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THE BEHAVIOR OF FATIGUE-CRACK GROWTH IN SHIPBUILDING STEEL USING THE ESACRACK APPROACH

MODELIRANJE RASTI UTRUJENOSTNE RAZPOKE JEKLA ZA LADIJSKE PLOČEVINE PO POSTOPKU ESACRACK

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Crack growth-rate calculations with NASGRO 3.0 using a relationship called the ESACRACK approach were developed by Forman and Newman at NASA. A simple assessment of the crack-growth analysis is given by the Paris law, called the analytic approach; however, for a complex case this assessment is conservative. In this paper we introduced and analyze the crack-growth curve for welded shipbuilding steel using the ESACRACK approach by identifying the crack-opening function, *f*, the threshold stress-intensity factor, ΔK_{th}, and the critical stress-intensity factor, K_C.

Keywords: fatigue-crack growth, structural steel, analytical approach ESACRACK

Izvedli smo izračune hitrosti rasti utrujenostne razpoke z NASGRO 3.0 na osnovi tako imenovanega postopka ESACRACK, ki sta ga razvila Forman in Newman pri NASI. Enostavna ocena rasti utrujenostne razpoke je možna z analitičnim načinom, ki temelji na Parisovem zakonu. Vendar pa je v kompliciranih primerih ocena preveč konzervativna. V tem prispevku smo zato analizirali rast utrujenostne razpoke v konstrukcijskem jeklu, namenjenem za varjenje ladijske pločevine po postopku ESACRACK, ki temelji na funkciji odpiranja razpoke *f*, mejni vrednosti faktorja intenzitete napetosti ΔK_{th} in kritičnem faktorju intenzitete napetosti K_C.

Ključne besede: rast utrujenostne razpoke, konstrukcijsko jeklo, analitični postopek ESACRACK

1 INTRODUCTION

Crack growth-rate calculations in NASGRO 3.0 use a relationship called the **ESACRACK equation (1)**. This equation was developed by Forman and Newman and is described by:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\dfrac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\dfrac{K_{max}}{K_c}\right)^q} \qquad (1)$$

where *N* is the number of applied fatigue cycles, a is the crack length, *R* is the stress ratio, d*a*/d*N* is the crack-growth rate, *f* is the crack opening function, ΔK is the stress-intensity factor range, ΔK_{th} is the threshold stress-intensity factor, *C*, *n*, *p*, and *q* are empirical constants, K_c is the critical stress-intensity factor, and K_{max} is the maximum stress-intensity factor.

2 CRACK-OPENING FUNCTION

The program incorporates fatigue-crack closure analysis for the calculation of the effect of the stress ratio, *R*, on the crack-growth rate under constant amplitude loading. The crack-opening function, *f*, for plastically induced crack closure has been defined by Newman using the following **equation (2)**:

$$f = \frac{K_{op}}{K_{max}} = \begin{cases} \max(R, A_0 + A_1R + A_2R^2 + A_3R^3) & R \geq 0 \\ A_0 + A_1R & -2 \leq R < 0 \end{cases} \qquad (2)$$

where K_{op} is the opening stress-intensity factor, K_{max} is the maximum stress-intensity factor, *f* is the rate of K_{op} with K_{max}, the constants A_0–A_3 are a function of the stress ratio of S_{max}/σ_0 as follows, where S_{max}/σ_0 is the ratio of the maximum applied stress to the flow stress.

$$A_0 = (0.825 - 0.34\alpha + 0.05\alpha^2)\left[\cos\left(\frac{\pi}{2}\right)\frac{S_{max}}{\sigma_0}\right]^{\frac{1}{\alpha}}$$

$$A_1 = (0.415 - 0.071\alpha)\frac{S_{max}}{\sigma_0}$$

$$A_2 = 1 - A_0 - A_1 - A_3$$

Some materials exhibit only a very small stress-ratio effect, so the crack-growth rate is modulated without considering the effect of crack closure. In this case a curve-fitting option that allowed the crack-opening function to be bypassed was chosen. The parameters for the by-pass are: α = 5,845 and S_{max}/σ_0 = 1.0, and $f = R$, or $(1–f)/(1–R) = 1$, as in **Figure 1**.

