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Accelerated Corrosion Fatigue Studies on SA 333 Gr.6 Carbon Steel

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ABSTRACT: Corrosion fatigue crack growth study was carried out on Eccentrically-loaded Single Edge notch Tension [ESE(T)] specimen made of SA 333 Gr.6 carbon steel. The corrosion process was accelerated by applying a direct current of 0.3 A using an external current source. The experiment was carried out under constant amplitude cyclic loading at the test frequency of 0.5 Hz and stress ratio of 0.1 by using a ± 250 kN capacity fatigue rated Universal Testing Machine. The crack initiation and growth were continuously monitored using a digital camera and images were recorded at regular intervals of fatigue cycles. The test was terminated when the crack growth in the specimen became unstable and the uncracked portion of the specimen was insufficient to take further load. ASTM E 647-13a and ASTM E 1820-13 standards were followed in fabricating the test specimen and carrying out the experiment respectively. The details of the experimental study carried out and the fatigue crack growth data obtained from the experiment have been discussed in this paper. The fatigue crack growth curve obtained from experiment and analytical results have been compared.

KEYWORDS: Fatigue damage, fatigue crack growth, corrosion fatigue, SA 333 Gr.6 carbon steel, ESE(T) specimen.

I. INTRODUCTION

Corrosion fatigue (CF) refers to the phenomenon of cracking in materials under the combined action of fatigue loading and corrosive environment. Corrosion fatigue is generally recognized as an important phenomenon that can lead to unexpected cracking behaviour and failure of structures under certain conditions. Such conditions depend on the specific combination of material, cyclic loading and environment of concern which in turn represent the metallurgical, mechanical and electrochemical components of the corrosion-fatigue problem. This phenomenon occurs in many engineering alloys over a broad range of environments and has been recognised as an important cause of failure in engineering structures. Because of the synergistic effect of cyclic loading and deleterious environment, corrosion fatigue can lead to far greater degradation of material load carrying capacity with either effect acting alone or with expectations based on linear superposition of the individual effects [1]. That is, repeated stressing accelerates the corrosive action and corrosive action accelerates the mechanical fatigue mechanisms. Because of the large number of variables involved and the complexity of the process, CF modelling is difficult; there have been continuous attempts in this direction. Generally, CF damage is considerable at lower frequencies of 0.5 Hz and below. Also, CF experimental investigations have to be carried out at the same frequency at which the environment acts in actual conditions.

Raghava et al. carried out fatigue crack growth studies on Eccentrically-loaded Single Edge notch Tension [ESE(T)] specimens made of IS 2062 steel in air environment and in corrosion environment under constant amplitude cyclic loading [2]. The corrosion process was accelerated by applying constant direct current (DC) at different levels namely 0.1 A, 0.2 A, 0.3 A and 0.6 A. It was found that a value in the range of 0.1 A to 0.2 A gives good corrosion fatigue crack growth results and the corrosion fatigue process was more pronounced than only the general corrosion of the

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specimen during the experiment. Significant increase in crack growth rate was observed with the increase of corrosion current. Lin Weng et al. conducted corrosion fatigue crack growth (CFCG) experiments on AISI 4340 high strength steel using pre-cracked compact tension specimens in dry air, distilled water, and 3.5% NaCl aqueous solution at different R -ratios (where R is the ratio of the minimum load over the maximum load in a loading cycle) and different loading frequencies [3]. The material displayed typical Type B CFCG behaviour: significant environmental effect when the maximum stress intensity factor is above K_{ISCC} (the threshold stress intensity for stress corrosion cracking) and minimal environmental effect when the applied load is below the threshold value or above a large stress intensity factor. Horstmann et al. studied the influence of environment and specimen geometry on fatigue crack growth in offshore structural steels with differing strength levels [4]. The studies were carried out in air and in synthetic sea water under freely corroding and cathodically polarized conditions. The effect of frequency under cathodic polarization was found to be more pronounced in an aggressive environment. Fatigue crack growth (FCG) behaviour of two varieties of high strength low-alloy (HSLA) steels used in naval structural applications was evaluated in air and 3.5% NaCl solution by Sivaprasad et al. [5]. The effect of stress ratio on air fatigue and corrosion fatigue crack growth (CFCG) behaviour was rationalised by the concept of crack closure and the effect of cyclic frequency on corrosion fatigue behaviour was also examined. Chinnaiah and Raghu Prakash conducted CFCG studies on Ni-Cr-Mn steel under 3.5% saturated NaCl aqueous environment [6]. An increase in the crack growth rate and reduction in the threshold stress intensity for the material was observed in aqueous environment in comparison with that under laboratory air environment.

