CORROSION FATIGUE IN OFFSHORE; INFLUENCE OF FREQUENCY AND ELECTROCHEMICAL CONDITIONS

R. HELMS and H. HENKE*

Load controlled constant amplitude bending tests with welded and not welded specimens out of a fine grained structural steel have been performed in a new servopneumatic test equipment. Different environmental influences have shown their effects: Air, seawater at free corrosion and cathodic polarization. The effect of the frequency as main test parameter on the number of cycles to failure was evaluated taking into account the total fracture as well as the crack propagation phase.

INTRODUCTION

Offshore structures are exposed to alternating loads by the sea.The excitation frequencies are quite different according to the wave amplitude. The highest loads are occurring relatively seldom; but they are combined with the lowest frequencies, even smaller than 0.1 Hz. Additional environmental influences are given by the sea water. A cathodic protection is applied all through. In the splash zone, however, this protection is not effective; conditions comparable with free sea water corrosion are therefore existing at that place.

It was suspected that especially the lowest frequencies with long immersion period drastically reduce the life of offshore structures in terms of the number of cycles to failure. This led to the present project in which the frequency as a main parameter was varied within a wide range (0.01...10 Hz) in order to get results of likewise practical and basic evidence. 4-point

* Federal Institute for Materials Testing -
D - 1000 Berlin 45

bending tests were performed with manual welded and not welded specimens out of steel StE 460 (German specification) in air, at free seawater corrosion and under cathodic polarization at the lower bound of the usual protection range.- The objective was the respective life given by the number of the cycles up to failure. In addition, the life up to the inition of a detectable "technical crack" as well as the crack propagation phase were evaluated, too. A newly developped 16-fold servo-pneumatic test equipment was applied with success. In order to arrive at a sufficient number of results in the available time (4 years) as a method of time lapsing the test loads have been slightly increased compared with those of offshore practice (1,2).

LITERATURE SURVEY

The survey was focused to the influences on the endurance up to total failure N_f, the occurrance of a first technical crack (N_c) and the crack propagation. There are many influencing parameters which are not mutually independent, but the cited references are here predominantly restricted to the problem of the frequency effect. A more comprehensive survey is given in the extended research report (1).

With respect to the endurance up to total failure or with respect to fatigue strength the loading intensity and the mode are important. According to (3,4) the effect of free seawater corrosion on N_f is small for random loading (factor 2, cf. (5)); the effect will be overestimated by constant amplitude tests (factor >2). For low and medium strength steels ($R_m \leq 690$ N/mm²), mainly at decreasing amplitudes ($N_f > 10$) pronounced shorter endurances are given at free seawater corrosion (5), whereas at higher load amplitudes in the LCF-range ($N_c < 5 \cdot 10$[illegible]) the effect of corrosion is small and marked only at very low frequencies (0.05; 0.003 Hz) (6). Further effects are given by the oxygen content, the water temperature and the p_H-values. - A quantitative survey about the effect of free corrosion is given in (7,8); according to this, the N_f-values for corrosion are smaller by the factor (<2...5) compared with those for air and at long endurances ($N_f = 10$[illegible]) even by one order of magnitude.

Some contradictional results are known about the additional effect of frequency at corrosion: According to (5) at immersion of welded samples up to 140 days the endurance of welded specimen is reduced only by 60% when reducing the frequency from 10 to 0.2 Hz (constant amplitude tests). Above 8 Hz there is no significant difference between air and salt solution; but there is no more fatigue limit when tested inside the corrosive medium. Lowering the frequency by the factor 1/50 in salt solution half of the endurance (N_f) is observed (9). When reducing the frequency from 42.5 to 4.08 Hz for carbon steel in a 1 % NaCl-solution in the range of $N_f = 5 \cdot 10^5 \ldots 10^7$ a reduction of life by the factor 2...3 is possible (10); the effect of frequency thereby becomes more pronounced at all at larger N_f - values. Contrary to these results in the low cycle fatigue (LCF) range ($N_c < 10^4$, $f = 0.0027 \ldots 0.45$ Hz) no f-effect was detected for smooth specimens (6).

