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93-77

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Influence of Cathodic Protection on the Fatigue Life of Welded Connections in Seawater

PROTECTED BUSINESS INFORMATION

MTL 94-17(CF) 93-77

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Work on this project was funded by API Resource Group.

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EXECUTIVE SUMMARY

This report presents results of a critical interpretive review of existing fatigue data for welded steel in seawater with cathodic protection as requested by API Resource Group 7. The objective of the review was to develop recommendations for accommodating the influence of cathodic protection on seawater corrosion fatigue on S-N design curves. The corrosion fatigue data of unprotected welded steel were also reviewed for comparison and completeness. Fatigue tests were neither proposed nor performed because an area of uncertainty exists in long life effects and the required test duration would be longer than one year (about twice the project length).

The available tests of welded plate and tubular joints in air and seawater were reviewed. Only tests manufactured to offshore standards and tested under conditions simulating the offshore environment were included in a selective database. Since the degree of cathodic protection affects the fatigue behaviour, the data were divided into two groups:

Tests under optimum cathodic protection potentials $(-0.8 \geq V \geq -0.95)$.

Tests under cathodic overprotection potentials $(-1.0 \geq V \geq -1.3)$.

Environmental strength and life reduction factors are evaluated from corrosion fatigue tests of plate joints compared with in-air test results. The few existing corrosion fatigue tests of tubular joints are used to verify the conclusions from plate joints.

Under optimum cathodic protection, the life reduction factors determined here from the selective database are in agreement with the recently proposed revision of the UK Guidance. At short life, a reduction factor of two applies. At long life ($N \geq 10^6$), the in-air behaviour is gradually restored, and at lives longer than 10^7 cycles, the S-N curve for air applies.

Under cathodic overprotection, the life reduction factor at short life is close to three. At long life the scarce data indicate that life in seawater approaches the life in air. However, it remains unresolved whether the in-air life is completely restored for overprotected joints.

Under free corrosion potentials, again in agreement with the proposed revision of the UK Guidance, the environmental life reduction factor is close to three and increases at longer life.

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INTRODUCTION

Cathodically protected welded joints for marine service are traditionally designed (1,2) using S-N curves derived from tests of similar joints in air. This approach is based on the assumption that adequate cathodic protection restores the fatigue life in seawater to values measured in air (3). However, extensive testing of welded plate and tubular joints during the past fifteen years has revealed that, at least at short lives and low cyclic frequencies, the corrosion fatigue lives of cathodically protected joints are significantly shorter than those in air.

Most corrosion fatigue data became available from major national and international research programs: The United Kingdom Offshore Steels Research Project (UKOSRP), the European Coal and Steel Community (ECSC) sponsored program, the Canadian and Norwegian national programs, Japanese projects, the UK Cohesive Research Programs supported by the U.K. Science and Engineering Research Council (SERC), and more recently from American (API sponsored), and Chinese projects.

Data on the effects of cathodic protection were reviewed in 1986 (4). That review concluded that the fatigue life of cathodically protected welded joints in seawater is shorter than in air by about a factor of two. Subsequently the basic design S-N curve for protected joints in the Canadian code for offshore structures was reduced by a factor of two (5).

The accumulated new experimental data prompted a recent major revision of the UK offshore guidance (2). In the proposed revision (6,7), a penalty factor of two is applied on the air S-N curve, to obtain the design curve for cathodically protected joints at short lives. At long lives ($N \geq 10^7$), cathodic protection is assumed to mitigate the adverse effect of seawater, and the section of the air S-N curve with increased slope ($m = 5$) becomes applicable. For intermediate lives, the long life section of the curve is extrapolated backwards to an intersection with the short life section.

The Canadian and UK approaches to design are in agreement for short lives. The paucity of relevant corrosion fatigue data at long lives (required test times are longer than one year), makes the evaluation of cathodic protection effects uncertain. However, the CSA code (3) is based on data reviewed in 1986. The data for the UK proposed revision (6,7) were reviewed in 1990. Since then more research has been completed. The objective of the present review of the upgraded database is to place the evaluation of the long term effects of cathodic protection on the soundest possible technical base.

A selective database has been used in this review. Only results from plate and tubular joints welded to offshore standards and tested under conditions simulating the offshore environment are included. Tests of plate joints are used to evaluate seawater effects on fatigue life under conditions of optimum cathodic protection (OCP), cathodic overprotection (COP), and free corrosion (FC). The few corrosion fatigue tests of tubular joints are used to verify the environmental effects measured on plate joints.

METHOD OF EVALUATION OF SEAWATER EFFECTS

Only fatigue lives to failure, usually defined by crack depth reaching half of the plate thickness for plate joints and wall penetration (identified as N_3 lives) for tubular joints, are reviewed. Fatigue crack initiation lives, reported in some tests, are not analyzed here. Definitions of the initiation life usually depend on the crack monitoring technique used and these vary between different laboratories and/or projects. Detection and sizing of small cracks, particulary in the seawater environment, is difficult and often inaccurate.

Ideally, the evaluation of seawater effects should be based on a comparison of tests in air and seawater on the same type of joint, manufactured to the same specification, using the same test procedures, preferably in the same laboratory. However, in many projects test sets were designed to evaluate effects of variables other than seawater. Thus, either tests in air or in seawater may be available from a single project, or a different type of joint may be used for air and seawater tests. The few available test sets designed to evaluate seawater effects under ideal conditions are too small to allow definitive conclusions because of the wide scatter typical for fatigue tests.

After a preliminary review, it was concluded that the most effective evaluation of the seawater effects can be obtained by a comparison of combined data sets from all available sources. In order to avoid bias, data in the sets were screened, e.g. the tests involving treatments strongly affecting fatigue life (like post-welding weld improvements) were excluded. For variables with smaller effects on fatigue life (e.g. joint type, weld shape, steel grade, stress relief, loading) it was assumed that the mix of test joints with different parameters in air and seawater environments is similar, and that the effects of these variables will average out. The screening methods and the effects of the additional variables will be discussed in detail in the next section.

Linear regression analysis (of log N on log S) of data in the combined sets has been carried out to obtain best fit S-N curves using the equation:

$$\log N = \log K - m \cdot \log S \qquad \text{Eq 1}$$

where m is the slope of the S-N curve and S is the stress range. Regression analyses were performed for four plate joint data sets:

1. Reference data from tests in air
2. Data from seawater tests under optimum cathodic protection, potential range $-0.8 \geq V \geq -0.95$ (vs SCE)

3. Data from seawater tests under cathodic overprotection, potential range $-1.0 \geq V \geq -1.3$ (vs SCE)
4. Data from seawater tests under free corrosion potential

The effects of seawater and cathodic protection were evaluated from the regression curves in terms of environmental strength (ESRF) and life (ELRF) reduction factors. Following a recommendation by Gurney (42), the ESRF are determined as

$$\mathrm{ESRF} = \frac{\text{strength in air}}{\text{strength in seawater}}$$

at short ($N = 10^5$) and long ($N = 2 \times 10^6$) lives. The ELRF are then calculated from the ESRF assuming a similar slope of the regression curves at m = 3 [i.e. ELRF = $(\mathrm{ESRF})^3$].

Scatter of the data is characterized by a standard deviation σ of log N and correlation coefficient R^2.

EFFECTS OF TEST JOINT, LOADING AND ENVIRONMENT

The total number of tested joints in combined data sets for each environmental condition, comprising the screened database, are given in Table 1. The most important test parameters, identifying joint type, steel grade, post weld heat treatment, dimensions, loading, and environmental conditions, are summarized for plate joints in Tables 2a and 2b, and for tubular joints in Tables 3a and 3b. Tables 2a and 3a contain the tests in air, Tables 2b and 3b summarize the tests in seawater. Keys to abbreviations are given below the tables.

TEST JOINT TYPE

Plate Joints

Either T or cruciform type joints, both with transverse full penetration welds, were evaluated. The test arrangements used either load-carrying or non-load-carrying welds. The type of joint does not appear to consistently affect fatigue life as long as the weld-toe stress (calculated from simple beam theory or linearly extrapolated from strain gauge measurements) is presented correctly (42). Cruciform joints loaded as a cantilever beam were used most often for testing in seawater. The most numerous seawater data from the UKOSRP (22,23) were obtained from cruciform joints with reported weld-toe stresses as measured by a strain gauge placed 7 mm from the weld toe. The original data when compared with results from air, measured on T-joints, showed almost negligible environmental effects. This disagreed with results from other programs. Reanalysis of the UKOSRP data (42) concluded that the strain gauge was too close to the weld toe and the measured stresses too high. The recommended reduction factor of 0.93 was used to correct stress ranges in the UKOSRP data presented here to make them comparible with the accepted weld-toe stress definition.

Tubular Joints

Only simple types of tubular joints, T, X, H, K and KT with either overlapping or non-overlapping braces were used in fatigue testing. Two tests of T-tubular joints with two internal ring stiffeners and six tests of pipe-to-plate joints in seawater from the Canadian program (35,36,41) are also included in the database. The hot spot (weld-toe) stress is defined by linear extrapolation as recommended by the UK Guidance (2). No consistent effect of joint type on fatigue life was reported.

STEEL GRADE

In addition to commonly used normalized steels with yield strength 300 to 360 MPa, a variety of steels with yield strength of up to 750 MPa are also included in the database. The higher strength steels were either of the quenched and tempered or thermo-mechanical control processed types.

A number of studies to evaluate the effects of increased yield strength on fatigue life in both air and seawater were reported (12,17,28,43-50). The studies conclude that the fatigue strength of as-welded joints does not increase with yield strength. A post-weld treatment is needed to improve the fatigue strength to match the increase in yield strength.

SECTION THICKNESS

The detrimental effect of increasing section thickness on fatigue life of welded joints has been recognized by offshore design codes (1,2). The first stress range correction for the thickness effect was introduced in the UK Guidance (2) in 1984, and was based on Eq 2, proposed by Gurney (51).

$$S_c = S(T/T_b)^n \qquad \text{Eq 2}$$

S_c is the corrected stress range, and T_b is the chosen basic plate thickness. The value of the exponent $n = 0.25$ was derived from fracture mechanics analysis. Since its introduction, the thickness effect has been measured in many research programs (12-14,18-20,22-23,51-58). The value of the exponent n was found to vary from 0.14 to 0.5 depending largely on the weld-toe stress concentration factor for the joint used in testing.

For plate joints with transverse welds and equal main and attachment plate thicknesses, $\tau = 1$ (reviewed here), the recent comprehensive analysis in the "Background" for the revision of the UK Guidance (6) determined the value of n as 0.29. A rounded value of 0.3 combined with basic plate thickness of 16 mm is recommended in the proposed revision for all welded joints (8). T_b = 16 mm was chosen as a minimum thickness of joints included in the database, in order to avoid joints with oversize welds. These values of n and minimum thickness [with the exception of plate joints where data from the USA project measured on 13 mm thick joints (19) were included] are used here in the analysis of seawater effects.

The thickness effect correction is based on the main plate (chord) thickness. For joints with thinner attachments and lower stress concentration factors (e.g. for loading in tension), the recommended value of the exponent may be too conservative (54,55,57,58). In the API Practice (1) the limited (only for thick sections depending on the weld shape) correction for thickness effect is based on the brace thickness.

Ideally, both chord and brace thicknesses should be incorporated in the correction. However, limited data and lack of consensus on how the correction should be applied makes it advisable to use the conservative approach based on chord thickness.

WELDING PROCEDURE AND WELD SHAPE

A variety of weld shapes, from straight fillet (with angle to the plate 45°-70°) to improved (Alternate 2) round profile as recommended by API Practice (1) for thicker sections, was used on reviewed joints. In the UKOSRP (22,23) and the Canadian (9,10) programs, using straight fillets, the weld-toe pass shape was controlled by a "dime" test similar to that used for the improved round profile.

