NTIS #PB2000-108444

SSC-412

INTERACTIVE NATURE OF CATHODIC POLARIZATION AND FATIGUE

SHIP STRUCTURE COMMITTEE
2000

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An Interagency Advisory Committee

SR-1335
SSC-412

September 2000

INTERACTIVE NATURE OF CATHODIC POLARIZATION AND FATIGUE

This report describes experimental studies and analytical modeling of the corrosion-fatigue behavior of cathodically protected ASTM A710, Grade A, Class 3 steel in seawater. The work consists of a comprehensive literature search, fatigue experiments on base-metal specimens in seawater, fatigue experiments on welded specimens in seawater, and development of a fatigue model. The corrosion-fatigue testing was performed in synthetic seawater at room temperature using sinusoidal loading at a stress ratio of 0.1 and a frequency of 1 Hz. Cathodic polarization levels of -0.09 and -1.13 V vs. Ag/AgCl were evaluated. The base-metal specimens had stress-concentration factors of 1.0, 2.0, 3.5, and 5.0, and they were subjected to cyclic axial loads. The weld-joint specimens were full-thickness (19mm) plate, either butt or fillet welded, and subjected to cyclic three-point bending loads. Fatigue crack growth data were developed for the base metal using compact-tension specimens. Both fatigue crack initiation and growth data were developed for the welded joints. Fatigue strength reduction factors were developed to account for the effects of notch severity and weld-joint configuration. A model that uses a fatigue curve to predict crack-initiation life and crack growth rate data to predict crack-propagation life was developed. This model can be employed in the fatigue design of marine structures.

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SSC-412		
4. Title and Subtitle Interactive Nature of Cathodic Polarization and Fatigue		5. Report Date September 2000
		6. Performing Organization Code **R 211-04**
7. Author(s) Carl E. Jaske		8. Performing Organization Report No. SR-1342
9. Performing Organization Name and Address CC Technologies Laboratories, Inc.		10. Work Unit No. (TRAIS)
6141 Avery Road Dublin, OH 43016-8761		11. Contract or Grant No. DTCG23-92-C-E01002
12. Sponsoring Agency Name and Address Ship Structure Committee C/O US Coast Guard (G-MSE/SSC)		13. Type of Report and Period Covered Final Report
2100 Second Street, SW Washington, DC 20593		14. Sponsoring Agency Code **G-M**
15. Supplementary Notes Sponsored by the Ship Structure Committee. Jointly funded by its member agencies		

16. Abstract

This report describes experimental studies and analytical modeling of the corrosion-fatigue behavior of cathodically protected ASTM A710, Grade A, Class 3 steel in seawater. The work consisted of a comprehensive literature search, fatigue experiments on base-metal specimens in seawater, fatigue experiments welded specimens in seawater, and development of fatigue model. The corrosion-fatigue testing was performed in synthetic seawater at room temperature using sinusoidal loading at a stress ratio of 0.1 and a frequency of 1 Hz. Cathodic polarization levels of -0.09 and -1.13 V vs. Ag/AgCl were evaluated. The base-metal specimens had stress-concentration factors of 1.0, 2.0, 3.5, and 5.0, and they were subjected to cyclic axial loads. The weld-joint specimens were full-thickness (19mm) plate that was either butt welded or fillet welded, and they were subjected to cyclic three-point bending loads. Fatigue crack growth data were developed for the base metal using compact-tension specimens. Both fatigue crack initiation and growth data were developed for the welded joints. Fatigue strength reduction factors were developed to account for the effects of notch severity and weld-joint configuration. A model that uses a fatigue curve to predict crack-initiation life and crack growth rate data to predict crack-propagation life was developed. The model can be employed in the fatigue design of marine structures.

17. Key Words	18. Distribution Statement
Fatigue, Corrosion, Cathodic Polarization	Distribution is available to the public through: National Technical Information Service U.S. Department of Commerce Springfield, VA 22151 Ph. (703) 605-6000

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FOREWORD

This project was funded by the Ship Structure Committee. The Ship Structure Committee is an interagency committee sponsoring ship structure research projects. Its membership is made up equally from the American Bureau of Shipping, Defence Research Establishment Atlantic (Canadian National Defence), Maritime Administration, Military Sealift Command, Navel Sea Systems Command, Transport Canada, and the U.S. Coast Guard.

The research by conducted by CC Technologies Laboratories, Inc. in Dublin, OH. The project is entitled SR-1342, Interactive Nature of Cathodic Polarization and Fatigue. The objective of the project was to investigate the effect of cathodic polarization on fatigue of steel in seawater and how this effect is influenced by notch severity, crack size, and material composition, microstructure, and strength and to formulate a model that predicts how the fatigue properties of steel in seawater are influenced by cathodic polarization.

EXECUTIVE SUMMARY

This report describes the results of a fatigue study of cathodically polarized steel in seawater. The research project was divided into the following four tasks: (1) comprehensive literature search, (2) fatigue experiments in seawater, (3) fatigue of welded specimens in seawater, and (4) development of a fatigue model. The experimental work of Tasks 2 and 3 was performed on specimens made from 19-mm thick ASTM A 710, Grade A, Class 3 steel plate.

The comprehensive literature search extended a previous review of publications on corrosion-fatigue of steels in marine environments (Jaske et al., 1981). Results from the review of the literature in the first task were used to finalize the plans for the fatigue testing in the second and third tasks and to help develop the fatigue model in the fourth task. A total of 296 documents were obtained and reviewed. The reference citation and notes relevant to the current research were recorded in a computerized database. The database then was used to prepare the detailed bibliography in Appendix A. It uses the key words and types of steels listed in Appendices B and C, respectively. A copy of the database is included with this report.

Task 2 consisted of fatigue testing axially loaded smooth (unnotched) and notched base-metal specimens to develop stress versus number-of-cycles-to-failure (S-N) curves and crack-growth testing of base-metal compact-tension (CT) specimens to develop cyclic crack-growth rate (da/dN) data. The smooth specimens were tested in both air and synthetic seawater at room temperature (RT). The notched specimens were tested only in synthetic seawater at RT. For testing in seawater, the loading was sinusoidal at a stress ratio (R) of 0.1 and a frequency of 1 Hz, and the specimens were cathodically polarized to either -0.90 or -1.13 V vs. Ag/AgCl (adequate or over cathodic protection).

For adequate cathodic protection, the fatigue crack initiation resistance was slightly better than that in air, while the fatigue crack growth rate was about the same as that in air. Over cathodic protection degraded the fatigue crack initiation resistance slightly, but did not reduce it below that in air. The fatigue resistance of notched specimens with stress concentration factors of 2.0, 3.5, and 5.0 decreased as the stress concentration factor increased. Over cathodic protection reduced fatigue crack growth rate by producing calcareous scale deposits within the crack that reduced the effective range of stress intensity factor. Where the current fatigue initiation and crack-growth data could be compared with published data from other corrosion-fatigue studies of ASTM A710 steel in seawater, the current results were in good agreement with those data.

Task 3 consisted of fatigue testing of butt-welded and fillet-welded specimens subjected to cyclic three-point bending to develop crack initiation and crack-growth data. The seawater environment, loading, and cathodic polarization conditions were the same as those used in testing the base-metal specimens. Specimens with as-welded or ground weld toes had similar fatigue strengths, while specimens with undercut weld toes had very low fatigue strengths. The butt welds had higher fatigue resistance than the fillet welds. The level of cathodic polarization did not have a significant effect on the fatigue strengths of the welded joints.

The DC electric potential drop method was used to detect crack initiation and measure crack growth in the welded-joint specimens. The fatigue crack growth behavior of welded joints was well characterized using the standard fracture-mechanics approach. The crack growth data obtained from tests of welded joints agreed with those from tests of standard fracture mechanics specimens.

The fatigue crack initiation resistance of notched specimens was well correlated with that of unnotched specimens by using Peterson's (1974) fatigue strength reduction factor to calculate local stress values at the notches. The fatigue strength reduction factor was determined using the stress concentration factor, a material parameter, and the notch root radius. This same fatigue strength reduction factor also gave good predictions of the fatigue crack initiation resistance of both butt-welded and fillet-welded joints.

The total fatigue life of welded joints can be predicted as the sum of the crack-initiation life and the crack-growth life. The crack-initiation life is obtained from a S-N curve using the local stress at the weld toe. The local stress is computed using the fatigue strength reduction factor. The crack-growth life is computed by using fracture mechanics and integrating the crack-growth rate relationship. This approach can be applied to the fatigue design of welded joints in marine structures.

CHAPTER 1

INTRODUCTION AND OBJECTIVE

Fatigue is an important potential degradation mechanism for structures that operate in marine environments. Typical marine structures subject to fatigue include ships, offshore platforms, harbor works, drilling rigs, and underwater pipelines. Fatigue damage is caused by cyclic loadings imposed by winds, waves, tides, and variations in operating conditions. These loadings, possibly coupled with dynamic amplification, produce locally high stresses at structural discontinuities such as joints, connections, notches, and welds. Fatigue damage results in the initiation and propagation of cracks at such structural locations. Thus, fatigue damage in marine structural systems is the initiation and growth of cracks at locations of high cyclic stress.

The majority of marine structures are fabricated from carbon or low-alloy steels. The rate of fatigue crack initiation and growth in carbon or low-alloy steels can be significantly increased by exposure to seawater. Seawater also causes corrosion of such steels. Cathodic polarization is the most widely used means of protecting submerged marine steel structures from corrosion. Depending on the nature of the seawater environment, the level of polarization, the type of steel, and the fatigue mechanism, cathodic polarization may or may not be an effective means of mitigating fatigue damage. In some situations, cathodic polarization may even aggravate the fatigue damage process. The interaction of cathodic polarization and fatigue crack initiation and growth in marine structural steels is an area of great practical engineering interest.

Cathodic polarization is effective in improving the corrosion-fatigue crack initiation resistance of smooth, uncracked steel specimens tested in seawater. When smooth specimens are tested in seawater under free-corrosion conditions, the fatigue strength is reduced below that measured in air. In other words, the stress versus number-of-cycles-to-failure (S-N) curve for specimens tested in seawater falls well below that of specimens tested in air, especially at low cyclic loading frequencies of 1 Hz or less. Experimental results show that cathodic polarization can improve the fatigue strength of smooth specimens tested in seawater to levels comparable or even slightly above those of smooth specimens tested in air.

For corrosion-fatigue crack initiation at notches, however, cathodic polarization may or may not provide effective protection. Lower levels of polarization provide a degree of benefit, while higher levels of polarization can actually degrade fatigue strength. This behavior is related to the strength and microstructure of the steel and the notch severity. The degradation of fatigue performance at higher levels of polarization is believed to be caused by the effect of hydrogen on the fatigue crack initiation process. As notch severity (notch-tip triaxiality) and material strength increase, the susceptibility to hydrogen effects also tends to increase. Corrosion-fatigue crack initiation at notches, such as weld toes and weld defects, is a significant problem for marine structures, so it is important to understand the effects of cathodic polarization on corrosion-fatigue crack initiation at notches.

Cathodic polarization also has mixed effects on corrosion-fatigue crack propagation in seawater. Mild levels of polarization may slightly improve corrosion-fatigue crack-growth resistance, but the levels typically employed in the protection of marine structures often accelerate corrosion-fatigue crack-growth rate because of the detrimental effects of hydrogen generated by the cathodic reaction. However, when calcareous deposits form within the crack, crack-growth rates can be decreased by crack-closure effects that decrease the effective crack-tip stress intensity factor range. For these reasons, cathodic polarization can either increase or decease the corrosion-fatigue crack propagation rates for steels in seawater.

The following seven variables can affect the interaction of cathodic polarization and corrosion-fatigue of structural steels in seawater:

1. *Magnitude of cyclic stress range*. High stress ranges cause relatively rapid fatigue damage and crack growth, so the effects of the environment are minimal. Low stress ranges cause fatigue damage to develop slowly, so corrosion has time to accelerate the rate of fatigue-crack initiation. Corrosion often has little effect on the rate of crack propagation at low stress ranges, but it can greatly increase the rate of fatigue crack growth at intermediate stress ranges.

2. *Cyclic frequency*. The lower range of the cyclic loading frequencies to which marine structures are typically exposed (0.1 to 1.0 Hz) can significantly lower fatigue strength and increase crack-growth rates.

3. *Level of cathodic polarization*. Levels of cathodic polarization sufficient to protect marine structures from corrosion can have either and beneficial or a detrimental effect on fatigue behavior, as was discussed previously.

4. *Notches and defects*. Notches and defects provide local stress concentrations where fatigue cracking is more likely to initiate and can reduce the effectiveness of cathodic polarization. Small notches and defects associated with welds are particularly important.

5. *Cracks*. It is difficult to effectively protect cracks from the detrimental effects of marine corrosion using cathodic polarization. Furthermore, hydrogen produced by the cathodic reaction often accelerates the fatigue crack growth rate. If calcareous deposits form within a crack, the rate of crack growth is usually decreased because of crack-closure effects.

6. *Alloy composition*. The alloying elements, at the levels that they are typically present in low-alloy structural steels, have little direct influence on their corrosion-fatigue resistance in seawater. They do, however, indirectly effect fatigue strength through their effect on microstructure and strength level after heat treatment and welding.

7. *Biological species*. Biologically active species can affect corrosion-fatigue of marine structures in two ways. Macrobial growths can increase hydrodynamic loading and, hence, reduce the fatigue performance of the structure. Microbial growths can increase the fatigue-crack-growth rate and decrease fatigue strength. This behavior is caused by the presence of small amounts of H_2S in the seawater. The H_2S is a metabolic product of sulfate-reducing bacteria.

The above factors were considered in developing the current research project. The experimental plan included tests at several different stress levels, three levels of cathodic polarization, and three degrees of notch severity. A reasonable cyclic frequency of 1 Hz was selected for all fatigue testing in seawater. Both crack initiation and crack growth were included in the experimental work. ASTM A710, Grade A, Class 3 steel plate was selected for the fatigue testing because it was considered to be representative of typical modern, high-strength low-alloy steels used for marine applications. The effects of biologically active species on corrosion fatigue were outside of the scope of the project, so all corrosion-fatigue tests were conducted in synthetic seawater. Thus, the main factors that are believed to influence the corrosion-fatigue behavior of cathodically polarized steel in seawater were addressed in this research project.

Objective. The objective of the project was to investigate the effect of cathodic polarization on fatigue of steel in seawater and how this effect is influenced by notch severity, crack size, and material composition, microstructure, and strength and to formulate a model that predicts how the fatigue properties of steel in seawater are influenced by cathodic polarization.

CHAPTER 2

TECHNICAL APPROACH

To achieve the objective stated at the end of Chapter 1, the research project was divided into four tasks. These four tasks were (1) comprehensive literature search, (2) fatigue experiments in seawater, (3) fatigue of welded specimens in seawater, and (4) development of a fatigue model. The literature search extended a previous extensive review of publications on corrosion-fatigue of steels in marine environments (Jaske et al., 1981). Results from the review of the literature in the first task were used to finalize the plans for the fatigue testing in the second and third tasks and to help develop the fatigue model in the fourth task.

Scope of Work

The literature on electrochemical potential and fatigue interactions for steels in seawater was comprehensively searched, concentrating on documents published since 1981 or after the review of Jaske, et al. (1981). The literature search utilized the resources of technical libraries at Battelle and The Ohio State University in Columbus, Ohio. The documents obtained from this comprehensive literature search were thoroughly reviewed and evaluated by members of CC Technologies Laboratories, Inc.'s (CC Technologies) technical staff.

Corrosion-fatigue experiments on specimens from ASTM A710, Grade A, Class 3 steel plate were performed in ASTM synthetic seawater. All of the fatigue specimens were subjected to sinusoidal loading at a stress ratio, ratio of minimum to maximum cyclic stress, (R) of 0.1. A few fatigue tests were conducted in air to develop baseline fatigue data. A cyclic frequency of 10 Hz was used for the tests in air, whereas a cyclic frequency of 1 Hz was used for the tests in seawater. S-N curves were developed for both smooth and notched specimens of base metal. Fatigue crack growth data also were developed for base metal. Both S-N curves based on crack initiation and fatigue crack growth data were developed for butt-welded and fillet-welded specimens with varying degrees of notch severity at the weld toes. Both typical (-0.90 V vs. Ag/AgCl) and high (-1.13 V vs. Ag/AgCl) levels of cathodic polarization were used in the experiments. Thus, these tests characterized the corrosion-fatigue behavior of cathodically polarized base metal and weldments in seawater.

Based on the experimental data and information collected from the literature, a model was developed to predict the influence cathodic polarization on the fatigue behavior of the steel in seawater. The model incorporates the effects of cathodic polarization on both fatigue crack initiation and propagation. It considers the effect of notch severity on crack initiation, and the effect of calcareous deposits on crack growth. The model is formulated in terms of straight-forward equations so that it can be implemented easily by marine engineers and incorporated into computer codes used for the fatigue assessment of marine structures.

Material

Three pieces from a 19-mm (3/4-inch) thick plate of ASTM A710, Grade A, Class 3 steel were obtained. Each piece was approximately 0.61 by 0.61 m (24 by 24 inches). The chemical composition and tensile properties of the plate are listed in Tables 2-1 and 2-2, respectively. These satisfy the requirements of the ASTM specification, as indicated. This material is a low-carbon age-hardened nickel-copper-chromium-molybdenum-niobium steel that was quenched and precipitation heat treated. This steel has a combination of reasonably high tensile strength and high toughness, making it an ideal material for demanding structural applications.

TABLE 2-1. CHEMICAL COMPOSITION OF ASTM A710, GRADE A, CLASS 3 PLATE.

Element	Specified Amount, %	Measured Amount, %
C	0.07 max.	0.07
Mn	0.40-0.70	0.57
P	0.025 max.	0.011
S	0.025 max.	0.002
Si	0.40 max.	0.34
Ni	0.70-1.00	0.95
Cr	0.60-0.90	0.68
Mo	0.15-0.25	0.22
Cu	1.00-1.30	1.07
Nb	0.02 min.	0.045
Sn	--	0.010
Al	--	0.024
V	--	0.003
Zr	--	0.000
Ti	--	0.002
B	--	0.0007
Ca	--	0.0017
Co	--	0.008
Pb	--	0.00

TABLE 2-2. TENSILE PROPERTIES OF ASTM A710, GRADE A, CLASS 3 PLATE.

Property	Specified Minimum Value	Measured Value
0.2% Offset Yield Strength, MPa (ksi)	515 (75)	640 (92.8)
Ultimate Strength, MPa (ksi)	585 (85)	697 (101)
Elongation in 2 inches, %	20	42

CHAPTER 3

COMPREHENSIVE LITERATURE SEARCH

A total of 330 relevant references were identified from computerized literature searches, files at CC Technologies, and written inquiries. The technical libraries at CC Technologies and Battelle Memorial Institute were used for computerized searches of Corrosion Abstracts, Metals Abstracts, and Engineering Index. Conference proceedings and reports that belong to CC Technologies staff members were searched for pertinent information. Finally, letters were sent to individuals known to have performed corrosion-fatigue tests on steels in marine environments to request copies of publications that could not be readily obtained through technical libraries. As pointed out in the introduction, the searches concentrated on the literature published since 1981 because the relevant literature up to 1980 was reviewed in detail by Jaske, et al. (1981).

Once 317 documents were identified, each one was given a unique number for filing and retrieval purposes. The numbers (1 to 317) were assigned in alphabetical order based on the last name of the first author. As each of the additional 13 documents were identified, they were given intermediate numbers, such as 64.5, in the appropriate alphabetical order. To facilitate review and evaluation of the documents, a computerized database was constructed. Key information and relevant notes regarding the documents were entered into a computerized database.

The database consists of one file with 330 records. Each record contains information for one of the references. That information is divided into 13 fields, as follows:

1. Document Number
2. Name of First Author
3. Name(s) of Other Author(s)
4. Title of Document
5. Name of Book or Journal (as applicable)
6. The Volume, Number and Month of Publication (as applicable)
7. The Year of Publication
8. The Name and City of the Publisher (as applicable)
9. The Page Numbers of the Document (as applicable)
10. Key Words for the Document
11. The Type of Steel(s) Tested (as applicable)
12. Relevant Notes for the Document
13. Indication of Document Receipt

The phase "as applicable" in parentheses indicates that the field may be blank it is not relevant for the document. All other fields contain entries. The last field indicates whether the document was received by CC Technologies. Thirty-four (34) of the references could not be obtained or were never actually published. Thus, a total of 296 documents were obtained and reviewed.

Each document was reviewed and notes relevant to the current research were recorded in the 12th field of each database record. The database then was used to prepare the bibliography in Appendix A. This bibliography gives all of the information for the 296 documents that were reviewed. Key words were entered for each document. Appendix B lists the key words used in the database. When fatigue data were reported in a document, the type(s) of steel was recorded. Appendix C lists the types of steel used in the database. With the database organized in this fashion, it is easy to search and rapidly find information on a specific topic or documents authored or co-authored by a specific individual.

The literature database was used to identify documents with information relevant to the scope and objective of the project. Articles and reports that are directly pertinent to the current

Document	1.0
First Author	Adams, R. J.
Rec'd	yes
Other Authors	P. Mehdizadeh
Title	Corrosion fatigue behavior of self-shielded flux-cored weldments
Book/Journal	Materials Performance
Vol., No., Month	Vol. 20, No. 3, March
Year	1981
Publisher, City	
Pages	44-52
Key Words	welded joint, S-N curve, synthetic seawater
Type of Steel	BS 4360:50D
Notes	Rotating bending corrosion-fatigue tests in synthetic seawater were performed on specimens from weldments made with two types of flux-cored wires (NR203M and NR203 1%Ni) and with AWS E7016 electrodes. The corrosion-fatigue strength of the weldments made with flux-cored wires was equal to that of the weldments made with AWS E7016 electrodes.

FIGURE 3-1. EXAMPLE DATABASE RECORD.

work were reviewed and evaluated in detail. Appropriate information from these documents was then used in the remaining research tasks of this project. Ten of the articles and reports contained test results for ASTM A710 steel (Badve, et al., 1989; Bavarian, et al., 1994; Hartt, 1990; Hartt, et al., 1989, Rajpathak and Hartt, 1988 and 1990; Reynolds and Todd, 1992; Sablok and Hartt, 1990; and Todd, et al., 1988 and 1992). These are Documents 18, 23.5, 58, 111, 113, 228.5, 229, 231, 233, and 271 in the database.

The work at Florida Atlantic University (Badve, et al., 1989; Hartt, 1990; Hartt, et al., 1989; and Rajpathak and Hartt, 1988 and 1990) concentrated on fatigue testing of keyhole compact-tension (CT) specimens in seawater and at a cyclic loading frequency of 1 Hz. Compared with free-corrosion conditions, moderate cathodic polarization to -0.90 V vs. SCE increased fatigue strength. The fatigue strength decreased with decreasing potential from -1.00 to -1.10 V vs. SCE because of hydrogen embrittlement. Sablok and Hartt (1990) developed corrosion- fatigue data for welded, tapered cantilever beam specimens and evaluated the effect of weld-toe stress concentration factor on fatigue strength.

Todd and co-workers (Reynolds and Todd, 1992; and Todd, et al., 1988 and 1992) and Bavarian, et al. (1994) conducted fatigue-crack propagation studies in synthetic seawater using pre-cracked CT specimens. The former work addressed near-threshold crack growth; the range of stress intensity factor had to be corrected for crack closure effects to obtain proper threshold values, especially when the specimens were cathodically polarized. The latter work evaluated fatigue crack growth in the Paris-Law regime well above the threshold. In all of these studies, the fracture-mechanics approach was used to evaluate crack-growth behavior and the data were presented in standard log-log plots of cyclic crack growth rate (da/dN) versus stress intensity factor range (ΔK).

The preceding review illustrates how the database can be utilized by researchers and engineers interested in the corrosion-fatigue of steels in marine environments. To facilitate future use of the database, it is included in two files on the disk supplied with this report. The files are named "LitSurvey.mdb" and "LitSurvey.txt." The first one is a Microsoft Access database file that can be opened and used by anyone who has the Access software or software that directly imports such files. The second one is a tab-delimited text file that can be imported into other database programs. The text file contains 330 records with 13 fields per record. The fields are Document No., First Author, Other Authors, Title, Book/Journal, Vol. No. Month, Year, Publisher City, Pages, Key Words, Type of Steel, Notes, and Rec'd. Experienced database users can easily import this type of file. Once a users have this file in their own databases, they can search it, add to it, and create custom reports for their own use.

CHAPTER 4

FATIGUE EXPERIMENTS IN SEAWATER

Fatigue experiments were performed on axially loaded smooth (unnotched) and notched base-metal specimens to develop stress versus number-of-cycles-to-failure (S-N) curves. Fatigue crack-growth experiments were performed on base-metal compact-tension (CT) specimens to develop cyclic crack-growth rate (da/dN) data as a function of the range of the applied stress intensity factor (ΔK).

S-N Fatigue

Fatigue specimens were machined to the configurations illustrated in Figures 4-1, 4-2, and 4-3. The smooth specimens (see Figure 4-1) had no notch, and there were three types of notched specimens (see Figures 4-2 and 4-3). The notched specimens were designed to produce three different levels of stress concentration. The stress concentration factor (K_t) was 2.0 for the mild notch (see Figure 4-2), while it was 3.5 or 5.0 for the sharp notches (see Figure 4-3). The values of K_t were determined using information from Peterson (1974).

Initial fatigue tests were performed using 12.7-mm thick specimens. However, these specimens failed at the loading pin region of the grip end. To avoid this problem, the specimen designs were modified to the "double dog-bone" configurations that are shown in Figures 4-1, 4-2, and 4-3. With this design, the specimen thickness in the test section was 6.35 mm.

The smooth fatigue specimens were tested in both air and synthetic seawater, whereas the notched fatigue specimens were tested only in synthetic seawater. The synthetic seawater was prepared in accordance with the procedures for "Preparation of Substitute Ocean Water" given in ASTM D1141. All testing was performed at room temperature (RT) using a closed-loop servo-hydraulic test system operated in load control. The axial loading was sinusoidal at a stress ratio of 0.1. The cyclic frequency was 10 Hz for tests in air and 1 Hz for tests in synthetic seawater. The specimens were cycled to failure or until they had been subjected to 1 million cycles without failure.

For tests in synthetic seawater, the fatigue specimens were enclosed in a clear plastic test cell. A batch of seawater was prepared and poured into a plastic tank. The seawater then was slowly pumped though the test cell. The seawater leaving the test cell was drained into another tank and periodically discarded. Batches of fresh seawater were prepared several times a week as needed. Thus, the test specimens were exposed to seawater that was continuously refreshed.

Initially, the test cell enclosed the grips as well as the specimen. However, after several tests in seawater, the grips cracked and failed because the hydrogen generated by cathodic polarization embrittle the steel. The test cell design then was modified so that only the test section of the specimen was enclosed and exposed to seawater. The grips were kept outside of the test cell. This modified test cell design was used to successfully complete the fatigue testing.

All of the fatigue specimens that were tested in synthetic seawater were cathodically polarized to either -0.90 V vs. Ag/AgCl or -1.13 V vs. Ag/AgCl. The level of -0.90 V vs. Ag/AgCl simulated adequate cathodic protection, while the level of -1.13 V vs. Ag/AgCl simulated over cathodic protection. The specimens were polarized using a laboratory potentiostat and platinum counter electrode.

The results of fatigue tests in air and synthetic seawater are summarized in Tables 4-1 and 4-2, respectively. The specimen number, maximum nominal stress, fatigue life, and comments are listed for each test condition. The polarization level also is listed for the tests that were in seawater (see Table 4-2). The maximum nominal stress (S_n) was computed by dividing the maximum cyclic load by the net cross-sectional area of the specimen; thus, it does not include the effect of stress concentration for notched specimens. Local stress (S_L) values that take the stress concentration into account are discussed in Chapter 6 of this report.

As noted in Tables 4-1 and 4-2, many of the tests ran out under certain test conditions, that is they reached a large number of cycles without failure under those conditions. In those cases, the stress level was increased, and cycling was continued until the specimen failed or again ran out. The fatigue lives listed in Tables 4-1 and 4-2 indicate the number of cycles applied at the corresponding stress level; they are not cumulative lives. For a run-out, the fatigue life is indicated to be greater than the number of applied loading cycles. After a run out, the stress was increased by an amount large enough that the prior cycling was expected to have a negligible effect on fatigue life at the increased stress level.

Three specimens (8, 9, and L1 in Table 4-2) failed at the grip end instead of within the test section, as noted. The fatigue life of each of these specimens is indicated to be greater than the number of cycles at which the grip end failed because there was no fatigue cracking in the test section.

All of the fatigue results are presented in Figure 4-4, which is a plot of the maximum nominal stress versus fatigue life. In cases where the specimen ran out at more than one stress level before reaching a stress level where failure occurred, only the run-out point immediately prior to the failure (i.e., the highest run-out stress level) is plotted. The plus symbols are for the results of tests in air, while the other symbols are for the results of tests in synthetic seawater. The filled symbols represent specimens tested with adequate cathodic protection, while the open symbols represent specimens tested with over cathodic protection.

The data in Figure 4-4 show that the fatigue strength decreased significantly as the notch severity increased, with the fatigue strength for $K_t = 5.0$ being about only one third of that for $K_t = 1.0$. The data for over cathodic protection of smooth specimens (open circular symbols) fell slightly below the results of tests in air (plus symbols), whereas the data for tests with adequate cathodic protection (filled circular symbols) had fatigue strength above that in air. Notched specimens with adequate cathodic protection (filled symbols) also exhibited better fatigue strength than comparable specimens with cathodic overprotection (open symbols).

TABLE 4-1. FATIGUE RESULTS FOR UNNOTCHED SPECIMENS OF ASTM A710, GRADE A, CLASS 3 PLATE TESTED IN AIR. Loading was sinusoidal at a frequency of 10 Hz and a stress ratio of 0.1.

Specimen Number	Maximum Stress, MPa	Fatigue Life, cycles	Comments
1	517	>1,200,000	Did not fail; load increased
1	621	247,289	Failed
2	586	>3,000,000	Did not fail; load increased
2	634	137,012	Failed
3	655	335	Failed
4	603	323,003	Failed

TABLE 4-2. FATIGUE RESULTS FOR SPECIMENS OF ASTM A710, GRADE A, CLASS 3 PLATE TESTED IN ASTM SYNTHETIC SEAWATER. Loading was sinusoidal at a frequency of 1 Hz and a stress ratio of 0.1.

Specimen Number	Polarization, V vs. Ag/AgCl	Maximum Stress, MPa	Fatigue Life, cycles	Comments
Smooth Specimen, K_t = 1.0				
5	-1.130	634	1/4	Failed on loading
6	-1.130	603	196,335	Failed
7	-1.130	586	222,040	Failed
8	-0.900	603	>426,665	Grips failed
9	-0.900	621	>842,190	Failed at grip end
0	-0.900	634	>1,000,000	Did not fail; load increased
0	-0.900	655	>1,000,000	Did not fail; load increased
0	-0.900	690	>1,000,000	Did not fail; test stopped
Notched Specimen, K_t = 2.0				
L3	-1.130	310	>1,000,000	Did not fail; load increased
L3	-1.130	327	202,185	Failed
L2	-1.130	360	558,000	Failed
L1	-1.130	343	>1,113,600	Did not fail; load increased
L1	-1.130	360	>740,550	Did not fail; load increased
L1	-1.130	378	>74,202	Failed at grip end
L5	-0.900	360	>1,000,000	Did not fail; load increased
L5	-0.900	414	>1,000,000	Did not fail; load increased
L5	-0.900	456	146,242	Failed
Notched Specimen, K_t = 3.5				
M1	-1.130	323	64,114	Failed
M3	-1.130	274	263,700	Failed
M5	-0.900	274	>1,000,000	Did not fail; load increased
M5	-0.900	323	937,100	Failed
Notched Specimen, K_t = 5.0				
S1	-1.130	159	>1,000,000	Did not fail; load increased
S1	-1.130	195	>1,000,000	Did not fail; load increased
S1	-1.130	234	184,959	Failed
S3	-1.130	224	373,640	Failed
S4	-0.900	234	>1,000,000	Did not fail; load increased
S4	-0.900	281	>1,000,000	Did not fail; load increased
S4	-0.900	337	47,654	Failed

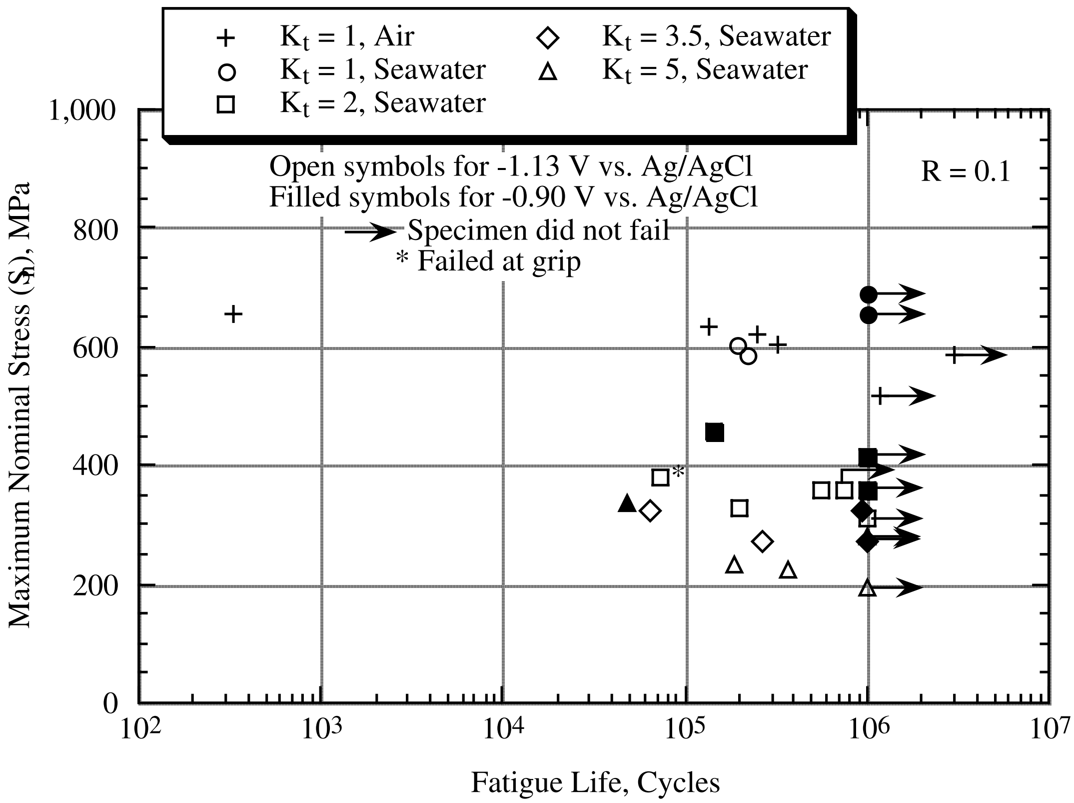

FIGURE 4-4. FATIGUE RESULTS FOR ASTM A710, GRADE A, CLASS 3 STEEL.

Fatigue Crack Growth

Three fatigue-crack-growth tests were performed in ASTM synthetic seawater at RT. The tests were performed in accordance with the procedures of ASTM E647. Standard 25.4-mm wide by 12.7-mm thick CT specimens were machined from the ASTM A710 steel plate, fatigue pre-cracked in air, and then tested in seawater. The synthetic seawater was prepared and circulated through a test cell that enclosed the CT specimen and test fixtures following the same procedures that were used in the S-N fatigue testing. One specimen was tested under free-corrosion conditions, one specimen was tested with a normal level of cathodic protection (-0.90 V vs. Ag/AgCl), and one specimen was tested with a high level of cathodic protection (-1.13 V vs. Ag/AgCl).

All fatigue-crack-growth testing was performed at room temperature (RT) using a closed-loop servo-hydraulic test system operated in load control. The applied load was cycled sinusoidally at a frequency of 1 Hz and a load ratio (R) of 0.1. These are the same frequency and load ratio that were used in the S-N fatigue testing. Crack length was measured by means of the DC electric potential drop method. The crack-length-versus cycles data were analyzed in accordance with the procedures of ASTM E647 to produce da/dN values as a function of ΔK.

The da/dN-ΔK data are presented in Figure 4-5 (open symbols) along with comparable data reported by Reynolds and Todd (1992) (filled symbols). For conditions of free corrosion and normal cathodic protection, the present results agree well with those of Reynolds and Todd

(1992). However, for the high level of cathodic protection (triangles), the present results fell well below those of Reynolds and Todd (1992). This result is believed to be caused by crack closure and a resulting low effective stress intensity factor range in the current test at a high level of cathodic protection. During this test, copious amounts of calcareous scale formation were observed. The formation of such scale on the crack faces is expected to markedly reduce the effective stress intensity factor range and in turn the cyclic crack growth rate. Based on the results for conditions of free corrosion and normal cathodic protection, it was concluded that the A710 steel used in the current study has corrosion-fatigue crack-growth behavior typical of that expected for this steel.

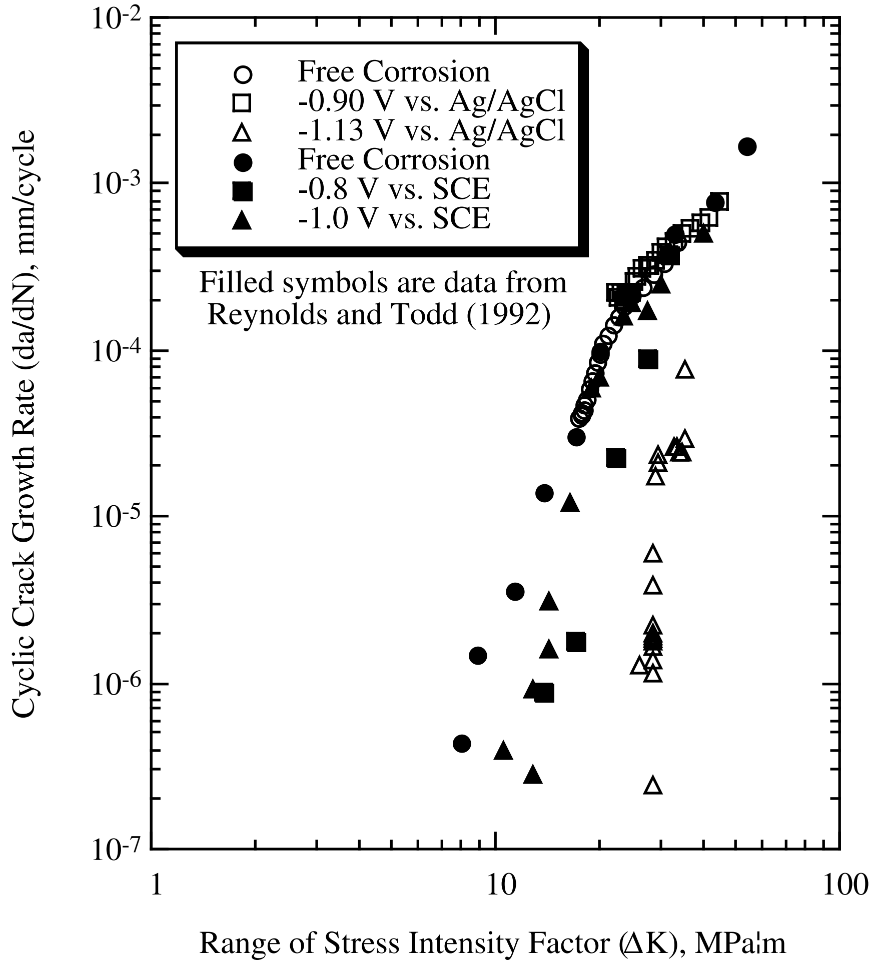

FIGURE 4-5. FATIGUE-CRACK-GROWTH RESULTS FOR ASTM A710, GRADE A, CLASS 3 STEEL IN SYNTHETIC SEAWATER AT ROOM TEMPERATURE.

CHAPTER 5

FATIGUE OF WELDED SPECIMENS IN SEAWATER

Steel marine structures are typically fabricated by welding various components together. The welds or base-metal regions adjacent to welds are the most likely locations for fatigue damage in marine structures that are subjected to cyclic loading. Thus, fatigue needs to be assessed in the design of these structures. For example, the API recommended practice for fixed offshore platforms (Anon., 1991) provides procedures for assessing fatigue in the design of welded tubular connections.

Design methods for welded structures are based on the results of fatigue tests of specimens with welded joints. As reviewed by Jaske (1998), Figure 5-1 illustrates configurations of welded joints that are commonly used for fatigue testing. Additionally, actual structural components such as tubular joints, built-up beams, piping connections, and pressure vessels are sometimes fatigue tested to develop data for realistic engineering equipment. These specimens and components have either full penetration welds or fillet welds. Either bending or axial cyclic loads are applied during fatigue testing. In some cases, pressure cycling is used in the fatigue testing.

The fatigue life of a welded joint consists of both a crack-initiation phase and a crack-propagation phase. Thus, total fatigue life depends on the relative contribution of each cracking phase and the definition of failure. Commonly used definitions of fatigue failure include initiation of a detectable crack, through-wall cracking, and total fracture. Total specimen fracture was the failure criterion for the S-N fatigue data developed in this study (see Chapter 4). Since these were relatively long-life fatigue tests performed in load control, the specimens failed rapidly once a significant crack (estimated to be 0.25 to 0.50 mm) developed. For this reason, the S-N curves presented in Chapter 4 provide a measure of the base metal's resistance to fatigue-crack initiation. Because both crack initiation and propagation can significantly contribute to the fatigue life of welded joints, the experimental procedures for testing welded joints in this study were designed to detect crack initiation and measure crack growth.

For the current study, butt-welded and fillet-welded joints were selected for corrosion-fatigue testing. The specimens were loaded in three-point bending, as illustrated in Figures 5-2 and 5-3. The specimen and loading illustrated in Figure 5-2 correspond to Case 3 in Figure 5-1, while the specimen and loading illustrated in Figure 5-3 correspond to Case 8 in Figure 5-1. Bending was selected for the loading condition so that the specimens could be made from the full thickness (19 mm) of the ASTM A710, Grade A, Class 3 steel plate.

Six butt-welded and six fillet-welded fatigue specimens were fabricated. Two pieces of plate were butt welded to produce a joined plate; then, six specimens were cut from the welded assembly. Also, a 13.5-mm tee piece of plate was fillet welded to another plate; then, six specimens were cut from the welded assembly. Each specimen was 229 mm long by 63.5 mm wide by 19 mm thick, with a load span of 210 mm. Three levels of weld-toe severity were produced for each of the two types of specimens. The weld toes were ground, as-welded, or undercut. Thus, there were duplicate specimens for each combination of weld-toe severity and weld-joint type.

The welds were made using a 1.14-mm diameter flux-cored electrode as the filler. The wire designation was Lincoln Electrode Outershield 91K2-H (equivalent to AWS E91T1-K2), and the shielding gas was C25 (75% Ar and 25% CO_2) at a flow rate of 0.85 m^3/hr. Welding was performed in the flat position. The butt welds were made using backing bars on one side and 45-degree included angle weld preparation, with a 6.4-mm root opening. The travel speed was 0.33 to 0.36 m/min, the current was 210 to 220 A DCRP, and the voltage was 25 V. These welding parameters were upset in an effort to produce the samples with weld-toe undercut, but the desired defect could not be produced. Therefore, simulated undercut was produced using a sharp vee-shaped milling cutter. The simulated undercut was 1.42 to 1.52 mm deep with a 0.13 mm root radius.

All fatigue testing of welded joints was performed at room temperature (RT) using a closed-loop servo-hydraulic test system operated in load control. The distance from each support pin to the central loading pin was 105 mm. The applied load was cycled sinusoidally at a frequency of 1 Hz and a load ratio (R) of 0.1. These are the same frequency and load ratio that were used in the S-N fatigue and fatigue-crack-growth testing. The refreshed, room-temperature synthetic seawater environment and cathodic polarization were maintained in the same manner as they were for the S-N fatigue and fatigue-crack-growth tests (see Chapter 4).

The DC electric potential drop method was used to detect crack initiation and measure crack growth. A constant current of 10 A was applied using a lead wire connected to each end of the specimen. These connections were centered on the mid-thickness and mid-width of the specimen. Lead wires for potential measurement were attached to the lower specimen surface (see Figures 5-2 and 5-3) adjacent to the toe of the weld. One lead wire was attached on one side of the weld joint near one edge of the specimen, while the other lead wire was attached on the other side of the weld joint near the other edge of the specimen. With this arrangement, the potential drop changes when cracking initiates on either side of the joint and gives a measure of average crack advance if the crack growth is non-uniform across the width of the specimen.

