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Assessment of the Remaining Fatigue Life of Defective Welded Joints

Evaluation de la durée de vie restante de joints soudés défectueux

Abschätzung der Restlebensdauer schadhafter Schweissverbindungen

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SUMMARY

This paper deals with the determination of the remaining fatigue life of defective welded steel structures. Highlighted are defect schematization and recategorization, crack-growth laws and their constants, stress-intensity-factor solutions for welded joints and a fatigue crack-growth calculation procedure. The information given can be used for two dimensional and three dimensional welded geometries.

RÉSUMÉ

Cet article traite de la détermination de la durée de vie restante de structures soudées en acier contenant des défauts. L'accent est mis plus particulièrement sur la schématisation et la classification des défauts, sur les lois de propagation des fissures et leurs constantes, sur les valeurs du facteur d'intensité de contraintes pour des joints soudés, et sur la procédure de calcul de la propagation des fissures de fatigue. L'information présentée ici peut être utilisée pour des géométries d'éléments soudés bidimensionnels et tridimensionnels.

ZUSAMMENFASSUNG

Dieser Bericht befasst sich mit der Bestimmung der Restlebensdauer geschweisster Stahltragwerke, die Schäden aufweisen. Beleuchtet werden die systematische Darstellung und Klassierung von Schäden, Rissfortschrittsgesetze und deren Konstanten, Spannungsintensitätsfaktoren für Schweissverbindungen sowie ein Verfahren zur Berechnung des Ermüdungsrisswachstums. Alle Angaben sind sowohl für geschweisste Verbindungen zweidimensionaler als auch für solche dreidimensionaler Geometrie gültig.

1. INTRODUCTION

Steel structures may contain defects in the (welded) connections. These defects can be discovered directly after fabrication by non destructive testing or during service by inspection. Repair of these defects is often costly and time consuming. The costs may be extremely high when an existing structure has to be taken out of service or when the use of a new structure is delayed. Furthermore, a repair of a structure has to be carried out in an unfavourable situation with regard to the accessibility and restraint. Therefore, these repairs are often not beneficial to the integrity of the structure.
The above mentioned reasons make that a "fitness for purpose" assessment of a defective joint may be useful and may lead to the conclusion that the safety of the structure is not reduced by the presence of the defect discovered. In a statically loaded structure an assessment of the risk of instable (brittle) fracture initiated from the defect discovered is sufficient. However, for a fatigue loaded structure a small non critical defect may grow to a larger defect with a critical size due to the service load. Therefore, crack growth estimation is essential for a fitness for purpose assessment of fatigue loaded structures. The crack growth estimation may show that a repair can be postponed to a more suitable time or even show that the defect will not become critical during the service life (This may be due to the fact that the defect is in or growing into a low stressed area).
This paper deals with the fatigue crack growth part of the fitness for purpose assessment. A brief summary of a guideline drawn up in the Netherlands [1] is given. The various parts of a fatigue assessment will be highlighted, such as: defect schematization and recategorization (see section 2), crack growth laws and their constants (see section 3), stress intensity factors (see section 4) and a calculation procedure (see section 5).
The paper ends with conclusions and recommendations for further research (section 6).
Sections 2,3,4 and 5 are mainly based on a study carried out by TNO (Netherlands Organisation for Applied Scientific Research) within the framework of a NIL (Nederlands Instituut voor Lastechniek) and CS (Centrum Staal) research project [1, 2, 3 and 4].

2. DEFECT SCHEMATIZATION

2.1. Idealization of defects

The size and the location of the defect is normally determined by non destructive testing. The actual measured dimensions can be irregular and not suited for a crack growth calculation procedure. In general a fatigue crack will tend to grow to an idealized shape. Therefore an idealization of the measured dimensions is allowed.
Three types of planar flaws can be considered:

- Through flaws	idealization:	rectangle	width 2a
- Surface flaws	:	semi-ellipse	depth a, width 2c
- Embedded flaws	:	ellipse	minor axis a and major axis c

Their dimensions (a and c) are determined from the height and the length of their containment rectangles (see table 1). The plane in which the idealized flaw is located is perpendicular to the stress that is used for the calculation of the fatigue crack extension. The actual flaw should be projected to that plane and then be idealized. This idealization procedure is in accordance with other guidelines [5 and 6].