The weld shapes, combined with the welding procedures used, have significant effects on fatigue life. However, the shape of weld varies along the weld length (all welds are manual) and thus the effects of shape are almost impossible to quantify.

The studies of gains in fatigue life from improved round weld profile (10,19,58,60) indicate mixed improvements available only for thick (more than 50 mm) sections. Review of the improvements (43) indicated an average 10% increase in strength corresponding to 30% extension of life. These are within the expected scatter of repeated tests of welded joints. For thin sections the small number of capping passes precludes achievement of meaningful round profile of the weld.

Past MTL/CANMET experience indicates that welding of test joints without restraint is imperative to produce conservative results. T-joints welded with restraint produced lives almost one order of magnitude longer than normal (unrestrained) joints.

POST-WELD TREATMENT

Post-weld improvement techniques such as grinding, TIG dressing, and hammer or shot peening can profoundly increase the fatigue strength, particularly at long lives (43, 59-62). These techniques combine removal of the weld-toe defects with improved profile (reducing stress concentration) and favourable redistribution of residual stresses. Joints with welds improved using these techniques were not included in the database because the resulting strong increases in fatigue strength, and fatigue limit in particular, could skew the evaluation of the seawater effects.

Post-weld heat treatment (stress relief) can significantly increase the fatigue strength only when a partly or fully compressive loading cycle with negative load ratio (R) is used (23,63). The compressive part of the load cycle is generally non-damaging. In the as-welded joints, high tensile residual stresses near the weld toe move compressive applied stresses into the tensile range locally, making applied compressive stress damaging. Thus, for stress relieved joints, only those tested using load cycles with positive R were included in the database.

LOADING PARAMETERS

The analysis of the seawater effects is performed on tests conducted under constant amplitude loading. Only very few results of variable amplitude tests of tubular joints, with stress presented in terms of the equivalent stress range, are included in the database.

Loading Mode

All tests of plate joints reviewed here were bending tests, conducted either under 3-point (in many cases load was applied through the attachment), 4-point or cantilever beam bending. Bending tests generally produce longer lives than tests in tension (42), but they are more representative of the stress state in tubular joints. Similarly to joint type, no systematic differences in fatigue lives under these loading modes were reported.

The tubular joints reviewed were loaded through the brace in three loading modes: axial (AX), in-plane bending (IPB), and out-of-plane bending (OPB). The effects of loading mode were examined on the most numerous test results from 16 mm thick joints (6). The examination showed that axial loading produced the shortest lives while out-of-plane bending was relatively beneficial. All tests are used in derivation of the design curve thus representing average conditions.

Load Ratio

The load ratios (R = min/max load or stress) used in testing varied from -1 to 0.5. The majority of tests were carried out at R near zero. As-welded joints show little effect of load ratio because the aforementioned high tensile stresses at the weld toe move the stress range into the tensile region (22,23). Stress-relieved joints, as stated earlier in the discussion of post-weld treatment, produce lives comparable to as-welded joints as long as they are tested at positive R. Stress-relieved joints tested at negative R can produce much longer lives and are excluded from the database.

Cyclic Frequency

Studies of corrosion fatigue crack growth rates in aqueous environments showed that strong environmental enhancement of crack growth in structural steels occurs only at low cyclic frequencies (near 0.1 Hz) (64,65). Because the fatigue crack growth phase is predominant in the fatigue life of welded joints, it is imperative to conduct the seawater tests at frequencies representative of sea wave loading.

The seawater tests were conducted at frequencies as high as 10 Hz. For the above reasons only results from tests conducted at frequencies of 0.1 to 0.5 Hz were included in the database.

SEAWATER PARAMETERS

The majority of welded joints were tested in synthetic seawater prepared according to the ASTM D1141 standard. Natural seawater was used only in the USA study (19) and in the Canadian program in tests of two tubular joints (10,41). No obvious differences in fatigue lives attributable to the two different environments were observed. During tests, the circulating seawater is usually continuously aerated by air bubbling through water in the storage/cooling tank. pH varied from 7 to 8.5. Cathodic protection was applied either potentiostatically or by sacrificial, zinc or aluminum anodes.

No data are available on effects on corrosion fatigue life of seawater composition, salinity or pollution. Only effects of seawater temperature and oxygen content were studied.

A fatigue crack growth rate study at free corrosion potential (67) indicated only minor effects of salinity (dilution with 50% pure water), changes in pH (from 6.5 to 8.5) and removal of buffering compounds (use of sodium chloride solution) on crack growth rate. Under cathodic protection the presence of buffering compounds will be important, particularly at low crack growth rates or long lives, because crack closure, induced by calcareous deposits, can inhibit or retard crack growth.

Temperature

The seawater tests were conducted at temperatures from 4°C (representative of northern seas) to 22°C (room temperature). The effect of temperature on fatigue life was evaluated in several series of plate joint tests carried out at 5 and 20°C under free corrosion conditions (17,23,25,27,63). The modest beneficial effect of lower temperature was indicated by these tests.

On average the life at a stress range of 100 MPa increased by a factor of 1.14 with a temperature decrease from 20 to 5°C (4).

The effect of temperature on fatigue crack growth rate at free corrosion and cathodic overprotection was reviewed by Vosikovsky et. al. (66). A decrease in temperature from 20 to 5°C resulted in a decrease in free corrosion crack growth rate by a factor of 0.71. At cathodic overprotection (-1 to -1.1 V) only the plateau growth rate (independent of stress intensity factor range) decreased significantly at lower temperature.

Overall the temperature effects are small, well within the typical scatter of fatigue tests. Consequently, data at all temperatures are used in the analysis without correction.

Oxygen Content

Effects of the oxygen content on fatigue life of welded joints under free corrosion and cathodic overprotection potentials (-1.2 V) were reported in a Japanese study (25). Experiments were conducted at low temperature (4°C). Oxygen concentrations were 0, 5, and 10 ppm (10 ppm is saturation level in fully aerated seawater at 4°C). Under free corrosion, significantly shorter life (by about a factor of two) was measured in the fully aerated water at high stress range (200 MPa) than in water with lower oxygen contents. The lives converged at lower stresses and were about the same at the 100 MPa stress range. Under cathodic overprotection, the fatigue lives were determined only at 5 and 10 ppm oxygen contents. No significant effect on life was observed.

In a study of fatigue crack growth rates in 5-10°C natural seawater under free corrosion potential (67), no significant change was observed when oxygen content was reduced from 7 to 1 ppm.

SUMMARY OF THE SCREENING CRITERIA

The database consists of test results of plate and tubular joints, tested in air and seawater with or without cathodic protection. Tests with parameters listed below are excluded from the database.

- Plate joints tested in tension
- Plate joints with the main plate thickness smaller than 13 mm, and with the main plate thickness different from the attachment thickness.
- Tubular joints with chord thickness smaller than 16 mm
- Joints with post-weld improved welds
- Joints tested under variable amplitude loading (except for two tubular joints)
- Stress relieved joints tested at negative load ratios
- Joints tested in seawater at cyclic frequencies higher than 0.5 Hz
- Joints tested in deoxygenated seawater

- Run-outs
- Plate joints 16 mm thick from the Chinese program (18). (Fatigue lives of these joints were almost an order of magnitude longer than those measured under comparable test conditions in other programs. Reasons for the long lives are not known; welding with restraint or improper definition of the weld-toe stress are possibilities.)

RESULTS AND DISCUSSION

PLATE JOINTS

The results from the plate joint tests in air and in seawater under OCP, COP, and FC are presented as S-N graphs in Figs. 1a,b to 4a,b. Figures 1a to 4a show the uncorrected data. The results with stress ranges corrected for thickness effect, to the 16 mm basic thickness using Eq 2 with n = 0.3, are presented in Figs. 1b to 4b. As can be seen from the comparison of the a and b figures, the thickness correction substantially narrowed the scatterbands. This is most prominent for the air data which involve the widest range of tested thicknesses (13-200 mm). For the FC potential with thickness range 13-102 mm (Fig. 4b), about 6% of corrected data show excessively long lives, outside the main scatterband. Most of these results are from the tests of thick joints.

Regression analysis using Eq 1 was performed on the corrected data sets, and the best fit curves are shown in Figs. 1b-4b. The class F design curves for the appropriate environmental conditions from the proposed UK Guidance (8) are added for comparison. In Figs. 2b-4b (seawater results) the best fit curves for air (from Fig. 1b) are also plotted. The best fit curves are used for evaluation of the environmental strength and life reduction factors, ESRF and ELRF. The values of slopes m, and intercepts log K for the best fit curves, and the scatter characteristics are given in Table 4. The fatigue strengths at short and long lives (10^5 and 2×10^6 cycles), and the corresponding ESRF and ELRF are given in Table 5.

As usually observed, the scatter is relatively smaller, and correlation better, for air and FC data (despite the outliers) than for the data from cathodically protected joints. Progressively longer lives of cathodically protected joints at low stress ranges (Figs. 2b, 3b), particularly for OCP where the existence of a fairly high fatigue limit or at least a change of slope is indicated, are responsible for poorer correlations.

The slope of the S-N curve in air is almost exactly three (Table 4), the value used for all S-N curves in the UK and Canadian codes (2,5,8). For the cathodically protected joints the slopes of the fitted curves are higher, close to 3.6. However, examination of the data in Figs. 2b and 3b indicates that the excessively long lives at low stress ranges are responsible for the higher slopes. For lives shorter than 10^6 cycles the best fit lines would be almost parallel with that for air. The lower slope of 2.7 for the FC potential can be explained because corrosion is a timedependent phenomenon; longer exposure will shorten the crack initiation life in the absence of cathodic protection.

Different slopes of the best fit curves for air and seawater environments give the different ELRF for short and long lives, Table 5. In the UK and Canadian offshore codes (2,5,8) the design S-N curves (defined as a mean curve minus two standard deviations) for both air and seawater environments have fixed slopes of three at short lives ($N \leq 10^7$ for air) changing to five at long lives ($N > 10^7$) with the exception of the unprotected joints where $m = 3$ for all lives. The change of slope at long life is a compromise to accommodate effects of variable amplitude loading; the fatigue limit present for constant amplitude loading is absent for variable amplitude loading.

Design life reduction factors (penalties) for seawater effects differ widely in different codes. For joints with cathodic protection, a penalty was first introduced in the Canadian code (5) (a factor of two at all lives with the change of slope for long lives maintained). A similar penalty, but only at short lives, is used in the recently proposed revision of the UK code (8); at lives longer than 10^7 cycles the air design curve with a slope of five applies. To complete the design curve the long life part is extrapolated backward to intercept with the short life curve, at slightly over 10^6 cycles.

For FC potential the penalty of two at short life combined with no change of slope at long lives was used in derivation of the design curve in the earlier codes (2,5). In the recently proposed revision of the UK Guidance (8) the penalty for unprotected joints was increased to a factor of three.

The appropriate basic (16 mm) design curves from the most recent code revision (8) for class F joints are shown together with the reviewed data in Figs. 1b-4b. As can be seen, all design curves are highly conservative. They were derived from the old database consisting mostly of tests of cruciform joints loaded in tension, which produces shorter lives. The fatigue lives of joints tested in bending included in the present database were also likely extended by use of the better (offshore) quality welds.

For OCP the ELRF (Table 5) are compatible with the penalty of two in the Canadian and proposed UK codes (5,8). For the long lives, the data support a change to a higher slope at shorter life (around 10^6 cycles), with no penalty at lives over 10^7 cycles, as in the proposed UK code (8), (see Fig. 2b).

For COP potentials the ELRF at short lives are close to three, i.e. significantly larger than the penalty of two. Data at lives over 10^6 cycles (Fig. 3b) indicate that the in-air behaviour may be restored at long life, although much less convincingly than under OCP because of the limited data. It should be noted that the design curve for COP is the least conservative.

The ELRF at FC potential, close to three at longer life, is consistent with the penalty of three in the proposed UK code (8) (Fig. 4b).