The results of the fatigue tests on the welded-joint specimens are summarized in Table 5-1. The condition of the weld toe, the polarization level, the maximum load, the maximum nominal bending stress, and the fatigue life is listed for each specimen. Two values of fatigue life are reported. One is the number of cycles to initiate cracking, while the other is the number of cycles to total specimen failure. Based on the sensitivity of the potential drop measurements, initiation was estimated to correspond to the development of 0.25 to 0.50 mm deep crack at the weld toe. This crack size is similar to the estimate of significant crack size for S-N fatigue specimens, so the initiation fatigue life of the welded joints should be compared with the previously reported (see Chapter 4) fatigue lives of the base metal specimens.

The values of maximum nominal bending stress (σ_{max}) were calculated from the maximum applied load (P_{max}) and the nominal specimen dimensions, based on elastic stress-strain behavior:

$$\sigma_{max} = M_{max}c/I \tag{5.1}$$

where M_{max} is maximum bending moment, c is the distance from neutral axis to the outer surface, and I is the rectangular moment of inertia. For three-point bending, the maximum moment is

$$M_{max} = P_{max}l/4 \tag{5.2}$$

where l is the load span or distance between supports. Then, for the nominal dimensions of the butt-welded specimens, Equation 5.1 gives

$$\sigma_{max} = P_{max}lc/[4I] = P_{max} \text{ x } 0.210 \text{ x } 0.00953/[(4 \text{ x } 0.0635 \text{ x } 0.0191^3)/12] = 13.64\ P_{max} \tag{5.3}$$

where the units are kN for load, m for specimen dimensions, and MPa for stress. For the fillet-welded specimens, the maximum stress was approximately 12.7 mm to either side of the point of applied load and was computed as follows:

$$\sigma_{max} = P_{max} \text{ x } 0.184 \text{ x } 0.00953/[(4 \text{ x } 0.0635 \text{ x } 0.0191^3)/12] = 11.99\ P_{max} \tag{5.4}$$

TABLE 5-1. RESULTS OF THREE-POINT BENDING FATIGUE TESTS OF WELDED SPECIMENS OF ASTM A710, GRADE A, CLASS 3 STEEL PLATE IN SYNTHETIC SEAWATER AT ROOM TEMPERATURE. The load was cycled sinusoidally at a frequency of 1 Hz and a load ratio of 0.1.

Specimen Number	**Condition of Toe**	**Polarization, V vs. Ag/AgCl**	**Maximum Load, kN**	**Maximum Nominal Bending Stress, MPa**	**Fatigue Life, cycles**	
					Initiation	**Total**
Butt-Welded Joints						
2	Ground	-0.900	50.55	690	99,130	123,144
1	As-welded	-0.900	50.55	690	60,000	75,652
3	Undercut	-0.900	16.45	224	148,300	167,611
8	Ground	-1.130	43.98	600	63,478	109,955
7	As-welded	-1.130	43.98	600	48,551	86,058
9	Undercut	-1.130	16.45	224	173,000	220,944
Fillet-Welded Tee Joints						
5	Ground	-0.900	50.55	527	12,000	16,422
4*	As-welded	-0.900	40.44	485	$> 1 \times 10^6$	$> 1 \times 10^6$
4	As-welded	-0.900	50.55	527	9,000	13,293
6	Undercut	-0.900	16.45	197	45,000	76,517
11	Ground	-1.130	43.98	527	11,815	18,902
10	As-welded	-1.130	43.98	527	21,812	33,000
12	Undercut	-1.130	16.45	197	32,391	54,832

* No cracking was detected at the 40.44 kN load level, so the load was increased to 50.55 kN.

where again the units are kN for load, m for specimen dimensions, and MPa for stress. Thus, Equations 5.3 and 5.4 were used to calculate maximum nominal bending stresses for the butt-welded specimens and fillet-welded specimens, respectively.

The cathodic polarization system was monitored throughout each test to make sure that reproducible levels of cathodic protection were obtained and maintained. Table 5-2 summarizes the typical data that were measured during each test. The applied or on potential, the off potential, the cathodic current, and the cathodic current density are listed. The applied potential was controlled using potentiostat. The off potential was measured just after the applied potential was briefly interrupted. The difference between the on and off potential is the potential drop caused by the resistance of the seawater solution. The cathodic current density was calculated by dividing the cathodic current and by the exposed surface area of the specimen. The data in Table 5-2 indicate that the cathodic protection was consistent from test to test.

The fatigue data for the welded joints are plotted in Figure 5-4. The open symbols indicate crack initiation, while the filled symbols indicate total failure. Specimens with as-welded or ground weld toes had similar fatigue strengths. Grinding the weld toes usually caused a slight improvement in fatigue resistance. Specimens with undercut weld toes had very low fatigue strengths. The fatigue strength for adequate cathodic protection (see circles and triangles in Figure 5-4) was not significantly different than that for over cathodic protection (see squares and diamonds in Figure 5-4). Butt welds (see circles and squares in Figure 5-4) had higher fatigue resistance than the fillet welds (see triangles and diamonds in Figure 5-4). The crack-initiation life ranged from 56 to 89 percent of the total life and was 69 percent of the total life on average.

TABLE 5-2. SUMMARY OF CATHODIC POLARIZATION MEASUREMENTS MADE ON WELDED SPECIMENS OF ASTM A710, GRADE A, CLASS 3 STEEL PLATE IN SYNTHETIC SEAWATER AT ROOM TEMPERATURE.

Specimen Number	**Applied Potential, V vs. Ag/AgCl**	**Off Potential, V**	**Cathodic Current, μA**	**Cathodic Current Density, μA/mm²**
Butt-Welded Joints				
2	-0.900	-0.879	6.800×10^3	1589
1	-0.900	-0.882	7.340×10^3	1741
3	-0.900	-0.887	7.100×10^3	1677
8	-1.130	-1.035	2.935×10^4	6856
7	-1.130	-1.028	2.943×10^4	6933
9	-1.130	-1.022	2.915×10^4	7050
Fillet-Welded Tee Joints				
5	-0.900	-0.890	8.800×10^3	2067
4	-0.900	-0.837	7.880×10^3	1864
6	-0.900	-0.850	7.200×10^3	1701
11	-1.130	-1.025	2.996×10^4	7063
10	-1.130	-0.946	2.953×10^4	7006
12	-1.130	-1.020	3.022×10^4	7176

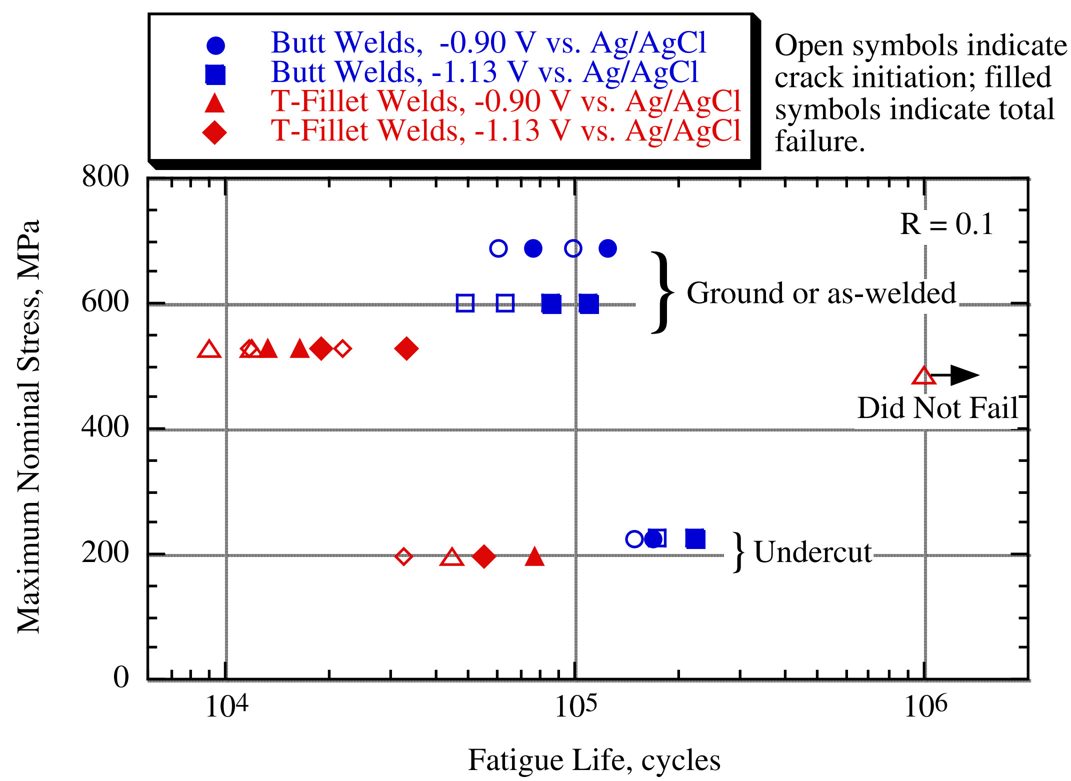

FIGURE 5-4. FATIGUE RESULTS FOR WELDED JOINTS OF ASTM A710, GRADE A, CLASS 3 STEEL IN SYNTHETIC SEAWATER AT ROOM TEMPERATURE.

As pointed out previously, fatigue cracking was detected and measured using the DC electric potential drop technique. Figure 5-5 shows a typical plot of the DC potential drop as a function of cycles for the fatigue tests of the welded joint specimens. In the first part of the test, there was no cracking, and except noise in the data, there was no change in potential drop. Once cracking started, the potential drop increased as cycling continued. In this example, fatigue crack initiated after approximately 60,000 cycles.

The average change in crack length (a) was calculated using the Johnson (1965) equation based on the calibration of Schwalbe and Hellmann (1981). Because of the noise in the potential drop measurements (see Figure 5-5), a smoothing function was used in calculating values of da/dN as a function of ΔK. Once a smooth plot of a versus N was obtained, da/dN was computed by the secant method. The ratio of the loading span to thickness was 229/19 = 11, so values of ΔK could be computed using Tada's solution for pure bending (Tada, et al., 1985), as follows:

$$\Delta K = 3(S - 2x)\ \Delta P\ (\pi a)^{0.5}\ F(a/W) / (2BW^2) \tag{5.5}$$

where ΔP is load range, S is the load span, x is the distance from the mid-span to the weld toe, B is specimen width, W is the specimen thickness, and F(a/W) is the following function:

$$F(a/W) = (2W\tan(\pi a/(2W))/(\pi a))^{0.5}\ ((0.923 + 0.199(1 - \sin(\pi a/(2W)))^4)/\cos(\pi a/(2W)) \tag{5.6}$$

The term (S -2x) appears in Equation 5.5 because the fatigue cracking occurred at the toe of the weld and not at the mid-span of the specimen.

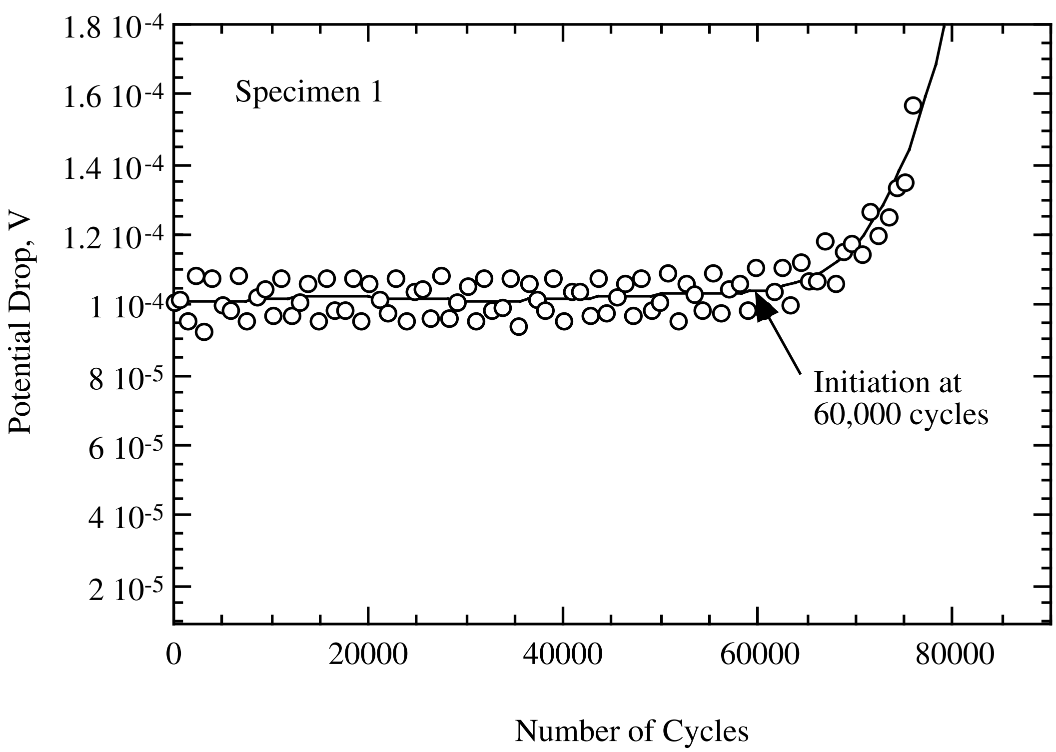

FIGURE 5-5. TYPICAL PLOT OF DC POTENTIAL DROP VERSUS CYCLES FOR A FATIGUE TEST OF A WELDED JOINT.

Figure 5-6 shows the fatigue-crack-growth data from the tests of the welded joints. The solid curve represents the trend to the data for CT specimens (see Figure 4-5). There is a large amount of scatter in the data, but the overall trend is similar to that obtained from the CT specimens. For adequate cathodic protection (filled and X symbols), the crack-growth data fell near the reference curve. For over cathodic protection (open and + symbols), the crack-growth data fell below the reference curve. Thus, cathodic protection did not increase crack-growth rate and some cases it decreased the crack-growth rate significantly. The low crack-growth rates were most likely caused by calcareous scale in the crack reducing the effective value of ΔK, as explained previously in the discussion of fatigue crack growth behavior of the base metal.

Based on the results presented in this chapter, it was concluded that the fatigue life of welded joints can be modeled as a two-stage process -- crack initiation followed by crack growth until final failure occurs. Crack initiation was defined as the development of a crack approximately 0.25 to 0.50 mm long. The crack initiation life can be described using S-N curves, while the crack growth life can be described using fracture mechanics. This approach is straight forward and should be applicable to other types of welded joints.

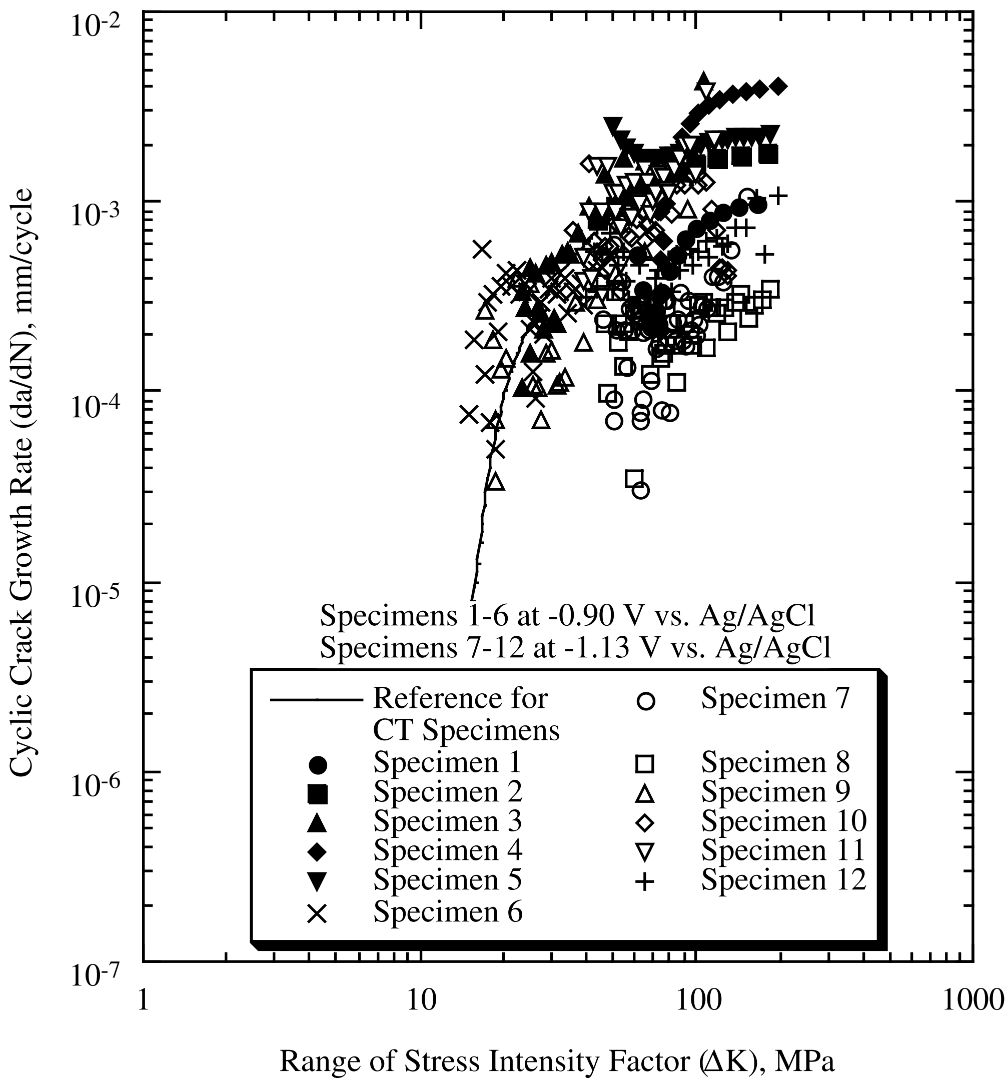

FIGURE 5-6. FATIGUE-CRACK-GROWTH DATA FROM TESTS OF WELDED JOINTS OF ASTM A710, GRADE A, CLASS 3 STEEL IN SYNTHETIC SEAWATER AT ROOM TEMPERATURE.

CHAPTER 6

FATIGUE MODEL

The results presented previously in this report provide the basis for the fatigue model presented in this chapter. As pointed out at the end of Chapter 5, the fatigue life of structural steel weldments can be modeled as a two-stage process made up of crack initiation and crack growth. If crack initiation is defined as the development of a crack approximately 0.25 to 0.50 mm long, fatigue crack initiation life can be described using S-N curves. Once the crack has reached this size, its growth can be characterized using fracture mechanics. Fatigue crack growth can be predicted by integrating the appropriate crack growth rate relationship. Then, total fatigue life is the sum of the crack initiation and growth lives.

Two approaches (Jaske, 1998) have been used to develop S-N fatigue data for weldments. One approach is to test many different configurations of welded joints (for example, see Figure 5-1) and develop an S-N curve for each type of joint. Then, in designing a welded structure, the engineer uses the S-N curve(s) for the type of joint(s) employed in the structure. This approach requires the development of large amount of fatigue test data and limits designs to the types of joints for which S-N curves are available. The other approach is to develop basic S-N curves for smooth or unnotched specimens of base metal and then to use fatigue-strength-reduction factors to predict the fatigue strengths of welded joints from the basic S-N data. The fatigue-strength-reduction factor (K_f) is the ratio of the fatigue strength of the smooth specimens to the fatigue strength of the welded specimens. The latter approach was applied in the current study.

As reviewed by Jaske (1998), K_f may vary as a function of fatigue life and may depend both on stress concentration at a local discontinuity as well as local variations in material properties. For typical structural steel weldments, K_f is primarily a function of the local stress concentration and plasticity when fatigue life is based on crack initiation, and values of K_f can be estimated using K_t, the notch root radius (r), and a material parameter. The following expression for K_f (Peterson, 1974) worked gave good results in the current study:

$$K_f = \frac{1}{\left(1 + \sqrt{a_N / r}\right)}\left(K_t - 1\right) + 1 \tag{6.1}$$

where a_N is Neuber's constant. A value of $a_N = 0.163$ mm gave good correlations for the ASTM A710, Grade A, Class 3 steel used in this research.

To compare the current results with those from past studies of ASTM A710 steel conducted by Rajpathak and Hartt (1988 and 1990), the parameter $\Delta K/\sqrt{r}$ also was evaluated for the notched specimens. This parameter is only valid for notched specimens, so it cannot be used to correlate the data from tests of notched specimens with those from test of smooth specimens.

Table 6-1 summarizes the calculations of local stress for the notched base-metal specimens, while Table 6-2 summarizes the local stress values that were calculated for the weld-joint specimens. For each type of specimen, K_t was calculated using the specimen configuration and the information presented by Peterson (1974). Then, K_f was calculated using Equation 6.1. The nominal stress at the weld toe was used to compute local stress for the weld-joint specimens because this was the region where fatigue cracking occurred. Values of the stress intensity factor (K) were computed using the following expression from Broek (1978):

$$K = (1.99 + 0.76\,(a/W) - 8.48\,(a/W)^2 + 27.36\,(a/W)^3)\, S_n \sqrt{a} \tag{6.2}$$

Equation 6.2 is for a double edge-notched specimen loaded in tension.

TABLE 6-1. LOCAL STRESS VALUES FOR BASE-METAL SPECIMENS.

Specimen Number	Polarization, V vs. Ag/AgCl	Maximum Nominal Stress (S_n), MPa	Maximum Local Stress (K_f x S_n), MPa	Maximum Local Stress ($K/\sqrt{r}$), MPa	Fatigue Life, cycles
Notched Specimen, K_t = 2.0					
L3	-1.130	310	576	411	>1,000,000
L3	-1.130	327	607	434	202,185
L2	-1.130	360	669	477	558,000
L1	-1.130	343	637	455	>1,113,600
L1	-1.130	360	669	477	>740,550
L1	-1.130	378	701	500	>74,202
L5	-0.900	360	669	477	>1,000,000
L5	-0.900	414	768	548	>1,000,000
L5	-0.900	456	847	605	146,242
Notched Specimen, K_t = 3.5					
M1	-1.130	323	740	829	64,114
M3	-1.130	274	629	705	263,700
M5	-0.900	274	629	732	>1,000,000
M5	-0.900	323	740	861	937,100
Notched Specimen, K_t = 5.0					
S1	-1.130	159	424	600	>1,000,000
S1	-1.130	195	518	734	>1,000,000
S1	-1.130	234	621	881	184,959
S3	-1.130	224	595	844	373,640
S4	-0.900	234	621	881	>1,000,000
S4	-0.900	281	746	1057	>1,000,000
S4	-0.900	337	894	1267	47,654

As can be seen from Table 6-1, the local stress based on K_f times S_n was more consistent from one type of notch to another than the local stress based on $K/\sqrt{r}$. Figure 6-1 shows the fatigue data for the base-metal specimens plotted using the former local-stress parameter. For each level of cathodic protection, the data were well correlated by the local stress computed using K_f. The data for specimens polarized to -1.13 V vs. Ag/AgCl (open symbols except inverted triangles) agreed well with those for specimens tested in air (inverted open triangles), while the data for specimens polarized to -0.90 V vs. Ag/AgCl (filled symbols) fell well above those for specimens tested in air (inverted open triangles). These results indicate that over cathodic protection was somewhat detrimental compared with adequate cathodic protection, but neither level of cathodic protection gave worse fatigue resistance than specimens tested in air. The reference curve in Figure 6-1 represents the mean trend of the data for tests in air and in seawater at -1.13 V vs. Ag/AgCl.

Figure 6-2 compares the current fatigue results for notched specimens tested with cathodic overprotection (open symbols) with comparable fatigue data from the work of Rajpathak and Hartt (1988 and 1990) (filled symbols). The latter work was performed using keyhole CT specimens. The keyhole had a 3.2 mm radius, and the local stress range (`S) was calculated as the value of ΔK/`r. In that study, fatigue curves were developed for both free-corrosion and over cathodic protection (-1.10 V vs. SCE) conditions, as is shown in Figure 6-2. For the current study, ΔS was computed using K_f and S_n ($\Delta S = 0.9 \times K_f \times S_n$). The factor of 0.9 is used because the stress

TABLE 6-2. LOCAL STRESS VALUES FOR WELD-JOINT SPECIMENS.

Specimen Number	Condition of Toe	Polarization, V vs. Ag/AgCl	Maximum Nominal Bending Stress, MPa	Maximum Local Stress at Weld Toe, MPa	Fatigue Life, cycles	
					Initiation	Total
Butt-Welded Joints						
2	Ground	-0.900	690	728	99,130	123,144
1	As-welded	-0.900	690	728	60,000	75,652
3	Undercut	-0.900	224	660	148,300	167,611
8	Ground	-1.130	600	633	63,478	109,955
7	As-welded	-1.130	600	633	48,551	86,058
9	Undercut	-1.130	224	660	173,000	220,944
Fillet-Welded Tee Joints						
5	Ground	-0.900	527	743	12,000	16,422
4	As-welded	-0.900	485	684	> 1 x 10^6	> 1 x 10^6
4	As-welded	-0.900	527	743	9,000	13,293
6	Undercut	-0.900	197	660	45,000	76,517
11	Ground	-1.130	527	743	11,815	18,902
10	As-welded	-1.130	527	743	21,812	33,000
12	Undercut	-1.130	197	660	32,391	54,832

* K_f was 1.20 and 1.41 for as-welded and ground toes on butt and fillet welds, respectively, and 3.35 for all undercut weld toes.

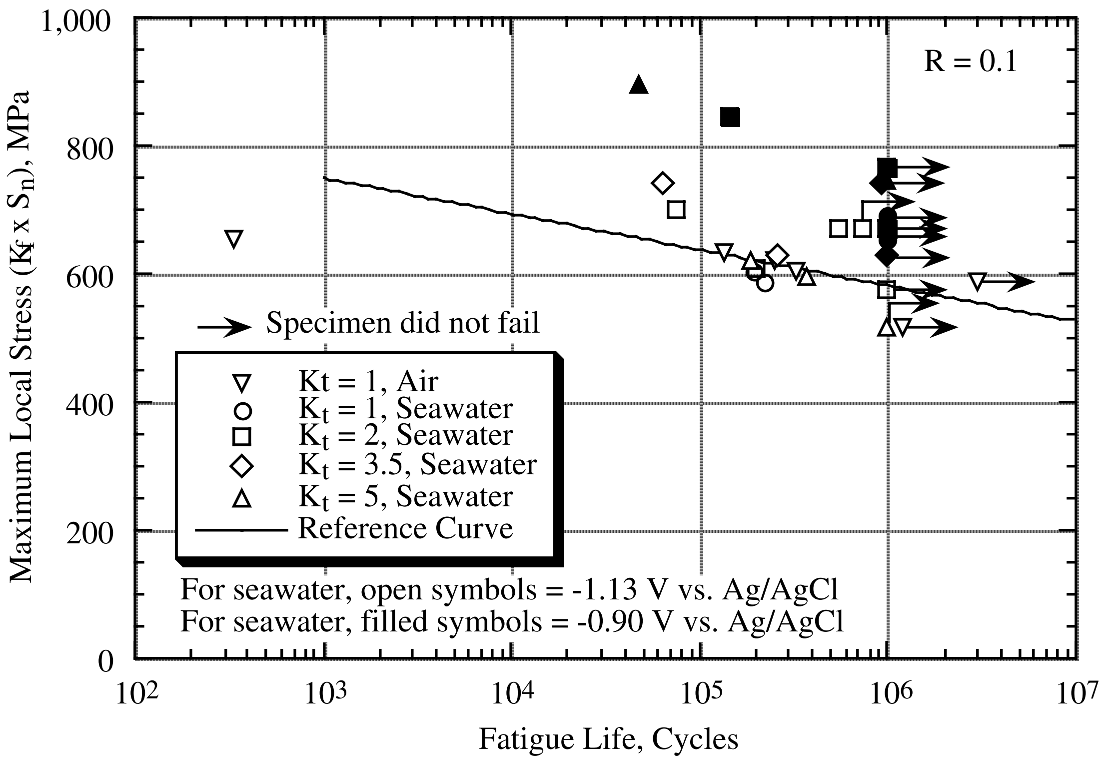

FIGURE 6-1. FATIGUE DATA FOR BASE-METAL SPECIMENS AS A FUNCTION OF MAXIMUM LOCAL STRESS.

ratio for the current work was 0.1. The stress ratio for the other study was 0.5. Considering the difference in specimen configuration, stress ratio, and the normal scatter in fatigue data, the current results were in good agreement with those of Rajpathak and Hartt (1988 and 1990).

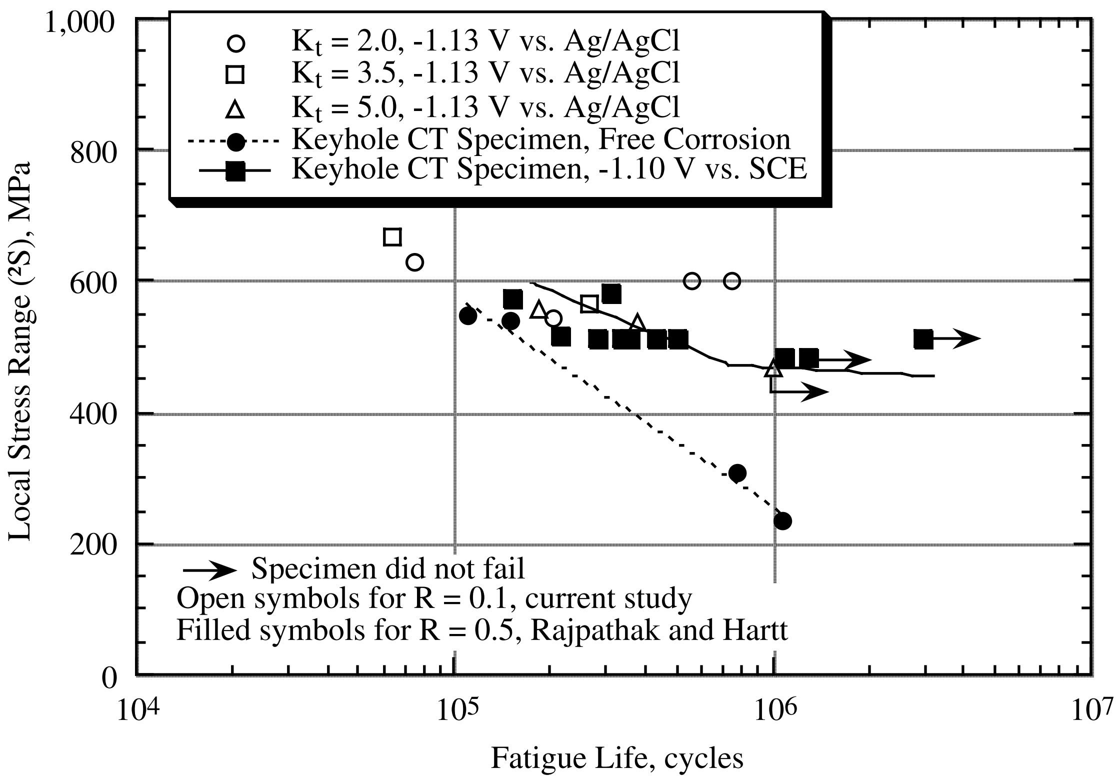

FIGURE 6-2. FATIGUE DATA FOR BASE-METAL SPECIMENS AS A FUNCTION OF LOCAL STRESS RANGE.

Figure 6-3 shows the fatigue data for the weld-joint specimens plotted in terms of maximum local stress versus crack-initiation life. The reference curve for base-metal specimens (see Figure 6-1) is included for comparison with the weld-joint data. The reference curve provides a slightly conservative approximation of the weld-joint data, but the local stress approach with fatigue life based on crack initiation gives a reasonably good overall consolidation of the results for various weld-joint and weld-toe configurations that were evaluated.

The information presented in this chapter showed that the local stress approach can be used to predict crack-initiation fatigue life (N_i), while the information presented in Chapter 5 showed that fracture mechanics can be used to predict crack-propagation fatigue life (N_p). Total fatigue life (N_f) is then equal to $N_i + N_p$. The value of N_i is obtained by computing K_t, using Equation 6.1 to compute K_f, and then using the reference S-N curve. The value of N_p is computed by integrating the relationship between ΔK and da/dN, which is the standard fracture-mechanics approach for determining fatigue crack-growth life. This approach is a straight-forward method that can be applied to the fatigue design of marine structures by engineers. Over cathodic protection did not significantly degrade the fatigue behavior of the ASTM A710, Grade A, Class 3 steel and welded joints, so the approach applies as long as an adequate level of cathodic protection is maintained.

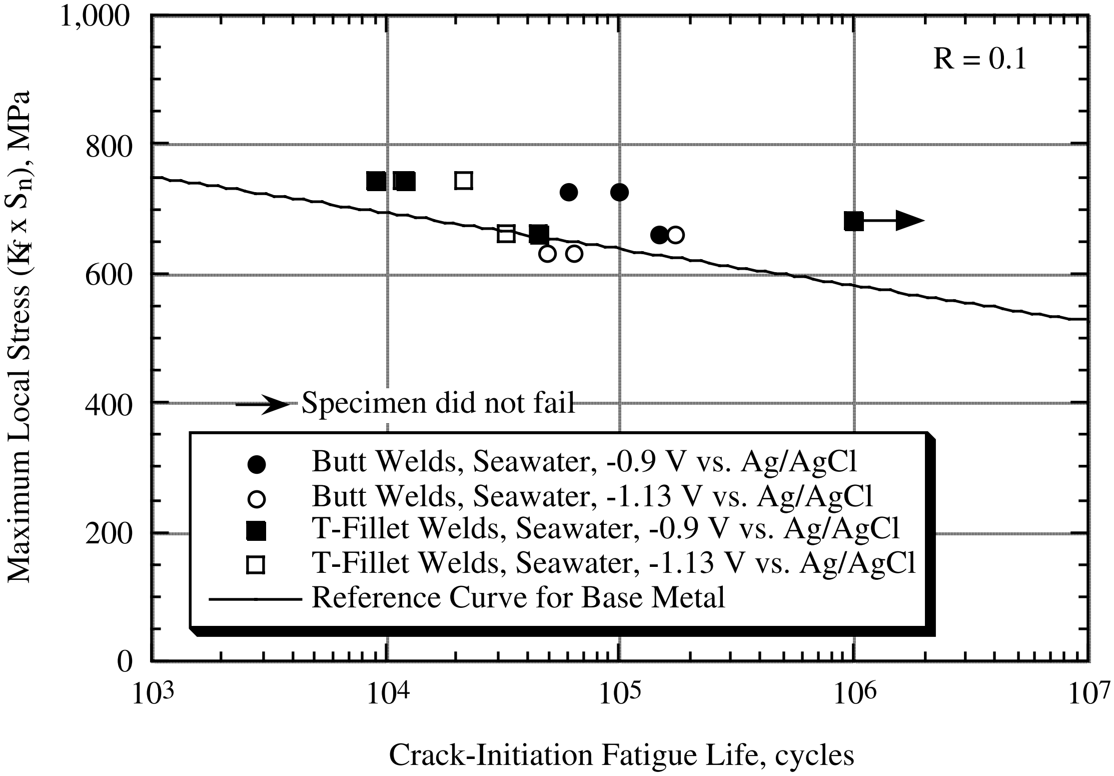

FIGURE 6-3. FATIGUE DATA FOR WELD-JOINT SPECIMENS AS A FUNCTION OF MAXIMUM LOCAL STRESS.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The conclusions presented in this chapter are based on the current corrosion-fatigue study of ASTM A710, Grade A, Class 3 steel plate and welded joints made from this plate. The corrosive environment was ASTM synthetic seawater at room temperature. The loading was sinusoidal at 1 Hz and at a stress ratio of 0.1. Where comparisons could be made with published data from other corrosion-fatigue studies of ASTM A710 steel in seawater, the current results were in good agreement with the published data. For this reason, the current results are believed to be representative of those expected of this steel in general.

When an adequate level of cathodic protection (-0.90 V vs. Ag/AgCl) was employed, the fatigue crack initiation resistance was slightly better than that in air, while the fatigue crack growth rate was about the same as that in air. Over cathodic protection (-1.13 V vs. Ag/AgCl) degraded the fatigue crack initiation resistance slightly, but did not reduce it below that in air. Over cathodic protection reduced fatigue crack growth rate by producing calcareous scale deposits within the crack that reduced the effective range of stress intensity factor.

The fatigue resistance of notched specimens with stress concentration factors of 2.0, 3.5, and 5.0 decreased as the stress concentration factor increased. It was well correlated with that of unnotched specimens by using Peterson's (1974) fatigue strength reduction factor to calculate local stress values at the notches. The fatigue strength reduction factor was determined using the stress concentration factor, a material parameter, and the notch root radius. Also, this same fatigue strength reduction factor gave good predictions of the fatigue crack initiation resistance of both butt-welded and fillet-welded joints.

The DC electric potential drop method was a good technique for detecting crack initiation and measuring crack growth in welded-joint specimens. The fatigue crack growth behavior of welded joints was well characterized using the standard fracture-mechanics approach. The crack growth data obtained from tests of welded joints agreed well with those from tests of standard fracture mechanics specimens.

The total fatigue life of welded joints can be predicted as the sum of the crack-initiation life and the crack-growth life. The crack-initiation life is obtained from a S-N curve using the local stress at the weld toe. The local stress is computed using the fatigue strength reduction factor. The crack-growth life is computed by using fracture mechanics and integrating the crack-growth rate relationship.

Future work should be undertaken to further confirm and extend the results of this project. Additional fatigue tests should be conducted on welded joints of the ASTM A710 steel to fully define the S-N curves. This work should include additional testing at a stress ratio of 0.1 as well as at other stress ratios and at frequencies as low as 0.1 Hz. Tests should also be performed on another steel with a different microstructure than the ASTM A710 steel. Based on information from the literature, other steels may be more affected by over cathodic protection than steel that was tested in this project.

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Jaske, C. E., Payer, J. H., and Balint, V. S., 1981, **Corrosion Fatigue of Metals in Marine Environments**, MCIC Report 81-42, Springer-Verlag, New York and Battelle Press, Columbus, Ohio.

Johnson, H. H., 1965, "Calibrating the Electric Potential Method for Studying Slow Crack Growth," **Materials Research & Standards**, Vol. 5, pp. 442-445.

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Rajpathak, S. S., and Hartt, W. H., 1990, "Keyhole Compact Tension Specimen Fatigue of Selected High-Strength Steels in Seawater**," Environmentally Assisted Cracking: Science and Engineering**, ASTM STP 1049, American Society for Testing and Materials, West Conshohocken, PA, pp. 425-446.

Reynolds, G. H., and Todd, J. A., 1992, "Threshold Corrosion Fatigue of Welded Shipbuilding Steels," Ship Structure Committee Report SSC-366, NTIS, Springfield, VA.

Sablok, A. K., and Hartt, W. H., 1990, “Fatigue of Welded Structural and High-Strength Steel Plate Specimens in Seawater,” **Fatigue and Fracture Testing of Weldments**, ASTM STP 1058, American Society for Testing and Materials, West Conshohocken, PA, pp. 78-95.

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Todd, J. A., Li, P., Liu, G., and Raman, V., 1988, “A New Mechanism of Crack Closure in Cathodically Protected ASTM A710 Steel,” **Scripta Metallurgica**, Vol. 22, No. 6, pp. 745-750.

Todd, J. A., Chen, L., Yankov, E. Y., Tao, H., and Reynolds, G. H., 1992, “A Comparison of the Near-Threshold Fatigue Crack Growth Propagation in Mil-S24645 HSLA Steel and Its Weld Metal, **Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering**, Vol. IIIB, ASME International, New York, pp. 557-564.

APPENDIX A

CORROSION FATIGUE BIBLIOGRAPHY

This appendix contains a bibliography of the corrosion-fatigue literature that was collected and reviewed in the first task of the project, as discussed in Chapter 3 of this report. Each document was assigned a unique numerical identification number for filing and retrieval purposes. The reference citation, key words, steel(s) tested, and notes were entered into a computerized database. The notes are specific to the research objective of the project and were prepared while reviewing each document. The bibliography was created by printing a text file report from the database and then importing that text file into a word processing document for final formatting and printing.

The information from the database is on a computer disk included with this report. There are two files on the disk, as follows: LitSurvey.mdb and LitSurvey.txt. The first one is a Microsoft Access database file that can be opened by anyone who has the Access software. The second one is a tab-delimited text file that can be imported into other database programs. The text file contains 330 records with 13 fields per record. The fields are Document No., First Author, Other Authors, Title, Book/Journal, Vol. No. Month, Year, Publisher City, Pages, Key Words, Type of Steel, Notes, and Rec'd. Experienced database users can easily import this type of file.

1.0 Adams, R. J., P. Mehdizadeh, "Corrosion fatigue behavior of self-shielded flux-cored weldments," Materials Performance, Vol. 20, No.-3, March, 1981, p. 44-52.
Key Words: welded joint, S-N curve, synthetic seawater
Steel(s): BS 4360:50D
Notes: Rotating bending corrosion-fatigue tests in synthetic seawater were performed on specimens from weldments made with two types of flux-cored wires (NR203M and NR203 1%Ni) and with AWS E7016 electrodes. The corrosion-fatigue strength of the weldments made with flux-cored wires was equal to that of the weldments made with AWS E7016 electrodes.

2.0 Al-Marafie, A. M. R., H. I. Malik, M. S. El-Mahedi Abdo, M. A. Awwal, "Corrosion fatigue of some carbon steels in main aqueous environments in Kuwait," Steel Research, Vol. 57, No. 10, 1986, p.-535-538.
Key Words: seawater, S-N curve
Steel(s): AISI 1018, AISI 4140
Notes: Rotating bending fatigue tests were performed in air, seawater, brackish water, and tap water. S-N curves were developed for each steel in each environment. The fatigue strength was significantly reduced below that in air in all three solutions. The reduction in fatigue strength was greatest for tests in seawater.

3.0 Andrews, R. M., “The effect of corrosion on the fracture and fatigue resistance of welds in pipelines,” Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. V-A, ASME, New York, 1992, p. 195-202.

Key Words: fatigue, corrosion damage, welded joint

Steel(s): carbon steel, HSLA steel

Notes: Issues that must be considered in assessing the fatigue strength and fracture resistance of corroded pipeline welds are discussed.

4.0 Andrews, R. M., R. L. Jones, “The fatigue performance of single sided closure welds in offshore structures,” Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 377-383.

Key Words: fatigue,welded joint, offshore service, stress concentration factor, weld defects

Steel(s): BS 4360:50D

Notes: Small and full scale fatigue testing was performed on single sided closure welds for tubular joints. The welds were fabricated to produce the worst misalignment and root gap likely to occur in service. Strain gage data were obtained to determine the stress concentrations caused by misalignment and thickness transition. Results of the fatigue testing showed performance consistent with current design guidelines of Class F2. A formula for estimating stress concentration factors was developed.

5.0 Anon., “Corrosion fatigue crack growth in BS4360 Grade 50D structural steel in seawater under narrow band variable amplitude loading,” Offshore Technology Report OTH 86232, HMSO, London, UK, 1986.

Key Words:

Steel(s):

Notes: Publication was not available.

6.0 Anon., “Corrosion fatigue of offshore structures - can crack tip electrochemistry help?,” Offshore Research Focus, Vol. 41, Feb., 1984, p. 7.

Key Words: fatigue, offshore service, crack propagation

Steel(s): structural

Notes: The UK Department of Energy is supporting research studies of crack-tip electrochemistry for corrosion-fatigue in seawater. The results of the work are to be used in modeling the corrosion-fatigue cracking of offshore structures. (See papers and reports by A. Turnbull for information on this research.)

7.0 Anon., “European Offshore Steels Research Seminar,” European Offshore Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980.

Key Words:
Steel(s):
Notes: See individual papers published in these proceedings.

8.0 Anon., "Fatigue studies: cathodic protection," Offshore Research Focus, Vol. 57, Feb., 1987, p. 10.

Key Words:
Steel(s):
Notes: Publication was not available.

9.0 Anon., "Long-term corrosion fatigue life of welded marine structures," Corros. Inf. Anal., Vol. 14, June, 1986, p. 1.

Key Words:
Steel(s):
Notes: Publication was not available.

10.0 Aoki, T., K. Nakano, H. Fukuhara, A. Okada, S. Kobayashi, K. Kimura, M. Inagaki, "Fatigue life and corrosion fatigue life prediction of welded joints of structural steel containing planar defects," Transactions of the Iron and Steel Institute of Japan, Vol. 26, No. 11, 1986, p. 977-984.

Key Words: welded joint, weld defects, synthetic seawater, cathodic protection
Steel(s): SM50B
Notes: Weldments were made with planar defects (lack of penetration and hot cracking) and fatigue tested at 10 Hz in air and at 0.5 Hz in seawater with (-1.05 V vs. SCE) and without cathodic protection. Before testing, the weldments were inspected ultrasonically to characterize the size and location of the defects to within 1 mm. Provided that defects can be sized and located with this level of accuracy and that the effects of corrosion and cathodic protection are taken into account, fracture mechanics models can be used to make good predictions of fatigue life. The defect sensitivity index was independent of stress range for tests in air, but strongly dependent on stress range for tests in seawater, especially with cathodic protection.

