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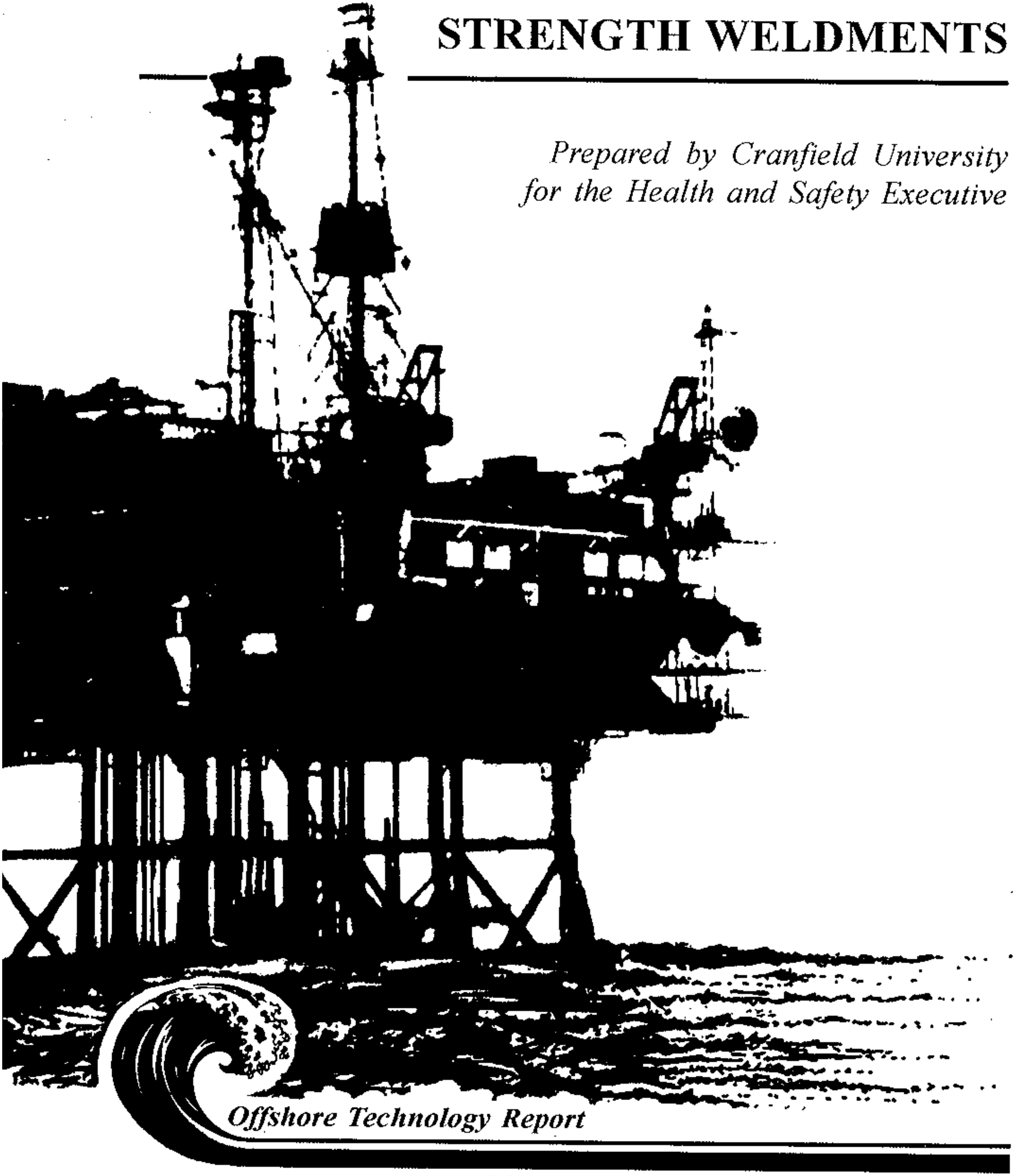
Prepared by Cranfield University
for the Health and Safety Executive



Offshore Technology Report

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A REVIEW OF THE CORROSION FATIGUE BEHAVIOUR OF STRUCTURAL STEELS IN THE STRENGTH RANGE 350-900MPa AND ASSOCIATED HIGH STRENGTH WELDMENTS

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HSE BOOKS

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ABSTRACT

In this survey, the fatigue performance for steels in the yield strength range 350 - 900MPa, expressed in terms of fatigue crack propagation rate (FCPR), is reviewed. The influence of environment; seawater, cathodic protection and mechanical loading: load ratio R, test frequency f, are assessed. Comparisons with the behaviour of conventional structural steels. BS4360: 50D and higher strength steels are established. Available data for the associated heat affected zone (HAZ) and weld metal are also reviewed.

In spite of the large number of corrosion fatigue investigations carried out over the past 10 years, few have generated data for conventional structural steel Grade 355, particularly under conditions of high mean stress R >0.5 and under applied cathodic protection. The most comprehensive data set dates back to the work carried out as part of the UKOSRP programmes.

From an examination of the FCPR behaviour of steels in the strength range 350 - 900MPa, within the range of applied cathodic protection levels and load ratios reviewed, environmental reduction factors (ERF) are similar for steels from each strength level for the specific environmental conditions. It highlights the combined detrimental influence of high mean stress and overprotection levels, -1100mV(SCE), where crack growth rates can be increased by a factor of 10 over that observed in-air. No evidence was found to suggest that the high strength (HS) steels (400 - 600MPa) or extra high strength steels (700 - 900MPa) were more susceptible to enhanced crack growth rates than were conventional structural steels.

The extensive database of HAZ fatigue tests on HS steel (400 - 600MPa) generated at Cranfield has also been assessed. It has been shown that the corrosion fatigue performance and crack growth mechanisms in the HAZ are similar to those observed in the parent plate, displaying a similar response to environmental test conditions. It is evident that welding under controlled conditions does not significantly affect FCPR in these steels.

Despite an extensive search of the literature, only limited data were available for the FCPR behaviour of weld metals. The available data at low R ratio, R = 0 - 0.1, suggests comparable behaviour to that observed for structural Grade 50D steel under similar conditions.

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1. INTRODUCTION

Fatigue is a major cause of failure in marine structures, and in welded fabrications most of the fatigue life is taken up in fatigue crack propagation. For this reason, measurement of crack propagation data in relevant steels tested under realistic conditions to simulate offshore environments is vital for both safe lifetime predications and for determining remedial actions when cracks are found during normal inspection programmes throughout the lifetime of the structure.

Most current fixed platform structures contain considerable quantities of structural steel. The conventional steel production route for this steel grade is normalising in order to produce satisfactory properties in thicker section. A primary requirement is to ensure adequate weldability by limiting steel hardenability through imposing compositional limits, which is usually imposed through restrictions in allowable carbon equivalent values. This factor, combined with the need for good notch ductility, has led to a continual reduction in carbon levels in such steels over the past two decades(1-4). The corrosion fatigue behaviour of welded joint constructions from such structural steel, BS4360: 50D, has been the subject of a number of studies over the years(5-12 etc.). As a result, the understanding of the influence of joint geometry, seawater environment and cathodic protection has reached a level where confident predictions on fatigue resistance behaviour can be made for this type of structure.

High strength steels have been available for many years, but their use in offshore engineering has been restricted except in specialised applications. For conventional quenched and tempered highly alloyed steels, high strength is usually associated with reduced ductility and weldability. Moreover, the corrosion fatigue behaviour is expected to deteriorate compared to medium strength steels, particularly under conditions of cathodic protection (CP), because of their greater susceptibility to hydrogen embrittlement. However, this is not necessarily the case for modern high strength structural steel in the yield strength range 400 - 600MPa. The development of modern high strength structural steels has been strongly influenced by the requirements of the pipeline industry. For example, advances in steel processing thermo-mechanical controlled processing (TMCP) to produce fine grain sizes (to improve strength and toughness), reduced carbon levels to ensure good weldability and toughness, and low levels of impurity elements such as sulphur and phosphorus, have been commonly adopted in the production of structural plate. Thus typical modern high strength steels possess exceptional combinations of strength, toughness and weldability. A number of research programmes have confirmed their suitability for offshore constructions(1-4, 13-16).

A number of studies have highlighted the weight-saving potential and cost benefits of using higher strength steels(17-19). This is reflected in the increased usage of such steels offshore, for example a recent review by the authors(1) has indicated that over the period 1988 - 1995, the use of high strength steel in offshore projects, typically grade 450, has increased from approximately 8% to 40%. Initially such steels were used on topsides but now, particularly in the UK, they are also used more frequently in jacket legs and bracing members not subject to fatigue. Recent laboratory results support the view that such steels may perform satisfactorily under conditions subjected to fatigue loading. However, doubts concerning their fatigue behaviour continue to restrict their wider consideration for this application area(1).

Even higher strength steels with 700MPa yield strengths have been used in jack-up platforms(20). Such steels usually have relatively high carbon contents because good abrasion resistance is also required in the jacking operation and weldability is not a prime consideration. Because of the periodic docking arrangements which allow easier inspection capabilities, fatigue is also not seen as a major design limitation. More recent proposals to use such structures on much longer term operational schedules has instigated a more widespread interest in the likely fatigue performance of the type of steel used in jack-ups(21).

In this survey the fatigue performance, expressed in terms of fatigue crack propagation rates for steels primarily in the yield strength range 350 - 900MPa, is reviewed. The influence of environment (i.e. seawater, cathodic protection) and mechanical loading (i.e. load ratio, R, and frequency, f,) is assessed. Comparisons between the behaviour of conventional structural steels and higher strength steels are established. Available data for the associated heat affected zone (HAZ) and weld metal are also reviewed.

2. SCOPE OF WORK

In-air and corrosion fatigue data for steels in the yield strength range 350 - 900MPa have been extracted from the literature covering the period 1975 - 1995. Sources of information include published papers, research theses, conference proceedings and technical reports presented by workers primarily in Europe, Japan and the USA.

Steels have been classified into 3 main groups based on yield strength and most likely application area:

CATEGORY	YIELD STRENGTH (MPa)	APPLICATIONS
I	350 (conventional structural steel)	Offshore structures, shipping.
II	400 - 600 (high strength steel)	Fixed and floating platforms, moorings.
III	700 - 900 (extra high strength steels)	Jack-up platforms, naval applications.

Composition/mechanical property details for each steel group are presented in Tables I, II and III respectively, where the fatigue behaviour is discussed. A number of introductory remarks related to steel performance and production methods are firstly discussed below.

For Group I steels of 350MPa yield strength, considerable flexibility exists with the selection of plate production method, steels being produced by either normalising, thermo-mechanical controlled processing (TMCP) or quench and tempering. In the 1970s normalised structural steels conforming to type BS4360:50D, Table I, were of a C-Mn variety, Si killed and microalloyed with Al. In this way strength levels of 370MPa combined with impact toughness values of >100J at -30°C were achieved. Modern normalised steels, conforming to EEMUA 150 Grade 355EMZ usually have reduced levels of carbon (0.1 - 0.15%) to improve their properties. Utilising additions of Nb, V, Ni and Cu, yield strengths in the range 350 - 500MPa can be achieved, balanced with excellent toughness and good weldability(1-4). As demonstrated in Table I, developments in TMCP incorporating both controlled rolling and accelerated cooling have enabled steels of comparable yield strength and toughness to be produced at much lower carbon equivalent values, the leaner chemistries thereby further enhancing weldability. Typical combinations of strength and toughness are 450 - 550MPa with up to 300J at -40°C. Plate thickness of the higher strength grades are limited to 30 to 40mm which has, in the past, been adequate for the primary area of pipeline applications. Both Japanese and European producers are examining means of overcoming this limitation, and the prediction of 50mm plate of yield strength 500MPa has been reported(1-3).

Section thickness and strength limitations experienced in normalised and TMCP steels has meant the quench and tempering process is currently the most effective way of producing higher strength steels (>500MPa) at thicknesses in excess of 50mm. Originally, the alloy strengthening route utilising high levels of hardening elements such as Ni, Cr, and Mo was adopted as typified by the HY series of steels. In this way, high hardenability was achieved promoting transformation to fine low temperature transformation products such as martensite and lower bainite during quenching from temperatures around 900 - 950°C. Subsequent tempering in the range 580 - 620°C was applied to obtain the required balance of strength and toughness. Because of the rich chemistries that were utilised, these steels were expensive to produce and difficult to weld(1,2).

Modern commercial quenched and tempered steels in the strength range 500 - 900MPa, (Tables II and III) still follow the same general production route. However, by using microalloying additions, such as Al, Ti, Nb and V for grain refining and precipitation strengthening, and by adding small amounts of boron (B=0.002%) to enhance hardenability, significant reductions in carbon and total alloying element contents have been achieved. Manufacturers will vary the levels and combinations of alloying elements, depending on the steel strength/toughness levels and on the cooling rates achieved in their respective quench units. This has led to a nett reduction in carbon equivalent values from 0.8 to typically 0.4 - 0.6, which produces high strength steels with enhanced mechanical properties combined with improved weldability(1,2).

In this review, fatigue data is presented in the format of fatigue crack propagation rate (FCPR), defined as crack growth rate (da/dN), usually determined as a function of stress intensity range (ΔK). Only data from constant amplitude loading are considered and are limited to the low to intermediate ΔK range $<30 MN/m^{3/2}$.

Following the initial survey, a number of screening criteria were applied to include data most applicable to offshore operating conditions and welded constructions. Those being moderately high loading ratios, R = 0.5 - 0.8, low frequency, f = 0.1 - 0.5Hz, and environments including in-air, free corrosion potential and cathodic protection levels of -800 to -1100mV(SCE). The influence of these variable are summarised in Figures 1 - 3 and the selected parameters will provide upper bound crack growth data for the materials considered. (In the absence of sufficient data being available, for example when considering weld metals, alternative conditions, as specified have been considered.) An indication of the influence of environment is given by the environmental reduction factor (ERF) which is defined as the ratio of the FCPR in seawater to that in air at a given stress intensity factor range. This has been calculated and the high strength steel data are compared with the behaviour of conventional structural steels.

3. FATIGUE CRACK PROPAGATION DATA - PARENT STEEL

3.1 Conventional Structural Steels - Nominal Yield Strength 350MPa

The performance of this group of materials which are currently widely used offshore will act as a baseline reference against which to judge the behaviour of the higher strength steel groups.

In spite of the number of corrosion fatigue investigations carried out over the past 10 years, few have generated information for this steel group, particularly under conditions of high mean stress R >0.5, and under conditions of cathodic protection (CP). The most comprehensive data dates back to work carried out as part of the UKOSRP programmes(5-7,8,24 etc.). This is supplemented by more recent data, notably Booth et al(22,23), Thorpe et al(22), BSC(25), and Kermani(26). Test details are summarised in Table IV. Chemical compositions and mechanical properties are detailed in Table I.

The steels used in these early test programmes mirroring the actual steels used offshore at that time conformed to BS4360: 50D and as shown in Table I, would not be acceptable according to the EEMUA 150 Grade 355EMZ specification used in current offshore jacket specifications(27,28). For example, phosphorus and sulphur levels of 0.037% and 0.023% are much higher than the now common levels of <0.01% and <0.005% respectively, although some of the earlier test samples did have lower impurity levels than given in the specifications. Carbon levels have also been dramatically reduced from values of 0.17% to now common levels of ~0.1%, introduced primarily to enhance both toughness and weldability. Therefore such fatigue data may not be truly representative of recent 350MPa yield steels and is an area requiring some consideration.

The fatigue crack propagation data for the various environmental conditions, air, free corrosion, CP of -800 to -850mV and -1000 to -1100mV(SCE), have been combined and are plotted in Figures 4(a - d), for two R ratios, R = 0.1 and R = 0.7 respectively. Upper and lower bounds have been applied to encapsulate the observed data set.

From Figure 4(a), in-air test data are relatively independent of stress ratio. The mean air data line for R = 0.1 and R = 0.7 derived from reference (6,7) are also indicated. Within the Paris region from $\Delta K = 15MN/m^{3/2}$ and upward, a slope of m = 3 described the data. Threshold values (ΔK_{th}) has been quoted in the range 6 - 9 $MN/m^{3/2}$. Similar data have been compiled for each environmental condition of free corrosion, CP -800 to -850mV and CP -1000 to -1100mV(SCE), and the combined data are presented in Figures 4(b-d). For each environment and load condition threshold values and ERFs have been determined with respect to in-air behaviour and are summarised in Table V.

Irrespective of environmental conditions, the influence of stress ratio is clearly demonstrated. Two effects occur simultaneously; firstly an increase in crack growth rate as R increases from 0.1 to 0.7 at any particular value of ΔK, and secondly a reduction in threshold stress intensity value, Table V and Figure 5. For R = 0.1, ERF values are in the range 1 - 2 for conditions of free corrosion and CP potential of -850mV(SCE). This value increases up to 4 at the intermediate $\Delta K = 20MN/m^{3/2}$ for the more negative potential of CP -1100mV(SCE). This is rationalised in terms of a hydrogen embrittlement mechanism becoming dominant at the more negative potential as characterised by the plateau effect on the da/dN-ΔK curve. The apparent increase in threshold values, from 6 - 9 in-air to 15 - 18 at -1100mV(SCE), is explained in terms of crack wedging due to calcareous deposits. Both these phenomena have been highlighted in numerous fractographic studies. Under conditions of high mean stress, R =

0.7, the sensitivity to environmental condition is greatly exacerbated. Under conditions of free corrosion, ERF values vary from 3 - 6 over the ΔK range 10 - 30MN/m$^{3/2}$. For the extreme condition of cathodic overprotection, -1100mV(SCE), ERF values increase up to 10 - 15 at low values of ΔK 10 - 15MN/m$^{3/2}$ and then fall again to 5 at ΔK 25 - 30MN/m$^{3/2}$. The characteristic plateau effect associated with hydrogen embrittlement is again apparent. Even at the nominally 'correct' level of CP, -850mV(SCE), evidence of hydrogen induced cracking is apparent with ERF values in the range 4 - 8. Irrespective of environmental condition, reported threshold stress intensity values for R = 0.7 are in the range 5 - 8MN/m$^{3/2}$. At the higher R ratio, R >0.5, the effect of crack wedging due to calcareous deposits is diminished due to increased crack opening displacement at each fatigue cycle and ΔK threshold remains essentially constant as shown in Figure 6.

