iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 4 **Issue:** V **Month of publication:** May 2016

DOI:

Volume 4 Issue V, May 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Accelerated Corrosion Fatigue Crack Growth Studies On Is 2062 Gr. E 300 Steel

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Abstract: Corrosion fatigue crack growth experiments were carried out on two Eccentrically-Loaded Single Edge notch Tension [ESE(T)] specimens made of IS 2062 steel in salt water environment. The tests were carried out using ±250 kN capacity servo controlled electro hydraulic fatigue rated Universal Testing Machine (UTM). The test location of the specimen was placed in a chamber containing 3.5% Sodium Chloride (NaCl) aqueous solution which acted as corrosive environment. The corrosion process was accelerated by passing a constant direct current of 0.1 A and 0.3 A using an external current source. The maximum and minimum load values were 15 kN and 1.5 kN. The test frequency was 0.375 Hz and stress ratio was 0.1. Crack growth was continuously monitored and crack growth curve was plotted. From this curve, the fatigue crack growth constants C and m were determined. Details of the experimental study and the results are presented in this paper.
Key words: Corrosion fatigue, Accelerated corrosion, Fatigue crack growth, ESE(T) specimen.

I. INTRODUCTION

Fatigue is defined as the "process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points which may culminate in cracks or complete fracture after a sufficient number of fluctuations" [1]. Corrosion is defined as a chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties [2]. Corrosion fatigue is the phenomenon of cracking in a structure under combined action of fatigue and corrosive environment. It is the "synergistic effect of fatigue and aggressive environment acting simultaneously, which leads to degradation in fatigue behavior" [3]. The coupled effects i.e., the combination of cyclic loading and deleterious environment both acting together is more detrimental than either acting separately [3]. Corrosion fatigue crack growth (CFCG) rate is important for the life prediction and safety assessment of engineering structures. It is evident that the life and strength of material are decreased under corrosion medium. It is found that in corrosive environment the threshold intensity for crack initiation is less compared to the laboratory air environment. The failure or initiation of crack in structural members in corrosive environment depends on several mechanisms, the loading condition and the environment.

Chinnaiah et al. [4] carried out studies on corrosion fatigue crack growth behavior in Ni-Cr-Mn steel under 3.5% saturated NaCl solution using C[T] specimen. It was observed that fatigue crack growth rate was higher and threshold stress intensities were lower in 3.5% NaCl solution compared to laboratory air condition. It was observed that crack growth rate increased at lower frequencies and higher stress ratio. Aarthi et al. [5] carried out corrosion fatigue crack growth rate studies on ESE(T) specimen made of SA 333 Gr.6 Carbon steel. The corrosion rate was accelerated by supplying a direct current of 0.3 A. The frequency and stress ratio were 0.375 Hz and 0.1. Kelita et al. [6] carried out corrosion fatigue crack growth experiment on an ESE(T) specimen made of IS 2062 Gr. E 300 steel in salt water environment. The corrosion process was accelerated by a constant direct current of 0.2 A. The frequency and stress ratio were 0.375 Hz and 0.1. Significant increase in crack growth rate was observed with increase of corrosion current. Raghava et al. [7] and Vishnuvardhan et al. [8] carried out corrosion fatigue crack growth experiments on eccentrically-loaded single edge notch tension [ESE(T)] specimens made of IS 2062 Gr. E 300 steel. The corrosion process was accelerated using an external current source by applying constant Direct Current (DC) of 0.1 A, 0.2 A and 0.3 A. At each level of corrosion current three specimens were tested at a loading frequency of 0.25 Hz, 0.50 Hz and 0.75 Hz. All the experiments were carried out under constant amplitude sinusoidal loading and stress ratio of 0.1. Results showed that decrease in fatigue life varied from 14% - 42% when applied current increased from 0.1 A to 0.3 A. The effect of corrosion current on fatigue life was observed to be more predominant at higher frequencies, i.e., 0.50 Hz and 0.75 Hz when compared with 0.25 Hz. Dong-Hwan Kang et al. [9] investigated fatigue and corrosion fatigue crack propagation behaviors of high strength steel, HSB800 in air and seawater environment. The corrosion fatigue crack propagation rates in seawater environment were higher than those in air environment. ΔK_{th} and K_{crit} values were not so much changed according to environmental changes.