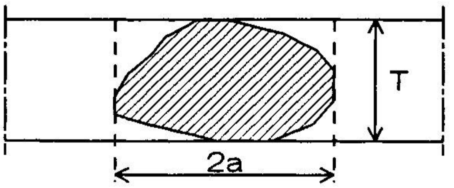
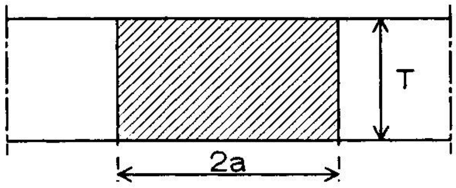
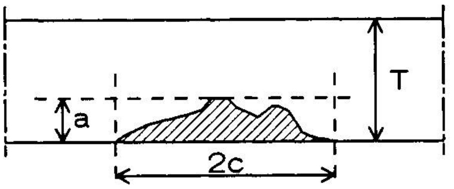
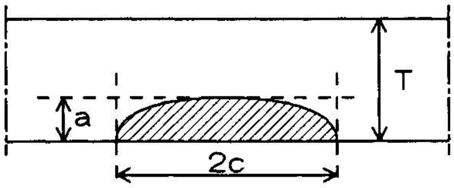
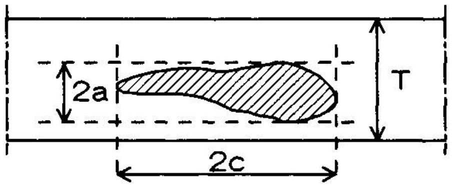
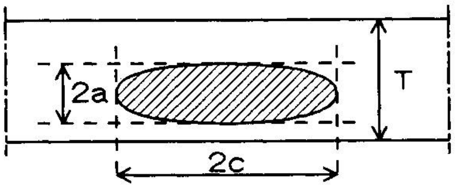
type of flaw	actual flaw	idealization
through flaw		
surface breaking flaw		
embedded flaw		

Table 1 Idealization of flaws

2.2 Interaction of defects

During the fatigue crack growth, interaction of two ore more defects can occur. This is often the case at weld toes, where multiple crack initiation followed by coalescence and crack growth at low aspect ratios occurs. Interaction between a defect and a free surface is also possible.
Existing interaction criteria [5 and 6] are developed for the assessment of instable (brittle) fracture and are not suitable for fatigue crack growth (see [20]). Therefore a new set of interaction criteria is proposed [4].
In general, interaction is considered if the distance of two flaws, in relation to the dimensions of these flaws, is smaller than a given value or zero. When this criterion is met the two flaws have to be considered as one single flaw with the idealization rules given in 2.1. Table 2 gives the new fatigue interaction criteria for through flaws, surface flaws and embedded flaws. Mutual interaction and interaction with a free surface is considered.
When interaction occurs during the fatigue crack growth, the calculation is resumed after recategorization, starting with the new idealized crack dimensions.

3. CRACK GROWTH MODELS AND CONSTANTS.

3.1. Crack growth models.

Fatigue crack growth models for welded structures, based on linear elastic fracture mechanics have been described recently by several authors [7, 8, 9, 10, 11, 12 and 14]. In general, the crack growth model gives the relation between the crack growth rate (da/dN) and the fatigue loading parameter (stress intensity factor range (ΔK)). This relation, called the Paris-Erdogan relation is as follows (see region II in figure 1) :