In the present study, fatigue crack growth experiment was carried out on SA 333 Gr.6 carbon steel under 3.5% NaCl aqueous environment. The corrosion process was accelerated by applying constant DC of 0.3 A; constant amplitude cyclic loading was applied by using a ± 250 kN capacity fatigue rated Universal Testing Machine (UTM). The test frequency was 0.5 Hz and the stress ratio was 0.1. Accelerated corrosion test method was preferred in order to reduce the time scale which yields data beneficial in establishing the fatigue life of structures in an aggressive environment. Details of the experimental study carried out and the fatigue crack growth data obtained during the experiment has been discussed. Based on this study, fatigue crack growth constants C and m were obtained for corrosion current of 0.3 A. The present study was taken up with an objective of evolving a procedure for accelerated corrosion fatigue (CF) studies in the laboratory, which would give meaningful results of CF damage in actual conditions.

II. MATERIAL PROPERTIES

The steel used in the present study is SA 333 Gr.6 carbon steel which is used in the fabrication of primary heat transfer (PHT) piping of the nuclear power plants. These components operate in the temperature range of 28 - 300°C. Chemical analysis and tension tests were carried out on samples taken from a pipe having length 525 mm, external diameter 415 mm and wall thickness 32 mm of the steel to evaluate chemical composition and mechanical properties. Table I gives the chemical composition of the steel and the specified values of various constituents as per ASTM A 333/A 333M - 13 [7].

Mechanical properties of the material were determined by carrying out tension tests as per ASTM E8/E8M - 13a [8]. Three tension test specimens were tested. The tests were carried out by using a ± 250 kN capacity UTM. An extensometer of 50 mm gauge length was used to measure the elongation during testing. Table II gives the mechanical properties of the steel, average values based on the three tests, and the specified values as per ASTM A 333/A 333M - 13. The average yield strength and ultimate tensile strength of the material were found to be 310 MPa and 465 MPa respectively. The Young's Modulus of the material was 205 GPa.

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TABLE I. CHEMICAL COMPOSITION OF THE STEEL

Element	Tested (per cent)	Specified (per cent) ASTM A333
Carbon	0.124	0.3 max
Manganese	0.919	0.29 - 1.06
Phosphorus	0.003	0.025 max
Sulphur	0.001	0.025 max
Silicon	0.314	0.10 min

TABLE II. MECHANICAL PROPERTIES OF THE STEEL

Properties	Tested	Specified ASTM A333 (min)
Yield strength, σ_y (MPa)	310	240
Ultimate strength , σ_u (MPa)	465	415
Modulus of Elasticity , E (GPa)	205	-

III. EXPERIMENTAL STUDIES

A. Specimen Details

ASTM E647 – 13a [9] recommends three types of specimens namely compact specimen C(T), middle tension specimen M(T) and eccentrically loaded single edge notch tension specimen ESE(T). ESE(T) specimen is chosen for the present study. ESE(T) specimen exhibits advantages over other two specimen types. The extended design of ESE(T) specimen gives additional working space, for example, for any instrumentation required, fixing environment chamber etc. Figure 1 shows the typical ESE(T) specimen configuration as per ASTM E647 - 13a. Where W is the width of the specimen, B is the thickness of the specimen, a_n is the initial notch length and a is the crack length. It is recommended that the ESE(T) specimen thickness be in the range $W/20 \leq B \leq W/4$.