In the present study, fatigue crack growth (FCG) experiments were carried out on IS 2062 Gr. E 300 steel under 3.5% NaCl aqueous environment and corrosion process was accelerated by applying direct current (DC) of 0.1 A and 0.3 A. The test was carried out by using a computer controlled electro hydraulic fatigue rated Universal Testing Machine (UTM) of ±250 kN capacity under constant amplitude sinusoidal cyclic loading. Accelerated corrosion test method was preferred to reduce the test time drastically. The test frequency was 0.375 Hz and the stress ratio was maintained as 0.1. The fatigue crack growth data were recorded at regular intervals of loading cycles. Using crack growth curves material constants *C* and *m* were determined.

II. MATERIAL PROPERTIES

The steel used in the present experimental study was a high tensile structural steel suitable for welded, bolted and riveted structures and for all general engineering purposes [10]. Table 1 gives the chemical composition of the material and the specified values of various constituents as per IS 2062. Tension testing was done as per ASTM E 8M - 13a [11] to find the mechanical properties of the material. Table 2 gives the mechanical properties of the steel and it satisfies the requirement of Gr. E 300 of IS 2062.

Table 1 CHEMICAL COMPOSITION OF IS 2062 STEEL

Composition	Tested values (%)	Specified (max.) for Gr. E 300 steel (as per IS 2062:2011) (%)
Carbon	0.164	0.200
Manganese	1.063	1.500
Phosphorous	0.013	0.045
Sulphur	0.002	0.045
Silicon	0.147	0.450

Table 2 MECHANICAL PROPERTIES OF IS 2062 STEEL

Properties	Tested values (%)	Specified (min.) for Gr. E 300 steel (as per IS 2062:2011) (%)
Yield strength, σ_y, (MPa)	306	300
Ultimate Tensile strength, σ_u (MPa)	455	400
% Elongation	25.65	22
Young's modulus, E (GPa)	190	-

III. EXPERIMENTAL DETAILS

A. Specimen Details

ASTM E 647 – 13a [12] recommends three types of specimen, viz., Compact [C(T)] Tension, Middle Tension [M(T)] and Eccentrically-loaded Single Edge notch Tension [ESE(T)] specimens for carrying out FCG studies on materials. In the present study ESE(T) specimen was chosen due to its extended design, as it gives additional working space compared to standard Compact [C(T)] Tension specimen configuration. And also, ESE(T) specimen requires lower applied force when compared to Middle

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Tension [M(T)] specimen configuration. Figure 1 shows a typical ESE(T) specimen used in the present study. ASTM E 647 - 13a [12] recommends that the thickness of the specimen be in the range of,

$$(W/20) \leq B \leq (W/4)$$

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.

The specimens were fabricated from a 10 mm thick plate and machined to 8 mm thickness. A notch of length 11.25 mm was cut at the mid height of the specimen using the EDM (electro-discharge machine) process. ASTM 1820 - 13 [13] specifies different types of notches (chevron notch, straight through notch, notch ending in drilled hole and narrow notch) and their configurations. The maximum width of the notch was *W/16* and the maximum included angle of the notch was 60^o.

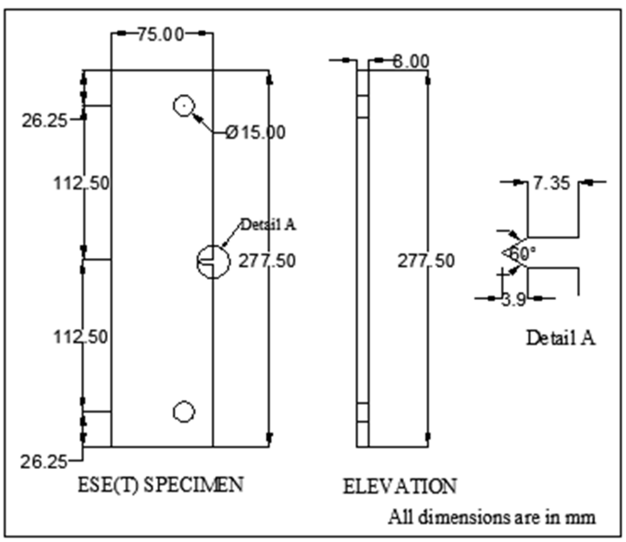

Fig.1 ESE(T) specimen configuration

B. Test Details

The FCG tests were carried out on ESE(T) specimens 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 was filled with 3.5% NaCl aqueous solution, which acted as the corrosive environment. The depth of the solution was 45 mm and this was maintained till the end of the test. The corrosion process was accelerated by applying a direct current of 0.1 A and 0.3 A. Direct current (DC) was supplied from an external current source which was 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 corrosion current density was calculated as per ASTM G 102 - 2010 [14],