TUBULAR JOINTS

The results from tubular joint tests are presented in Figs. 5a-7b. The uncorrected data in Figs. 5a-7a are compared with the X and X' design curves from the API code (1). The data with stress ranges corrected for chord thickness effect (Eq 2 with n = 3) to the basic thickness of 16 mm are shown in Figs. 5b-7b. The basic mean and design curves for air, T', from the proposed revision of the UK code (8) are shown with air and seawater data.

The T' mean curve was derived as the best fit curve for joints with a 16 mm thick chord; the T' design is the T' mean minus two standard deviations. The T' mean is also nearly the best fit curve for all corrected data in Fig. 5b with the exception of data from 32 mm thick joints recently reported by Tubby et al. (40) (denoted by crosses) and data from 26 mm thick pipe-to-plate joints (denoted by upright triangles).

Comparison of the uncorrected data from tubular joint tests in air (Fig. 5a) with the API X and X' design curves indicate that the slopes m of the curves, particularly that of X, are too high. Secondly, eight points are below the X curve. Seven of these points represent tests with brace thickness less than 25 mm. If the welds were qualified as welds with controlled profile, the X curve would apply with no correction for thickness up to 25 mm, and its use in design would be unconservative. The use of controlled weld profile for thicknesses smaller than 25 mm is ambiguous since a meaningful improved profile is not achievable due to the small number of capping passes (10,43,58).

Comparison of the corrected test data with T' curves in Fig. 5b shows that the slope m = 3 is about correct. However, seven test points are also below the T' design curve. Six of these tests are from the joint UK-Norway project designed to evaluate effects of cathodic protection at long lives by tests of full scale tubular joints with real-time load history representative of wave-loaded structures with a good reference data base in air (68). Twenty-eight tubular joints of uncommon design (two parallel braces on one chord loaded in in-plane bending by an actuator suspended between the braces) were tested. Half of the tests were conducted under constant amplitude loading (eight in air, six in seawater under COP), the other half under variable amplitude loading (four in air, ten in seawater under COP).

Possible reasons for unusually short lives measured on these joints were analyzed by Berge et al (69,70), with the following conclusions:

- Definition of hot spot stress by linear extrapolation (2) may not be consistent for all tubular joint geometries. Alternative definitions assuming a nonlinear (quadratic) distribution may better represent the design stress.
- Through-thickness distribution of stress, characterized by "degree of bending" (bending/hot spot stress) depending strongly on joint geometry and loading, may significantly affect fatigue strength, and may be used as a second parameter in defining fatigue strength. The

degree of bending in these joints was lower than in T-joints with an anchored chord, commonly used in fatigue tests.

Acceptance of a new definition of hot spot stress is still far away and as a result current design may be slightly unconservative for some geometries.

Mean curves for air with a factor of two penalty for cathodic protection and a factor of three penalty for FC potential, are shown for comparison with the reviewed seawater data in Figs. 6b and 7b. Since the database for cathodically protected tubular joints (Table 3b) included only six tests under COP, all cathodically protected data are presented together in Figs. 6a,b. The four COP tests from (40) are again denominated by crosses, and the two shorter life results from four 26 mm thick pipe-to-plate joints tested at two stress ranges by upright triangles.

Four out of forty two test results in Fig. 6a are below the X design curve. The data corrected for thickness in Fig. 6b are all above the T' design line. The proposed mean line for cathodically protected joints (1/2 Air) appears to represent a good fit to data under OCP. Five out of the six results from tests under COP (two triangles and three crosses) lie on the bottom edge of the scatterband. This confirms the conclusion from analysis of plate joints that a higher penalty factor (closer to three) should apply to overprotected joints.

Results from tests of unprotected joints in Fig. 7a show two data points (at long life) of the total of twelve below the X design line. The data corrected for thickness are shown in Fig. 7b. The mean line with a penalty factor of three fits the data reasonably well, at least at longer life.

TUBULAR JOINTS TESTED UNDER VARIABLE AMPLITUDE LOADING

Results of variable amplitude tests of tubular joints (T/D = 32/914 mm) tested in air and seawater under COP (-1.03 V), from the UK-Norway joint research project (40), are reproduced in Fig. 8. The WASH-W load sequence characteristic of sea wave loading, applied at an average frequency of 0.24 Hz, was used for loading. As for constant amplitude loading reported earlier, two braces on one chord were loaded in in-plane bending. The stresses in Fig. 8 are presented in terms of maximum hot spot stress range in the sequence.

The T design curve shown for 32 mm thickness was predicted using Miner's rule with a sum of one. As can be seen the four in-air test results are about uniformly distributed around the T design curve. The lives in seawater are significantly shorter than in air; the average value of ELRF was determined as 1.7. However, in the long life region of main interest, the scatter of measured lives of the order of 4 to 5 makes any conclusions on long-term effects of cathodic overprotection uncertain.

CONCLUSIONS

The following conclusions can be drawn from this review of fatigue tests of plate and tubular welded joints, tested in air or seawater with or without cathodic protection.

- Under optimum cathodic protection potentials ($-0.8 \geq V \geq -0.95$) the fatigue life reduction factor (as compared to air) is close to two at short life. At long life ($N \geq 10^6$ cycles) the life in seawater becomes progressively longer and eventually exceeds the life in air.

- Under cathodic overprotection potentials ($-1 \geq V \geq -1.3$) the fatigue life reduction factor at short life is close to three. At long life the scarce data indicate that life in seawater approaches the life in air; however, it remains unresolved whether the in-air life is completely restored for overprotected joints.

- Under free corrosion potentials the life reduction factor is close to three and increases at longer life.

- The design S-N curves for tubular joints in the API RP2A recommended practice do not represent the recent test results and need revision.

- The definition of hot spot stress by linear extrapolation in the UK guidance does not correctly represent the design stress for some joint geometries. Development of a new definition with more general applicability should be considered.

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Table 1 - Number of tests of tubular and plate welded joints in the database.

	Tubular Joints	Plate Joints
Air	101	169
Seawater:		
Optimum Cathodic Protection	36	138
(-0.8 to -0.95 V vs SCE)		
Cathodic Overprotection	6	52
(-1.0 to -1.3 V vs SCE)		
Free Corrosion	12	169
Total	155	528

Table 2a - Summary of plate joints tested in air

Ref.	Number of tests	Joint type	Loading	Plate thickness mm	Steel grade MPa	Post weld treatment	Load ratio
9,10	7	T	3PBA	16	350	AW	0.05
	8			26			
	8			52			
	6			78			
	15			103			
11	7	T	BA	20	350	AW,SR	0
	10			100			
	8			150			
12	6	T	3PB	22	350	AW	0
	6			40			
	8			80			
13	3	CL	CB	25	350	AW	0
	5			50			
	3	CL	3PB	100			
	1			200			
14	5	T	4PB	25	350	AW	0
	8			50			
	7			75			
	8			100			
15	7	T	3PB	38	350	AW	0
16	4	T	4PB	4	350	AW	0
17	7	CN	CB	15	350,750	AW	0
	10			30			
	11			60			
18	8	CL	CB,3PB	30	350	AW	-1
	8			40			

T - T-joint
CL - cruciform joint load-carrying welds
CN - cruciform joint non-load carrying welds

AW - as welded
SR - stress relieved

3PB - 3 point bending
3PBA - 3point bending, loadec through attachment
4PB - 4 point bending
BA - bending on attachment
CB - cantilever beam bendin(

Table 2b - Summary of plate joints tested in seawater

Ref.	Number of tests	Joint type	Loading	Plate thickness (mm)	Steel grade (MPa)	Post weld treatment	Load ratio	Freq-uency (Hz)	Tempe-rature (C)	Potential (V)
19	4	T	3PBA	13	300	AW	0.1	0.3	22	-0.8
	10			25						
	32			51						
	2			102						
20	5	T	3PBA	26	350	AW	0.05	0.2	5	-0.85
	5			78						
21	8	T	CB	30	350	SR	0.1	0.2	10	-0.85
18	10	CL	CB	32	350	AW	-1	0.2	20	-0.85
	10		4PB	40						
22,23	43	CL	CB	38	350	AW,SR	0,.5,-1	0.167	5	-0.85
24	3	T	4PB	70	350	AW	0.1	0.2	5	-0.9
11	4	T	CB	100	350	SR	0.1	0.2	10	-0.85
	3			160						
25	15	T	3PBA	16	600	AW	0.1	0.17	4	-1.2
20	4	T	3PBA	26	350	AW	0.05	0.2	5	-1.05
	5			78						
21	3	T	CB	30	350	SR	0.1	0.5	10	-1
22,23	20	CL	CB	38	350	AW	0,.5,-1	0.176	5	-1.1,-1.3
26	2	T	4PB	40	350	AW	0	0.4	20	-1.1
27	3		4PB	70	350	AW	0.1	0.2	5	-1.1
19	4	T	3PBA	13	300	AW	0.1	0.3	22	F.C.
	8			25						
	11			51						
	8			102						
25	7	T	3PBA	16	600	AW	0.1	0.17	4	F.C.
20	5	T	3PBA	26	350	AW	0.05	0.2	5	F.C.
	5			78						
21	3	T	CB	30	350	AW	0.1	0.5	10	F.C.
17	30	CN	CB	30	350,750	AW	0	0.167	5,25	F.C.
28	6	CN	CB	30	350,450	AW	0	0.167	5	F.C.
	6			50						
18	8	CL	CB	32	350	AW	-1	0.2	20	F.C.
	10		4PB	40						
24,27	25	T	4PB	40	350	AW	0.1	0.2	20	F.C.
	13			70						
26	5	T	4PB	40	350	AW	0	0.4	20	F.C.

Table 3a - Summary of tubular joints tested in air

Ref.	Number of tests	Joint type	Loading	Chord Dia D (mm)	Thickness T (mm)	Beta d/D	Tau t/T	Load ratio
22	3	T	OPB	458	17	1	1	0
	3						0.6	
	2					0.3	0.4	0.3
	3			460	16	1	1	
	5		IPB	457			1.1	-1
	3		AX					
	2		IPB				0.6	
	3		AX					
	1		IPB			0.2	0.4	
	1		AX					
	2	OK	OPB			0.5	0.2	0
	2				18		0.7	
	1	NK	AX		16		0.5	
	1	OKT	OPB					
	3						0.8	
	1	NKT	AX				0.5	
	2	T	IPB	914	32		1	-1
	1		AX					
	2		AX				0.3	
	1		IPB					
	1					0.2	0.5	
29	1	K	AX	508	16	0.6	0.8	-1
	1	Y				0.5	0.6	
	2	X	IPB	640	40		0.5	0.1
24	5	T	AX	457	16	0.5	0.5	0
	2					0.2	0.4	-1
	3	X				1	1	
	5	T		914	32	0.5	0.5	0
	4	X						

Table 3a - (continued)

Ref.	Number of tests	Joint type	Loading	Chord Dia D (mm)	Thickness T (mm)	Beta d/D	Tau t/T	Load ratio
30	3	T	OPB	457	16	0.5	0.8	0
	7							-1
31	1	X	AX	473	22	0.7	0.9	0.1
	1		IPB				1	
	1		AX	684	40	0.5	0.6	0.1
	1		IPB					
	1		AX	949	42	0.7	1	
	1		IPB					
	1		AX	1280	76	0.3	0.3	
	1					0.5	0.5	
	1		IPB				0.6	
23	3	T	AX	914	32	0.5	0.5	0
	4	H		1830	76			-1

T - T-joint
X - X-joint
H - H-joint
OK - non-overlapped K-joint
OKT - non-overlapped KT-joint
NK - overlapped K-joint
NKT - overlapped KT-joint

AX - axial loading
IPB - in-plane bending
OPB - out-of-plane bending

Table 3b - Summary of tubular joints tested in seawater

Ref.	Number of tests	Joint type	Loading	Chord T/D (mm)	Steel grade (MPa)	Post weld treatment	Load ratio	Freq-uency (Hz)	Tempe-rature (C)	Potential (V)
23	4	T	AX	32/914	350	AW	0	0.167	5	-0.85
32	4	T	AX	19/457	350	SR	0.1,0.3	0.167	8	-0.85
33*	4	T	AX	16/457	350	AW	0.1	0.167	8	-0.85
27	1	T	AX	32/914	350	AW	0	0.2	20	-0.8
31	1	X	IPB	40/320	460	AW	0.1	0.5	15	-0.8
35,41	2	T**	AX	19/914	350	AW	0.05	0.2	5	-0.85
36	2	T***	IPB	26	350	AW	0.05	0.2	5	-0.85
	2									-1.05
37	8	X	IPB	32/950	400	AW	0.1	0.35	10	-0.85
	4		IPB		450					
	4		AX		400					
40	4	T****	IPB	32/914	350	AW	0	0.16	6	-1.03
24,27	2	T	AX	16/457	350	AW	-1	0.2	20	F.C.
	2			32/914			0			
38	4	T	AX	20/508	490	AW	-1	0.3	5	F.C.
39	2	T	OPB	20/457	350	AW	0	0.167	10	F.C.
36	2	T***	IPB	26	350	AW	0.05	0.2	5	F.C.