The combined effects of stress ratio and environment have been demonstrated and it is clear that under the extreme condition of high negative protection levels and high mean stress, these conventional structural steels are susceptible to hydrogen embrittlement with ERF values of 10 - 15 not being uncommon. These data will subsequently be used for comparative purposes when considering the behaviour of the higher strength steels.

3.2 High Strength Steels (HS) Yield Strength Range 400 - 600MPa

Similar fatigue crack propagation data have been compiled for this steel group with yield strengths 400 - 600MPa. Information included covers a range of steels manufactured in Europe, Japan and the USA, which typify modern high strength steel production for both structural and pipeline applications. The material composition and mechanical properties and test details examined are summarised in Table II(13-16,29-46).

For this strength range, steels produced by the two primary production processes, quenched and tempered (Q & T) and thermo-mechanical controlled processing (TMCP), are included. Greater flexibility is associated with the Q & T steels, these span the strength range 400 - 600MPa, whereas as TMCP steels are generally limited to <500MPa. The modern steels are characterised by low carbon contents; ≈0.1% for Q & T and as low as 0.05% for TMCP plates, with a high degree of cleanliness, typically S<0.005%, P≤0.010%. In comparison to the conventional structural steels of relatively simple C-Mn type, Table II, the moderate use of small amounts of alloying elements, (Ni<1%, Cr<0.5%), together with the use of combinations of microalloying elements, (Nb, V, Al and Ti), ensure adequate strength, good toughness and satisfactory weldability. Carbon equivalent values are limited to the range 0.3 - 0.5(2,3).

In this analysis, only data for load ratio R >0.5, generally 0.6 - 0.8, are included for each environmental condition, thus an average 10 - 12 steels are incorporated within each data set. These are presented in Figures 7(a - d). The mean air line for BS4360: 50D R = 0.7 (Section 3.1) is superimposed on the diagram and ERF values (or relative crack growth rates) are defined with respect to this base line data. This information is summarised in Table V and plotted in Figure 8.

In-air crack growth rates lie in the range 0.5 - 2 times that of BS4360: 50D. From Figure 7(a) and Table VI it can be seen that in general the bulk of the data lie below the mean line for 50D, indicating reduced crack growth rates. At the free corrosion potential, generally ERF values are 3 - 5 for low ΔK<20MN/m$^{3/2}$, decreasing at higher values of ΔK, values typically being 2.5 for ΔK 30MN/m$^{3/2}$. In general, the bulk of the data lies within a factor of 3 from the in-air line. This behaviour is in line with that observed for the structural steels with 350MPa yield. The effects of CP are again more pronounced at low ΔK values <15MN/m$^{3/2}$. ERF values of up to 4 occurring for ΔK 10 - 15MN/m$^{3/2}$ under applied cathodic protection of -850mV(SCE), increasing up to the range 4 - 10 under the condition of overprotection at

-1100mV(SCE). Several fractographic studies have confirmed the change in crack propagation mode, from ductile with secondary cracking to quasi-cleavage fracture, at the high negative potentials(13-16,41,42-45,47-51). However, it is notable that the fatigue performance of the high strength steel group is comparable, if not slightly improved over that of the structural grade 50D steels, Table V and Figure 9, both steel types responding similarly to the environmental effects. For the steels examined, no discernable effect of manufacturing process, Q & T or TMCP, is seen on the resultant fatigue crack propagation behaviour.

Limited studies have focused on generating threshold data, ΔK_{th}, for this steel group. However, some data on the influence of test condition, R value and environment on the determined values is indicated in Table VI. For low R ratio, an apparent increase in threshold value occurs with increased CP level, compared with the in-air behaviour values increasing from 4 - 7 in-air to typically 15 - 18 at the highest negative potential, -1100mV(SCE). Many studies have demonstrated that this behaviour is due to crack wedging effects reducing the effective stress intensity range(42-51 etc.). Under conditions of high load ratio, this mechanism is diminished and the true threshold values are determined, these being similar to those in-air and of the order 4 - $9MN/m^{3/2}$ (Figure 6).

An approach adopted by workers in the USA(30-32, 42-45) takes account of these closure effects by measuring the crack opening displacement and calculating a parameter 'effective' stress intensity range. In this case tests carried out under different R ratio converge to indicate the true threshold behaviour.

Overall, laboratory fatigue crack propagation behaviour of this group of HS steels compares well with that of the lower strength structural steels. However, in the absence of sufficient large scale S-N data, insufficient confidence exists to promote the wider use of such materials in fatigue dominated area, i.e. primary nodal joint. However, several programmes are addressing these issues in an attempt to provide this additional guidance. Interestingly, a number of recent Norwegian structures comprised approximately 95% higher strength Grade 420 steels in the jacket. This is considered to be due to the less restrictive design rules and procedures, particularly with respect to their application in fatigue critical areas(1).

3.3 Extra High Strength Steels (EHS) - Yield Strength Range 700 - 900MPa

Extra high strength steels (EHS) of yield strength ≈700MPa have been widely used in jack-up structures(20). Recent proposals to use such structures on longer term operational schedules have prompted a more widespread interest in the fatigue performance of the type of steel used(21). Additional interest exists in this type of material for use in moorings and in the use of even higher strength steels up to 900MPa in both these application areas.

From an examination of the literature, there are limited data available for this group of steels, particularly at low frequency <0.5Hz, and under applied CP appropriate to offshore conditions. The available data for steels in the strength range 700 - 900MPa test conditions and materials are summarised in Table III.

At this strength level, the Q & T process is the only effective method of producing steels with satisfactory strength and toughness and in section thicknesses suitable for offshore applications(2,3). In line with modern steel production, carbon levels are low, generally in the range 0.1 - 0.15%, together with high steel cleanliness, S<0.005% and P<0.01%. In order to achieve high strength combined with adequate toughness, traditional alloying elements are added, typically Ni = 1% (up to 5% in HY130), Cr = 0.5%, Mo = 0.5%, combined with microalloying elements Al, V and Nb. Copper is also often added at levels of 0.2%. Carbon equivalent values will be higher, typically 0.5 - 0.6, and such steels require significant preheat and post-weld heat treatment (PWHT) in welding to ensure adequate weldability.

The fatigue behaviour of the steels tested at R ratios of 0 - 0.1 is presented in Figure 10. In-air fatigue performance is comparable to that observed for structural Grade 50D under similar conditions. The overall effect of the seawater environment, for both conditions of free corrosion potential and CP at -850mV(SCE), is to reduce the fatigue life by a factor of approximately 2 over the ΔK range 10 - 30MN/m$^{3/2}$. This is similar to that observed for structural and intermediate strength steels. One study examined the effect of high negative cathodic protection, (-1030mV(SCE)), on HY130(58) and again, crack growth rates were enhanced by a factor of 10 - 12 at low ΔK <15MN/m$^{3/2}$.

At the higher mean stress level, $0.6 \leq R \leq 0.8$ fatigue data in-air and under CP of -1030 to -1100mV(SCE) were available for a number of steels, notably HY100, HT80 (yield strength 750 - 810MPa) and HY130 (yield strength 990MPa)(54-58). These are presented in Figure 11 and ERF values are defined in Table VIII. In-air data falls close to that observed for structural grade 50D steels. As observed for both the structural grade 50D steels and intermediate strength steels, the effect of cathodic overprotection is most pronounced at low ΔK levels 10 - 15MN/m$^{1/2}$, where fatigue crack growth rates are increased by a factor of 6 up to 14. At higher ΔK levels >20MN/m$^{3/2}$ this enhancement is reduced to a factor of approximately 4.

3.4 Summary

In the previous sections, information has been presented on the FCPR behaviour of steels in the strength range 350 - 990MPa. A summary of ERF for the 3 steel groups examined is presented in Table IX for a condition of high mean stress, i.e. $0.6 \leq R \leq 0.8$.

Within the range of applied CP potentials examined, ERF values are similar for steel from each strength level for the specific environmental conditions. It highlights the combined detrimental influence of high mean stress and overprotection levels (-1100mV(SCE)), where crack growth rates can be increased by a factor of 10 - 15 over that observed in-air. No evidence was found to suggest that the HS steels (400 - 600MPa) or even EHS steels (700 - 900MPa) were more susceptible to enhanced crack growth rates over conventional structural steels.

4. FATIGUE CRACK PROPAGATION BEHAVIOUR OF HIGH STRENGTH STEEL WELDMENTS

In contrast to the large database of information for high strength parent plate, very limited data has been generated for the corresponding weldments, e.g. HAZ and weld metals. Despite the close controls exerted by the manufacturer, in welding the resultant HAZ can be highly heterogeneous in terms of microstructure and mechanical properties. Moreover, weldments will contain defects, microcracks, slag entrapment, undercut, etc., which may serve as sites for fatigue initiation. In addition to having low toughness, and being susceptible to hydrogen induced cold cracking, these harder and stronger regions may also be prone to accelerated fatigue crack growth. High strength weld metals depend on the use of traditional alloying elements such as Ni, Cr and Mo, to achieve the required levels of strength and toughness which, in turn, both enhance their hardenability and may modify their corrosion fatigue behaviour.

4.1 HAZ Fatigue Performance

For several years high strength steels in the strength range 400 - 600MPa and their associated HAZs have been studied at Cranfield in a number of Managed Programmes of University Research(13-16) and associated research theses(35,36,59-61). The steels assessed came from Europe (UK, France, Germany & Sweden), Japan and the USA. They were produced primarily by the Q & T process or by the accelerated cooled process as summarised in Table X.

Representative HAZ fatigue crack growth data for this group of steels in the strength range 500 - 580MPa are presented in Figures 12 and 13 and ERF values defined in Tables XI and XII. Generally a weld heat input of 3kJ/mm is considered and all tests have been carried out at high mean stress level, $R = 0.6$, and test frequency of 0.5Hz.

Figure 12 and Table XI show the in-air behaviour of both parent plates and associated HAZs compared with the structural grade steel BS4360: 50D. As discussed in Section 3.2, the HS steels considered have shown reduced crack growth rates, typically by a factor in the range 0.5 to 0.9. The high strength HAZs show increased crack growth rates relative to 50D, typically in the range 0.6 to 1.5 with a mean ratio of ~1. However, compared to the HS plate data, mean crack growth rates were increased by a factor of 1 - 2 at low ΔK 13 - 15MN/m$^{3/2}$, reducing to ~1 at higher ΔK 30MN/m$^{3/2}$. Corrosion fatigue crack growth data for the HAZ is presented in Figure 13 and summarised in Table XII for conditions of free corrosion and cathodic protection of -850mV and -1100mV(SCE).

Under conditions of free corrosion, crack growth rates at low ΔK <15MN/m$^{3/2}$ are roughly equal to that in-air for the HAZ, increasing by a factor of 2 at the higher ΔK level 30MN/m$^{3/2}$. At the CP potential of -850mV(SCE), crack growth rates are approximately twice that for in-air at low ΔK 10 - 15MN/m$^{3/2}$, and approached in-air behaviour as ΔK increased. However, as the CP potential was increased to the more negative level of -1100mV(SCE), significant acceleration in growth rates occurred, typically 5 - 7 times at low ΔK 10 - 15MN/m$^{3/2}$, and up to a factor of 3 at high ΔK 30MN/m$^{3/2}$. However, it is important to appreciate that the fatigue performance of the HAZ is certainly no worse than that observed for either the structural grade steel or the HS steel parent plate data.

Extensive metallographic and fractographic studies have also been carried out. These studies have shown that these HS steels in the yield strength range 500 - 600MPa are not susceptible to excessive hardening in the welded condition. In general, HAZ hardness levels are <350Hv(5kg), typically 300Hv or below(13-16). This can be related to changes in composition and process developments which have occurred over the years, for example reduced carbon levels ≈0.1%, leaner total alloying with Ni, Cr, Mo combined with microalloying Nb, V, Al, Ti etc. Additionally, the fatigue crack failure mechanisms in the HAZ are similar to those observed in the parent plate, displaying a similar response to environmental test conditions. The influence of welding heat inputs in the range 1 - 3.5kJ/mm on fatigue behaviour has been assessed at Cranfield(13-16, 59-61). In general, no adverse effect of weld heat input was observed for this group of steels when welded. Threshold behaviour has not been examined in these studies; however, near threshold crack growth rates indicate comparable behaviour to that observed for the parent plate.

It is evident that welding under controlled conditions does not significantly affect FCPRs in these steels. It is suggested that a preliminary screening of the corrosion fatigue behaviour on the parent plate may therefore be also used to assess the suitability of the steel when welded.

4.2 Weld Metal Performance

Despite an extensive search of the literature, little information is available on weld metal fatigue performance. Older studies on high strength weldments, HY100, HY130, generally have been concerned with the higher ΔK range typically 40 - 100MN/m$^{3/2}$ (62,63). More recently, data for weld metals of yield strength 500MPa, Zang et al(64,65), and of yield strength 590MPa, Todd et al(30-32), have been published. These initial studies have aimed at assessing weld metal FCPRs at low R ratio and near threshold data has been assessed by Todd et al.

Information for parent plate A537 of yield strength 500MPa and two matching strength weld metals tested by Zang et al(64,65) is presented in Figure 14. Tests were conducted in-air and under free corrosion at R = 0 and f = 0.167Hz. It is concluded that in this case both fatigue crack growth rates and crack growth threshold values for the weld metals are higher than those of the base plate in both air and seawater at the free corrosion potential. Indicated threshold values are increased from 6 to 8MN/m$^{3/2}$ for the parent plate to 10 - 15MN/m$^{3/2}$ for the weld metal under the conditions examined. This has been attributed to the effects of weld residual stress(64,65). The mean line for structural grade 50D steel R = 0.1 tested in-air, is superimposed on the diagram which indicates the comparable performance of the weld metals. Fatigue crack propagation rates under free corrosion are within a factor of 2 from this line. The importance of mean stress level and CP potential on FCPRs and threshold behaviour have been highlighted in Section 3; it is likely that a similar shift in FCPR behaviour would occur if weld metals were tested under these conditions.

Data reported by Todd et al(30-32) for a naval steel, MILS24645, of yield strength 590MPa and its matching weld metal are presented in Figure 15. In this instance an R ratio of 0.1 has been used with a test frequency of 10Hz, only tests on parent plate at f = 0.2Hz have been reported. Under these conditions, FCPR performance for the parent plate is comparable to that of 50D. The weld metal shows significantly improved performance compared to parent plate. The detrimental effects of cathodic overprotection are not reported. However, this may be due to the time dependency of the environmental conditions, and these effects may be masked by the high testing frequency of 10Hz. For the parent plate an apparent increase in threshold is observed with more negative CP potential, this is behaviour associated with crack closure due to calcareous deposits. Interestingly, as observed in work by Zang et al, an increase in weld metal threshold value occurs irrespective of environmental test conditions.

The primary reasons behind the difference in FCPRs observed for the weld metals are unclear; however, it is suspected that as test frequency is reduced to 0.1Hz, then FCPRs would increase. Indeed, work by Zang et al(64,65) has indicated that under conditions of free corrosion a reduction in test frequency from 10 to 0.167Hz caused FCPRs to increase by a factor of 3 -

4. This may shift the observed curves of Todd et al upward in line with the data of Zang et al. Again, no information is available for conditions of high mean stress.

At this time no clear statement can be made on the FCP performance of the weld metal. Although the most 'suitable' data generated by Zang et al indicates performance comparable to structural Grade 50D steel.

5. CONCLUSIONS

The fatigue performance, expressed in terms of FCPRs, has been reviewed for steels in the strength range 350 - 900MPa. Available data for higher strength weld metal and HAZ has also been assessed. The influence of environment - seawater, CP, and mechanical loading - R and f are established. The following conclusions have been drawn:

1. BS4360: 50D - corrosion fatigue crack growth rates in BS4360: 50D structural steels have been reviewed to serve as a baseline against which the higher strength steels could be compared.

    (a) In spite of the large number of corrosion fatigue investigations carried out over the past 10 years, few have generated information for this steel group, particularly under conditions of high mean stress, $R > 0.5$, and under cathodic protection. The most comprehensive data dates back to work carried out as part of the UKOSRP programmes(5-8) when steel compositions were somewhat different to modern 350 structural steels used offshore today.

    (b) In-air test data is relatively independent of stress ratio. Within the Paris regions $\Delta K = 15MN/m^{3/2}$ and above, a slope $M = 3$ described the data. Threshold values have been quoted in the range 6 - $9MN/m^{3/2}$.

    (c) Irrespective of seawater environment, the influence of increased stress ratio has been clearly demonstrated. Two effects occur; firstly, an increase in growth rate at any particular ΔK range, and secondly, a return to in-air threshold levels. For $R = 0.1$ and low ΔK, less than $20MN/m^{3/2}$, ERF values are in the range 1 - 3 for free corrosion and CP potential of -850mV(SCE), increasing up to 5 at the more negative potential of -1100mV(SCE). This increase in growth rate has been associated with hydrogen embrittlement. The apparent increase in threshold value from 6 - 9 in-air to 15 - $18MN/m^{3/2}$ at the potential of -1100mV(SCE) is explained in terms of crack wedging due to calcareous deposits. Under conditions of high mean stress, the sensitivity to environment at low ΔK values below $15MN/m^{3/2}$ is exacerbated. Under conditions of free corrosion, ERF values are in the range 4 - 8, increasing to 10 - 15 for the CP potential of -1100mV(SCE). Reported threshold values are in the range 5 - $8MN/m^{3/2}$. At the higher R value, the effect of crack closure due to calcareous deposits is diminished.