With respect to the first occurrance of the fatigue crack there are only few results available. In low carbon steel the fatigue cracks do not initiate at corrosion pits; pits are arising after having observed the first small cracks (11). An important factor in suppressing fatigue cracks in seawater is the calcareous deposit arising at cathodic corrosion protection (11). Regarding the case of active corrosion - as carbon steel in seawater - the fatigue cracks initiate very early ($N_c/N_f = 0.05 \ldots 0.1$); that means that the crack propagation phase dominates the total endurance (12). On the other hand in passivating agents the initiation phase is predominant ($N_c/N_f \approx 0.9$). In any case, the ratio N_c/N_f depends strongly on the crack detection sensitivity.

For an air environment there are more results available (13). For welded joints with root gaps a ratio $N_c/N_f = 0.1 \ldots 0.5$ is calculated out of the observed crack propagation; the highest value of 0.5 is thereby attributed to the fatigue limit range. For cracks initiating at an undercut the respective ratio is ≈ 0.25 and for strain gauge crack detection a ratio of 0.4...0.6 is given. - And at last there are considerations to use only the crack propagation phase for life time accessment not taking N_C into account (14).

Comprehensive results are available concerning the crack propagation phase. General interpretation of the typical behaviour of carbon steel in seawater is a superposition of accelerated fatigue crack propagation by corrosion and pure stress corrosion (15...19). This leads to a more or less well marked plateau effect in the usual da/dn-ΔK-curves; that means that a crack propagation is then independent of the mechanical load amplitude. The propagation is then influenced only by time and temperature dependent hydrogen diffusion (18,20,21) and is mainly accelerated by the amount of cathodically emerging hydrogen; and this amount depends on the cathodic potential (20,21). A good survey about the effects of time (frequency) and cathodic potential is given by Fig. 1 (18). It reveals the disadvantageous effect of an overprotection, too. With respect to the frequency effect the electrochemical conditions are important in any case. At free corrosion and low frequency (0.1 Hz) an accelerated propagation is observed at medium and high ΔK (22), whereas according to (23) the f-effect is more pronounced at small K-amplitudes. -

TEST MATERIAL, TEST PARAMETER AND TEST EQUIPMENT

Transverse specimens of a width of 50 mm were machined from plates of 20 mm thickness of StE 460 (German specification) with leaved rolling skin. Chemical composition, basic mechanical behaviour and welding parameters are given in Table 1. The used butt welding geometry and the layer situation is demonstrated in Fig. 2. The maximum hardness of the heat affected zone was approx. 300 HV 0.3.

TABLE 1 - Details of material and welding

C	Si	Mn	P	S	Al
0,19	0,42	1,50	0,008	0,006	0,010

N	Cu	Cr	Ni	Sn	V
0,0150	0,02	0,03	0,53	0,003	0,15

mass - %

specimen	$R_{p0,2}$ N/mm^2	R_m N/mm^2	A_5 %	Charpy energy (J) at - 20°C (Keyhole specimen)
longitudinal	528	672	27	68
transverse	532	683	26	69

	current A	voltage V	heat input kJ/cm
root	130	20...22	11...12
intermediate pass	180	20...22	9...10
final pass	160	20...22	11...12

The following test parameters have been regarded:

- Welded and not welded (base material) specimens.
- 4-pt-bending und load-controlled triangular load-time function (Fig. 3), several load horizons.
- Test frequencies 10 and 1 Hz performed in a servo-hydraulic testing machine, frequencies 0.1 and 0.01 Hz performed in a 15-fold servopneumatic test equipment.
- Environmental influence: Air and artificial seawater (ASTM D 1141)
- Free seawater corrosion (approx. - 650 mV Ag/AgCl) and cathodic protection with - 850 mV Ag/AgCl.
- Temperature 20 °C, seawater air saturated (O_2 content 7.5 mg/l), $p_H = 8.2$, kept constant.

All the tests have been performed load controlled with a load ratio $R = F_{min}/F_{max} \approx 0$. In addition to the double load amplitudes ΔF the according specimen deflection Δf has been evaluated, too, cycle per cycle by a transducer. Both the load as well as the deflection signals have been fed into a computer and the compliance $C = \Delta f/\Delta F$ is recorded continuously. Based on a precalibration of specimens with sawcuts of different depth the occurrance of a "technical" fatigue crack as well as the crack propagation could then be detected by the deviation of the compliance. For cracks of predominant straight contour a first detectable deviation of the compliance $\Delta C = 2 \cdot 10^{-4}$ mm/kN relates to a crack depth of $a \approx 0.4$ mm.