* Variable amplitude loading
** Internal ring stiffened joints
*** Pipe-to-plate joints
****Bending of two braces on one chord

Table 4 Constants in equation (1) best fit, standard deviations and coefficients of correlation

Environment	Slope m	Log K	Stand. dev. of log N	Coef. of correlation
Air	3.01	12.788	0.196	0.875
Seawater:				
OCP	3.61	13.945	0.288	0.729
COP	3.56	13.578	0.281	0.744
FC	2.67	11.635	0.220	0.844

Table 5 Fatigue strengths and environmental strength and life reduction factors at short and long lives

Environment	N = 10^5 cycles			N = $2*10^6$ cycles		
	S (MPa)	ESRF	ELRF	S (MPa)	ESRF	ELRF
Air	387.61			143.21		
Seawater:						
OCP	300.90	1.29	2.14	131.20	1.09	1.30
COP	257.31	1.51	3.42	110.88	1.29	2.15
FC	304.34	1.27	2.07	99.17	1.44	3.01

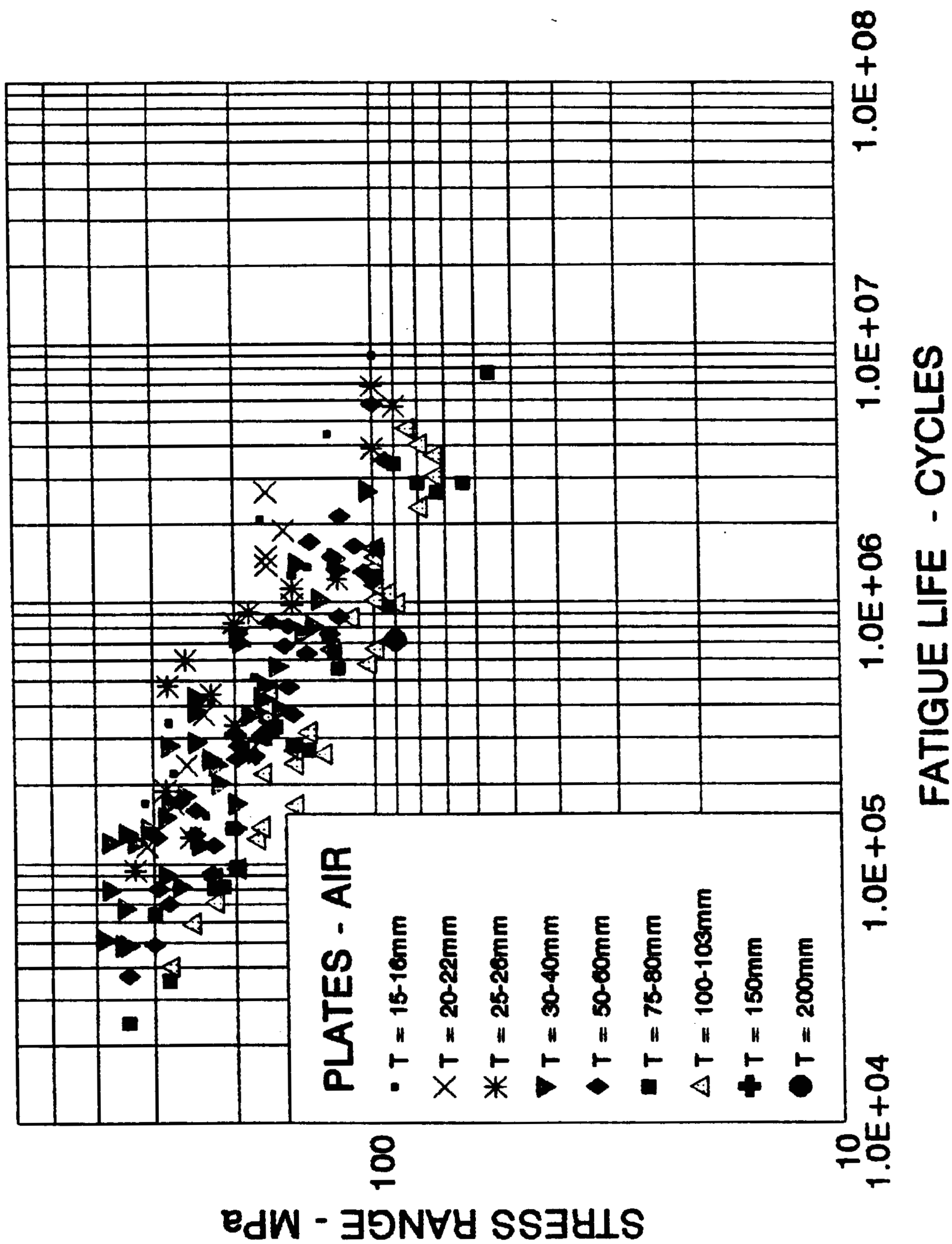

Fig.1a - Plate joints tested in air

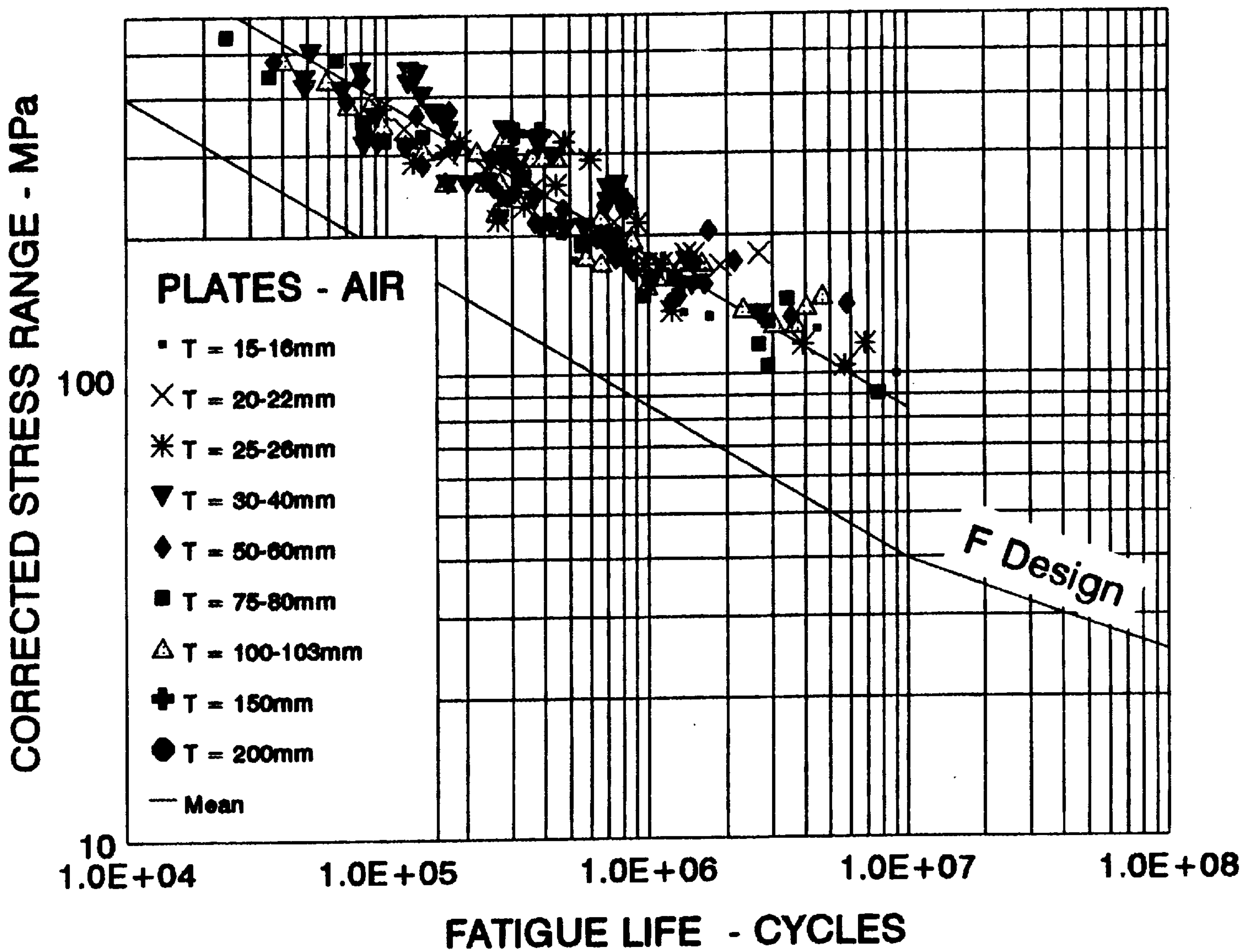

Fig.1b - Plate joints tested in air: stress corrected for thickness effect

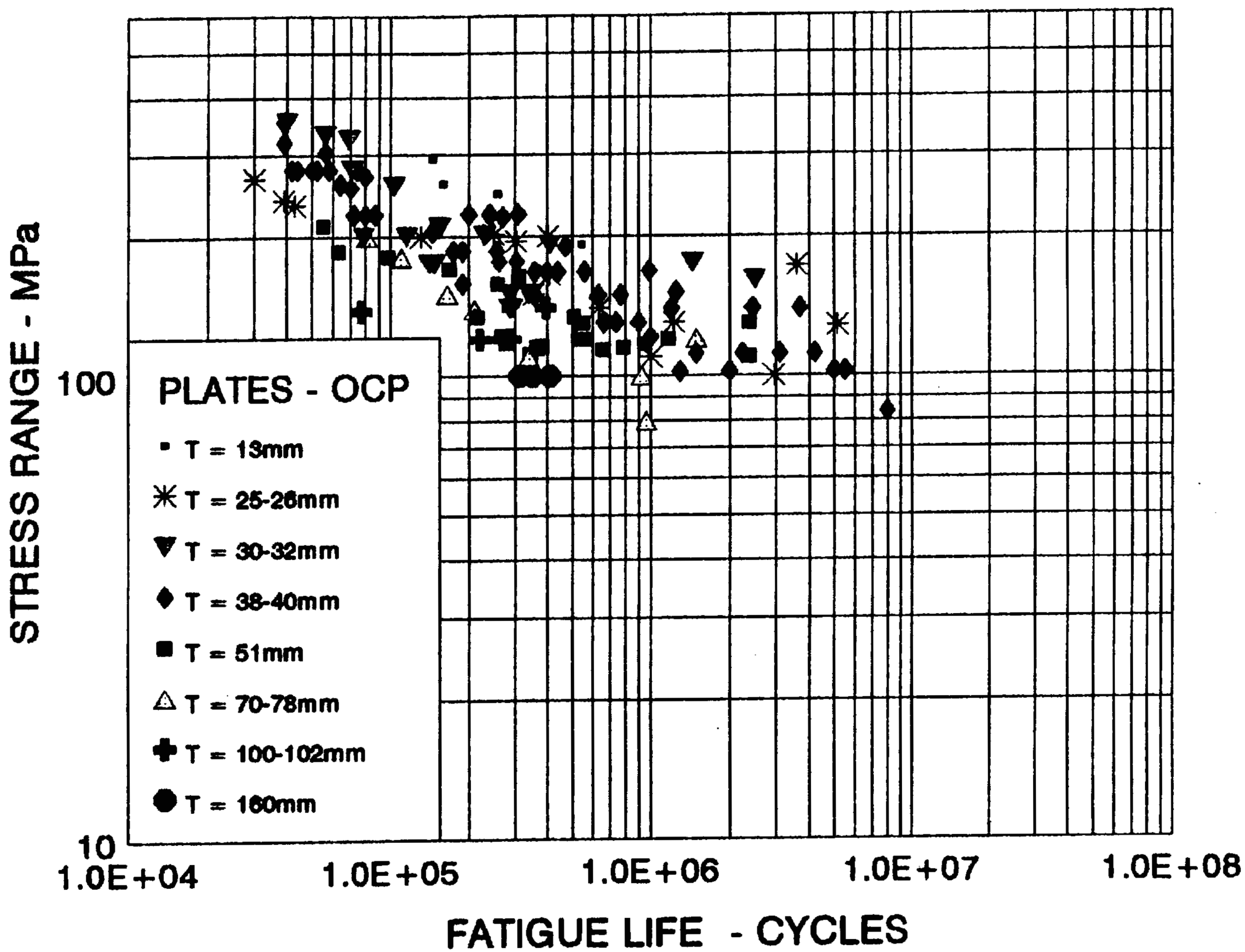

Fig.2a - Plate joints tested in seawater under OCP

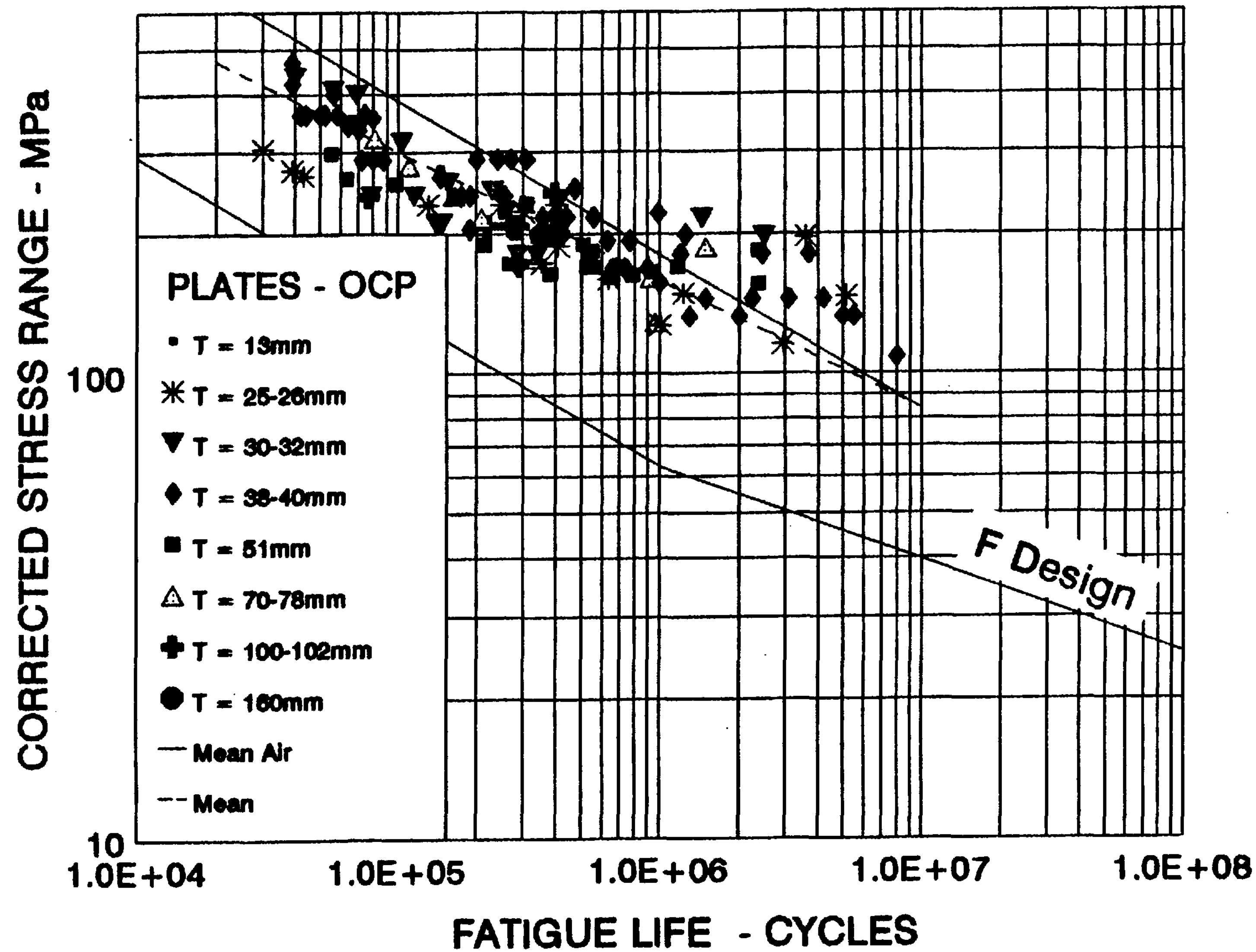

Fig.2b - Plate joints tested in seawater under OCP: stress corrected for thickness effect

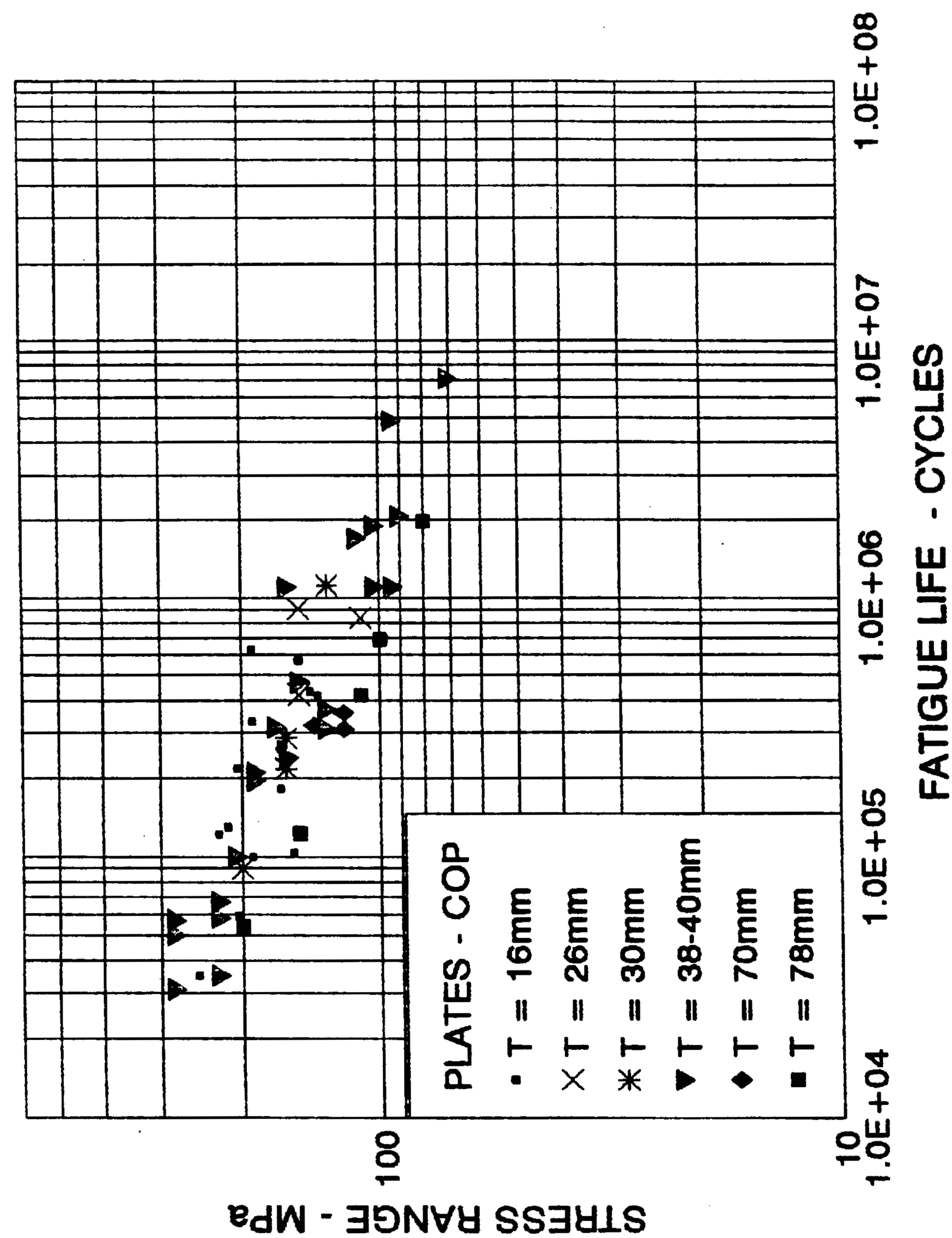

Fig.3a - Plate joints tested in seawater under COP

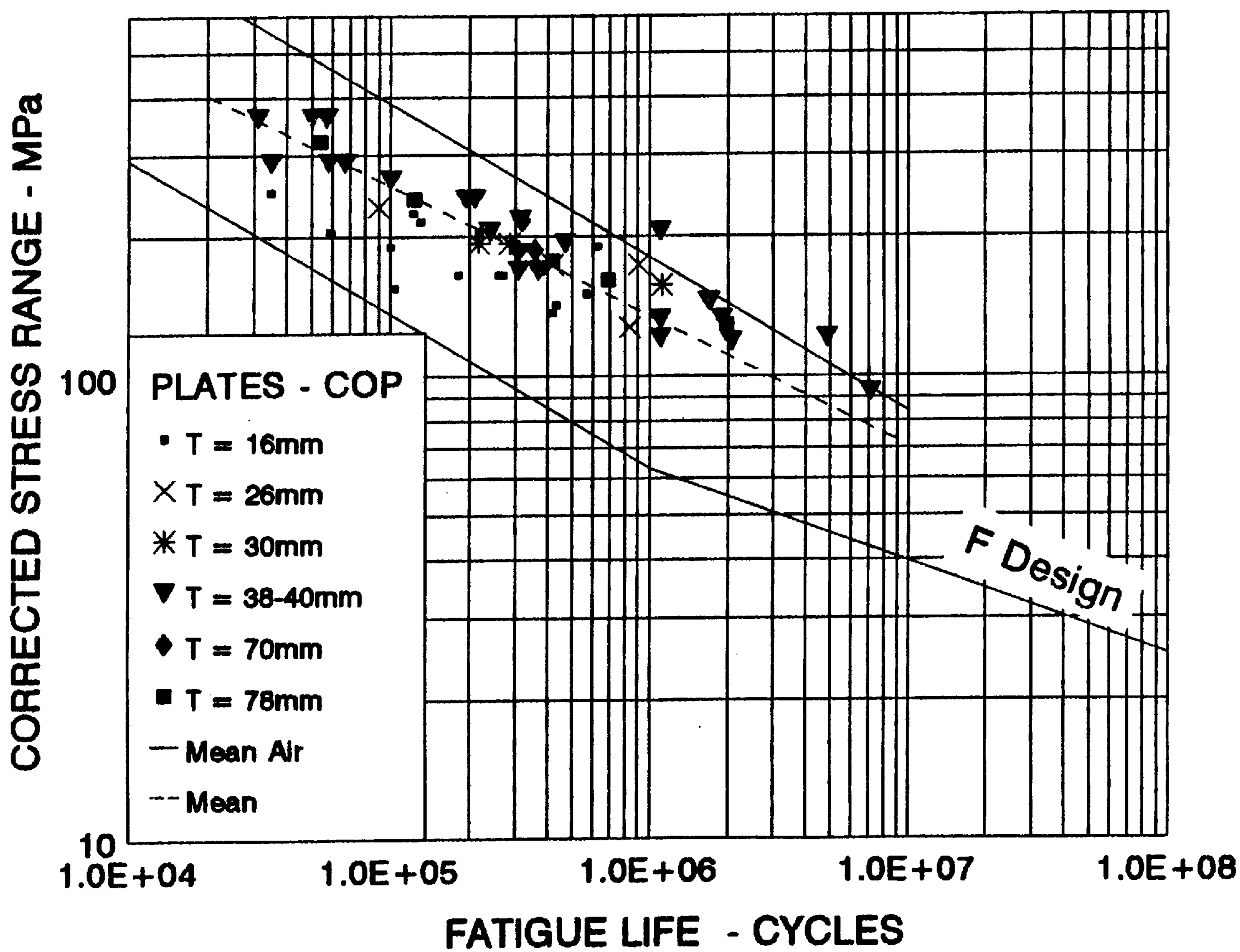

Fig.3b - Plate joints tested in seawater under COP: stress corrected for thickness effect

