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Fatigue Strength Analysis of Low Carbon Steel under Corrosive and Non-Corrosive Environment

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ABSTRACT

Failure due to cyclic loads in corrosive atmosphere is important in mining equipment's, underwater pipeline, aerospace components and much more. Low carbon steel is selected as the material. An experimental study is provided on the impact of salinity and time reliance on corrosion fatigue life. The fatigue corrosion testing is done by varying the concentration of saline environment. The Immersion time testing is done under 3.5% NaCl Aqueous solution with different Pre-corrosion times. For both tests the numbers of cycles to failure were observed around 10^4 cycles. Testing is done under constant amplitude by applying desired force in axial testing samples. The test environments were in-situ corrosive environment with 0 %, 0.7%, 1.4%, 2.1%, 2.8% and 3.5 % NaCl aqueous solution concentrations. The pre-corrosion time period of Immersion test was 1, 2, 4, 7, 14, 21 and 30 days. The research seeks to understand how the salinity of corrosive medium and pre-corrosion duration impacts the fatigue life and premature failure of the selected material.

Keywords – Failure, Fatigue, Fatigue life, Precorrosion, Salinity

1. INTRODUCTION

Corrosion along with fatigue loads is influenced by environmental conditions and loading levels. The effect of fatigue loads acting in corrosive environment has dependence on structural state of material under micro level, the applied level of stress intensity, working environment and test frequency. The failure mechanism for mechanical components running under saline atmosphere subjected to cyclic loads, for example impeller of pumps, rotating shafts in marine conditions, underwater pipelines is Corrosion fatigue. Delamination of coating and material erosion arising from corrosion is often observed in equipment's working in marine atmosphere. This influences the cross-sectional properties of components, surface roughness values, irregularities in surfaces, corrosion pits, and material strength degradation.

The main cause of decayed integrity of structural components is Corrosion. The major effects caused by this include slimming of thickness, surface discrepancies and focusing of stress in one area. Pitting corrosion is the main concern in this regard. The electrochemical effects also influence the life of component in a negative way. The focused stresses will promote and starts the cracking of member in the area where stresses are concentrated. Crack initiation will accelerate due to these effects. When stress is applied continuously in corrosive atmosphere it is defined as stress corrosion cracking (SCC).

Studies continue to emphasize the importance of further investigation of corrosion fatigue characteristics due to the ingrain behavior of materials to corrosion. In the high-cycle fatigue regime, the impact of salinity on the life of component under fatigue load in connection with crack formation and fracture propagation is not much discussed in literary works. The research seeks to know how the corrosive medium's salinity impacts the material's fatigue life. The effect real time corrosion and time period during which corrosion takes place on the fatigue life are investigated.

The various factors which impact the fatigue life of a material subjected to corrosion in cyclic loads include corrosion type, atmospheric parameters, corrosion rate and metallic composition. Laboratory testing of corroded samples is generally common for simulating the life of metals subjected to fatigue corrosion. And various models and relations are developed for the fatigue life calculations. The intention of this work is to understand which relation will give accurate values of fatigue life. Faster evaluation of fatigue life of corroded metals requires easier methodologies. To meet this need, this work inspects the possibilities of a method to calculate the corroded material's fatigue life.

2. MATERIAL USED IN TESTING

2.1 Specification of Material Used

The experimented material is steel with having low carbon content (LCS). Because of its low cost and high strength, it is used in almost all structural and mechanical components. In these applications, the material is subjected to static as well as dynamic loads

Table 1: Chemical properties of used carbon steel (%)

C	Mn	Si	P	S	Cr	Ni	Mo	Al
0.2	1.32	0.34	0.009	0.002	0.01	0.03	0.01	0.042

Table 2: Mechanical Attributes of used carbon steel

Young's Modulus [GPa]	Upper Yield Point [MPa]	Lower Yield Point [MPa]	Ultimate Stress [MPa]	Yield Point Extension [mm]	Strain Hardening Exponent
192.5	379.74	386.346	560	0.449	0.248

3. TESTING CONDITIONS

3.1 Specimens and testing condition

3.1.1 Pre-Corrosion Testing

Fatigues testing of samples are carried out in non-corrosive atmosphere with pre-corroded samples. Pre-corrosion times of samples were 1,2,4,7,14,21 and 30 days. All the samples were pre-corroded at aqueous sodium chloride solution with saline concentration of 3.5%. Pre-corrosion testing specimen consists of 6 mm diameter circular cross section (*Fig 1*).