All tests have been run up to a maximum number of cycles $\leq 2 \cdot 10^6$. In order to meet the practical requirements of offshore structures, the evaluated S-N-curves can be extrapolated to longer service values.

TEST RESULTS

All the results of the tests are plotted in log-log-diagrams and represented by linear repressions in terms of so-called reference S-N-lines (24...26).

$$\frac{\sigma_a}{\sigma_{ar}} = \left[\frac{N_f}{N_{fr}}\right]^{-1/k} \qquad \text{for } N_f \leq N_{fr}$$

where the index r shows values of reference, e.g. $N_{fr} = 2 \cdot 10^6$.

The slope of the S-N-curve is then generally given by k. The different test amplitudes are exemplified with 2 or 3 specimens only; therefore, the regression curves represent a survival probability of approx. 50 % and no other percentages are allowed here.

Fig. 4 demonstrates the results of welded and not welded specimens as tested in air. The difference between the results and especially the different slopes of the S-N-curves are in accordance with other results. Mainly the smaller k-value of welded specimens represents an earlier fatigue crack initiation as compared with the situation of base material. There is almost no remarkable effect of the frequency, with the exception of the high amplitude values at f = 0.01 Hz.

In Fig. 5 the respective results of the tests in artificial seawater are collected. It is remarkable that there are larger dispersions of the results and a pronounced grading with the frequency. The k-value for welded specimens is smaller and represents a smaller N_c/N_f-value. - The test results for an air environment are analysed together while for artificial seawater the respective analysis is performed frequency by frequency; then all results can be represented by the survey in Fig. 6. A reasonable grading of the regression lines from base material in air down to welded specimens in seawater at the lowest frequency of 0.01 Hz is detectable. - For two selected stress amplitudes the values N_f are plotted over the applied frequencies in Fig. 7. According to that the maximum seawater effect is observed at the lowest frequency; but in the range $N_f < 2 \cdot 10^6$ the effect is moderate anyway: Based on the N_f-values for a 50 % survival probability, the endurance shortening by seawater corrosion is given by a factor < 5. But it is known that this effect increases at decreasing amplitudes, mainly in the range of fatigue limit of steel in normal environment (air).

In order to find out how time depending stress corrosion and pure cyclic fatigue contribute to the above mentioned frequency-influenced fatigue in seawater, a parameter plot of the stress amplitudes against test time t_f up to failure (up to approx. 1 year) is given in Fig. 8. The results for different frequencies diverge largely, so that pure fatigue is dominating the observed behaviour even in seawater. There is only a relative small time (frequency) effect - probably by hydrogen induced stress corrosion - contributing to damage. According to some competent literature (27,28) nothing else is to be expected because the applied strain rates $\dot{\varepsilon}$ are still too large (minimum 10^{-5} s^{-1}), Fig. 3) for hydrogen induced stress corrosion.

The effect of a cathodic protection is of special interest. The potential applied here by impressed current (- 850 mV Ag/AgCl) is at the lower bound of the usual range to prevent corrosion of steel in seawater. The available results from welded specimens tested at different frequencies are plotted in the S-N-diagram of Fig. 9 for comparance with the scatterbands of all other results of welded specimens. According to this the effect of a cathodic protection is not uniform: Some results are inside of the intersecting area of the scatterbands, some inside the range of air testing and - especially at lower amplitudes - some reveal a much better endurance.

In Fig. 10 the part of the results of cathodic protection with $N_f < 10^6$ is plotted as a base for a linear regression to quantify the slope of the S-N-curve. Notwithstanding the large dispersion of the results for cathodic polarization, the k-value shows distinct differences in comparance with other ones. Neglecting the additional frequency effect, the following grading of the slopes (mean values $\bar{k}$) of the S-N-curves is remarkable (welded specimens only):

- Free corrosion in seawater: $\bar{k} = 2.8$;
- Tests in air $\bar{k} = 3.8$;
- Cathodic protection $\bar{k} = 5.6$.