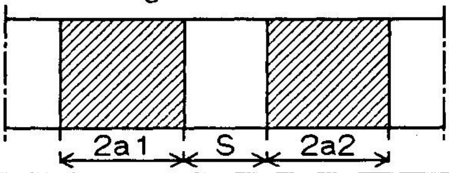
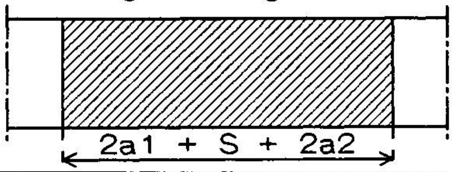
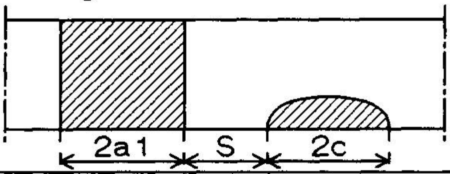
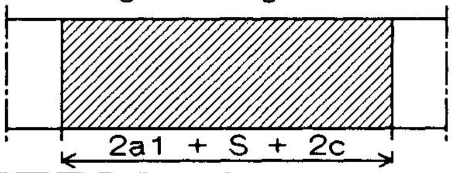
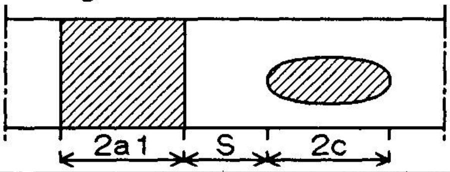
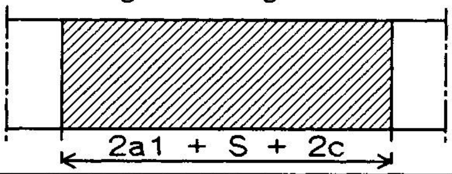
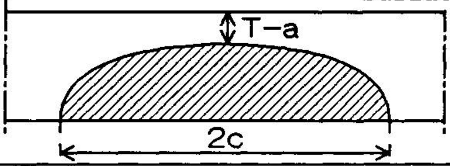
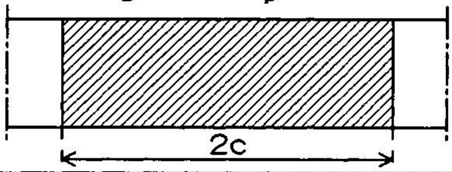
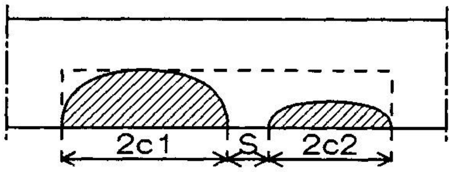
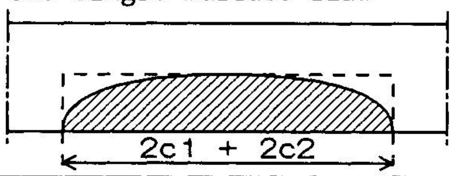
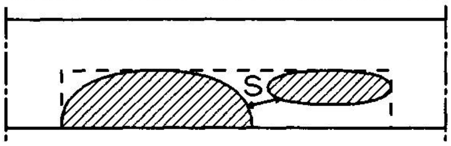
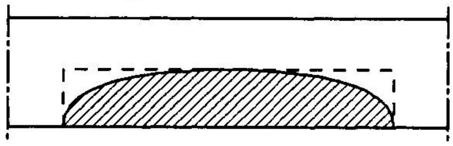
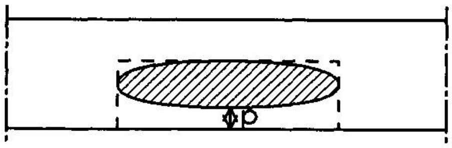
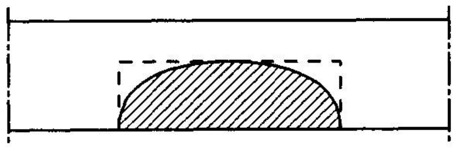
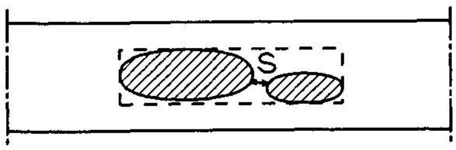
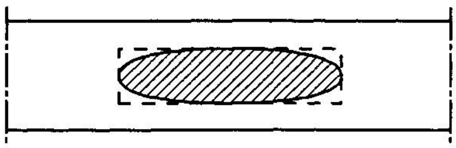
interacting flaws and surfaces	criteria	recategorized flaw
two through flaws 	$a_1 < a_2$ and $S < 2a_1$	one single through flaw 
through flaw and surface flaw 	$S < 2a_1$ and $S < 2c$	one single through flaw 
through flaw and embedded flaw 	$S < 2a_1$ and $S < 2c$	one single through flaw 
surface flaw and opposite surface 	$T-a = 0$	one single through flaw 
two surface flaws 	$S = 0$	one single surface flaw 
surface flaw and embedded flaw 	$S = 0$	one single surface flaw 
embedded flaw and free surface 	$p = 0$	one single surface flaw 
two embedded flaws 	$S = 0$	one single embedded flaw 

Table 2 Interaction of coplanar flaws during fatigue crack growth.

$$da/dN = C\,(\Delta K)^m \qquad (1)$$

where C and m are crack propagation constants.

In the near threshold range (region I) the influence of the threshold value of ΔK (ΔK_{th}) can also be incorporated in the relation:

$$da/dN = C\,(\Delta K^m - \Delta K_{th}^m) \qquad (2)$$

In the upswing of the crack growth curve (region III) the influence of the critical value of K (K_c), combined with the load ratio R ($=F_{min}/F_{max}$) can be taken into account.

$$da/dN = \frac{C\,(\Delta K)^m}{(1-R)K_c - \Delta K} \qquad (3)$$

Fig 1 gives a general view of the da/dN-ΔK curve and the validity of the three crack growth relations mentioned above.

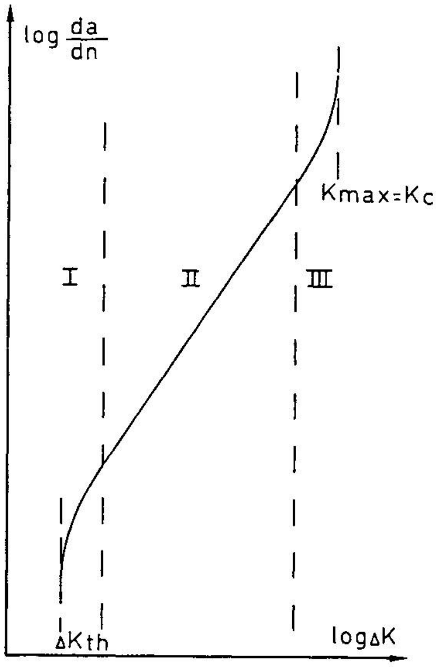


Fig. 1 Crack growth rate curve.