ASTM E466 standard have been used to design the dimensions of samples. The gauge area roughness values are between Ra=0.1 micron and Ra=0.2 microns. Pre-corrosion of specimen is done by dipping it in 3.5% saline aqueous sodium chloride solution for the desired period of time.

3.1.2 Real Time Corrosion Fatigue Testing

Fatigue test in real time corrosive atmosphere were carried at room temperature and in various salinities of corrosive aqueous solution, such as 0 %, 0.7%, 1.4%, 2.1%, 2.8% and 3.5%. All the experiments were conducted using 6 mm gauge diameter circular cross section samples at various saline concentration of aqueous sodium chloride solution. ASTM E466 standard was used in designing the sample geometry. The gauge area roughness values are between Ra=0.1 micron and Ra=0.2 microns.

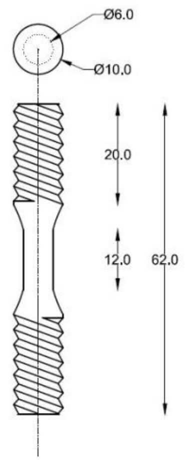


Fig 1: Geometry of pre-corrosion samples

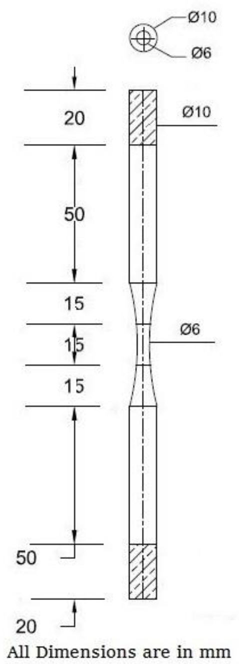


Fig 2: Geometry for real time corrosion fatigue testing

3.2 Corrosion Chamber

An Atmospheric chamber made of Polyethylene terephthalate was custom manufactured for providing a bath of corrosive fluid around the specimen. A leak proof joint is made between the chamber and test sample using silicone sealant. Extreme care was taken while testing the sample to avoid leaking of corrosive fluid.

Fig 3: Corrosion chamber mounted in testing machine

4. EXPERIMENTAL SETUP

All Fatigue tests were conducted in Biss 25KN servo-hydraulic controlled Fatigue testing machine. The specimen is subjected to axial loads with operating mode as load control. All the attachments are made compatible with the machine. The specimen with external threads on both ends is mounted on the machine using fixture having internal thread. The chamber allows continuous flow of corrosive fluid using a closed pipe circuit. The chamber has an inlet port and outlet port to allow flow of fluid. A water pump with nominal flow rate of 800 L/hr drives the fluid through the pipe circuit. The diameter of pipeline used is 9 mm. A storage tank of 60 L capacity is used for storing the fluid. In-order to oxygenate the corrosive fluid an air pump with nominal capability 150 L/hr is used.

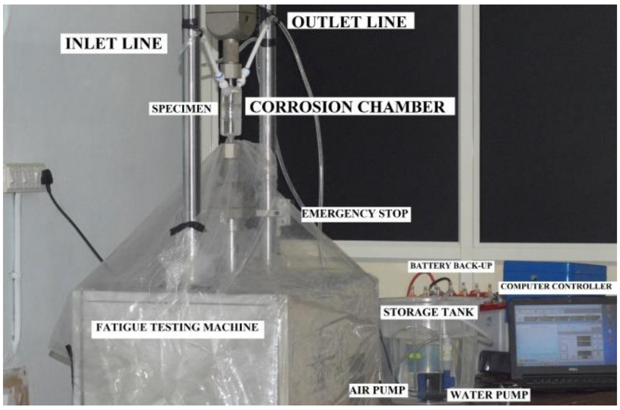


Fig 4: Experimental setup

5. EXPERIMENTAL RESULTS AND DISCUSSION

The experiment was conducted by loading the samples by applying force in KN which corresponds to the desired stress values. Specimens are subjected to axial loads with a test frequency of 3Hz for all the experiments. The loads that are applied in the experiment are listed below. The room temperature at which all tests conducted was 25° C.