    (d) Under the extreme conditions of high mean stress and high negative potential, these conventional structural steels are susceptible to hydrogen embrittlement with ERF values of 10 not being uncommon.

2. A substantial body of information exists on the FCPRs rates in high strength steels, yield strength 400 - 600MPa. Data for high mean stress level $R > 0.5$ generally 0.6 - 0.8 has been assessed.

    (a) Relative 50D steels, in-air crack growth rates lie in the range 0.4 - 1.5. The bulk of the data lie below the mean air line for 50D, indicating reduced crack growth rates.

    (b) Under free corrosion ERF values are generally 3 - 5 for low ΔK values below $20MN/m^{3/2}$, increasing to approximately 2.5 for ΔK values around

30MN/m$^{3/2}$. This behaviour is in line with that observed for structural grade steel.

(c) The effects of CP are again pronounced at low ΔK, i.e. less than 15MN/m$^{3/2}$. Under applied CP of -850mV(SCE), ERF values of up to 4 occur in the ΔK range 10 - 15MN/m$^{3/2}$, increasing to the range 4 - 10 under the condition of overprotection at -1100mV(SCE).

(d) Threshold values observed in each environment are similar to those observed in-air and are of the order 4 - 7MN/m$^{3/2}$.

(e) The laboratory fatigue crack propagation behaviour of this group of steels is broadly comparable to that observed for the conventional structural grade steels.

3. EHS steels - on examination of the literature it was revealed that only limited data is available for this group of steels of yield strength 600 - 900MPa, particularly at low test frequency below 0.5Hz and under conditions of CP. At high mean stress values 0.6 - 0.8 the in-air data falls close to that observed for grade 50D steels. As observed for both Grade 50D steels and HS steels, the effect of CP is dominant at low ΔK levels 10 - 15MN/m$^{3/2}$, where fatigue crack growth rates can be increased by a factor of 6 - 14.

4. Under the range of applied cathodic potentials examined, ERF values are similar for each steel group. It highlights the combined detrimental effect of high mean stress and overprotection levels, -1100mV(SCE), where crack growth rates can be increased by a factor of 10 - 15 over that observed in-air.

5. A review of HAZ fatigue data for high strength steels in the yield strength range 500 - 600MPa, generated mainly at Cranfield, indicated that:

(a) In-air crack growth rates are in the range 1 - 2 times that observed for the parent material. Under conditions of free corrosion, crack growth rates at low ΔK <15MN/m$^{3/2}$ are roughly equal in both parent plate and HAZ, increasing to a factor of 2 times greater for the HAZ at higher ΔK levels 30MN/m$^{3/2}$. At CP potentials of -850mV(SCE), crack growth rates were approximately twice that for in-air at low ΔK 10 - 15MN/m$^{3/2}$, and approach the in-air behaviour as ΔK increased. At the high negative potential of -1100mV(SCE), significant acceleration in crack growth rates occurred, typically 5 - 7 times at low ΔK 10 - 15MN/m$^{3/2}$. It is important to appreciate that the HAZ fatigue performance is comparable to that observed for both the structural grade steels or the HS parent plate data.

(b) It is evident that welding under controlled conditions does not significantly affect FCPRs in these steels. A preliminary screening of the corrosion fatigue behaviour of the parent plate may therefore be also used to assess the suitability of the steels when welded.

6. Weld Metal - Despite an extensive search of the literature, only limited data were available for the FCPR behaviour of weld metals. The available data at low R ratio, R = 0 - 0.1, suggests comparable behaviour to that observed for structural grade 50D steel under similar conditions. A need exists to generate a more comprehensive data set at higher mean stress and under conditions of CP.

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TABLE I

Chemical composition and mechanical properties of 350MPa structural steels

Old - BS4360: 50D(27) New - EEMUA 150 Grade 355 EM/EMZ(28)

	BS4360: 50D		355 EMZ		
	Specification (27)	Actual Normalised (2)	Specification (28)	Actual (2)	
				Normal	TMCP
C%	0.18max	0.17	0.15	0.12	0.06
Si%	0.1-0.5	0.35	0.25-0.55	0.34	0.19
Mn%	1.5max	1.35	1-1.65	1.49	1.52
Ni%	-	-	0.45	0.36	0.39
Cr%	-	-	0.25	-	0.03
Mo%	-	-	0.08	-	-
V%	0.10max	0.01	0.015	-	-
Nb%	0.10max	0.03	0.040	0.023	0.009
Cu%	-	-	0.30	0.22	0.22
Ti%	-	-	0.01	-	0.016
Al%	-	-	0.055	0.028	0.023
N%	-	-	0.010	-	-
P%	0.04	0.037	0.025	0.009	0.006
S%	0.04	0.023	0.008	0.001	0.003
YP(MPa)	345 min	370	340	356	374
UTS(MPa)	450-620	538	460-620	496	473
Elong(%)	18 min	32	20	34	35
CVN(J)	41 @ -20°C 27 @ -30°C	119 @ -30°C	50 @ -40°C	196 @ -30°C	300 @ -30°C

TABLE II
Corrosion fatigue crack growth data for high strength steels, yield strength range 400 - 600MPa. Composition, mechanical properties and test conditions

Investigators	Material	Process^{*1}	Composition (weight %)	Mechanical Properties Yield Strength (YP) UTS (MPa)	Test Type^{*2}	Conditions^{*3}	Ref
Tubby et al 1992	SAR60	Q & T	0.12C; 0.24Si; 1.07Mn; 0.007S; 0.015P; 0.18Cr; 0.14Mo; 0.03V; 0.017Ti; 0.034Al	YP 480MPa UTS 590 CVN = 190J @ -30°C	R=0.7; f=0.167Hz SENB, t = 19mm	Air free, CP -850mV(SCE) CP -1100mV(SCE)	29
Todd et al 1993/1992	MILS S 24645	Q & T	0.03C; 0.50Mn; 0.010P; 0.002S; 1.17Cu; 0.35Si; 1.0Ni; 0.72Cr; 0.20Mo; 0.018Al; 0.032Nb	YP 560, UTS 590 CVN = 200J @ 30°C	R=0.1; f=0.1Hz CT, t = 12.5mm	Air free CP-850mV CP-1100mV	30 - 32
Nippon 1986	A710	Q & T	0.04C; 0.30Si; 0.45Mn; 0.004P; 0.002S; 1.14Cu	YP 570, UTS 630	R = 0.7 f = 0.167Hz SENB	Air	33
	HITEN 62	Q & T	0.08C; 0.23Si; 1.4Mn; 0.010P; 0.002S	YP 550, UTS 625			
Cigada et al 1985	X65	CR	0.07C; 1.57Mn; 0.28Si; 0.007P; 0.001S; 0.027Al; 0.05Nb; 0.12Cu; 0.22Cr	YP 500, UTS 580	R=0.6 f=0.2Hz(SW) SENB, t = 17mm	Air free CP -900mV	34
Cranfield	55F	Q & T	0.12C; 0.35Si; 1.18Mn; 0.004S; 0.02P; 0.14Mo; 0.04Al; 0.05V	YP 580	R = 0.6 f = 0.5Hz SENB, t = 18mm	Air free CP -850mV CP-1100mV	35 36
	X80	CR	0.08C; 0.43Si; 1.7Mn; 0.003S; 0.017P; 0.04Nb; 0.02V; 0.05Al	YP 550			
	SE500	Q & T	0.08C; 1.35Mn; 0.35Si; 0.001S; 0.007P; 0.35Cr; 0.18Mo; 0.35Ni; 0.20Cu; 0.06V; 0.02Al	YP 560, UTS 655			
UMIST 1986	X70	CR	0.04C, 0.32Si; 1.71Mn; 0.005S; 0.008P; 0.12Ni; 0.05Cr; 0.30Cu; 0.05Nb; 0.016Ti; 0.03Al; 0.09V	YP 450, UTS 560	R = 0.15 or 0.5 f = 0.1Hz CT, t = 12.5mm	Air free CP-850mV	37
	RQT501	Q & T	0.13C; 0.32Si; 1.25Mn, 0.005S; 0.016P, 0.17Mo; 0.04Ni, 0.057V	YP 600, UTS 700			

TABLE II (cont)

Corrosion fatigue crack growth data for high strength steels, yield strength range 400 - 600MPa. Composition, mechanical properties and test conditions

Investigators	Material	Process[*1]	Composition (weight %)	Mechanical Properties Yield Strength (YP) UTS (MPa)	Test Type[*2]	Conditions[*3]	Ref
Vosikosky	X70	CR	0.06C; 1.90Mn; 0.28Si; 0.009P; 0.002S; 0.25Ni; 0.39Mo; 0.058Nb; 0.073Al	YP 530, UTS 670	SENB Pin loaded R = 0.7 f =0.1Hz	Air, free	38 - 41
Yang et al 1993/94 Kim - Hartt 1992/93	A537	Direct quenched	0.12C; 0.41Si; 1.30Mn; 0.014P; 0.003S; 0.044V	YP 500, UTS 590	Tapered CT or SENB R = 0.5-0.8 f = 0.3Hz t = 5mm	Air, free CP -800mV CP -1100mV	42 - 45
	QT80	Microalloy Q & T	0.08C; 0.23Si; 1.4Mn; 0.01P; 0.002S; 0.43Ni; 0.1Cr; 0.06Mo; 0.04V; 0.05Al	YP 537, UTS 631			
	AC70	AC	0.09C; 0.30Si; 1.5Mn; 0.007P; 0.003S; 0.18Cu; 0.40Ni; 0.016Nb	YP 503, UTS 618			
	EH36	CR	0.13C; 0.37Si; 1.42Mn; 0.018P; 0.002S; 0.025Nb; 0.046Al	YP 380			
Yu et al	CSM355	TMCP	0.05C; 1.44Mn; 0.29Si; 0.010P; <0.001S; 0.30Ni; 0.02Nb; 0.039Al	YP 410, UTS 510 CVN = 300J @ 20°C	R = 0.7 f = 0.35Hz CT t = 5mm	Free CP -850mV CP -1100mV	46

Notes:

*1 CR = Controlled Rolled; Q & T = Quenched & Tempered; AC = Accelerated Cooled

*2 Specimen type: CT = Compact Tension; SENB = Single End Notch Bend; t - Thickness

*3 Environment: Artificial seawater conforming to ASTM D1141 or BSI equivalent BS3900 (Cranfield, UMIST) except Yang et al, Kim and Hartt who utilised seawater and Vosikovsky who utilised 3.5%NaCl solution

TABLE III
Corrosion fatigue crack growth data for extra high strength steels, yield strength range 700 - 900MPa
Composition, mechanical properties and test conditions

Material	Composition (weight %)	Mechanical Properties (MPa)	Conditions	Test Type	Ref
HT80	0.11C; 0.24Si; 0.84Mn; 0.007P; 0.002S; 0.17Cu; 1.02Ni; 0.49Cr; 0.41Mo; 0.03V; 0 0009B	YP 760, UTS 810 Elong 24%	Air, free CP -850mV(SCE)	R = 0.1	52, 53
Hiten80B	0.12C; 0.24Si, 0.94Mn; 0.012P; 0.004S; 0.82Ni; 0.67Cr; 0.18Mo; 0.037Nb; 0.004V; 0.0001B	YP 860, UTS 920 Elong 33%	Air, free CP -850mV	R = 0	33
HT80	0.11C; 0.19Si; 1.01Mn; 0.003P; 0.002S; 0.77Ni; o.68Cr; 0.44Mo; 0.24Cu	YP 813, UTS 852 Elong 32%	Air, free	R = 0.05 f = 0.16Hz	54 - 56
			Air CP -1000mV	R = 0.8 f = 0.16Hz	
HT80	0.12C; 0.19Si; 1.01Mn; 0.003P; 0.002S; 0.77Ni; 0.68Cr; 0.44Mo; 0.24Cu	YP 784, UTS 843	CP -1000mV	R = 0.6 f = 0.3Hz	56
HY100	0.16C; 0.24Mn; 0.11Si; 0.007S; 0.008P; 1.41Cr; 2.94Ni; 0.34Mo; 0.13Cu; 0.02V; 0.007Al	YP 810, UTS 985 Elong 15%	Free CP -850mV	R = 0.6 f = 0.3Hz	57
HY 130*1	0.09C; 0.26Si; 0.60Mn; 0.009P; 0.007S; 5%Ni; 0.48Cr; 0.47Mo; 0.08V; 0.05Cu; 0.05Al	YP 993, UTS 1034 Elong 22%	Air CP -1030mV	R = 0.05	39, 41, 58
			Air CP -1030mV	R = 0.7 f = 0.1Hz	

Note: Environment - all tests carried out in artificial seawater solution conforming to ASTM D1141, except *1 which was 3.5% NaCl solution

TABLE IV
Corrosion fatigue crack growth data for structural steels Grade BS4360: 50D - nominal yield strength 350MPa

Investigators (Year)	Test Type*1	Environment	Test Condition	Ref
Scott & Silvester UKOSRP 3/03 (1975)	CT t=25.4mm R=0.1 f=0.1Hz	Natural Seawater	Air, free, CP -800mV(SCE) CP -1000mV	5, 7, 8, 24
Scott & Silvester UKOSRP 3/02 (1977)	CT t=38mm R=0.1-0.85 f=0.1Hz	Natural Seawater	Air, free CP -850mV CP -1100mV	6, 7
Booth et al (1984)	SENB t=20mm $0<R\leq 0.1$ f=0.167Hz	Artifical Seawater ASTM D1141	Air, free	22, 23
BSC (1981)	CT t=25mm R=0.1, 0.7 f=0.125Hz	Artificial Seawater BS 3900	Air, free	25
Kermani (1993)	CT t=12.5mm R=0, f=0.1Hz	3.5% NaCl Solution	Air, free CP -850mV CP -1100mV	26

Notes: *1 CT = Compact Tension; SENB = Single End Notch Bend Specimen; t = Thickness

TABLE V
Environmental reduction factors (ERF) for BS4360: 50D

R, f	Conditions	Threshold ΔK (MN/m$^{3/2}$)	ERF value forΔK (MN/m$^{3/2}$)				
			10	15	20	25	30
Air R=0.1 & 0.7	Air	6 - 9	-	-	-	-	-
R = 0.1	Free Corrosion	4 - 10	0.7 0.5 - 0.8	1.2 0.7 - 1.7	2 0.8 - 3.3	1.7 1 - 2.5	1.8 1.3 2.5
f = 0.167Hz	-850mV(SCE)	10 - 15	-	-	1.2 1 - 1.4	2.6 1 - 4.2	1.6 1 - 2.3
wrt Mean air (5)	-1100mV	15 - 18	-	-	4	2.7 2.1 - 3.3	2.1 1.7 - 2.6
R = 0.7	Free Corrosion	6 - 8	5.9 3.8 - 8	5 4 - 6	6.6 5 - 8.3	4.7 - 6.7	-
f = 0.1Hz	-850mV	5 - 8	5	8.3	4.1	5	-
wrt Mean air (6)	-1100mV	5 - 6	10	15	5.4	5	-

TABLE VI

ERF values for high strength steels 400 - 600MPa, R = 0.6 - 0.8.
[NOTE: ERF values defined wrt BS4360: 50D mean air line R = 0.7]
Values given indicate: { min → max }
{ Trend }

Condition	Stress Intensity Range ΔK (MN/m$^{3/2}$)					No. of steels & conditions
	10	15	20	25	30	
Air	0.5 - 1.3 (<1)	0.4 - 1.3 (<1)	0.6 - 1.7 (<1)	0.6 - 1.4 (≈1)	0.7 - 2 (≈1)	R = 0.6 - 0.7 12 steels
Free Corrosion	0.5 - 1.5 -	0.7 - 5 (0.5 - 2)	0.7 - 4.3 (0.7 - 3)	0.8 - 3.6 (1 - 2)	-	R = 0.5 - 0.7 12 steels
CP -850mV (SCE)	3.8 -	0.7 - 3 (≈1)	0.6 - 2.7 (≈1)	≈1	-	R = 0.6 - 0.8 CP -800 to -850mV 10 steels
CP -1100mV	3.8 -	3.3 - 10 (10)	2.1 - 5.7 (5.7)	1 - 2.7	-	R = 0.6 - 0.8 CP -1000 to -1100mV 9 steels

TABLE VII

Threshold Values (ΔK_{th}) for high strength steel (f = 0.1 - 0.35Hz)

Material/Ref	Test Conditions	Air	Free Corrosion	-800mV (SCE)	-850mV	-950mV	-1000mV	-1100mV	Ref.
50D	R = 0.1 R = 0.7	6 - 9 6 - 9	4 - 10 6 - 8	-	10 - 15	-	-	15 - 18 5 - 6	5 - 7
CSM 355 YP = 410MPa	R = 0.1 R = 0.7	- -	8 8	-	10 7.5	-	14 6.5	-	46
4 steels≈500MPa	R = 0.1	7.0	9	-	-	-	-	16	30 - 32
4 steels≈500MPa	R = 0.5 R = 0.8	5 - 7 4 - 6	6 - 8 3.8 - 4.8	10 - 12 8 - 9	-	12.2 - 15 9.5 - 11	-	15 - 17 11 - 13.5	42 - 45

TABLE VIII

ERF values for EHS steels [NOTE: ERF values defined wrt BS4360: 50D mean-air line R = 0.7]

Material	R	f(Hz)	Potential (mV(SCE))	ΔK MN/m$^{3/2}$				Ref
				10	15	20	25	
HY100	0.6	0.3	Free/-850	1 - 1.5	N/A	N/A	1.5 - 2	57
HT80	0.6	0.3	-1100	4.5	9	10	N/A	56
HT80	0.8	0.16	-1100	6.3	13.1	5.7	N/A	54, 55
HY130	0.7	0.1	-1030	6.3	11.7	7.1	4	58

TABLE IX

Comparison of ERF values for each steel group as a function of stress intensity range ΔK and environment.