$$i_{cor} = \frac{I_{cor}}{A}$$

Where,

i_{cor} = corrosion current density, $\mu A/cm^2$

I_{cor} = total anodic current, μA

A = exposed specimen area, cm^2

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

$$P_m = \frac{0.4 B b_0 \sigma_y}{2W + a_0}$$

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

σy = yield strength of the material, MPa

As per ASTM E 647 – 13a [12], for the FCG results to be valid, it is required that the specimen be predominantly elastic at all values of applied force. For the ESE(T) specimen, the following has to be satisfied:

$$(W - a) \geq \left(\frac{4}{\pi}\right)\left(\frac{k_{max}}{\sigma_{ys}}\right)^2$$

where,

$(W - a)$ = uncracked ligament

σ_{ys} = yield strength, MPa

K_{max} = maximum SIF, MPa√mm

The tests were conducted at a frequency of 0.375 Hz and stress ratio 0.1. Maximum and minimum load values were 15 kN and 1.5 kN respectively. Table 3 gives the details of the two FCG tests. Figure 3 shows the experimental set-up and Figure 4 shows the close-up view of the set-up. Number of cycles for crack initiation was recorded. Crack growth was continuously monitored. The experiment was terminated when the crack growth in the specimen became unstable and the uncracked ligament was insufficient to take further load. Figure 5 shows the close-up view of specimen after failure.

Table 3 DETAILS OF FCG TESTS FOR THE SPECIMENS

Specimen ID	Test frequency, f (Hz)	Corrosion current (A)	Corrosion density, i_{cor} (μA/cm^2)
IS/CFCG8-5AC	0.375	0.1	1340
IS/CFCG8-6AC	0.375	0.3	4017

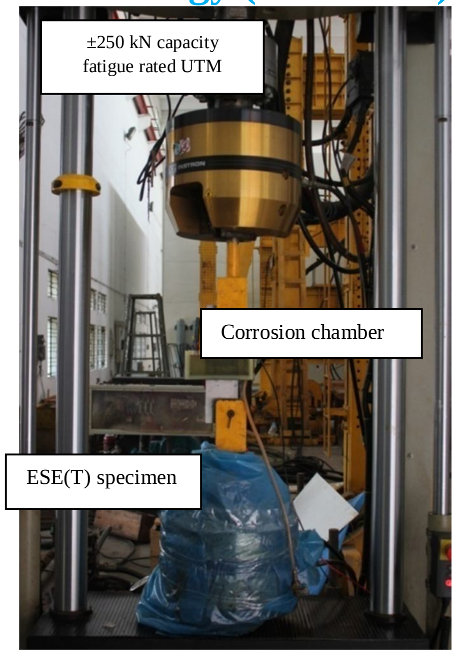

Fig.3 Experimental set-up for corrosion fatigue studies on ESE(T) specimen

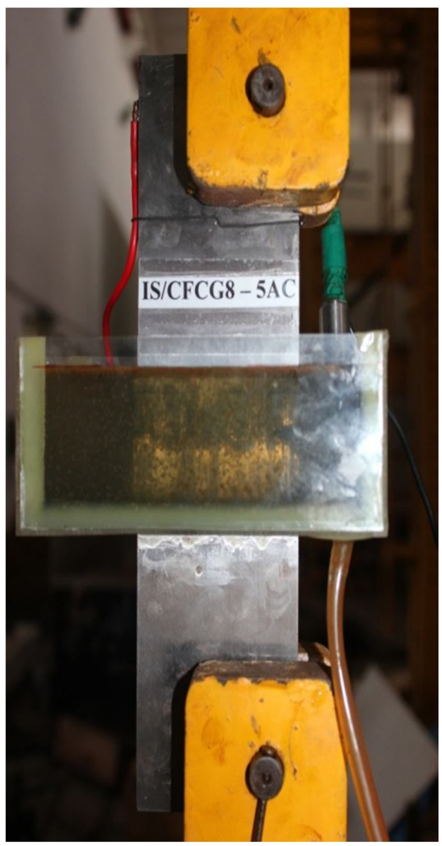

Fig.4 Close-up view of experimental set-up

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Fig. 5 Close-up view of specimen after failure

