Two Methods for Determination of Fatigue Crack Propagation Limit Curves and their Applicability for High Strength Steels

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Abstract. There are different documents containing fatigue crack propagation limit or design curves and rules for the prediction of crack growth. The research work aimed to characterise the fatigue crack propagation resistance of different steels using limit curves and determination of limit curves for different structural steels and high strength steels, and their welded joints, under different loading conditions, based on statistical analysis of test results and the Paris-Erdogan law. With the help of the characteristic values of threshold stress intensity factor range (ΔK_{th}), two constants of Paris-Erdogan law (C and n), and fatigue fracture toughness (ΔK_{fc}) two reliable methods – a simplified method and a two stages method – can be proposed. Our testing results were compared with the testing results can be found in the literature. The limit curves calculated by the new method represent a compromise of rational risk (not the most disadvantageous case is considered) and striving for safety (uncertainty is known).

Introduction

Reliability of a structural element having crack or crack-like defect under cyclic loading conditions is determined by

- the geometrical features of the structural element and the flaws,
- the loading conditions as well as
- the material resistance to fatigue crack propagation.

There are different documents [1-3], standards and recommendations [4-6] containing fatigue crack propagation limit or design curves and rules for the prediction of crack growth [6,7]. The background of the fatigue crack propagation limit curves and the calculations consist of two basic parts: statistical analysis of numerous experiments (fatigue crack propagation tests) and fatigue crack propagation law, frequently the Paris-Erdogan law [8].

The research work aimed

- to characterise the fatigue crack propagation resistance of different steels using limit curves [9], [10], based on statistical analysis of test results and the Paris-Erdogan law;
- determination of limit curves for different structural steels and high strength steels, and their welded joints, under mode I and mixed mode I+II loading conditions.

Experiments

Materials. The most important characteristics of the investigated structural steels and high strength steels, and their welded joints are summarized in Table 1.

The chemical composition, the measured (R_y, R_m, A_5, Z) and calculated (R_y/R_m, R_m*A_5) mechanical properties of the investigated base materials (bm) and weld metals (wm) are summarized in Table 2. and Table 3., respectively.

Table 1. Characteristics of the investigated materials.

Material type	Mark	Welding method	Shielding gas	Filler material
Micro-alloyed steel	37C	Gas Metal Arc	100 % CO_2	VIH-2
DP low alloyed steel	DP-25156	–	–	–
Micro-alloyed steel	E420C	Gas Metal Arc	80 % Ar + 20 % CO_2	Union K56
HSLA	X80TM	Gas Metal Arc	82 % Ar + 18 % CO_2	X-90 IG
HSLA TRIP	TRIP-28670	–	–	–
HSLA	QStE690TM	–	–	–
HSLA	XABO 1100	–	–	–

Table 2. Chemical composition of the investigated structural steels and high strength steels, wt % (bm: base material; wm: weld metal).

Material	C	Si	Mn	P	S	Al	Nb	V	Cu
37C bm	0.15	0.38	0.89	0.029	0.016	0.016	0.021	0.023	–
VIH-2 wm	0.08-0.1	0.40-0.63	0.69-0.98	0.011-0.017	0.027-0.030	–	–	–	–
DP-25156 bm	0.101	0.374	1.39	0.014	0.003	0.037	0.042	0.006	0.06
E420C bm(1)	0.18	0.46	1.44	0.027	0.013	0.025	0.035	0.045	0.08
Union K56 wm	0.10	1.10	1.70	≤0.020	≤0.020	≤0.020	–	≤0.020	–
TRIP-28670 bm	0.203	0.354	1.68	0.112	0.008	0.5	0.003	0.006	0.06
X80TM bm(2)	0.077	0.30	1.84	0.012	0.002	0.036	0.046	–	–
QStE690TM bm(3)	0.08	0.29	1.75	0.011	0.002	0.041	0.04	0.061	0.33
Böhler X90-IG wm(4)	0.10	0.60	1.75	–	–	–	–	–	–
XABO 1100 bm(5)	0.16	0.29	0.98	0.012	0.0020	0.025	0.001	0.070	0.040