Test conditions f = 0.1 - 0.5Hz, R = 0.6 - 0.8

ERF values defined wrt BS4360:50D mean-air line, R = 0.7

Material	R/f	Potential (mV(SCE))	ΔK 10-15MN/m$^{3/2}$	ΔK 20-30MN/m$^{3/2}$
50D Structural Steels Nominal YP ≈350MPa	0.7/0.1Hz	Free	4 - 6	5 - 7
		-850	5 - 8	≈5
		-1100	10 - 15	≈5
HS steels Nominal YP 400 - 600MPa	0.6 - 0.8/ 0.1 - 0.5Hz	Free	1 - 5	1 - 4
		-850	1 - 4	1 - 3
		-1100	4 - 10	1 - 3
EHS steels Nominal YP 600 - 990MPa	0.6 - 0.8/ 0.1 - 0.3Hz	-1030 to -1100	5 - 13	4 - 6

Table X

Fatigue crack propagation studies carried out at Cranfield on both unwelded and welded high strength steels[12-14,28,34,38-41]

Steel designation	Manufacturer	Production route	Chemical Composition (Weight %)													Mechanical Properties	
			C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Nb	V	Al	Ti	YP (MPa)	2CVN J@ -40°C
50E	BSC	Normalised	0.14	1.48	0.32	0.010	0.013	0.07	0.11	0.02	0.20	-	0.01	0.03	-	393	195
X80	Mannesman	CR	0.08	1.7	0.43	0.005	0.017	0.04	0.05	0.04	0.06	0.035	-	0.05	-	550	230
RQT501	BSC	Q & T	0.12	1.33	0.23	0.005	0.012	0.03	0.01	0.10	0.03	<0.01	0.044	0.04	-	560	200
	BSC	Q & T	0.11	1.32	0.30	0.004	0.02	0.03	0.02	0.12	-	-	0.045	0.037	-	580	164
SE500	Creusot Loire	Q & T	0.09	1.13	0.31	0.001	0.008	0.48	0.18	0.24	0.30	<0.01	0.05	0.02	0.005	564	214
FG47	Thyssen	Normalised & tempered	0.13	1.52	0.49	0.005	0.015	0.72	0.06	0.04	0.25	0.03	0.02	0.02	0.02	498	170 @ 20°C
55FMZ	Svenskt Steel	Q & T	0.09	1.29	0.30	0.001	0.012	0.25	0.01	0.07	0.08	-	0.04	0.04	0.011	505	267
HSLA80	Lukens	Q & T	0.06	0.60	0.31	0.003	0.012	0.87	0.75	-	1.15	0.036	-	0.024	0.004	640	136 @ 50°C
XABO 500	Thyssen	Q & T	0.10	1.44	0.4	0.002	0.008	0.51	-	-	-	-	-	-	-	574	230 @ 60°C
HS420	Fab. de Fer	Q & T	0.11	1.3	0.41	0.001	0.011	0.55	0.13	0.04	0.19	0.025	-	0.04	0.004	479	252
450EMZ	BSC	Q & T	0.08	1.23	0.29	0.001	0.011	0.50	0.02	0.17	0.02	-	0.046	0.028	0.004	460	300
Q1N	BSC	Q & T	0.16	0.30	0.27	0.010	0.010	2.83	1.37	0.38	0.12	0.011	-	0.035	-	610	205 @ -84°C

Table X (cont.)
Fatigue crack propagation studies carried out at Cranfield on both unwelded and welded high strength steels[illegible]

Steel designation	Manufacturer	Production route	Chemical Composition (Weight %)													Mechanical Properties	
			C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Nb	V	Al	Ti	YP (MPa)	2CVN J@ -40°C
NAXTRA 70	Thyssen	Q & T	0.15	1.01	0.62	0.007	0.017	0.09	0.78	0.38	0.06	0.05	0.01	0.04	<0.02	690	>30
DSE690	Dillinger	Q & T	0.15	0.90	0.33	0.001	0.009	1.28	0.49	0.45	0.2	-	0.03	0.073	-	690	140
TiO steel	Nippon	AC	0.08	1.5	0.17	0.002	0.004	0.24	-	-	0.22	0.013	-	0.003	0.014	460	150
OLAC 50D	NKK	AC	0.12	1.35	0.30	0.004	0.013	0.03	-	-	0.01	-	-	-	-	398	311 @ -20°C
HIWEL 50D	NKK	AC	0.11	1.44	0.34	0.003	0.010	0.03	-	-	0.01	-	-	-	-	404	392 @ -20°C
50E CLC	Nippon	AC	0.07	1.30	0.14	0.001	0.004	0.38	0.02	-	0.12	0.06	-	-	0.01	411	344
KCL	Kobe	AC	0.04	1.52	0.22	0.003	0.005	0.49	0.02	0.01	0.60	-	-	-	-	460	-
HIWEL 55F	NKK	AC	0.07	1.59	0.34	0.001	0.010	0.45	-	-	0.26	0.01	-	-	-	506	375
Histar 460	Arbed	AC 'I' Beam	0.10	1.45	0.29	0.002	0.010	0.07	0.03	0.02	0.08	0.027	-	0.037	0.004	460	150
CSN3	BSC	Cast	0.14	1.3	0.26	0.005	0.010	0.43	0.09	0.11	-	0.025	0.005	0.024	-	>320	80
OS540	Lokomo	Cast	0.09	0.49	0.24	0.001	0.008	2.55	1.22	0.48	0.10	<0.01	<0.01	0.031	<0.01	570	175
OS690	Lokomo	Cast	0.09	0.42	0.19	0.001	0.008	4.30	0.90	0.61	0.10	<0.01	<0.01	0.038	<0.01	695	150

Note: CR = Controlled Rolled; Q & T = Quenched & Tempered; AC = Accelerated Cooled; Cast = Cast steel

TABLE XI
Comparison between FCP behaviour of high strength steel and HAZ tested in-air.
Plate yield strength 500 - 580MPa, HAZ welded at 3kJ/mm, R = 0.6, f = 0.5

Comparison	**Stress Intensity Range - ΔK (MN/m$^{3/2}$)**			
	Lowest ΔK	**15**	**20**	**30**
HS steels versus 50D	13	0.5 - 1.1	0.5 - 1.0	0.5 - 0.9
HAZ wrt 50D mean	N/A	0.8 - 2.0	0.7 - 1.2	0.7 - 1.0
HAZ wrt HSS mean	N/A	1 - 2	0.9 - 1.6	1.1 - 1.3

TABLE XII
ERF values for HAZ of high strength steels

Environment	**Material**	**Stress Intensity Range - ΔK (MN/m$^{3/2}$)**		
		12	**15**	**25**
Free Corrosion	50D	-	0.5 - 0.9	0.4 - 1.9
	HSS	-	0.8 - 1.3	0.6 - 2.8
CP -850 mV(SCE)	50D	0.4 - 1.7	0.7 - 1.8	0.4 - 0.9
	HSS	0.5 - 2.1	0.9 - 2.5	0.6 - 1.3
CP -1100 mV(SCE)	50D	? - 5.6	0.9 - 5.8	1.3 - 2
	HSS	? - 7.1	1.3 - 7.9	2 - 3

TABLE XIII
Typical composition and mechanical properties of high strength weld metals

Three steels of nominal yield strengths 450, 550 and 700MPa. Suggested materials typical of modern commercially available steels include 450EMZ, RQT501 and WX700.

Steel Grade	Typical Composition (Weight%)						Mechanical Properties		
	C	Si	Mn	Ni	Cr	Mo	Yield strength (MPa)	UTS (MPa)	CVN J @ -40°C
450	0.08	0.1	1.0	1.5	-	0.25	510	580	140
550	0.08	0.1	1.5	1.5	-	0.45	550	620	100
700	0.09	0.2	1.5	2.16	0.32	0.6	700	780	60

Welding procedures:

- SAW process at 2 heat inputs - nominally, 1 and 3.5kJ/mm
- Preheat/interpass temperatures 120/150°C
- Weld preparation, double vee, fully restrained

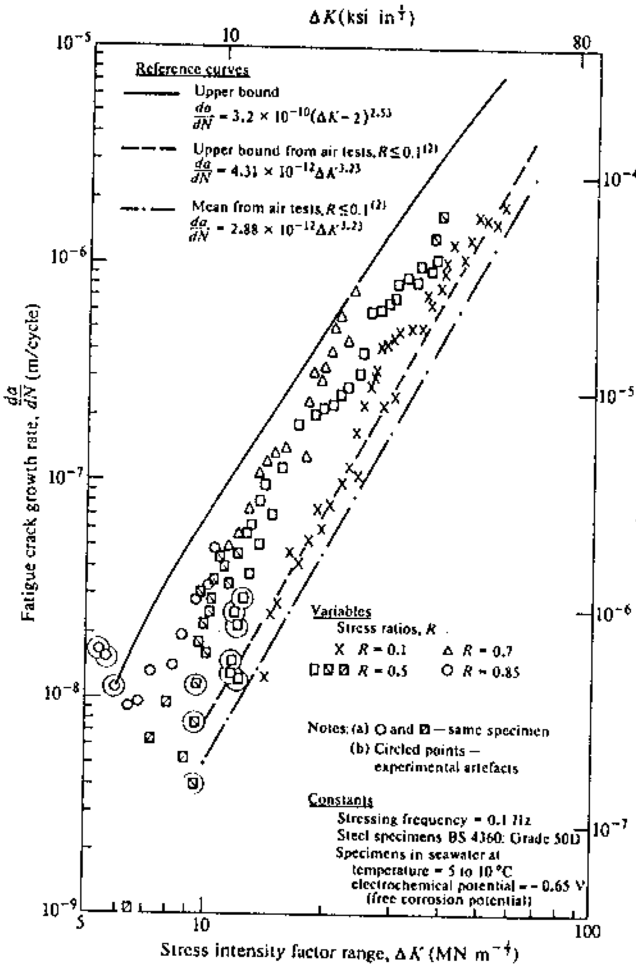


Figure 1a

Effect of R ratio on fatigue crack growth rate BS4360: 50D tested in seawater, f = 0.1Hz, free corrosion potential(6,7)

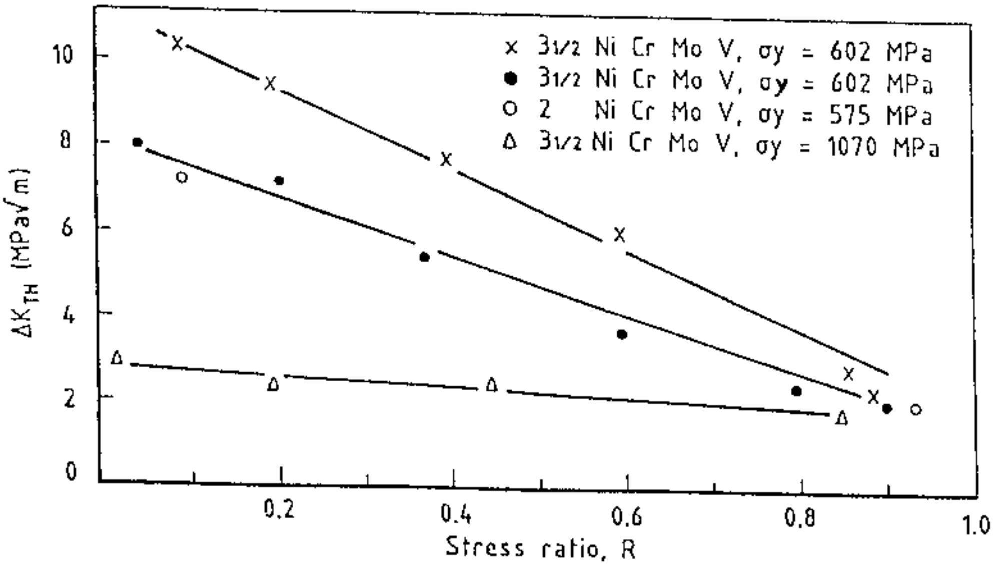


Figure 1b

The influence of stress ratio and yield stress on ΔK_{th} for low alloy high strength steels in-air(59)

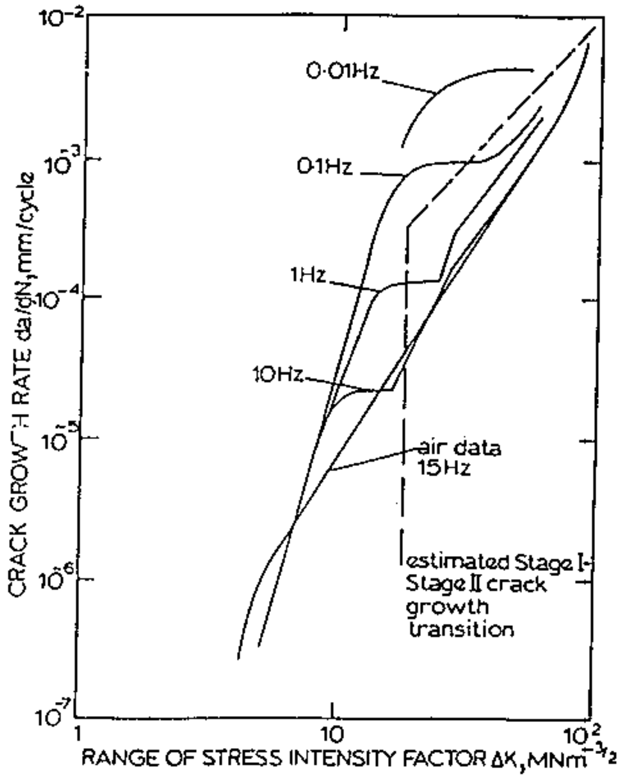


Figure 2

Effect of cyclic frequency on corrosion fatigue crack growth for a C-Mn pipeline steel (yield strength 460MPa) tested in 3.5% NaCl solution, R = 0.2[59]

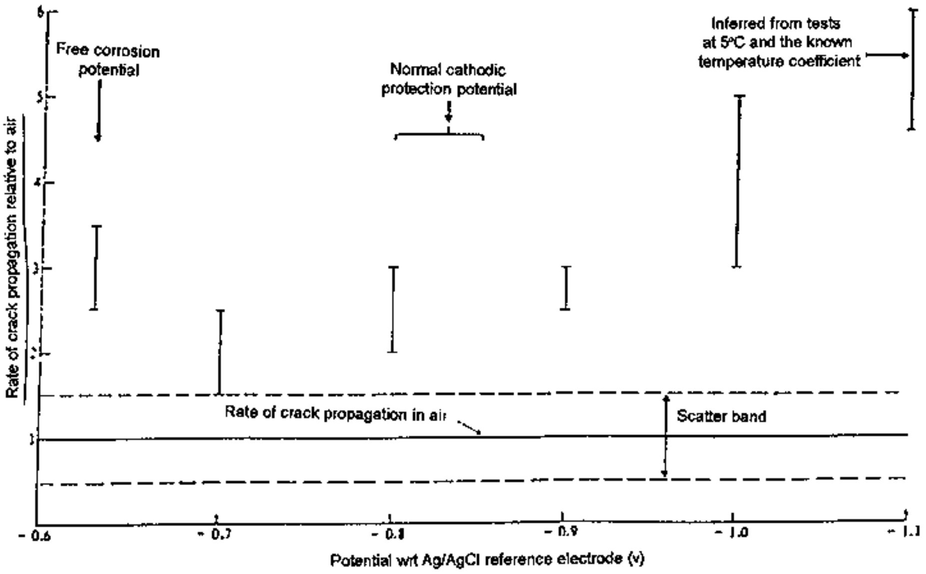


Figure 3

Relative fatigue crack propagation rates for BS4360: 50D tested at 0.1Hz in seawater, R ≤ 0.1, ΔK 20 - 40MN/m^3/2 (5)

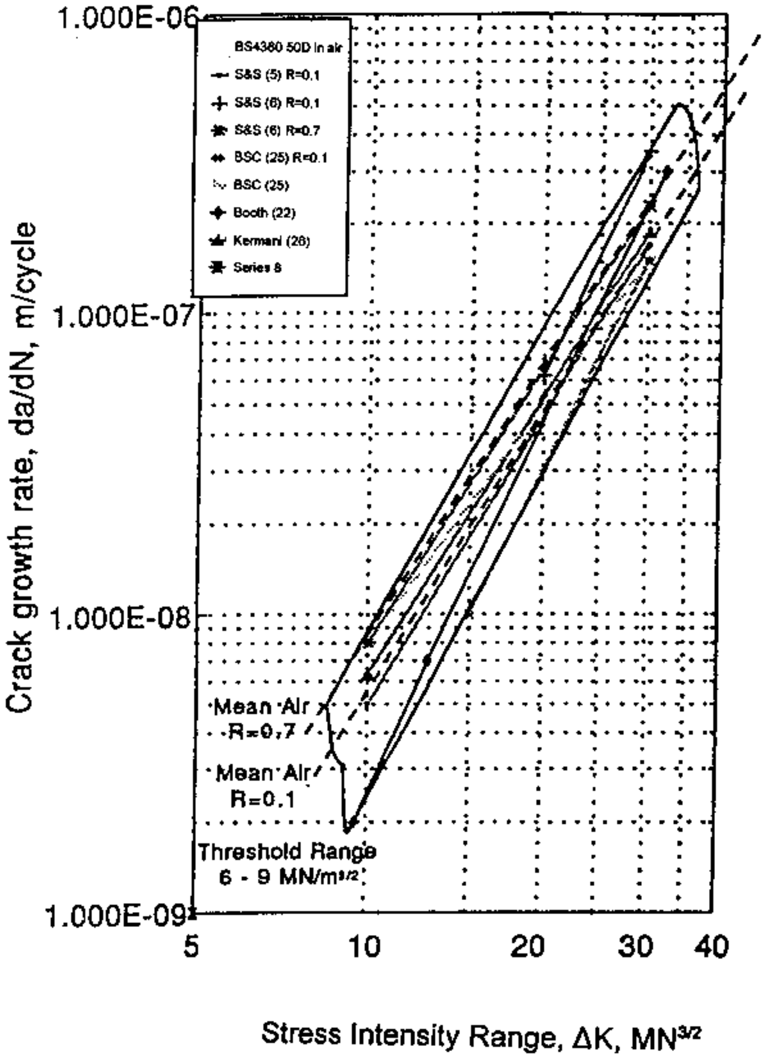


Figure 4
Fatigue crack propagation behaviour of structural steels
Grade BS4360: 50D - nominal yield strength 350MPa(5-8, 22-26)
(a) In-air data f = 1 - 10Hz, R = ≤0.1 and R = 0.7