11.0 Arup, H., E. Maahn, F. Jacobsen, P. Press, "Environmental effects in corrosion fatigue," Report Number EUR 9551 EN, Contract Number 7210-KG/901, Commission of the European Communities, Luxembourg, 1985.

Key Words:
Steel(s):
Notes: Publication was not available.

12.0 Assefpour-Dezfuly, M., W. G. Ferguson, "Corrosion fatigue of a C-Mn structural steel in various seawater environments," 1987 Australasian Conference on Materials for Industrial Development,

	Institute of Metals and Materials Australasia Ltd., Parkville, Australia, 1987, p. 27-31.
Key Words:	crack propagation, cathodic protection, seawater, hydrogen sulfide, hydrogen embrittlement
Steel(s):	C-Mn
Notes:	The fatigue-crack-growth behavior of base metal and weldments was characterized in air, in seawater under free corrosion, and in seawater with cathodic protection to -1.0 V vs. SCE and with and without additions of hydrogen sulfide. Compared with growth rates in air, growth rates were 2.4 times faster in seawater under free corrosion and 5 times faster in seawater with cathodic protection. In seawater with cathodic protection, the addition of 2 to 10 ppm hydrogen sulfide increased growth rates by 2.5 times.

13.0	Assefpour-Dezfuly, M., W. G. Ferguson, "Effect of low concentrations of hydrogen sulfide in seawater on fatigue crack growth in a C-Mn Structural steel," Corrosion, Vol. 44, No. 7, July, 1988, p. 443-449.
Key Words:	fatigue, crack propagation, seawater, cathodic protection, hydrogen sulfide, potential drop measurement, weld metal, hydrogen embrittlement
Steel(s):	C-Mn
Notes:	Fatigue crack growth tests were performed on C-Mn steel base metal and weldments in air and seawater. Four conditions were used for testing in seawater -- free corrosion (FC) and under cathodic protection (CP) to -1.0 V vs. SCE with and without additions of hydrogen sulfide. Tests were performed at a stress ratio of R =0.5. The frequency was 20 Hz for tests in air and 0.1 Hz for tests in seawater. For FC conditions, the crack growth rate in seawater was 2.4 times faster than that in air. With CP, a 3-stage growth rate curve was observed and the growth rates in the plateau region were 2 times those for FC conditions. Under CP, the addition of hydrogen sulfide significantly increased crack growth rates.

14.0	Austen, I. M., E. F. Walker, "Corrosion fatigue crack growth rate information for offshore life prediction," Steel in Marine Structures--SIMS '87, Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 859-870.
Key Words:	crack propagation, hydrogen sulfide, cathodic protection, random loading, threshold, frequency, seawater, stress ratio
Steel(s):	BS 4360:50D, RQT501, RQT701
Notes:	Additions of hydrogen sulfide in the range of 100 to 1000 ppm were found to increase crack-growth rates in RQT701 steel in seawater. For similar concentrations, biologically produced hydrogen sulfide additions increased crack growth rates much less non-biological additions. Constant and variable amplitude fatigue tests were conducted on the BS 4360:50D steel at 10 and 1/6 Hz, at stress ratios of 0.05, 0.25, 0.50, and 0.75. The environments were seawater under conditions of free corrosion, seawater plus hydrogen sulfide, and

seawater with cathodic protection levels of -0.85 and -1.10 V (ref. electrode not reported). An equivalent âK value was used to correlate crack-growth data for random loading with that for constant-amplitude loading. Threshold values of âK as a function of R value are reported, and predictive modeling of overload effects on crack-growth are discussed.

15.0 Austen, I. M., E. F. Walker, "Corrosion fatigue crack propagation in steels under simulated offshore conditions," Fatigue '84, Papers Presented at the 2nd International Conference on Fatigue and Fatigue Thresholds, Vol. 3, Engineering Materials Advisory Services Ltd, Warley, England, 1984, p. 1457-1469.

Key Words: fatigue, crack propagation, offshore service, cathodic protection, hydrogen sulfide, synthetic seawater

Steel(s): BS 4360:50D

Notes: Fatigue crack growth tests were performed in air and synthetic seawater. Four conditions were used for the tests in seawater -- free corrosion (FC), FC with addition of hydrogen sulfide, and cathodic protection (CP) to -0.85 and -1.10 V vs. Ag/AgCl with addition of hydrogen sulfide. Stress ratios of R = 0.05 and 0.7 were used, and the frequency was 0.167 for tests in seawater. In the worst case, crack growth rates in seawater were 571 times greater than those in air.

16.0 Austen, I. M., W. J. Rudd, E. F. Walker, "Factors affecting corrosion fatigue and stress corrosion crack growth in offshore steels," L'Acier dans les Structures Marines. Conference Internationale (Session Technique 1-5.), Report EUR 7347, ST 5. 4, Commission of the European Communities, Luxembourg, 1981.

Key Words:

Steel(s):

Notes: Publication was not available.

17.0 Austen, I. M., C. J. Thomas, R. Brook, R. G. J. Edyvean, "Predicting the effect of corrosion fatigue of steels in biologically active seawater," Plant Corrosion: Prediction of Materials Performance, Ellis Horwood, Chichester, UK, 1987, p. 167-180.

Key Words: fatigue, crack propagation, offshore service, hydrogen sulfide, seawater, life prediction model

Steel(s): EN24, BS 4360:50D, X65, RQT501, RQT701

Notes: This paper discusses a model for predicting the corrosion fatigue crack growth of steels in biologically active seawater. Realistic simulation of the service environment in laboratory testing is essential to providing the data needed for realistic fatigue life prediction. For environments containing hydrogen sulfide, the maximum growth rates predicted by the model can be exceeded. More detailed mechanistic modeling of crack-tip microprocesses and more data for fatigue crack growth in biologically active seawater are needed for improved fatigue life predictions.

18.0 Badve, A. P., W. H. Hartt, S. S. Rajpathak, “Effects of cathodic polarization upon fatigue of selected high strength steels in seawater,” Corrosion 89, Paper 570, NACE, Houston, 1989.

Key Words: seawater, cathodic protection, hydrogen embrittlement, pitting, S-N curve

Steel(s): A710, X70, QT108

Notes: Corrosion-fatigue tests were conducted using keyhole CT specimens exposed to natural seawater under conditions varying from free corrosion to -1.10 V vs. SCE cathodic polarization. The fatigue strength of the A710 and QT108 steels increased with decreasing potential from free-corrosion conditions to -0.90 V vs. SCE and decreased with decreasing potential from -1.00 to -1.10 V vs. SCE. This behavior was similar even though the crack-initiation mechanisms were different for each steel. Hydrogen production was believed to degrade the fatigue resistance regardless to the crack-initiation mechanism.

19.0 Bardal, E., P. J. Haagensen, M. Grovlen, F. Saether, “Effects of cathodic protection on corrosion fatigue crack growth in a platform steel in sea water,” Fatigue '84, Papers Presented at the 2nd International Conference on Fatigue and Fatigue Thresholds, Vol. 3, Engineering Materials Advisory Services Ltd, Warley, England, 1984, p. 1541-1551.

Key Words: crack propagation, cathodic protection, short cracks, synthetic seawater, random loading

Steel(s): BS 4360:50D

Notes: Fatigue-crack-growth rates were determined using synthetic seawater under conditions of free corrosion and cathodic protection (CP) at levels down to -1.10 V vs. Ag/AgCl. The total effect of CP on predicted service life was evaluated by integrating the crack-growth-rate data for a linear load spectrum. For small defects (1 mm) and long lives (>20 years), CP increased predicted life up to a factor of 10. Under the most unfavorable conditions, CP was predicted to cause a slight reduction in fatigue life.

20.0 Bardal, E., “Effects of corrosion and cathodic protection on crack growth in offshore platform steels in sea water,” Fatigue '87, Vol. III, Engineering Materials Advisory Services Ltd, Warley, England, 1987, p. 1169-1178.

Key Words: calcareous deposits, cathodic protection, crack propagation, threshold, synthetic seawater

Steel(s): BS 4360:50D

Notes: This paper reviews the data reported in Document Nos. 103 and 104. It discusses the results of fatigue studies conducted at SINTEF since

1973. Emphasis is placed on near threshold crack growth rates and the effect of cathodic protection in synthetic seawater. (This paper is essentially the same as Document No. 21.)

21.0 Bardal, E., “Effects of free corrosion and cathodic protection on fatigue crack growth in structural steel in sea water,” Eurocorr '87, European Corrosion Meeting, Preprints, DECHEMA, Frankfurt am Main, FRG, 1987, p. 451-457.

Key Words: calcareous deposits, cathodic protection, crack propagation, threshold, synthetic seawater

Steel(s): BS 4360:50D

Notes: This paper reviews the data reported in Document Nos. 103 and 104. It discusses the results of fatigue studies conducted at SINTEF since 1973. Emphasis is placed on near threshold crack growth rates and the effect of cathodic protection in synthetic seawater. (This paper is essentially the same as Document No. 20.)

22.0 Bardal, E., T. Berge, M. Grovlen, P. J. Haagensen, B. M. Forre, “Measurements of very low corrosion fatigue crack growth rates in structural steel in artificial sea water,” Fatigue Thresholds, Fundamentals and Engineering Applications, Proceedings of an International Conference, Engineering Materials Advisory Services Ltd, Warley, England, 1982, p. 471-487.

Key Words: cathodic protection, crack propagation, threshold, synthetic seawater, stress ratio, frequency, short cracks, potential drop measurement

Steel(s): BS 4360:50D

Notes: This paper discusses some of the data reported later in Document Nos. 20, 21, 103, and 104. The equipment used to measure near threshold crack growth by means of pulsed DC potential drop technique and obtain threshold crack-growth data at low frequencies (0.167 and 1 Hz) are described. The data were developed at $R = 0.05$ and 0.5 and for crack depths from 1 to 7 mm.

23.0 Bardall, E., J. M. Sondenfor, P. O. Gartland, “Slow corrosion fatigue crack growth in a structural steel in artificial sea water at different potentials, crack depths, and loading frequencies,” European Offshore Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. VI/16-1 to 16-12.

Key Words: cathodic protection, crack propagation, synthetic seawater, frequency, short cracks

Steel(s): BS 4360:50D

Notes: Differences in growth-rate data for short (1-3 mm) and longer (3-7 mm) cracks are shown. Under free corrosion, the shorter cracks grew more rapidly. Under cathodic protection (-0.80 to -1.10 V vs. SCE), the deeper cracks grew more rapidly. This paper is Ref. No. 124 in Jaske, et al. (Document No. 140).

23.5	Bavarian, B., M. Zakaria, C. Rodriguez, A. Magee, "Environmental Effects on the Fatigue Crack Growth Rate of High Strength Low Alloy Structural Steel (HSLA 80)," Corrosion 94, Paper 216, NACE, Houston, 1994.
Key Words:	3.5% NaCl, synthetic seawater, corrosion fatigue, crack propagation, stress ratio
Steel(s):	HSLA 80, A710
Notes:	Fatigue crack growth rate was measured in air, 3.5% NaCl solution, and synthetic seawater. Loading was sinusoidal at R = 0.1 and 0.8 and at frequencies of 1 and 10 Hz. The aqueous environments showed no significant effect on crack growth behavior compared with air.

24.0	Bell, R., O. Vosikovsky, "A fatigue life prediction model for multiple cracks in welded joints for offshore structures," Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1992, p. 501-507.
Key Words:	crack propagation, T joint, life prediction model, multiple cracks, welded joint, potential drop measurement
Steel(s):	LT60, CSA G40.21M 350 WT
Notes:	Fatigue tests were conducted on welded T joints. Crack growth was measured using AC potential, ink staining, and beach marking. The fatigue limit (10E7 cycles) increased from about 80 MPa for 45-degree straight welds to about 170 MPa for fully ground welds. The fatigue life improvement achieved by grinding the full weld profile per AWS recommendations is comparable with that achieved by weld toe grinding per European code recommendations. Grinding extends crack initiation life more than crack growth — from about 27% of total life for 45-degree straight welds to about 67% of total life for fully ground welds. A fracture mechanics model was developed to predict the growth an coalescence of a linear array of cracks. Predictions made using the model were in reasonable agreement with the experimental data.

25.0	Vosikovsky, O., R. Bell, "Attachment thickness and weld-profile effects on fatigue life of welded joints," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 339-362.
Key Words:	fatigue, crack initiation, crack propagation, thickness, weld profile, welded joint, T joint, potential drop measurement
Steel(s):	Grade 350
Notes:	T joints were fatigue tested to evaluate the effect of thickness in the range of 25 to 100 mm. AC potential drop, ink staining, and beach marking were used to monitor crack initiation and development. The AWS improved weld profile significantly reduced the effect of thickness on fatigue strength compared with that of 45-degree welds. Fracture mechanics predictions provided reasonable estimates of crack propagation lives, except the thickness effect was predicted to be

greater than observed for 26-mm thick joints with 45-degree welds and for equal thickness attachment to base plate welds with the AWS profile.

26.0 Bell, R., O. Vosikovsky, “Fatigue life prediction of welded joints for offshore structures under variable amplitude loading,” Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 385-393.

Key Words: fatigue, welded joint, offshore service, spectrum loading, T joint, stress concentration factor, fracture mechanics

Steel(s): Grade 350

Notes: A fracture mechanics model was developed to predict the fatigue life of welded joints under variable amplitude spectrum loading. Variable amplitude loading fatigue tests were conducted on welded T joint specimens to validate the model. Root mean square (RMS) and effective (root mean cube) stress ranges were representative parameters for the loading spectrum that was used; the effective stress range provided slightly better correlation between variable amplitude and constant amplitude results than the RMS stress range. An empirical relationship was developed to predict coalescence and shape development for weld toe cracks. A stress concentration factor was used to compute weld toe peak stress.

27.0 Berge, S., M. Grovlen, E. Bardal, O. I. Eide, K. Engesvik, P. J. Haagensen, O. Orjasaeter, “Effect of localized corrosion damage on fatigue strength of welded steel joints,” Proceedings of EVALMAT 89 - International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 1, The Iron and Steel Institute of Japan, Tokyo, 1989, p. 87-96.

Key Words: pitting, welded joint, tubular joint, seawater, S-N curve, crack propagation, cathodic protection

Steel(s): St 52-3

Notes: Fatigue tests were conducted on welded steel joints with simulated pitting corrosion. Pitting was simulate by spark erosion and subsequent accelerated corrosion. Tests were in air and in natural seawater without and with cathodic protection to -1.00 V vs. SCE. Both T and tubular joints were tested. S-N curves and fatigue notch factors were developed for six different pit geometries using the T-joint specimens. Both S-N and crack-growth data were developed for the tubular joints. The pitting had no significant effect on the fatigue strength of the tubular joints. Elongated grooves along the weld toe degraded the fatigue strength of the T joints. The pitting reduced fatigue life in seawater by a factor of 2.5 compared with air; this reduction is similar to that observed for unpitted welded joints tested under similar conditions.

28.0 Bertini, L., “Influence of seawater and residual stresses on fatigue crack growth in C-Mn steel weld joints,” Theoretical and Applied Fracture Mechanics, Vol. 16, No. 2, 1991, p. 135-144.

Key Words: crack propagation, welded joint, synthetic seawater, cathodic protection, frequency, stress ratio, residual stress, crack closure

Steel(s): C-Mn

Notes: Fatigue-crack-growth rates were measured for welded joints tested in air and in synthetic seawater with cathodic polarization to -0.80 and -1.00 V vs. Ag/AgCl. The frequency was 0.3 and 1.0 Hz and the stress ratios were 0.1 and 0.7. At low âK levels cracks grew more slowly in the welded joints than in base metal because of residual stress. An effective âK that accounted for residual stress and crack closure was used to obtain measured and predicted crack-growth rate behavior.

29.0 Bhuyan, G. S., A. S. J. Swamidas, O. Vosikovsky, “Influence of environmental and mechanical variables on fatigue crack growth rates in CSA G40.21M 350 WT steel,” International Journal of Fatigue, Vol. 10, No. 1, 1988, p. 37-42.

Key Words: crack propagation, seawater, frequency, stress ratio, temperature

Steel(s): CSA G40.21M 350 WT

Notes: Fatigue-crack-growth behavior was determined in air and natural seawater. Tests were conducted at temperatures from -15 to 21 C, stress ratios from 0.05 to 0.3, frequencies from 0.05 to 2.0 Hz. Compared with data in air, the maximum increase in crack-growth rate in seawater was 2.7 times at 35 MPa m, 0.05 Hz, 0 to 4 C, and R = 0.1. The difference in growth rate was negligible at frequencies greater than or equal to 0.5 Hz. The growth rate at 35 MPa m decreased by 1.7 times when the temperature was decreased from 21 to 0 C, but no significant effect of temperature was observed over the range of -15 to 4 C. In the range of 0.05 to 0.3, stress ratio had no significant effect on crack-growth rate.

30.0 Bignonnet, A., H. P. Lieurode, “Corrosion fatigue of high strength steel in marine structures,” Proceedings of the 8th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1989, p. 527-534.

Key Words: welded joint, shot peening, TIG dressing, cathodic protection, seawater, tubular joint

Steel(s): E460

Notes: Fatigue tests were performed on welded T joints and tubular X nodes in air and in seawater with cathodic protection to -0.95 V vs. Ag/AgCl. The benefits of using a high-strength steel combined with improved welding procedures and treatments was evaluated. Improved weld profile and TIG dressing greatly improved fatigue resistance of the welded joints because of reductions in local stress where cracking initiates. Shot peening induces compressive stresses and delays fatigue crack initiation. With cathodic protection, the fatigue strength in seawater is similar to that measured in air. (The same fatigue data on X nodes also are reported in Document No. 31.)

31.0 Bignonnet, A., J. Gerald, H. P. Lieurade, G. Garrigues, "Corrosion fatigue of high strength steel tubular nodes," Proceedings of the 8th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1989, p. 405-412.

Key Words: welded joint, shot peening, TIG dressing, cathodic protection, seawater, tubular joint

Steel(s): E460

Notes: Fatigue tests were performed on welded tubular X nodes in air and in seawater with cathodic protection to -0.95 V vs. Ag/AgCl. The benefits of using a high-strength steel combined with improved welding procedures and treatments was evaluated. Improved weld profile and TIG dressing greatly improved fatigue resistance of the welded joints because of reductions in local stress where cracking initiates. Shot peening induces compressive stresses and delays fatigue crack initiation. With cathodic protection, the fatigue strength in seawater is similar to that measured in air. (The same fatigue data on X nodes also are reported in Document No. 30.)

32.0 Bignonnet, A., "Corrosion fatigue of steel in marine structures," Cathodic Protection: A + or - In Corrosion Fatigue?, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada, 1986, p. 161-180.

Key Words: cathodic protection, crack initiation, crack propagation, welded joint, calcareous deposits, short cracks

Steel(s): E355, X65, E460, BS 4360:50D

Notes: This paper is similar to Document No. 33 and reviews the effects of cathodic protection on the fatigue behavior of steels in marine environments. The best method of improving fatigue life is to delay crack initiation as long as possible. The best approach is to use smooth-shaped welds, post-weld improvement, and maintaining a moderate potential. Electrochemical conditions that promote the formation of calcareous scale may reduce the growth rate of short cracks.

33.0 Bignonnet, A., "Corrosion fatigue of steel in marine structures - a decade of progress," Steel in Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 119-135.

Key Words: cathodic protection, crack initiation, crack propagation, welded joint, calcareous deposits, short cracks, threshold, frequency

Steel(s): E355, X65, E460, BS 4360:50D

Notes: This paper is similar to Document No. 32 and reviews the effects of cathodic protection on the fatigue behavior of steels in marine environments. The best method of improving fatigue life is to delay crack initiation as long as possible. The best approach is to use smooth-shaped welds, post-weld improvement, and maintaining a moderate potential. Electrochemical conditions that promote the formation of calcareous scale may reduce the growth rate of short cracks. Threshold crack-growth data are reported for E355 steel tested in seawater under free corrosion and cathodic protection, at R values from 0 to 0.75, and at frequencies from 1/6 to 10 Hz.

34.0 Bignonnet, A., M. Olagnon, “Fatigue life prediction for variable amplitude loading,” Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 395-401.

Key Words: fatigue, crack propagation, offshore service, spectrum loading, cycle counting

Steel(s): E36Z

Notes: Variable amplitude fatigue crack growth tests were conducted on compact type (CT) and center cracked tension (CCT) specimens to provide data for validation of fatigue life prediction methods. Using an equivalent load concept, where the load history is reduced to constant amplitude cycles, gave a fair prediction of fatigue life. The following five cycle counting methods were evaluated: all transitions, zero crossing transitions, rainflow, peak amplitude, and zero crossing peak amplitude. For narrow band loading, all of the counting methods gave similar results. For wider band loading, the life predictions were very sensitive to the counting method. Only the zero crossing transitions method gave good predictions for all test cases. Rainflow counting may give nonconservative results for some cases when used with the equivalent load method.

35.0 Bignonnet, A., J. L. Brazy, C. Vallet, F. Barrere, “The influence of electrochemical parameters on the corrosion fatigue at notches of a structural steel,” Steel in Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 711-718.

Key Words: notch, cathodic protection, 3% NaCl, synthetic seawater, crack initiation, hydrogen embrittlement

Steel(s): E355

Notes: The effects of cathodic potential on fatigue-crack initiation at notches was evaluated. The environments were air and synthetic seawater under free corrosion and cathodic polarization to -0.80 and -1.00 V vs. Ag/AgCl. Keyhole notched CT specimens with a K_t of 3.0 were used. Crack initiation was detected by change in compliance and by change in the cathodic protection current. For high strain ranges (low-cycle fatigue) and a polarization level of -1.00 V vs. Ag/AgCl, cracks initiated rapidly and reduced fatigue life because of hydrogen embrittlement. At -0.80 V vs. Ag/AgCl for high strain ranges and at both levels for low strain ranges (high-cycle fatigue), crack initiation was delayed and fatigue lives were close to or greater than those for comparable tests in air. A local-strain model based on strain energy was used to predict fatigue-crack initiation behavior. The low-cycle fatigue constants depended on the environment, including level of cathodic protection.

36.0 Bogar, F. D., T. W. Crooker, "Fatigue testing in natural and marine corrosion environments substitute ocean waters," Materials Performance, Vol. 22, No. 8, Aug., 1983, p. 37.

Key Words: S-N curve, seawater, synthetic seawater, 3.5% NaCl

Steel(s): HY80, 17-4 PH

Notes: Smooth hourglass-shaped specimens of three alloys: HY80 steel, 17-4 PH steel, and 5083-H118 aluminum were tested in natural seawater, synthetic seawater, and 3.5% NaCl solution under free-corrosion conditions. S-N data were developed for fatigue lives close to or greater than 1 million cycles to failure, where most of the life is fatigue-crack initiation. The differences in fatigue lives among the three environments were small (less than a factor of two in all cases), and the ASTM synthetic seawater never gave the lowest fatigue life.

37.0 Boomer, D., R. Hermann, A. Turnbull, "Refilming kinetics of scraped steel electrodes in simulated corrosion fatigue crack-tip environments," Corrosion Science, Vol. 29, No. 9, 1989, p. 1087-1101.

Key Words: 3.5% NaCl, seawater, scraping electrode,

Steel(s): BS 4360:50D

Notes: The scraping electrode technique was employed to investigate reactions on the surface of bare metal. Transient cathodic and anodic currents were measured in environments simulating those at the tip of a fatigue crack in 3.5% NaCl solution and in seawater.

38.0 Booth, G. S., "Constant amplitude corrosion fatigue strength of welded joints," Fatigue in Offshore Structural Steels, Paper 2, Thomas Telford Ltd., London, 1981.

Key Words: S-N curve, welded joint, stress ratio, synthetic seawater, cathodic protection

Steel(s): BS 4360:50D

Notes: Welded joints were fatigue tested at 0.167 Hz and at R = -1 and 0 in air and in synthetic seawater under conditions of free corrosion, alternate immersion, and full immersion with cathodic protection at -0.85 V vs. Ag/AgCl. S-N curves were developed for cyclic lives between 1E4 and 1E7 cycles to failure. S-N curves for free-corrosion and alternate-immersion conditions were about the same as those in air. With cathodic protection, the S-N curves were about the same as the others at high stress ranges and gradually increased above the others at lower stress ranges (longer lives). Grinding the weld toes increased the fatigue resistance only slightly under free corrosion conditions.

39.0 Booth, G. S., "Constant amplitude fatigue tests on welded steel joints performed in air," European Offshore Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. III/4-1 to 4-15.

Key Words: S-N curve, welded joint, stress ratio, thickness, hammer peening, TIG dressing

Steel(s): BS 4360:50D

Notes: Fatigue tests of welded joints were conducted in air. In order of decreasing improvement, hammer peening, toe grinding, and TIG dressing increased fatigue strength. S-N curves were developed at R = -1 and 0; 25-mm thick joints had better bending fatigue strength than those of 38-mm thick joints. This paper is Ref. No. 96 in Jaske, et al. (Document No. 140).

40.0 Booth, G. S., J. G. Wylde, T. Iwasaki, "Corrosion fatigue crack propagation and threshold determinations in structural steel," Fatigue '84, Papers Presented at the 2nd International Conference on Fatigue and Fatigue Thresholds, Vol. 3, Engineering Materials Advisory Services Ltd, Warley, England, 1984, p. 1471-1484.

Key Words: crack propagation, threshold, synthetic seawater, cathodic protection

Steel(s): BS 4360:50D

Notes: Fatigue-crack-growth tests were conducted at R = 0 and a frequency of 0.167 Hz. The environments used were air, free corrosion in synthetic seawater at 10 C, and cathodic protection (CP) to -0.85 V vs. Ag/AgCl in synthetic seawater at 10 C. The threshold âK values for these three conditions were 250, 195, and 250 MPa m, respectively. Thus, CP restored the threshold to the level measured in air. At intermediate âK levels, the freely corroding synthetic seawater increased crack growth rates by a factor of 7 to 10 times. With CP in synthetic seawater, the crack growth rates at intermediate âK levels were decreased slightly below those measured for free corrosion conditions.

41.0 Booth, G. S., R. Holmes, "Corrosion fatigue of welded joints under narrow band random loading," Fatigue in Offshore Structural Steels, Institution of Civil Engineers, Thomas Telford Ltd., London, 1981, p. 17-24.

Key Words: welded joint, random loading, Miner's rule, seawater, cathodic protection

Steel(s): BS 4360:50D

Notes: Fatigue tests of longitudinal and transverse welded joints were carried out under narrow-band random loading in seawater under conditions of (1) free corrosion, (2) intermittent immersion, and (3) cathodic protection. The RMS stress range was used to correlate the results with constant-amplitude data. Miner's rule was found to adequately account for fatigue damage accumulation. Cathodic protection was beneficial only in the low-stress (long-life) regime for transverse joints tested at R = -1.

42.0 Booth, G. S., "Corrosion fatigue of welded steel joints in sea water," UK National Corrosion Conference 1982, The Institution of Corrosion Science and Technology, Birmingham, UK, 1982, p. 179-181.

Key Words: welded joint, random loading, Miner's rule, seawater, cathodic protection

Steel(s): BS 4360:50D

Notes: Fatigue tests were conducted on welded joints under constant amplitude and narrow band random loading in four environments: air, freely corroding seawater, intermittent immersion in seawater, and cathodic protection to -0.85 V vs. Ag/AgCl in seawater. The cyclic frequency was 0.167 Hz. The results from random loading were correlated with those from constant amplitude loading using the r.m.s. stress range. The use of Miner's rule also was evaluated. (These same data are included in Document No. 43.)

43.0 Booth, G. S., "Corrosion fatigue of welded steel joints under narrow-band random loading," Corrosion Fatigue: Mechanics, Metallurgy, Electrochemistry, and Engineering, STP 801, ASTM, Philadelphia, 1981, p. 472-490.

Key Words: welded joint, random loading, Miner's rule, synthetic seawater, cathodic protection

Steel(s): BS 4360:50D

Notes: Fatigue tests were conducted on welded joints under constant amplitude and narrow band random loading in four environments: air, freely corroding synthetic seawater, intermittent immersion in synthetic seawater, and cathodic protection to -0.85 V vs. Ag/AgCl in synthetic seawater. The cyclic frequency was 0.167 Hz and R was -1 and 0. The results from random loading were correlated with those from constant amplitude loading using the r.m.s. stress range. The use of Miner's rule also was evaluated. (Some of these same data are included in Document No. 42.)

44.0 Tubby, P. J. , G. S. Booth, "Corrosion fatigue crack growth rate studies in two weldable high strength steels," Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1992, p. 539-547.

Key Words: crack propagation, cathodic protection, synthetic seawater, welded joint

Steel(s): SAR 60, MACS

Notes: Single edge notched three point bend specimens were tested at a stress ratio of $R = 0.7$ to develop fatigue crack growth data in air and seawater. Tests in seawater were under free corrosion and under cathodic protection (CP) to -0.85 and -1.10 V vs. Ag/AgCl. The data for base metal in air were similar to those for a range of similar structural steels. Free corrosion increased crack growth rates in the base metal. Heat-affected-zone (HAZ) material for the two steels had similar crack propagation rates for free corrosion and adequate CP (-

0.85 V vs. Ag/AgCl). However, CP gave rise to transient accelerations in fatigue crack growth rate for the SAR 60 HAZ material. Overall, the results were similar to those obtained in past studies of BS 4360:50D steel base metal and HAZ material.

45.0 Booth, G. S., "Improving the corrosion fatigue strength of welded joints -- the effect of cathodic protection," Cathodic Protection: A + or - In Corrosion Fatigue?, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada, 1986, p. 137-152.

Key Words: cathodic protection, seawater, welded joint, crack initiation

Steel(s): structural

Notes: Two methods of weld-toe treatment, profile modification and residual-stress modification, are reviewed. The weld-toe profile can be modified by local machining, remelting, using special electrodes, and controlling the weld profile. The weld-toe residual-stress distribution can be modified by stress relief treatment, prior overloading, peening, local compressive loading, and spot welding. The benefits of these weld-toe treatments have been demonstrated for fatigue in air. Limited testing in seawater under free-corrosion conditions has shown much smaller benefits than in air. However, these techniques may be much more beneficial under conditions of cathodic protection. The benefits of residual-stress modification may be reduced by periodic overloads.

46.0 Booth, G. S., J. G. Wylde, "Procedural considerations relating to the fatigue testing of steel weldments," Fatigue and Fracture Testing of Weldments, STP 1058, ASTM, Philadelphia, 1990, p. 3-15.

Key Words: welded joint, cathodic protection, synthetic seawater

Steel(s): BS 4360:50D

Notes: This paper discusses the main items that should be addressed in fatigue testing of welded joints. The four areas covered are - specimen design and fabrication, specimen preparation, testing, and reporting. Material, configuration, size, residual stress, thickness, and welding procedures are included in the first area. Strain gaging, specimen straightness and alignment, and edge grinding are included in the second area. Calibration, loading, number of tests, environment, monitoring, and failure criterion are included in the third area. Finally, the information required for the report and presentation of the data are discussed. The S-N curves reported in this paper are discussed in more detail in Document No. 43.

47.0 Booth, G. S., J. G. Wylde, "Some mean stress effects on the corrosion fatigue performance of welded joints," Integrity of Offshore Structures, Papers presented at the 2nd International Symposium, Applied Science Publ., London and Englewood, NJ, 1981, p. 199-217.

Key Words: welded joint, residual stress, synthetic seawater, tubular joint, S-N curve, stress relief

Steel(s): BS 4360:50D

Notes: Welded joints with high levels of residual stress were fatigue tested under four point bending at 0.167 Hz and R = -1 in air and synthetic seawater, and welded tubular joints were fatigue tested under out-of-plane bending at 1 to 5 Hz and R = 0 in air. A post weld heat treatment (PWHT) of 1.5 hours at 600 C reduced residual stress and improved fatigue resistance in both air and synthetic seawater. Compressive chord loading did not affect the fatigue strength of the tubular joints tested in the as-welded condition, but it could affect stress-relieved tubular joints.

48.0 Booth, G. S., “Techniques for improving the corrosion fatigue strength of plate welded joints,” Steel in Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 747-757.

Key Words: welded joint, shot peening, hammer peening, cathodic protection, synthetic seawater

Steel(s): BS 4360:50D

Notes: Constant-amplitude fatigue tests were performed on 38-mm thick welded joints. Cathodically protected (-0.85 V vs. Ag/AgCl) joints had better fatigue strength than those tested under free-corrosion conditions. With this level of cathodic protection, the benefit of grinding the joints was the same as observed for tests in air. The fatigue strength of hammer-peened joints was similar to that observed in air when the specimens were cathodically protected to either -0.85 or -1.10 V vs. Ag/AgCl. Shot peening also was beneficial, but to a lesser extent than hammer peening. Six weeks of pre-corrosion caused a small decrease in the fatigue strength of ground joints.

49.0 Brazy, J. L., A. Bignonnet, C. Vallet, “Influence of electrochemical parameters on the low-cycle corrosion fatigue of a structural steel,” ECF 6: Fracture Control of Engineering Structures, Proceedings of the 6th Biennial European Conference on Fracture, Vol. 2, Engineering Materials Advisory Services Ltd, Warley, England, 1986, p. 1227-1239.

Key Words: cathodic protection, crack initiation, low-cycle fatigue, synthetic seawater, strain cycling

Steel(s): E355

Notes: Strain controlled, low-cycle fatigue tests were conducted in air and in synthetic seawater at three different potentials: free corrosion, cathodic protection (CP) to -0.80 V vs. Ag/AgCl, and CP to -1.00 V vs. Ag/AgCl. The change in polarization current was used to detect crack initiation within 0.25 mm. Coffin-Manson curves were developed for all four test conditions. At high strain ranges, the highest level of CP significantly reduced fatigue life. At low strain ranges, CP improved fatigue life to the levels measured in air.

50.0 Bristoll, P., J. A. Roeleveld, “Fatigue of offshore structures: effect of sea water on crack propagation in structural steel,” European Offshore

	Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. VI/18-1 to 18-10.
Key Words:	crack propagation, synthetic seawater, hydrogen sulfide, stress ratio
Steel(s):	St 52
Notes:	Fatigue-crack growth rates were measured in air and in freely corroding synthetic seawater at 20 C. The loading period was 5 sec, which is equivalent to a frequency of 0.1 Hz, and R was 0.6 or greater. For growth rates less than 10E-6 mm/cycle, the synthetic seawater had little effect on crack-growth behavior. For âK up to 28.5 MPa m, the growth rate in synthetic seawater was up to 3 times faster than that in air. Addition of hydrogen sulfide to the seawater increased crack growth rates up to 40 times at âK levels above 9.5 MPa m. The threshold âK was about 2.85 MPa m in all three environments. Intermittent seawater exposure retarded crack growth in the low âK regime. This paper is Ref. No. 118 in Jaske, et al. (Document No. 140).
51.0	Burns, D. J., O. Vosikovsky, "Some factors affecting the corrosion fatigue performance of welded joints in offshore structures," Time-Dependent Fracture, Proceedings of the Eleventh Canadian Fracture Conference, Martinus Nijhoff Publ., Dordrecht, Netherlands and Boston, 1985, p. 53-67.
Key Words:	crack initiation, crack propagation, cathodic protection, synthetic seawater, tubular joint, stress ratio, temperature, welded joint
Steel(s):	X65
Notes:	Factors that affect the corrosion-fatigue performance of welded steel offshore structures are reviewed. Published data on the initiation and growth of fatigue cracks in tubular joints are discussed. For large tubular joints, more than half of the fatigue life is typically consumed by crack propagation. Crack-growth data for X65 steel at 0 and 25 C in freely corroding synthetic seawater and synthetic seawater with cathodic protection (CP) to -1.04 V vs. SCE are presented for R = 0.05 and 0.5 and for a loading frequency of 0.1 Hz. Decreasing the test temperature decreased the crack growth rate. Compared with data from tests in air, CP markedly increased crack growth rate at intermediate âK levels and lowered it at low levels of âK. The former effect is believed to be caused by hydrogen embrittlement, whereas the latter effect is believed to be caused by the formation of calcareous scale at the crack tip.
52.0	Burnside, O. H., S. J. Hudak Jr., E. Oelkers, K. Chan, R. J. Dexter, "Long-term corrosion fatigue of welded marine steels," Ship Structure Committee Report SSC-326, 1984.
Key Words:	life prediction model, crack initiation, crack propagation, cathodic protection, seawater, synthetic seawater, welded joint, tubular joint
Steel(s):	835M30, BS 4360:50D, X65, and others
Notes:	This report extensively reviews the factors that influence the long-term corrosion fatigue of structural steels in marine environments. Fatigue

life prediction models were formulated to take into account both crack initiation and propagation and important environmental and loading variables. The initiation model used the local stress-strain approach with a modified Neuber rule, while the propagation model used a fracture mechanics approach based on the stress intensity factor. The model gave life predictions that correlated well with test results for planar and tubular welded joints at low R values in both air and seawater. From a probabilistic analysis, it was determined that the most important variable in fatigue life prediction is the applied loadings.

53.0 Buttle, D. J., C. B. Scruby, "Acoustic emission monitoring of a fatigue crack in 50D steel in a sea-water environment," NDT International, Vol. 22, No. 2, 1989, p. 81-96.

Key Words: acoustic emission, crack propagation, calcareous deposits, cathodic protection, seawater

Steel(s): BS 4360:50D

Notes: Four laboratory tests were conducted to assess the feasibility of detecting fatigue crack growth using acoustic emission (AE) monitoring. Three tests were at R = -1. Crack growth in air (first test) gave little or no AE. Crack growth in freely corroding natural seawater (second test) gave significant secondary AE from points behind the crack tip. With cathodic protection (CP) in seawater (third test), the secondary AE was even larger. The secondary AE signals are believed to be caused by fracture and debonding of calcareous scale behind the crack tip. When a stress ratio of R = 0.4 was used with CP in seawater (fourth test), the AE was greatly reduced, which is consistent with decreased debonding of the scale on the crack face behind the crack tip.

54.0 Charbonnier, J. C., H. Margot-Marette, M. Truchon, "Technical Session 5: Stress corrosion and corrosion fatigue of weldable steels in marine environments," L'Acier dans les Structures Marines. Conference Internationale (Paris), Report EUR 7347, 1981.

Key Words:

Steel(s):

Notes: Publication was not available.

55.0 Charbonnier, J. C., H. Margot-Marette, M. Truchon, "Stress corrosion and corrosion fatigue of weldable steels in marine environment," Metallic Corrosion: Proceedings - 8th International Congress on Metallic Corrosion, 7th Congress of the European Federation of Corrosion (111th Event), Vol. 2, DECHEMA, Frankfurt am Main, FRG, 1981, p. 1315-1320.

Key Words: cathodic protection, fatigue, synthetic seawater, weld metal, rotating bending

Steel(s): E36Z

Notes:	Samples of the steel were heat treated to produce different simulated microstructures that are typical of those found in welded joints. Using seawater saturated with hydrogen sulfide and cathodic protection (CP), the base metal was found to be the most sensitive to delayed fracture. For high-frequency (3000 rpm) fatigue, CP did not produce a hydrogen embrittlement effect.
56.0	Charles, E. A., J. Congleton, R. N. Parkins, "Various electrochemical measurements in a simulated corrosion fatigue crack," Corrosion 1988, Vol. 44, No. 9, Sept., 1988, p. 599-605.
Key Words:	corrosion fatigue, seawater, electrochemical, crack propagation
Steel(s):	HY80
Notes:	Potential, current, pH, and chloride ion concentrations were measured along a simulated corrosion-fatigue crack in HY80 steel. The results were similar to those for real cracks, allowing the prediction of potential gradients. Movement of the crevice sides to promote pumping did not significantly refresh the solution within the enclave at frequencies between 0.02 and 0.10 Hz, but flow across the crack mouth did alter the solution chemistry. Diffusion experiments in the crevice were performed. No detectable chloride ion concentration gradients across the enclave were found for the range of potentials examined.
57.0	Chen, J., Y. Yao, S. Lin, C. Hsiao, "The corrosion fatigue characteristics of X65 pipeline steel with shallow crack in 3.5% NaCl solution," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 112-116.
Key Words:	corrosion fatigue, 3.5% NaCl, crack propagation, threshold, shallow crack
Steel(s):	X65
Notes:	Threshold fatigue crack growth tests were conducted on specimens of X65 pipeline steel in 3.5% NaCl solution. Tests were performed at R = 0.1 and at frequencies of 10 and 75 Hz. At 75 Hz, the cracking at low âK occurred by quasi-cleavage. It changed to intergranular and then transgranular cracking as the value of âK increased. At 10 Hz, the cracking at low âK was intergranular rather than quasi-cleavage.
58.0	Todd, J. A., L. Chen, E. Y. Yankov, H. Tao, G. H. Reynolds, "A comparison of the near-threshold fatigue crack growth propagation in Mil-S24645 HSLA steel and its weld metal," Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1992, p. 557-564.
Key Words:	threshold, crack propagation, synthetic seawater, crack closure, cathodic protection, weld metal
Steel(s):	Mil S-24645, A710, C-Mn-Ni

Notes: Near threshold crack growth tests were conducted on compact tension (CT) specimens of Mil S-24645 and ASTM A710 steels and a C-Mn-Ni weld metal. The tests were performed in ASTM synthetic seawater under conditions of free corrosion and cathodic protection (CP) to either -0.8 or -0.1 V vs. SCE. The frequency was 10 Hz, and the stress ratio was R = 0.1. The weld metal had higher threshold values than the base metal in both air and seawater. The threshold level for the weld metal in air and in seawater with CP was similar and in the range of 11 to 14 MPa m. After correction for crack closure, the base metal had threshold values in the range of 3.5 to 5.5 MPa m

59.0 Cheng, Y.W., "The fatigue crack growth of a ship steel in seawater under spectrum loading," International Journal of Fatigue, Vol. 7, No. 2, 1985, p. 95-100.

Key Words: crack propagation, 3.5% NaCl, frequency, spectrum loading, offshore service

Steel(s): EH36

Notes: Constant-amplitude and spectrum loading fatigue crack growth tests were conducted in air and in 3.5% NaCl solution. For constant-amplitude loading, the stress ratio was either R = 0.1 or 0.5. Tests in air were at 10 Hz, while those in saltwater were at 0.1 Hz. The spectrum loading had a power density characteristic of North Sea structures. The effects of specimen orientation and R value were negligible for constant amplitude loading and crack growth rates in the range of 2E-05 to 1E-03 mm/cycle. For stress intensity factor ranges from 25 and 60 MPa m, crack growth rates in saltwater were 2 to 5 times faster than those in air. Average crack growth rates in constant amplitude and spectrum loading agreed well when plotted as a function of an equivalent stress intensity factor range.

60.0 Chong Rhee, H., J. H. Delgado, "Fracture and corrosion fatigue crack growth properties of high strength riser coupling material," Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1992, p. 533-538.

Key Words: fracture, crack propagation, brine, synthetic seawater, cathodic protection

Steel(s): API 5AC C-90

Notes: Fracture toughness and fatigue-crack-growth behavior were measured for a high strength riser coupling steel. CTOD fracture toughness values were in the range of 0.42 to 0.45 mm for temperatures between -17.8 and +17.8 C. Fatigue crack growth tests were conducted in air and in brine and ASTM synthetic seawater with cathodic protection to -0.85 V vs. SCE. Calcareous deposits made the threshold in seawater greater than that in air. There was little calcareous deposition in the brine, and consequently the threshold was similar to that in air. At higher âK levels, the crack growth rate in seawater and in brine was higher than that in air. The effects of variable stress ratio were evaluated.

61.0 Cigada, A., T. Pastore, G. Re, G. Rondelli, B. Vicentini, “Application of the slow strain rate technique on fracture mechanics precracked specimens,” Proceedings of the 9th Congress on Material Testing, Budapest, Hung, Sep 29-Oct 3 1986, Vol. 1, Gepipari Tudomanyos Egyesulet, Hung, 1986, p. 310-311.

Key Words: constant extension rate, synthetic seawater, cathodic protection, crack propagation

Steel(s): X65

Notes: Constant extension rate (slow strain rate) tests were conducted on 1/2T compact type specimens in air and synthetic seawater with over cathodic protection to -1.05 V vs. SCE. The extension rate was varied from 1.2E-04 to 5E-07 mm/s. The maximum load decreased and the rate of crack growth increased as the rate of extension decreased for the tests in seawater.

62.0 Cigada, A., et al., “Fatigue behaviour in seawater of an offshore steel in the presence of sharp defects (Italian),” Metall. Ital., Vol. 74, No. 12, Dec., 1984, p. 550-559.

Key Words:

Steel(s):

Notes: Publication was not available.

63.0 Cigada, A., B. Mazza, T. Pastore, P. Pedeferri, “Fatigue crack growth of a HSLA steel in seawater,” HSLA Steels: Metallurgy and Applications, ASM International, Metals Park, Ohio, 1986, p. 777-783.