(1) Cr = 0.06 %, Ni = 0.03 %.
(2) Ti = 0.018 %, N = 0.0051 %.
(3) Cr = 0.037 %, Ni = 0.52 %, Mo = 0.32 %, Ti = 0.024 %.
(4) Cr = 0.30 %, Ni = 2.5 %, Mo = 0.45 %.
(5) Cr = 0.66 %, Ni = 1.93 %, Mo = 0.51 %, Ti = 0.001 %, N = 0.0049 %, B = 0.0002 %.

Table 3. Mechanical properties of the investigated structural steels and high strength steels (bm: base material; wm: weld metal).

Material	R_y(1) N/mm^2	R_m N/mm^2	R_y/R_m –	A_5 %	$R_m * A_5$ $N/mm^2 * \%$	Z %
37C bm	270	405	0.666	33.5	13567	63.5
VIH-2 wm	410-485	535-585	0.766-0.829	22.0-24.8	≥11770	40.9-63.9
DP-25156 bm	350-380	790-820	0.427-0.481	12.5-19.8(2)	≥9875(2)	–
E420C bm	450	595	0.756	30.7	18266	–
Union K56 wm	≥500	560-720	0.694-0.893	≥22.0	≥12320	–
TRIP-28670 bm	≥500	560-720	0.694-0.893	≥22.0	≥12320	–
X80TM bm	540	625	0.864	25.1	15687	73.1
QStE690TM bm	780	850	0.918	18.3	15555	–
Böhler X90-IG wm	≥890	≥940	≈0.947	≥16.0	≥15040	–
XABO 1100 bm	1125	1339	0.840	11.0(3)	14729(3)	–

(1) R_y means R_{eH} or $R_{p0.2}$.
(2) For these material A_{80} instead of A_5.
(3) For these material A_{97} instead of A_5.

Fig. 1 shows the types of the investigated materials and the relation between tensile strength and fracture strain for the base materials [11].

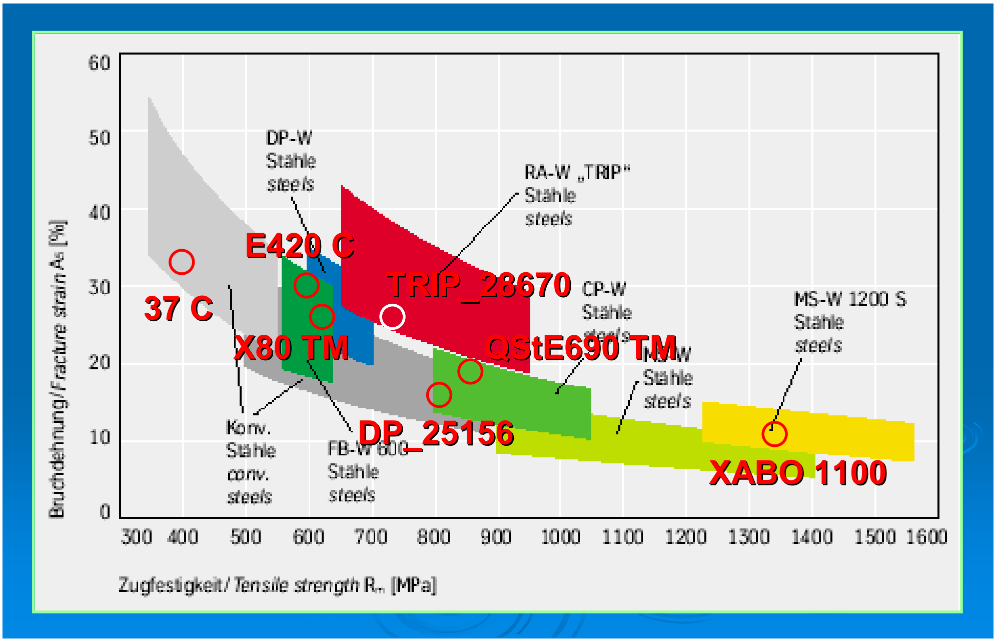

Figure 1. Relation between tensile strength and fracture strain for the investigated base materials.