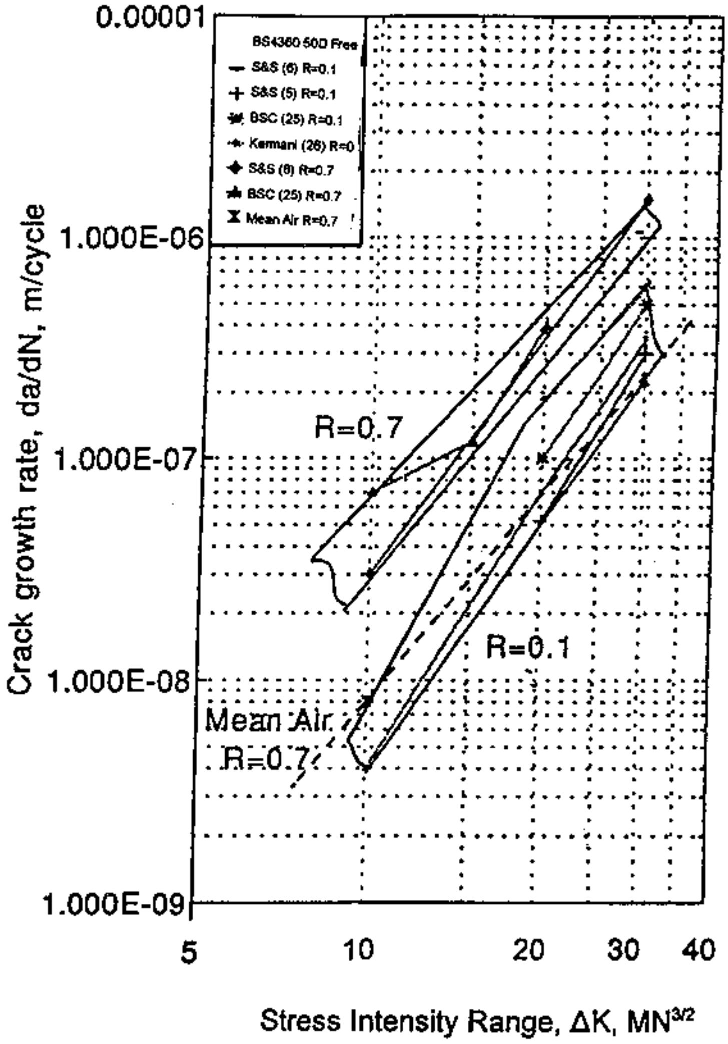


Figure 4
Fatigue crack propagation behaviour of structural steels
Grade BS4360: 50D - nominal yield strength 350MPa(5-8, 22-28)
(b) Free corrosion potential f = 0.1Hz, R = 0 - 0.1 and R = 0.7

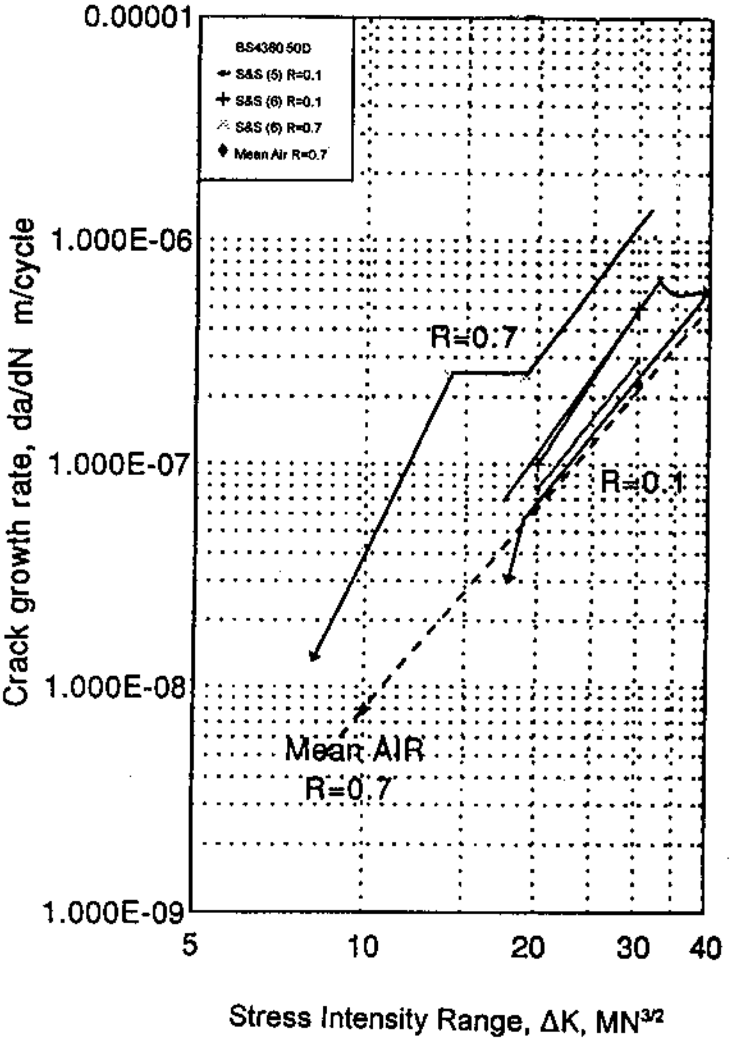


Figure 4
Fatigue crack propagation behaviour of structural steels
Grade BS4360: 50D - nominal yield strength 350MPa(5-6, 22-26)
(c) Cathodic protection CP = -800 to -850mV, f = 0.1Hz, R = 0 - 0.1 and R = 0.7

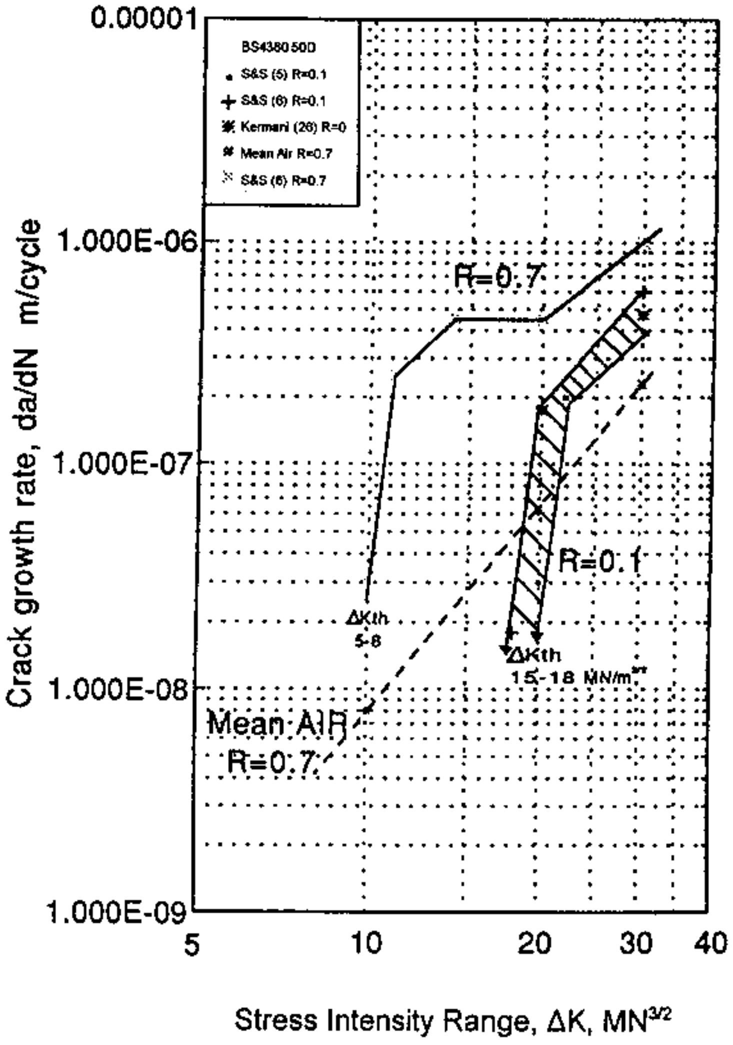


Figure 4
Fatigue crack propagation behaviour of structural steels
Grade BS4360: 50D - nominal yield strength 350MPa(5-8, 22-26)
(d) Overprotection CP = -1000 to -1100mV, f = 0.1Hz, R = 0 - 0.1 and R = 0.7

Figure 5(a) 50D, R=0.1

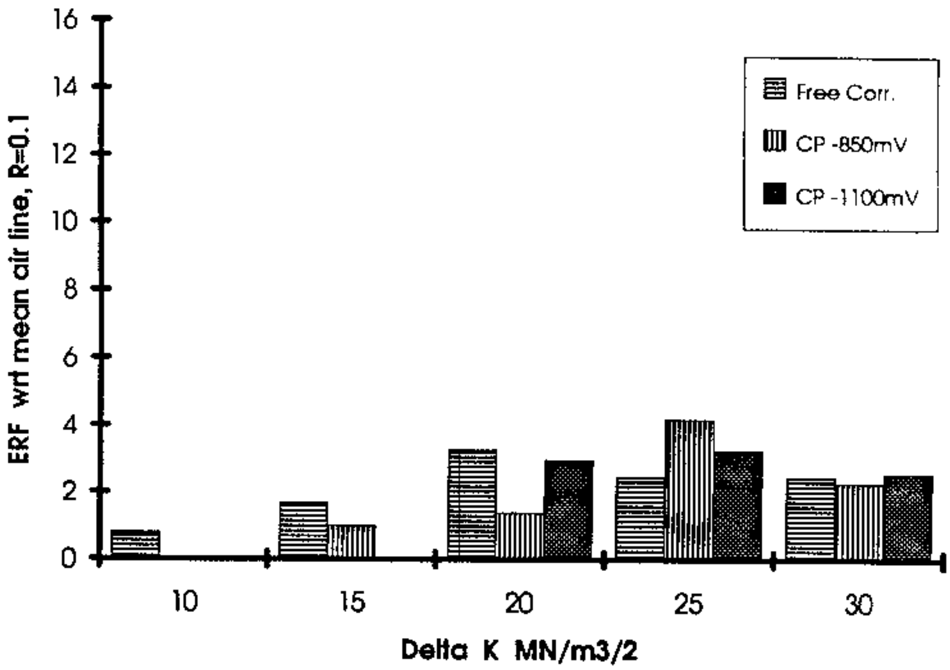


Figure 5(b) 50D, R=0.7

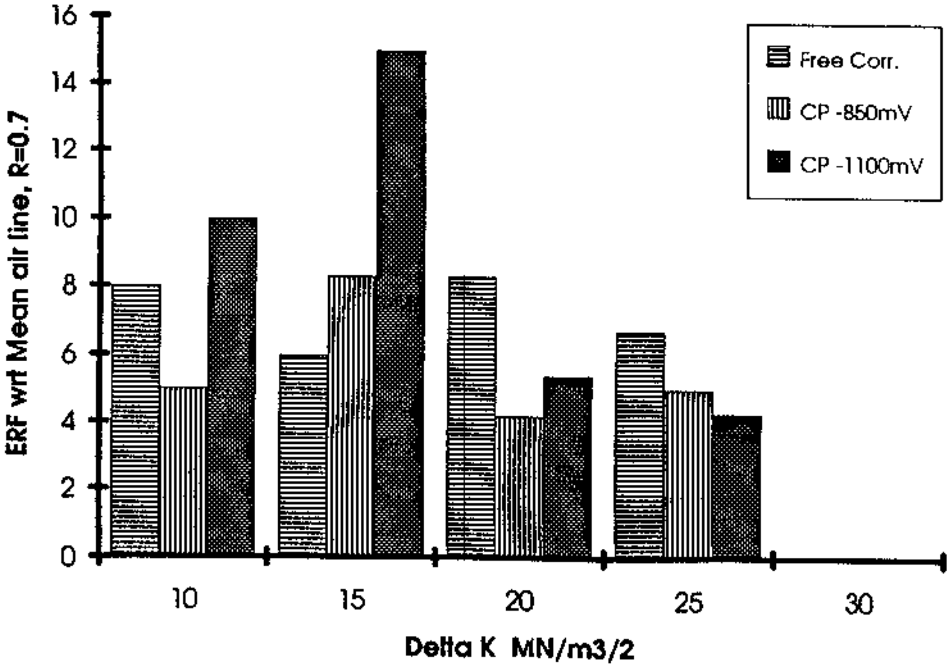


Figure 5
ERF values for BS4360: 50D as a function of stress intensity (ΔK) and applied potential, (a) $R = 0.1$, (b) $R = 0.7$

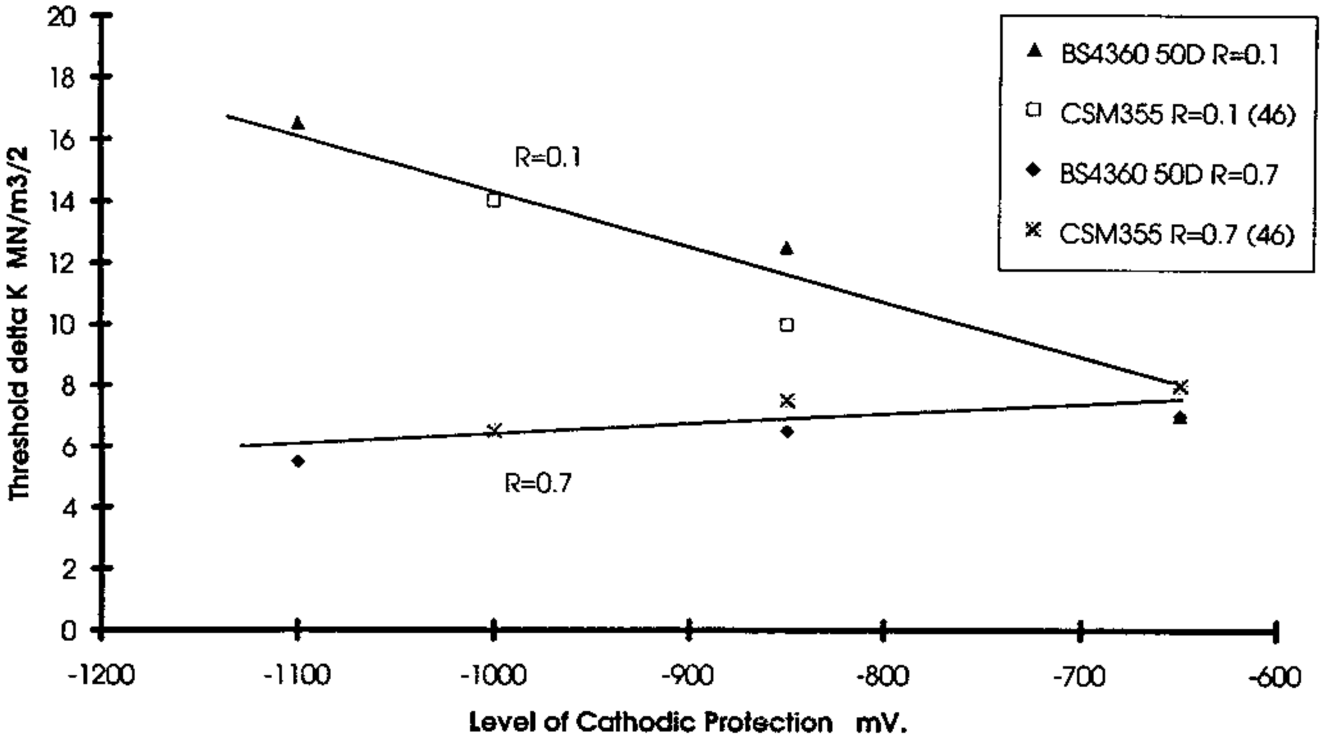


Figure 6

Effect of applied potential and R ratio on measured threshold value ΔK_{th}

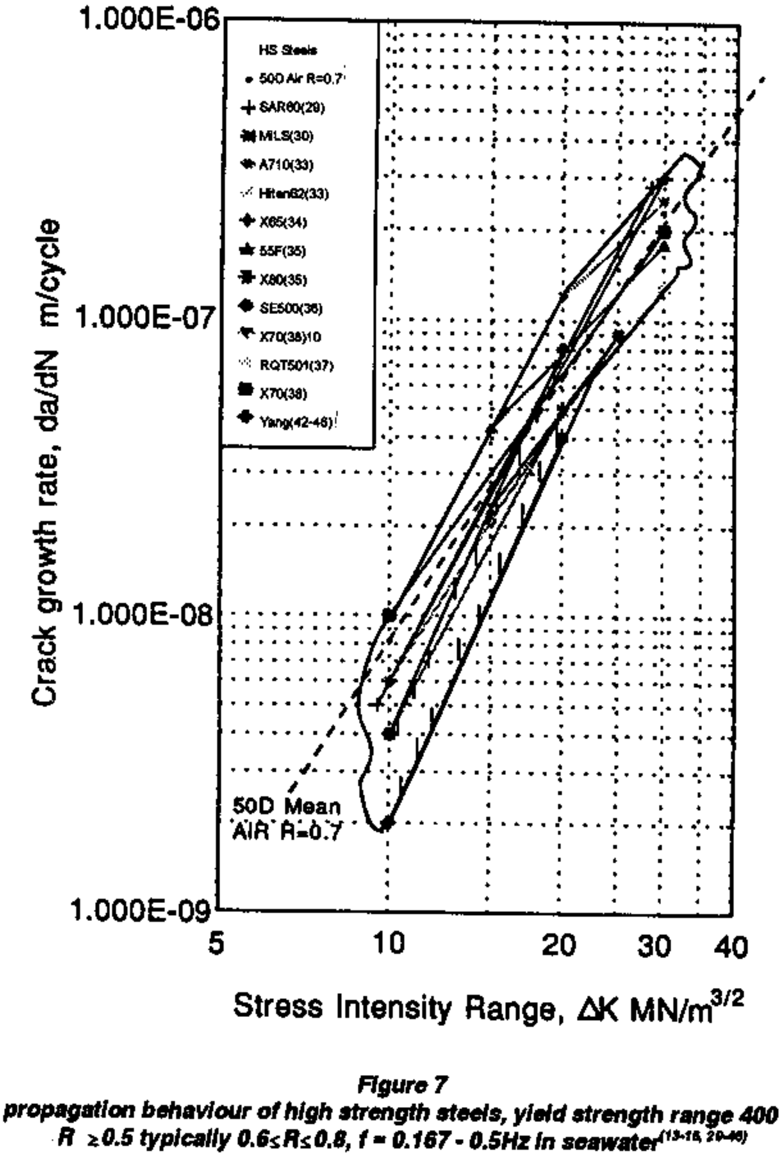


Figure 7
Fatigue propagation behaviour of high strength steels, yield strength range 400 - 600MPa, $R \geq 0.5$ typically $0.6 \leq R \leq 0.8$, $f = 0.167 - 0.5$Hz in seawater(13-15, 20-46)
(a) In-air data