Key Words: crack propagation, synthetic seawater, 3.2% NaCl, cathodic protection, stress ratio, threshold

Steel(s): X65

Notes: Fatigue crack growth tests were conducted in air, synthetic seawater, and 3.2% NaCl solution. In seawater and saltwater, conditions of both free corrosion (FC) and cathodic protection (CP) at -0.90 to -0.92 V vs. SCE were employed. The loading was sinusoidal at 10 to 20 Hz for tests in air and at 0.2 Hz for tests in seawater and saltwater. Stress ratios of R = 0.1 and 0.6 were used. Seawater increased the rate of crack growth at intermediate values of âK but not at low values of âK. CP further increased the crack growth rate and decreased the value of âK above which the environmental effect occurred. Increasing R from 0.1 to 0.6 also increased the deleterious environmental effect on crack growth. At low âK, CP increased the threshold level compared with air, probably because of the formation of calcareous scale inside of the crack.

64.0 Cigada, A., T. Pastore, G. Re, B. Rondelli, B. Vicentini, “Stress corrosion cracking in sea water of HSLA steel type API 5L X65 (extended abstract),” HSLA Steels '85, Chinese Society of Metals, Beijing, P. Repub. China, 1985, p. 190-191.

Key Words:

Steel(s):

Notes: Publication was not available.

64.5 Cole, I., O. Vittori, “TMCP steels and the thickness effect,” Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 331-337.

Key Words: corrosion fatigue, life prediction model, synthetic seawater, cathodic protection, T joint, weld profile, thickness

Steel(s): BS 4360:50D

Notes: Fatigue tests of welded T joints were performed in air and synthetic seawater with cathodic protection to -0.85 V vs SCE. The weld profile was characterized in detail. Even though the average profiles are held constant, minor variations in the profiles occur and significantly affect joint fatigue life. The observed and predicted thickness effects were greater than those given by Gurney's formula and were explained solely by geometric stress concentration factors. The predicted thickness effects were based on a two stage model of joint fatigue life. Thickness effects the crack initiation stage and crack shape development.

65.0 Congleton, J., “Corrosion fatigue of a constructional steel and of wire rope material in sea water,” Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 118-124.

Key Words: corrosion fatigue, seawater, 3.5% NaCl, steel ropes, crack initiation

Steel(s): BS 4360:50D, C-Mn

Notes: Corrosion fatigue tests were conducted in seawater and in 3.5% NaCl solution. Fatigue curves for the BS 4360:50D steel were developed from tests at a stress ratio of R = 0.1, at a frequency of 20 Hz, and under free corrosion (FC) conditions in 3.5% NaCl solutions with various pH levels. Crack initiation in both steels was studied at R = 0.1 and 0.5 Hz under both free corrosion and cathodic potential control in 3.5% NaCl solution and seawater. Corrosion fatigue was most pronounced at pH = 10. Fatigue cracking initiated most readily under FC conditions for both steels. With cathodic protection, cracks did not initiate in the BS 4360:50D steel, but they did initiate in the C-Mn wire rope steels.

66.0 Cottis, R. A., K. R. Gowers, M. Haji-Ghassemi, E. A. Taqi, “The application of hydrogen permeation measurements to the study of corrosion fatigue crack growth in steels,” Electrochemical Methods in

Corrosion Research (Conf.), Toulouse, France, July 1985, Mater. Sci. Forum, Vol. 8, 1986, p. 243-252.

Key Words:

Steel(s):

Notes: Publication was not available.

67.0 Cottis, R. A., E. A. Taqi, M. Haji-Ghassemi, "The influence of crack conditions on hydrogen uptake by steels," Fatigue '87, Vol. III, Engineering Materials Advisory Services Ltd, Warley, England, 1987, p. 1179-1188.

Key Words: hydrogen embrittlement, crack propagation

Steel(s): BS 4360:50E

Notes: Experiments confirmed that hydrogen uptake by steel can occur within a simulated crack when the external surface of the test sample is anodically polarized. Also, it was found that hydrogen embrittlement is possible under anodic polarization by conducting tests using an occluded cell around a slow strain rate test specimen.

68.0 Cowling, M. J., R. J. Appleton, "Corrosion fatigue of a C-Mn steel in sea water solutions," International Conference on Fatigue and Crack Growth in Offshore Structures, I Mech E Conference Publication 1986-2, Mechanical Engineering Publications, London, 1986, p. 77-92.

Key Words: corrosion fatigue, crack propagation, offshore service, 3% NaCl, seawater, hydrogen embrittlement, hydrogen sulfide, stress ratio, bacteria

Steel(s): BS 4360:50D

Notes: This paper reviews three studies of fatigue crack growth in marine environments. Under free corrosion (FC), anodic dissolution appears to the mechanism that causes increased crack growth rates in 3 to 3.5% NaCl solutions or seawater. Applying a cathodic potential or adding chemicals such as arsenic, thiourea, or hydrogen sulfide to the solution promotes the entry of hydrogen in the steel and causes increased crack growth rates by the mechanism of hydrogen embrittlement. Without debris or deposits within the fatigue crack, stress ratio has no apparent effect on crack growth rate. At potentials equal to or more positive than the FC potential, a dissolution mechanism appears to be responsible for enhanced crack growth. Sulfate reducing bacteria in seawater increase crack growth rates by up to a factor of 10 times compared with rates in plain seawater, and hydrogen sulfide does not adequately simulate bacterial activity for all levels of âK.

69.0 Cozens, K. O., P. J. Kovach, "Seawater corrosion fatigue of 2-1/4Cr-1Mo and 4130 steels for marine riser application," OTC '84, Proceedings - 16th Annual Offshore Technology Conference, Vol. 2, Offshore Technology Conference, Dallas, 1984, p. 489-494.

Key Words: corrosion fatigue, synthetic seawater, shot peening, nitriding

Steel(s): 2-1/4Cr-1Mo, AISI 4130

Notes: Axial corrosion fatigue tests were performed in air and in synthetic seawater under free corrosion conditions. Seawater significantly reduced fatigue strength compared with air. Shot peening improved fatigue strength but did not restore it to levels observed in air. Nitriding appeared to further degrade the fatigue strength in seawater.

70.0 Crooker, T. W., B. N. Leis (Editors), "Corrosion Fatigue: Mechanics, Metallurgy, Electrochemistry, and Engineering," Corrosion Fatigue: Mechanics, Metallurgy, Electrochemistry, and Engineering, STP 801, ASTM, Philadelphia, 1981.

Key Words:

Steel(s):

Notes: Proceedings of ASTM Conference. See relevant individual papers.

71.0 Crooker, T. W., S. J. Gill, G. R. Yoder, F. D. Bogar, "Development of a Navy standard test method for fatigue crack growth rates in marine environments," Environment-Sensitive Fracture: Evaluation and Comparison of Test Methods, STP 821, ASTM, Philadelphia, 1984, p. 415-425.

Key Words: corrosion fatigue, crack propagation, marine environments, fracture mechanics

Steel(s):

Notes: A standard test method for determining fatigue crack growth rates in marine environments is discussed. The purpose of the method was to address testing problems that were beyond the scope of ASTM E 647 procedures in 1984. These areas included measurement of crack length, possible transient effects caused by changes in testing conditions, control and application of the corrosive environment, and the effects of corrosion product buildups, especially within fatigue cracks.

72.0 Davis, D. A., E. J. Czyryca, "Corrosion fatigue crack-growth behavior of HY-130 steel and weldments," Journal of Pressure Vessel Technology, Vol. 103, No. 4, 1981, p. 314-321.

Key Words: corrosion fatigue, crack propagation, weld metal, seawater, cathodic protection, frequency

Steel(s): HY130

Notes: Fatigue crack growth tests were performed in seawater under conditions of free corrosion (FC) and cathodic protection (CP) to -1.05 and -1.4 V vs. SCE. Loading followed either a square or triangular waveform with a stress ratio of R = 0.05 and frequencies of 0.1 and 10 cpm. Seawater increased fatigue crack growth rates for âK values less than about 66 MPa m. There was no significant effect of waveform or frequency for base material in seawater. CP increased crack growth rates, most likely by the mechanism of hydrogen embrittlement. Cracks were more difficult to initiate in weld metal, and the crack growth rate curves for weld metal generally were steeper than those for base metal. For all environmental conditions, crack growth in the weld metal was slower than that in the base metal for comparable conditions.

73.0 Davis, D. A., E. J. Czyryca, "Corrosion-fatigue crack growth characteristics of several HY-100 steel weldments with cathodic protection," Corrosion Fatigue: Mechanics, Metallurgy, Electrochemistry, and Engineering, STP 801, ASTM, Philadelphia, 1981, p. 175-196.

Key Words: corrosion fatigue, crack propagation, weld metal, seawater, cathodic protection

Steel(s): HY100

Notes: Fatigue crack growth tests were performed in seawater under conditions of free corrosion (FC) and cathodic protection (CP) to -1.05 V vs. SCE. Loading followed triangular waveform with stress ratio of R= 0.1 and a frequency 10 cpm. All weldments had lower fatigue crack growth rates than the base metal in seawater with CP. Variations in crack growth behavior were caused by variations in residual stress and weld metallurgy that resulted from the weld process and heat input. Weld factors had a more significant effect on crack growth than environment. The behavior of HY100 weldments was similar to that of HY80 and HY130 weldments in the same environments. (Also see Report DTNSRDC/SME-82/82, Naval Ship Research and Development Center, Annapolis, Oct. 1982.)

74.0 de Back, J., G. H. G. Vaessen, "Effect of plate thickness, temperature and weld toe profile on the fatigue and corrosion fatigue behaviour of welded offshore structures, Parts I & II," Commission of the European Communities Report No. EUR 10309 EN, Commission of the European Communities, Luxembourg, 1986.

Key Words: synthetic seawater, cathodic protection, welded joint, T joint, tubular joint, temperature, thickness, notch, stress concentration factor

Steel(s): E355 KT

Notes: Part I involved corrosion fatigue of small-scale welded T joints under four-point bending, while Part II involved corrosion fatigue of welded tubular joints under axial loading of the brace. Tests were performed in air, 20 C synthetic seawater, and 5 C synthetic seawater. Two tubular joints were tested with cathodic protection at -0.80 V vs. Ag/AgCl. Over the range of 16 to 70 mm, fatigue strength decreased with increased thickness; this effect was more severe in seawater. Temperature had no effect on fatigue strength. Decreasing the weld toe flank angle increased fatigue strength slightly, whereas grinding the weld toe significantly improved fatigue strength. Seawater (free corrosion) reduced fatigue life of the tubular joints to about 40% of that observed in air. Cathodic protection of the tubular joints significantly improved fatigue life at the low strain range used in this study.

75.0 Deshayes, F. R., W. H. Hartt, “A novel approach to fatigue crack growth rate determinations under conditions relevant to offshore applications,” Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1992, p. 549-556.

Key Words: crack propagation, seawater, multiple specimens, offshore service, potential drop measurement

Steel(s): HY80, EH36, A537DQ, QT80, AC70

Notes: A procedure was developed for testing multiple (up to 5) tapered compact type specimens in series. The procedure was used to obtain crack growth data for 5 steels in air and in seawater (free corrosion conditions). Tests were performed at a stress ratio of R = 0.8. The cyclic frequency was 3 and 0.3 Hz for tests in air and seawater, respectively. DC potential drop was used to measure crack growth. Results of this study show that testing of multiple specimens is a viable procedure.

75.5 Dexter, R. J., M. Kaczinski, “Large-Scale Fatigue Tests of Advanced Double Hull Weld Joints,” Proceedings of the Advanced (unidirectional) Double-Hull Technical Symposium, October 25-26, U. S. Navy and the Maritime Administration, Gaithersberg, Maryland, 1994.

Key Words: fatigue, S-N curve, welded joint, fracture mechanics, crack propagation

Steel(s): HSLA 80, C-Mn

Notes: Over 180 large-scale members with a variety of welded details of HSLA 80 steel were fatigue tested and found to fatigue strengths consistent with those of similar C-Mn steel welded details. Box-section members were tested to show the inherent redundancy of the double-hull structure. Fracture mechanics was used to predict fatigue crack propagation.

76.0 Dickson, J. I., Y. Blanchette, J.-P. Baillon, “The effect of cathodic protection on the propagation of long and short fatigue cracks,” Cathodic Protection: A + or - In Corrosion Fatigue?, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada, 1986, p. 57-85.

Key Words: calcareous deposits, cathodic protection, crack closure, crack propagation, short cracks, fatigue limit, threshold, 3.5% NaCl, synthetic seawater

Steel(s): X65, LT60, AISI 4130

Notes: This paper reviews published information on the effect of cathodic protection on the growth of short and long cracks. Cathodic protection increases growth rates at intermediate âK levels. At low âK levels, cathodic protection increases calcareous deposits and, in turn, the amount of crack closure and the threshold level of âK. Limited data for short cracks indicate that cathodic protection decreases their growth rate because of the formation of calcareous deposits and crack-closure effects.

77.0 Dijkstra, O. D., C. Noordhoek, “The effect of grinding and a special weld profile on the fatigue behaviour of large-scale tubular joints,” OTC '85, Proceedings - 17th Annual Offshore Technology Conference, Vol. III, Offshore Technology Conference, Richardson, Texas, 1985, p. 229-235.

Key Words: corrosion fatigue, cathodic protection, synthetic seawater, tubular joint, weld profile, grinding, welded joint

Steel(s): X52

Notes: Fatigue tests were conducted on large-scale tubular joints in air, in synthetic seawater under free corrosion (FC) and cathodic protection (CP) to -0.8 V vs Ag/AgCl. Grinding of the welds improved fatigue life by 50 percent in air but had no significant in seawater. Improved weld profile can decrease the hot spot strain range and in turn improve fatigue life. The fatigue life of a tubular joint is seawater was about 40% of that in air. CP appears to have a beneficial effect on fatigue life in seawater. Also, weld grinding combined with CP appears to be beneficial. (Also, see Reference 240.)

78.0 Dolphin, A. S., A. Turnbull, “Experimental determination of the electrochemistry in corrosion-fatigue cracks in structural steel in marine environments,” Corrosion Chemistry Within Pits, Crevices and Cracks, HMSO Books, London, UK, 1987, p. 397-412.

Key Words: corrosion fatigue, crack propagation, 3.5% NaCl, electrochemical

Steel(s): BS 4360:50D

Notes: The potential and pH were measured at the tip of a growing fatigue crack in 3.5% NaCl solution at pH = 8. The specimens were cycled at 0.1 Hz and a stress ratio of R = 0.5. Cathodic polarization was controlled to levels in the range of -0.8 to -1.1 V vs. SCE. The potential drop in a fatigue crack varied with âK and level of applied potential. It was as large as -0.12 V at âK = 6.5 MPa m and -1.1 V vs. SCE applied potential, but it was always in a region of 'protection' for the conditions studied. The crack-tip pH was alkaline with values as high as 12.5 at -1.1 V vs. SCE applied potential. There was reasonable agreement between experimental measurements and theoretical predictions of crack-tip pH and potential.

79.0 Dover, W. D., Wilson, T. J., “Corrosion fatigue of tubular welded joints,” Advances in Fracture Research (Fracture 84), Proceedings of the 6th International Conference on Fracture (ICF6), Vol. 4, Pergamon Press, Oxford, 1984, p. 2505-2512.

Key Words: corrosion fatigue, synthetic seawater, T joint, cathodic protection, tubular joint, random loading, fracture mechanics, crack shape, welded joint

Steel(s): BS 4360:50D

Notes: Random loading fatigue tests were conducted on welded T joint and tubular joint specimens. The tests were in air and in ASTM synthetic seawater under conditions of free corrosion (FC) and cathodic protection (CP) to -1.05 V vs. SCE. Data on crack shape evolution were developed. In seawater, the crack depth growth rate increased by 2 to 6 times above comparable growth rates in air.

80.0 Dover, W. D., G. Glinka, A. G. Reynolds (Editors), "International conference on fatigue and crack growth in offshore structures," International Conference on Fatigue and Crack Growth in Offshore Structures, I Mech E Conference Publication 1986-2, Mechanical Engineering Publications, London, 1986.

Key Words:

Steel(s):

Notes: Conference Proceedings. See relevant individual papers.

81.0 Ebara, R., Y. Yamada, K. Fujishima, T. Nawata, I. Soya, "Corrosion fatigue behavior of high-strength steels for offshore structure in 4 deg C sea water," Transactions of the Iron and Steel Institute of Japan, Vol. 26, No. 12, 1986, p. B-374.

Key Words: cathodic protection, crack initiation, crack propagation, synthetic seawater, T joint, S-N curve

Steel(s): HT60, HT80

Notes: Fatigue life and crack propagation tests were in synthetic seawater at 4 C. The frequency was 0.16 Hz and R was 0.05. Specimens were cathodically polarized to -0.8, -1.0, -1.2, and -1.4 V vs. SCE for fatigue tests of welded T joints and to -0.8 V vs. SCE for fatigue-crack propagation tests on center-cracked plates. Proper cathodic protection (-0.8 V vs. SCE) retarded crack initiation in the T joints and crack growth in the base metal, but accelerated crack growth in the weld heat-affected zone (HAZ). (Also published in Proceedings of the 5th International Conference on Offshore Mechanics and Arctic Engineering, Vol. II, ASME, New York, 1986, p. 288-292.)

82.0 Ebara, R., Y. Yamada, K. Fujishima, A. Ozawa, T. Ishiguro, M. Hanzawa, "Corrosion fatigue behavior of high strength steels and welded joints for offshore structures," Fundamental and Practical Approaches to the Reliability of Welded Structures, The 4th International Symposium of the Japan Welding Society, Vol. 1, Japan Welding Society, Tokyo, 1982, p. 327-332.

Key Words: fatigue, crack propagation, S-N curve, seawater, synthetic seawater, 3% NaCl, frequency, cathodic protection, welded joint

Steel(s): HT80, HY130, SM41, SM50

Notes: This paper reviews published information on crack growth and S-N curves for fatigue of high strength steels and welded joints in marine environments. Ebara's data on crack growth behavior of HT80 steel are presented. The effect of frequency on fatigue crack growth behavior is shown. Data on the effect of cathodic potential on S-N fatigue life is presented. S-N curves are shown for TIG dressed welded joints and aluminum and zinc coated steel.

83.0 Ebara, R., H. Kino, S. Nakano, M. Hanzawa, H. Yokota, "Corrosion fatigue crack propagation behavior of HT 80 in 4 deg C sea water," Materials, Experimentation and Design in Fatigue, IPC Science and Technology Press Ltd., Guildford, England, 1981, p. 424-430.

Key Words: fatigue, crack propagation, synthetic seawater, temperature, welded joint, frequency

Steel(s): HT80

Notes: Fatigue crack growth tests were conducted in seawater at 4 C and in air at room temperature (RT) and -60 C. Cyclic frequencies of 0.16, 1.6, and 5 Hz and stress ratios of R = 0.1 and 0.4 were employed in the testing. Decreasing the temperature to -60 C decreased the growth rate to about 1/2 of that at RT for tests in air. Testing at 4 C in seawater increased the crack growth rate to about 4 times that observed in RT air. Crack growth rates in heat affected zone (HAZ) metal were slower than those in base metal for comparable test conditions. Decreased frequency lowered the critical corrosion fatigue crack propagation rate.

84.0 Ebara, R., "Evaluation of corrosion fatigue resistance of marine structural materials," Proceedings of EVALMAT 89 - International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 2, The Iron and Steel Institute of Japan, Tokyo, 1989, p. 1033-1041.

Key Words: S-N curve, synthetic seawater, temperature, frequency, cathodic protection, dissolved oxygen, stress concentration factor, notch

Steel(s): HT50, HT50CR, HT60, HT80

Notes: The fatigue performance of high-strength marine structural steels is reviewed. S-N data for specimens and welded T joints tested at 0.16-0.17 Hz in synthetic seawater are presented and compared with AWS, DOE, and BS S-N curves. S-N data showing the effects of cathodic protection, seawater temperature, dissolved oxygen content, and stress concentration factor are presented. Crack-growth data for HT80 steel tested in synthetic seawater at 4 C are presented. The effects of frequency (0.16 to 5 Hz) and cathodic protection (-0.8 V vs. SCE) on crack-growth rate are shown.

84.5 Ebara, R., "Current Status and Future Problems on Corrosion Fatigue Research of Structural Materials (in Japanese)," Transactions of the JSME, Series A, Vol. 59, No. 557, 1993, p. 1-11.

Key Words: S-N curve, crack initiation, crack propagation, high-cycle fatigue, pitting

Steel(s): HT50, HT50CR, HT60, HT80

Notes: The corrosion-fatigue behavior of metals in various environments is reviewed. The work in marine environments is the same as that discussed in more detail in Document No. 84. S-N curves for AISI 410 stainless steel in NaCl solutions, for AISI 410 stainless steel and Ti-6Al-4V in NaOH and steam environments, and for 0.20 carbon steel, 2-1/4Cr-1Mo steel, and AISI 309 stainless steel in molten salt are presented.

85.0 Edwards, R. A. H., P. Schuitemaker, “Determination of crack-tip pH and electrode potential during corrosion fatigue of steel,” Corrosion Chemistry Within Pits, Crevices and Cracks, HMSO Books, London, UK, 1987, p. 413-433.

Key Words: fatigue, crack propagation, hydrogen embrittlement, synthetic seawater, potential drop measurement

Steel(s): St E47

Notes: Electrode potential and crack-tip pH were measured inside of a growing fatigue crack in a pipeline steel specimen cyclically loaded at a stress ratio of R = 0.7, a stress intensity factor range of 17 MPa m, and frequency of 1 Hz. The DC potential drop method was used to measure crack length. The potential drop in the crack was slightly greater than that in a comparably sized crevice, and zero potential drop in the crack occurred at a potential of -0.76 to -0.75 V vs. SCE. The crack-tip pH varied with applied potential and was always more acid than a comparable crevice. Increased crack growth rates with polarization were explained by a hydrogen embrittlement mechanism.

86.0 Edyvean, R., “Algal-bacterial interactions and their effects on corrosion and corrosion-fatigue,” Microbial Corrosion, Proc. First European Fed. of Corrosion Workshop, Vol. 1, Elsevier Applied Science, London, 1988, p. 40-52.

Key Words: crack propagation, bacteria, algae, fatigue, hydrogen sulfide, hydrogen embrittlement, corrosion fatigue, seawater

Steel(s): RQT501

Notes: Algal-bacteria interactions that may occur in seawater are reviewed, and their potential effects on corrosion and corrosion fatigue are discussed. Large algae can increase hydrodynamic loading. Algal-bacteria interactions can produce hydrogen sulfide, which leads to greatly enhanced rates of corrosion fatigue crack growth because of hydrogen embrittlement.

87.0 Edyvean, R. G. J., C. J. Thomas, R. Brook, I. M. Austen, “The use of biologically active environments for testing corrosion fatigue properties of offshore structural steels,” Biologically Induced Corrosion (Proc. Conf.), NACE, Houston, 1986, p. 254-267.

Key Words: seawater, hydrogen sulfide, corrosion fatigue, bacteria, crack propagation, synthetic seawater

Steel(s): BS 4360:50D, RQT701

Notes: Biologically active seawater environments were used to characterize corrosion fatigue crack propagation behavior. Tests were performed in air, synthetic seawater at 5 C, synthetic seawater saturated with hydrogen sulfide at 20 C, natural seawater at 20 C, and natural seawater at 20 C with various levels of naturally produced hydrogen sulfide. Stress ratios of R = 0.05 and 0.7 were used. Plots of crack-growth rate versus the range of stress intensity factor were developed. The presence of hydrogen sulfide greatly increased crack-growth rate.

88.0 Eid, N. M. A., "Environmental effects on the nucleation of fatigue cracks in a low-alloy steel, under high-cycle fatigue conditions and uniaxial loading," Proceedings of the 7th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1988, p. 333-340.
Key Words: high-cycle fatigue, crack initiation, seawater, corrosion fatigue, inclusions
Steel(s): EN16
Notes: Crack initiation on the surface of rotating bending fatigue specimens was studied. The cyclic frequency was 66.67 Hz, and the stress amplitude was 50% of the fatigue limit in air. Fatigue cracking nucleated at debonded alumina inclusion/matrix boundaries or at corrosion pits in the matrix. Manganese sulfide and duplex inclusions played no part in fatigue crack initiation.

89.0 Esdohr, J., "Fatigue corrosion cracking of a high strength steel in sea water (abstract)," Metallic Corrosion. 8th International Congress on Metallic Corrosion, Vol. 1, DECHEMA, Frankfurt am Main, FRG, 1981, p. 612.
Key Words:
Steel(s):
Notes: Publication was not available.

90.0 Esdohr, J., K. Bohnenkamp, "Investigations of corrosion fatigue of steel in seawater (German)," Werkstoffe und Korrosion, Vol. 38, No. 4, Apr., 1987, p. 155-165.
Key Words: synthetic seawater, corrosion fatigue, crack propagation, hydrogen embrittlement, cathodic protection, threshold
Steel(s): E460, E690
Notes: Fatigue crack growth data were developed by testing specimens in air, in seawater, in seawater with cathodic polarization to -1000 vs. H, and in gaseous hydrogen. Tests were at a stress ratio of R = 0.2 and at frequencies of 0.2, 1, and 10 Hz. Compared with data in air, the crack growth threshold was greatly reduced in both synthetic seawater and hydrogen. Hydrogen was most detrimental at the high frequency (10 Hz), while seawater was most detrimental at the low frequency (0.2 Hz). Cathodic polarization raised the crack growth thresholds above the comparable values for test in air.

91.0 Ferguson, W. G., Y. Zhang, F. J. Stevens, M. Assefpour-Dezfuly, "Effects of an anaerobic environment on corrosion fatigue," CHEMECA '90, Eighteenth Australasian Chemical Engineering Conference Part 1, Univ. of Auckland, Auckland, NZ, 1990, p. 286-295.

Key Words: welded joint, hydrogen sulfide, corrosion fatigue, crack propagation, threshold, cathodic polarization

Steel(s): St 52-3N, C-Mn

Notes: Additions of hydrogen sulfide to seawater were used to simulate the effects of anaerobic environments on fatigue crack growth. Tests were conducted in air and seawater with cathodic polarization (CP) to -1.0 V vs. SCE. The stress ratio was R = 0.5 for all tests. Tests in air were at a frequency of 20 Hz, while those in seawater were at a frequency of 0.1 Hz. CP increased the threshold because calcareous scale formed within the cracks and promoted crack closure. CP increased crack growth rates in the plateau region above the threshold. Increasing the level of hydrogen sulfide up to a level of 150 ppm increased crack growth rates in the plateau region above the threshold. The effect of hydrogen sulfide addition on crack growth rate saturated at 150 ppm.

92.0 Fukuda, T., T. Iwadate, M. Shimazaki, "Consideration on the scatter of COD and fatigue crack propagation characteristics of heavy section C-Mn-V forged steel for offshore structure," OTC '82, Proceedings - 14th Annual Offshore Technology Conference, Vol. 2, Offshore Technology Conference, Dallas, 1982, p. 109-125.

Key Words: welded joint, corrosion fatigue, crack propagation, fracture, synthetic seawater

Steel(s): BS 4360:50D

Notes: Tensile, Charpy V-notch impact, CTOD, and corrosion fatigue tests were conducted on specimens from a welded forged steel plate. CTOD fracture toughness (CTODc) was well correlated with J fracture toughness (Jc) by the following relationship: Jc/Sy = 2 CTODc, where Sy is yield strength. Fatigue tests were performed at a stress ratio of R = 0.05 and at frequencies of 0.133 and 5 Hz. ASTM synthetic seawater was used for the corrosion fatigue tests; some fatigue tests were also performed in air. Crack growth rate (da/dN) was determined as a function of the range of stress intensity factor and Paris-Law constants were developed. Seawater increased da/dN, but there was no difference in da/dN values for base metal and heat-affected-zone (HAZ) metal.

93.0 Galsworthy, J. C., "Low frequency corrosion fatigue of electron beam weldments in a marine steel," Power Beam Technology, The Welding Institute, Cambridge, UK, 1987, p. 361-369.

Key Words: welded joint, stress ratio, stress relief, corrosion fatigue, seawater, crack propagation

Steel(s): Q1N

Notes: Fatigue crack growth tests were performed in air (3.33 Hz frequency) and seawater (0.0083 Hz frequency). Stress ratios of R = 0 and 0.5 were used. Electron beam welding was used to produce autogenous weldments for test specimens. Post weld heat treatment (PWHT) of 2 hours at 610 C relieved residual stress and produced a slight tempering of the martensite microstructure. Crack growth rates in seawater were faster than those in air. PWHT reduced crack growth rates in weld metal specimens to levels observed in base metal.

94.0 Gangloff, R. P., “Crack size effects on the chemical driving force for aqueous corrosion fatigue,” Metallurgical Transactions A, Vol. 16A, No. 5, May, 1985, p. 953-969.
Key Words: short cracks, 3.5% NaCl, corrosion fatigue, crack propagation
Steel(s): AISI 4130
Notes: Small crack size was found to greatly increase the rate of corrosion fatigue crack growth for testing in 3.5% NaCl. The increase was maximum at low levels of the stress intensity factor range and is believed related to crack configuration dependent mass transport and the electrochemical reaction processes that control hydrogen embrittlement.

95.0 Gangloff, R. P., “Inhibition of aqueous chloride corrosion fatigue by control of crack hydrogen production,” Critical Issues in Reducing the Corrosion of Steels, NACE, Houston, 1986, p. 28-50.
Key Words: short cracks, 3.5% NaCl, corrosion fatigue, crack propagation
Steel(s): AISI 4130
Notes: Experiments were conducted on specimens with small cracks to evaluate various approaches for inhibiting brittle corrosion fatigue crack growth in chloride solutions. Moderate cathodic polarization (CP) reduced crack growth rates. Also, the early stages of crack initiation and growth are inhibited by CP.

96.0 Gao, H., “Corrosion fatigue crack growth of high tensile steel HT60 in synthetic seawater (in Chinese),” Acta Metallurgica Sinica, Vol. 27, No. 4, 1991, p. B265-B270.
Key Words: corrosion fatigue, crack propagation, synthetic seawater
Steel(s): HT60
Notes: Corrosion fatigue crack growth data were developed at R = 0.1 and 0.7. The frequency was 30 Hz for tests in air and 5 Hz for tests in synthetic seawater.

97.0 Garf, E. F., A. E. Litvinenko, V. V. Zaitsev, O. I. Steklov, A. Kh. Smirnov, “Evaluating the resistance of tubular welded assemblies to fatigue failure in sea water (translation),” Automatic Welding, Vol. 38, No. 12, Dec., 1985, p. 12-14.
Key Words: welded joint, corrosion fatigue, synthetic seawater, T joint
Steel(s): structural

Notes: This paper briefly reviews Russian work on fatigue of welded tubular T joints. The load ratio was R = -1, and the cyclic frequency was 12.5 Hz. Fatigue curves between 10,000 and 10 million cycles to failure were developed for air and synthetic seawater.

98.0 Gerald, J., A. Bignonnet, H. P. Lieurade, H.Lecoq, "Corrosion fatigue tests on high strength steel tubular X nodes with improved welds," Steel in Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 455-463.

Key Words: tubular joint, welded joint, cathodic protection, synthetic seawater, shot peening, TIG dressing

Steel(s): E460

Notes: In-plane bending fatigue tests were conducted on tubular X-nodes in air and in synthetic seawater with cathodic protection (-0.80 V vs. Ag/AgCl). Improved weld shape was found to improve fatigue resistance. TIG dressing and shot peening improved the resistance to fatigue-crack initiation. The cathodic protection restored fatigue life to the level observed for tests in air.

99.0 Gill, S. J., K. M. Htun, M. I. Jolles, T. W. Crooker, "Influences of marine environment and electrochemical potential on fatigue crack closure in a high-strength steel," Embrittlement by the Localized Crack Environment, Proceedings of an International Symposium, Metallurgical Society of AIME, Warrendale, PA, 1984, p. 471-483.

Key Words: crack closure, crack propagation, corrosion fatigue, synthetic seawater, cathodic protection

Steel(s): HY130

Notes: A clip gage and a crack closure gage were used to measure crack closure loads in WOL specimens. Tests in air were at a frequency of 5 Hz, while those in synthetic seawater were at 0.1 Hz. The load ratio was R = 0.1. The addition of seawater produced corrosion deposits and increased crack opening loads. An effective stress intensity factor range was used to correct for crack closure effects. Compared with air, seawater increased crack growth rate. The increase was the same under both freely corroding and cathodically polarized (zinc anode couple) conditions.

100.0 Gowda, S. S., M. Arockiasamy, D. V. Reddy, D. B. Muggeridge, "Corrosion fatigue strength of offshore monopod tubular joints in cold ocean environment," OTC '83, Proceedings - 15th Annual Offshore Technology Conference, Vol. 2, Offshore Technology Conference, Dallas, 1983, p. 93-102.

Key Words: welded joint, corrosion fatigue, seawater, fracture mechanics, grinding, random loading, tubular joint, temperature

Steel(s): A53, A36

Notes: Seven monopod tubular joints were fatigue tested in seawater at 0 C. Both constant amplitude and random loading were employed. Fatigue cracks initiated on either side of the weld symmetry line but not at the critical hot spots; this was believed to be caused by weld defects and slag inclusions. Toe grinding did not appear to improve corrosion fatigue life. Crack initiation ranged from 38.2 to 64.2 percent of the total fatigue life. Fatigue lives were shorter than those of T or Y joints with comparable dimensions. (See Reference 101, also.)

101.0 Gowda, S. S., M. Arockiasamy, D. B. Muggeridge, D. V. Reddy, "Experimental and analytical investigation of corrosion fatigue behaviour of monopod tubular joints," Proceedings of the 4th Engineering Mechanics Division Specialty Conference: Recent Advances in Engineering Mechanics and their Impact on Civil Engineering Practice, Vol. 1, ASCE, New York, 1983, p. 593-596.

Key Words: welded joint, corrosion fatigue, seawater, fracture mechanics, grinding, random loading, tubular joint, temperature

Steel(s): A53, A36

Notes: Seven monopod tubular joints were fatigue tested in seawater at 0 C. Both constant amplitude and random loading were employed. Fatigue cracks initiated on either side of the weld symmetry line but not at the critical hot spots; this was believed to be caused by weld defects and slag inclusions. Toe grinding did not appear to improve corrosion fatigue life. Crack initiation ranged from 38.2 to 64.2 percent of the total fatigue life. Fatigue lives were shorter than those of T or Y joints with comparable dimensions. (See Reference 100, also.)

102.0 Grimme, D., H. J. Hansen, H. Herkens, H. J. Klehe, J. M. Motz, B. Musgen, H. Schonfeldt, K. Seifert, "Corrosion fatigue strength of welded K-joints and HSLA cast steel hybrid K-nodes at component-similar scale," Steel in Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 465-478.

Key Words: K joint, shot peening, cathodic protection, synthetic seawater, welded joint, potential drop measurement

Steel(s): E355, E690, GS8Mn7 cast steel

Notes: Procedures and equipment for testing large K joints at R = -1 under variable amplitude loading and in synthetic seawater with and without cathodic protection are described, and preliminary results are presented. Crack initiation is detected by measuring AC potential drop so that total fatigue life can be divided into crack initiation and propagation phases. The benefit of shot peening the E690 steel joints was small.

103.0 Grovlen, M., E. Bardal, "Some aspects of corrosion fatigue crack growth of structural steels," 10th Scandinavian Corrosion Congress, NKM 10 Proceedings, Swedish Corrosion Institute, Stockholm, Sweden, 1986, p. 431-434.

Key Words: crack propagation, 3% NaCl, synthetic seawater, cathodic protection, calcareous deposits, threshold, crack closure

Steel(s): BS 4360:50D

Notes: Fatigue-crack growth experiments were conducted at R = 0.1 and 10 Hz in the following three environments: (1) air, (2) 3% NaCl with -0.80 V vs. SCE polarization, and (3) synthetic seawater with -0.80 V vs. SCE polarization. The lowest crack-growth threshold was in the second enviroment, while the highest was in the third environment. In the synthetic seawater with -0.80 V vs. SCE polarization, calcareous deposits formed within the cracks. These deposits produced crack closure, which in turn reduced crack-growth rates. The composition of the deposits was predominantly $CaCO_3$ and varied with distance from the crack tip. The Ca/Mg ratio decreased as the distance from the crack tip decreased. (This paper is essentially the same as Document 104.)

104.0 Grovlen, M., “Some aspects of corrosion fatigue of structural steels,” Steel in Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 719-727.

Key Words: crack propagation, 3% NaCl, synthetic seawater, cathodic protection, calcareous deposits, threshold, crack closure

Steel(s): BS 4360:50D

Notes: Fatigue-crack growth experiments were conducted at R = 0.1 and 10 Hz in the following three environments: (1) air, (2) 3% NaCl with -0.80 V vs. SCE polarization, and (3) synthetic seawater with -0.80 V vs. SCE polarization. The lowest crack-growth threshold was in the second environment, while the highest was in the third environment. In the synthetic seawater with -0.80 V vs. SCE polarization, calcareous deposits formed within the cracks. These deposits produced crack closure, which in turn reduced crack-growth rates. The composition of the deposits was predominantly $CaCO_3$ and varied with distance from the crack tip. The Ca/Mg ratio decreased as the distance from the crack tip decreased. (This paper is essentially the same as Document 103.)

105.0 Guang-Li, Y., D. Yan-Liang, Z. Tie-Yu, “The growth of short fatigue cracks in axle steel,” Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 413-416.

Key Words: fatigue, short cracks, crack propagation

Steel(s): C-Mn

Notes: Fatigue crack growth tests were conducted on specimens of a 0.4C-0.2Si-0.6Mn axle steel with short cracks. The tests were in air, at a frequency of 30 Hz, and stress ratios of R = 0.1 and 0.2. The fraction of total fatigue life related to the growth of short cracks is up to 60 percent of the total life for many engineering components. Short cracks grow faster than long cracks at low âK values, and short cracks grow at values of âK below the threshold for growth of long cracks. The growth of short cracks is complex because it is affected by surface roughness, microstructure, grain size, and other material properties.

The replication method was used to successfully measure the growth of short cracks.

106.0 Haagensen, P. J., P. d'Erasmo, B. Pettersen, "Fatigue performance in air and sea water and fracture toughness of TIG-dressed steel weldments," European Offshore Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. III/8-1 to 8-8.

Key Words: welded joint, synthetic seawater, TIG dressing, corrosion fatigue

Steel(s): St 52E

Notes: Bending fatigue tests were performed on plate specimens with T plate fillet welded to them at their mid span. Tests in air were at 5 Hz, while tests in synthetic seawater were at 1 Hz. Compared with air, seawater reduced fatigue life slightly. TIG dressing improved the fatigue strength in air. No TIG-dressed specimens were tested in seawater. This paper is Ref. No. 100 in Jaske, et al. (Document No. 140).

107.0 Haagensen, P. J., V. Dagestad, "Random load crack propagation in sea water in a medium-strength structural steel," European Offshore Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. VII/22-1 to 22-8.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, random loading

Steel(s): BS 4360:50D

Notes: Corrosion fatigue crack growth tests were performed on multiple edge notch specimens immersed in synthetic seawater. The load ratio was R = 0, and the frequency was 1 Hz. Reference tests in air were at 1 and 5 Hz. Seawater significantly increased crack growth rates under random loading. Using crack growth data from constant amplitude tests and the linear damage rule gave good predictions of fatigue life under stationary random loading. This paper is Ref. No. 120 in Jaske, et al. (Document No. 140).

108.0 Habashi, M., G. Philipponneau, S. Widawski, J. Galland, "Interactions between fatigue crack growth rate and kinetics of magnesium calcium deposits formation at crack tip of mild steel cathodically polarized in sea water," Advances in Fracture Research (Fracture 84), Proceedings of the 6th International Conference on Fracture (ICF6), Vol. 4, Pergamon Press, Oxford, 1984, p. 2521-2528.

Key Words: corrosion fatigue, cathodic polarization, synthetic seawater, crack propagation, calcareous deposits

Steel(s): E355

Notes: The kinetics of calcareous scale formation were studied at cathodic potentials from -0.96 to -1.1 V vs. SCE and pH values of 4 and 8 for synthetic seawater at room temperature. The Mg/(Mg+Ca) ratio was a linear function of cathodic potential over this range. Magnesium hydroxide formed more rapidly than calcium carbonate at -1.05 V vs. SCE. Data on the effect of cathodic polarization (CP) level on crack growth rate as a function of stress intensity factor range are presented. For CP levels down to -1.2 V vs. SCE, CP was increasingly beneficial. Below -1.2 V vs. SCE and down to -1.5 V vs. SCE, the formation of hydrogen bubbles reduced the effectiveness of the calcareous scale. Based on analyses of fracture surfaces after fatigue testing, the Mg/(Mg+Ca) ratio decreased as the range of stress intensity factor increased.

109.0 Hara, M., Y. Kawai, A. Narumoto, S. Matsumoto, "Corrosion fatigue strength of 490 MPa class high-strength steels produced by the thermo-mechanical control process," OTC '86, Proceedings - 18th Annual Offshore Technology Conference, Vol. 4, Offshore Technology Conference, Richardson, Texas, 1986, p. 179-185.

Key Words: welded joint, corrosion fatigue, T joint, cruciform joint, synthetic seawater, grinding, potential drop measurement, S-N curve, tubular joint

Steel(s): BS 4360:50D

Notes: Tubular T joint and cruciform joint specimens were fatigue tested in synthetic seawater at 5 C. The steel used to make the specimens was produced by either conventional processing or thermo-mechanically controlled processing (TMCP). The frequency was 0.3 Hz for all tests. The load ratio was R = -1 for the T joints and R = 0 for the cruciform joints. Fatigue curves were developed and compared with the API X and X' fatigue curves. The TMCP steel had fatigue lives equal to or slightly greater than those of the conventionally processed steel. Weld toe grinding provided a slight increase in fatigue resistance. DC electric potential drop provided an effective means of monitoring crack propagation.

110.0 Harrison, J. D., "Why aren't high strength steels used more widely in marine structures? Is it because of problems caused by fatigue, corrosion fatigue, weldability, or others?," Proceedings of EVALMAT 89 - International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 2, The Iron and Steel Institute of Japan, Tokyo, 1989, p. 1003-1011.

Key Words: fatigue, buckling, stiffness, weldability

Steel(s): structural

Notes: Factors that work against the use of high-strength steels in marine structures are discussed. The greatest factor limiting their application is fatigue strength. Buckling and stiffness also can limit the yield strength of the steel in some structures. Weldability does not limit the use of high-strength steels for yield strengths up to 700 MPa (100 ksi). High-strength steels are being used successfully in some parts of offshore structures. They offer potential cost savings for the construction of marine structures.

111.0 Hartt, W. H., W. Wang, S. S. Rajpathak, "Cathodic polarization induced laminar fracture propensity of TMCP steels," Proceedings of

EVALMAT 89 - International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 2, The Iron and Steel Institute of Japan, Tokyo, 1989, p. 901-909.

Key Words: cathodic protection, TMCP steels, hydrogen embrittlement, constant extension rate, lamellar tearing, seawater

Steel(s): HY80, A710, QT80, QT108, EH36, A537, X70, HY130

Notes: Corrosion fatigue tests of keyhole compact type specimens and constant extension rate tests of hourglass-shaped, 51-mm long specimens were performed on eight steels (see above list) in seawater and at 1 Hz. Cathodic polarization potentials ranged from free corrosion to -1.10 V vs. SCE. The fracture mode of EH36, A537, and X70 steels changed in the potential range of -0.90 to -1.10 V vs. SCE; secondary cracking and fissures in the rolling plane were present in these three steels, but not in the other five steels, at -1.10 V vs. SCE. This type of fracture was believed to be caused by hydrogen embrittlement of the ferritic-pearlitic microstructures.

112.0 Hartt, W. H., "Cathodic protection and fatigue of offshore structures," Materials Performance, Vol. 20, No. 11, 1981, p. 50-53.

Key Words: welded joint, corrosion fatigue, crack propagation, S-N curve, cathodic polarization, seawater

Steel(s): structural

Notes: This paper provides a general review and discussion of the corrosion fatigue of welded structural steel components. The effects of cathodic protection are discussed. Fatigue data for welded specimens are compared with the API X and X' curves. Fatigue crack growth data for seawater environment are compared to similar data for an air environment.

113.0 Hartt, W. H., "Corrosion fatigue testing of steels as applicable to offshore structures," Corrosion in Natural Waters, STP 1086, ASTM, Philadelphia, 1990, p. 54-69.