For further details cf. (1). - The higher k-values thereby indicate a smaller slope and a larger contribution of the number of cycles N_c up to the crack initiation to the total endurance N_f.

Further investigations have been directed to the fatigue crack initiation and the crack propagation. In not welded specimens all the cracks are situated between the two midspan loading points (distance 40 mm). In welded specimens the respective point was the undercut at the border between filler metal and base material. The exact position has been looked for by preparing metallographic sections. According to this the fatigue cracks were situated either in the filler or in the base material of the surface of the specimens but outside the peak hardness point in the heat affected zone.

The proper evaluation of the number of cycles N_c at fatigue crack initiation was difficult because of quite different geometries of the crack front. A more or less straight crack front has been developped firstly at some mm of crack depth. Formally based on the crack detection sensitivity of 0.4 mm a ratio $N_c/N_f = 0.64...0.93$ was found for the used relative small specimens under constant load amplitudes applied here; this is higher than given in literature. But in qualitative accordance with the above mentioned k-values smaller ratios have been evaluated for welded specimens compared with not welded ones and a later crack initiation was found at a cathodic polarization.

The fatigue cracks in any case propagated inside the base material because of the X-shaped geometry of the butt weldings. The used specimens, of course, have not been optimized for that purpose and are not appropriate for evaluation of the usual da/dn-ΔK-relationship. Yet rough estimates of the propagation rates $\Delta a/\Delta N$ could be correlated to the nominal bending stress amplitudes. In Fig. 11 as an example this relationship is given for free seawater corrosion, cathodic polarization and air environment and for two test frequencies. Summarizing the following results have been found:

- The crack propagation rate ($a = 2...5$ mm) in seawater (free corrosion) is significantly higher than in air.
- There is an additional frequency effect, which is more pronounced in seawater than in air. Cathodic protection reveals propagation rates comparable to those in air.

These results agree at least qualitatively with those given in literature.

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SYMBOLS USED

a = crack depth (mm)

C = $\Delta f/\Delta F$ = compliance (mm/kN)

f = frequency (Hz)

Δf = specimen deflection (mm)

F = Load (kN)

k = constant marking slope of S-N-curve

K = stress intensity factor ($N/mm^{3/2}$)

N_c = number of cycles up to the first occurrance of a crack

N_f = number of cycles up to total failure

R = F_{min}/F_{max} = load ratio

t_f = time up to total failure (h)

σ_a = stress amplitude (N/mm²)

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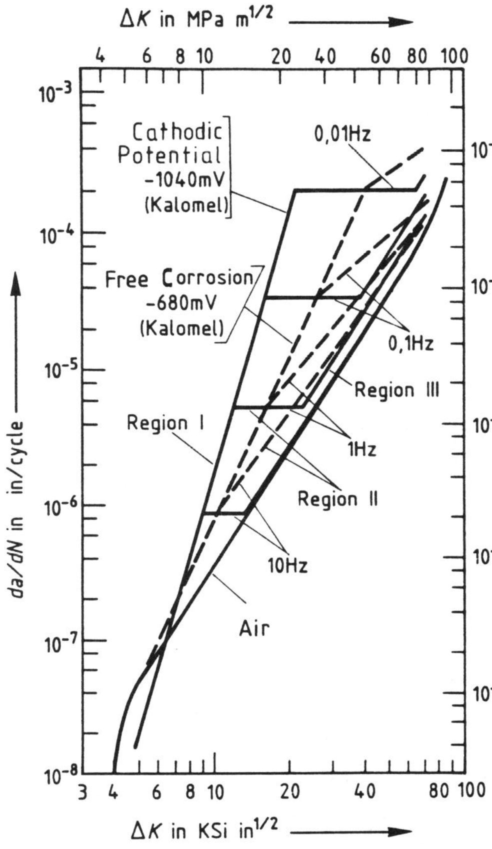


According to Vosikovsky (18) (schematically)