The ESE(T) specimen was fabricated from pipe specimen having length 525 mm, outer diameter 415 mm and wall thickness 32 mm. From this pipe, a rectangular plate of dimensions 525 mm $\times$ 85 mm $\times$ 20 mm was cut along the longitudinal direction and taken out. This plate was further sliced into two along the length direction to get two plates of 10 mm thickness. These plates were then machined to get rectangular plates of dimensions 277.5 mm $\times$ 75 mm $\times$ 8 mm. A straight through notch of length 11.25 mm at the mid height of the specimen was made by wire cutting. Details of the ESE(T) specimen are shown in Fig.1.

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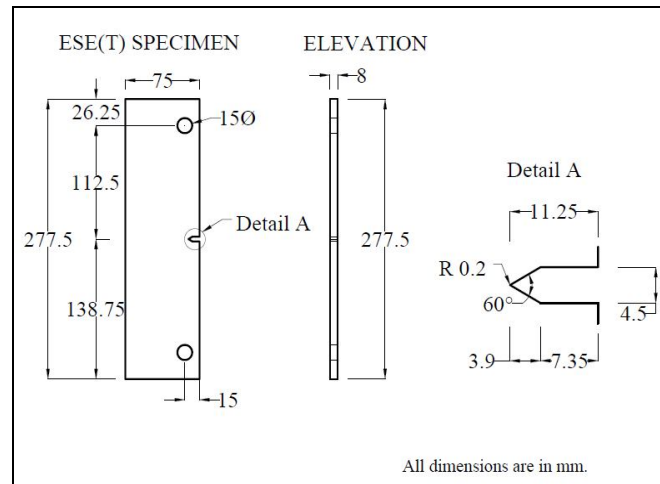


Fig. 1 ESE(T) specimen dimensions

B. Test Details

The FCG test was carried out on ESE(T) specimen by using a servo-hydraulic fatigue rated UTM of capacity ± 250 kN. Constant amplitude sinusoidal cyclic loading was applied. A corrosion chamber made of 'Perspex' sheet was fixed to the test specimen at the notch portion; this chamber contained 3.5% sodium chloride solution, which acted as the corrosive environment. The depth of the solution was 45 mm. The corrosion process was accelerated by increasing the corrosion current, using an external current source. Figure 2 shows the schematic representation of accelerated corrosion fatigue experimental set-up. Direct Current (DC) was supplied from an external current source which passed through the cathode (a piece of stainless steel kept in the corrosion chamber), electrolyte (3.5% sodium chloride solution) and anode (test specimen in this case). The test was conducted by applying corrosion current of 0.3 A. The corrosion current density was calculated as per ASTM G 102 - 2010 [10] and the value of corrosion current density was $4016.06 \mu\text{A}/\text{cm}^2$.

$$i_{cor} = \frac{I_{cor}}{A} \quad (1)$$

where

i_{cor} = corrosion current density, $\mu\text{A}/\text{cm}^2$
 I_{cor} = total anodic current, μA
 A = exposed specimen area, cm^2

The load applied during the FCG tests was decided based on the P_m value, recommended in ASTM E 1820 - 13 [11] and it is given as follows:

$$P_m = \frac{0.4Bb_0^2\sigma_y}{2W + a_0} \quad (2)$$

where

B = thickness of the specimen, mm
 W = width of the specimen, mm
 a_0 = initial notch length, mm
 b_0 = uncracked ligament = $W - a_0$, mm

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σ_y = yield strength of the material, MPa

As per ASTM E647 - 13a, in order for results to be valid, it is required that the specimen be predominantly elastic at all values of applied force [9]. For the ESE(T) specimen the following is required:

$$(W - a) \geq \left(\frac{4}{\Pi} \right) \left(\frac{K_{max}}{\sigma_y} \right)^2 \quad (3)$$

where

$W - a$ = uncracked ligament, mm

σ_{ys} = yield strength, MPa

K_{max} = maximum SIF, MPa $\sqrt{\text{mm}}$

The test was conducted at a frequency of 0.5 Hz and stress ratio of 0.1. Maximum and minimum load values of 15 kN and 1.5 kN were maintained. Table III gives the details of FCG tests. Figure 3 shows the close-up view of experimental set-up. Number of cycles for crack initiation was recorded. Crack growth was continuously monitored using a digital camera and images were recorded at regular intervals of fatigue cycles. The experiment was continued till crack growth in the specimen became unstable. Figure 4 shows the close-up view of specimen after failure.