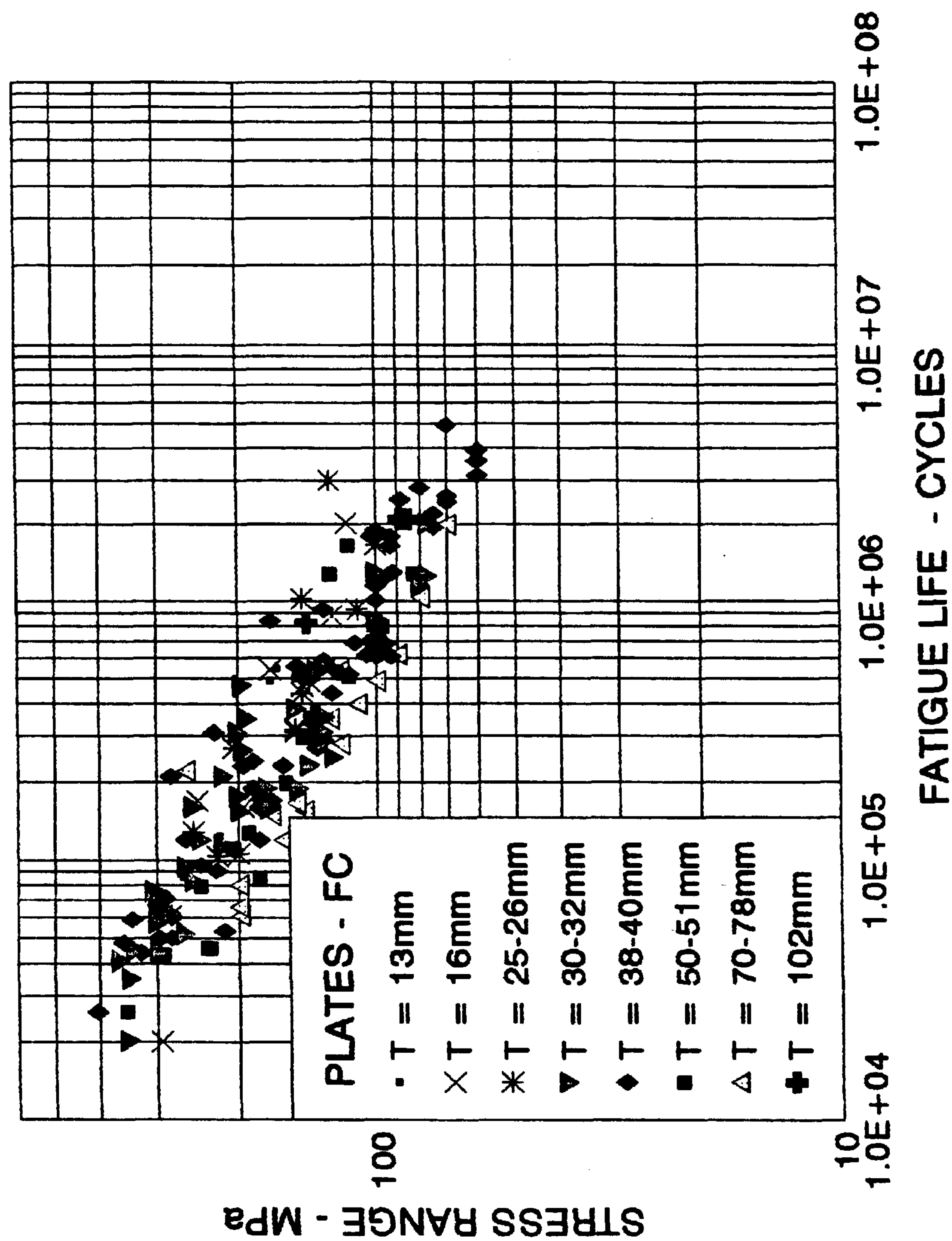

Fig.4a - Unprotected plate joints tested in seawater

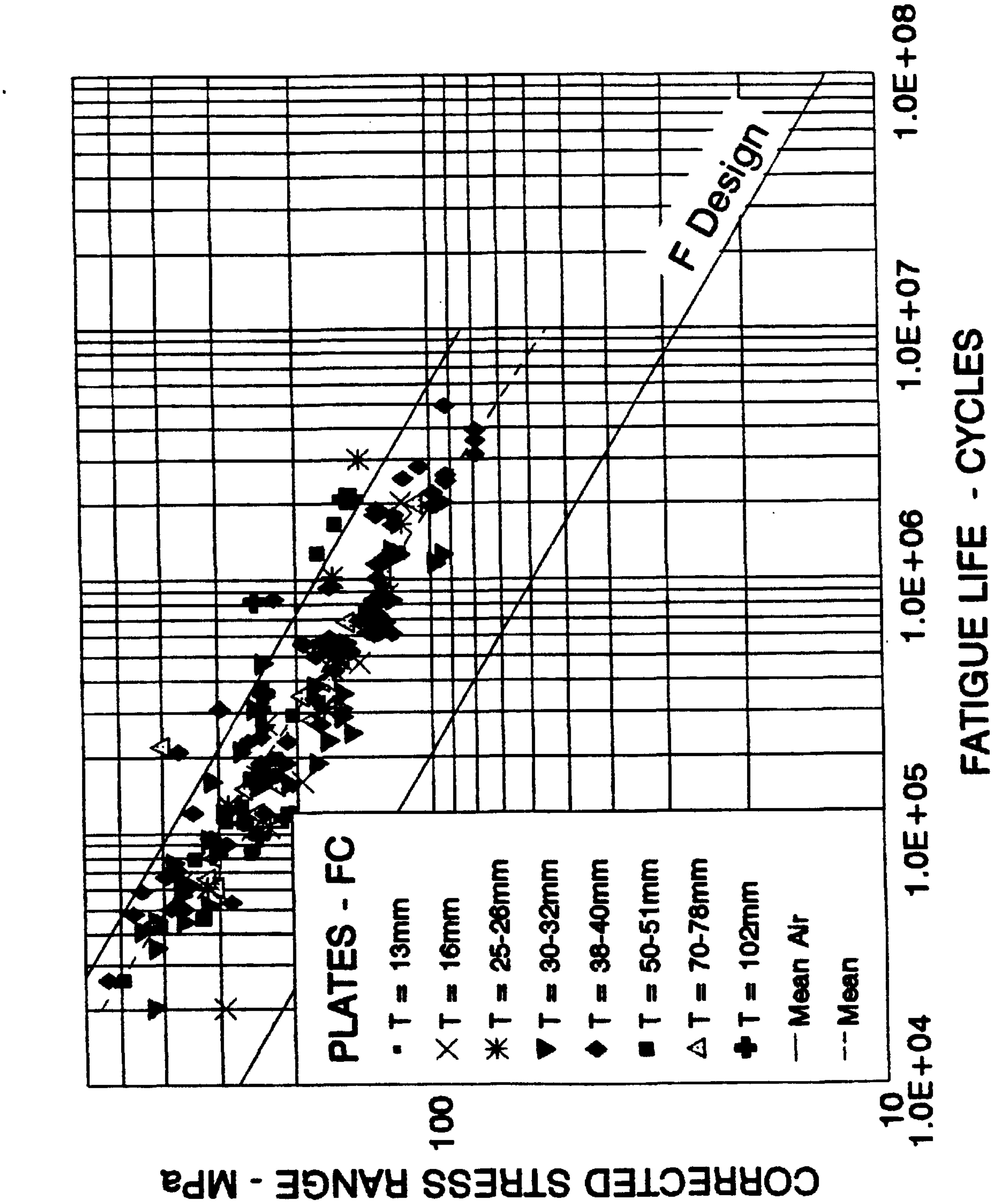

Fig.4b - Unprotected plate joints tested in seawater: stress corrected for thickness effect