Examinations. Compact tension (CT), three point bending (TPB) and single edge notched tension (SENT) specimens were tested for base materials and welded joints, while for testing of weld metal TPB type specimens were used. CT type specimens were cut from the sheets parallel and perpendicular to the rolling direction, so the directions of fatigue crack propagation were the same. For testing of weld metals cracks, which propagate parallel or perpendicular to the axis of the joint were also distinguished.

Compact tension shear (CTS) specimens were used for tests under mixed mode I+II loading condition. The specimens were cut parallel to the rolling direction, so the cracks were propagated perpendicular to the rolling direction.

Tests were carried out according to the ASTM prescription [12] by an universal electrohydraulic MTS testing machine. Experiments were performed by ΔK-decreasing and constant load amplitude methods, at room temperature, in air, following sinusoidal loading wave form. Stress ratio was constant ($R = 0.1$), crack propagation was registered by compliance and/or optical method.

Kinetic diagrams of tested DP-25156 and TRIP-28670 steel specimens. Fig. 2 and Fig. 3 show the calculated kinetic diagrams (fatigue crack propagation rate vs. stress intensity factor range curves) of tested DP-25156 and TRIP-28670 steel SENT specimens using secant method [12]. FCP means fatigue crack propagation.

Determination of fatigue design limit curves

First step: determination of measuring values. Values of threshold stress intensity factor range (ΔK_{th}) and two parameters of Paris-Erdogan law (C and n) were calculated according to ASTM prescriptions [12]. Fatigue crack propagation rate was determined by secant method or seven point incremental polynomial method. Values of fatigue fracture toughness (ΔK_{fc}) were calculated from crack size determined on the fracture surface of the specimens by the means of stereo-microscope.

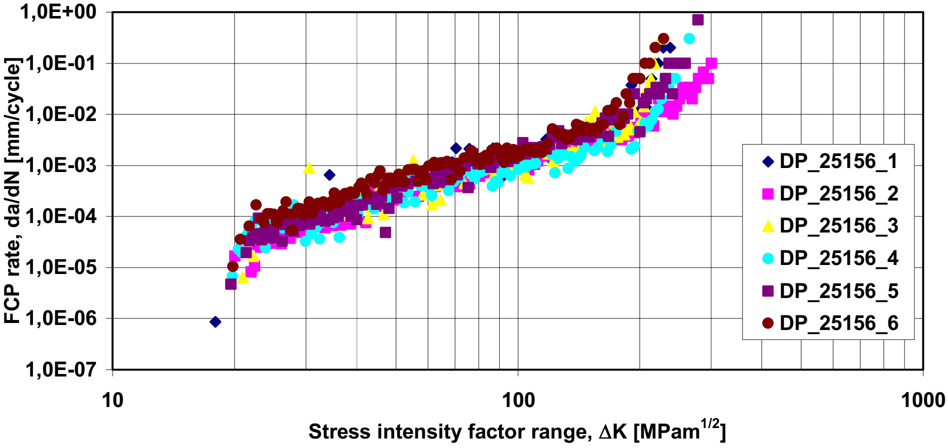

Figure 2. Kinetic diagrams of fatigue crack propagation from tested DP-25156 SENT specimens.