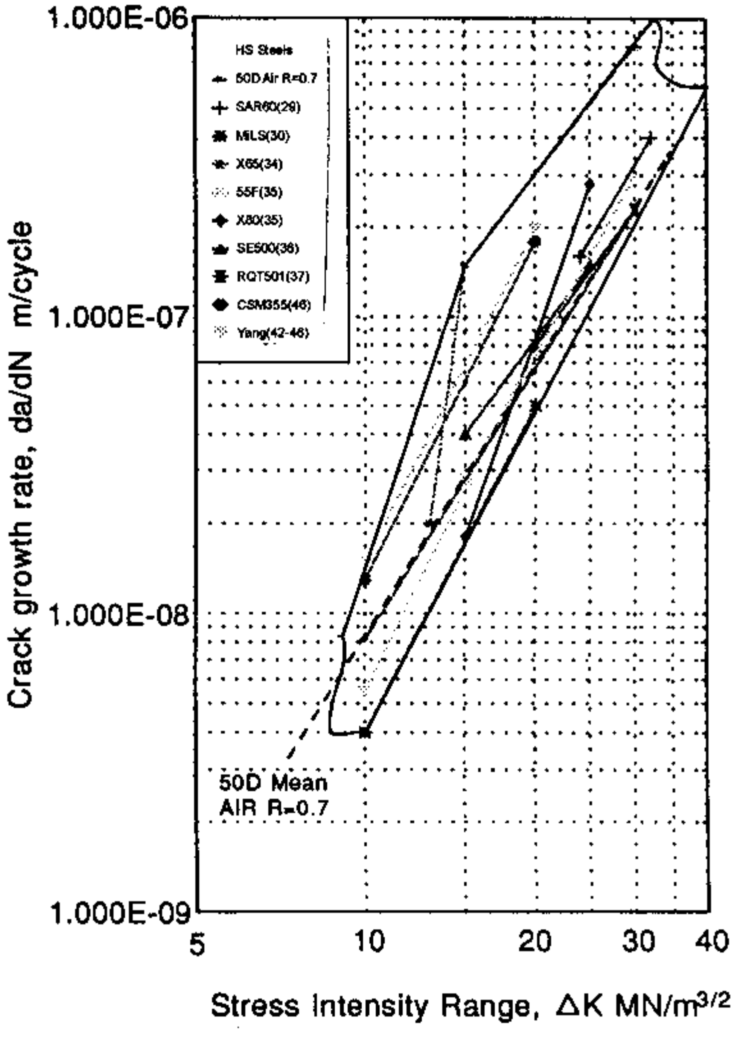


Figure 7
Fatigue propagation behaviour of high strength steels, yield strength range 400 - 600MPa, $R \geq 0.5$ typically $0.6 \leq R \leq 0.8$, $f = 0.167 - 0.5$Hz in seawater(13-16, 20-46)
(b) Free corrosion potential

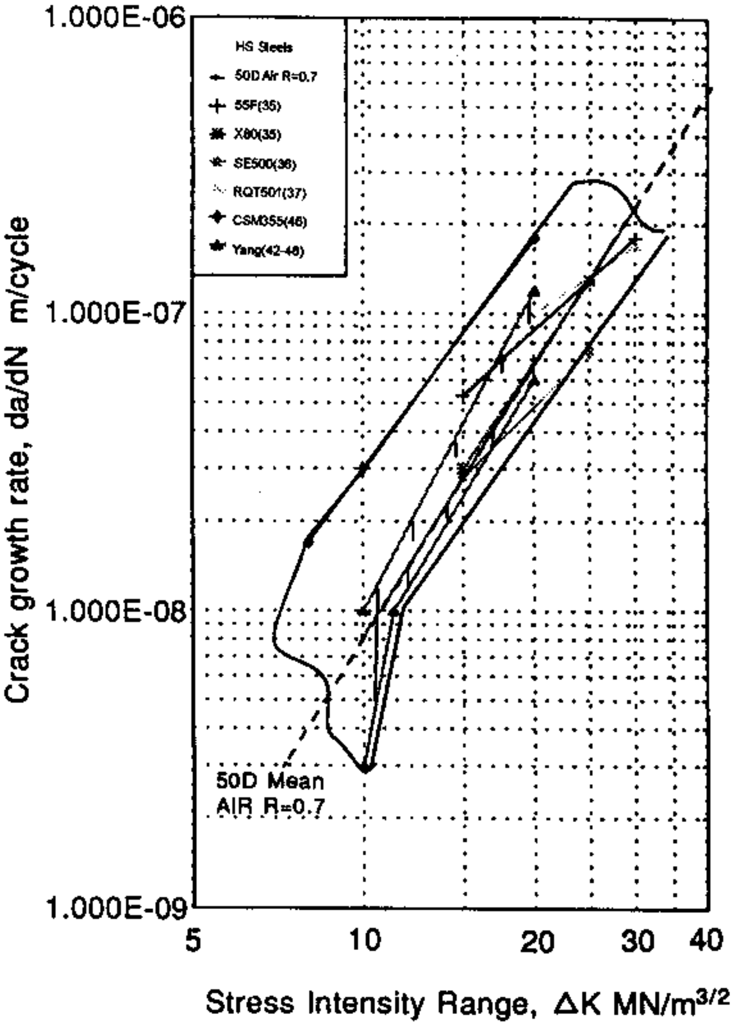


Figure 7
Fatigue propagation behaviour of high strength steels, yield strength range 400 - 600MPa, $R \geq 0.5$ typically $0.6 \leq R \leq 0.8$, $f = 0.167 - 0.5$Hz in seawater(13-16, 29-46)
(c) Cathodic protection CP -800 to -850mV

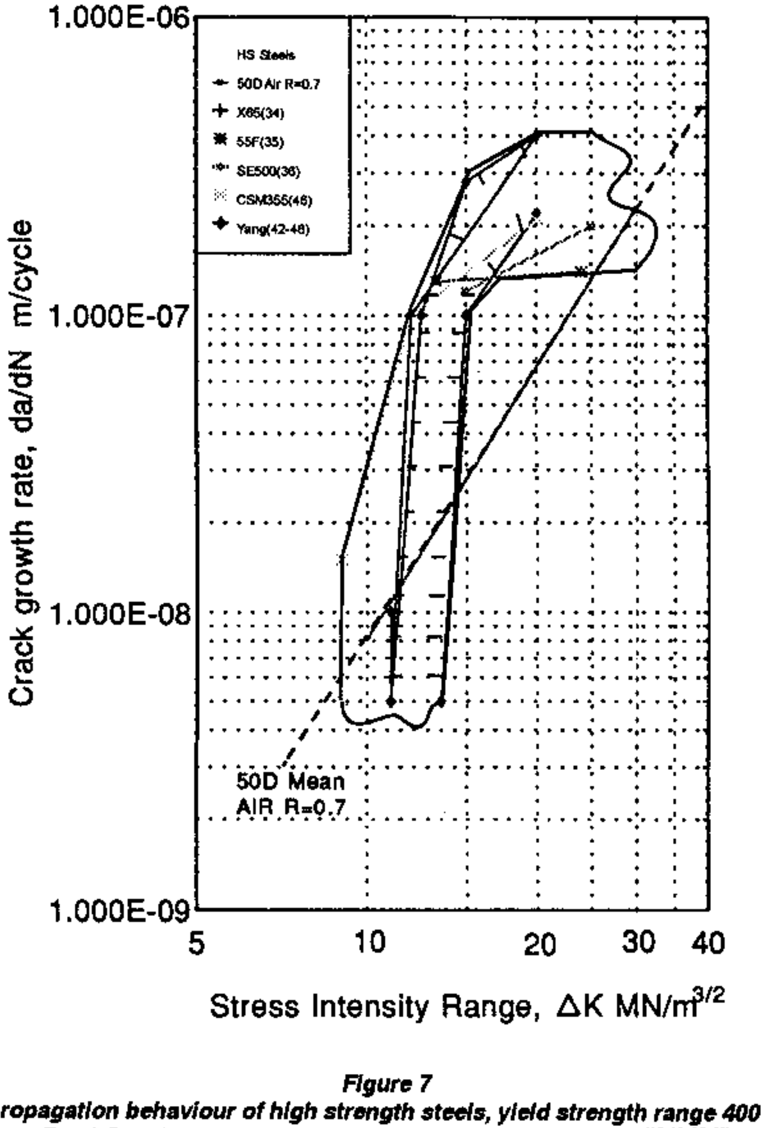


Figure 7
Fatigue propagation behaviour of high strength steels, yield strength range 400 - 600MPa, $R \geq 0.5$ typically $0.6 \leq R \leq 0.8$, $f = 0.167 - 0.5$Hz in seawater(13-16, 29-46)
(d) Overprotection CP -1000 to -1100mV

Fig 8(a) In Air.

Fig 8(b)Free Corrosion.

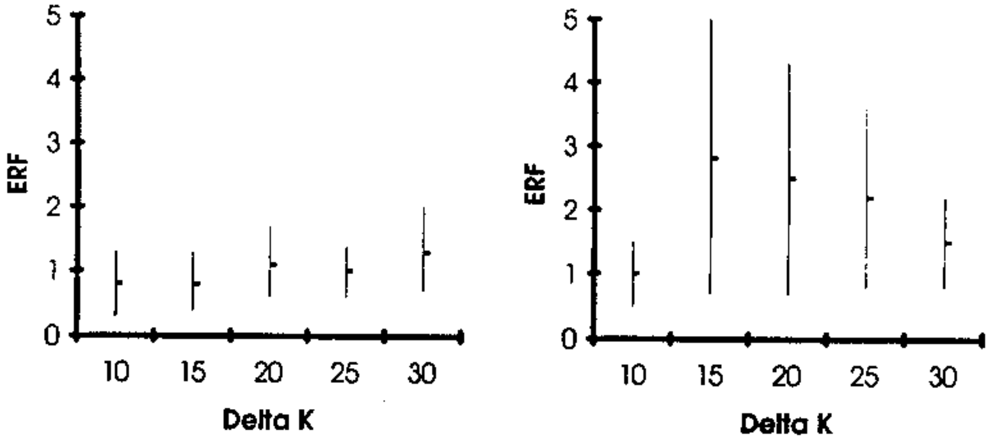


Fig 8(c) CP-850mV

Fig 8(d) CP-1100mV

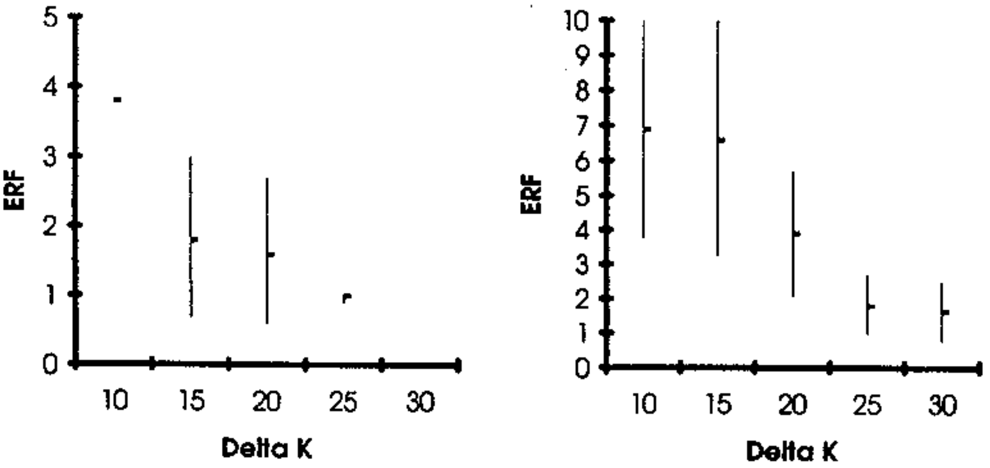
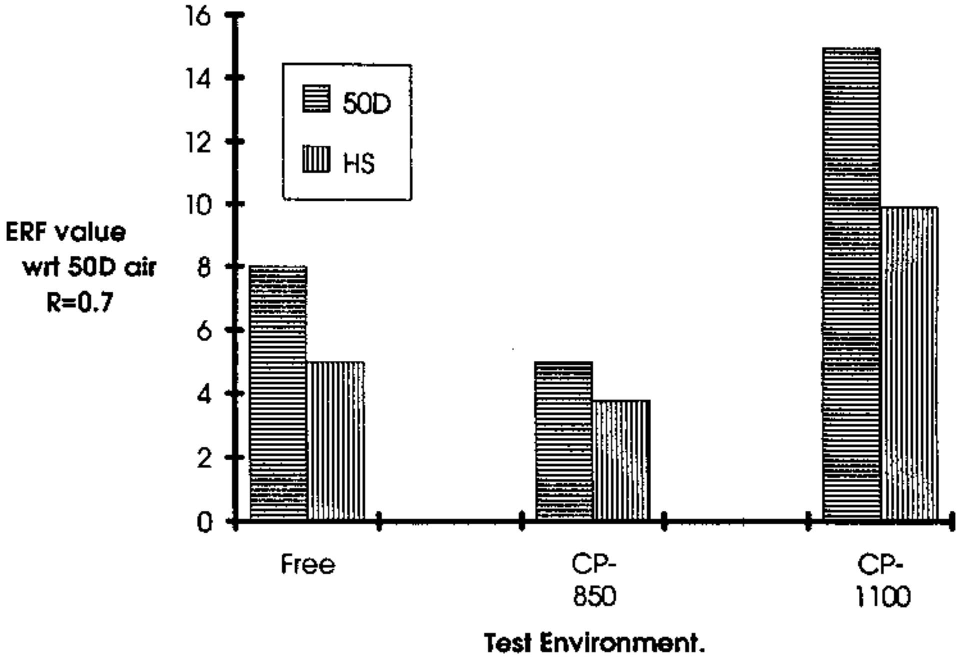


Figure 8
ERF values for HS steels 400 - 600MPa, as a function of stress intensity range and applied potential.