3.2. Crack propagation constants

The crack growth constants C and m, and ΔK_{th} have to be determined for the relevant material and conditions (environment, frequency, etc). Figure 2 shows an experimental crack growth curve of an Fe E 355-KT material used in an ECSC-SMOZ project [12]
When no specific data are available the following values can be used for ferritic steels with a proof stress below 600 N/mm2 operating in air or other non aggressive environments at temperatures up to 100 °C:

$$m = 3$$

$$C = 3\ 10^{-13} \text{ (units N and mm)} \qquad (4)$$

For marine environment and normal wave frequency ($\approx$ 0.1 Hz) C becomes:

$$C = 2.3\ 10^{-12} \text{ (units N and mm)} \qquad (5)$$

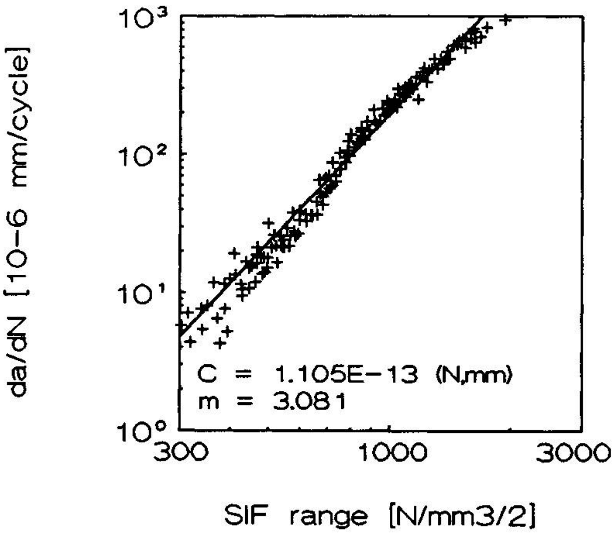


Fig. 2 Experimental da/dN-ΔK curve.

The values of (4) and (5) are a safe upperbound of the crack growth data.
For as-welded structures the following threshold value of ΔK should be used:

$$\Delta K_{th} = 63\ N/mm^{3/2} \qquad (6)$$

4. STRESS INTENSITY FACTORS

4.1. Governing stresses.

The stress intensity factor (SIF,K) range is the difference between the maximum SIF and the minimum SIF during a load cycle. The SIF is a measure for the magnitude of the stresses near the crack tip; eqn. (7).

$$K = Y \sigma \sqrt{(\pi a)} \qquad (7)$$

where: σ = remotely applied stress
Y = correction factor depending on geometry and loading conditions
a = crack depth

The stress variations for a fatigue crack growth calculation have to be determined from the complete load history during the (remaining part of the) service life or from the expected load history to the next inspection.
The stresses in a welded detail can be separated in (see figure 3):

a) Membrane stresses (σ_m), being the average nominal stress across the section thickness due to the applied load on the section.
b) Bending stress (σ_b), being the bending part of the nominal stress across the section thickness due to the applied load on the section.
c) Residual stress (σ_r) across the section thickness. These stresses are self-equilibrating. σ_r is often due to the welding or fabrication process of the detail.
d) Peak stress (σ_p) due to local discontinuities (such as: weld toes, etc.).

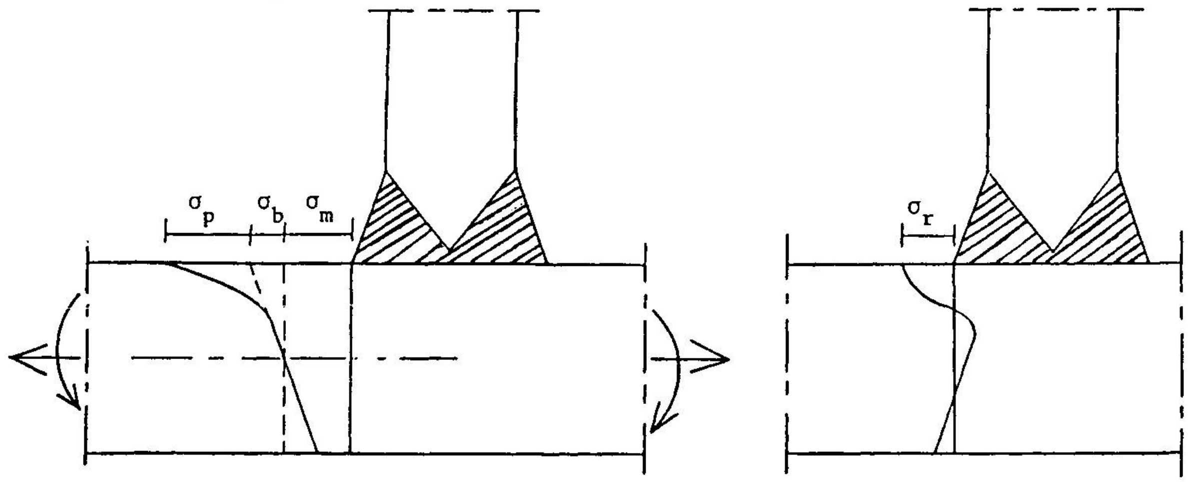


Fig. 3 Stresses in a welded detail.