For the positive stress ratios $R > 0$, the crack-growth relationship reduces to:

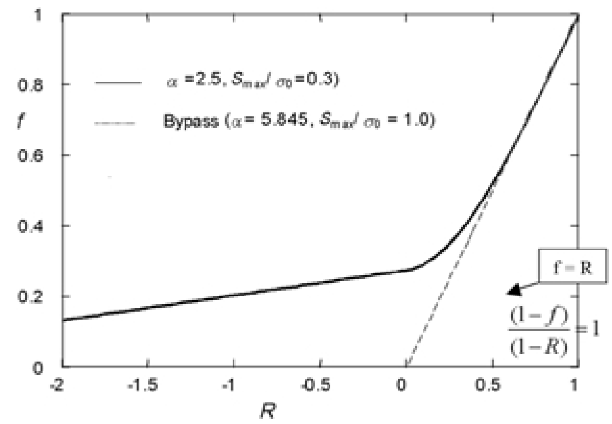

Figure 1: Crack-growth function, *f*, versus *R*
Slika 1: Funkcija rasti utrujenostne razpoke *f*, v odvisnosti od napetostnega razmerja *R*

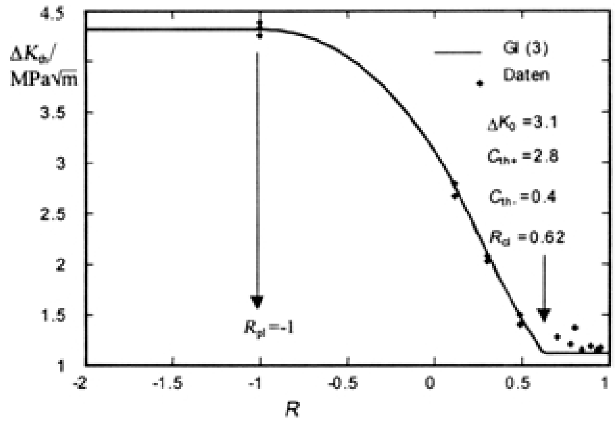

Figure 2: Dependence of $\Delta K_{\rm th}$ on *R*
Slika 2: Odvisnost mejne vrednosti faktorja intenzitete napetosti $\Delta K_{\rm th}$ od napetostnega razmerja *R*

$$\frac{\mathrm{d}a}{\mathrm{d}N}=C\left[\Delta K\right]^{n}\frac{\left(1-\dfrac{\Delta K_{\rm th}}{\Delta K}\right)^{p}}{\left(1-\dfrac{K_{\max}}{K_{\rm c}}\right)^{q}} \tag{3}$$

Note that *f* reflects the amount of plastically induced crack closure. It should also be noted that **Equation 3** (the closure-bypass option for $R > 0$) can be reduced to the Paris equation, $\mathrm{d}a/\mathrm{d}N = C[\Delta K]^n$, by setting the parameters *p* and *q* equal to zero. In this case the threshold ($\Delta K_{\rm th}$) and probably the fracture-toughness ($K_{\rm c}$) asymptotes are retained as cut off values.

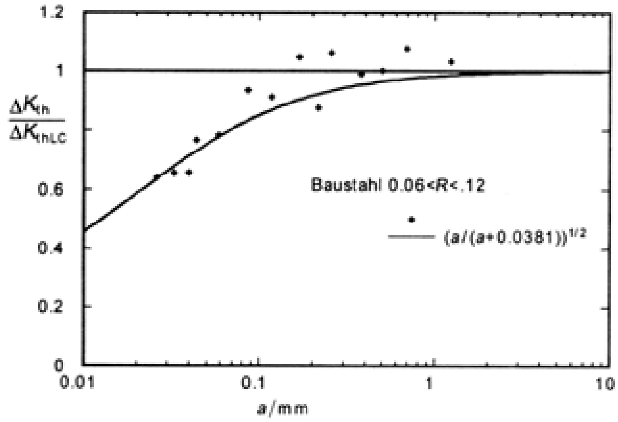

Figure 3: Dependence of $\Delta K_{\rm th}/\Delta K_{\rm th(LC)}$ on crack size
Slika 3: Odvisnost med razmerjem $\Delta K_{\rm th}/\Delta K_{\rm th(LC)}$ in velikostjo razpoke

3 THRESHOLD STRESS-INTENSITY FACTOR RANGE

The threshold intensity factor range in **Equation 1** is approximated by the following empirical **equation 4**:

$$\Delta K_{\rm th}=\frac{\Delta K_0\left(\dfrac{a}{a+a_0}\right)^{1/2}}{\left(\dfrac{1-f}{(1-A_0)(1-R)}\right)^{(1+C_{\rm th}R)}} \tag{4}$$

The distribution for various *R* ratios can be controlled much better using the $C_{\rm th}$ ($C_{\rm th+}$; $C_{\rm th-}$) for negative and positive values of *R*, as in **Figure 2**.