Key Words: welded joint, corrosion fatigue, S-N curve

Steel(s): API 2H Grade 42, HY80, A710, QT80, QT108, EH36, A537, X70

Notes: This paper reviews methods for corrosion fatigue testing steels and weldments for offshore structural applications. Development of S-N curves and crack growth data is discussed. Procedures are described for fatigue testing welded constant taper specimens under bending loads and in seawater. Fatigue data are presented for butt welded and welded tee stub specimens tested using these procedures. Crack initiation testing of keyhole compact tension (CT) specimens is also described. Fatigue data are presented for CT specimens tested in seawater under freely corroding conditions and at a frequency of 1 Hz.

114.0 Hartt, W. H., W. C. Hooper, "Endurance limit enhancement of notched, 1018 steel in seawater - specimen size and frequency effects," Corrosion, Vol. 36, No. 3, 1980, p. 107-112.

Key Words: corrosion fatigue, cathodic protection, notch, calcareous deposits
Steel(s): AISI 1018
Notes: Reverse bending fatigue tests were conducted on notched specimens in seawater and at a frequencies of 3.3 and 31 Hz. Fatigue limit was determined as a function of the level of cathodic polarization (CP). The application of CP enhanced the fatigue limit in seawater compared to that in air. The enhancement was larger for thinner specimens and lower cyclic frequency. Formation of calcareous deposits on the surface of the specimen was believed to be responsible for the fatigue limit enhancement.

115.0 Hartt, W. H., N. K. Lin, Z. H. Chu, "Fatigue life of welded structural steel under realistic loading in seawater," Proceedings of the 5th International Conference on Offshore Mechanics and Arctic Engineering, Vol. II, ASME, New York, 1986, p. 256-261.
Key Words: welded joint, seawater, cathodic protection, random loading, corrosion fatigue
Steel(s): ABS DH32
Notes: Specimens of butt welded plate were tested in seawater under both freely corroding and cathodically protected conditions. Wide-band, nonstationary random loading was applied to the specimens. For free corrosion conditions, the results were well predicted using linear damage summation. With cathodic protection, fatigue lives are predicted to be approximately 16 times longer than those under free corrosion for comparable loading conditions.

116.0 Hartt, W. H., "Fatigue of welded steel in seawater as applicable to offshore structures," Corrosion 86, Paper 326, NACE, Houston, 1986.
Key Words: welded joint, corrosion fatigue, seawater, cathodic protection, crack initiation, crack propagation
Steel(s): ABS DH32
Notes: The fatigue of welded steel was evaluated from the standpoints of tubular joint design and crack initiation and propagation. Critical variables that were addressed include electrochemical potential, stress state at notches, and steel strength. Fatigue data for butt welded specimens tested in seawater indicated that small cracks at the weld toes arrest at -1.0 V vs. Cu/CuSO4 but tend to propagate at potentials above or below this value. The concept of a significant crack size is used to explain the effects of microstructure and weld quality on fatigue behavior. Below the significant crack size crack initiation plays a major role in fatigue life, whereas crack propagation plays a major role above the significant crack size.

117.0 Hartt, W. H., S. S. Ragpathak, "Formation of calcareous deposits within simulated fatigue cracks in seawater - Part 1," Corrosion 83, Paper 62, NACE, Houston, 1983.
Key Words: calcareous deposits, fatigue, seawater

Steel(s): AISI 1018

Notes: The buildup of calcareous deposits within simulated fatigue cracks was studied experimentally. Variables evaluated included polarization potential, cyclic frequency, and electrolyte velocity. The structure and chemistry of the deposits and the potential profile within the simulated cracks were evaluated. A model was developed to explain the observed behavior.

118.0 Hartt, W. H., "The effects of cathodic protection on fatigue crack initiation," Cathodic Protection: A + or - In Corrosion Fatigue?, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada, 1986, p. 45-56.

Key Words: cathodic protection, crack initiation, offshore service

Steel(s): structural

Notes: This paper presents a general review of the factors that influence fatigue in marine environments. The effect of cathodic protection (CP) on fatigue at notches is emphasized. Anodic dissolution, for which CP is beneficial, is believed to be the dominant mechanism of crack initiation in smooth specimens. Debonding, for which CP may be detrimental, is believed to be the dominant mechanism of crack initiation in notched specimens, especially those of high-strength steels.

119.0 Hattori, S., T. Okada, "Influence of localized corrosion on corrosion-fatigue crack initiation and growth behaviors of structural steels (translation: MITS BISI 26901)," J. Soc. Mater. Sci. Jpn., Vol. 37, No. 415, Apr., 1988, p. 410-415.

Key Words:

Steel(s):

Notes: Publication was not available.

120.0 Havn, T., A. Almar-Nass, "Corrosion fatigue of steel in seawater crack growth under pulsed cathodic current," Offshore and Arctic Operations Symposium - 1987, PD Vol. 10, ASME, New York, 1987, p. 61-67.

Key Words: corrosion fatigue, crack propagation, cathodic protection, synthetic seawater, 3% NaCl, calcareous deposits, stress ratio

Steel(s): ABS DH32

Notes: Fatigue crack growth data were developed for tests in synthetic seawater, 3% NaCl solution, and air. Pulsed cathodic polarization (CP) to -1.0 V vs. SCE was used for some of the tests in synthetic seawater. The results of these tests showed that CP reduced crack growth rate at low stress levels and increased it at high stress levels. This behavior was caused by the formation of calcareous deposits within the fatigue cracks. Pulsing the CP current showed that crack growth rate was higher when it was on during only the rising portion of the cycle than when it was on during only the decreasing portion of the cycle. This effect is believed to be caused by the release of hydrogen when CP is on.

121.0 Helms, R., H. Henke, C.-P. Bork, “Corrosion fatigue of structural steel in offshore structures at different frequencies and environmental conditions (German),” Werkstoffe und Korrosion, Vol. 39, 1988, p. 441-452.

Key Words: welded joint, corrosion fatigue, frequency, cathodic protection, synthetic seawater

Steel(s): E460

Notes: The effect of frequency on corrosion fatigue was evaluated by testing both welded and unwelded specimens of 20 mm thick plate in bending. The frequencies used were 10, 1, 0.1, and 0.01 Hz. Reference tests were performed in air. Three conditions were used for tests in synthetic seawater: free corrosion, cathodic polarization (CP) to -0.65 V vs. H, and CP to -0.85 V vs. H. At -0.65 V vs. H, results fell within or well above the scatterband of comparable data for tests in air. At -0.85 V vs. H, some specimens had significantly lower lives than those tested in air, indicating a hydrogen embrittlement effect. (This paper contains the same results as Reference 122.)

122.0 Helms, R., H. Henke, “Corrosion fatigue in offshore; influence of frequency and electrochemical conditions,” ECF 6: Fracture Control of Engineering Structures, Proceedings of the 6th Biennial European Conference on Fracture, Vol. 2, Engineering Materials Advisory Services Ltd, Warley, England, 1986, p. 1211-1226.

Key Words: welded joint, corrosion fatigue, frequency, cathodic protection, synthetic seawater

Steel(s): E460

Notes: The effect of frequency on corrosion fatigue was evaluated by testing both welded and unwelded specimens of 20 mm thick plate in bending. The frequencies used were 10, 1, 0.1, and 0.01 Hz. Reference tests were performed in air. Three conditions were used for tests in synthetic seawater: free corrosion, cathodic polarization (CP) to -0.65 V vs. H, and CP to -0.85 V vs. H. At -0.65 V vs. H, results fell within or well above the scatterband of comparable data for tests in air. At -0.85 V vs. H, some specimens had significantly lower lives than those tested in air, indicating a hydrogen embrittlement effect. (This paper contains the same results as Reference 121.)

123.0 Hirakawa, K., I. Kitaura, “Corrosion fatigue of steel in seawater,” The Sumitomo Search, No. 26, Sumitomo Met. Ind., Osaka, Japan, 1981, p. 136-151.

Key Words: corrosion fatigue, S-N curve, frequency, cathodic protection, 3% NaCl, notch

Steel(s): SS41, SM50, HT80, HT100, anti-weather A, anti-weather B, SUS304, SUS316, DP3

Notes: Fatigue (S-N) curves were developed for a number of steels using both smooth and notched (K_t = 3.5) specimens loaded in cantilever bending. Cyclic frequencies were 0.5 and 0.1 Hz. Three test environments were used -- air, 3% NaCl under free corrosion conditions, and 3% NaCl with cathodic polarization to -1.0 V vs. SCE. In 3% NaCl under free corrosion conditions, the fatigue strength of medium strength structural steels at 2 million cycles to failure was reduced to 22 to 35 percent of those in air. Cathodic protection was very effective at 0.5 Hz, but only somewhat effective at 0.1 Hz.

124.0 Hodgkiess, T., M. J. Cannon, A. McLachlan, "Electrochemical measurements within fatigue cracks in structural steel," Corrosion Chemistry Within Pits, Crevices and Cracks, HMSO Books, London, UK, 1987, p. 435-451.

Key Words: corrosion fatigue, crack propagation, cathodic protection, electrochemical, seawater

Steel(s): BS 4360:50D

Notes: Methods for making electrochemical measurements within growing corrosion fatigue cracks were developed. Both pH and potential were measured under load free and cyclic loading conditions in seawater. Crack tip potentials start out being more negative than external ones, but the relative values of these potentials reverse with time. These potential changes are related to pH changes. Initially crack tip pH values are in the range of 6.3 to 7.0, but they become more alkaline with time. Cathodic protection can increase the crack tip pH to 11 or higher. (See Reference 125, also.)

125.0 Hodgkiess, T., M. J. Cannon, "An experimental study of crack-tip electrochemistry during corrosion fatigue of structural steel in sea water," International Conference on Fatigue and Crack Growth in Offshore Structures, I Mech E Conference Publication 1986-2, Mechanical Engineering Publications, London, 1986, p. 69-76.

Key Words: corrosion fatigue, crack propagation, cathodic protection, electrochemical, seawater

Steel(s): BS 4360:50D

Notes: Methods for making electrochemical measurements within growing corrosion fatigue cracks were developed. Both pH and potential were measured under load free and cyclic loading conditions in seawater. Crack tip potentials start out being more negative than external ones, but the relative values of these potentials reverse with time. These potential changes are related to pH changes. Initially crack tip pH values are in the range of 6.3 to 7.0, but they become more alkaline with time. Cathodic protection can increase the crack tip pH to 11 or higher. (See Reference 124, also.)

126.0 Hodgkiess, T., "The effect of periods of stress-free corrosion on the fatigue behaviour of structural steel in sea water," European Offshore

Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. V/B-1 to B-5.

Key Words: corrosion fatigue, crack propagation, corrosion damage, seawater

Steel(s): BS 4360:50D

Notes: The effects of stress free periods of exposure of fatigue cracks to seawater were studied. Crack growth testing was performed in seawater and at a cyclic frequency of 0.17 Hz. After a period of growth, the test specimens were removed from the test machine and exposed to seawater for periods of 15 to 670 hours under load free conditions. Upon subsequent fatigue testing, it was found that crack growth was temporarily arrested or severely retarded for some period of cyclic loading.

127.0 Holmes, R., “Fatigue and corrosion fatigue of welded joints under random loading conditions,” European Offshore Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. IV/11-1 to 11-26.

Key Words: welded joint, corrosion fatigue, cathodic protection, synthetic seawater, random loading

Steel(s): BS 4360:50D

Notes: Fatigue data were developed for weldments. Results of tests in air agreed well with the BS 153, Class F fatigue curve. Fatigue strength was the same for axial loading and bending. In seawater, the fatigue strength was reduced about 12% below that in air. Using nominal RMS amplitude for random loading in seawater gave results about 10% below the fatigue curve for constant amplitude loading in seawater. Data are still be developed for the high cycle (long life) fatigue regime. This paper is Ref. No. 102 in Jaske, et al. (Document No. 140).

128.0 Holmes, R., J. Kerr, “The fatigue strength of welded connections subjected to north sea environmental and random loading conditions,” Behavior of Off-Shore Structures, Vol. 2, Hemisphere Publishing Corp., New York, 1983, p. 26-36.

Key Words: welded joint, fatigue, corrosion fatigue, synthetic seawater, random loading, cruciform joint, tubular joint, Miner's rule, cathodic protection

Steel(s): BS 4360:50C, BS 4360:50D, BS 4360:50E

Notes: This paper reviews the results of an extensive experimental program conducted at the National Engineering Laboratory (NEL) in the UK. Fatigue curves were developed for tests of welded joints in air and in seawater. These curves are compared with design curves. Cathodic protection at -0.85 V vs. Ag/AgCl was beneficial. Results for random loading were assessed using RMS stress amplitude and Miner's Rule.

129.0 Hopkins, R. M., C. C. Monahan, “Calcareous deposits and the fatigue crack growth behavior of offshore steels under cathodic protection in seawater,” Cathodic Protection: A + or - In Corrosion Fatigue?, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada, 1986, p. 107-135.

Key Words: calcareous deposits, cathodic protection, crack propagation, seawater, hydrogen embrittlement, crack closure

Steel(s): structural

Notes: The reasons that calcareous deposits form, their role in fatigue-crack growth, and factors that influence their deposition are reviewed and discussed. Hydrogen embrittlement controls the rate of fatigue-crack propagation in cathodically protected, medium-strength structural steels in seawater. The formation of calcareous scale on the surfaces of the growing fatigue crack retards crack growth at low âK levels. Most investigators believe that this behavior is caused by crack closure, but the scale's limiting the access of water molecules to the crack surfaces may have as much or even more influence on the crack-growth rate.

130.0 Horibe, S., M. Nakamura, M. Sumita, “The effect of seawater on fracture mode transition in fatigue,” International Journal of Fatigue, Vol. 7, No. 4, 1985, p. 224-227.

Key Words: fatigue, crack propagation, synthetic seawater

Steel(s): Medium-Tensile Strength Steel, High-Tensile Strength Steel

Notes: Crack growth tests were performed in air and seawater. The stress ratio was R = 0.1. Testing in air was at 20 Hz, while testing in seawater was at 1 Hz. Crack growth rate versus range of stress intensity factor curves were developed, and the transition from normal to shear fracture was investigated.

131.0 Horibe, S., M. Sumita, “Transient fatigue crack growth caused by change in environmental conditions,” Journal of Materials Science Letters, Vol. 4, No. 12, Dec, 1985, p. 1498-1500.

Key Words: fatigue, crack propagation, synthetic seawater, cathodic protection

Steel(s): High-Tensile Strength Steel

Notes: Fatigue crack growth testing was conducted in synthetic seawater at 25 C. The stress ratio was R = 0.1, and the frequency was 1 Hz. Crack growth transients after the application of cathodic protection by means of a zinc couple were studied. Such transients can cause unstable high rates of crack growth.

131.5 Hou, C. Y., Chen, N., and Lawrence, F. V., “Computer Simulation Of Weldment Fatigue Life,” , Research Report MR9503, Edison Welding Institute, Columbus, 1995.

Key Words: crack closure, crack initiation, crack propagation, fatigue, S-N curve, welded joint, short cracks

Steel(s): A36, carbon steel

Notes: Three types of models for predicting the fatigue life of weldments were evaluated. Models (Type 1) based only on linear elastic fracture mechanics without consideration of crack closure underestimate fatigue life. Models (Type 2) based on crack growth with consideration of crack closure and the effects of short cracks, and models (Type 3) based on initiation and propagation give about the same reasonably good predictions of fatigue life. Type 2 models are complex and computationally intensive. Type 3 models are more empirical than Type 2 models but require only simple calculations.

132.0 Hudak, Jr., S. J., O. H. Burnside, K. S. Chan, "Analysis of corrosion fatigue crack growth in welded tubular joints," Journal of Energy Resources Technology, Vol. 107, No. 2, June, 1985, p. 212-219.
Key Words: welded joint, tubular joint, fatigue, crack propagation, fracture mechanics
Steel(s): structural
Notes: A fracture mechanics model for fatigue crack propagation in welded tubular joints was developed. It uses a wide range equation for fatigue crack growth properties and includes the effect of local weld toe geometry in the calculation of stress intensity factors. The model was validated for data from tests in air but not for tests in seawater.

133.0 Ishihara, S., K. Shiozawa, K. Miyao, "Distribution of corrosion fatigue crack lengths in carbon steel (1st report, the cracks which grow individually)," Bulletin of the JSME, Vol. 28, No. 236, 1985, p. 185-193.
Key Words: corrosion fatigue, crack initiation, high-cycle fatigue, 3% NaCl
Steel(s): carbon steel
Notes: Crack initiation on the surface of carbon steel specimens was studied. The specimens were tested under high-cycle (long life) conditions and reversed bending loads. The environment was 3% NaCl solution. The distribution of small surface cracks was characterized statistically based on the number of cracks and the scatter in fatigue crack growth rates. (See Reference 134, also.)

134.0 Ishihara, S., K. Shiozawa, K. Miyao, "Distribution of corrosion fatigue crack lengths in carbon steel (2nd report, the distributed cracks which interact and coalesce)," Bulletin of the JSME, Vol. 28, No. 236, 1985, p. 194-201.
Key Words: corrosion fatigue, crack initiation, high-cycle fatigue, 3% NaCl
Steel(s): carbon steel
Notes: Crack initiation on the surface of carbon steel specimens was studied. The specimens were tested under high-cycle (long life) conditions and reversed bending loads. The environment was 3% NaCl solution. The interaction and coalescence of small surface cracks was characterized and modeled. (See Reference 133, also.)

135.0 Iwasaki, T., A. Katoh, M. Kawahara, "Corrosion fatigue strength of welded T joints fabricated from on-line accelerated cooled steel plate," International Conference on Fatigue of Engineering Materials and

	Structures, I Mech E Conference Publication 1986-9, Vol. 2, Mechanical Engineering Publications, London, 1986, p. 371-386.
Key Words:	welded joint, T joint, corrosion fatigue, cathodic protection, crack propagation, fracture mechanics, synthetic seawater
Steel(s):	KD36 (similar to BS 4360:50D)
Notes:	Welded steel plate T joints were fatigue tested under bending. The tests in air were at a frequency of 3.33 Hz, and the tests in synthetic seawater were at 0.17 Hz. Results for specimens from a plate produced using On-Line Accelerated Cooling (OLAC) were compared with those for specimens from a conventionally produced normalized plate. Both materials had the same fatigue properties in air and in seawater. Fatigue crack propagation tests were conducted on base metal. A fracture mechanics model was developed to predicted the fatigue lives of the welded T joints. Cathodic protection at -0.85 V vs. Ag/AgCl restored the fatigue strength in seawater to that observed in air.

136.0	Iwasaki, T., J. G. Wylde, “Corrosion fatigue tests on welded tubular joints,” Journal of Energy Resources Technology, Vol. 107, No. 1, Mar., 1985, p. 68-73.
Key Words:	welded joint, corrosion fatigue, tubular joint, synthetic seawater, K joint
Steel(s):	BS 4360:50C
Notes:	Corrosion fatigue tests were conducted on weld K and KT joints using synthetic seawater and a cyclic frequency of 0.17 Hz. The results were compared with those from comparable tests performed in air, and life reduction factors between 2 and 5 were observed. The largest life reduction factor was in the low-stress, high-cycle fatigue regime. The effect of seawater under free corrosion conditions seemed to more detrimental to the fatigue strength of these joints than to the fatigue strength of simple welded joints used in previous studies. The results also were compared with fatigue design curves for welded tubular joints.

137.0	Jakubowski, M., “A study on crack length effect on the fatigue crack growth rate for ordinary shipbuilding steel in salt water,” Proceedings of the 5th International Conference on Offshore Mechanics and Arctic Engineering, Vol. II, ASME, New York, 1986, p. 212-217.
Key Words:	corrosion fatigue, crack propagation, cathodic protection, 3.5% NaCl
Steel(s):	St 41U5
Notes:	Fatigue crack growth tests were conducted in air, distilled water, and 3.5% NaCl solution. The stress ratio was approximately R = 0.13 for all tests. Tests in air were at a frequency of 5 Hz, while those in water were at a frequency of 0.2 Hz. For the same level of stress intensity factor range, crack growth rate increased by up to 3 times as crack length increased for free corrosion conditions in 3.5% NaCl solution. This crack length effect was not observed in distilled water or when

cathodic potential (-1.5 V vs. Ag/AgCl by coupling with magnesium anodes) was applied in 3.5% NaCl solution.

138.0 Jang, S.-S., T. Shoji, H. Takahashi, Y. Watanabe, “Corrosion fatigue of high strength steel in flowing sea water,” Boshoku Gijutsu (Corrosion Engineering), Vol. 35, No. 9, 1986, p. 503-508.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, electrochemical, embrittlement

Steel(s): HT80

Notes: The effect of flow rate on fatigue crack propagation behavior was studied. Tests were conducted at various electrochemical potentials in synthetic seawater at 25 C. The cyclic frequency was 0.17 Hz, and the stress ratios were R = 0.05 and R = 0.5. Under free corrosion, increasing the flow rate increased the crack growth rate by increasing the cathodic reaction rate of oxygen reduction. At -0.45 V vs. Ag/AgCl, hydrogen embrittlement governed at low flow rates, but oxygen reduction governed at high flow rates. At -0.523 V vs. Ag/AgCl, the crack growth rate was high, and flow rate had no effect on crack growth rate. (Also, see Reference 139.)

139.0 Jang, S.-S., T. Shoji, H. Takahashi, “Effects of electrochemical potential and flow rate on corrosion fatigue crack growth behavior of high strength steel in sea water,” Transactions of the Iron and Steel Institute of Japan, Vol. 27, No. 5, 1987, p. B-152.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, electrochemical, embrittlement

Steel(s): HT80

Notes: The effect of flow rate on fatigue crack propagation behavior was studied. Tests were conducted at various electrochemical potentials in synthetic seawater at 25 C. The cyclic frequency was 0.17 Hz, and the stress ratios were R = 0.05 and R = 0.5. Under free corrosion, increasing the flow rate increased the crack growth rate by increasing the cathodic reaction rate of oxygen reduction. At -0.45 V vs. Ag/AgCl, hydrogen embrittlement governed at low flow rates, but oxygen reduction governed at high flow rates. At -0.523 V vs. Ag/AgCl, the crack growth rate was high, and flow rate had no effect on crack growth rate. (Also, see Reference 138.)

140.0 Jaske, C. E., J. H. Payer, V. S. Balint, “Corrosion fatigue of metals in marine environments,” MCIC Rep. 81-42, Metals and Ceramics Information Center, Battelle, Columbus, Ohio, 1981.

Key Words: welded joint, corrosion fatigue, seawater, crack initiation, crack propagation, cathodic protection, frequency, stress ratio

Steel(s): structural

Notes: This book provides an extensive review of information on corrosion fatigue of metals in marine environments. The data reviewed are taken from 267 documents published before 1980.

141.0 Johnson, R., I. Bretherton, B. Tomkins, P. M. Scott, D. R. V. Silvester, "The effect of sea water corrosion on fatigue crack propagation in structural steel," European Offshore Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. VI/15-1 to 15-15.

Key Words: corrosion fatigue, crack propagation, seawater, cathodic protection, temperature, stress ratio

Steel(s): BS 4360:50D

Notes: This paper reviews the results from the first part of a extensive project conducted at Harwell Research Laboratories in the UK. Tests in seawater were at frequencies of 0.1 to 0.17 Hz, and stress ratios ranged from R = -1 to R = 0.85. Cathodic potentials were between -0.65 and -1.1 V vs. Ag/AgCl. Plots of crack growth rate versus the range of stress intensity factor are given. This paper is Ref. No. 122 in Jaske, et al. (Document No. 140).

142.0 Jones, B. F., J. C. Galsworthy, "Corrosion fatigue crack growth rates of weldments in Q1N steel," Report AMTE(M)-R 83003, June, Admiralty Marine Technology Establishment, Poole, England, 1983.

Key Words: welded joint, corrosion fatigue, crack propagation, seawater

Steel(s): Q1N

Notes: Fatigue crack growth tests were conducted at 0.008 Hz. The stress ratio was R = 0. Crack growth rate versus range of stress intensity factor curves were developed for as-welded material, post-weld heat treated (PWHT) material, and parent material tested in air and in natural seawater. Four types of welds were evaluated: manual metal arc, synergic metal inert gas, electron beam, and laser beam. Except for the as-welded laser-beam welds, all welds showed similar crack growth behavior. In seawater, the laser-beam welds exhibited very fast crack growth rates. (See Reference 143 for data on Q1N steel parent material.)

143.0 Jones, B. F., "Influence of environment and stress ratio on the low frequency fatigue crack growth behaviour of two medium-strength quenched and tempered steels," International Journal of Fatigue, Vol. 6, No. 2, Apr., 1984, p. 75-81.

Key Words: corrosion fatigue, crack propagation, seawater, stress ratio, frequency

Steel(s): HY130, Q1N

Notes: Fatigue crack growth tests were conducted at 20, 1, and 0.008 Hz. The stress ratios were R = 0 and R = 0.5. Crack growth rate versus range of stress intensity factor curves were developed for specimens tested in air and in natural seawater. The low frequency fatigue crack growth rates of HY130 and Q1N steels were similar in dry air at R = 0 and in seawater at R = 0 and R = 0.5. HY130 steel had faster low frequency crack growth rates than Q1N steel in dry air at R = 0.5 and in laboratory air at R = 0 and R = 0.5. Increasing the stress ratio from R

= 0 to R = 0.5 increase the fatigue crack growth rates of both steels in seawater. (See Reference 142 for data on welded Q1N steel.)

144.0 Jones, B. F., "The influence of crack depth on the fatigue crack propagation rate for a marine steel in seawater," Journal of Materials Science, Vol. 17, No. 2, 1982, p. 499-507.

Key Words: corrosion fatigue, crack propagation, seawater, shallow crack

Steel(s): Q1N

Notes: Fatigue crack growth tests were conducted at 0.008 Hz. The stress ratio was R = 0 for most tests; a few tests were conducted at R = 0.5. Crack growth rate versus range of stress intensity factor curves were developed for specimens tested in air and seawater. For shallow cracks in the range of 0.5 to 2 mm deep, cracks growth rates were faster than those for deeper cracks when the range of stress intensity factor was less than about 30 MPa m. At higher values of stress intensity factor range, there was little effect of crack depth on growth rate.

145.0 Jones, W. D., A. P. Blackie, "Cyclic tension corrosion fatigue of three quenched and tempered low alloy steels in sea water," International Conference on Fatigue and Crack Growth in Offshore Structures, I Mech E Conference Publication 1986-2, Mechanical Engineering Publications, London, 1986, p. 199-212.

Key Words: corrosion fatigue, S-N curve, synthetic seawater, cathodic protection, notch

Steel(s): BS 970:817M40, BS 970:722M24, BS 970:976M33

Notes: Corrosion fatigue tests were performed using cyclic tensile loading at a stress ratio of R = 0.05 and a frequency of 0.167 Hz. The environment was synthetic seawater at 8 C with the following levels of cathodic protection (CP): free corrosion, -0.85 V vs. Ag/AgCl, and -1.05 V vs. Ag/AgCl. Both smooth and notched (K_t = 2.15) specimens were tested. S-N curves are presented and compared. Free corrosion in seawater reduced the fatigue strength of all three steels, compared with results of tests in air. CP effectively restored the fatigue strength of the 817M40 and 722M24 steels to levels observed for tests in air. CP at -1.05 V vs. Ag/AgCl degraded the fatigue strength of the 976M33 steel. However, for CP at -0.85 V vs. Ag/AgCl or for free corrosion, the 976M33 steel had better fatigue strength than the other two steels. (See Reference 146 for additional results.)

146.0 Jones, W. J. D., A. P. Blackie, "Cyclic tension corrosion fatigue of high-strength steels in seawater," Environmentally Assisted Cracking: Science and Engineering, STP 1049, ASTM, Philadelphia, 1990, p. 447-462.

Key Words: corrosion fatigue, S-N curve, synthetic seawater, cathodic protection, notch

Steel(s): BS 970:817M40, BS 970:722M24, BS 970:976M33, BS 970:835M30

Notes: Corrosion fatigue tests were performed using cyclic tensile loading at a stress ratio of R = 0.05 and a frequency of 0.167 Hz. The environment was synthetic seawater at 8 C with the following levels of cathodic protection (CP): free corrosion, -0.85 V vs. Ag/AgCl, and -1.05 V vs. Ag/AgCl. Both smooth and notched (K_t = 2.15) specimens were tested. S-N curves are presented and compared. Free corrosion in seawater reduced the fatigue strength of all four steels, compared with results of tests in air. CP at -0.85 V vs. Ag/AgCl restored the fatigue strength of smooth specimens to or close to levels observed for tests in air. However, the fatigue strength of notched specimens was not restored to the same degree. CP at -1.05 V vs. Ag/AgCl restored the fatigue strength for both smooth and notched specimens of steel 817M40 and for smooth specimens of steel 722M24. The fatigue performance of steels 835M30 and 976M33 were reduced by increasing the CP level -1.05 V vs. Ag/AgCl. (See Reference 145 for previous results.)

147.0 Jones, W. J. D., A. P. Blackie, "Effect of stress ratio on the cyclic tension corrosion fatigue life of notched steel BS970:976M33 in seawater with cathodic protection," International Journal of Fatigue, Vol. 11, No. 6, 1989, p. 417-422.

Key Words: corrosion fatigue, S-N curve, synthetic seawater, cathodic protection, notch, stress ratio

Steel(s): BS 970:976M33

Notes: Corrosion fatigue tests were performed using cyclic tensile loading at stress ratios between R = 0.05 and 0.75 and a frequency of 0.167 Hz. The environment was synthetic seawater at 8 C with the following levels of cathodic protection (CP): free corrosion and -1.05 V vs. Ag/AgCl. Only notched (K_t = 2.15) specimens were tested. Modified Goodman constant life diagrams were developed. (See References 145 and 146 for previous results.)

148.0 Kam, J. C. P., "A study on the non-destructive inspection and corrosion fatigue crack growth in tubular welded joints using reliability methodologies," Proceedings of the 9th International Conference on Offshore Mechanics and Arctic Engineering, Vol. II, ASME, New York, 1990.

Key Words: welded joint, corrosion fatigue, crack propagation, tubular joint

Steel(s):

Notes: Modeling fatigue crack growth in tubular joints was reviewed, and a reliability analysis for assessing fatigue cracking in welded tubular joints was developed.

149.0 Mshana, Y., J. C. P. Kam, D. McDiarmid, "Fatigue crack growth of welded tubular joints under sequential multiple axis loading," Proceedings of the 11th International Conference on Offshore

Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1992, p. 257-266.

Key Words: tubular joint, crack propagation, mixed mode, welded joint
Steel(s): BS 4360:50D
Notes: Tubular joints were fatigue tested by sequential application of in-plane and out-of-plane bending and vice versa. In such tests, a crack is first produced in the 'wrong place' and then driven to grow when it is distant from the hot spot. Cracks at the 'wrong place' tended to grow in length rather than depth. The growth of normal cracks did not seem to be affected by the presence of the cracks at the 'wrong place'. These results do not apply to conditions where the multiple axis loading occurs concurrently rather than sequentially.

150.0 Kam, J. C. P., J. Vinas-Pich, "Techniques of fatigue load history assessment and tubular joint crack growth modelling in a micro-computer environment," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 487-494.

Key Words: fatigue, crack propagation, life prediction model, tubular joint
Steel(s):
Notes: Experiences from the development of fatigue analysis software are discussed, with emphasis on load history assessment and crack growth modelling. The loading power spectral density (PSD) was analyzed to compute a weighted average stress range (WASR), which is an equivalent constant amplitude stress range. Better life predictions were obtained using the instantaneous sea state stress range probability distribution (SRPD) than using the total SRPD.

151.0 Kam, J. C. P., J. Austin, W. D. Dover, "The corrosion fatigue crack growth in welded tubular T joints," Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1992.

Key Words:
Steel(s):
Notes: not in publication

152.0 Kawahara, M., T. Fujita, M. Kurihara, H. Inagaki, H. Kitagawa, "Corrosion fatigue crack initiation of carbon steels in seawater," Basic Questions in Fatigue, Vol. II, STP 924, ASTM, Philadelphia, 1988, p. 145-163.

Key Words: corrosion fatigue, crack initiation, synthetic seawater, S-N curve
Steel(s): ABS DH36
Notes: Corrosion fatigue tests were conducted on two kinds of ABS DH36 steel. Steel A was produced by controlled rolling and had a fine-grained ferrite plus bainite microstructure. Steel B was produced by on-line accelerated cooling (OLAC) and had a ferrite plus lamellar pearlite microstructure. The cyclic frequency was 0.17 Hz, and the

stress ratio was R = 0.1. The environment was synthetic seawater at 20 C under free corrosion conditions. Compared with reference data for tests in air, the seawater significantly reduced the fatigue strength. The fatigue strength of Steel B was degraded more than that of Steel A. Mechanisms of crack initiation are reviewed and discussed in detail. (Also, see Reference 154.)

153.0 Kawahara, M., M. Kurihara, T. Fujita, J. Sakai, M. Honda, A. Tamada, "Corrosion fatigue of structural steels in sea water," Nippon Kokan Technical Report, Overseas, No. 40, 1984, p. 39-46.

Key Words: corrosion fatigue, S-N curve, crack propagation, cathodic protection, synthetic seawater, notch

Steel(s): SM50B, HT80B

Notes: Corrosion fatigue life (S-N) and fatigue crack propagation tests were conducted in synthetic seawater. The stress ratio was R = 0.01 for fatigue life tests and R = 0.1 for fatigue crack propagation tests. The cyclic frequency was 0.17 Hz for both types of tests in seawater. Both smooth and notched (K_t = 1.89 and 2.06) specimens were used for fatigue life testing. Cathodic polarization (CP) levels were in the range of -0.8 to -1.3 V vs. SCE. Free corrosion significantly degraded fatigue life. For S-N data, CP was beneficial at low stress levels but detrimental at high stress levels. CP increased the rate of fatigue crack growth compared with free corrosion conditions.

154.0 Kawahara, M., T. Fujita, H. Inagaki, T. Iwasaki, A. Katoh, "Simulation of crack initiation and growth in corrosion fatigue of carbon steels in seawater," Corrosion Cracking, ASM International, Metals Park, Ohio, 1986, p. 129-136.

Key Words: corrosion fatigue, crack initiation, synthetic seawater, S-N curve

Steel(s): ABS DH36

Notes: The simulation of corrosion fatigue cracking is discussed. A model is developed based on (1) formation and growth of pits, (2) crack initiation at pits, (3) coalescence and growth of distributed short cracks, and (4) propagation of long cracks. Simulations of corrosion fatigue were performed using four parameters -- pit dissolution constant, numbers of pits per unit area, and two crack propagation constants (Paris Law). The difference in pit dissolution constant is believed to be responsible for the difference in fatigue life for the two steels that were evaluated. (Also, see Reference 152.)

155.0 Kerr, J., R. Holmes, G. M. Brown, "Fatigue of large tubular joints subjected to cathodic protection," Steel in Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 479-487.

Key Words: cathodic protection, crack initiation, crack propagation, synthetic seawater, tubular joint

Steel(s): BS 4360:50D, API 5LX-52

Notes: Large tubular joints were fatigue tested in air and in synthetic seawater with cathodic protection of -0.85 V vs. Ag/AgCl. The results were compared with UK Department of Energy's design fatigue curves. The fatigue lives in air agreed well with the design fatigue curve. However, the fatigue lives in seawater with cathodic protection were approximately a factor of two lower than those in air, except at the lowest stress range (about 1 million cycles to crack initiation) where the life was approximately the same as that expected in air. The reduction in fatigue life was related to early crack initiation and growth in the seawater. The design fatigue curve adequately bounded all of the results.

155.5 Kihl, D. P., "Axial Fatigue Behavior of Advanced Double Hull Combatant Weld Details," Proceedings of the Advanced (unidirectional) Double-Hull Technical Symposium, October 25-26, U. S. Navy and the Maritime Administration, Gaithersberg, Maryland, 1994.

Key Words: fatigue, S-N curve, random loading, welded joint, stress ratio, cruciform joint

Steel(s): HSLA 80, HS60, OS45

Notes: Axial load fatigue tests were conducted in air on cruciform welded joints to develop S-N curves. The effects of yield strength (type of steel), stress ratio (mean stress), and fabrication quality on fatigue strength were evaluated. The modified Goodman relation was found to describe the effect of mean stress. Satisfactory life predictions were made for specimens subject to narrow band random fatigue loading.

156.0 Kim, K., W. H. Hartt, "Growth rate of short fatigue cracks as relevant to higher strength steels for offshore structures in seawater," Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1992, p. 565-575.

Key Words: crack propagation, short cracks, seawater, offshore service, potential drop measurement, crack initiation

Steel(s): AC70, A537DQ, QT80, EH36, A707

Notes: Fatigue crack growth tests were performed in air and seawater using specimens with short (less than or equal to 0.1 mm) cracks. Literature on crack-size effects on corrosion fatigue in aqueous environments is summarized. DC potential drop was used to measure crack growth. The stress ratio was R = 0.5. Prior to crack initiation (about 0.03 mm crack extension), the frequency was 3 Hz for tests in air and 1 Hz for tests in seawater. After crack initiation, it was decreased to 1.0 Hz for tests in air and 0.3 Hz for tests in seawater. In air, the short cracks grew 3 to 20 times faster than long cracks. In seawater, the short cracks grew 2 to 6 times faster than long cracks. Growth rates of short cracks became the same as those of long cracks near and above da/dN = 1.4E-05 mm/cycle irrespective of the type of steel or environment.

157.0 Kim, K. B., T. Sakai, H. Tsubakino, K. Yamakawa, Y.-H. Lee, "Corrosion fatigue crack initiation of HT50-Cr steel in marine environment," Boshoku Gijutsu (Corrosion Engineering), Vol. 35, No. 9, 1986, p. 495-502.

Key Words: corrosion fatigue, crack initiation, synthetic seawater, high-cycle fatigue

Steel(s): HT50CR

Notes: Rotating bending fatigue tests were performed at 30 Hz using specimens exposed to synthetic seawater under free corrosion conditions. Quantitative metallography was performed to gain understanding of the crack initiation process. Localized pitting and grooving corrosion were observed on the surfaces of the specimens. Preferential dissolution of ferrite around degenerate pearlite or elongated manganese sulfide inclusions was the mechanism of local attack. The relationship of fatigue crack initiation to the observed local corrosion is discussed.

158.0 King, R. N., J. V. Sharp, "The influence of seawater and cathodic protection on the fatigue performance of high-strength steels for jack-up drilling units," Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1992.

Key Words:

Steel(s):
Notes: not in publication

159.0 Kobayashi, H., S. Ishizaki, H. Gao, "Corrosion fatigue crack growth characteristics of high strength steel in synthetic seawater," Proceedings of EVALMAT 89 - International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 1, The Iron and Steel Institute of Japan, Tokyo, 1989, p. 191-198.
Key Words: corrosion fatigue, crack propagation, threshold, stress ratio, synthetic seawater
Steel(s): AISI 4340, HT60
Notes: Fatigue crack growth tests were conducted on compact tension specimens exposed to synthetic seawater. The cyclic frequency was 5 Hz. Stress ratios were R = 0.1 and R = 0.7. Tests were performed in the near threshold regime using load shedding to decrease the range of stress intensity factor. Effective stress intensity factor was determined using measured values of the crack opening stress intensity factor and was used to characterize the cyclic crack growth rate.

160.0 Kobzaruk, A. B., L. T. Balatskii, N. A. Stepanok, "The corrosion and corrosion-fatigue resistance of steel in the sea and under laboratory conditions (translation)," Soviet Materials Science, Vol. 17, No. 2, 1981, p. 15-21.
Key Words: corrosion fatigue, seawater, low-cycle fatigue, 3.5% NaCl
Steel(s): 15KhN5DMF
Notes: Low-cycle, corrosion fatigue tests were conducted in air, in the sea, in seawater at the laboratory, and in 3.5% NaCl solution. The cyclic frequency was 0.017 Hz. Strain range versus fatigue life data were developed for the following conditions: (1) in the sea after prior corrosion, (2) in the sea after prior corrosion under stress, (3) in 3.5% NaCl solution after prior corrosion, (4) in seawater in the laboratory, (5) in seawater in the laboratory after prior corrosion under stress, (6) in air after prior deformation, and (7) in air. The fatigue lives were in the range of 300 to 3000 cycles.

161.0 Kobzaruk, A. V., "Influence of a change in loading frequency on the low-cycle fatigue resistance of a constructional steel in sea water (translation)," Soviet Materials Science, Vol. 19, No. 2, Mar.-Apr., 1983, p. 109-111.
Key Words: corrosion fatigue, frequency, low-cycle fatigue, seawater, crack initiation
Steel(s): 12KhN4DMF
Notes: The effects of changing frequency on low-cycle fatigue behavior in air and seawater were studied. Loading frequencies of 0.00167, 0.167, and 8 Hz were used. The specimens were conditioned by cycling at the low or high frequency before cycling to failure at the medium

frequency. Low frequency conditioning significantly reduced fatigue life in air and in seawater, and high frequency conditioning significantly reduced fatigue life in air. High frequency conditioning in seawater was deceased fatigue before crack initiation but increase it after crack initiation.

162.0 Kolomiitsev, E. V., A. N. Serenko, "Experiments to evaluate the fatigue strength of butt joints in low alloy steels in corrosive media," Automatic Welding, Vol. 38, No. 4, April, 1985, p. 50-52.

Key Words: welded joint, corrosion fatigue, synthetic seawater, S-N curve

Steel(s): 15G2, 15G2F, 15G2FB

Notes: Fatigue (S-N) curves were developed for lives between 1 and 100 million cycles to failure. Tests were perform in air and in synthetic seawater. The cyclic frequency was 35 to 45 Hz. The test machine operated under fully reversed bending at resonance. Specimen cracking caused a 15 to 20 Hz drop in the frequency and was defined as failure. S-N curves were developed for specimens of parent and weld metal tested in air and seawater.

163.0 Komai, K., K. Minoshima, G. Kim, "An estimation method of long-term corrosion fatigue crack growth characteristics," JSME International Journal, Series I, Vol. 32, No. 2, Apr., 1989, p. 282-286.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, threshold

Steel(s): HT50, HT50-TMCP, HT80

Notes: A model for long-term crack growth in seawater uses a modified effective stress intensity factor range. The threshold value for long-term crack growth is close to the threshold value for pitting of these steels in synthetic seawater.

164.0 Komai, K., "Collaborative research work on corrosion fatigue and stress corrosion cracking of steels in ocean environment in Japan," Proceedings of the 5th International Conference on Offshore Mechanics and Arctic Engineering, Vol. II, ASME, New York, 1986, p. 283-287.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, S-N curve, frequency, cathodic protection, calcareous deposits, crack closure

Steel(s): HT50, HT50CR, HT80

Notes: S-N curves were developed for tests in air and for tests at 30 and 0.17 Hz in synthetic seawater. Rotating bending fatigue specimens were used for these tests. Fatigue strength was greatly reduced by exposure to seawater. Compact tension specimens were used to develop crack growth data in air (0.17 to 35 Hz and stress ratios of R = 0.05 to R = 0.1) and in synthetic seawater (0.17 Hz and a stress ratio of R = 0.1). Crack growth rate was increased by the seawater environment, compared with air. Cathodic polarization of the HT80 steel to -1.0 V vs. SCE increased the threshold for crack growth because the formation of calcareous deposits promoted crack closure.

165.0 Komai, K., H. Okamoto, "Corrosion fatigue crack growth characteristics of a 50 kgf/mm^2 TMCP steel in synthetic sea water," Tetsu to Hagane, Vol. 74, 1988, p. 358-364.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, cathodic protection, stress ratio, crack closure, calcareous deposits

Steel(s): HT50-TMCP

Notes: Fatigue crack growth tests were performed using compact tension specimens tested in synthetic seawater. The frequency was 0.17 Hz, and the stress ratios were R = 0.1 and 0.8. Environmental variables were free corrosion and cathodic polarization (CP) to -1.0 V vs. SCE. At R = 0.1, the crack growth rates in seawater were lower than those in air. At low ranges of stress intensity factor, crack growth resistance is increased by CP. At high ranges of stress intensity factor, crack growth resistance is decreased by CP because of hydrogen embrittlement effects.

166.0 Komai, K., K. Minoshima, S. Kinoshita, and G. Kim, "Corrosion fatigue crack initiation of high-tensile-strength steels in synthetic seawater," JSME International Journal, Series I, Vol. 31, No. 3, 1988, p. 606-612.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, S-N curve, welded joint

Steel(s): HT50, HT50-TMCP, HT80

Notes: Rotating bending and plane bending (stress ratio of R = -1) fatigue specimens were tested at 0.17 Hz in synthetic seawater. Fatigue strength was greatly reduced by exposure to seawater. The corrosion fatigue strengths of HT50 weldments were similar to those of base metal. The threshold value for long-term crack growth is close to the threshold value for pitting of these steels in synthetic seawater.