The governing fatigue stresses for an as-welded structure are the elastic stress ranges of σ_m and σ_b at the crack location for the uncracked geometry. The effect of the global geometry should be incorporated in the stress analysis, while the effect of the local geometry (weld shape, etc.; causing σ_p) should be excluded. This effect of the local geometry will be incorporated in the determination of the stress intensity factor by the stress intensity concentration factor (M_k). For as welded structures the mean stress level has no influence on the fatigue crack growth. The residual stress level at the weld toe in as welded structures generally approaches the tensile yield stress. This implies that the stress range is always fluctuating from tensile yield stress downwards and the complete stress range is effective for crack growth.
For stress-relieved structures loaded with a fatigue load with a negative R ($=\sigma_{min}/\sigma_{max}$)ratio, the complete stress range may not be effective. However due to settlements or assembling stresses the actual stress level may differ from the calculated one. Therefore it is recommended for steel structures not to use the possible beneficial effect due to stress relieving. For special structures

where the value of the mean stress is known (e.g. a complete stress relieved structure) the beneficial effect of a low mean stress level may be used.
In case of a random load sequence a counting procedure (such as rainflow counting) may be used to determine the governing stress ranges.
The stress range perpendicular to the crack surface (mode I stress range) is the governing stress range in complex stress situations (e.g. biaxial stresses).

4.2. SIF in 2-D geometries

The SIF of a constant depth edge crack in a welded 2D geometry (see fig. 4) is generally given as follows:

$$K = [M_{k,m} M_m \sigma_m + M_{k,b} M_b \sigma_b] \sqrt{(\pi a)} \qquad (8)$$

where: M_k = stress intensity concentration factor for the influence of the weld geometry
M = stress intensity correction factor for the strip without the weld geometry
m and b as index means for membrane stress and for bending stress respectively.

M is a function of the relative crack depth (a/T). Formulas can be found in literature [1, 9 and 13].
M_k is a function of a/T, the weld dimensions (see fig. 4) and the weld type. Assuming no interaction between the influence of the relative weld width (L/T), the weld angle (θ) and the relative weld toe radius (ρ/T) the following formula for M_k can be written.

$$M_k = f_L(a/T, L/T) . f_\theta(a/T, \theta) . f_\rho(a/T, \rho/T) \qquad (9)$$

where: f_L = a correction factor for the influence of the relative weld width (L/T) for a specific weld type with a certain weld angle and weld toe radius.
f_θ = a correction factor for the influence of the weld angle (θ).
f_ρ = a correction factor for the influence of the relative weld toe radius (ρ/T).

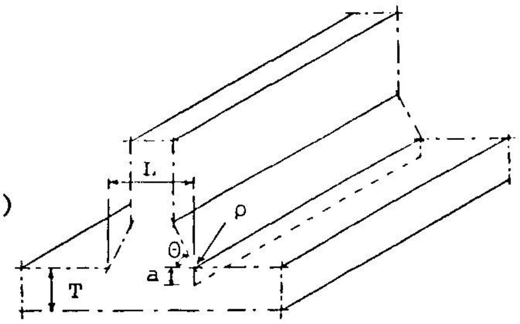


Fig. 4 Constant depth crack.

A powerful tool to determine SIFs and M_k values of weld geometries is the finite element method (FEM) [9 , 14 and 18].
Smith and Hurworth [15] and Maddox et al. [16] have determined M_k values with a FEM technique for butt welds and T-and X-joint geometries (see fig. 5). For butt welds and X-joints a set of formulas for M_k values was derived by Maddox et al. [16]. These formulas are valid for weld toe angle $\theta = 45°$ and weld toe radius $\rho = 0$. The formulas are functions of the relative crack depth (a/T) and relative weld width (L/T).

$$M_k = f_L(a/T, L/T) \qquad (10)$$

The functions f_L and the range of applicability can be found in [5, 14 and 16]

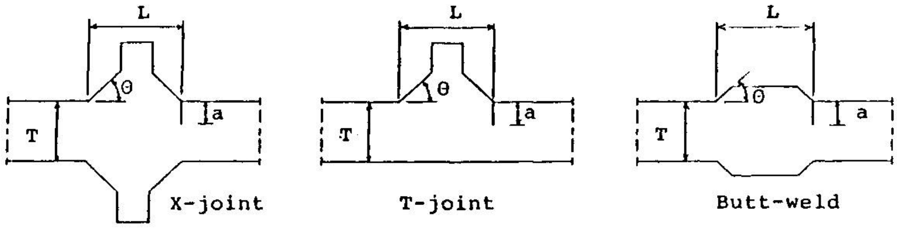


Fig. 5 Geometries studied by Smith and Hurworth [15] and Maddox et al. [16].