Figure 1 Survey about the influences on crack propagation

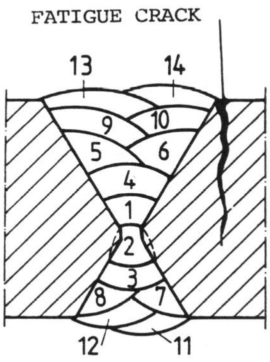
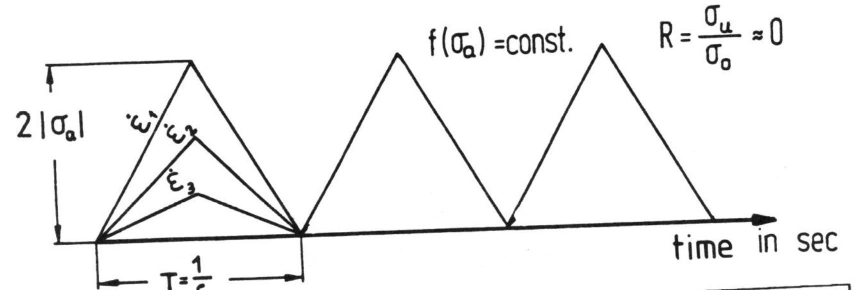


Figure 2 Butt welding geometry and layer situation



f in Hz	$\dot\varepsilon = 4\cdot\lvert\sigma_a\rvert\cdot f/E$ in s^{-1} at σ_a =		
	± 80	± 160	± 240 N/mm²
10 1 0,1 0,01	$1{,}6\cdot\left\{\begin{matrix}10^{-2}\\10^{-3}\\10^{-4}\\10^{-5}\end{matrix}\right.$	$3{,}2\cdot\left\{\begin{matrix}10^{-2}\\10^{-3}\\10^{-4}\\10^{-5}\end{matrix}\right.$	$4{,}8\cdot\left\{\begin{matrix}10^{-2}\\10^{-3}\\10^{-4}\\10^{-5}\end{matrix}\right.$