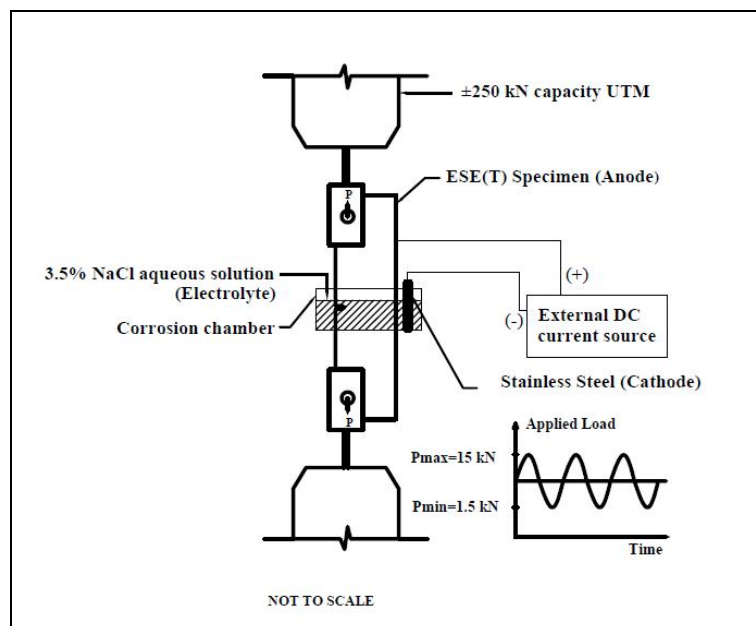


Fig. 2 Schematic view of accelerated corrosion fatigue experimental set-up

TABLE III. Details of FCG Tests

Specimen ID.	Test frequency, f (Hz)	Corrosion current (A)	Corrosion density, i_{cor} ($\mu\text{A}/\text{cm}^2$)
S3/CFCG8 - 1AC	0.5	0.3	4016.06

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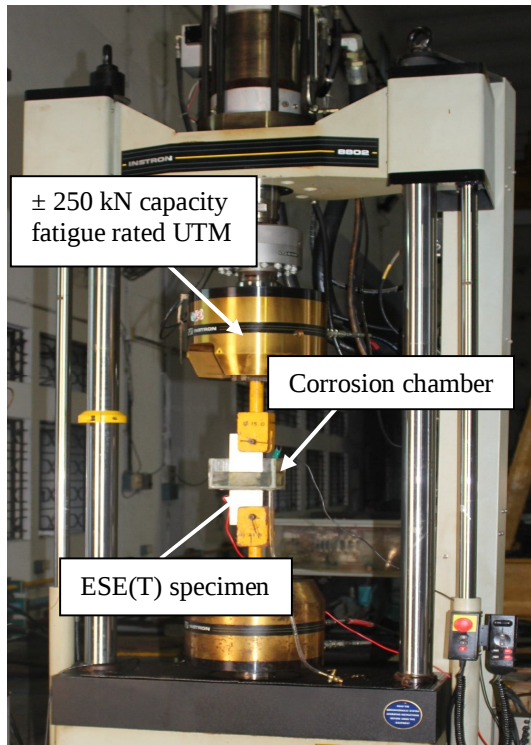