IV. CORROSION RATE CALCULATION

The rate of corrosion (*CR*) was calculated as per ASTM G 102 – 2010 [14] and the expression is as follows:

$$CR = K_1 \frac{i_{cor}}{\rho} EW$$

where,

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

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*, $n = 2$)

Table 4 gives the details of corrosion current and corrosion rate for the ESE(T) specimens. Table 5 gives the details of crack length and corresponding stress intensity factor (SIF) range for the ESE(T) specimens.

Table 4 DETAILS OF CORROSION CURRENT AND CORROSION RATE FOR THE ESE(T) SPECIMENS

Specimen ID	Corrosion current (A)	Current density, i_{cor} (μA/cm^2)	Corrosion rate (mm/yr)
IS/CFCG8-5AC	0.1	1340	15.4
IS/CFCG8-6AC	0.3	4017	46.3

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V. FATIGUE CRACK GROWTH RATE CALCULATION

Table 6 gives the details of crack initiation and growth till end of the test, including details corresponding to the point up to which the elastic validity check is applicable. Stress intensity factor range (ΔK) values were evaluated using the following expressions given in ASTM E 647 – 13a [12]:

$$\Delta K = [\Delta P/ (B\sqrt{W})]\, F$$

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

Where,

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

ΔP =load range; $\alpha = a/W$, for $0< \alpha < 1$

Table 5 SIF RANGE FOR THE ESE(T) SPECIMENS AS PER ASTM E 647 – 13a [12]

IS/CFCG8-5AC		IS/CFCG8-6AC	
Crack length, *a*, mm	SIF range, ΔK, MPa$\sqrt{m}$	Crack length, *a*, mm	SIF range, ΔK, MPa$\sqrt{m}$
11.25	13.273	11.25	13.273
13.74	14.992	13.96	15.147
15.73	16.411	15.92	16.553
18.75	18.718	18.77	18.734
20.65	20.294	22.56	21.999
24.66	24.043	29.64	29.793

Figures 6 & 7 show images at different stages of fatigue cycles for the specimens IS/CFCG8-5AC and IS/CFCG8-6AC. Figure 8 shows the crack growth in the two ESE(T) specimens, plotted in terms of crack length versus number of fatigue load cycles.

Figures 9 & 10 show the variation of fatigue crack growth rate with respect to log of stress intensity factor range. Using the crack growth rate (*da/dN*) vs. stress intensity factor range (ΔK) plots, best fit curves following power law in the form of Paris' equation were obtained. Based on this relation, the fatigue crack growth constants *C* and *m* were found and the same is given in Table 7.

Table 6 DETAILS OF CRACK GROWTH IN ESE(T) SPECIMENS

Specimen id	Crack initiation		No of cycles satisfying elastic check	End of test	
	No of cycles	Crack length		No of cycles	Crack length*
IS/CFCG8-5AC	79,664	0.193	1,92,864	1,97,962	51.02
IS/CFCG8-6AC	70,000	0.779	2,01,000	2,02,859	52.75
*INCLUDING INITIAL NOTCH LENGTH 11.25 mm					