Figure 3 shows a plot of $\Delta K_{\rm th}/\Delta K_{\rm th(LC)}$ versus crack size, where $\Delta K_{\rm th(LC)}$ represents the "long-crack" fatigue threshold and the constant values are: a_0 = 0,0381 mm, $C_{\rm th+}$ = 1,9 dhe $C_{\rm th-}$ = 0,1.

The parameter $R_{\rm cl}$ is the cut-off stress ratio, above which the threshold is assumed to be constant, and independent for negative and positive *R* values: $R_{\rm cl}$ = 0.62, $R_{\rm pl}$ = –1(plastic zone).

Figure 4 shows a plot of ΔK_0 (threshold stress-intensity factor range at $R = 0$) versus yield stress for various steels with 235–960 MPa.

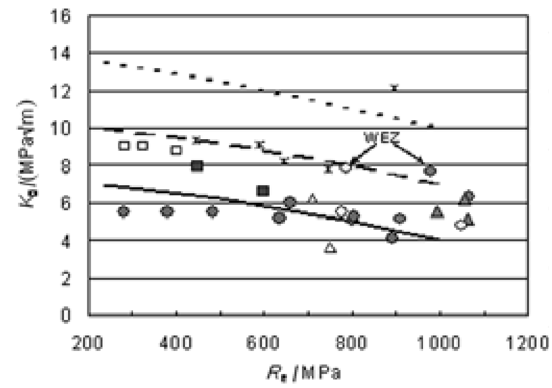

Figure 4: Dependence of ΔK_0 on $R_{\rm e}$.
Slika 4: Odvisnost med mejno vrednostjo faktorja intenzitete napetosti ΔK_0 (R = 0) in mejo tečenja $R_{\rm e}$ za različna jekla v trdnostnem razredu med 235 MPa in 960 MPa

When modeling the crack growth, in the HAZ (heat-affected zone) K_0 is given by the upper values, as shown in **Figure 4**.

3.1 The ESACRACK model for structural steel

Using the model (1) for different steels with a yield stress range 235–885 MPa and for a stress ratio R = 0.1 shows that in the second zone we have a smaller difference with the model, which leads to a small difference in the crack growth, as indicated in **Figure 5**.

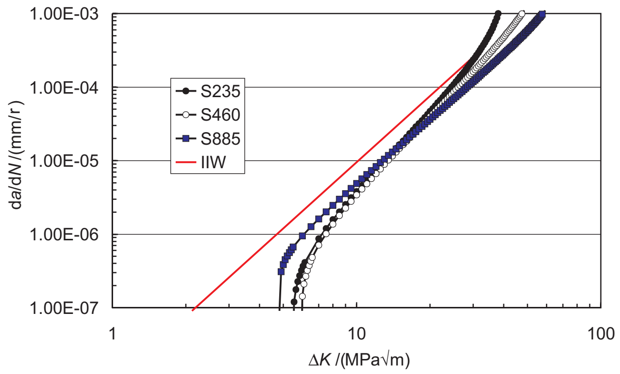

Figure 5: Fatigue-crack growth according to the model for three different steels and for the stress ratio R = 0
Slika 5: Model rasti utrujenostne razpoke treh različnih jekel pri napetostnem razmerju R = 0

As a recommendation II W [7] are given the crack-growth curve for the value of R = 0.1, but they are conservative, and for R = 0.5 we do not have a dependence for the crack-growth curve according to II W.

3.2 The ESACRACK model for different steels

Figures 6, 7, 8, 9, 10,11 show for the steel S 885 in the HAZ (heat-affected zone), BM (base metal), WM (weld metal), S403, S283, S325 for different stress ratios R = 0.1, 0.3, 0.5, experimental and ESACRACK crack-growth rate curves.