Fig. 3 Close up view of experimental set-up

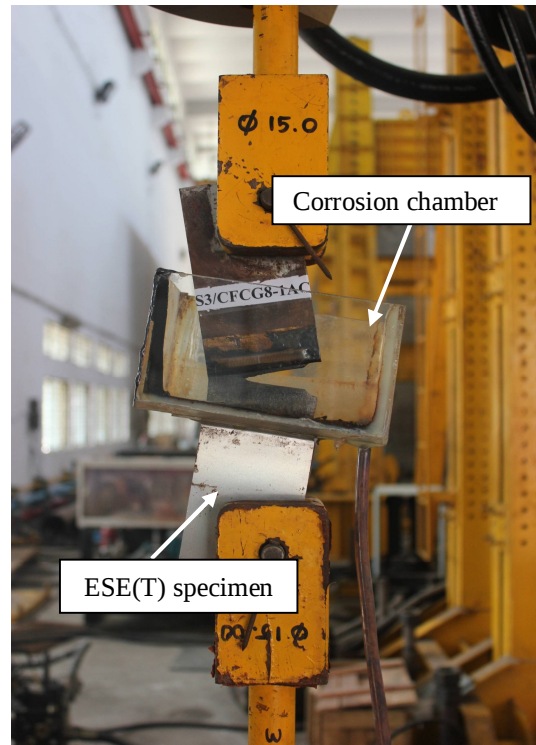


Fig. 4 Close-up view of specimen after failure

IV. RESULTS AND DISCUSSION

Table IV gives number of cycles to crack initiation, end of experiment, and the corresponding crack length including initial notch length. The test was terminated when the crack growth in the specimen became unstable and the uncracked ligament was insufficient to take further load. Figure 5 shows crack length versus number of cycles for the specimen S3/CFCG8-1AC. Figure 6 shows images at different stages of fatigue cycles for the ESE(T) specimen.

TABLE IV. RESULTS OF FCG TESTS

Specimen ID.	Crack initiation		End of experiment	
	Number of cycles	Crack length* (mm)	Number of cycles	Crack length* (mm)
S3/CFCG8 -1AC	50,000	12.04	1,69,302	50.82
* Including initial notch length of 11.25mm				

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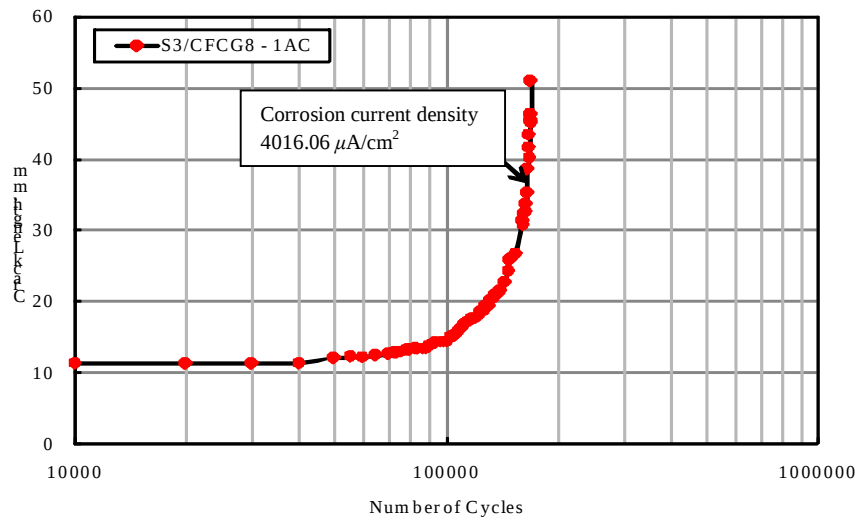
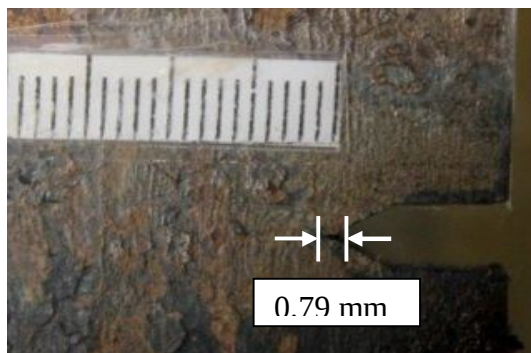
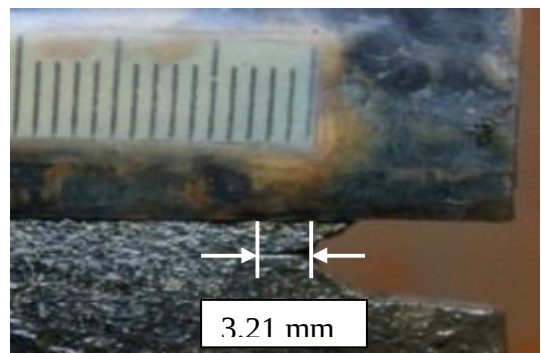