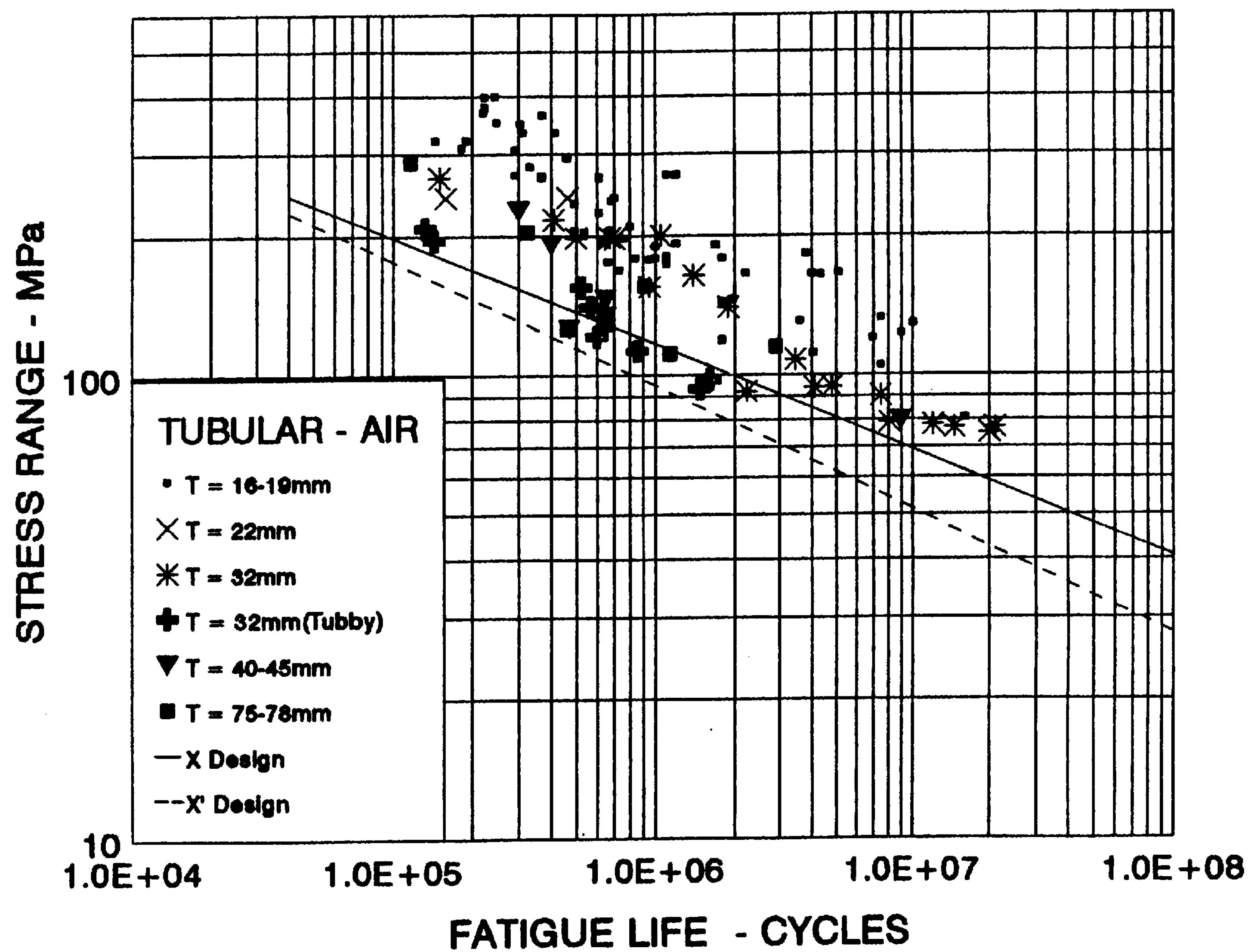

Fig.5a - Tubular joints tested in air

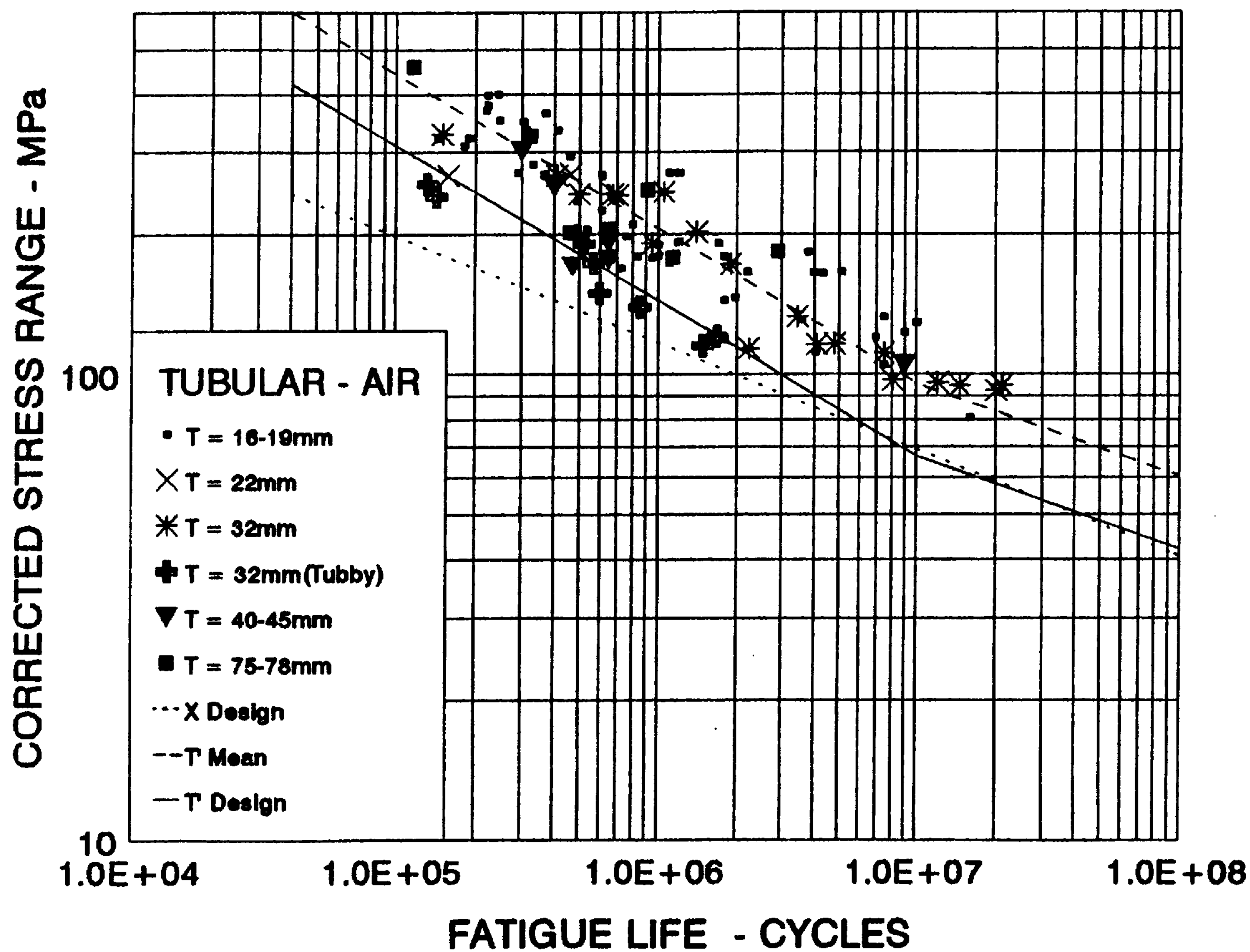

Fig.5b - Tubular joints tested in air: stress corrected for thickness effect

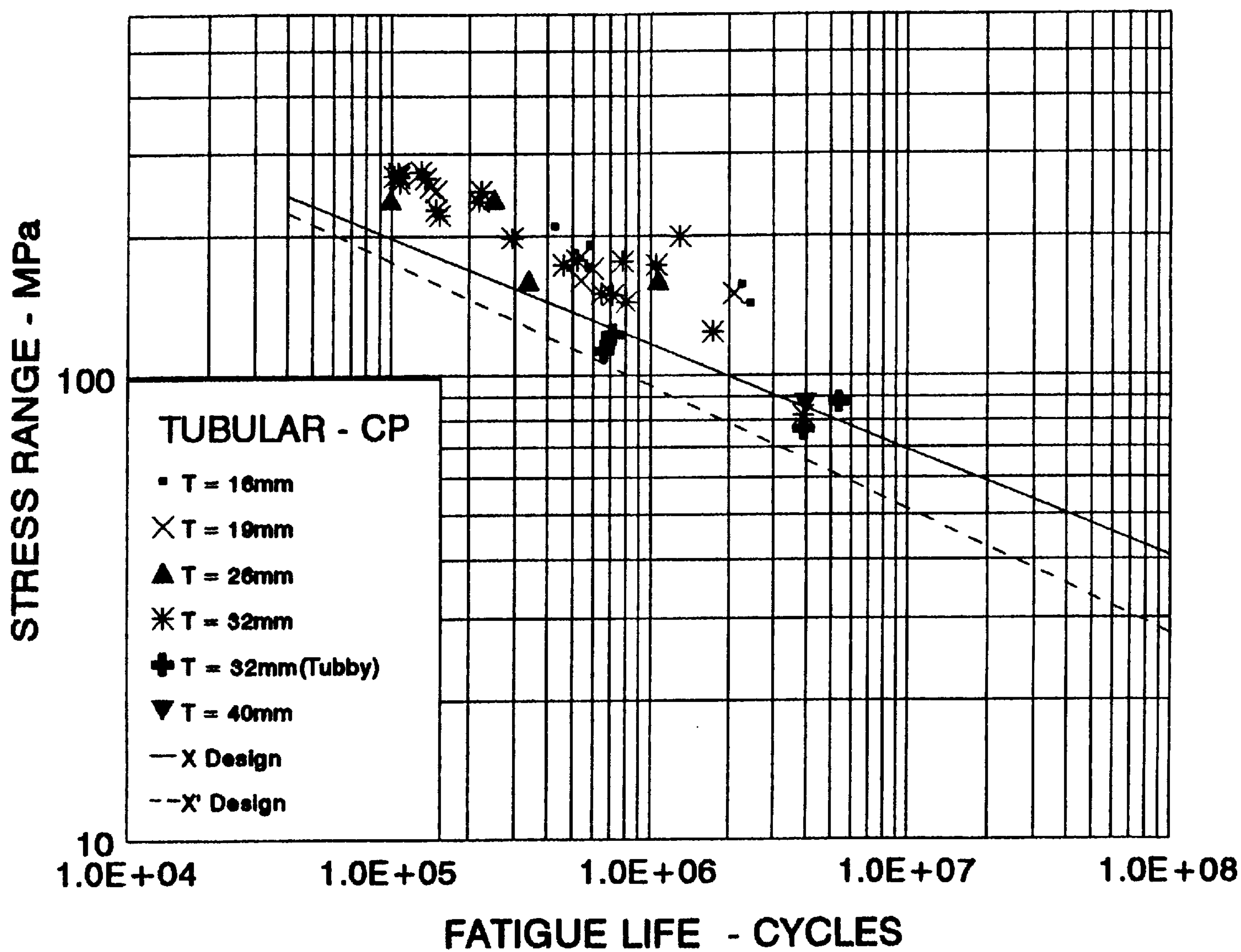

Fig.6a - Tubular joints tested in seawater under OCP

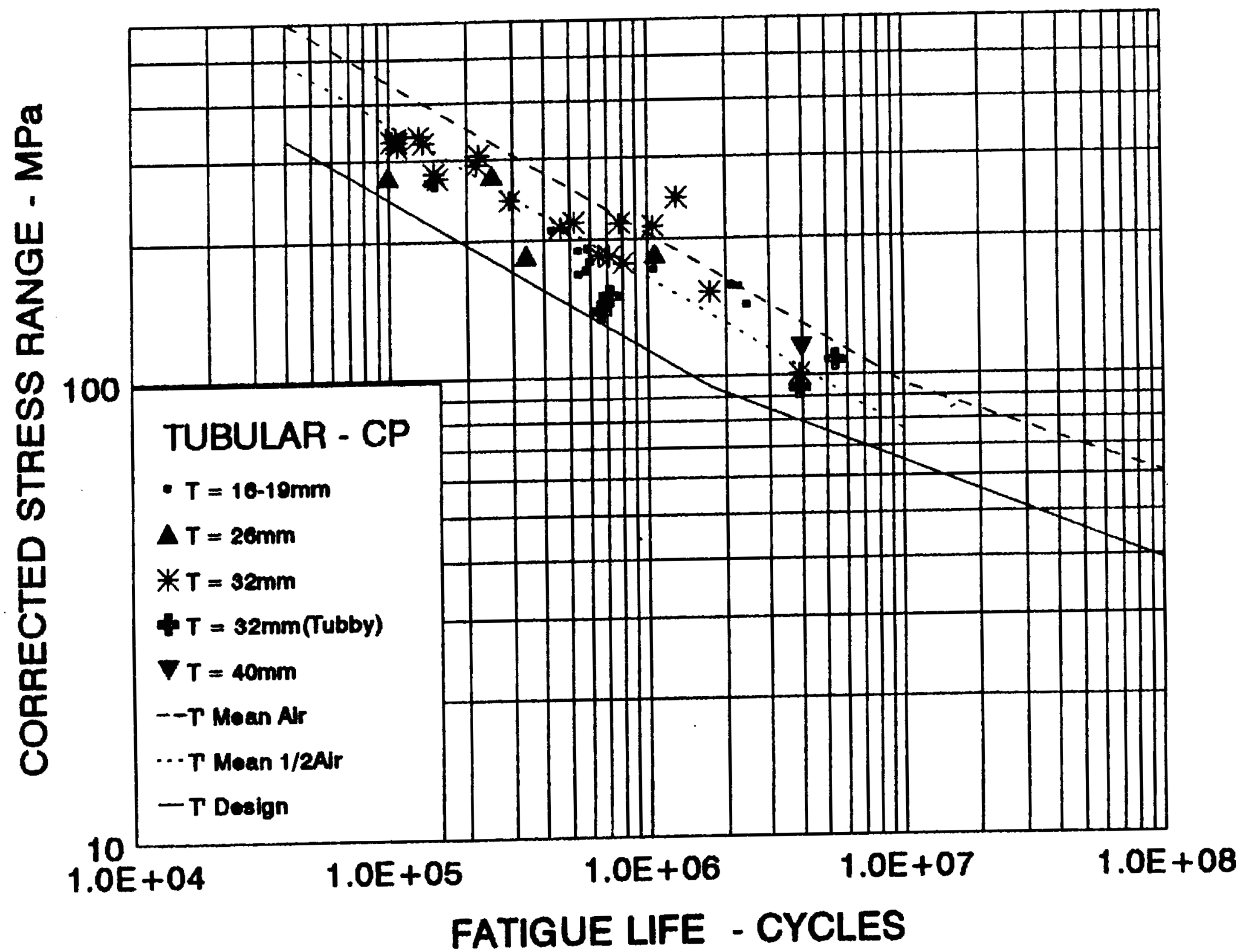

Fig.6b - Tubular joints tested in seawater under OCP: stress corrected for thickness effect