Figure 3 Load-time function and respective strain rates $\dot\varepsilon$

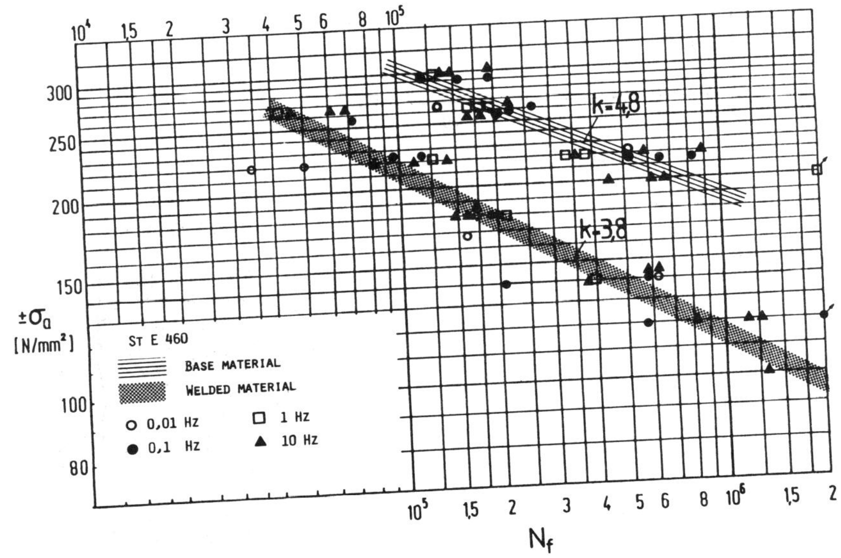


Figure 4 Results of the tests in air

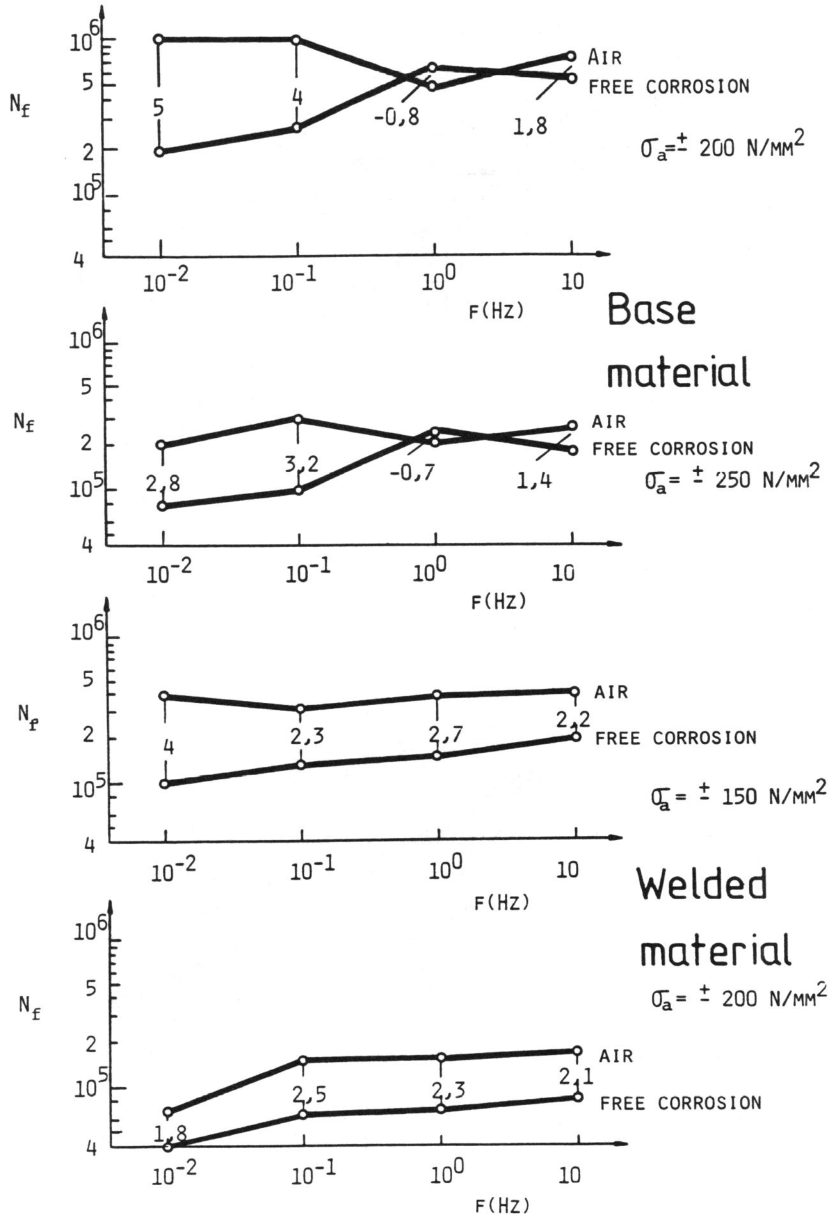


Figure 7 Effect of free seawater corrosion on the endurance at different frequencies