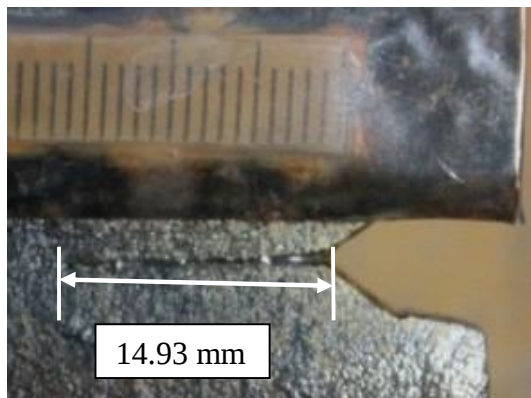
Fig. 5 Crack length vs. number of cycles for the ESE(T) specimen



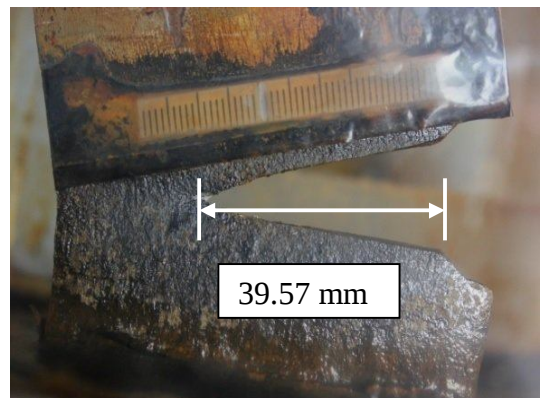
(a) 50,000 Cycles



(b) 1,00,000 Cycles



(c) 1,50,000 Cycles



(d) 1,69,302 Cycles

Fig. 6 Digital camera images for the ESE(T) specimen

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Stress intensity factor range (ΔK) for different crack length values was obtained using the expression given in ASTM E647-13a:

$$\Delta K = \left[\frac{\Delta P}{B\sqrt{W}} \right] F \quad (4)$$

where

ΔP = force range, N

B = thickness of the specimen, mm

W = width of the specimen, m

$F = \alpha^{1/2} [1.4 + \alpha] [1 - \alpha]^{-3/2} G$

$G = 3.97 - 10.88\alpha + 26.25\alpha^2 - 38.9\alpha^3 + 30.15\alpha^4 - 9.27\alpha^5$

$\alpha = a/W$ for $0 < \alpha < 1$

Using the crack growth data, fatigue crack growth rate (da/dN) was evaluated for different crack length values. Plot between da/dN and ΔK was obtained for the specimen as shown in Fig.7. The da/dN vs. ΔK curve was fitted using the Paris' law and FCG constants C and m were evaluated for given corrosion current condition. Table V gives values of the FCG constants.