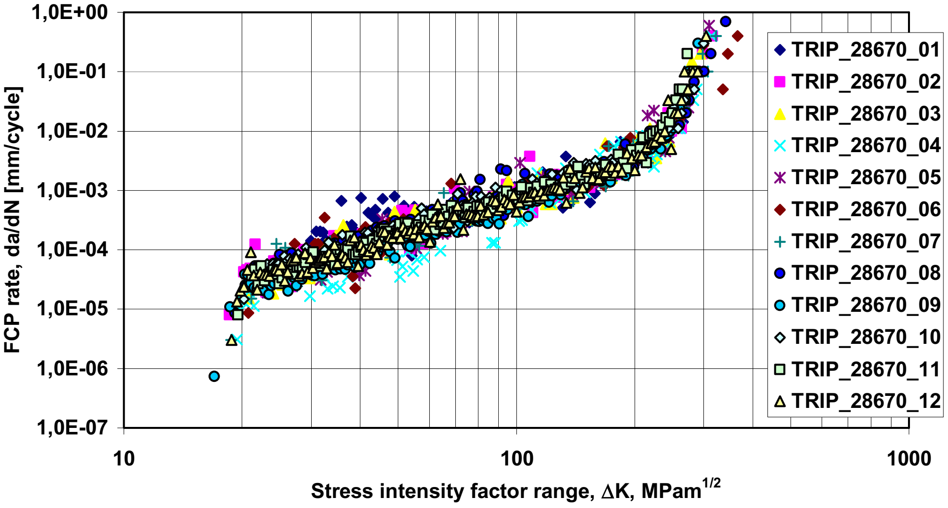

Figure 3. Kinetic diagrams of fatigue crack propagation from tested TRIP-28670 SENT specimens.

Second step: sorting measured values into statistical samples. On the basis of calculated test results, mathematical-statistical samples were examined for each testing groups. As its method, Wilcoxon-probe was applied [13], furthermore statistical parameters (average, standard deviation and standard deviation coefficient) of the samples were calculated. Standard deviation coefficients (standard deviation/average) of the samples were generally less than 0.2, which means reliable and reproducible testing and data processing methods.

Third step: selection of the distribution function. Afterwards it was examined, what kind of distribution functions can be used for describing the samples. For this aim different statistical probes were used at a level of significance $\varepsilon = 0.05$ [13]. It was concluded, that three parameter Weibull-distribution is the only function suitable for describing all the samples.

Fourth step: calculation of the parameters of the distribution functions. Parameters of three parameter Weibull-distribution function were calculated for all the samples:

$$F(x) = 1 - \exp\left[-\left(\frac{x - N_0}{\beta}\right)^{1/\alpha}\right], \tag{1}$$

where N_0 = threshold parameter, α = shape parameter and β = scale parameter of the three parameter Weibull distribution function.

Fifth step: selection of the characteristic values of the distribution functions. Based on the calculated distribution functions, considering their influencing effect on life-time, characteristic values of ΔK_{th}, n and ΔK_{fc}, were selected. With the help of these values a reliable method can be proposed for determination of fatigue crack propagation limit curves:

- the threshold stress intensity factor range, ΔK_{th}, is that value which belongs to the 95 % probability of the Weibull-distribution function;
- the exponent of the Paris-Erdogan law, n, is that value belonging the 5 % probability of Weibull-distribution function;
- the Paris-Erdogan constant, C, is calculated on the basis of the correlation between C and n;
- the critical value of the stress intensity factor range or fatigue fracture toughness, ΔK_{fc}, is that value which belongs to the 5 % probability of the Weibull-distribution function.

Sixth step: calculation of the parameters of the fatigue crack propagation limit curves. Two types of limit curves were calculated using the above mentioned five steps. The first type is bottomed on simple crack growth law; the second one was calculated using two stage crack growth relationship. The details of the curves can be found in the Table 4. and Table 5, and on Fig. 4..

Table 4. Details of determined fatigue crack propagation limit curves (simple law).