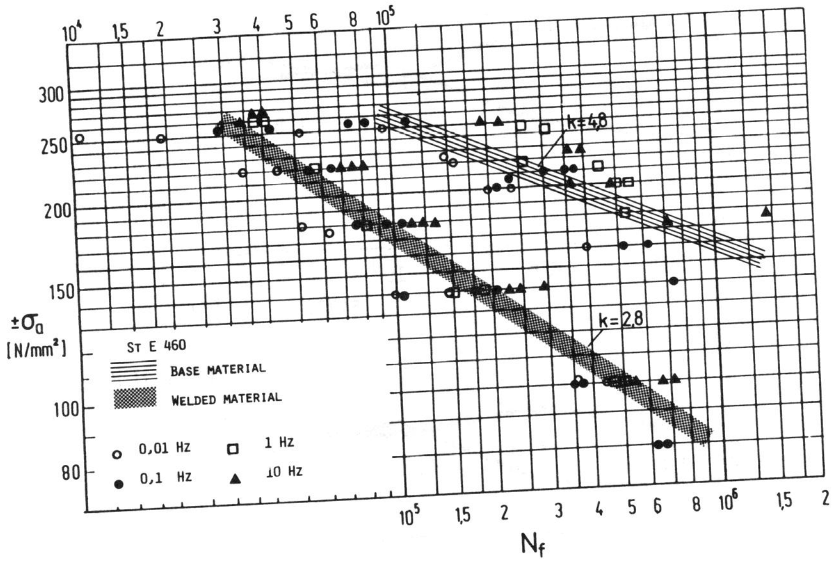


Figure 5 Results of the tests in artificial seawater at free corrosion potential

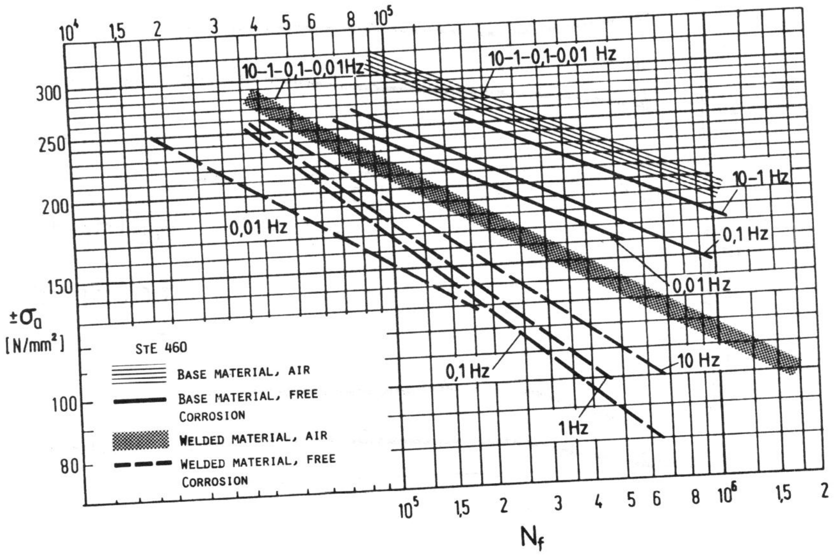


Figure 6 Grading of the test results based on the regression lines $\pm\sigma_a - N_f$

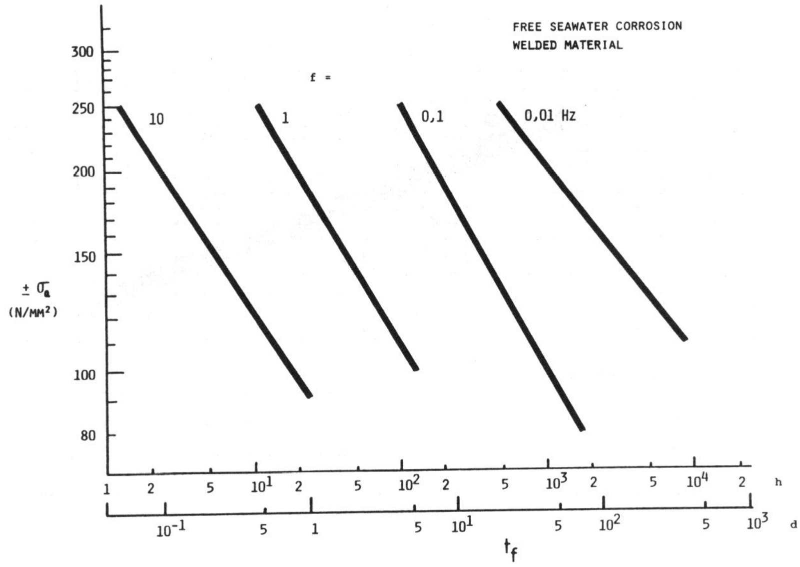


Figure 8 Grading of the test results for welded specimens based on the regression lines of $\pm\sigma_a - t_f$