168.0 Komai, K., M. Noguchi, H. Okamoto, "Growth characteristics of surface fatigue cracks of high-tensile strength steel in synthetic seawater," JSME International Journal, Series I, Vol. 31, No. 3, 1988, p. 613-618.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, cathodic protection, crack closure, calcareous deposits

Steel(s): HT80

Notes: The growth of surface cracks was studied in seawater under conditions of free corrosion and cathodic polarization (CP) to -1.0 V vs. SCE. The cyclic frequency was 0.17 Hz, and the stress ratios were R = 0.1 and R = 0.8. The effects of environment on crack aspect ratio during fatigue crack growth are discussed. The threshold for crack growth was significantly increased by CP.

169.0 Komai, K., K. Minoshima, S. Ogawa, "In-situ observations of corrosion fatigue damage of offshore structural steel by scanning vibrating electrode techniques," Innovation and Technology Transfer for Corrosion Control, 11th International Corrosion Congress, Vol. 5 of 5, Associazione Italiana di Metallurgia, Milan, Italy, 1990, p. 5.477-5.484.

Key Words: synthetic seawater, scanning vibrating electrode, corrosion damage

Steel(s): 3.5NiCrMoV

Notes: A scanning vibrating electrode system was developed to make in-situ measurements of localized corrosion damage by measuring the distributions of corrosion current density with time. The system was used to make measurements on a structural steel during corrosion fatigue testing in synthetic seawater. Upon loading, corrosion first occurred near the edge of the specimen and then spread to the middle of the specimen. The corrosion was more localized at higher stress levels than at lower stress levels. The factors controlling measured current density are discussed.

170.0 Krokhmal'nyi, A. M., A. G. Khanlarova, I. N. Zin', Ya. M. Nagieva, A. G. Aliev, "Corrosion-fatigue endurance of 09G2S steel with an allowance made for cathodic protection (translation)," Soviet Materials Science, Vol. 25, No. 3, 1989, p. 101-102.

Key Words: corrosion fatigue, cathodic protection, 3% NaCl, S-N curve

Steel(s): 09G2S

Notes: Specimens were tested under rotating bending load at 50 Hz. The free corrosion potential was in the range of -0.64 to -0.66 V (reference electrode was not reported), while cathodic polarization (CP) was at -0.85 V. S-N curves were developed for fatigue lives between 0.01 and 50 million cycles. The test conditions environments were air, free corrosion in 3% NaCl, and CP to -0.85 V in 3% NaCl. Under free corrosion conditions, fatigue strength was greatly reduced by exposure to 3% NaCl. CP in 3% NaCl gave fatigue strengths about the same or somewhat greater than those in air.

170.5 Kurihara, Y., S. Takasaki, M. Kobayashi, R. Ebara, Y. Yamada, Y. Murakami, "Corrosion Fatigue Behavior of Automobile Suspension Spring Steels," Impact of Improved Material Quality on Properties, Product Performance, and Design, MD-Vol. 28, ASME, New York, 1991, p. 51-62.

Key Words: 3% NaCl, bending fatigue, pitting, leaf spring, shot peening, surface finish

Steel(s): SUP9, SUP10M

Notes: The high-cycle (2E07 cycles) fatigue strength of two automotive leaf spring steels in 3% NaCl solution was determined. Three-point bending fatigue tests were conducted at 13.3 Hz and R = 0.05. Compared with the fatigue strength in air, the environment reduced the fatigue strength by about 90 percent. Surface finish had little effect on corrosion-fatigue strength, while shot peening improved the corrosion fatigue strength to about 74 percent of that in air. Corrosion-fatigue cracking occurred at regions of corrosion pit initiation and growth.

171.0 Lachmann, E., W. Schutz, C. M. Sonsino, “Corrosion fatigue of V-shaped welded and cast specimens in seawater under variable amplitude loading,” Steel in Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 551-564.

Key Words: cathodic protection, welded joint, shot peening, TIG dressing, synthetic seawater, fatigue, random loading

Steel(s): E355, E460, E690, GS8Mn7 cast steel

Notes: The fatigue strength of welded and cast V-shaped joints was determined in air, in synthetic seawater under free-corrosion conditions, and in synthetic seawater with cathodic protection (-0.85 and -1.05 V vs. Ag/AgCl). Both constant-amplitude and variable-amplitude loadings with mean frequencies from 1 to 10 Hz were used. Seawater (free corrosion) reduced fatigue life by a factor of about two, while either level of cathodic protection restored fatigue to levels similar to those obtained from tests in air. TIG dressing or shot peening the welds, especially those of the higher strength steels, significantly increased fatigue resistance. The fatigue strength of the cast specimens in seawater was about twice that of untreated welded specimens.

172.0 Lambert, S. B., “Effects of seawater on fatigue crack shape development,” Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1992, p. 577-584.

Key Words: seawater, crack shape, potential drop measurement, life prediction model, T joint, welded joint, pipe-plate joint, crack initiation, crack propagation

Steel(s): LT60

Notes: Tests were conducted to monitor the development of crack shape for T and pipe-plate welded joints under cyclic loading in air and seawater. Conditions of both free corrosion (FC) and cathodic protection (CP) to -0.85 V vs. Ag/AgCl and over cathodic protection (OCP) to -1.05 V vs. Ag/AgCl were investigated. Seawater has a large effect on crack shape; the effect is largely a result of the crack initiation behavior. For FC in seawater, fatigue crack initiation is relatively rapid and uniform, leading to the formation of long shallow cracks early in life. CP has a beneficial effect on initiation life, but this benefit is counteracted by increased crack growth rates. OCP also has a beneficial effect on initiation life, but it greatly increases crack growth rates and reduces total life by a factor of 3 to 4 times. A combined crack initiation and propagation model is needed to account for the observed effects.

173.0 Landles, K., J. Congleton, R. N. Parkins, “Potential measurements along actual and simulated cracks,” Corrosion Chemistry Within Pits, Crevices and Cracks, HMSO Books, London, UK, 1987, p. 453-470.

Key Words: corrosion fatigue, crack propagation, cathodic protection

Steel(s): HY80

Notes: Potential and current flow measurements were made along simulated and real fatigue cracks exposed to seawater. The pH within a simulated crack was about 4 at an applied potential of -0.4 V vs. SCE and about 12 at an applied potential of -1.2 V vs. SCE. Potential, current, and pH values were affected only slightly by cyclic movement of the simulated crack.

174.0 Lawrence, F. V., "The effect of the size of weldments on their fatigue strength," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 323-329.
Key Words: fatigue, crack initiation, crack propagation, thickness, welded joint
Steel(s): A36
Notes: A fatigue crack initiation-propagation model based on A36 steel cycled at a stress ratio of R = 0 was used to assess the thickness effect. An approximately -1/3 power dependence was predicted for the effect of thickness on the long-life fatigue strength of low stress concentration mild steel weldments. The thickness effect is most strongly influenced by crack initiation life and, hence, by notch severity. The pessimistic value of fatigue strength reduction factor provides a rational basis for estimating the thickness effect.

175.0 Lee, J.-G., T. Shoji, H. Takahashi, J. K. Lim, S.-H. Chung, "Surface crack growth behaviour in corrosion fatigue of off-shore structural steel," Proceedings of the KSME/JSME Joint Conference, Fracture and Strength '90 Key Engineering Materials, Vol. 51-52, Trans Tech Publ, Zuerich, Switz, 1990, p. 227-232.
Key Words: corrosion fatigue, crack propagation, synthetic seawater, cathodic protection
Steel(s): SS41, SM53B, HT80
Notes: The growth of surface cracks was studied in synthetic seawater at 25 C under conditions of free corrosion and cathodic polarization (CP) to -0.9 V vs. Ag/AgCl. The cyclic frequency was 0.17 Hz, and the stress ratio was R = 0.1. In comparison with free corrosion, CP decreased the crack growth rate for SS41 and HT80 steel, but no significant effect on the crack growth rate was found for SM53B steel.

176.0 Lian, B., A. Gunleiksrud, T. Simonsen, P. J. Haagensen, T. Slind, O. Orjasæter, "The crack growth properties in air and seawater of an offshore high strength QT steel," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1991.
Key Words:
Steel(s):
Notes: not in publication

177.0 Lian, B., A. Gunleiksrud, T. Simonsen, P. J. Haagensen, T. Slind, O. Orjasæter, "The effect of different weld improvement methods on the fatigue strength of an offshore high strength QT steel," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1991.

Key Words:

Steel(s):

Notes: not in publication

178.0 Lian, B., A. Gunleiksrud, T. Simonsen, P. J. Haagensen, T. Slind, O. Orjasæter, "The fatigue life of small scale welded specimens tested with an offshore load spectrum," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1991.

Key Words:

Steel(s):

Notes: not in publication

179.0 Liaw, P. K., H. R. Hartmann, E. J. Helm, "Corrosion fatigue crack propagation testing with the Krak-Gage® in salt water," Engineering Fracture Mechanics, Vol. 18, No. 1, 1983, p. 121-131.

Key Words: corrosion fatigue, crack propagation, 3.5% NaCl

Steel(s): HY80

Notes: KRAK-GAGES (R) were used to measure fatigue crack growth in 3.5% NaCl solution. It was shown that these gages produced data comparable to those obtained using compliance or visual methods of measuring crack length.

180.0 Lisagor, W. B., T. W. Crooker, B. N. Leis (Editors), Environmentally Assisted Cracking: Science and Engineering, STP 1049, ASTM, Philadelphia, 1990.

Key Words:

Steel(s):

Notes: This book is a collection of papers from an ASTM Symposium. See individual papers in this book.

181.0 Maahn, E., "Crack tip chemistry under cathodic protection and its influence on fatigue crack growth," Cathodic Protection: A + or - In Corrosion Fatigue?, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada, 1986, p. 87-106.

Key Words: cathodic protection, crack propagation, hydrogen embrittlement, calcareous deposits, seawater, crack closure

Steel(s): BS 4360:50D

Notes: The author discusses the role of crack-tip chemistry under conditions of free corrosion and cathodic protection on fatigue-crack growth behavior. For most free-corrosion situations, the increase in crack-growth rate is caused by the corrosion process, although hydrogen embrittlement may play a role for long cracks at high stress intensities. Cathodic protection causes calcareous deposits and hydrogen evolution and uptake in the steel. Hydrogen uptake increases crack-growth rate, whereas calcareous deposits decrease crack-growth rate when they promote crack closure. Deposits that form during an overload can reduce or even stop crack growth; this factor is important to consider in random loading. Magnesium hydroxide is the predominant deposit near the crack tip.

182.0 Maahn, E., "The influence of cathodic protection on mechanical properties of steel in offshore structures," Eurocorr '87, European Corrosion Meeting, Preprints, DECHEMA, Frankfurt am Main, FRG, 1987, p. 13-17.

Key Words: corrosion fatigue, cathodic protection, crack initiation, crack propagation, calcareous deposits

Steel(s): structural

Notes: This note briefly reviews the effects of cathodic protection (CP) on structural steels in seawater. CP inhibits corrosion attack and fatigue crack initiation. Hydrogen generated by CP can accelerate fatigue crack at high stress levels; therefore, overprotection should be avoided. Calcareous deposits help retard fatigue crack initiation and growth at moderate stress levels. The optimum level of CP for preventing or delaying fatigue cracking is -0.90 to -0.95 V vs. SCE.

182.5 Maahn, E., H. P. Nielsen, "Influence of cathodic protection on the initiation and growth of small cracks in steel under fatigue loading in seawater," Environment Assisted Fatigue, EGF7, Mechanical Engineering Publications, London, 1990, p. 395-414.

Key Words: corrosion fatigue, crack initiation, calcareous deposits, synthetic seawater, cathodic protection, short cracks

Steel(s): BS 4360:50D

Notes: Charpy specimens with a notch root radius of 0.25 mm were used to study fatigue crack initiation in synthetic seawater at 5 C. The specimens were tested under cyclic bending at a frequency of 0.1 Hz and at a stress ratio of R = 0.2. Cathodic protection levels of -0.7 to -1.2 V vs. SCE were employed. The maximum delay in crack initiation was observed at -1.0 V vs. SCE. Both hydrogen permeation and calcareous deposits affect the initiation and early crack-growth behavior.

183.0 Maksimovich, G. G., A. V. Kobzaruk, "Efficiency of protection of structural steel by polarization in low-cycle fatigue in sea water," Soviet Materials Science, Vol. 24, No. 5, 1988, p. 32-37.

Key Words: corrosion fatigue, S-N curve, cathodic protection, seawater, low-cycle fatigue, frequency

Steel(s): 15KhN5DMF

Notes: Low-cycle fatigue tests were performed in seawater and at cyclic frequencies of 0.00167 and 0.167 Hz. Cathodic polarization (CP) was at -0.75 and -0.90 V vs. H. Strain amplitude versus cyclic life curves are presented for specimens tested in air, at the free corrosion potential in seawater, and at the cathodic potentials in seawater. The effects of specimen surface finish (ground versus polished) also were evaluated.

184.0 Maksimovich, G. G., A. V. Kobzaruk, "Origin and development of low-cycle fatigue cracks in 15 KhN5DMF steel in sea water," Soviet Materials Science, Vol. 20, No. 5, 1984, p. 16-20.
Key Words: corrosion fatigue, crack initiation, crack propagation, seawater, low-cycle fatigue, frequency
Steel(s): 15KhN5DMF
Notes: Low-cycle fatigue tests were performed in seawater and at cyclic frequencies of 0.00167, 0.0167, and 0.167 Hz. The initiation and propagation of fatigue cracking in specimens with ground and specimens with polished surfaces were studied. The effects of loading cycle shape on fatigue cracking were also studied.

185.0 Marsh, K. J., "Large scale service-loading fatigue testing with particular reference to offshore structures," NEL Report, Dec., National Engineering Laboratory, East Kilbride, Scotland, 1980.
Key Words: welded joint, tubular joint, fatigue, cruciform joint, random loading
Steel(s): structural
Notes: Methods for fatigue testing large welded structural components and welded specimens are reviewed.

186.0 Marsh, K. J., R. Holmes, "The fatigue strength of offshore structures and components," Full-Scale Fatigue Testing of Components and Structures, 1980, p. 109-133.
Key Words:
Steel(s):
Notes: Publication was not available.

187.0 Martin, A., V. Sanchez-Galvez, "Environmentally assisted fatigue crack growth in high strength eutectoid cold drawn steel," British Corrosion Journal, Vol. 23, No. 2, 1988, p. 96-101.
Key Words: corrosion fatigue, crack propagation, stress ratio, frequency, synthetic seawater, cathodic protection
Steel(s): AISI 1080
Notes: Crack propagation tests of a cold-drawn eutectoid steel were conducted in air and synthetic seawater. Cyclic frequencies of 0.1, 1.0, and 10 Hz were used. Stress ratios of R = 0.1, R = 0.5, and R = 0.8 were used. Cathodic protection was evaluated by coupling some of the specimens tested in seawater to a zinc anode. The results are presented in plots of cyclic crack growth rate versus range of stress intensity factor.

188.0 Maruyama, N., S. Horibe, M. Sumita, "Corrosion fatigue in simulated aggressive marine environment," Journal of Materials Science Letters, Vol. 5, No. 9, 1986, p. 953-955.

Key Words: corrosion fatigue, synthetic seawater, S-N curve

Steel(s): High-Tensile Strength Steel

Notes: Corrosion fatigue tests were performed at a frequency of 0.5 Hz and a stress ratio of R = 0.1. Specimens were either immersed in the synthetic seawater or exposed to simulated splash zone environments using the synthetic seawater. Below a stress amplitude of 150 MPa (greater than about 500,000 cycles to failure), both types of environments gave the same S-N curve. However, above this stress amplitude, simulated splash zone environments gave lower fatigue lives than the fully immersed environment.

189.0 Masuda, H., S. Matsuoka, S. Nishijima, M. Shimodaira, "Effect of frequency on corrosion fatigue life prediction of high-tensile steel (HT 80) in synthetic sea water (Japanese)," Boshoku Gijutsu (Corrosion Engineering), Vol. 37, No. 1, Jan., 1988, p. 25-29.

Key Words: corrosion fatigue, crack propagation, frequency, synthetic seawater, cathodic protection, weld metal, threshold, welded joint

Steel(s): HT80

Notes: Fatigue crack growth tests of compact tension specimens were conducted in synthetic seawater at 25 C. The cyclic frequency was between 0.03 and 50 Hz, while the stress ratio was between R = 0.5 and R = 0.95. At 0.3 and 3 Hz, the effect of cathodic potentials between -0.6 and -1.1 V vs. Ag/AgCl were evaluated. Crack growth rate versus stress intensity factor range curves were developed in the near threshold regime, as well as the intermediate crack growth regime. Base metal exhibited intergranular cracking in the intermediate crack growth regime, but weld metal did not exhibit such cracking. The minimum crack growth rate at 0.3 Hz was at cathodic polarization level of -0.7 V vs. Ag/AgCl. Prediction of fatigue life requires proper understanding of the near threshold crack growth behavior.

190.0 Mathieson, P. A. R., "Acoustic emissions from fatigue cracks in steels (dissertation)," Dissertation Abstracts International, Vol. 49, No. 3, Sept., Cranfield Institute of Technology, 1988.

Key Words:

Steel(s):

Notes: Publication was not available.

191.0 Matlock, D. K., G. R. Edwards, D. L. Olson, S. Ibarra, "Effect of sea water on the fatigue crack propagation characteristics of welds for offshore structures," Corrosion Cracking, ASM International, Metals Park, Ohio, 1986, p. 113-122.

Key Words: welded joint, weld metal, corrosion fatigue, crack propagation, synthetic seawater
Steel(s): A36
Notes: Fatigue crack growth tests were conducted on base metal and weld metal in air and in synthetic seawater at 32 C. Welded joints were produced by conventional surface welding and by underwater repair welding techniques. The stress ratio was R = 0.06. The frequency was 30 Hz for tests in air and 30 and 0.3 Hz for tests in synthetic seawater. The results are shown in plots of crack growth rate versus stress intensity factor range. It was concluded that underwater wet welding procedures produce fatigue resistant weld metal that is adequate for use at low levels of applied stress.

192.0 Matsumoto, S., Y. Nakano, C. Shiga, A. Narumoto, S. Kikukawa, "Improvement of corrosion fatigue strength of cruciform fillet welded joints of steel plates for offshore structures," Proceedings of EVALMAT 89 - International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 1, The Iron and Steel Institute of Japan, Tokyo, 1989, p. 159-166.
Key Words: welded joint, corrosion fatigue, synthetic seawater, cruciform joint, hammer peening, grinding, TIG dressing, cathodic protection, S-N curve
Steel(s): BS 4360:50D, YS46, YS70
Notes: Corrosion fatigue tests were performed on cruciform fillet welded joints exposed to synthetic seawater at 5 C. The stress ratio was R = 0, and the frequency was 0.167 Hz. Tests were under conditions of free corrosion (-0.65 V vs. SCE) or cathodic polarization (CP) by coupling with an aluminum anode (-0.85 to -0.95 V vs. SCE). S-N curves were developed for cyclic lives in the range of 100,000 to 10 million cycles to failure. Hammer peening was the most effective fatigue improvement procedure that was evaluated. It gave fatigue strengths equal to those of base metal even without the benefit of CP. Toe grinding and TIG dressing also improved fatigue strength but to a much lesser degree than hammer peening.

193.0 Miller, G. A., "Strain-cycle fatigue of steel sheet and plate grades in ambient and aqueous environments," SAE Paper No. 840288, 1984 SAE International Congress and Exposition, Detroit, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, 1984.
Key Words: strain cycling, synthetic seawater, galvanizing, frequency, crack initiation
Steel(s): AISI 1012, Galvalume, B50XK, B80RK, BethStar 80
Notes: Strain-cycle fatigue tests were conducted in air and synthetic seawater and at cyclic frequencies of 0.01 to 18.8 Hz. There was no effect of environment on the cyclic stress-strain behavior of the five steels that were tested. For lives greater than 50,000 cycles, the fatigue strength of the steels in air was proportional to their tensile strength, but the fatigue strength in the environment was independent of their tensile

strength. The Galvalume and galvanized coatings were beneficial at high strain amplitudes (short lives) but not at low strain amplitudes (long lives). At low frequencies and low strain amplitudes, both bare and coated steels had about the same fatigue resistance. The major portion of fatigue life in these tests was crack initiation.

194.0 Misawa, T., M. Ogasawara, E. Moriyama, H. Sugawara, "Effect of cathodic protection potential on corrosion fatigue crack growth of high-tensile steel in synthetic sea water (Japanese)," Boshoku Gijutsu (Corrosion Engineering), Vol. 36, No. 12, Dec., 1987, p. 767-773.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, cathodic protection, calcareous deposits, crack closure, embrittlement

Steel(s): HT80

Notes: Fatigue crack growth tests were performed on compact tension specimens exposed to synthetic seawater at 25 C. The cyclic frequency was 0.17 Hz (10 Hz for reference tests in air), and the stress ratio was R = 0.1. Cathodic polarization (CP) levels of -0.7 to -1.1 V vs. Ag/AgCl were evaluated. Effective stress intensity factor range was used to account for crack closure effects caused by the formation of calcareous deposits. CP levels of -0.7 to -0.9 V vs. Ag/AgCl gave lower crack growth rates than observed under free corrosion conditions. CP levels more negative than -1.0 V vs. Ag/AgCl gave a large increase in crack growth rate because of hydrogen embrittlement.

195.0 Morgan, H. G., "Determination of fatigue thresholds and short crack behaviour in structural steel to BS4360:50D in air and seawater," Report Number ND-R-985 (S), UKAEA, Risley, UK, Sept., 1985.

Key Words:

Steel(s):

Notes: Publication was not available.

196.0 Morgan, H. G., I. Bretherton, "Fatigue crack growth tests on BS4360:50D steel in marine environments," Report Number ND-R-990 (S), UKAEA, Risley, UK, Aug., 1985.

Key Words:

Steel(s):

Notes: Publication was not available.

197.0 Morgan, H. G., T. W. Thorpe, A. Rance, D. R. V. Sylvester, P. M. Scott, "Investigation of the corrosion fatigue crack growth behavior of structural steels in seawater," L'Acier dans les Structures Marines. Conference Internationale (Session Technique 1-5.), Report EUR 7347, ST 5. 1, Commission of the European Communities, Luxembourg, 1981.

Key Words:

Steel(s):

Notes: Publication was not available.

198.0 Murakami, R., T. Tsumura, K. Akizono, "The effects of welded residual stress and corrosion deposits on corrosion fatigue crack propagation rate of butt welded joints in natural seawater (in Japanese)," J. Soc. Mater. Sci. Jpn., Vol. 36, No. 408, 1987, p. 986-991.

Key Words: welded joint, corrosion fatigue, crack propagation, seawater, crack closure, residual stress

Steel(s): carbon steel

Notes: Fatigue crack growth tests were conducted on butt-welded joints. The testing environments included air and seawater. Stress ratios of R = 0.05 and R =0.6 were used. Compressive residual stress reduced the crack growth rate in air, but tensile residual stress had little effect on the crack growth rate in air. The benefit of compressive residual stress was much less in seawater than in air at R =0.05 and was negligible at R = 0.6. Corrosion deposits on the crack faces were fractured when closure occurred, particularly under the presence of compressive residual stress, which lead to a significant acceleration of crack growth rate. The effective stress intensity factor range was used to correlate crack growth data.

199.0 Murakami, R., W. G. Ferguson, "The effects of cathodic potential and calcareous deposits on corrosion fatigue crack growth rate in seawater for two offshore structural steels," Fatigue & Fracture of Engineering Materials & Structures, Vol. 9, No. 6, 1987, p. 477-488.

Key Words: corrosion fatigue, crack propagation, seawater, 3% NaCl, stress ratio, cathodic protection, calcareous deposits, crack closure, embrittlement

Steel(s): St 52-3N

Notes: Fatigue crack growth tests on a standard and a clean heat of a C-Mn steel. For tests in air, the cyclic frequency was 20 Hz, and the stress ratio was R = 0.03. For tests in seawater or saltwater, the cyclic frequency was 0.1 Hz, and the stress ratios were R = 0.03 and R = 0.7. Cathodic polarization (CP) levels of -0.8, -1.0, and -1.1 vs. SCE were employed in seawater and saltwater. The formation of calcareous deposits within fatigue cracks caused crack closure. The effect of closure was taken into account by use of an effective stress intensity factor range. Fatigue loading and hydrogen embrittlement promoted crack growth, whereas calcareous scale tended to reduce crack growth rate. These mechanisms compete during crack growth.

199.5 Nakano, Y., Matsumoto, S., Watanabe, O., Hatomura, T., "Corrosion fatigue crack propagation behavior of TMCP steels," Proceedings of the 12th International Conference on Offshore Mechanics and Arctic Engineering, Vol. V, Pipeline Technology, ASME, New York, 1993, p. 215-223.

Key Words: fatigue, crack propagation, synthetic seawater, cathodic protection, temperature

Steel(s): YS36, YS46

Notes: Corrosion fatigue crack propagation tests were conducted on two steels produced by the Thermo Mechanical Control Process (TMCP). Compact type (CT) specimens were tested in ASTM synthetic seawater at room temperature and 5 C. The load ratio was 0.05 and the cyclic frequency was 0.167 Hz. Tests were under conditions of free corrosion (FC) and -0.8, -0.9, -1.0, and -1.1 V vs. SCE. The crack growth rate of the TMCP steel in the rolling direction was greater than that of a normalized steel. The potential of -1.0 V vs. SCE gave crack growth rates similar to those in air, while FC and the other potentials gave higher crack growth rates than those in air. The normalized steel exhibited secondary cracks while the TMCP steel did not.

200.0 Narumoto, A., K. Akahide, S. Kikukawa, Y. Kawai, O. Hashimoto, "Corrosion fatigue strength of high-strength low alloy steels for offshore structures," OTC '85, Proceedings - 17th Annual Offshore Technology Conference, Vol. III, Offshore Technology Conference, Richardson, Texas, 1985, p. 377-384.

Key Words: welded joint, cruciform joint, corrosion fatigue, S-N curve, TIG dressing, synthetic seawater, cathodic protection, stress concentration factor, grinding

Steel(s): A514F, BS 4360:50D, API 5LUX-80, A541 Cl6, A508 Cl2a, A372 Cl6

Notes: Cruciform of A514F and BS 4360:50D steels and simulated tether joints of high-strength low-alloy steels were fatigue tested in air and synthetic seawater. The stress ratio was R = 0. The frequency was 0.17 Hz for cruciform joints and 0.30 Hz for tether joints. Seawater temperature was 5 C for tests of the cruciform joints and 25 C for tests of the tether joints. Some specimens were cathodically polarized to -0.95 V vs. Ag/AgCl. The effect of TIG dressing was evaluated for the cruciform joints, and the effect of surface grinding was evaluated for the tether joints. S-N curves were developed for fatigue lives in the range of 10,000 to 10 million cycles to failure. Stress concentration factor as a function of fatigue strength at 1 million cycles to failure is presented.

201.0 Narumoto, A., S. Ueda, "Corrosion fatigue strength of the steels for offshore structures (synopsis)," Transactions of the Iron and Steel Institute of Japan, Vol. 24, No. 8, Aug., 1984, p. B-282.

Key Words: welded joint, cruciform joint, corrosion fatigue, synthetic seawater, cathodic protection, TIG dressing, temperature

Steel(s): BS 4360:50D, HT80

Notes: Cantilever bending fatigue tests were conducted on cruciform welded joints. The stress ratio was R = 0, and the frequency was 0.17 Hz. Tests were performed in synthetic seawater at 5 and 25 C; temperature had no effect on fatigue strength. The fatigue strength of TIG-dressed HT80 steel joints was significantly improved by cathodic protection via a sacrificial aluminum anode. HT80 steel joints also showed no size effect for tests in air and plate thicknesses of 15, 30, and 60 mm.

202.0 Nazarenko, G. T., I. I. Ishchenko, “Development of corrosion-fatigue cracks in round cross section samples,” Soviet Materials Science, Vol. 17, No. 4, Jul.-Aug., 1981, p. 366-371.

Key Words: corrosion fatigue, crack initiation, water, bending fatigue

Steel(s): 30KhN3A, 45

Notes: No data are reported for tests in seawater or saltwater. The development of corrosion fatigue cracks on bending specimens exposed to dripping water was studied. The specimens were subjected to fully reversed loading (R = -1) at 50 to 60 Hz.

203.0 Nerolich, S. M., P. E. Martin, W. H. Hartt, “Influence of weld profile on fatigue of welded structural steel in sea water,” Corrosion Fatigue: Mechanics, Metallurgy, Electrochemistry, and Engineering, STP 801, ASTM, Philadelphia, 1983, p. 491-507.

Key Words: welded joint, corrosion fatigue, cathodic protection, stress concentration factor, seawater

Steel(s): ABS DH32

Notes: Bending fatigue tests were conducted in seawater under free corrosion conditions and under cathodic polarization (CP) to -0.85 and -1.0 V vs. $Cu/CuSO_4$. The effect of weld toe profile on fatigue strength was investigated. Finite element stress analyses were conducted to compute stress concentration factor (K_t) as a function of reinforcement height and angle, distance along the surface near the weld toe, weld toe radius, and included angle. An included angle of 150 degrees and a toe radius of 0.4 mm were found to common values for butt welds and gave a K_t of approximately 1.75. Extreme values of 120 degrees and 0.1 mm gave a K_t of approximately 4.2. Weld toe undercut can significantly reduce fatigue life.

204.0 Nibbering, J. J. W., “Behavior of mild steel under very low frequency loading in seawater,” Corrosion Science, Vol. 23, No. 6, 1983, p. 645-662.

Key Words: corrosion fatigue, crack propagation, frequency, seawater

Steel(s): Fe 410, Fe 510

Notes: Fatigue crack growth tests were performed at very low frequencies in the range of 0.0003 to 0.05 Hz. Crack growth rate versus stress intensity factor range data were developed for tests in air and in seawater. The very low frequencies were found to significantly increase crack growth rate. Simple programmed loading, consisting of one peak among 200 low-stress cycles, retarded crack growth in air but was not beneficial in seawater. (Also, see Reference 206.)

205.0 Nibbering, J. J. W., B. C. Buisman, H. Wildschut, E. van Rietbergen, “Corrosion fatigue strength of T-type welded connections of thick plates for high numbers of load cycles (MaTS-ST-IV-10),” Steel in

	Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 773-786.
Key Words:	high-cycle fatigue, cathodic protection, welded joint, seawater, S-N curve
Steel(s):	E355 KT
Notes:	Four-point bending corrosion-fatigue tests were performed on welded T joints in air and seawater and at a frequency of 0.4 Hz. The results were compared with those of other investigators. Initial and intermediate high loads were found to be beneficial to high-cycle fatigue resistance. Cathodic protection also was found to be beneficial for crack initiation. Classic measures of fatigue improvement (stress relief, overloads, favorable weld-toe profile, etc.) have little effect unless cathodic protection is used. (Also, see Reference 240 for related data.)

206.0	Nibbering, J. J. W., "Ultra-low-frequent fatigue experiments in seawater," Low Frequency Cyclic Loading Effects in Environment Sensitive Fracture, 113th Event of the European Federation of Corrosion, Associazione Italiana di Metallurgia, Milan, Italy, 1982.
Key Words:	corrosion fatigue, crack propagation, frequency, seawater
Steel(s):	Fe 410, Fe 510
Notes:	Fatigue crack growth tests were performed at very low frequencies in the range of 0.0003 to 0.05 Hz. Crack growth rate versus stress intensity factor range data were developed for tests in air and in seawater. The very low frequencies were found to significantly increase crack growth rate. Simple programmed loading, consisting of one peak among 200 low-stress cycles, retarded crack growth in air but was not beneficial in seawater. (Also, see Reference 204.)

207.0	Nishida, S.-I., C. Urashima, "Corrosion fatigue properties of high tensile steels for offshore structures," Fatigue '84, Papers Presented at the 2nd International Conference on Fatigue and Fatigue Thresholds, Vol. 3, Engineering Materials Advisory Services Ltd, Warley, England, 1984, p. 1485-1494.
Key Words:	corrosion fatigue, seawater, S-N curve, frequency
Steel(s):	SM50, HT60, HT62, HT80
Notes:	Rotating bending fatigue tests were conducted in fresh water and seawater at 24 C. Cyclic frequencies of 0.067, 0.83, 2.5, 8.3, and 25 Hz were used. Reference tests were conducted in air and at 25 Hz. Data are presented in S-N curves and fatigue strength versus cyclic frequency plots. Exposure to seawater significantly reduced fatigue strength, compared with data for tests in air, and fatigue strength decreased as the cyclic frequency decreased.

208.0	Oberparleiter, W. J., "Corrosion fatigue of welded offshore steels and tubular connections," Theoretical and Applied Fracture Mechanics, Vol. 4, No. 2, Oct., 1985, p. 97-107.

Key Words: welded joint, corrosion fatigue, crack initiation, crack propagation, synthetic seawater, frequency, tubular joint, Miner's rule

Steel(s): E355 KT

Notes: This paper reviews the German contribution to the ECSC program on corrosion fatigue of offshore structures. Welded V joint specimens and tubular Y joint specimens were tested in air and synthetic seawater. Cyclic frequencies of 0.2, 1.0, and 10 Hz were used. This range in variation of loading frequency did not significantly affect the corrosion fatigue life of welded V joint specimens tested in seawater. Crack initiation lives of the welded joints in seawater were well predicted using S-N curves and Miner's rule with a damage sum of 0.5. (Also, see Reference 209.)

209.0 Oberparleiter, W. J., “Effect of corrosive environment on the fatigue life of cyclic loaded specimen and structures,” Application of Fracture Mechanics to Materials and Structures, Proceedings of the International Conference, Martinus Nijhoff Publ, The Hague and Boston, 1984, p. 919-929.

Key Words: welded joint, corrosion fatigue, synthetic seawater, frequency, cathodic protection

Steel(s): E355 KT

Notes: This paper reviews some of the German contribution to the ECSC program on corrosion fatigue of offshore structures. Welded V joint specimens were tested in air and synthetic seawater. Exposure to seawater reduced fatigue life by a factor of about 2 compared with data from tests in air. Cyclic frequencies of 0.2, 1.0, and 10 Hz were used. This range in variation of loading frequency did not significantly affect the corrosion fatigue life of welded V joint specimens tested in seawater, when crack propagation was only a small part of total life. Cathodic protection at -0.85 V vs. Ag/AgCl eliminated the detrimental effect of seawater on fatigue life. (Also, see Reference 208.)

210.0 Oerjasaeter, O., A. Draagen, “Fatigue crack growth in seawater under random loading,” File Number DE86751071, Mar., SINTEF, Trondheim, Norway, 1985.

Key Words:

Steel(s):

Notes: Publication was not available.

211.0 Oh, S. W., H. M. Kang, “Influence of artificial seawater corrosion on the fatigue-fracture behaviours of dual phase steel,” Proceedings of the 6th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1987, p. 439-444.

Key Words: fatigue, corrosion damage, 3.5% NaCl, S-N curve, crack propagation

Steel(s): A283 70a

Notes: Mild steel (as-received A283 70a) and dual phase steel (heat treated A283 70a) were fatigue tested in air after prior corrosion in 3.5% NaCl solution at 25 C. The dual phase microstructure was martensite encapsulated islands of ferrite. The fatigue tests were at 30 Hz and a stress ratio of R = -1. The saltwater exposures were for 250 and 1000 hours. Some specimens were fully immersed during exposure while others were exposed to a splash zone. The splash zone exposure decreased fatigue resistance more than the immersion exposure. The dual phase steel had much better fatigue strength, after corrosion exposure, than the mild steel. The dual phase steel also had better crack growth resistance than the mild steel. S-N curves and crack growth rate versus stress intensity factor range plots are presented.

212.0 Okada, T., S. Hattori, Y. Asai, "Corrosion-fatigue strength of notched high-tension steel specimens under cathodic protection in synthetic seawater," JSME International Journal, Series I, Vol. 33, No. 3, 1990, p. 375-381.

Key Words: welded joint, corrosion fatigue, synthetic seawater, cathodic protection, notch, stress concentration factor, S-N curve

Steel(s): HT50, HT80

Notes: Smooth and notched specimens were fatigue tested under rotating bending at 11 Hz. Butt welded joints were fatigue tested under four-point bending at 11 Hz and a stress ratio of R = 0. The tests were in synthetic seawater at 25 C. Some specimens were cathodically protected by coupling with a sacrificial anode. Values of stress concentration factor (K_t) for notched specimens were 1.03, 1.82, 2.40, 3.50, and 4.60. Corrosion fatigue strength at 10 million cycles to failure decreased as K_t increased from about 1 to 2 and was essentially constant for K_t values greater than 2. Stress concentration factors for the welded specimens were calculated from the toe shape. The fatigue strength of the welded specimens correlated well with that of the notched specimens. (Also, see Reference 214.)

213.0 Okada, T., S. Hattori, "Relation between concentration of salt water and corrosion fatigue strength on 0. 37 percent carbon structural steel," Journal of Engineering Materials and Technology, Vol. 107, No. 3, Jul., 1985, p. 235-239.

Key Words: corrosion fatigue, 3% NaCl, S-N curve

Steel(s): AISI 1035

Notes: Rotating bending, axial, and torsional load fatigue tests were conducted in saltwater at 25 C. The stress ratio was R = -1. The cyclic frequency 30 Hz for rotating bending and 20 Hz for axial and torsional loading. The saltwater concentrations ranged from 0.008% to 10% NaCl. Tests were also conducted in tap and deionized water. The fatigue strength at 10 million cycles to failure decreased linearly with the logarithm of NaCl concentration for values between 0.005% and 3%. Below 0.005% NaCl concentration, the fatigue strength in saltwater was the same as that in deionized water.

214.0 Okada, T., S. Hattori, S. Yamagishi, “The notch effect on corrosion-fatigue strength of high-strength steels,” Bulletin of the JSME, Vol. 29, No. 255, 1986, p. 2765-2770.

Key Words: corrosion fatigue, synthetic seawater, S-N curve, notch, stress concentration factor

Steel(s): HT50, HT80, AISI 1035

Notes: Notched specimens were fatigue tested under rotating bending at 11 Hz. The tests were in deionized water and synthetic seawater at 25 C. Values of stress concentration factor (K_t) for the notched specimens were 1.03, 1.82, 2.40, 3.50, and 4.60. Corrosion fatigue strength in synthetic seawater at 10 million cycles to failure decreased as K_t increased from about 1 to 2 and was essentially constant for K_t values greater than 2. In synthetic seawater, all three steels had about the same corrosion fatigue strength as a function of notch severity. In deionized water, the HT80 and AISI 1035 steel were less affected by slight notches than the HT50 steel. (Also, see Reference 212.)

215.0 Oliver, R., M. Greif, W. Oberparleiter, W. Schuetz, “Corrosion fatigue behavior of offshore steel structures under constant amplitude loading,” L'Acier dans les Structures Marines. Conference Internationale (Session Technique 1-5.), Report EUR 7347, ST 2. 4, Commission of the European Communities, Luxembourg, 1981.

Key Words:

Steel(s):

Notes: Publication was not available.

216.0 Onoufriou, A., A. Mangiavacchi, “A comparison of fatigue crack growth methods for offshore tubular joints,” Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 469-476.

Key Words: fatigue, fracture mechanics, crack propagation, offshore service, S-N curve, tubular joint, stress concentration factor, life prediction model

Steel(s):

Notes: Both fracture mechanics and S-N curve methods were used to predict the fatigue lives of tubular joints for which experimental data were published. The FACTS computer code was used to perform the fracture mechanics analyses. The stress concentration factors predicted by FACTS were reasonable but conservative compared with results of finite element analyses. Various methods of computing the stress intensity factor were evaluated. The fracture mechanics method of life prediction was very conservative (6 times shorter mean cyclic lives) compared with the S-N method. Accurate measurement of crack size is important in applying the fracture mechanics method. Seawater is predicted to significantly reduce crack growth lives.

217.0 Ouchi, H., I. Soya, R. Ebara, Y. Yamada, “Effects of dissolved oxygen and cathodic protection on corrosion fatigue properties of welded joints in cold sea water (synopsis)," Transactions of the Iron and Steel Institute of Japan, Vol. 27, No. 3, 1987, p. B-77.

Key Words: welded joint, corrosion fatigue, synthetic seawater, T joint, cathodic protection, S-N curve

Steel(s): HT60, HT80

Notes: Specimens from welded T joints were fatigue tested in synthetic seawater at 4 C. The cyclic frequency was 0.17 Hz, and the stress ratio was R = 0. Tests conditions included free corrosion and cathodic polarization (CP) at -0.8, -1.0, or - 1.2 V vs. SCE. The dissolved oxygen was 1.8 or 5 ppm. The fatigue strength under free corrosion conditions and low oxygen level was close to that observed in air at room temperature. CP at -1.0 V vs. SCE improved fatigue strength. However, CP at -1.2 V vs. SCE decreased fatigue strength because of the detrimental effect of hydrogen produced by the cathodic reaction. (Also, see Reference 217.5.)

217.5 Ouchi, H., I. Soya, R. Ebara, Y. Yamada, "Effects of temperature and dissolved oxygen in seawater on the fatigue strength of welded steel joints," Environment Assisted Fatigue, EGF7, Mechanical Engineering Publications, London, 1990, p. 17-30.

Key Words: dissolved oxygen, cathodic protection, T joint, welded joint, temperature, synthetic seawater, hydrogen embrittlement

Steel(s): HT60

Notes: Corrosion-fatigue tests were conducted on welded T joints in ASTM synthetic seawater at 4 C. The loading was sinusoidal at 0.17 Hz and R = 0.04 to 0.12. Tests were conducted under conditions of free corrosion and cathodic polarization to -0.8, -1.0, and -1.2 V vs. SCE. The dissolved oxygen content ranged from 0 to 10 ppm. Under free corrosion, seawater decreased the fatigue strength compared with data in air, the effect of low temperature was negligible, and decreased dissolved oxygen content increased corrosion-fatigue strength to levels approaching those measured in air. Cathodic protection at -0.8 and -1.0 V vs. SCE increased the long-life fatigue strength to levels above those measured in air, but cathodic overprotection at -1.2 V vs. SCE decreased the fatigue strength to levels below those measured under free corrosion because of hydrogen evolution. (Also, see Reference 217.0.)

218.0 Ouchi, H., J. Kobayashi, "Effects of environmental variables on fatigue crack growth rate in steel immersed in seawater," Proceedings of EVALMAT 89 - International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 1, The Iron and Steel Institute of Japan, Tokyo, 1989, p. 183-190.

Key Words: corrosion fatigue, crack propagation, cathodic protection, synthetic seawater

Steel(s): High-Tensile Strength Steel, carbon steel

Notes: Fatigue crack growth tests were conducted on compact specimens in synthetic seawater. The test conditions included free corrosion and polarization to -0.6 or -0.8 V vs. SCE. The stress ratio was R = 0.25, and the cyclic frequency was 0.17 Hz. Crack growth rates in seawater were above those in air and were not affected by polarization. Plots of crack growth rate versus range of stress intensity factor are presented.

219.0 Panasyuk, V. V., O. N. Romaniv, "Mechanics of corrosion fatigue," Corrosion Fatigue, Proceedings of the First USSR-UK Seminar on Corrosion Fatigue of Metals, The Metals Society, London, UK, 1983, p. 24-35.
Key Words:
Steel(s):
Notes: Publication was not available.

220.0 Parkins, R. N., Y. M. Kolotyrkin (Editors), "Proceedings of the First USSR-UK Seminar on Corrosion Fatigue of Metals," Corrosion Fatigue, Proceedings of the First USSR-UK Seminar on Corrosion Fatigue of Metals, The Metals Society, London, UK, 1983.
Key Words:
Steel(s):
Notes: Publication was not available.

221.0 Pei, H., J. Yang, W. Ke, "Growth of short cracks of A537 CL 1 steel under fatigue loading in 3.5% NaCl solution," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 162-167.
Key Words: corrosion fatigue, crack propagation, short cracks, 3.5% NaCl, crack closure, threshold
Steel(s): A537
Notes: Fatigue crack growth tests were conducted in 3.5% NaCl solution. Cyclic frequencies were 1 and 10 Hz, and the stress ratio was R = 0. The growth of short (0.05 to 0.15 mm long) edge cracks was studied. Short cracks grew much faster than long cracks at stress intensity factor ranges near the threshold for crack growth. The threshold stress intensity factor range decreased with decreasing crack length for short cracks. Crack closure and environmental effects are discussed.

221.5 Peng, Y., F. Yu, Y. Zhang, W. Zheng, "An investigation of corrosion fatigue fracture for 40CrNiMo steel in seawater by positron annihilation," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 150-155.
Key Words: corrosion fatigue, seawater, crack propagation
Steel(s): 40CrNiMo
Notes: Positron annihilation and Doppler broadening were used to studied samples removed from specimens that had been fatigue cracked in air and in seawater. Hydrogen produced during corrosion fatigue can

affect positron annihilation. The role of hydrogen in initial fatigue cracking and in fatigue crack growth is discussed.