(a) $\Delta K = 10$ to $15 MN/m^{3/2}$



(b) $\Delta K = 25$ to $30 MN/m^{3/2}$

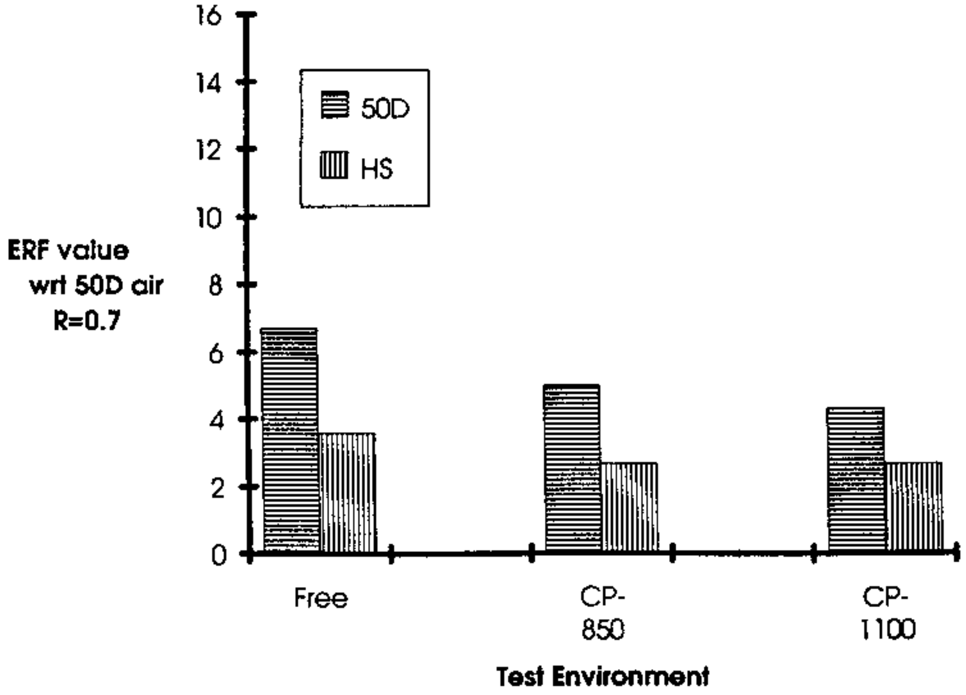


Figure 9
Comparison of the ERF values for structural steels and high strength steels as a function of applied potential and stress intensity range. Structural steels - BS4360: 50D yield 350MPa, R = 0.7. High strength steels - yield strength range 400 - 600MPa, R = 0.6 -0.7. (a) $\Delta K = 10$ to $15 MN/m^{3/2}$, (b) $\Delta K = 25$ to $30 MN/m^{3/2}$

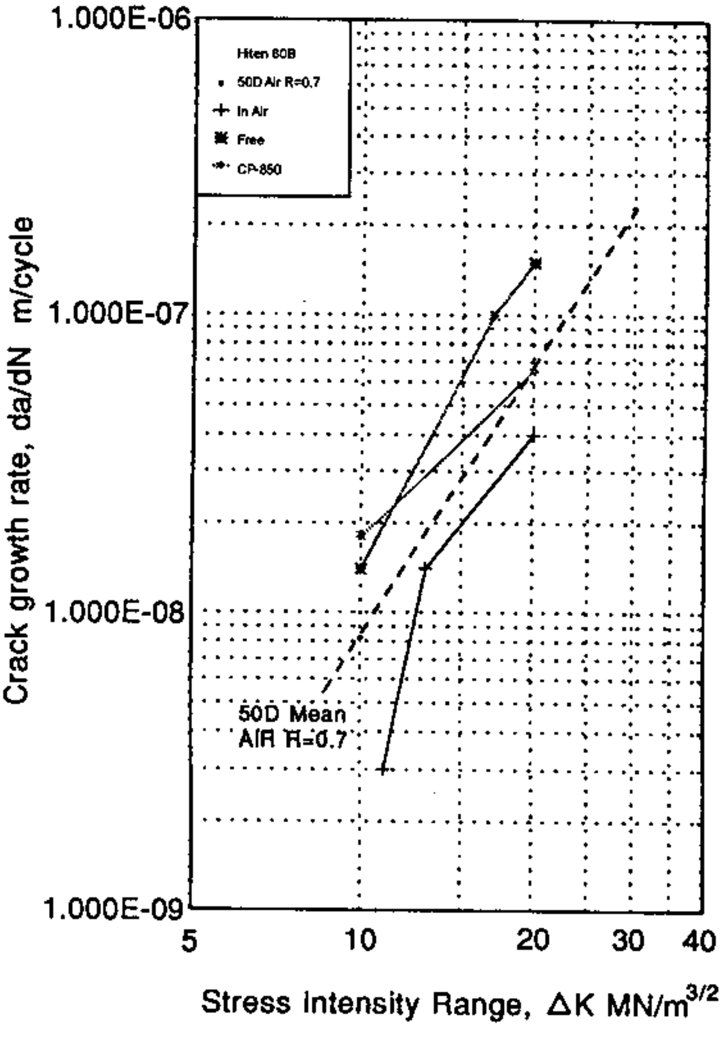


Fig 10(a) - Hiten80B, R=0, Nippon(33)

Figure 10

Fatigue crack propagation behaviour of ultra high strength steels, yield strength range 700 - 900MPa, R = 0 - 0.1, f = 0.167Hz in seawater (see Table VII)

Fig 10(b) HT80, R=0.1, Ebara et al(52,53)

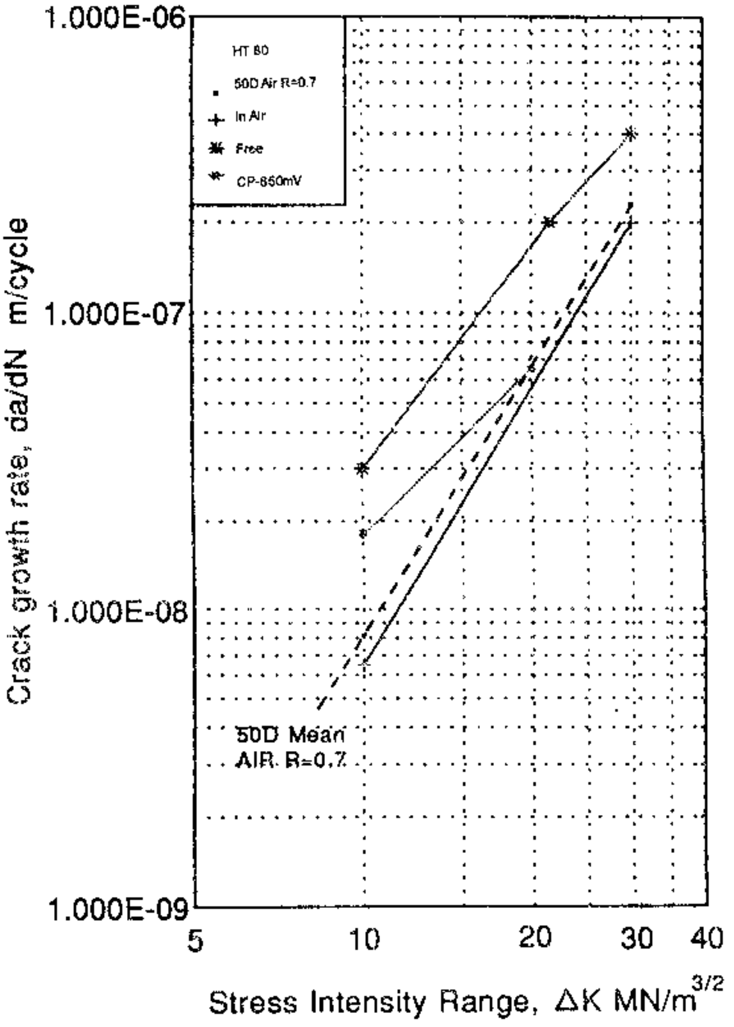


Figure 10

Fatigue crack propagation behaviour of ultra high strength steels, yield strength range 700 - 900MPa, R = 0 - 0.1, f = 0.167Hz in seawater (see Table VII)

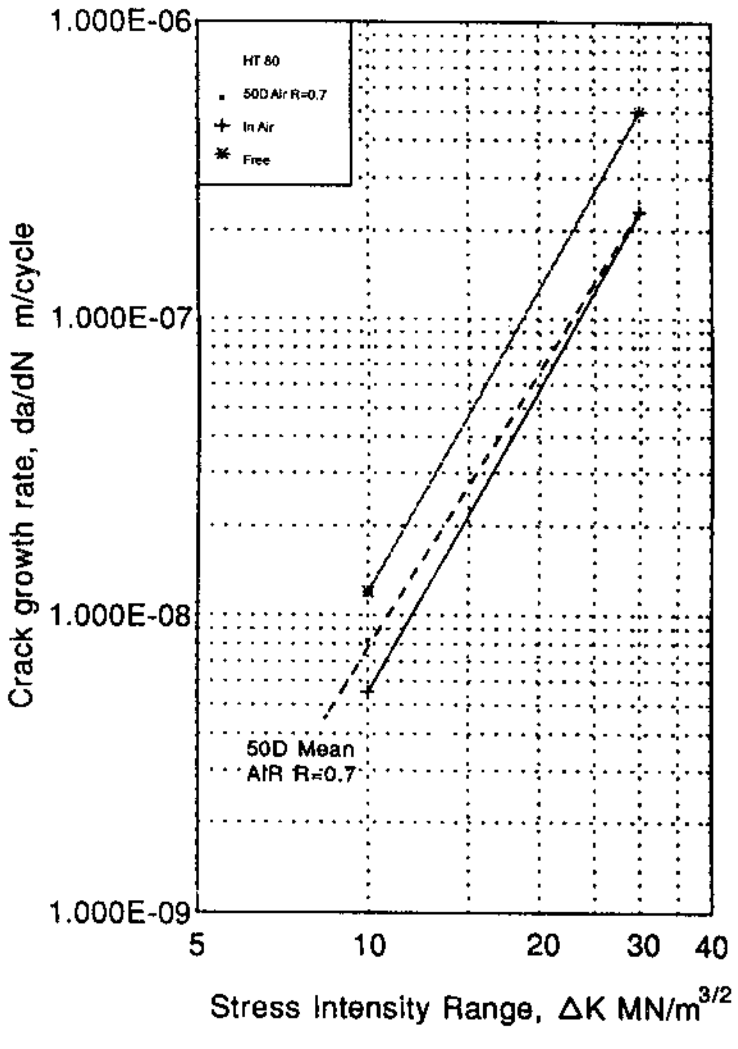


Fig 10(c) HT80, R=0.1, Komai et al(55)

Figure 10
Fatigue crack propagation behaviour of ultra high strength steels, yield strength range 700 - 900MPa, R = 0 - 0.1, f = 0.167Hz in seawater (see Table VII)

Fig 10(d) HY130, R=0.05, Vosikovsky(58)

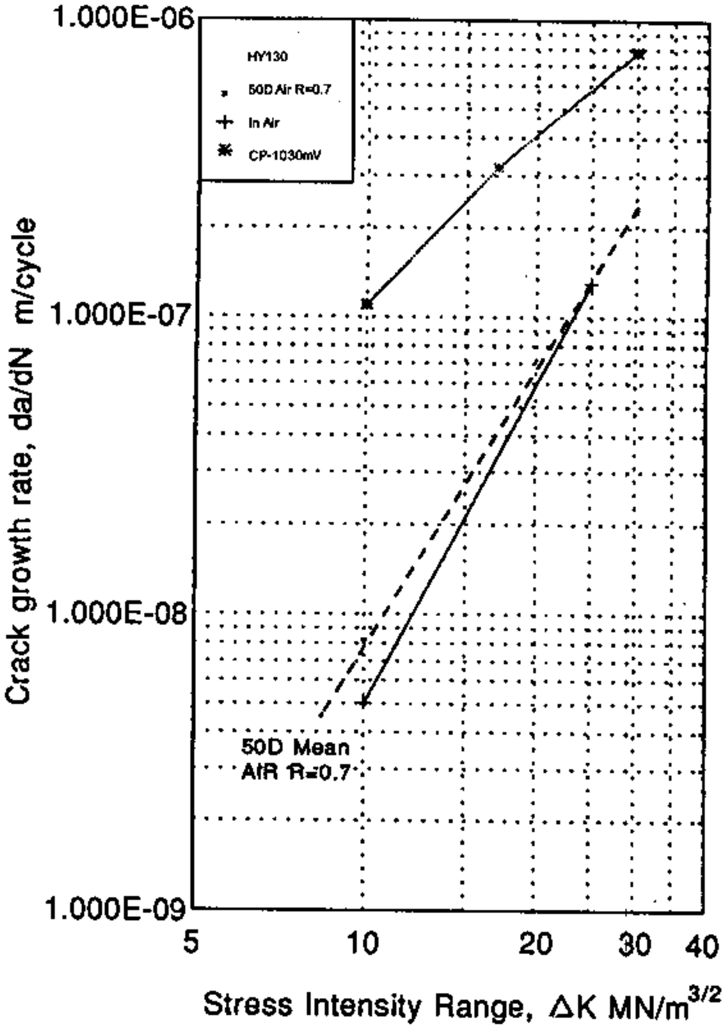


Figure 10
Fatigue crack propagation behaviour of ultra high strength steels, yield strength range 700 - 900MPa, R = 0 - 0.1, f = 0.167Hz in seawater (see Table VII)

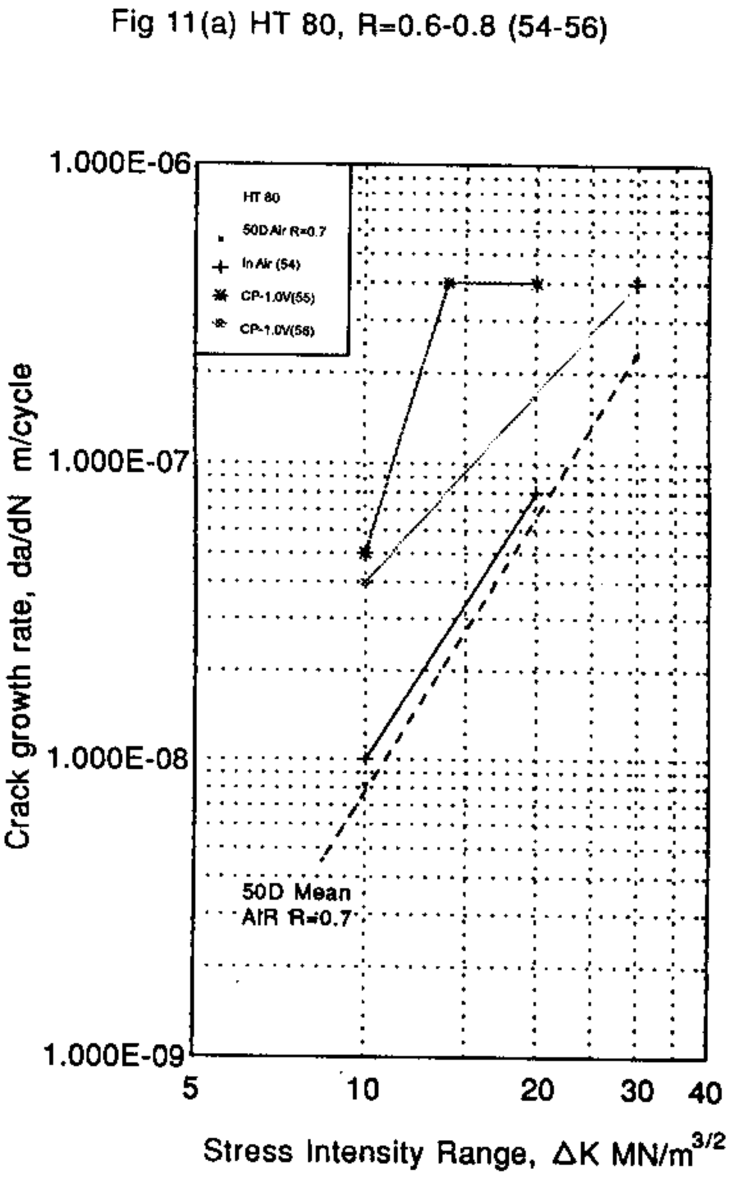


Figure 11
Fatigue crack propagation behaviour of ultra high strength steels, yield strength range 700 -900MPa, R = 0.6 - 0.8, f = 0.16 - 0.3 in seawater (see Table VII)

Fig 11(b) HY100, R=0.6, Zheng et al(57)

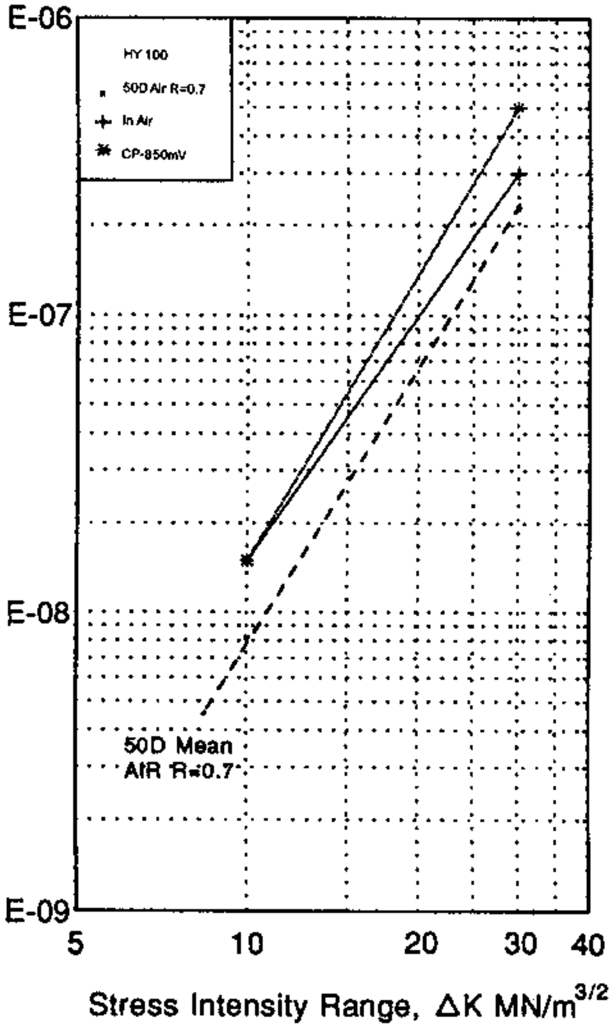


Figure 11
Fatigue crack propagation behaviour of ultra high strength steels, yield strength range 700 -900MPa, R = 0.6 - 0.8, f = 0.16 - 0.3 in seawater (see Table VII)

Fig 11(c) HY130, R=0.7, Vosikovsky(58)