Dijkstra et al. [14] determined M_k values for T-joint geometries (see fig 6). A formula (eqn. 11) was developed for geometries with $\theta = 70°$ and $\rho = 0$.

$$M_k = A + \frac{B}{a/T - C} \qquad (11)$$

The values of A, B, and C are given in table 3.
The influence of the relative weld toe radius was also expressed in a formula (eqn 12).

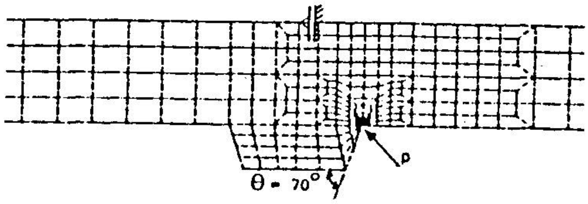


Fig 6. Finite element mesh of T-joint.

$$f_\rho = 1 - A_\rho . e^{-B_\rho . a/T} \quad \text{for } a/T \le 0.1 \qquad (12) \quad \text{and} \quad f_\rho = 1 \quad \text{for } a/T > 0.1 \qquad (13)$$

$$\text{where: } A_\rho = A_{\rho 1} + A_{\rho 2}/(\rho/T - A_{\rho 3}) \qquad (14) \quad \text{and} \quad B_\rho = B_{\rho 1} + B_{\rho 2}.(\rho/T)^2 \qquad (15)$$

See table 4 for the coefficients $A_{\rho 1}$ to $B_{\rho 2}$ (applicability $.00714 \le (\rho/T) \le .125$).

So the M_k value for a T-joint with $\theta = 70°$ and a relative weld toe radius $0.00714 \le (\rho/T) \le 0.125$ can be determined as follows:

$$M_k = [A + B/(a/T-C)].f_\rho \qquad (16)$$

where: A, B, and C are the values given in table 3.
f_ρ is the function of eqn. (12 to 15)

Based on the information given by Smith and Hurworth [15] Dijkstra et al. [14] developed a formula for f_θ with $\theta = 45°$ as reference value:

$$f_\theta = (10.a/T)^{-\frac{1}{2}\log A_\theta} \quad \text{for } 0.001 \le a/T \le 0.1 \qquad (17)$$

$$\text{where: } A_\theta = 13.096\ 10^{-3} + 28.119\ 10^{-3}\theta - 139.45\ 10^{-6}\theta^2 \qquad (18)$$

$$f_\theta = 1 \quad \text{for } a/T > 0.1 \qquad (19)$$

The range of application of eqns. (17 to 19) is: $25° \le \theta \le 65°$.

With the information given in this section one can determine the SIF of a welded T- or X-joint taking the influence of L/T, ρ/T and θ into account for a 2-D geometry.

region	load case	A	B	C
I	b	1.1362	0.015011	-0.0034398
$0 \le a/T < 0.025$	m	1.0291	0.012040	-0.0034689
II	b	0.88539	0.031426	-0.015361
$0.025 \le a/T < 0.1$	m	0.93832	0.016203	-0.0065430
III	b	0.95471	0.019388	0.0047441
$0.1 \le a/T < 0.4$	m	0.96858	0.011363	0.0044927

Table 3 Curve fitting coefficients for Mks at weld toes in T-joints with $\theta = 70°$ and $\rho = 0$.

loading	$A_{\rho 1}$	$A_{\rho 2}$	$A_{\rho 3}$	$B_{\rho 1}$	$B_{\rho 2}$
bending	0.70754	-0.020160	-0.024502	75.323	-1541.7
membrane	0.71032	-0.024015	-0.028061	105.29	-1993.8

Table 4 Curve fitting coefficients for f_ρ.

4.3 SIF in 3-D geometries.

The SIF of a semi-elliptical crack at a weld toe in a 3D geometry can be expressed in the crack depth (a) direction and in the crack width (c) direction (see fig. 7) as follows:

$$K_a = [M_{k,m,a}\, M_{m,a}\, \sigma_m + M_{k,b,a}\, M_{b,a}\, \sigma_b]\sqrt{(\pi a)}/\Phi \qquad (20a)$$

$$K_c = [M_{k,m,c}\, M_{m,c}\, \sigma_m + M_{k,b,c}\, M_{b,c}\, \sigma_b]\sqrt{(\pi a)}/\Phi \qquad (20b)$$

where: a and c as index means for crack depth and for crack width direction respectively.
Φ = elliptical integral of the second kind,
approximation $\Phi = [1 + 1.464\ (a/c)^{1.65}]^{0.5}$
for other symbols see equation (8)

The correction factors for the flat plate ($M_{m,a}$, $M_{b,a}$, $M_{m,c}$ and $M_{b,c}$) presented by Newman and Raju [17] can be used.