Material	ΔK_{th}	n	C	ΔK_{fc}
	$MPam^{1/2}$	$MPam^{1/2}$ and mm/cycle		$MPam^{1/2}$
37C base material	10.4	2.98	8.22E-09	53
37C welded joint	– (1), (2)	3.16	2.42E-09	70
DP-25156 base material	–	2.02	1.68E-07	–
E420C base material	8.0	2.26	9.78E-08	92
E420C welded joint	– (1), (3)	2.74	1.16E-08	101
TRIP-28670 base material	–	1.84	3.06E-07	250
X80TM base material	–	1.78	3.74E-07	129
X80TM welded joint	– (1)	1.86	3.13E-07	–
QStE690TM base material	–	1.82	3.27E-07	–
QStE690TM base material (4), (5)	–	2.15	1.09E-07	–
XABO 1100 base material	–	1.76	4.00E-07	104

(1) It can be derived from data concerning to the base metal after the evaluation of characteristic and assessment of magnitude of residual stresses.
(2) Average value of 16 tests under compressive residual stress: $\Delta K_{th} = 16.9\ MPam^{1/2}$.
(3) Average value of 4 tests under compressive residual stress: $\Delta K_{th} = 16.3\ MPam^{1/2}$.
(4) Under mixed mode I+II loading condition.
(5) ΔK should be replaced by ΔK_{eff}.

Table 5. Details of determined fatigue crack propagation limit curves based on two stage crack growth relationship (two stage law).

Material	ΔK_{th}	n_1	C_1	n_2	C_2	ΔK_{fc}
	$MPam^{1/2}$]	mm/cycle] and [$MPam^{1/2}$				$MPam^{1/2}$
TRIP-28670 base material	–	3.47	1.26E-09	1.81	1.74E-07	250
XABO 1100 base material	–	5.09	7.94E-12	1.90	1.55E-07	104