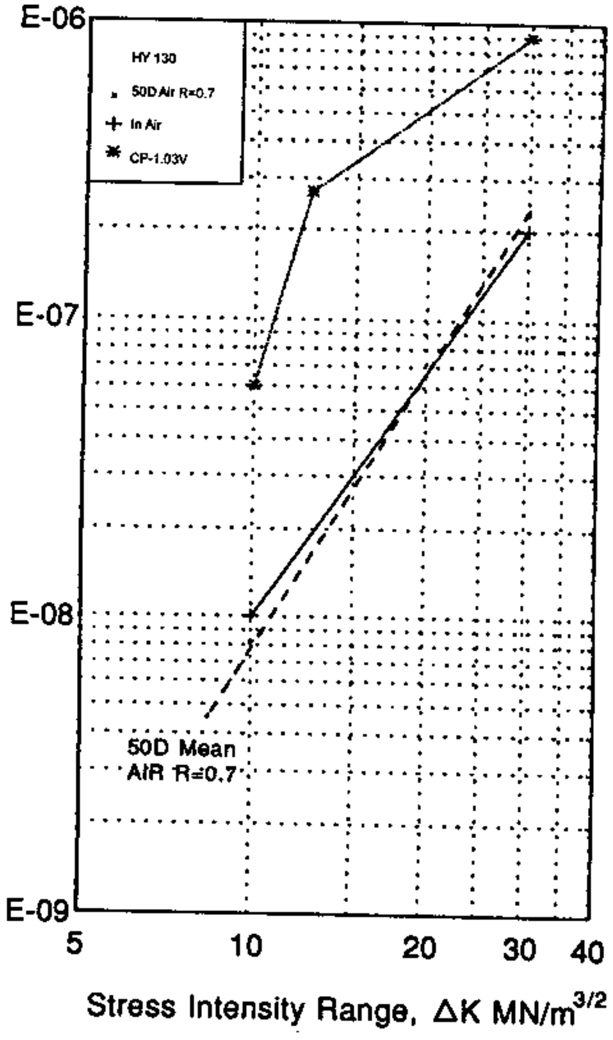


Figure 11

Fatigue crack propagation behaviour of ultra high strength steels, yield strength range 700 - 900MPa, R = 0.6 - 0.8, f = 0.16 - 0.3 in seawater (see Table VII)

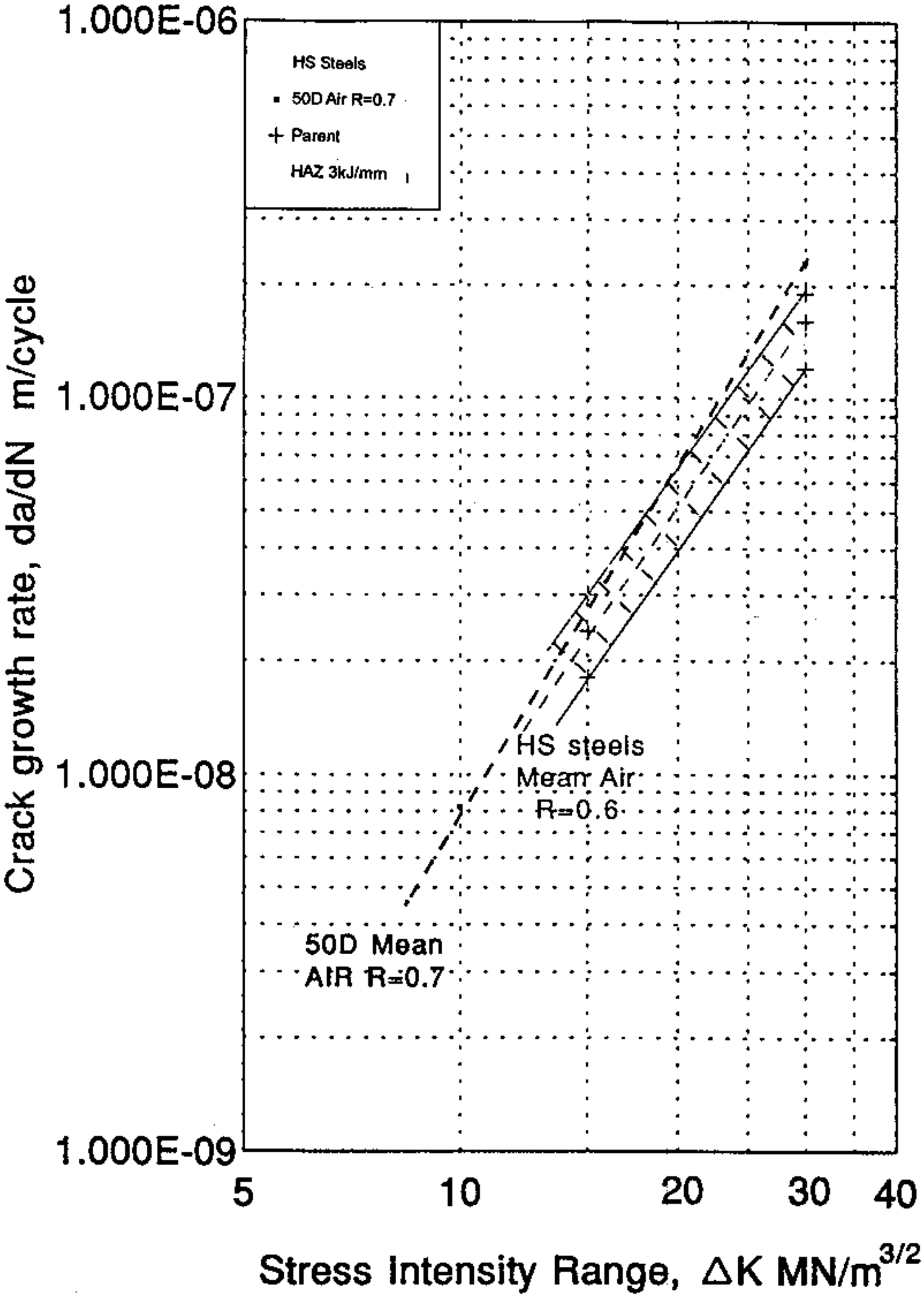


Figure 12

In-air fatigue crack propagation rates for high strength steels, yield strength range 500 - 580MPa, unwelded and welded at 3kJ/mm, R = 0.6, f = 0.5Hz(13-16, 35, 36)

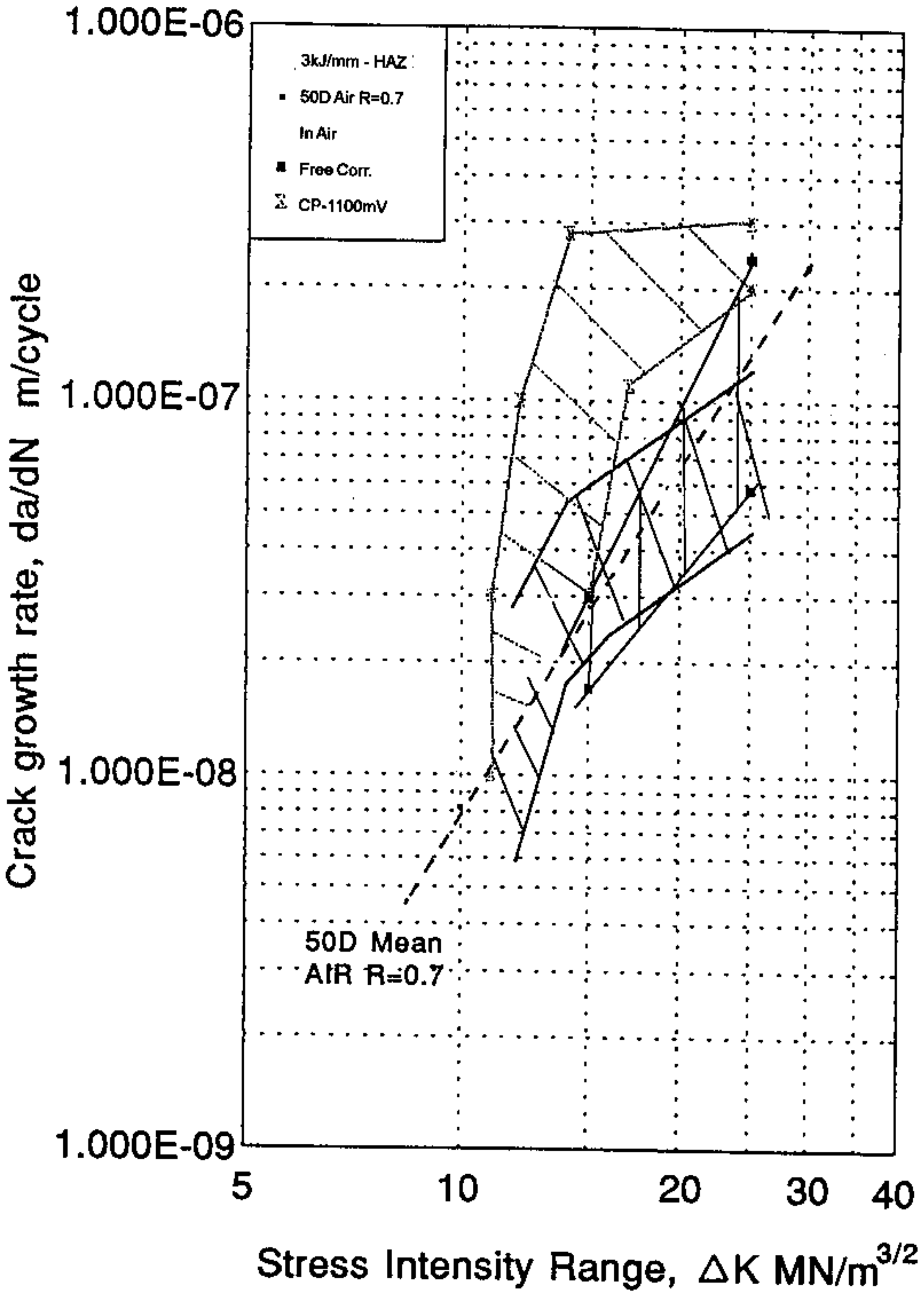


Figure 13

Corrosion fatigue crack propagation rates for HAZs of high strength steels, $R = 0.6$, $f = 0.5$Hz(13-16, 35, 38, 59-61)

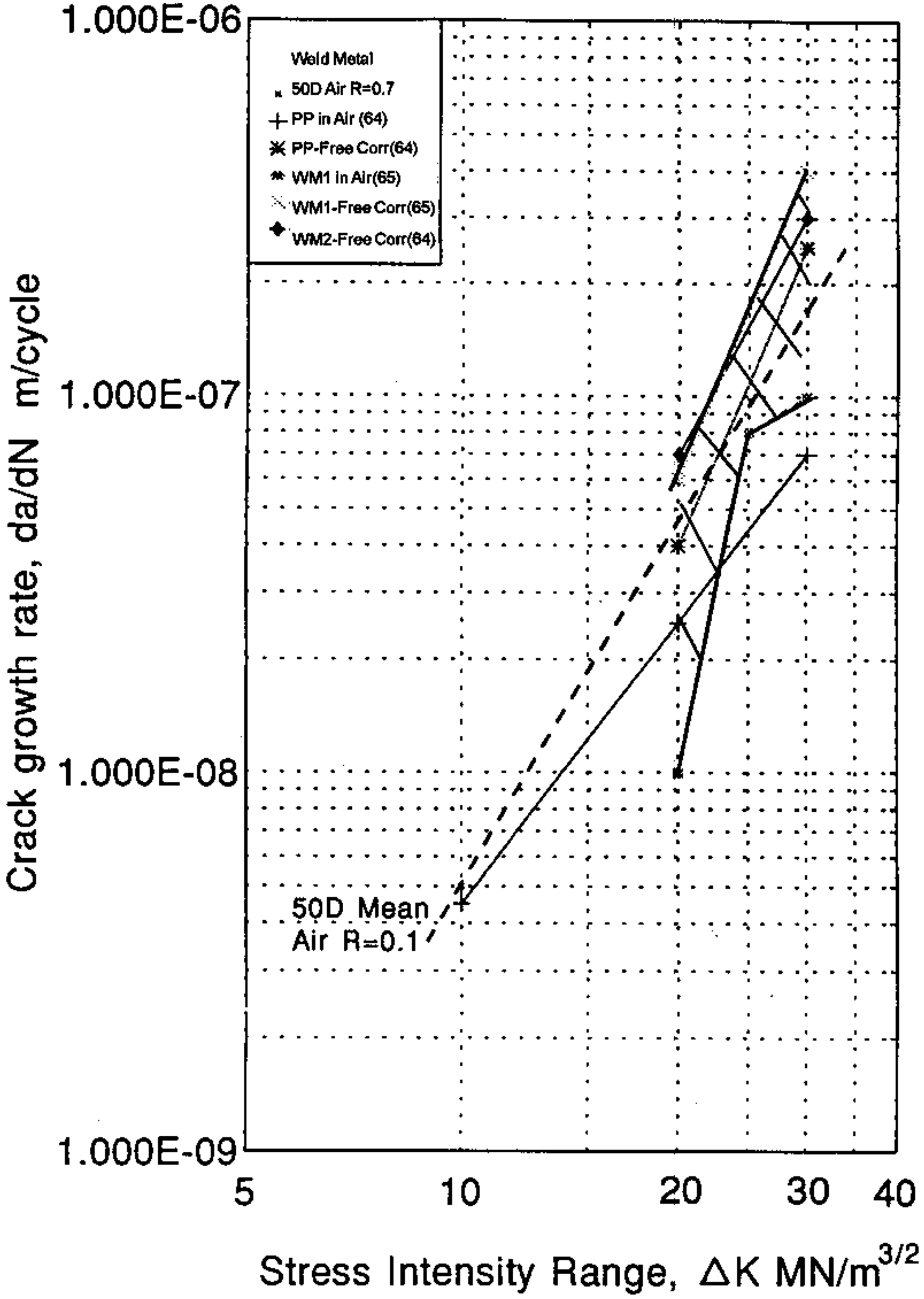


Figure 14
Fatigue crack propagation rates for a high strength steel, A537, and weld metals, nominal yield strength 500MPa, R = 0, f = 0.167Hz in seawater(64,65)

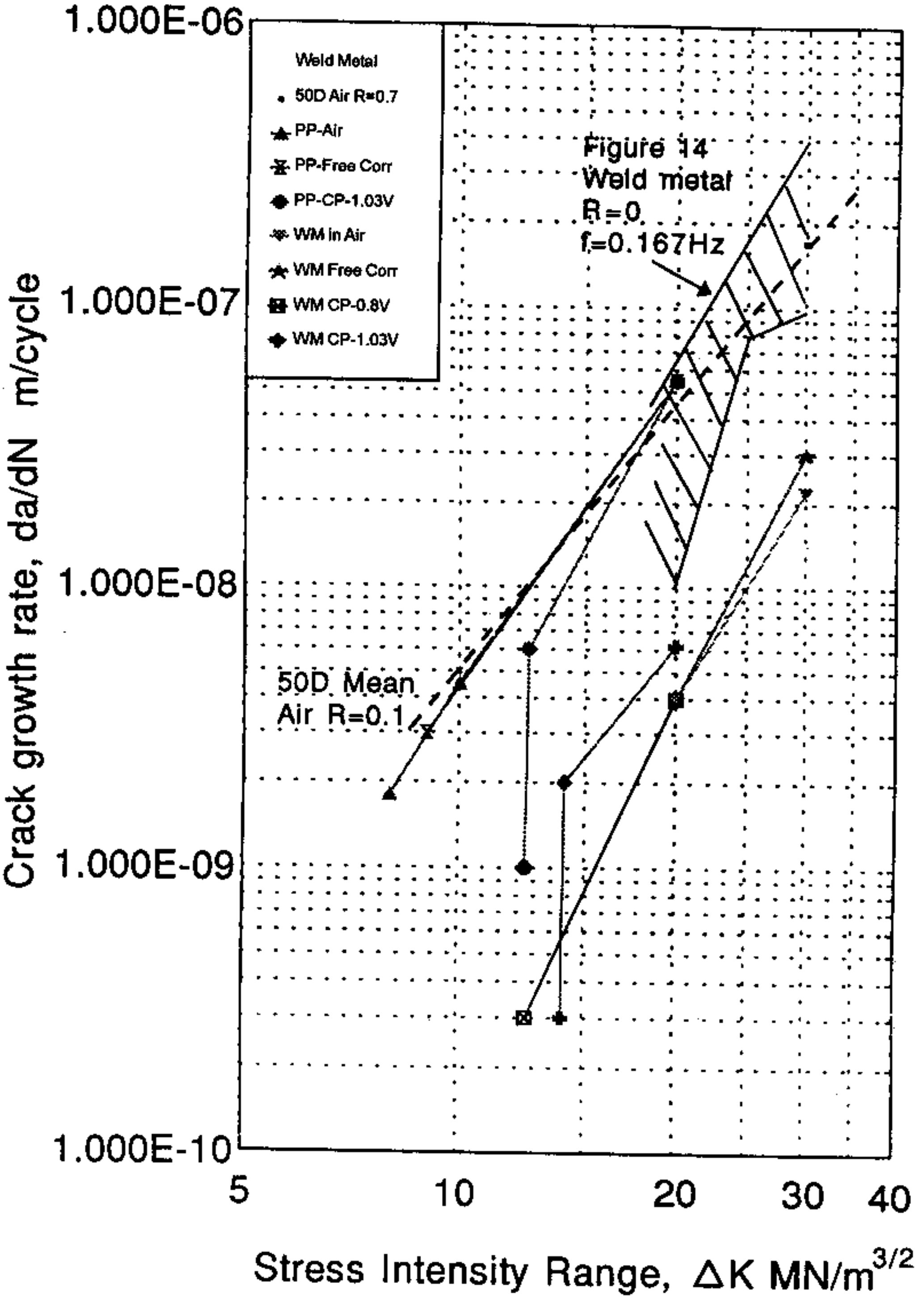


Figure 15
Fatigue crack propagation rates for a high strength steel MILS 24645 and weld metal, nominal yield strength 570MPa, SAW welded at 2kJ/mm, R = 0.1, f = 10Hz(30-32)

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