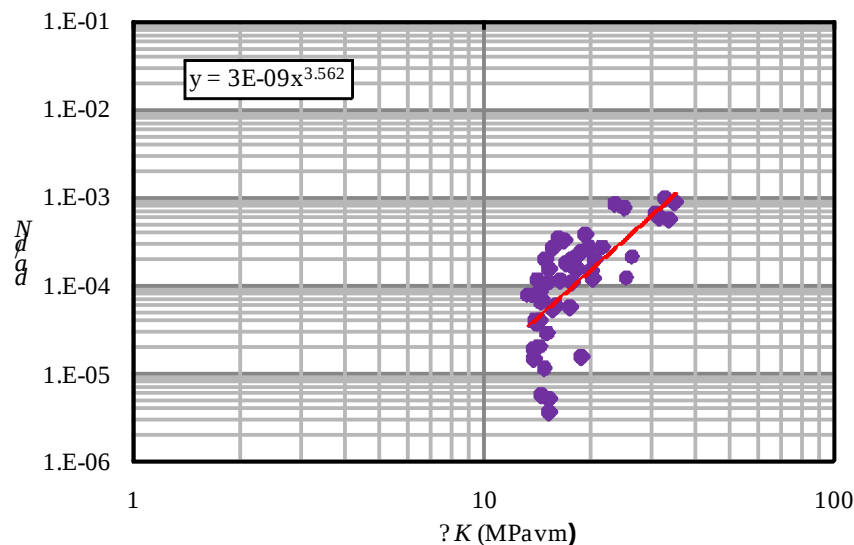


Fig. 7 da/dN vs. ΔK curve for S3/CFCG8-1 AC

TABLE V. FCG CONSTANTS

FCG constants	S3/CFCG8-1 AC
C	3×10^{-9}
m	3.562

The rate of corrosion (CR) was determined using the expression given in ASTM G102 - 2010 and the expression for calculating corrosion rate is as follows:

$$CR = K_1 \frac{i_{cor}}{\rho} EW \quad (5)$$

where

$$K_1 = 3.273 \times 10^{-3} \text{ mm g / } \mu\text{A cm yr}$$

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P = density in g/cm^3
 EW = equivalent weight = W/n
 i_{cor} = corrosion density
 W = the atomic weight of the element
 n = the number of electrons required to oxidize an atom of the element in the corrosion process, that is, the valence of the element (for Fe = 2)

Based on the above equation the corrosion rate of ESE(T) specimen for the applied corrosion current was found to be 45.86 mm/yr. The corrosion rate of steel structures in an ordinary sea environment is said to be around 2.5 mils/yr which comes out to about 0.0635 mm/yr. On comparing this value with the corrosion rate obtained for the specimen, it shows that the actual corrosion process is accelerated by 722 times on application of external DC current.

The ESE(T) specimen was modelled using user friendly software Abaqus 6.13. Abaqus 6.13 is a software application for FEA and computer aided engineering. It is highly sophisticated, general purpose finite element program, designed primarily to simulate the behaviour of solids and structures under extremely applied loading. Stress intensity factor range values for various crack lengths were obtained after analysis. Table VI gives the stress intensity factor range values obtained using expressions given in ASTM E647-13a and Abaqus 6.13.

TABLE VI. STRESS INTENSITY FACTOR RANGE VALUES

Crack length (mm)	ΔK from ASTM (MPa $\sqrt{\text{m}}$)	ΔK from Abaqus (MPa $\sqrt{\text{m}}$)
11.25	13.27	8.97
15.07	15.94	11.18
20.00	19.74	13.93
30.65	31.15	21.88
33.59	43.45	24.95

V. CONCLUSIONS

Fatigue crack growth in an ESE(T) specimen made of SA 333 Gr.6 carbon steel in corrosion environment was studied at a corrosion current of 0.3 A and frequency of 0.5 Hz. The specimen took 50,000 fatigue load cycles for the crack to initiate. The experiment was stopped at 1,69,302 cycles, since the specimen became unstable and the uncracked ligament was insufficient to take further load. The total crack growth during the experiment was 39.57 mm. For this crack growth, the specimen underwent 1,19,302 cycles of fatigue loading, excluding the cycles required for crack initiation.

Based on the corrosion fatigue crack growth data for the specimen, the FCG constants C and m for the material are found to be 3×10^{-9} and 3.562 respectively. The present experiment is the first in the series of accelerated corrosion fatigue studies planned on SA 333 Gr.6 carbon steel at different values of corrosion current and test frequency. The results of these studies will be very useful in coming out with an accelerated corrosion fatigue experimental methodology for this steel.

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