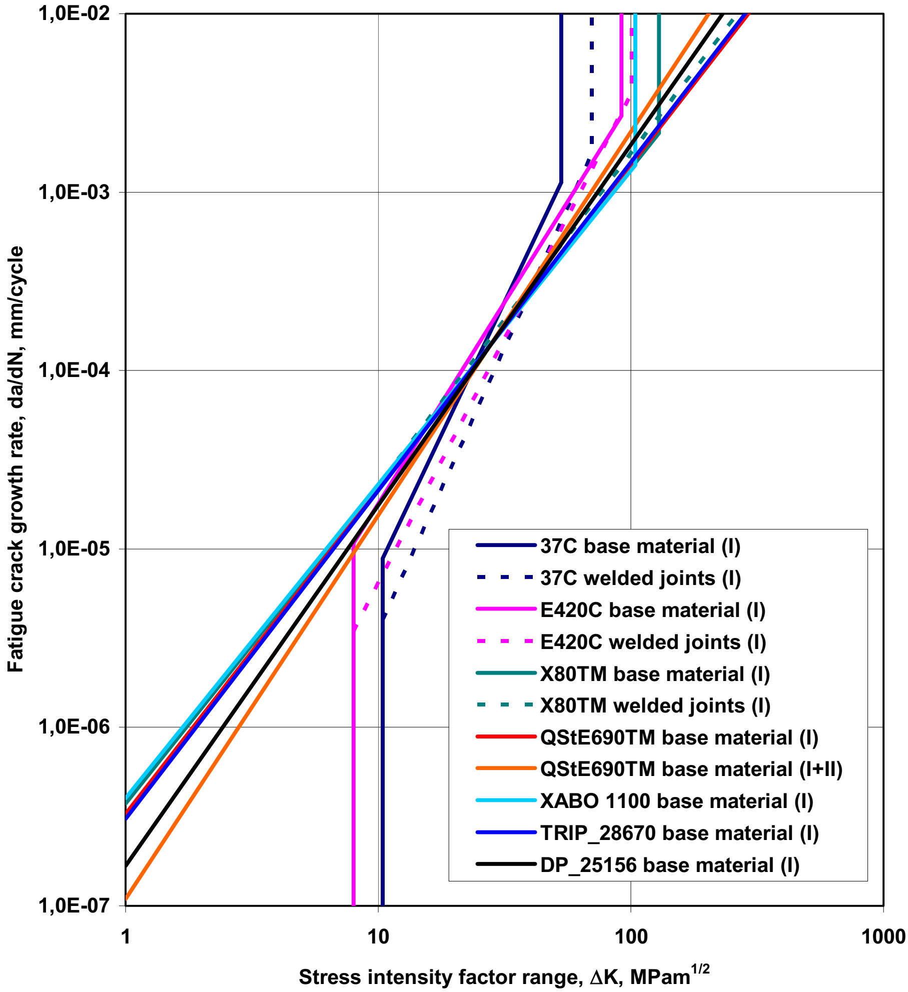

Figure 4. Fatigue design limit curves for micro-alloyed and HSLA steels, and their welded joints.

Discussion

For the investigated steels and their welded joints both the threshold stress intensity factor range (ΔK_{th}) and the exponent of the Paris-Erdogan law (n) decrease with the increase of the strength of steel, while the fatigue fracture toughness (ΔK_{fc}) increases.

For the investigated steels both the exponent of the Paris-Erdogan law (n) and the fatigue fracture toughness (ΔK_{fc}) for welded joints are higher than those of base materials.

The proposed method is suitable for determination of fatigue crack propagation design curves under mixed mode I+II loading condition, too. For this case stress intensity factor range (ΔK) should be replaced by effective stress intensity factor range (ΔK_{eff}).

The design curves of welded joints in the near threshold region are open. The threshold stress intensity factor range, ΔK_{th}, must be reduce by tensile residual stress field and may be increase by compressive residual stress field (e.g. welding residual stresses).

The calculated fatigue crack propagation limit curves of steels locate among the design curves determined by various procedures.

Table 6. summarizes our measured average data and measured individual data can be found in the literature [14]. It can be concluded that our average values are in harmony with the individual values.

Table 6. Comparison of measured data (white lines) with data from the literature (grey lines).

Material	R_y	R_m	ΔK_{th}	n	ΔK_{fc}
	N/mm^2	N/mm^2	$MPam^{1/2}$	$MPam^{1/2}$ and mm/cycle	$MPam^{1/2}$
37C	270	405	7.69	3.60	62.70
St38b-2	280	440	5.5	3.7	45
DP-25156	350-380	790-820	–	2.20	261.01
E420C	450	595	5.72	2.55	100.41
H60-3	500	630	5.9	3.8	50
TRIP-28670	≥500	560-720	–	2.06	320.73
X80TM	540	625	–	2.49	136.57
H75-3	600-680	–	4.3-5.2	2.5-2.7	70-75
QStE690TM	780	850	–	2.39	–
N-A-XTRA 70	810	850	2.7	2.7	88
XABO 1100	1125	1339	–	2.00	116.41

Conclusions

Based on the results of our experimental tests, evaluated samples and data can be found in the literature the following conclusions can be drawn.

– The proposed method can be generally applied for determination of fatigue crack propagation limit curves for steels and high strength steels, and their welded joints under mode I and mixed mode I+II loading conditions. Additional information of applications of the proposed method for metallic (e.g. pressure vessel steels, aluminium alloys, austempered ductile iron) and non-metallic (e.g. silicon nitride ceramics, polymers, reinforced polymer matrix composites) materials see in our earlier works in the literature [10, 15-18].
– The limit curves calculated by both methods represent a compromise of rational risk (not the most disadvantageous case is considered) and striving for safety (uncertainty is known).
– Based on the determined fatigue design limit curves integrity assessment calculations can be done for operating structural elements and structures having cracks or crack-like defects:
  = determination of propagable an critical crack sizes,
  = calculation of lifetime determined by the propagable crack size,
  = calculations of remaining lifetime functions, influences on the lifetime values and lifetime function (parameter study),
  = reliability of remaining lifetime estimation,
  = calculation of damage parameter and damage function [19].

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