0	0	22	29	33	36	38	41	44	45	46	47	48	50
4	0	19	30	35	39	41	43	45	47	48	49	50	51	52
3	26	32	38	42	45	47	48	50	51	52	53	53	54	54
2	40	44	48	51	53	54	55	56	57	57	58	58	58	56
1	58	60	62	63	64	65	65	65	66	65	64	64	63	58
0.5	72	73	74	74	74	74	73	72	71	69	68	67	65	60
0.2	86	86	84	82	81	80	78	76	74	72	71	70	68	61
0.1	93	91	88	86	84	82	81	78	76	74	72	71	69	62

(continued)

Table 3.25 (continued)

Long crack at butt weld toe, L/t = 1, a:c = 0.1														
a\ t	5	6	8	10	12	14	16	20	25	30	35	40	50	100
25		0	0	0	0	0	0	0	0	0	0	8	12	22
20	0	0	0	0	0	0	0	0	0	7	11	13	17	26
16	0	0	0	0	0	0	0	0	9	12	15	17	21	29
12	0	0	0	0	0	0	0	10	15	18	21	23	26	33
10	0	0	0	0	0	0	10	15	19	22	24	26	29	36
8	0	0	0	0	8	12	15	19	23	26	28	30	33	39
6	0	0	0	12	16	19	22	26	29	32	34	35	38	42
5	0	0	11	16	20	23	26	29	33	35	37	38	40	44
4	0	10	17	22	26	28	31	34	37	39	41	42	44	46
3	13	18	24	29	32	35	37	40	42	44	45	46	47	49
2	25	29	35	38	41	43	45	47	49	50	51	51	52	52
1	44	47	51	53	55	56	57	58	59	59	59	59	58	56
0.5	61	63	65	66	66	66	66	66	65	65	64	64	63	58
0.2	77	78	77	77	76	75	75	73	72	70	69	68	67	61
0.1	86	85	84	83	81	80	79	77	75	73	72	71	68	62
Short crack at butt weld toe, L/t = 1, a:c = 0.5														
a\ t	5	6	8	10	12	14	16	20	25	30	35	40	50	100
25	0	0	0	0	0	0	0	0	0	0	0	16	22	31
20	0	0	0	0	0	0	0	0	0	15	20	23	27	34
16	0	0	0	0	0	0	0	0	17	22	25	28	31	37
12	0	0	0	0	0	0	0	20	26	29	31	33	36	41
10	0	0	0	0	0	0	19	26	30	33	35	37	39	43
8	0	0	0	0	17	23	26	31	35	37	39	40	42	45
6	0	0	0	23	28	31	34	37	40	42	43	44	46	48
5	0	0	22	29	33	36	38	41	43	45	46	47	48	50
4	0	19	30	35	38	41	43	45	47	48	49	50	51	52
3	26	31	38	42	45	47	48	50	51	52	53	53	54	54
2	40	43	48	51	53	54	55	56	57	57	58	58	58	56
1	58	60	62	63	64	65	65	65	66	66	65	64	63	59
0.5	72	73	74	74	75	74	74	73	71	70	69	68	66	61
0.2	86	86	85	83	82	81	79	77	75	74	72	71	69	62
0.1	94	92	89	87	85	84	82	80	77	75	74	72	70	63

(continued)

Table 3.25 (continued)