222.0	Pook, L. P., J. C. P. Kam, Y. Mshana, “On mixed mode fatigue crack growth in tubular welded joints,” Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1992, p. 251-256.
Key Words:	tubular joint, crack propagation, mixed mode, welded joint
Steel(s):	BS 4360:50D
Notes:	Information on mixed mode fatigue crack growth in tubular joints is reviewed. A saddle crack is produced when an X joint is loaded in out-of-plane bending. This crack becomes a 'crack-in-the-wrong-place' when the joint is loaded in in-plane bending. Such a crack is not serious because it grows in an innocuous manner in length rather than in depth and does not appear to affect normal crack development elsewhere in the joint. The behavior of this cracking is consistent with current fracture mechanics analyses of mixed mode fatigue crack growth, but the behavior cannot be predicted in detail with the current models.
223.0	Potter, J. M., H. I. McHenry (Editors), “Symposium on Fatigue and Fracture Testing of Weldments,” Fatigue and Fracture Testing of Weldments, STP 1058, ASTM, Philadelphia, 1990.
Key Words:	welded joint, fatigue, fracture, corrosion fatigue
Steel(s):	
Notes:	This book contains six papers on fatigue testing of weldments and nine papers on fracture testing of weldments.
224.0	Procter, R. P. M., “Detrimental effects of cathodic protection: embrittlement and cracking phenomena,” Cathodic Protection: Theory and Practice, Ellis Horwood, Chichester, UK, 1986, p. 293-313.
Key Words:	cathodic protection, hydrogen embrittlement, crack initiation, crack propagation, seawater, corrosion fatigue,
Steel(s):	BS 4360:50D, X65
Notes:	This paper is a general review of past work on the effect of cathodic protection (CP) on stress corrosion cracking and hydrogen embrittlement of pipeline steels and corrosion fatigue of offshore structural steels. CP of buried pipelines can generate carbonate/bicarbonate at disbonded regions of coatings. Severe over-CP of offshore pipelines can lead to reduced ductility and cracking caused hydrogen embrittlement. Normal CP restores corrosion-fatigue strength in seawater. CP, especially over-CP, can significantly increase cyclic crack growth rates in seawater.
225.0	Pustovoi, V. N., “Corrosion-fatigue crack resistance of steels and weld joints of the metal structures of load-lifting machines,” Soviet Materials Science, Vol. 27, No. 2, Sept., 1991, p. 203-210.

Key Words: corrosion fatigue, crack propagation, welded joint, seawater, cathodic protection

Steel(s): 10KhSND, St 38 b2

Notes: Fatigue crack growth tests were conducted on both steels in seawater spray environment. Specimens were loaded by cantilever bending at stress ratios of R = -1, R = 0, and R = 0.7. Crack closure was measured by the compliance method using a strain gage sensor. Effective stress intensity factor range was used to account for the effect of crack closure. The 10KhSND steel also was tested fully immersed in seawater and at a stress ratio of R = 0.7. In this case, data were developed for both free corrosion and cathodic polarization conditions. Plots of crack growth rate versus stress intensity factor range and effective stress intensity factor range are presented.

226.0 Quan, G, S. Huang, Y. Song, “Effects of loading frequency on crack propagation behaviors of corrosion fatigue,” Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 174-180.

Key Words: corrosion fatigue, crack propagation, 3.5% NaCl, frequency

Steel(s): SiMn, CrNi

Notes: Fatigue crack growth tests were conducted in 3.5% NaCl solution at 25 C. Cyclic frequencies of 0.33, 5.5, and 11 Hz were used. Stress corrosion cracking tests were also conducted under constant load. Plots of crack growth rate (da/dN) versus stress intensity factor range and crack velocity (da/dt) versus maximum stress intensity factor are presented. In the intermediate regime of crack growth, da/dN increased with decreasing frequency.

227.0 Raghava, G., P. Gandhi, A. G. Madhava Rao, “Corrosion fatigue in offshore structural steels. A review,” Fatigue and Fracture in Steel and Concrete Structures - ISFF '91 Proceedings, Oxford & IBH Publishing Co. Pvt. Ltd, New Delhi, India, 1991, p. 759-776.

Key Words: corrosion fatigue, crack initiation, crack propagation, welded joint, seawater, tubular joint, cathodic protection

Steel(s): structural

Notes: This paper provides a general review of the corrosion fatigue behavior of structural steels for offshore applications. Experimental studies that have been conducted by others are discussed and typical results are presented. The important topics addressed include crack initiation, crack propagation, welded joints, tubular joints, and cathodic protection.

228.0 Rajpathak, S. S., W. H. Hartt, “Formation of calcareous deposits within simulated fatigue cracks in seawater,” Corrosion, Vol. 43, No. 6, June, 1987, p. 339-347.

Key Words: corrosion fatigue, crack propagation, seawater, 3.5% NaCl, cathodic protection, frequency, calcareous deposits

Steel(s): AISI 1018

Notes: The formation of calcareous deposits within simulated corrosion fatigue cracks was studied in seawater and in 3.5% NaCl solution. Cyclic frequencies of 0.1, 0.5, and 1.0 Hz were used. Water flow velocities were 1.6, 8, and 16 mm/s. Cathodic potentials of -0.78, -0.9, -1.0, and -1.1 V vs. SCE were used. Potential profiles within simulated cracks and changes in current were measured.

228.5 Rajpathak, S. S., W. H. Hartt, "Fatigue crack initiation of selected high strength steels in seawater," Proceedings of the 7th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1988, p. 323-341.

Key Words: seawater, S-N curve, cathodic protection, crack initiation

Steel(s): HY80, A710, QT80, QT108, EH36, A537, X70, HY130

Notes: Keyhole CT specimens were tested in natural seawater under free corrosion and under cathodic protection (CP) to -1.10 V vs. SCE. The frequency was 1 Hz, and the stress ratio was 0.5 for all tests. Fatigue life was defined as the initiation of an approximately 1-mm long crack, and S-N curves were developed for each of the alloys tested. For CP conditions, the fatigue limit was proportional to one half of the ultimate tensile strength (UTS) up to a UTS of 720 MPa (104 ksi). Above that UTS value, the fatigue strength was independent of UTS value.

229.0 Rajpathak, S. S., W. H. Hartt, "Keyhole compact tension specimen fatigue of selected high-strength steels in seawater," Environmentally Assisted Cracking: Science and Engineering, STP 1049, ASTM, Philadelphia, 1990, p. 425-446.

Key Words: corrosion fatigue, cathodic protection, crack initiation, fatigue limit, fracture, fatigue, seawater

Steel(s): A710, HY80, QT80, QT108, EH36, A537, X70, HY130

Notes: Keyhole CT specimens were tested in natural seawater under free corrosion (FC) and under cathodic protection (CP) to -1.10 V vs. SCE. The frequency was 1 Hz, and the stress ratio was 0.5 for all tests. Fatigue life was defined as the initiation of an approximately 1-mm long crack, and S-N curves were developed for each of the alloys tested. CP improved fatigue strength compared with that for FC conditions. For tests with CP, the fatigue limit was proportional to ultimate tensile strength (UTS) up to a UTS of 680 MPa (99 ksi). Above that UTS value, the fatigue strength was independent of UTS.

230.0 Raoof, M., "Cable fatigue prediction in offshore applications," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 403-411.

Key Words: fatigue, offshore service, steel ropes, seawater

Steel(s):

Notes: A theoretical model for predicting the axial fatigue life of multi-layered, spiral stranded wire cable was developed. The model was used to help understand the mechanisms of fatigue failure in such cables. Internal wire failures can be predicted. The effects of seawater and fretting are considered in the model.

231.0 Reynolds, G. H., J. A. Todd, "Threshold corrosion fatigue of welded shipbuilding steels," Ship Structure Committee Report SSC-366, 1992.

Key Words: welded joint, corrosion fatigue, crack propagation, threshold, crack closure

Steel(s): Mil S-24645, A710

Notes: Near threshold corrosion fatigue crack growth tests were conducted. Data were developed for the following materials and test conditions: (1) Mil S-24645 steel base metal -- 10 Hz, R = 0.1, air, 22 C; 10 Hz, R = 0.1, free corrosion in seawater, 22 C; 10 Hz, R = 0.1, at -1.0 V vs. SCE in seawater, 22 C; 0.2 Hz, R = 0.1, free corrosion in seawater, 22 C; 2 Hz, R = 0.1, free corrosion in seawater, 22 C; (2) A710 steel base metal -- 2 Hz, R = 0.1, air, 22 C; 2 Hz, R = 0.1, free corrosion in seawater, 22 C; 2 Hz, R = 0.1, at -1.0 V vs. SCE in seawater, 22 C; 2 Hz, R = 0.1, at -0.8 V vs. SCE in seawater, 22 C; (3) Mil S-24645 weld and HAZ metal -- 10 Hz, R = 0.1, air, 22 C; 10 Hz, R = 0.1, at -1.0 V vs. SCE in seawater, 22 C; 10 Hz, R = 0.1, at -0.8 V vs. SCE in seawater, 22 C. Stress intensity factor range needed to be corrected for crack closure effects.

232.0 Sablok, A., W. H. Hartt, "Fatigue of high strength steels in sea water," Proceedings of the 7th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1988, p. 477-485.

Key Words: corrosion fatigue, welded joint, seawater, S-N curve, notch, stress concentration factor, heat treatment, cathodic protection, grinding

Steel(s): 2-1/4Cr-1Mo, U80, HY80

Notes: Corrosion fatigue tests were conducted in seawater under free corrosion conditions or with cathodic polarization (CP) of -0.9 V vs. SCE. The loading frequency was 0.3 Hz. The tapered cantilever beam specimens were either welded or notched. The welds were ground and post weld heat treated. The notches had stress concentration factor (K_t) values of 1.68 and 2.18. For free corrosion, the data for all three materials were represented by a single S-N curve. The notched specimens had lower fatigue strength than the welded ones under free corrosion conditions. CP improved fatigue strength compared with results under free corrosion.

233.0 Sablok, A. K., W. H. Hartt, "Fatigue of welded structural and high-strength steel plate specimens in seawater," Fatigue and Fracture Testing of Weldments, STP 1058, ASTM, Philadelphia, 1990, p. 78-95.

Key Words: corrosion fatigue, welded joint, seawater, S-N curve, notch, stress concentration factor, heat treatment, cathodic protection, grinding, stress ratio

Steel(s): ABS DH32, 2-1/4Cr-1Mo, U80, HY80, A710, QT80, QT108, ABS EH36, A537DQ, A537

Notes: Corrosion fatigue tests were conducted in seawater under free corrosion conditions or with cathodic polarization (CP) of -0.78 to -1.1 V vs. SCE. The loading frequencies were 0.3, 0.5, and 3 Hz. The tapered cantilever beam specimens were either as welded or welded followed by grinding and post weld heat treatment. S-N curves are presented for specimens tested under free corrosion conditions. Weld toe stress concentration factor accounted for the scatter in some of the data when they were plotted using nominal stress range. Overall, there was little variation is fatigue strength among all of the steels under free corrosion. Based on limited data, CP improved fatigue strength compared with results under free corrosion.

234.0 Sablok, A. K., W. H. Hartt, "The influence of weld profile upon the thickness dependence of fatigue strength for steel in seawater," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 347-362.

Key Words: fatigue, thickness, weld profile, welded joint, T joint, seawater, cathodic protection

Steel(s): API 2H Grade 42

Notes: Fatigue tests were conducted using welded T joint specimens with thicknesses ranging from 13 to 102 mm. Three weld profiles were evaluated: AWS basic, AWS Alternate 1, and AWS Alternate 2. The tests were performed in seawater under conditions of free corrosion (FC) and cathodic protection (CP) to -0.8 V vs. SCE. The stress ratio was R = 0.1, and the frequency was 0.3 Hz. Improved weld profiling gave thickness independent fatigue lives up to a thickness of 30 to 40 mm. Above this thickness range, fatigue life decreased with increasing thickness. The benefits of weld profile improvement appeared to be the greatest in the long-life, low-stress regime.

235.0 Saenz de Santa Maria, M., R. P. M. Procter, "Environmental cracking (corrosion fatigue and hydrogen embrittlement) X-70 linepipe steel," International Conference on Fatigue and Crack Growth in Offshore Structures, I Mech E Conference Publication 1986-2, Mechanical Engineering Publications, London, 1986, p. 101-108.

Key Words: corrosion fatigue, crack propagation, cathodic protection, synthetic seawater, hydrogen embrittlement

Steel(s): X70

Notes: Fatigue crack growth tests were performed on compact tension specimens in seawater at 5 C. The cyclic frequency was 0.167 Hz, and the stress ratio was R = 0.15. Data were generated for conditions of free corrosion and cathodic polarization (CP) at -0.9 and -1.2 V vs.

SCE. Slow strain rate tensile tests were also conducted at rates down to 2.2E-07 per second to develop stress corrosion cracking (SCC) data. Crack growth rates in seawater were 1.4 to 2.6 times higher than those in air. For potentials more negative than -0.8 V vs. SCE, SCC failures showed increasing amounts of transgranular cleavage fracture caused by hydrogen embrittlement. Intergranular fatigue cracking occurred under free corrosion, while transgranular cleavage fatigue cracking occurred at a CP level of -1.2 V vs. SCE.

236.0 Saito, T., I. Uchiyama, "Influence of cathodic polarization on stress corrosion cracking of high strength steels in synthetic sea water," Transactions of the Iron and Steel Institute of Japan, Vol. 22, No. 6, 1982, p. 457-461.

Key Words: synthetic seawater, cathodic protection, threshold

Steel(s): Ni-Cr-Mo

Notes: Stress corrosion cracking (SCC) behavior was evaluated using bolt-loaded modified wedge-open load (WOL) specimens. The specimens were exposed to synthetic seawater at 25 C under free corrosion or coupled to a zinc anode (-0.97 to -0.98 V vs. Ag/AgCl). Crack velocity (da/dt) was determined as a function of maximum stress intensity factor. The SCC threshold was decreased by cathodic polarization (CP) compared with that under free corrosion. SCC was observed even after 9000 hours under free corrosion but arrested after about 800 hours under CP. (See References 237 and 238 for related fatigue crack growth data.)

237.0 Saito, T., I. Uchiyama, "Influence of electrochemical potential on crack growth rate by corrosion fatigue in synthetic seawater," Transactions of the Iron and Steel Institute of Japan, Vol. 22, No. 8, 1982, p. 586-592.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, cathodic protection, calcareous deposits

Steel(s): Ni-Cr-Mo

Notes: Fatigue crack growth tests were conducted on single-edge notched specimens in synthetic seawater at 30 C. The cyclic frequency was 1 Hz, and the stress ratio was R = 0.1. The effects of anodic and cathodic polarization (CP) on crack growth rate (da/dN) were evaluated. Compared with free corrosion, anodic potential increased da/dN by a dissolution-assisted mechanism. Compared with free corrosion, CP increased da/dN at high stress intensity factor ranges by a hydrogen-assisted mechanism and decreased da/dN at low stress intensity factor ranges by a calcareous-deposit crack-wedging mechanism (See References 236 and 238 for related crack growth data.)

238.0 Saito, T., "Kinetics of corrosion fatigue crack growth in high strength low-alloy steels in 3. 5% NaCl aqueous solution," Transactions of the

Iron and Steel Institute of Japan, Vol. 24, No. 12, Dec., 1984, p. 1055-1062.

Key Words: corrosion fatigue, crack propagation, 3.5% NaCl, cathodic protection, temperature

Steel(s): Ni-Cr-Mo

Notes: Fatigue crack growth tests were conducted on single-edge notched specimens in 3.5% NaCl solution at temperatures from 5 to 60 C. The cyclic frequency was 1 Hz, and the stress ratio was R = 0.1. Cathodic polarization (CP) at -1.05 V vs. Ag/AgCl was applied in all cases. The effect of temperature on crack growth rate (da/dN) was characterized for three regions of stress intensity factor range (âK), as follows: (1) in the low region, da/dN was highly dependent on âK and increased with increasing temperature, (2) in the intermediate region, da/dN was moderately dependent on âK and increased with increasing temperature, and (3) in the high region, da/dN was dependent on âK and independent of temperature.

239.0 Salama, M. M., R. M. Vennett, "Assessment of corrosion fatigue behavior of offshore structures," Environmental Degradation of Engineering Materials in Aggressive Environments, Virginia Polytechnic Institute, Blacksburg, Virginia, 1981, p. 83-95.

Key Words: corrosion fatigue, welded joint, seawater, synthetic seawater, cathodic protection, stress ratio, frequency, heat treatment, S-N curve

Steel(s): BS 4360:50D

Notes: More than 230 data points from fatigue tests of welded joints were analyzed to develop statistically based S-N curves and assess the effects of important variables on corrosion fatigue strength. Test environments included air, seawater, and synthetic seawater. Other test variables were weld configuration, post weld heat treatment (PWHT), stress ratio (R = -1, R = 0, and R = 0.1), frequency (0.125 to 10 Hz), temperature (4 C to ambient), and level of cathodic polarization (free corrosion to -1.12 V vs. Ag/AgCl). Design rules for fatigue of welded joints are satisfactory, even for free corrosion seawater. Cathodic protection improved high-cycle fatigue strength (greater than 1 million cycles to failure) to levels above those for tests in air. Under free corrosion, fatigue life was a factor of about 2-1/2 times below that in air.

240.0 Scholte, H. G., J. L. Overbeeke, O. D. Dijkstra, H. Wildschut, C. Noordhoek, "Fatigue and corrosion fatigue on flat specimens and tubular joints - Dutch results," Proceedings of the 8th International Conference on Offshore

Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1989, p. 565-572.

Key Words: corrosion fatigue, welded joint, seawater, S-N curve, cathodic protection, stress ratio, tubular joint, crack propagation, fracture mechanics, heat treatment, random loading, stress concentration factor

Steel(s): E355 KT

Notes: This paper provides a review of the Dutch part of the ECSC corrosion fatigue program. Tests were conducted in air and seawater on both small welded plate specimens and large welded tubular joints. Cathodic polarization (CP) was used for some of the tests in seawater. Stress ratios of R = -1 and R = 0.1 were used. Crack growth tests were performed on specimens with semi-elliptical surface cracks, and the results were used to evaluate fatigue analysis based on fracture mechanics. Fatigue life under free corrosion conditions in seawater was reduced to at least 50 percent of that in air. Stress ratio had only a small effect of the fatigue strength of welded joints. CP is beneficial for crack initiation at low stress ranges. Calculated stress concentration factors for tubular joints are compared with measured ones. (Also, see Reference 77 for data on the tests of tubular joints and Reference 205 for data on T joints.)

241.0 Scholte, H. G., H. Wildschut, "Fatigue crack propagation tests on welded specimens in air and sea water," L'Acier dans les Structures Marines. Conference Internationale (Session Technique 1-5.), Report EUR 7347, ST 5. 2, Commission of the European Communities, Luxembourg, 1981.

Key Words:

Steel(s):

Notes: Publication was not available. See Reference 240 for a review of the data.

242.0 Schutz, W., "Corrosion fatigue," International Journal of Materials & Product Technology, Vol. 3, No. 1, 1988, p. 20-37.

Key Words: corrosion fatigue, synthetic seawater, crack initiation, crack propagation

Steel(s): structural

Notes: This paper reviews corrosion fatigue behavior of metallic materials in synthetic seawater, tap water, and boiler feed water. Effects of the following variables are discussed: frequency, loading spectrum, stress level, protection systems, welding parameters, and surface treatment.

243.0 Schutz, W., "Corrosion fatigue of offshore and ship-building steels," AGARD (NATO) (CP-316), Oct., 1981, p. 4.1-4.17.

Key Words: welded joint, corrosion fatigue, stress concentration factor, synthetic seawater, frequency, tubular joint

Steel(s): structural

Notes: This paper reviews the results of several corrosion fatigue test programs on offshore and ship-building steels. The detrimental effect of synthetic seawater was much larger for variable amplitude loading than for constant amplitude loading. Miner's Rule can be used to predict fatigue life under variable amplitude loading. Under random loading, variations of test frequency in the range of 0.1 to 10 Hz had only a small effect on corrosion fatigue life in synthetic seawater. Fatigue testing of tubular joints for offshore structures is also discussed.

244.0 Scott, P. M., T. W. Thorpe, R. F. A. Carney, “Corrosion fatigue crack initiation from blunt notches in structural steel exposed to seawater,” Proceedings of the 7th International Conference on Fracture (ICF7), Vol. 2, Pergamon Press, Oxford, 1989, p. 1595-1602.

Key Words: corrosion fatigue, crack initiation, S-N curve, seawater, cathodic protection

Steel(s): BS 4360:50D

Notes: Corrosion fatigue tests were conducted on blunt-notched compact tension specimens with notch radii of 0.25, 1.0, and 4.0 mm. Both constant and variable amplitude loading was used. Crack initiation lives were determined for tests in air, in freely corroding seawater, and under cathodic polarization (CP) to -0.85 V vs. SCE in seawater. Linear elastic analysis of the notch tip strain amplitude provided adequate correlations for high-cycle fatigue. At low stress ranges, exposure to seawater has a detrimental effect on fatigue life, while CP in seawater has a beneficial effect.

245.0 Scott, P. M., “Crack growth rate studies on structural steel in seawater,” UK National Corrosion Conference 1982, The Institution of Corrosion Science and Technology, Birmingham, UK, 1982, p. 183-186.

Key Words: corrosion fatigue, crack propagation, seawater, stress ratio, cathodic protection, welded joint, S-N curve, cruciform joint

Steel(s): BS 4360:50D

Notes: Results of fatigue crack growth studies are discussed. Crack growth rate (da/dN) versus range of stress intensity factor data are presented for tests in seawater at 5 to 10 C under free corrosion conditions or under cathodic polarization to -0.85 V vs. SCE. The cyclic frequency was 0.1 Hz, and the stress ratios were R = -1, R = 0 to 0.1, R = 0.5, R = 0.7, and R = 0.85. High values of R increased da/dN. S-N curves are presented for welded cruciform joints tested at R = 0 and R = -1 under similar environmental conditions.

246.0 Scott, P. M., T. W. Thorpe, D. R. V. Silvester, “Rate-determining processes for corrosion fatigue crack growth in ferritic steels in seawater,” Corrosion Science, Vol. 23, No. 6, 1983, p. 559-575.

Key Words: corrosion fatigue, seawater, crack propagation, electrochemical, cathodic protection, frequency, stress ratio, hydrogen embrittlement

Steel(s): BS 4360:50D

Notes: Crack growth tests were conducted on specimens immersed in seawater with and without cathodic polarization (CP). Electrochemical potentials were measured near the tip of growing cracks. In air, crack growth rate (da/dN) was not affected by frequency or stress ratios of R = -1 to R = 0.85. For tests in seawater and at R = 0.5, frequencies of 0.01, 0.1, and 1 Hz were used. At 0.01, da/dN values were about an order of magnitude higher than comparable values for tests in air. For all CP levels in the range of -0.65 to -1.3 V vs. Ag/AgCl, high R values (greater than 0.5) increased da/dN compared with low and negative R values. The mechanism of environmentally enhanced fatigue crack growth in seawater is believed to be hydrogen embrittlement.

247.0 Scott, P. M., “The effects of seawater on corrosion fatigue in structural steels,” Corrosion Fatigue, Proceedings of the First USSR-UK Seminar on Corrosion Fatigue of Metals, The Metals Society, London, UK, 1983, p. 89-100.

Key Words:	cathodic protection, seawater, crack propagation, frequency, stress ratio, S-N curve, welded joint
Steel(s):	BS 4360:50D
Notes:	Corrosion-fatigue crack growth experiments were conducted on CT, SEN, elliptically surface-notched specimens in seawater at 5 to 10 C and at a cyclic frequency of 0.1 Hz. S-N tests at R = 0 and -1 were conducted on cruciform specimens with full penetration fillet welds. Tests were performed in air, continuous immersion in seawater, intermittent immersion in seawater, and in seawater with cathodic protection. Fatigue crack growth rates up to six times higher than those observed in air were found in seawater, and high R ratios gave faster growth rates than low R ratios of 0 or less. Cathodic protection reduces corrosion fatigue crack growths at low positive R ratios but not at high positive R ratios. Crack initiation plays a significant role in the fatigue life of welded joints.
248.0	Sekiguchi, S., and others, "Effects of frequency and electrochemical potential on fatigue crack growth of HY130 in synthetic sea-water (Synopsis In Japanese)," 99th ISIJ Meeting, April, 1980.
Key Words:	corrosion fatigue, crack propagation, synthetic seawater, cathodic protection
Steel(s):	HY130
Notes:	Fatigue crack growth data were developed for tests in synthetic seawater. The stress ratio was R = 0. Cyclic frequencies of 0.1, 1, and 10 Hz were used. Cathodic polarization (CP) levels of -0.8 and -1.05 V vs. SCE were used in addition to free corrosion. Plots of crack growth rate (da/dN) versus range of stress intensity factor are presented. Above the threshold regime, decreased frequency increased da/dN under free corrosion conditions, and more negative CP level increased da/dN at 0.1 Hz.
249.0	Shah Khan, M. Z., I. A. Burch, "Effect of cyclic waveforms with superimposed high frequency flutter on the corrosion fatigue behaviour of a submarine hull steel," International Journal of Fracture, Vol. 52, No. 4, 1991, p. R57-R60.
Key Words:	corrosion fatigue, frequency, low-cycle fatigue, seawater
Steel(s):	BIS 812 EMA
Notes:	The effect of small amplitude flutter loading on low-cycle fatigue life in seawater was evaluated. A triangular waveform with a frequency of 0.075 Hz was employed. Also, a trapezoidal waveform with the same ramp rate was used. The superimposed flutter loading was at frequencies from 1 to 30 Hz. Up to 20 Hz, the fatigue life decreased as the flutter frequency increased. (Also, see Reference 251.)
249.5	Shah Khan, M. Z., I. A. Burch, "Effect of plate orientation and weld metal on the corrosion fatigue crack propagation behaviour of a new submarine hull steel," Proceedings of Fatigue '93, Montreal, Canada, 1993.
Key Words:	welded joint, corrosion fatigue, crack propagation, seawater, weld metal
Steel(s):	BIS 812 EMA
Notes:	Fatigue crack growth tests were conducted on compact tension specimens immersed in natural seawater under free corrosion conditions. The stress ratio was R = 0, and the cyclic frequency was 0.014 to 0.015 Hz. Plate orientation had only a small effect on crack growth behavior. Crack growth rate was less

in weld metal than in base metal for tests in air and in seawater. (Also, see Reference 250.)

250.0 Shah Khan, M. Z., I. A. Burch, "Effect of seawater on the fatigue life and crack growth behaviour of a new microalloyed steel for submarine hull application," International Journal of Fatigue, Vol. 14, No. 5, 1992, p. 313-318.
Key Words: corrosion fatigue, crack propagation, S-N curve, seawater
Steel(s): BIS 812 EMA
Notes: Hourglass-shaped and compact tension specimens were tested in seawater. The former specimens were used to develop S-N curves for a trapezoidal loading waveform at a stress ratio of R = 0 and at cyclic frequencies of 0.013 to 0.015 Hz. The latter specimens were used to develop crack growth data for a trapezoidal loading waveform at a stress ratio of R = 0 and a cyclic frequency of 0.015 Hz. Crack growth rate versus range of stress intensity factor data are presented. (Also, see Reference 249.5.)

251.0 Shah Khan, M. Z., I. A. Burch, "Effect of superimposed high frequency flutter on the fatigue life of a submarine hull steel," International Journal of Fracture, Vol. 44, No. 3, Aug., 1990, p. R35-R38.
Key Words: corrosion fatigue, frequency, low-cycle fatigue, seawater
Steel(s): BIS 812 EMA
Notes: The effect of small amplitude flutter loading on low-cycle fatigue life in seawater was evaluated. A trapezoidal waveform with a frequency of 0.015 Hz was employed. The superimposed flutter loading was at frequencies from 1 to 30 Hz. Up to 20 Hz, the fatigue life decreased as the flutter frequency increased. (Also, see Reference 249.)

252.0 Shi, L., B. Huang, M. Yao, M. Zhou, "An experimental study on the sea water corrosion fatigue of tubular joints in offshore platforms," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 137-143.
Key Words: welded joint, tubular joint, T joint, corrosion fatigue, seawater, cathodic protection, stress concentration factor, TIG dressing
Steel(s): A537
Notes: Corrosion fatigue tests, in seawater at 20 C, were conducted on five tubular joints. Four specimens were tested under free corrosion conditions, while cathodic polarization (CP) was applied to one specimen. In-plane bending or axial loading was applied at a cyclic frequency of 0.2 Hz. Stress concentration factors for in-plane bending were computed using finite element analysis. Free corrosion in seawater reduced fatigue life to 1/3 to 1/2 of that in air. TIG dressing of the welded joints improved fatigue life by a factor of two. CP did not improve fatigue life for lives less than 100,000 cycles to failure.

253.0 Shoji, T., K. Yamaki, H. Tashiro, "Electrochemical and mechanical aspects of corrosion fatigue crack growth behavior of high strength steels in synthetic sea water," Proceedings of EVALMAT 89 - International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 1, The Iron and Steel Institute of Japan, Tokyo, 1989, p. 175-182.

Key Words: synthetic seawater, short cracks, crack propagation, cathodic protection, threshold, crack closure
Steel(s): HT80
Notes: A specially instrumented specimen was used to measure the electrochemical potential near the tip of a simulated fatigue crack in synthetic seawater. At the start of the test, the potential in the crack was noble -0.392 to -0.445 V vs. Ag/AgCl, increasing in value from the crack mouth to the crack tip. As time increased (up to 53 hours), the potential became less noble and decreased in value from the crack mouth to the crack tip. Time-domain analysis was used to model and predict fatigue crack growth data. Crack growth data were developed for chemically short cracks in synthetic seawater and with cathodic protection to -1.0 V vs. SCE. The threshold âK value was lower for short cracks than for long crack in CT specimens tested under comparable conditions because crack closure occurred in the CT specimens.

254.0 Sigaev, A. A., V. I. Pyndak, B. V. Perunov, V. D. Repin, M. A. Zhuravlev, “Corrosion resistance and fatigue strength of welded joints in 30KhMA steel in structures of offshore drilling rigs of the 'SHEL'F-2' type (translation),” Welding Production, Vol. 30, No. 11, Nov., 1983, p. 40-42.
Key Words: welded joint, corrosion fatigue, S-N curve, 3% NaCl, hydrogen sulfide
Steel(s): 30KhMA
Notes: Corrosion fatigue tests were conducted on welded specimens immersed in 3% NaCl solution at 20 to 28 C. S-N curves, in the range of 10,000 to 1 million cycles to failure are presented for air, saltwater, and NACE solution (hydrogen sulfide).

255.0 Solin, J., “Analysis of spectrum fatigue tests in sea water,” Proceedings of the 9th International Conference on Offshore Mechanics and Arctic Engineering, Vol. II, ASME, New York, 1990, p. 197-203.
Key Words: corrosion fatigue, crack propagation, seawater, spectrum loading, life prediction model
Steel(s): structural
Notes: This paper outlines a model for predicting fatigue crack growth life based on mechanisms of corrosion fatigue. Total cyclic crack growth rate (da/dN) is based on the superposition three crack growth rates: inert or mechanical fatigue, true corrosion fatigue, and stress corrosion fatigue. Its application to spectrum loading is discussed.

256.0 Solli, O., “Corrosion fatigue of welded joints in structural steels and the effect of cathodic protection,” European Offshore Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. IV/10-1 to 10-20.
Key Words: welded joint, corrosion fatigue, cathodic protection, synthetic seawater, S-N curve
Steel(s): C-Mn
Notes: Butt welded joints were tested in four-point bending. The specimens were exposed to air or synthetic seawater at 10 to 12 C under free corrosion or under cathodic polarization (CP) to -0.78 or -1.1 V vs. SCE. The cyclic frequency was 1 Hz. CP at -0.78 V vs. SCE restored fatigue strength to the level observed in air. CP at -1.1 V vs. SCE improved the fatigue, compared with

free corrosion, but did not restore it to the level observed in air. This paper is Ref. No. 101 in Jaske, et al. (Document No. 140).

257.0 Solli, O., “Corrosion fatigue of weldments of C-Mn steel the effect of cathodic protection, stress relieving treatment and saline atmosphere,” L'Acier dans les Structures Marines. Conference Internationale (Session Technique 1-5.), Report EUR 7347, ST 2. 2, Commission of the European Communities, Luxembourg, 1981.

Key Words:

Steel(s):

Notes: Publication was not available.

258.0 Stacey, A., “Remaining fatigue life predictions for a tubular joint in a fixed platform,” Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 477-486.

Key Words: fatigue, crack propagation, tubular joint, life prediction model, offshore service

Steel(s):

Notes: A remaining life and structural integrity assessment was performed for a cracked KT tubular joint in an offshore platform. The predictions were performed in accordance with the procedures of BS PD 6493 and using results of 2-D finite element stress analysis of local weld configuration. Fatigue life predictions were found to be very sensitive to the assumptions employed, especially those regarding residual stresses, crack growth rate behavior, and value of stress intensity factor. These factors caused much uncertainty in the predictions of remaining fatigue life. Further developments are needed in these areas to provide greater confidence in fatigue life predictions.

259.0 Stonesifer, F. R., J. M. Krafft, “Fatigue crack growth in A36/A283 plate in air and sea water environments,” Report NRL-MR-4467, March 26, Naval Research Laboratory, Washington, D. C., 1981.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, frequency, stress ratio

Steel(s): A36, A283C

Notes: Fatigue crack growth tests were conducted in air and synthetic seawater. Stress ratios of R = 0 and R = 0.8 and frequencies of 0.1, 1, 3, and 10 Hz were used in the testing. The crack growth behavior in air was similar to that of steels with up to twice the strength of A36 steel. For frequencies greater than or equal to 1 Hz, the crack growth rate in seawater was about the same as that in air. For 0.1 Hz cycling in seawater, the crack growth rate in seawater was accelerated by a factor of about three compared with that in air.

260.0 Suzuki, Y., “Corrosion fatigue crack propagation of mild steel in sea water (Japanese),” Boshoku Gijutsu (Corrosion Engineering), Vol. 32, No. 6, 1983, p. 318-323.

Key Words: corrosion fatigue, seawater, crack propagation, threshold

Steel(s): C-Mn

Notes: Cantilever bending fatigue specimens with surface cracks were used to develop crack growth data in natural seawater. The cyclic frequency was 0.33 Hz, and the stress ratio was R = 0. The threshold stress intensity factor range was 6 MPa-m^1/2 for air and 3.8 MPa-m^1/2 for seawater. The crack growth rate in seawater was 5 to 10 times greater than that in air. Data on crack growth rate versus crack aspect ratio are presented. (Also, see References 261 and 262.)

261.0 Suzuki, Y., "Corrosion fatigue crack propagation of mild steel under cathodic protection in natural seawater (Japanese)," Boshoku Gijutsu (Corrosion Engineering), Vol. 33, No. 7, 1984, p. 402-408.

Key Words: corrosion fatigue, seawater, crack propagation, threshold, cathodic protection

Steel(s): C-Mn

Notes: Cantilever bending fatigue specimens with surface cracks were used to develop crack growth data in natural seawater. The cyclic frequency was 0.33 Hz, and the stress ratio was R = 0. The effect of cathodic polarization (CP) to -0.8 V vs. SCE was evaluated. The threshold stress intensity factors were 3.9 MPa-m^1/2 for air, 2.3 MPa-m^1/2 for free corrosion in seawater, and 5.4 MPa-m^1/2 with CP in seawater. The threshold values for air and seawater do not agree with those reported in earlier work (Reference 260). (Also, see Reference 262.)

262.0 Suzuki, Y., S. Motoda, "Surface fatigue crack growth for mild steel in seawater (Japanese)," Boshoku Gijutsu (Corrosion Engineering), Vol. 37, No. 7, 1988, p. 432-437.

Key Words: corrosion fatigue, seawater, crack propagation, frequency

Steel(s): C-Mn

Notes: Cantilever bending fatigue specimens with surface cracks were used to develop crack growth data in natural seawater. Cyclic frequencies was 0.33, 0.25, 0.17, and 0.09 Hz. The stress ratio was R = 0. Testing at decreased frequency had no effect on early crack growth, but it caused growth rate to slow down and eventually arrest beyond a certain crack depth. This behavior was related to crack-tip blunting from dissolution in the seawater. (Also, see References 260 and 261.)

263.0 Takeuchi, M., R.B. Waterhouse, "Fretting-corrosion-fatigue of high strength steel roping wire and some protective measures," Proceedings of EVALMAT 89 - International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 1, The Iron and Steel Institute of Japan, Tokyo, 1989, p. 453-460.

Key Words: fretting, corrosion fatigue, synthetic seawater, cathodic protection, S-N curve

Steel(s): High-Tensile Strength Steel

Notes: Fretting fatigue tests were conducted on 1.5-mm diameter steel wires. The stress ratio was R = 0.3, and the frequency was 5 Hz. Exposure to seawater seriously degraded fretting fatigue resistance. Cathodic polarization (CP) in the range of -0.95 to - 1.0 V vs. SCE was improved fretting fatigue strength to levels above those observed in air. Hot-dip galvanizing provided effective CP, but the Fe-Zn compound formed on the substrate was deleterious to fatigue performance. Electrodepositing a suitably thick layer of zinc was a good means of enhancing fatigue performance.

264.0 Takeuchi, M., R. B. Waterhouse, Y. Mutoh, T. Satoh, "The behaviour of fatigue crack growth in the fretting-corrosion-fatigue of high tensile roping steel in air and seawater," Fatigue & Fracture of Engineering Materials & Structures, Vol. 14, No. 1, 1991, p. 69-77.

Key Words: fretting, corrosion fatigue, synthetic seawater, cathodic protection, crack propagation, S-N curve

Steel(s): High-Tensile Strength Steel

Notes: Fretting fatigue tests were conducted on 1.5-mm diameter steel wires exposed to air or synthetic seawater. The stress ratio was R = 0.3, and the frequency was 5 Hz. Cathodic polarization (CP) at -0.85 V vs. SCE was evaluated. S-N curves were developed, and crack growth rate (da/dN) versus range of stress intensity factor curves were developed. The Tanaka-Mutoh model was used to predict fretting fatigue life. It gave good predictions for the results in air but gave incorrect predictions for results in seawater.

265.0 Terasaki, T., T. Akiyama, Y. Matsuo, M. Etoh, "Behavior of corrosion fatigue crack propagation in weldments," Transactions of the Iron and Steel Institute of Japan, Vol. 27, No. 5, 1987, p. B-164.

Key Words: welded joint, crack propagation, synthetic seawater

Steel(s): HT80

Notes: Crack growth tests were conducted in air and seawater. The stress ratio was R = 0.1, and the frequency was 0.17 Hz. Crack growth rate (da/dN) was correlated with the range of effective stress intensity factor. Grain size affected da/dN only at low values of the range of effective stress intensity factor, where resistance to crack growth increased with decreased grain size.

266.0 Terasaki, T., T. Akiyama, M. Eto, Y. Matsuo, M. Kusuhara, "Effects of various factors produced by welding on the corrosion fatigue crack growth rate (Japanese)," Boshoku Gijutsu (Corrosion Engineering), Vol. 36, No. 12, 1987, p. 774-780.

Key Words: welded joint, corrosion fatigue, crack propagation, synthetic seawater, residual stress

Steel(s): HT80

Notes: Crack growth tests were conducted in synthetic seawater at 30 C. The cyclic frequency was 0.17 Hz, and the stress ratio was R = 0.1. Increased hardness and residual stress decreased crack growth rate (da/dN). Large grain size material had the same da/dN values as the base metal. The da/dN values for weld metal were lower than those for base metal.

267.0 Thomas, C. J., I. M. Austen, R. Brook, R. G. J. Edyvean, "Corrosion fatigue properties of an offshore structural steel in seawater containing hydrogen sulphide," ECF 6: Fracture Control of Engineering Structures, Proceedings of the 6th Biennial European Conference on Fracture, Vol. 2, Engineering Materials Advisory Services Ltd, Warley, England, 1986, p. 1199-1210.

Key Words: corrosion fatigue, crack propagation, seawater, hydrogen sulfide

Steel(s): RQT701

Notes: Fatigue crack growth tests were conducted at a stress ratio of R = 0.7 and a cyclic frequency of 0.167 Hz. The test environments were seawater at 5 C, seawater at 20 C saturated with hydrogen sulfide, seawater at 20 C with various levels of abiotic hydrogen sulfide or various levels of hydrogen sulfide produced by biological decomposition of algae. Crack growth rate increased with increased level of hydrogen sulfide, but naturally produced hydrogen sulfide was less potent than synthetically added hydrogen sulfide. There was a limit to the deleterious effect of added hydrogen sulfide in the range of 200 to 500 ppm.

268.0 Thomas, C. J., R. G. J. Edyvean, R. Brook, I. M. Austen, "The effects of microbially produced hydrogen sulphide on the corrosion fatigue of offshore structural steels," Corrosion Science, Vol. 27, No. 10/11, 1987, p. 1197-1204.
Key Words: corrosion fatigue, crack propagation, seawater, hydrogen sulfide
Steel(s): RQT501, RQT701
Notes: Fatigue crack growth tests were conducted at a stress ratio of R = 0.7 and a cyclic frequency of 0.167 Hz. The test environments were seawater at 5 C and seawater at 20 C with various levels of abiotic hydrogen sulfide or various levels of hydrogen sulfide produced by biological decomposition of algae. Crack growth rate increased with increased level of hydrogen sulfide, but naturally produced hydrogen sulfide was less potent than synthetically added hydrogen sulfide.

269.0 Thorpe, T. W., P. M. Scott, A. Rance, D. Silvester, "Corrosion fatigue of BS 4360:50D structural steel in seawater," International Journal of Fatigue, Vol. 5, No. 3, 1983, p. 123-133.
Key Words: corrosion fatigue, crack propagation, seawater, stress ratio, cathodic protection, calcareous deposits
Steel(s): BS 4360:50D
Notes: Fatigue crack growth tests were conducted on compact tension (CT) and three-point bending (TPB) specimens in seawater at 5 to 10 C. The TPB specimens contained semi-elliptical surface cracks with aspect ratios of 1 to 0.25. Crack growth rate (da/dN) versus range of stress intensity factor plots are presented for stress ratios of R = -1 to R = 0.85. Test environments include air and seawater under free corrosion conditions, cathodic polarization (CP) to -0.85 V vs. Ag/AgCl, CP to -1.1 V vs. Ag/AgCl, and CP to -1.3 V vs. Ag/AgCl. The surface cracks grew at the same rate as the through cracks (CT specimens) in air or seawater under free corrosion. Under CP they grew slower than through cracks because of calcareous deposits.

270.0 Timonin, V., J. Ojiganov, "On electrochemical identification and suppression of metal corrosion fatigue in sea water (abstract only)," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, International Academic Publishers, Beijing, China, 1988, p. 117.
Key Words: corrosion fatigue, seawater, electrochemical
Steel(s):
Notes: This paper discusses mechanisms of corrosion fatigue attack on the surface of metal specimens. The changes in electrochemical condition at the electrolyte/metal interface are important.

271.0 Todd, J. A., P. Li, G. Liu, V. Raman, "A new mechanism of crack closure in cathodically protected ASTM A710 steel," Scripta Metallurgica, Vol. 22, No. 6, 1988, p. 745-750.

Key Words: corrosion fatigue, crack propagation, cathodic protection, crack closure, threshold, hydrogen embrittlement, calcareous deposits

Steel(s): A710

Notes: Near threshold fatigue crack growth tests were conducted in air and synthetic seawater at 25 C. The stress ratio was R = 0.1, and the cyclic frequency was 2 Hz. Test conditions in synthetic seawater included free corrosion and cathodic polarization (CP) to -0.8 and -1.0 V vs. SCE. Crack closure loads were measured. The threshold stress intensity factor range (âK_{th}) was higher under free corrosion than in air because of corrosion debris induced crack closure. The maximum retardation of near threshold fatigue crack growth was at the CP level of -0.8 V vs. SCE and was attributed calcareous deposits causing crack closure. Hydrogen embrittlement caused metal wedges to form in the crack wake at -1.0 V vs. SCE and promote crack closure.

272.0 Todoroki, R., S. Sekiguchi, T. Ishiguro, T. Zaizen, “Problems on improvement of corrosion fatigue strength of steel in sea water,” Proceedings - 8th International Congress on Metallic Corrosion, 7th Congress of the European Federation of Corrosion (111th Event), Vol. 2, DECHEMA, Frankfurt am Main, FRG, 1981, p. 1292-1297.