The 3-D SIF can also be determined with FEM. Van Straalen et al. [18] determined SIFs for a T-plate with a weld discontinuity. The geometry and the finite element model are given in fig. 8 and 9. SIFs were calculated for four crack geometries. The most important results are given in table 5. More results are given in [18 and 14]. For comparison the M_k values for a similar 2D geometry have also been tabulated. The 2D M_k values are higher than the 3D M_k values. This can be explained by the stiffening effect of the stub in the uncracked part of the plate in the 3D geometry. The ratio (ω) of $M_{k,3D}$ and $M_{k,2D}$ is also given in table 5. This ratio can be seen as a reduction factor for the application of 2D M_k values in a 3D geometry. Due to the limited amount of data no general expression of this reduction factor can be given.

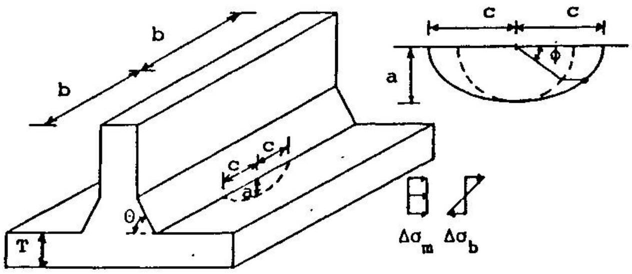


Fig 7 Semi-elliptical crack at the weld toe.

Comparison of the calculated SIF with experimental crack growth data showed a lower crack growth rate than predicted with the theoretical SIF for the geometry of fig 8 and 9 [12].

loadcase	direction	crack depth a [mm]	crack width c [mm]	M_k 3D	M_k 2D	ratio $\frac{M_{k,3D}}{M_{k,2D}}$ ω
membrane	depth a	6.49	10.14	0.964	1.041	0.926
		8.95	15.80	0.930	1.020	0.912
		11.85	25.90	0.920	1.008	0.913
		16.00	40.70	0.926	1.000	0.927
membrane	width c	6.49	10.14	1.260	1.498	0.841
		8.95	15.80	1.234	1.498	0.824
		11.85	25.90	1.166	1.498	0.778
		16.00	40.70	1.225	1.498	0.818
bending	depth a	6.49	10.14	0.986	1.078	0.915
		8.95	15.80	0.926	1.043	0.888
		11.85	25.90	0.899	1.021	0.872
		16.00	40.70	0.895	1.000	0.895
bending	width c	6.49	10.14	1.353	1.650	0.820
		8.95	15.80	1.325	1.650	0.803
		11.85	25.90	1.286	1.650	0.779
		16.00	40.70	1.324	1.650	0.802

Table 5 SIF and M_k for geometry D-2-2

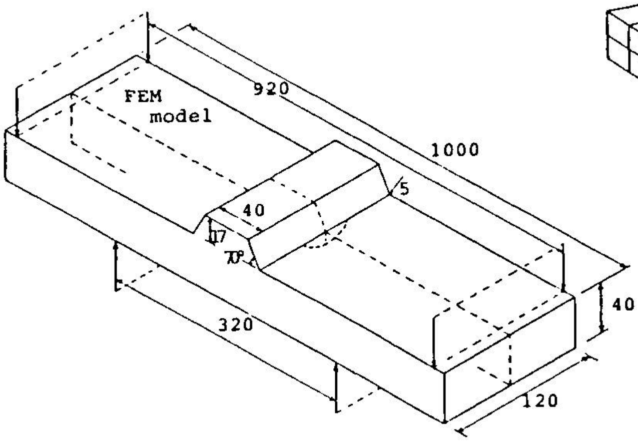


Fig 8. Dimensions of 3-D specimen

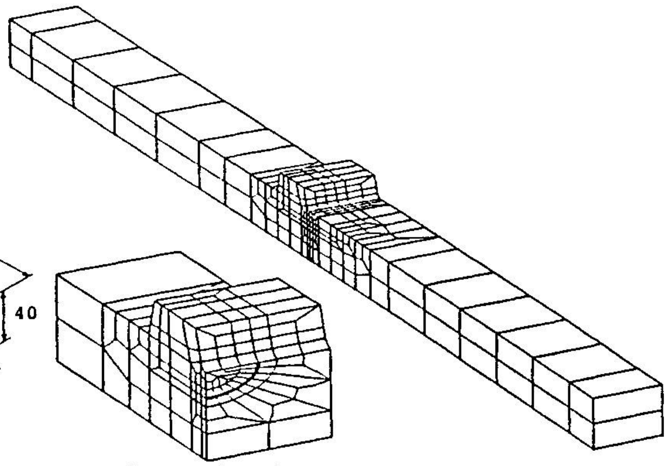


Fig 9. Mesh of 3-D specimen.