Stress amplitude: σ_A =220 MPa

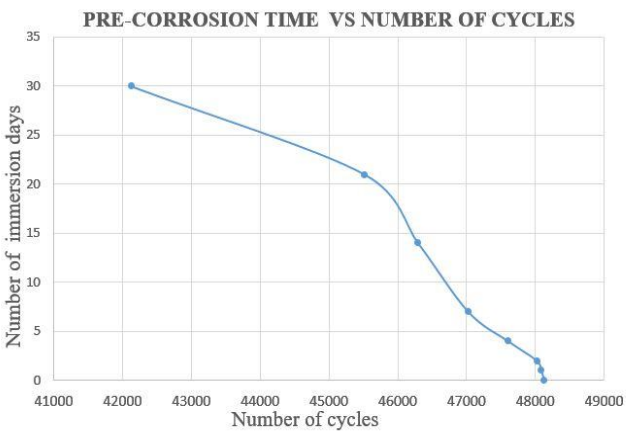
Mean stress: σ_m =220 MPa

5.1 Pre-Corrosion Fatigue Testing

The precorroded sample are tested at different corrosion times such as 1,2,4,7,14,21& 30 days.

Table 3: Pre-corrosion time v/s Fatigue life

Pre-corrosion time	Fatigue life
0 day	48125
1 day	48084
2 day	48021
4 day	47602
7 day	47021
14 day	46291
21 day	45513
30 day	42118



Graph 1: Pre-corrosion time v/s No: of cycle

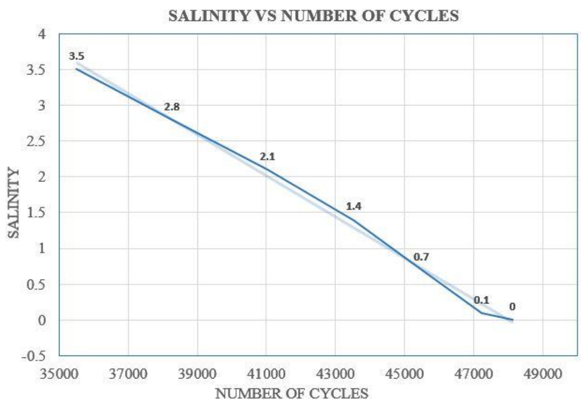
5.2 Real Time Corrosion Fatigue Testing

The samples are tested at various levels of salinity. The concentration (w/v) of the used NaCl aqueous solution are 0 %, 0.7%, 1.4%, 2.1%, 2.8% and 3.5%.

To investigate the stress effects under various saline concentrations a study on different correlations have been considered. Since loading forces in experiment imparts mainly elastic effects in the material, stress life analysis is used to determine the results.

Table 4: Fatigue life v/s Salinity

Environment	Fatigue life
Non-corrosive	48116
0.1 % NaCl	47225
0.7 % NaCl	45484
1.4 % NaCl	43523
2.1 % NaCl	41030
2.8 % NaCl	38265
3.5 % NaCl	35509



Graph 2: Salinity v/s No: of cycles

The relations perceived in stress models are:

1. Goodman relation: $\frac{\sigma_A}{\sigma_{eq}} + \frac{\sigma_m}{\sigma_U} = \mathbf{1}$ (1)

2. Walker relation: $\boldsymbol{\sigma_{eq}} = \boldsymbol{\sigma_A}\left(\frac{2}{1-R}\right)^{\gamma}$ (2)

where:

σ_A is the stress amplitude, σ_m is the mean stress, σ_{eq} is the equivalent stress, σ_y the yield point stress, σ_u is the ultimate strength, R is the stress ratio, 'γ' is a material parameter, its used to accurately predict data obtained from experiments using equations.

Using Goodman relation,
The equivalent stress is obtained as σ_{eq} =362 MPa and Number of cycles to failure is 48870.

Using Walker relation,

The equivalent stress is obtained as σ_{eq}=362.38 MPa and Number of cycles to failure is 48275.

6. FATIGUE FRACTURE MECHANISMS

Fatigue cracks generally originate from the area of stress concentration. Formation of fatigue crack is due to the localized corrosion pits. Micro cracks will germinate from the corrosion pit surface and propagate along grain boundaries when the corrosion pit grows to a certain extent. When the micro sized cracks created due to corrosion under applied stress reach a critical length the growth of crack across trans-granular direction will start. Microstructural analysis of the specimen section demonstrates that cracks initiate and propagate from the bottom of the corrosion pit.