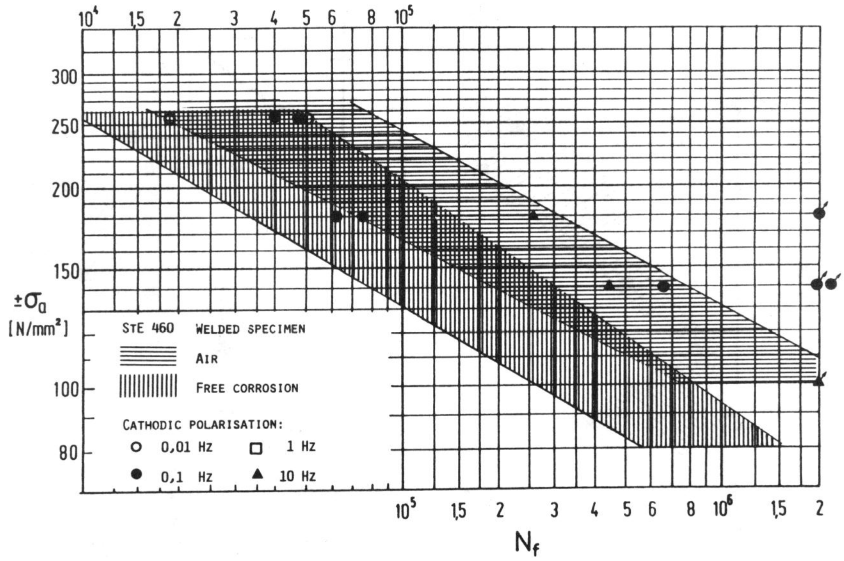


Figure 9 Behaviour of specimens under cathodic protection with - 850 mV (Ag/AgCl)

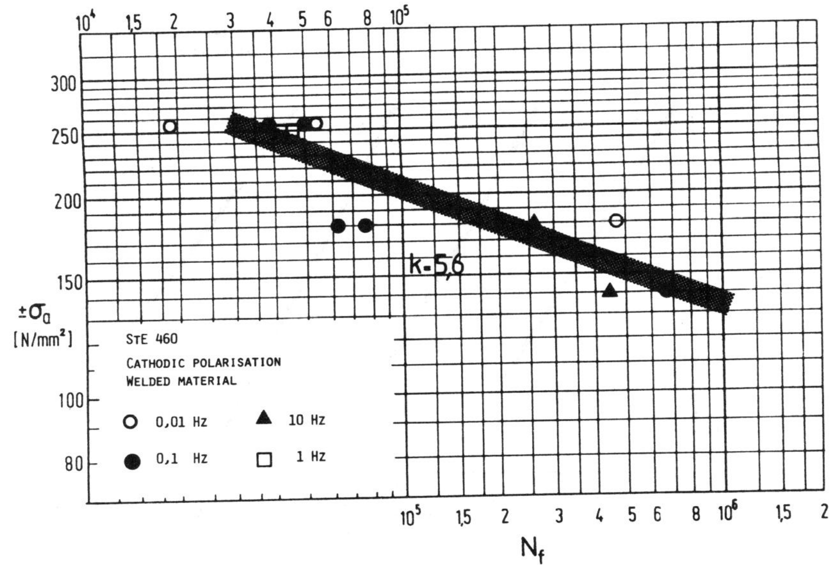


Figure 10 Separate evaluation of test results for cathodic protection

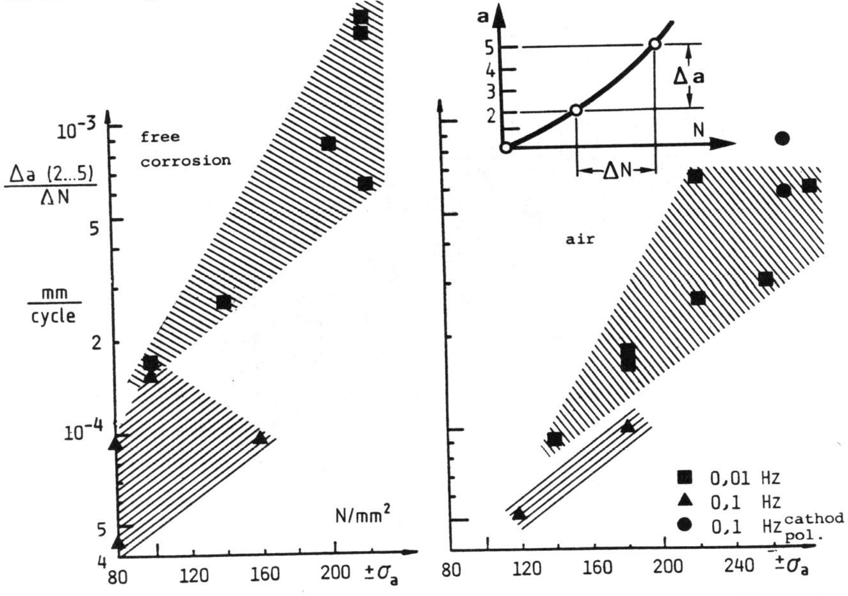


Figure 11 Mean crack propagation rate for different environmental conditions