Long surface crack at weld ground flush to surface, a:c = 0.1														
a\ t	5	6	8	10	12	14	16	20	25	30	35	40	50	100
25.0	0	0	0	0	0	0	0	0	0	0	0	8	13	23
20.0	0	0	0	0	0	0	0	0	0	7	11	13	17	26
16.0	0	0	0	0	0	0	0	0	9	12	15	17	21	30
12.0	0	0	0	0	0	0	0	10	15	18	21	23	26	34
10.0	0	0	0	0	0	0	10	15	19	22	24	26	29	37
8.0	0	0	0	0	8	12	15	20	23	26	29	30	33	41
6.0	0	0	0	12	16	19	22	26	29	32	34	36	38	45
5.0	0	0	11	16	20	23	26	30	33	36	38	39	42	48
4.0	0	10	17	22	26	28	31	34	38	40	42	43	46	52
3.0	13	18	25	29	32	35	37	40	43	45	47	49	51	56
2.0	25	29	35	39	42	44	46	49	51	53	55	56	58	63
1.0	44	47	52	55	58	59	61	63	66	67	68	69	71	74
0.5	63	65	69	72	74	75	77	78	80	81	82	83	84	86
0.2	87	89	91	93	95	96	96	98	99	99	100	101	101	103
0.1	105	106	109	110	111	112	112	113	114	115	115	115	116	117
Short surface crack at weld ground flush to surface, a:c = 0.5														
a\ t	5	6	8	10	12	14	16	20	25	30	35	40	50	100
25	0	0	0	0	0	0	0	0	0	0	0	17	23	95
20	0	0	0	0	0	0	0	0	0	15	20	24	29	39
16	0	0	0	0	0	0	0	0	17	23	27	30	34	43
12	0	0	0	0	0	0	0	21	27	31	35	37	40	48
10	0	0	0	0	0	0	20	27	32	36	39	41	44	51
8	0	0	0	0	17	24	28	34	38	42	44	46	49	55
6	0	0	0	23	29	34	37	41	45	48	50	52	54	59
5	0	0	22	30	35	39	42	46	50	52	54	55	58	62
4	0	20	31	38	42	45	48	52	55	57	58	60	62	66
3	27	33	41	47	50	53	55	58	61	63	64	65	67	71
2	43	48	54	58	61	63	65	67	69	71	72	73	74	77
1	66	69	73	76	78	79	80	82	84	85	86	86	87	90
0.5	86	88	91	93	94	95	96	98	99	99	100	100	101	103
0.2	111	112	114	115	116	117	117	118	119	119	120	120	121	122
0.1	129	130	132	133	133	134	134	135	136	136	136	137	137	138

(continued)

Table 3.25 (continued)

Long embedded crack, t = distance to nearest surface, a:c = 0.1															
a\ t	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50
25	0	0	0	0	0	0	0	0	0	0	0	0	0	4	7
20	0	0	0	0	0	0	0	0	0	0	0	3	5	7	11
16	0	0	0	0	0	0	0	0	0	0	4	6	9	11	14
12	0	0	0	0	0	0	0	0	0	5	8	11	14	16	19
10	0	0	0	0	0	0	0	0	4	8	12	15	17	19	23
8	0	0	0	0	0	0	3	6	8	12	16	19	22	24	27
6	0	0	0	0	0	5	9	12	14	18	22	25	27	29	32
5	0	0	0	0	5	9	12	15	18	22	26	28	31	32	35
4	0	0	0	4	9	14	17	20	23	26	30	33	35	37	39
3	0	0	6	10	16	20	24	27	29	32	36	38	40	42	45
2	4	10	15	19	25	30	33	36	38	41	44	46	48	50	52
1	22	29	33	37	42	46	49	51	53	56	59	61	63	64	67
0.5	42	47	52	55	60	63	66	68	69	72	75	77	79	80	82
0.2	68	73	77	80	84	87	90	92	93	96	98	100	101	103	105
0.1	90	94	98	101	105	107	110	111	113	115	117	119	120	122	124
Short embedded crack, t = distance to nearest surface, a:c = 0.5															
a\ t	3	4	5	6	8	10	12	14	16	20	25	30	35	40	50
25	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10
20	0	0	0	0	0	0	0	0	0	0	0	4	7	10	14
16	0	0	0	0	0	0	0	0	0	0	5	9	12	15	19
12	0	0	0	0	0	0	0	0	0	7	12	15	19	21	26
10	0	0	0	0	0	0	0	0	6	11	16	20	23	26	30
8	0	0	0	0	0	0	5	9	12	17	21	25	28	31	35
6	0	0	0	0	0	8	12	16	19	24	29	32	35	38	42
5	0	0	0	0	7	12	17	21	24	29	33	37	40	42	46
4	0	0	0	6	13	19	23	27	30	35	39	43	45	48	51
3	0	0	9	14	21	27	31	35	38	42	47	50	53	55	58
2	6	15	21	26	33	39	43	46	49	54	58	61	63	65	68
1	29	37	44	48	55	60	64	67	69	73	76	79	81	82	85
0.5	54	62	67	72	78	82	85	87	89	92	95	97	99	100	102
0.2	89	95	99	103	107	111	113	115	116	119	121	123	124	125	127
0.1	115	121	124	127	131	133	135	137	138	140	142	144	145	146	148