Table 1 lists all the constants according to the ESACRACK model for the structural steel, shipbuilding steel and the welding joints with α = 2.5, S_{max}/σ_0 = 0.3 and C_{th-} = 0,1.

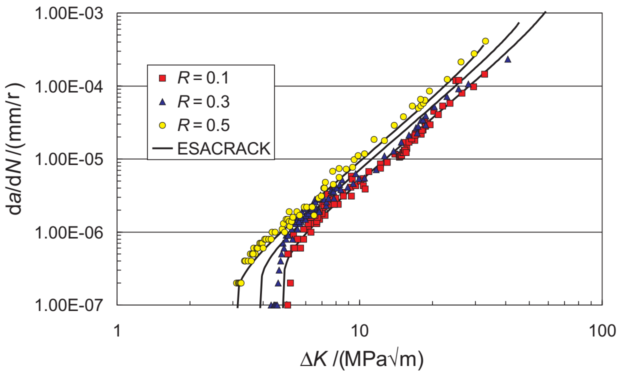

Figure 6: Crack growth-rate curves for S885 steel (Base metal) and for three R ratios, modeling with ESACRACK
Slika 6: Krivulje hitrosti rasti razpoke jekla vrste S885 (osnovni material) pri treh različnih napetostnih razmerjih R, modelirano z ESACRACK

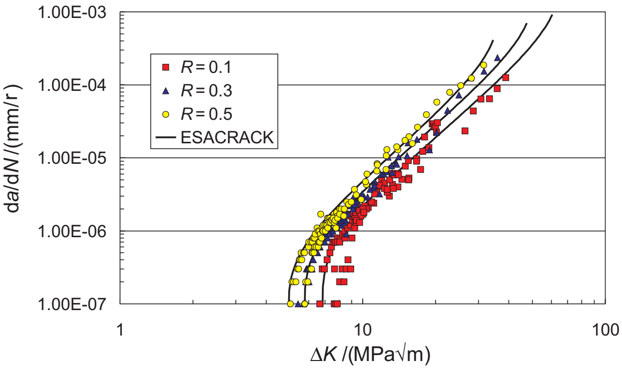

Figure 7: Crack growth-rate curves for S885 steel (HAZI) and for three R ratios, modeling with ESACRACK
Slika 7: Krivulje hitrosti rasti razpoke jekla vrste S885 (toplotno vplivana cona) pri treh različnih napetostnih razmerjih R, modelirano z ESACRACK

Table 1: Constants according to the ESACRACK model for the structural steel, shipbuilding steel and the welding joints
Tabela 1: Konstante konstrukcijskega jekla za ladijske pločevine in zvarne spoje, dobljene z modelom ESACRACK

Steel	ΔK_0	K_C	C	n	p	q	C_{th+}	C_{th-}
S235	6.0	45	10^{-8}	3	0.5	0.5	1.9	0.1
S460	6.5	70	10^{-8}	3	0.5	0.5	1.9	0.1
S690	5.1	98	$5\cdot10^{-8}$	2.3	0.5	0.5	1.9	0.1
S325	8.7	40	$5\cdot10^{-8}$	3.3	0.25	0.25	3	0.25
S283	9.00	33	$4\cdot10^{-8}$	3.3	0.25	0.25	2	0.25
S403	8.7	30	$4\cdot10^{-8}$	2.2	0.25	0.25	2.7	0.25
S885 MB	5.11	106	$2.4\cdot10^{-8}$	2.7	0.25	0.25	1.9	0.1
S885HAZ	7.68	98	$2\cdot10^{-8}$	2.5	0.5	0.5	1	0.1
S885 WM	5.6	70	$4\cdot10^{-8}$	2.5	0.5	0.5	2.5	0.1
S960 MB	5.0	60	$5\cdot10^{-8}$	2.5	0.5	0.5	1.9	0.1
S960HAZ	7.8	75	$4.5\cdot10^{-9}$	3.1	0.6	0.25	1.9	0.1
S960 WM	5.5	62	$1.3\cdot10^{-8}$	2.8	0.5	0.5	1.9	0.1