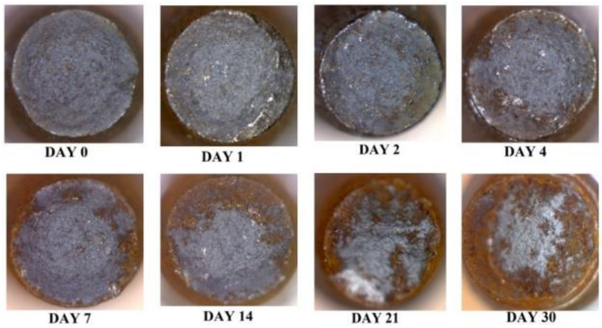


Fig 5: Fracture morphologies specimens after precorrosion testing.

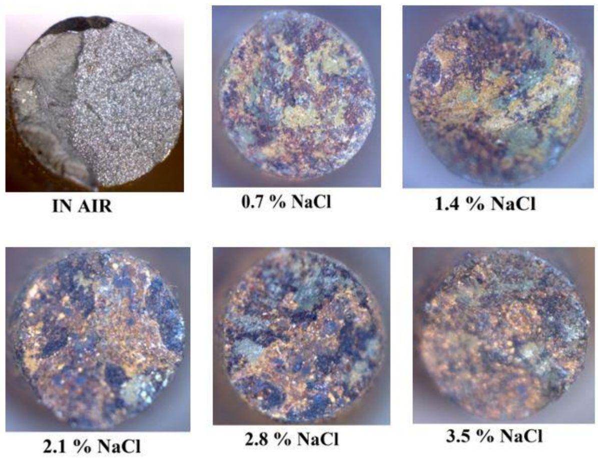
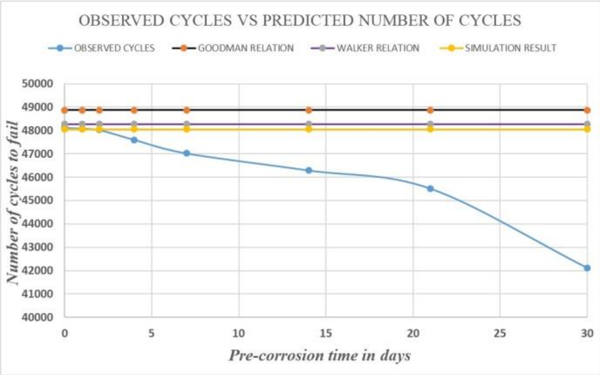
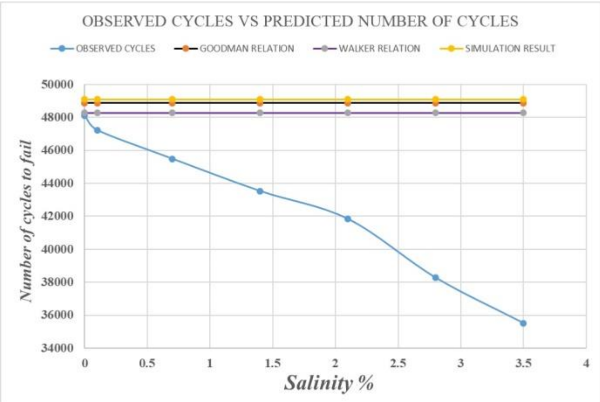


Fig 6: fracture morphologies specimen after real time corrosion fatigue testing.

Goodman and walker Relations are used to predict the material's fatigue life relative to the loads applied. Applied mean and alternating stress have been used to assess the number of experimental cycles that will fail the specimens. For each method, the estimated number of cycles was plotted against the observed number of experimental cycles.



Graph 3: Precorrosion testing results



Graph 4: Real time corrosion testing results

7. CONCLUSION

When the salinity changes from 0 to 3.5% a reduction of 26.2% in fatigue life is observed in real time corrosion fatigue testing. In immersion testing a drop of 12.48% is noticed in fatigue life when the duration of precorrosion changes from 0 days to 30 days.

When there is an increment in the period of precorrosion, the corrosion pits get larger and deeper. Also, the fatigue life of the material is significantly reduced. Corrosion pits acts as crack formation sites and the time for crack formation phase is reduced significantly when compared with virgin specimens.

In corrosion fatigue multiple crack formation sites could be observed. These multiple crack initiation sites in corrosion fatigue drastically reduces the fatigue life of material. In this experimental condition, the equation give accurate results when mathematical parameter used in the relation, 'γ' becomes 0.72. It can be inferred that corrosion fatigue is more dangerous than pre-corrosion fatigue.

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