5 CALCULATION PROCEDURE.

The lifetime can be calculated by integrating the crack growth law from the initial defect size (a_i) to the final (allowable) defect size (a_f). The integration can be done either analytically or numerically. Due to the complex relation between ΔK and a the analytical integration of the crack growth law is an impractical procedure. Therefore a numerical (step by step) calculation procedure carried out by a computer is recommended.
TNO-IBBC has developed the program FAFRAM (FAtigue FRActure Mechanics) [19]. As the governing parameter for the calculation a crack extension (Δa) relative to the existing crack depth (a) was chosen. In order to get acceptable accuracy relatively small values should be taken for Δa (Crack extensions Δa of 5% of the present crack size give in general acceptable results). The numerical procedure will be illustrated for the semi-elliptical crack of figure 7. Assuming only bending stresses ($\Delta\sigma$) the expressions for ΔK_a and ΔK_c can be simplified to:

$$\Delta K_a = f_a \cdot \Delta\sigma \sqrt{\pi a} \qquad (21a)$$

$$\Delta K_c = f_c \cdot \Delta\sigma \sqrt{\pi a} \qquad (21b)$$

$$\text{where: } f_a = \frac{M_{k,b,a} \cdot M_{b,a}}{\Phi} \qquad (22a)$$

$$f_c = \frac{M_{k,b,c} \cdot M_{b,c}}{\Phi} \qquad (22b)$$

The procedure is as follows (see table 6 as a way of presenting the results):

1. With the actual crack depth (a_i) and half crack width (c_i) and the other geometrical parameters the values for f_a and f_c can be calculated.
2. Using the stress range ($\Delta\sigma$) the SIFs for crack depth (ΔK_a) and crack width (ΔK_c) can be calculated with equation (21).
3. Assuming a crack extension Δa the corresponding number of cycles can be calculated with the Paris relation.

$$\frac{\Delta a}{\Delta N} = C\,(\Delta K_a)^m \qquad \text{or:} \qquad \Delta N = \frac{\Delta a}{C\,(\Delta K_a)^m} \qquad (23)$$

4. The crack extension in the width direction can also be calculated with the Paris relation.

$$\frac{\Delta c}{\Delta N} = C\,(\Delta K_c)^m \qquad \text{or:} \qquad \Delta c = \Delta N\, C\,(\Delta K_c)^m = \Delta a\,\left(\frac{\Delta K_c}{\Delta K_a}\right)^m \qquad (24)$$

5. The number of cycles has to be increased with ΔN.

$$N_{i+1} = N_i + \Delta N \tag{25}$$

6. The crack dimensions have to be increased with the crack extensions:

$$a_{i+1} = a_i + \Delta a \quad \text{and:} \quad c_{i+1} = c_i + \Delta c \tag{26}$$

7. With the new crack dimensions (a_{i+1}, c_{i+1}) the next step can be calculated, starting with point 1 above.
8. The calculation has to be continued until the allowable crack depth (a_f) or until the required number of cycles (N_{req}).
9. The calculated number of cycles or crack size has to be assessed at its acceptability.

For 2D geometries the calculation has to be carried out in the a-direction only.

crack dimensions		a-direction			c-direction			number of cycles		
depth a [mm]	width c [mm]	f_a [-]	ΔK_a [N/mm$^{1.5}$]	Δa [mm]	f_c [-]	ΔK_c [N/mm$^{1.5}$]	Δc [mm]	N_i [-]	ΔN [-]	N_{i+1} [-]
0.25	0.25	2.177	196.12	0.025	2.901	270.19	0.065	0	33141	33141
0.28	0.32	2.242	217.60	0.028	2.929	285.14	0.062	33141	26692	59834
a_i $a_i + \Delta a$	c_i $c_i + \Delta c$	f_{a_i}	ΔK_{a_i}	Δa	f_{c_i}	ΔK_{c_i}	Δc	N_i	ΔN	$N_i + \Delta N$

Table 6. Calculation of crack growth

More results of crack growth calculations can be found in earlier papers and reports [8, 9, 12, 14 and 20]. The effect of several parameters are demonstrated in these publications.

6 CONCLUDING REMARKS AND RECOMMENDATIONS

- With the information in the paper and the references given to open literature a fatigue crack growth calculation of a defective welded joint can be carried out.
- The recategorization rules for interacting fatigue cracks given in this paper are less conservative than existing rules (Existing rules are developed for instable (brittle) fracture).
- The Paris-Erdogan relation can be applied in most cases as the crack growth law.
- Stress intensity factors for 2-D weld geometries are given.
- The influence of the weld on the stress intensity factor (SIF) is smaller for a 3-D geometry (semi-elliptical crack) than for a 2-D geometry (constant depth crack). However the information of 3-D SIF is limited. Therefore it is recommended to generate more information for 3-D cracks.
- Experimental crack growth data for 3-D geometries is needed to validate the crack growth model for a 3-D situation.
- A fatigue crack growth calculation procedure suitable for a computer program is given.

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