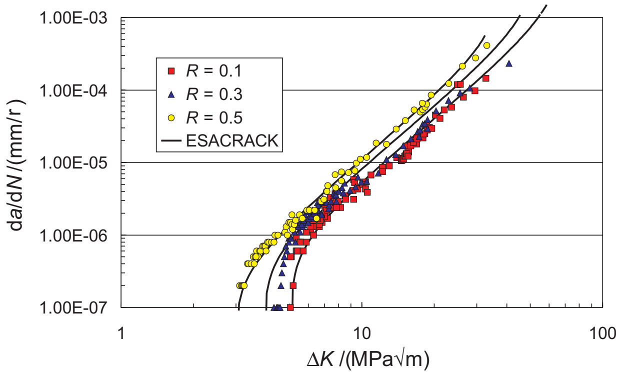

Figure 8: Crack growth-rate curves for S885 steel (Weld metal) and for three R ratios, modeling with ESACRACK

Slika 8: Krivulje hitrosti rasti razpoke jekla vrste S885 (material za varjenje) pri treh različnih napetostnih razmerjih *R*, modelirano z ESACRACK

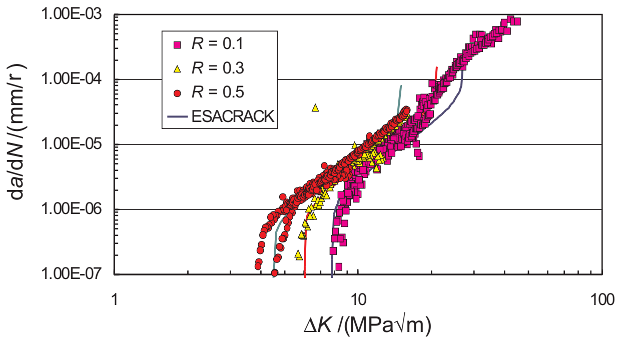

Figure 9: Crack growth-rate curves for shipbuilding steel S403 steel and for three *R* ratios, modeling with ESACRACK

Slika 9: Krivulje hitrosti rasti razpoke konstrukcijskega jekla vrste S403 pri treh različnih napetostnih razmerjih *R*, modelirano z ESA-CRACK

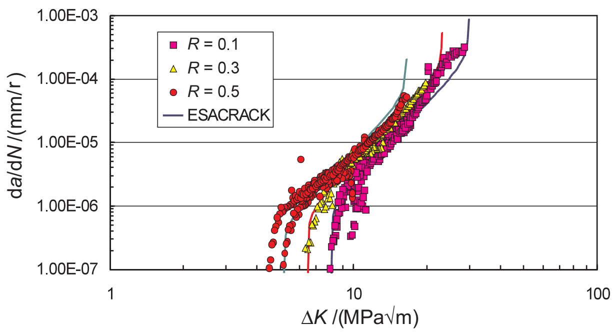

Figure 10: Crack growth-rate curves for shipbuilding steel S283 steel and for three *R* ratios, modeling with ESACRACK

Slika 10: Krivulje hitrosti rasti razpoke konstrukcijskega jekla vrste S238 pri treh različnih napetostnih razmerjih *R*, modelirano z ESA-CRACK

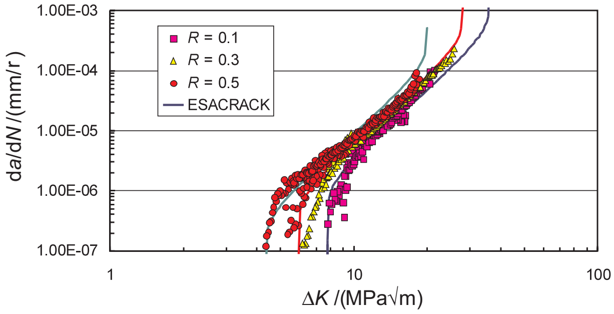

Figure 11: Crack growth-rate curves for shipbuilding steel S325 steel and for three R ratios, modeling with ESACRACK

Slika 11: Krivulje hitrosti rasti razpoke konstrukcijskega jekla vrste S325 pri treh različnih napetostnih razmerjih *R*, modelirano z ESA-CRACK

4 CONCLUSION

The ESACRACK model used for the crack-growth curve gives a description of the crack-growth curve for different structural and shipbuilding steels, welding joints, and for different stress ratios, R, during cyclic loading.

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