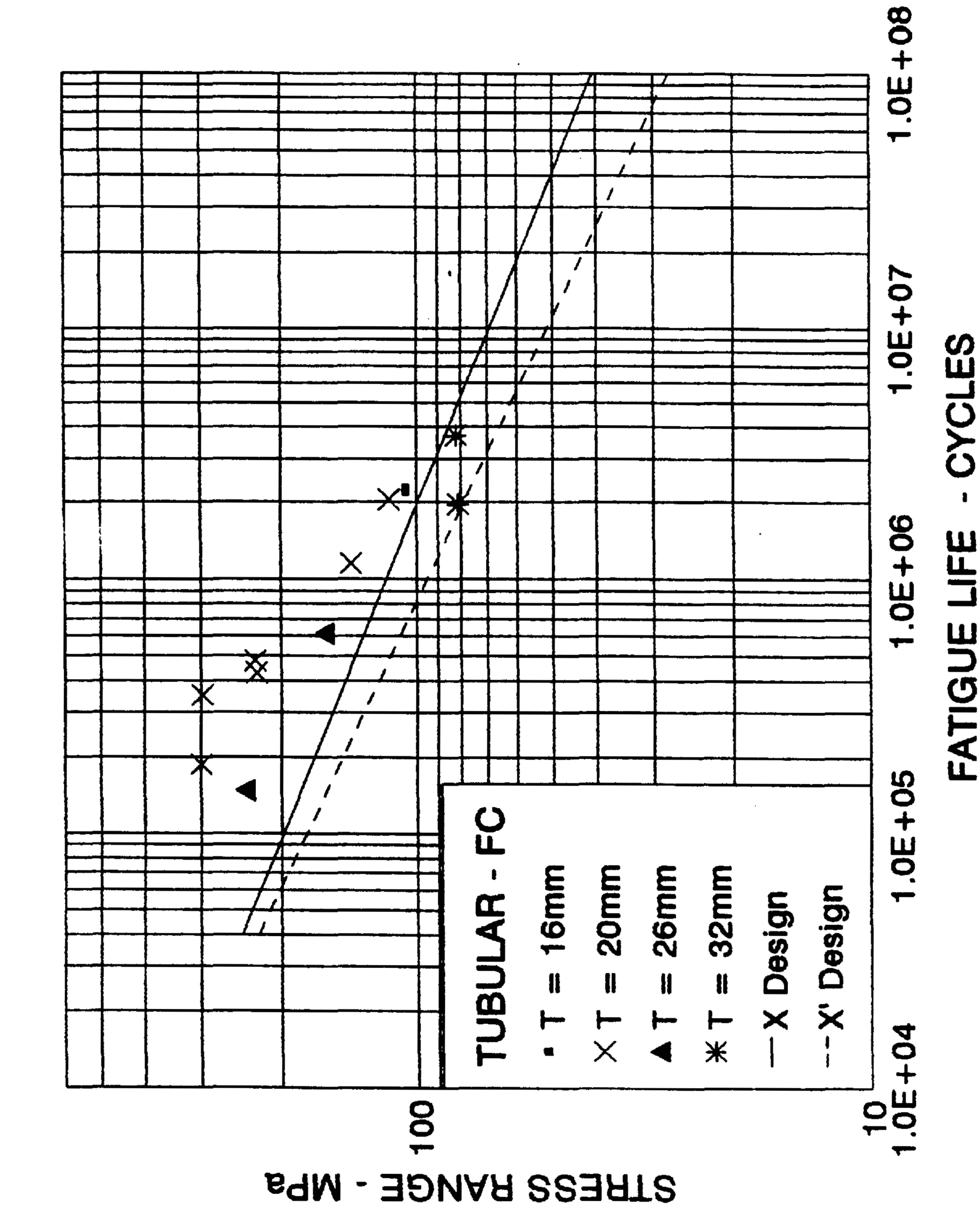

Fig.7a - Unprotected tubular joints tested in seawater

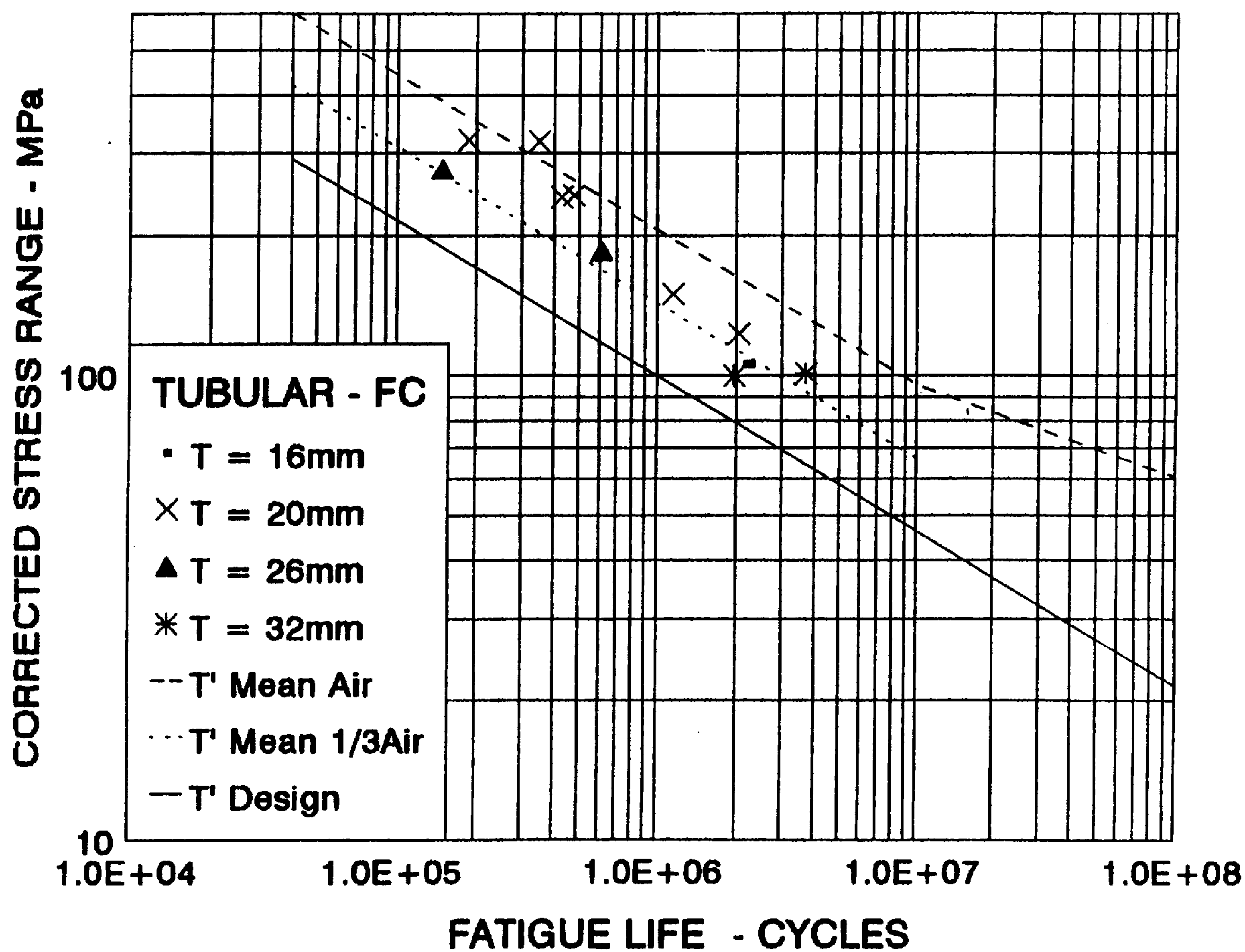

Fig.7b - Unprotected tubular joints tested in seawater: stress corrected for thickness effect

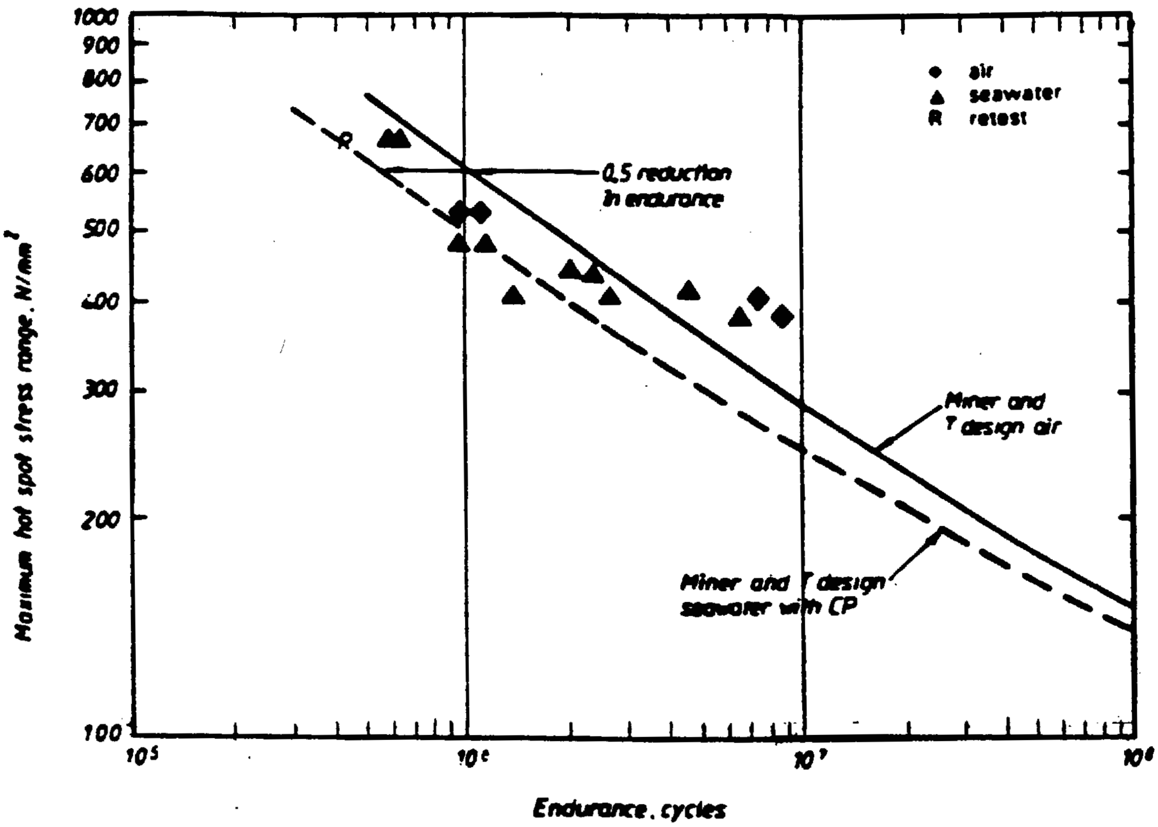

Fig.8 - Varible load amplitude tests of tubular joints in air and seawater under COP (40)