Key Words: corrosion fatigue, welded joint, S-N curve, cathodic protection, synthetic seawater, stress concentration factor, notch, hydrogen embrittlement, TIG dressing

Steel(s): SM41, SM50, HT60, HT70, HT80, HT100, HT130

Notes: Corrosion fatigue tests were performed on smooth, notched (K_t = 3), and fillet welded specimens in synthetic seawater at 30 C under conditions of free corrosion or cathodic polarization (CP). The cyclic frequency was 0.17 Hz, and the stress ratio was R = 0. Under free corrosion, the fatigue strength did not depend on material strength. Optimum CP (-0.8 to -1.0 V vs. SCE) improved corrosion fatigue strength, but overprotection (-1.2 to -1.4 V vs. SCE) of notched specimens degraded fatigue performance because of hydrogen embrittlement. The fatigue strength of the welded joints depended on the stress concentration factor (K_t) of the weld toe profile. TIG improved the fatigue strength of the welded joints.

273.0 Tsokur, N. I., A. V. Kobzaruk, “Corrosion and corrosion-fatigue properties of 10KhSND steel in natural sea water and in a medium saturated with marine bacteria (translation),” Soviet Materials Science, Vol. 20, No. 2, 1984, p. 36-38.

Key Words: corrosion fatigue, seawater, bacteria, low-cycle fatigue

Steel(s): 10KhSND

Notes: Bending fatigue tests were conducted in natural seawater with additions of bacteria. The cyclic frequency was 0.17 Hz. S-N curves from 2,000 to 100,000 cycles to failure were developed for (1) sterile seawater with bacteria, (2) sterile seawater with bacteria and beef-extract bouillon, (3) sterile seawater, (4) natural seawater, and (5) air.

274.0 Tubby, P. J., G. S. Booth, “Corrosion fatigue of two weldable high strength steels for offshore structures,” Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 363-369.

Key Words: fatigue, cathodic protection, synthetic seawater, welded joint, grinding

Steel(s): SAR 60, MACS

Notes: Cantilever bending fatigue tests were performed on K-butt-joint specimens to develop fatigue curves in air and synthetic seawater. The stress ratio was R = 0, and the frequency was 1 to 5 Hz and 0.167 Hz for testing in air and seawater, respectively. Tests in seawater were under free corrosion (FC) and under cathodic protection (CP) to -0.85 and -1.10 V vs. Ag/AgCl. Overall, the fatigue strengths were similar to those obtained in past studies of BS 4360:50D steel. FC in seawater reduced the fatigue strength, which was not fully restored by CP to -0.85 V vs. Ag/AgCl. Weld toe grinding significantly increased fatigue strength in air and in seawater with CP to -0.85 V vs. Ag/AgCl.

275.0 Turnbull, A., A. S. Dolphin, F. A. Rackley, "Experimental determination of the electrochemistry in corrosion fatigue cracks in structural steel in artificial seawater," Corrosion, Vol. 44, No. 1, Jan., 1988, p. 55-61.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, electrochemical

Steel(s): BS 4360:50D

Notes: An experimental technique was developed to measure the potential and pH at the tip of a growing fatigue crack in seawater. Separate 1- to 2-mm diameter glass and reference electrodes were inserted into holes drilled into the side of a compact tension specimen. Potential and pH was measured for a range of applied potentials at various levels of stress intensity factor range and stress ratio. At cathodic potentials, the pH was alkaline. At free corrosion or anodic potentials, the pH was neutral to slightly alkaline. Generalizations regarding potential drop were not possible. Theoretical predictions of pH and potential were in reasonable agreement with experimental measurements.

276.0 Turnbull, A., D. H. Ferriss, "Mathematical modeling of the electrochemistry in corrosion fatigue cracks in steel corroding in marine environments," Corrosion Science, Vol. 27, No. 12, 1987, p. 1323-1350.

Key Words: corrosion fatigue, crack propagation, electrochemical, 3.5% NaCl, seawater

Steel(s): BS 4360:50D

Notes: A mathematical model was developed to describe mass transport and electrochemical conditions in a corrosion fatigue crack growing in steel in seawater and 3.5% NaCl solution under conditions of free corrosion or anodic polarization. At 5 C, the crack-tip pH was predicted to be between 7 and 8.5 for a wide range of conditions. Convective mixing with the bulk solution was minimized at low cyclic frequencies. The potential drop in the crack was less than 30 mV for a wide range of free corrosion conditions. Predictions of crack-tip pH and potential made using the model were in good agreement with experimental measurements.

277.0 Turnbull, A., D. H. Ferriss, "Mathematical modeling of the electrochemistry in corrosion fatigue cracks: 2. The influence of the bicarbonate/carbonate reactions of sea water on crack electrochemistry for cathodically protected structural steels," Modeling Environmental Effects on Crack Growth Processes, Metallurgical Society of AIME, Warrendale, PA, 1986, p. 3-39.

Key Words: corrosion fatigue, crack propagation, electrochemical, 3.5% NaCl, seawater, cathodic protection
Steel(s): BS 4360:50D
Notes: A mathematical model was developed to describe mass transport and electrochemical conditions in a corrosion fatigue crack growing in steel in seawater under conditions of cathodic polarization. The buffering action of seawater was simulated by including the equilibrium between bicarbonate and carbonate ions, and the deposition of calcium carbonate as argonite on the crack walls was taken into account. Results of scratching electrode tests indicate that the generation of hydrogen atoms on the external surface will control long-time crack growth rates at sufficiently negative potentials. Experimental data indicate that bulk charging may dominate at cathodic potentials more negative than about -1.0 V vs. SCE.

278.0 Turnbull, A., D. H. Ferriss, "Mathematical modelling of the electrochemistry in corrosion fatigue cracks in structural steel cathodically protected in seawater--practical and mechanistic implications," Plant Corrosion: Prediction of Materials Performance, Ellis Horwood, Chichester, UK, 1987, p. 133-166.
Key Words: corrosion fatigue, crack propagation, electrochemical, 3.5% NaCl, seawater, cathodic protection
Steel(s): BS 4360:50D
Notes: A mathematical model was developed to describe mass transport and electrochemical conditions in a corrosion fatigue crack growing in steel in seawater under conditions of cathodic polarization. The buffering action of seawater was simulated by including (1) the equilibrium between bicarbonate and carbonate ions, with the deposition of calcium carbonate as argonite, and (2) the precipitation of magnesium hydroxide. Predictions of crack-tip potential agreed well with experimental data, while predictions of crack-tip pH with and without magnesium bounded experimental data. Results of scratching electrode tests indicate that the generation of hydrogen atoms on the external surface will control long-time crack growth rates at sufficiently negative potentials. Experimental data indicate that bulk charging may dominate at cathodic potentials more negative than about -1.0 V vs. SCE.

279.0 Turnbull, A., D. H. Ferriss, "Mathematical modelling of the electrochemistry in corrosion fatigue cracks in structural steel cathodically protected in seawater," Corrosion Science, Vol. 26, No. 8, 1986, p. 601-628.
Key Words: corrosion fatigue, crack propagation, electrochemical, 3.5% NaCl, seawater, cathodic protection
Steel(s): BS 4360:50D
Notes: A mathematical model was developed to describe mass transport and electrochemical conditions in a corrosion fatigue crack growing in steel in seawater under conditions of cathodic polarization. The buffering action of seawater was simulated by including (1) the equilibrium between bicarbonate and carbonate ions, with the deposition of calcium carbonate as argonite, and (2) the precipitation of magnesium hydroxide. Predictions of crack-tip potential agreed well with experimental data, while predictions of crack-tip pH with and without magnesium bounded experimental data. Results of scratching electrode tests indicate that the generation of hydrogen atoms on the external surface will

control long-time crack growth rates at sufficiently negative potentials. Experimental data indicate that bulk charging may dominate at cathodic potentials more negative than about -1.0 V vs. SCE.

280.0 Turnbull, A., M. Saenz de Santa Maria, "Modelling of crack-tip deformation and transient electrochemical processes in relation to corrosion fatigue of steels cathodically protected in marine environments," NPL Report DMA(A) 145, April, National Physical Laboratory, Teddington, UK, 1987.

Key Words: cathodic protection, frequency, hydrogen embrittlement, crack propagation, 3.5% NaCl, seawater, tubular joint

Steel(s): BS 4360:50D

Notes: (Document No. 281 is the published, with only minor differences, version of this report.) A model was developed for the generation of hydrogen at fatigue crack tips of cathodically protected steel in marine environments. Bulk charging of the steel is predicted to be the main source of hydrogen at potentials less than approximately -0.90 V vs. SCE. Test times should be long enough to make sure that hydrogen charging reaches a steady-state level. Crack-growth data obtained from tests of fracture-mechanics specimens may not be directly relevant to crack growth in tubular joints because of differences in hydrogen concentration gradients.

281.0 Turnbull, A., M. Saenz de Santa Maria, "Predicting the kinetics of hydrogen generation at the tips of corrosion fatigue cracks," Metallurgical Transactions A, Vol. 19A, No. 7, 1988, p. 1795-1806.

Key Words: cathodic protection, frequency, hydrogen embrittlement, crack propagation, 3.5% NaCl, seawater, tubular joint

Steel(s): BS 4360:50D

Notes: A model was developed for the generation of hydrogen at fatigue crack tips of cathodically protected steel in marine environments. Bulk charging of the steel is predicted to be the main source of hydrogen at potentials less than approximately -0.90 V vs. SCE. Test times should be long enough to make sure that hydrogen charging reaches a steady-state level. Crack-growth data obtained from tests of fracture-mechanics specimens may not be directly relevant to crack growth in tubular joints because of differences in hydrogen concentration gradients.

282.0 Turnbull, A., "Progress in the understanding of the electrochemistry in cracks," Embrittlement by the Localized Crack Environment, Proceedings of an International Symposium, Metallurgical Society of AIME, Warrendale, PA, 1984, p. 3-31.

Key Words: corrosion fatigue, crack propagation, electrochemical, seawater

Steel(s): BS 4360:50D, AISI 1018, carbon steel

Notes: Published information on the electrochemistry of cracks and crevices in seawater is reviewed. Local potential in the crack or crevice is plotted as a function external potential. Local potential is also plotted as a function of local pH. The essential steps in determining the rates of electrode reactions in cracks are reviewed. For structural steels in marine environments, local pH values were in the range of 4 to 11. With cathodic protection, local pH values as high as 13 have been measured.

283.0 Turnbull, A., M. Saenz de Santa Maria, “Relative importance of crack-tip charging and bulk charging in hydrogen-assisted cracking in aqueous solutions,” Environment-Induced Cracking of Metals, EICM Proceedings, NACE, Houston, 1988, p. 193-196.

Key Words: cathodic protection, frequency, hydrogen embrittlement, crack propagation, 3.5% NaCl, seawater

Steel(s): BS 4360:50D

Notes: Bulk charging, compared with crack-tip charging, is the dominant source of hydrogen at potentials less than about -0.90 V vs. SCE and frequencies of 0.1 Hz or less. Section thickness, component configuration, and paint coatings are important factors to consider when bulk charging is dominant.

284.0 Turnbull, A., “Review of the electrochemical conditions in cracks with particular reference to corrosion fatigue of structural steels in sea water,” Reviews in Coatings and Corrosion, Vol. 5, No. 1-4, 1982, p. 43-171.

Key Words: corrosion fatigue, crack propagation, crack initiation, seawater, electrochemical

Steel(s): structural

Notes: This paper presents an extensive review of information on the electrochemical conditions in cracks. It covers experimental techniques, theoretical modelling, an assessment of the existing knowledge on iron and steel in chloride solutions, electrode reaction rates for structural steels in chloride solutions, the relation of fatigue crack initiation to localized corrosion, and the electrochemical conditions associated with propagating corrosion fatigue cracks.

285.0 Turnbull, A., M. Saenz de Santa Maria, N. D. Thomas, “Steady-state electrochemical kinetics of structural steel in simulated fatigue crack-tip environments,” Corrosion Science, Vol. 28, No. 10, 1988, p. 1029-1038.

Key Words: corrosion fatigue, 3.5% NaCl, crack propagation, electrochemical

Steel(s): BS 4360:50D

Notes: Anodic and cathodic polarization studies were conducted in de-aerated NaCl and $FeCl_2$ solutions over a range of concentrations and pH values. These environments simulated those predicted to exist at the tip of a fatigue crack in seawater under free corrosion conditions. Ferrous hydroxide precipitated as the pH of 3.5% NaCl solution containing ferrous chloride was increased and, in turn, caused a significant decrease in the anodic current density relative to that in 3.5% NaCl solution. The cathodic reduction of ferrous ions was also suppressed by the precipitate film, even at a bulk pH of 4. Thus, the precipitate film acts as both an anodic and cathodic inhibitor.

286.0 Vaessen, G. H. G., J. de Back, J. L. van Leeuwen, “Fatigue behavior of welded steel joints in air and seawater,” Journal of Petroleum Technology, Vol. 34, No. 2, Feb., 1982, p. 440-446.

Key Words: corrosion fatigue, welded joint, T joint, synthetic seawater, stress ratio, thickness, grinding, TIG dressing, cathodic protection, heat treatment, S-N curve

Steel(s): Fe 510

Notes: Fatigue tests were conducted on welded T joints in air and synthetic seawater. Stress ratios of R = -1 and R = 0.1 were used. The cyclic frequency was 2 to 5 Hz for tests in air and 0.2 Hz for tests in synthetic seawater at 20 C. Under free corrosion conditions in seawater, the fatigue life was at least two to three times shorter than that in air. In the range of 40 to 70 mm, plate thickness did not affect fatigue strength. Stress ratio had only a small effect on fatigue strength. The effect of stress ratio was increased by stress-relief heat treatment. Grinding and plasma dressing increased fatigue life, but TIG dress gave only a slight improvement in fatigue resistance. Cathodic protection was very effective at low stress ranges. Cathodic overprotection reduced fatigue strength compared with that under cathodic protection, but it was still well above that for free corrosion conditions.

287.0 van der Velden, R., H. L. Ewalds, W. A. Schultze, A. Punter, "Anomalous fatigue crack growth retardation in steels for offshore applications," Corrosion Fatigue: Mechanics, Metallurgy, Electrochemistry, and Engineering, STP 801, ASTM, Philadelphia, 1981, p. 64-80., STP 801, ASTM, Philadelphia, 1981, p. 64-80.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, frequency, crack closure

Steel(s): Fe 510, Union 47

Notes: Fatigue crack growth tests were performed on compact tension specimens in synthetic seawater at 20 C. For tests at a stress ratio of R = 0, crack growth retardation was observed at frequencies of 5 and 10 Hz but not at 2 Hz. Tests at constant stress intensity factor range were performed to determine the regime where retardation occurs at a stress ratio of R = 0.1. Wedging of corrosion products and crack closure caused the crack growth retardation. This behavior is most likely to occur at low stress ratios. The critical factor controlling retardation appeared to be the supply of dissolved oxygen, which is difficult to account for in crack growth prediction models. Threshold values of stress intensity range can be dangerously overestimated if tests are conducted in a regime where wedging occurs.

288.0 van der Wekken, C. J., J. Zuidema, "Electrochemical conditions at the crack tip and crack propagation rates during corrosion fatigue of steel in deaerated sea water," 10th International Congress on Metallic Corrosion, November 1987, Vol. 20-28, part 1-4, 1988, part 3, 1987, Key Engineering Materials, Madras, India, 1987, p. 1871-1880.

Key Words: corrosion fatigue, crack propagation, electrochemical, synthetic seawater, hydrogen embrittlement

Steel(s): St E47

Notes: Fatigue crack growth tests were conducted on compact tension specimens in deaerated synthetic seawater at 25 C. The potential and pH at the crack tip were measured for various anodic and cathodic polarization potentials. Solution mixing played a major role in establishing crack-tip pH level. Crack growth rates were related to the overpotential of hydrogen evolution at the crack tip. For both cathodic and anodic polarization, the data supported a crack growth mechanism based on hydrogen embrittlement of the crack tip region.

289.0 Van Leeuwen, J. L., J. De Back, G. H. G. Vaessen, "Technical Session 2: Constant amplitude fatigue tests on welded steel joints performed in air and seawater," L'Acier dans les Structures Marines. Conference Internationale (Paris), Report EUR 7347, 1981.

Key Words:

Steel(s):

Notes: Publication was not available.

290.0 Voronin, V. P., A. Yu. Shul'te, Yu. V. Sukhinin, "Influence of chloride-containing media on the crack resistance of 07Kh16N6 steel (translation)," Soviet Materials Science, Vol. 20, No. 2, 1984, p. 23-25.

Key Words: corrosion fatigue, crack propagation, 3% NaCl, seawater

Steel(s): 07Kh16N6

Notes: Fatigue crack growth tests were conducted in seawater and 3% NaCl solution with additions of NaF and $FeCl_3$. Low-cycle crack growth rate data are presented for cyclic loading at frequencies of 0.05 to 0.09 Hz.

291.0 Vosikovsky, O., R. Bell, D. J. Burns, U. H. Mohaupt, "Effects of cathodic protection and thickness on corrosion fatigue life of welded plate T-joints," Steel in Marine Structures (SIMS '87), Elsevier Science Publishers, Amsterdam, The Netherlands, 1987, p. 787-798.

Key Words: corrosion fatigue, crack initiation, crack propagation, welded joint, T joint, cathodic protection, synthetic seawater, thickness, S-N curve

Steel(s): LT60

Notes: Fatigue tests were conducted on welded T joints in synthetic seawater at 5 C. The stress ratio was R = 0.05, and the frequency was 0.2 Hz. The tests were conducted under conditions of free corrosion and under cathodic polarization (CP) at -0.85 or -1.05 V vs. Ag/AgCl. S-N curves were developed for crack initiation life, crack propagation life, and total life. Seawater reduced total fatigue life by a factor of two to three. CP was beneficial only at long lives (low stress ranges). Fatigue life in seawater dropped linearly with increasing plate thickness for thickness values in the range of 15 to 100 mm.

292.0 Vosikovsky, O., W. R. Tyson, "Effects of cathodic protection on fatigue life of steel welded joints in seawater," Cathodic Protection: A + or - In Corrosion Fatigue?, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada, 1986, p. 1-43.

Key Words: cathodic protection, synthetic seawater, welded joint, S-N curve, thickness, frequency, temperature

Steel(s): BS 4360:50D, Grade 490, HT80

Notes: This paper reviews results of UK, EC, CANMET, Kawasaki, UCL, and TWI fatigue research programs on welded steel joints tested in synthetic seawater at three conditions -- free corrosion (FC), adequate cathodic protection (CP) of -0.80 to -0.90 V vs. Ag/AgCl, and over CP of -1.0 to -1.1 V vs. Ag/AgCl. S-N curves were fit to data using the following equation: $\log N = K - m \log S$. Fatigue crack propagation is the major fraction of the fatigue life of welded joints, and frequencies of 1 Hz or more show little effect of environment on crack growth rate. Thus, only data from tests at frequencies of 0.1 to 0.3 Hz were analyzed. The effect of temperature is secondary. As-welded joints show little effect of stress ratio (R), and stress-relieved joints tested at positive R behave similar to as-welded joints. The effect of joint type is secondary. Environmental effects are greater for higher strength steels. Increased thickness degrades the fatigue life of welded joints; the thickness effect was accounted for using the following equation: N = NB tB/t. For FC, seawater degrades fatigue life at all stress ranges. CP has little benefit at high stress ranges but tends to improve fatigue life at low stress ranges; thus, the S-N curves are rotated counter clockwise. The benefit of CP at low stress ranges (long lives) is believed to be caused by the delayed initiation of fatigue cracks at weld-toe defects and impeded crack growth by calcareous deposits within the crack.

293.0 Vosikovsky, O., W. R. Neill, D. A. Carlyle, A. Rivard, "The effect of sea water temperature on corrosion fatigue-crack growth in structural steels," Canadian Metallurgical Quarterly, Vol. 26, No. 3, 1987, p. 251-257.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, temperature, stress ratio, cathodic protection, calcareous deposits, threshold

Steel(s): X65

Notes: Fatigue crack growth tests were conducted in synthetic seawater at 0 and 25 C. The cyclic frequency was 0.1 Hz, and the stress ratios were R = 0.05 and R = 0.5. Both free corrosion and cathodic polarization (CP) to -1.04 V vs. SCE were evaluated. Reduction in seawater temperature from 25 to 0 C significantly decreased the crack growth rate, by almost a factor of two under free corrosion conditions. With CP, the plateau crack growth rates were reduced by almost a factor of four. With CP, the formation of calcareous deposits in the crack reduced the effective stress intensity factor range and increased the apparent threshold for crack growth.

294.0 Walker, E. F., "Effects of size and geometry on the influence of cathodic protection," Cathodic Protection: A + or - In Corrosion Fatigue?, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada, 1986, p. 153-159.

Key Words: cathodic protection, crack initiation, crack propagation, tubular joint, welded joint

Steel(s): BS 4360:50D

Notes: This paper reviews the effects of size and geometry on the fatigue performance of cathodically protected structures. Other than normal size effects related to the probability of critical stress raising defects, there is no evidence of size or geometry effects on fatigue-crack initiation under conditions of cathodic protection. However, there is evidence that cathodic protection reduces the fatigue life of welded joints and tubular joints because a significant portion of that life is fatigue-crack propagation. Thin-section joints are found to have lower fatigue lives than thick-section joints.

295.0 Waterhouse, R. B., M. Takeuchi, "The influence of cathodic protection and hot-dip galvanizing on the propagation of fretting-fatigue cracks in high-strength roping steel wires in seawater," Innovation and Technology Transfer for Corrosion Control, 11th International Corrosion Congress, Vol. 3 of 5, Associazione Italiana di Metallurgia, Milan, Italy, 1990, p. 3.265-3.271.

Key Words: crack propagation, fretting, galvanizing, synthetic seawater, cathodic protection, steel ropes
Steel(s): 0.64C
Notes: Fretting fatigue tests were conducted at a stress ratio of 0.3 and a frequency of 5 Hz. The tests were on 0.64C (1770 MPa UTS) steel cold-drawn wire in synthetic seawater. Galvanizing slightly retarded fretting fatigue in air. The crack growth rate of galvanized steel in seawater was slightly below that in air and slightly below that of plain steel cathodically protected to -1.2 V vs. SCE. Applying cathodic protection to a crack that had grown 40&m did not stop crack growth.

296.0 Webster, S. E., I. M. Austen, W. J. Rudd, "Fatigue, corrosion fatigue and stress corrosion of steels for offshore structures," Report Number EUR 9460 EN, Contract Number 7210-KG/801, Commission of the European Communities, Luxembourg, 1985.
Key Words:
Steel(s):
Notes: Publication was not available.

297.0 Wildschut, H., J. de Back, W. Dortland, J. L. van Leeuwen, "Fatigue behaviour of welded joints in air and sea water," European Offshore Steels Research Seminar, The Welding Institute, Cambridge, UK, 1980, p. III/5-1 to 5-22.
Key Words: welded joint, fatigue, corrosion fatigue, synthetic seawater, TIG dressing, heat treatment, T joint, cruciform joint, stress ratio
Steel(s): Fe 510
Notes: Corrosion fatigue tests were conducted on T-shaped and cruciform welded joints in synthetic seawater at 20 C. The frequency was 0.2 Hz, and the stress ratios were R = 0 and R = -1. Seawater reduced fatigue life by a factor of two to three compared with that in air. Fatigue strength was very dependent on the local configuration of the welded joint. This paper is Ref. No. 98 in Jaske, et al. (Document No. 140). Also, see Reference 240 for additional data.

298.0 Wilson, A. D., "Corrosion fatigue crack propagation behavior of a C-Mn-Nb steel," Journal of Engineering Materials and Technology, Vol. 106, No. 3, July, 1984, p. 233-241.
Key Words: corrosion fatigue, crack propagation, frequency, 3.5% NaCl, hydrogen embrittlement
Steel(s): A633C
Notes: Fatigue crack growth tests were conducted in a 3.5% NaCl solution. The stress ratio was R = 0.1, and the cyclic frequencies were 0.1, 1, and 10 Hz. At 0.1 Hz, the crack growth rate increased by a factor of 2 to 5 compared with data from tests in air. Some increase in crack growth was also observed at 1 Hz. The acceleration of fatigue crack propagation in saltwater was attributed to a hydrogen embrittlement mechanism that caused bursts of cleavage-like transgranular fracture of ferrite grains. High levels of oxygen in the saltwater could lead to corrosion product wedging in the crack and, in turn, retardation of crack growth.

299.0 Wilson, T. J., W. D. Dover, "Corrosion fatigue of tubular welded joints," Fatigue '84, Papers Presented at the 2nd International Conference on Fatigue and Fatigue Thresholds, Vol. 3, Engineering Materials Advisory Services Ltd, Warley, England, 1984, p. 1495-1504.
Key Words: corrosion fatigue, welded joint, tubular joint, crack propagation, fracture mechanics, synthetic seawater, random loading, heat treatment, cathodic protection
Steel(s): BS 4360:50D
Notes: Fatigue tests were performed on welded tubular T joints in air at room temperature and aerated synthetic seawater at 8 C. Post weld heat treatment (PWHT) was used to stress relieve the joints. Random loading at frequencies of 0.169 and 1.69 Hz was used. One specimen was cathodically polarized to -1.05 V vs. Ag/AgCl. The evolution of crack shape during growth was measured. Crack growth rates in seawater were 2 to 6 times higher than those in air, even with cathodic protection. Fracture mechanics models were developed to predict crack growth behavior in air and seawater.

300.0 Wu, X., Z. Zhu, W. Ke, "Influence of environments and potential on fatigue behaviour of an offshore structural steel," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 125-130.
Key Words: corrosion fatigue, crack propagation, synthetic seawater, cathodic protection, temperature, stress ratio, calcareous deposits
Steel(s): A537 Cl1
Notes: Fatigue crack growth tests were performed in synthetic seawater at 0, 20, and 40 C. In addition to free corrosion conditions, tests were performed under cathodic polarization at -0.70, -0.85, -1.00, and -1.25 V vs. SCE. The cyclic frequency was 10 Hz. The stress ratios were R = 0 and R = 0.3. The optimum potential for cathodic protection was in the range of -0.85 to -0.90 V vs. SCE. Crack growth rate increase with increasing temperature in the range of 0 to 40 C. Corrosion products may retard crack growth in oxygen-rich solutions. The formation of calcareous deposits reduced the effective stress intensity factor range and, in turn, decreased the crack growth rate.

301.0 Xiaochun, Z., Z. Wenlong, "The influence of loading on conditional âK$_{th}$ measured on 4340 steel in seawater (Chinese)," J. Chinese Society of Corrosion and Protection, Vol. 9, No. 2, June, 1989, p. 143-152.
Key Words:
Steel(s):
Notes: Publication was not available.

302.0 Xing, Z., S. Huang, Y. Song, "Corrosion fatigue of 15Mn steel in artificial seawater," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 168-173.
Key Words: corrosion fatigue, crack propagation, 3.5% NaCl, crack closure, hydrogen embrittlement, frequency, heat treatment
Steel(s): 15Mn (C-Mn-Si)

Notes: Fatigue crack growth tests were performed in 3.5% NaCl solution. The cyclic frequencies were 0.5 and 5.5 Hz, while the stress ratio was R = 0.33. Five different heat treatments of the mild steel were used to evaluate the effect of microstructure. The microstructures consisted of ferrite-pearlite, ferrite with 29%, 58%, or 77% martensite, and martensite. At 5.5 Hz, crack growth rate (da/dN) decreased with increasing martensite content. The crack growth rate at 0.5 Hz was much higher than that at 5.5 Hz and was not affected by microstructure. Crack-tip hydrogen level was measured using a quick-sampling method and was found to increase with decreasing martensite fraction and increasing stress intensity factor range. The crack growth is caused by the compound effects of anodic dissolution and hydrogen embrittlement.

303.0 Xue, Y., J. Xu, H. Li, Y. Li, "Influence of plate thickness on fatigue behaviour of welded joints in air and in sea water," China Ocean Engineering, Vol. 4, No. 2, 1990, p. 179-188.

Key Words: corrosion fatigue, welded joint, S-N curve, cathodic protection, synthetic seawater, cruciform joint, thickness, fracture mechanics

Steel(s): E36-Z35

Notes: Bending fatigue tests were conducted on cruciform welded joints in air and synthetic seawater at 20 C. Plates of 16, 32, and 40 mm thickness were used to make the joints. The stress ratio was R = -1. The cyclic frequency was 1 Hz in air and 0.2 Hz in seawater. Tests were performed under free corrosion conditions and at cathodic polarization (CP) to -0.85 V vs. SCE. Fatigue strength decreased with increasing plate thickness. Different thickness corrections were proposed for each environmental condition -- air, free corrosion in seawater, and CP in seawater. Fracture mechanics is used to explain the effect of thickness on fatigue strength.

304.0 Yagi, J., S. Machida, Y. Tomita, M. Matoba, I. Soya, "Influencing factors on thickness effect of fatigue strength in as-welded joints for steel structures," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 305-313.

Key Words: fatigue, welded joint, thickness, crack initiation, crack propagation, T joint

Steel(s): EH36 Mod.

Notes: Fatigue tests were conducted on welded T joint and cruciform joint specimens with thicknesses ranging from 10 to 80 mm. Load was cycled at stress ratios in the range of R = 0 to 0.1. To properly understand the thickness effect, both crack initiation (1 to 2 mm deep crack) and propagation stages of fatigue life were measured. Most of the thickness effect was on initiation; the effect on propagation was small. The thickness effect was large when the attachment size is large compared with the size of the main plate. The thickness effect was greater for bending fatigue than for tensile fatigue and greater at 2E06 cycles than at 1E05 cycles. Results of stress analysis indicated that the thickness effect was largely accounted for by the stress concentration factor, which would mainly affect crack initiation and the development of shallow cracks (about 1 mm deep).

305.0 Yagi, J., S. Machida, Y. Tomita, M. Matoba, I. Soya, "Thickness effect criterion for fatigue strength evaluation of welded steel structures," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 315-322.

Key Words: fatigue, welded joint, thickness, crack initiation, crack propagation, T joint, grinding, weld profile

Steel(s): EH36 Mod.

Notes: Weld improvement techniques were evaluated by conducting fatigue tests of T and cruciform joints. An thickness effect evaluation criterion for design was developed. Grinding and improved weld profiles were used to improve fatigue strength; both techniques were equally effective. Weld improvement increased fatigue strength and reduced the thickness effect. The thickness effect exponent was -1/3, -1/5, or -1/10 depending on the type of joint and the mode of loading.

306.0 You-Wei, X., X. Liang-Feng, "Effect of frequency on corrosion fatigue crack growth rate below KIscc," Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III, ASME, New York, 1992.

Key Words:

Steel(s):

Notes: Paper is not in the publication.

307.0 Xia, Y.-W., L.-D. Xia, Z.-D. Chou, "Growth behavior of surface fatigue crack of a high-tensile strength steel in 3.5% NaCl solution," Proceedings of the 10th International Conference on Offshore Mechanics and Arctic Engineering, Vol. IIIB, ASME, New York, 1991, p. 371-376.

Key Words: fatigue, crack propagation, 3.5% NaCl, shallow crack

Steel(s): High-Tensile Strength Steel

Notes: Fatigue crack growth tests were conducted on specimens with a 1 mm deep by 3 mm long initial electrical-discharge-machined notch. Testing was at 5 Hz and at âK levels greater than 50 MPa m. Beach marking was used to develop data on evolution of crack shape. For the above test conditions, growth rates in 3.5% NaCl solution were similar to those in air. The growth- rate data followed a Paris law.

308.0 Zang, Q., W. Ke, Y. Zeng, Z. Yao, "Corrosion fatigue behaviour of structural steels in sea water under constant immersion & intermittent wetting," 1986 Asian Inspection, Repairs & Maintenance for Offshore Structures, Institute of Metal Research, Academia Sinica, 1986, p. 115-125.

Key Words: corrosion fatigue, S-N curve, synthetic seawater, crack propagation, pitting

Steel(s): A537 Cl1, X60

Notes: Corrosion fatigue tests were conducted in air and in synthetic seawater at 30 C. A seawater spray was used to evaluate the effect of intermittent wetting compared with full immersion. The cyclic frequency was 10 Hz, and the stress ratio was R = 0. Compared with results of tests in air, fatigue strength was degraded by immersion in seawater and degraded even more by the seawater spray. Pitting was found to play an important role in the crack initiation process. Localized anodic dissolution adjacent to inclusions lead to pitting, small cracks initiated at the base of the pits, and the small cracks linked to form a large crack that grew to failure. Crack propagation was retarded by intermittent wetting.

309.0 Zang, Q., K. Liu, W. Ke, Y. Zheng, "Crack growth rate in weld metal of homemade offshore structural steel 36Z," Acta Metallurgica Sinica (English Edition), Series B, Vol. 5, No. 2, April, 1992, p. 99-103.

Key Words: corrosion fatigue, crack propagation, welded joint, synthetic seawater, weld metal, frequency

Steel(s): E36Z, A537 Cl1

Notes: Fatigue crack growth tests were conducted on weld metal and heat-affected-zone (HAZ) metal in synthetic seawater at 20 C. Cyclic frequencies of 0.167, 1, and 10 Hz were used. At low frequency, the crack growth rate (da/dN) in weld metal and HAZ metal may be 3 to 5 and 4 to 10 times greater than that at high frequency, respectively. The data for the Chinese E36Z steel agreed reasonably well with those for the A537 steel, although at high frequencies the A537 steel had higher crack growth thresholds than the E36Z steel.

310.0 Zang, Q., K. Liu, W. Ke, Z. Zhu, "Corrosion fatigue crack growth of A357 steel and its weld metal in artificial sea water," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 131-136.

Key Words: welded joint, weld metal, corrosion fatigue, crack propagation, synthetic seawater, stress ratio, frequency, residual stress

Steel(s): A537 Cl1

Notes: Fatigue crack growth tests were conducted on base metal and weld metal in synthetic seawater at 20 C. Cyclic frequencies of 0.167, 1, and 10 Hz and stress ratios of R = 0, R = 0.1, R = 0.3, and R = 0.5 were used. The crack growth rate (da/dN) in seawater increased up to 10 times as the frequency decreased from 10 to 0.167 Hz. The da/dN values at 10 Hz in seawater were similar to those in air. The crack growth threshold stress intensity factor range decreased as the stress ratio increased.

311.0 Zang, Q., K. Liu, W. Ke, Y. Zheng, "Effect of intermittent overload on corrosion fatigue crack growth of A537 offshore structural steel (Chinese)," Journal of Chinese Society of Corrosion and Protection, Vol., 9, No. 3, 1989, p. 169-175.

Key Words: corrosion fatigue, crack propagation, 3.5% NaCl

Steel(s): A537 Cl1

Notes: The effect of intermittent overloads was evaluated in air and 3.5% NaCl solution at 20 C. Periodic overloads of 1.5 to 2 times the peak cyclic load retarded crack growth in both air and saltwater, but the effect was much smaller in saltwater than in air. Fractographic examinations revealed evidence of high plastic strain and secondary cracking in the overload regions.

311.5 Zang, Q., X. Zhou, K. Liu, W. Ke, "Role of pits in corrosion fatigue of offshore structural steel," Chin. J. Met. Sci. Technol., Vol. 8, 1992, p. 123-126.

Key Words: corrosion fatigue, pitting, S-N curve, 3.5% NaCl, crack propagation

Steel(s): A537 Cl1

Notes: Corrosion fatigue tests were conducted in air and 3.5% NaCl solution. A saltwater spray was used to evaluate the effect of intermittent wetting compared with full immersion. Pitting was found to play an important role in the crack initiation process. The role of pitting in crack development is discussed. Crack propagation was retarded by intermittent wetting.

312.0 Zhang, W., X. Zhu, L. Su, "Effect of cathodic protection on fracture behaviour of low-alloy steels in seawater (translation)," Acta Metallurgica Sinica, Series A, Vol. 2A, No. 1, Jan., 1989, p. 57-62.

Key Words:

Steel(s):

Notes: Publication was not available.

313.0 Zhang, X. D., Y. J. Song, "Crack arrest behaviour and a proposed model," International Journal of Fatigue, Vol. 13, No. 5, Sept., 1991, p. 411-416.

Key Words: corrosion fatigue, 3.5% NaCl, crack propagation, hydrogen embrittlement, crack closure

Steel(s): AISI 4135, AISI 4340

Notes: Fatigue crack growth tests were conducted in a 3.5% NaCl spray (intermittent wetting) and in a 3.5% NaCl solution (immersion). Cyclic frequencies of 0.1 and 5.5 Hz were used. Crack arrest tendencies were observed for tests in the saltwater spray but not for tests in air or in the saltwater solution. The arrest was caused by crack closure because of thick oxide deposits in the cracks. Based on fractographic examinations by means of scanning electron microscopy (SEM) and theoretical analysis, the dominant crack growth mechanism was anodic dissolution in the saltspray and hydrogen embrittlement in the saltwater.

314.0 Zheng, W., et al., "Effect of strength on corrosion fatigue behaviour of low alloy steels in artificial seawater (in Chinese)," Acta Metallurgica Sinica, Vol. 22, No. 3, June, 1986, p. A275-A282.

Key Words: corrosion fatigue, crack propagation, synthetic seawater, heat treatment

Steel(s): 30CrNi3Mo, 40CrNiMo

Notes: Stress corrosion cracking (SCC) and fatigue crack growth tests of low-alloy steels heat treated to different strength levels were conducted in synthetic seawater. The fatigue testing was at a stress ratio of R = 0.8 and a frequency of 0.3 Hz. Plots of crack velocity (da/dt) versus maximum stress intensity factor were developed from the SCC data, and plots of crack growth rate (da/dN) versus stress intensity factor range were developed from the fatigue crack growth data. Both SCC susceptibility and da/dN increased as yield strength increased.

315.0 Zheng, W., A. Cai, X. Zhu, "The resistance of offshore platform joint materials to stress corrosion cracking and corrosion fatigue," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 187-192.

Key Words: corrosion fatigue, welded joint, crack propagation, synthetic seawater, cathodic protection, weld metal

Steel(s): A537, A131, A36, Welton60, HY100

Notes: Fatigue crack growth tests were conducted in synthetic seawater under free corrosion conditions and with cathodic polarization (CP) to -0.85 V vs. SCE. The cyclic frequency was 0.3 Hz, and the stress ratio was R = 0.6 to 0.7. Data were developed for base metal, weld metal, and heat-affected-zone (HAZ) metal. The weld metal and HAZ metal were more resistant to fatigue crack growth that base metal. CP was beneficial in the near-threshold region of crack growth.

316.0 Zhou, X., W. Ke, Q. Zang, "A statistical study of pit-associated cracking under fatigue loading," Corrosion and Corrosion Control for Offshore and Marine Construction, International Academic Publishers, Beijing, China, 1988, p. 156-161.

Key Words: corrosion fatigue, pitting, 3.5% NaCl, crack initiation

Steel(s): A537 Cl1

Notes: Corrosion fatigue tests were conducted with intermittent wetting by a 3.5% NaCl solution. The stress ratio was R = 0. Pits and pit-associated cracks were measured using replicas and quantitative metallography. Pit size, depth, out-of-roundness, and other parameters were statistically characterized. The ratio of pit width to depth played an important role in crack initiation. A stochastic evolutionary model was developed to simulate the interaction and coalescence of the small, closely located cracks that initiate at pits. Experimental data agree well with predictions.

317.0 Zwaans, M. H. J. M., P. A. M. Jonkers, J. L. Overbeeke, "Endurance of a welded joint under two-types of random loading in air and seawater," L'Acier dans les Structures Marines. Conference Internationale (Session Technique 1-5.), Report EUR 7347, ST 7. 3, Commission of the European Communities, Luxembourg, 1981.

Key Words:

Steel(s):

Notes: Publication was not available. See Reference 240 for a review of the data.

APPENDIX C

LIST OF STEEL TYPES

The following list provides the names used for various types of steel indexed in the literature review. These are the names that were entered in the Type of Steel field of the database, so they can be used to search the database for information on a specific steel.

0.64C
07Kh16N6
09G2S
10KhSND
12KhN4DMF
15G2
15G2F
15G2FB
15KhN5DMF
15Mn
17-4 PH
2-1/4Cr-1Mo
3.5NiCrMoV
30CrNi3Mo
30KhMA
30KhN3A
40CrNiMo
45
835M30
A131
A283 70a
A283C
A36
A372 Cl6
A508 Cl2a
A514F
A53
A537
A537 Cl1
A537DQ
A541 Cl6
A633C
A707
A710
ABS DH32
ABS DH36
ABS EH36
AC70
AISI 1012
AISI 1018
AISI 1035
AISI 1080
AISI 4130
AISI 4135
AISI 4140
AISI 4340
anti-weather A
anti-weather B
API 2H Grade 42
API 5AC C-90
API 5LUX-80
API 5LX-52
B50XK
B80RK
BethStar 80
BIS 812 EMA
BS 4360:50C
BS 4360:50D (Fe 510)
BS 4360:50E
BS 970:722M24
BS 970:817M40
BS 970:835M30
BS 970:976M33
C-Mn
C-Mn-Ni
carbon steel
CrNi
CSA G40.21M 350 WT
DP3
E355
E355 KT
E36-Z35
E36Z
E460
E690
EH36
EH36 Mod.
EN16
EN24
Fe 410

Fe 510 (BS 4360:50D)
Galvalume
Grade 350
Grade 490
GS8Mn7 cast steel
High-Tensile Strength Steel
HS60
HSLA 80
HSLA steel
HT100
HT130
HT50
HT50-TMCP
HT50CR
HT60
HT62
HT70
HT80
HT80B
HY100
HY130
HY80
KD36
LT60
MACS
Medium-Tensile Strength Steel
Mil S-24645
Ni-Cr-Mo
OS45
Q1N
QT108
QT80
RQT501
RQT701
SAR 60
SiMn
SM41
SM50
SM50B
SM53B
SS41
St 38 b2
St 41U5
St 52
St 52-3
St 52-3N
St 52E
St E47
structural
SUP10M
SUP9
SUS304
SUS316
U80
Union 47 (A533B)
Welton60
X52
X60
X65
X70
YS36
YS46
YS70

APPENDIX B

LIST OF KEY WORDS

The following list provides the key words used in the literature review. These key words were entered in the Key Words field of the database, so they can be used to search the database for information on a specific topic.

3% NaCl
3.2% NaCl
3.5% NaCl
acoustic emission
algae
bacteria
bending fatigue
brine
buckling
calcareous deposits
cathodic protection
constant extension rate
corrosion damage
corrosion fatigue
crack closure
crack initiation
crack propagation
crack shape
cruciform joint
cycle counting
dissolved oxygen
electrochemical
embrittlement
fatigue
fatigue limit
fracture
fracture mechanics
frequency
fretting
galvanizing
grinding
hammer peening
heat treatment
high-cycle fatigue
hydrogen embrittlement
hydrogen sulfide
inclusions
K joint
lamellar tearing
leaf spring
life prediction model
low-cycle fatigue
marine environments
Miner's rule
mixed mode
multiple cracks
multiple specimens
nitriding
notch
offshore service
pipe-plate joint
pitting
potential drop measurement
random loading
residual stress
rotating bending
S-N curve
scanning vibrating electrode
scraping electrode
seawater
shallow crack
short cracks
shot peening
spectrum loading
steel ropes
stiffness
strain cycling
stress concentration factor
stress ratio
stress relief
surface finish
synthetic seawater
T joint
temperature
thickness
threshold
TIG dressing
TMCP steels
tubular joint
water

weld defects
weld metal
weld profile
weldability
welded joint

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SSC Report Number	Report Bibliography
SSC 411	Evaluation of Effect of Construction Tolerances on Vessel Strength D. Bruchman, D. Kihl, J. Adamchak 2000
SSC 410	Fatigue of Aluminum Structural Weldments R. Kramer, P. Fontneau 2000
SSC 409	Guide to Damage Tolerance Analysis of Marine Structures I. F. Glen, A. Dinovitzer, L. Malik, R. I. Basu, R. Yee 2000
SSC 408	Detection Probability Assessment of Visual Inspection of Ships, L .A. Demsetz, J. Cabrera 1999
SSC 407	Optimal Strategies for Inspection of Ships for Fatigue and Corrosion Damage, K. Ma, I. R. Orisamolu, R. G. Bea, 1999
SSC 406	Sea Operational Profile for Structural Reliability Assessments, I. F. Glenn, R. B. Paterson, L. Luznik, 1999
SSC 405	Fatigue Resistant Detail Design Guide for Ship Structures, I. F. Glenn, A. Dinovitzer, R. B. Paterson, L. Luznik, C. Bayley, 1999
SSC 404	Ship Structural Integrity Information System (SSIS) Phase III: Ship Quality Information System, H. P. Reeve, R. G. Bea, 1998
SSC 403	Design Guide for Marine Applications of Composites, E. Greene, 1997
SSC 402	Guide to Damage Tolerance Analysis of Marine Structures, R. D. Yee, L. Malik, R. Basu, K. Kirkhope, 1997
SSC 401	State of the Art in Hull Reponse Monitoring Systems, S. B. Slaughter, Dr. M. C. Cheung, D. Sucharski, B. Cowper, 1997
SSC 400	Weld Detail Fatigue Life Improvement Techniques, K. J. Kirkhope, R. Bell, L. Caron, R. I. Basu, 1997