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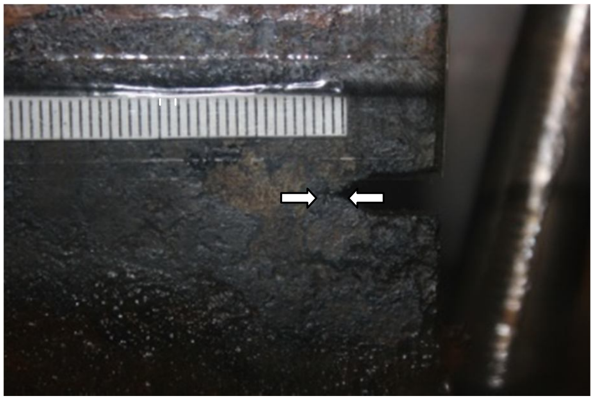
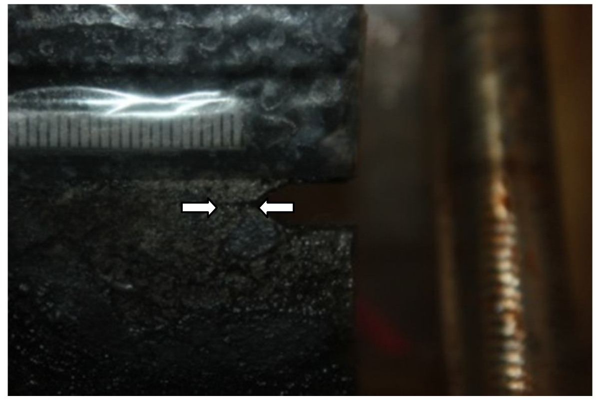
Table 7 FCG CONSTANTS CALCULATED BASED ON EXPERIMENTAL STUDIES

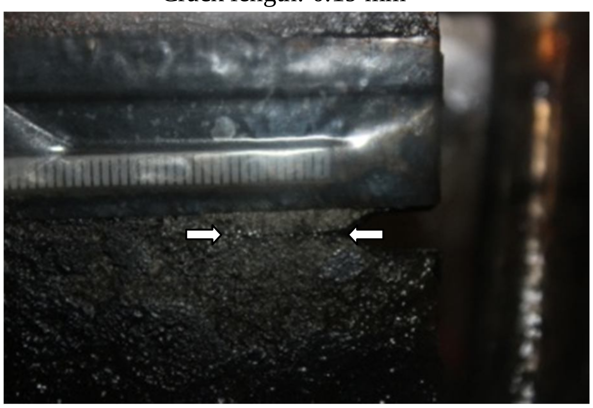
Specimen ID	*C*	*m*
IS/CFCG8-5AC	2×10^{-13}	6.8664
IS/CFCG8-6AC	7×10^{-9}	3.1946



(a). 79,664 cycles
Crack length: 0.19 mm



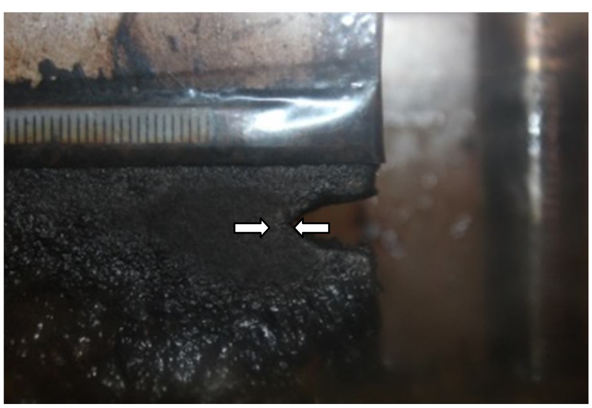
(b). 1,55,864 cycles
Crack length: 5.43 mm



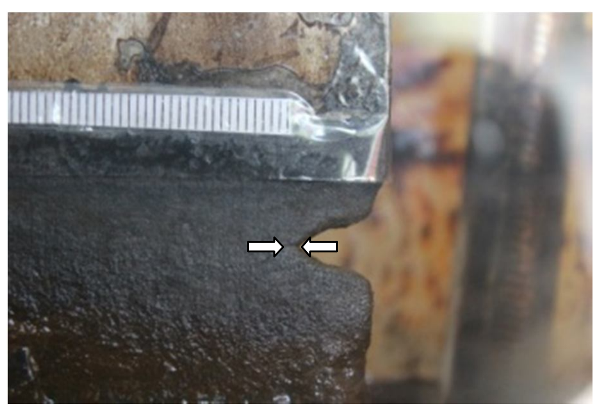
(c). 1,88,364 cycles
Crack length: 13.33 mm

(d). 1,97,962 cycles
Crack length: 39.77 mm

Fig. 6 Crack growth images of the specimen IS/CFCG8-5AC



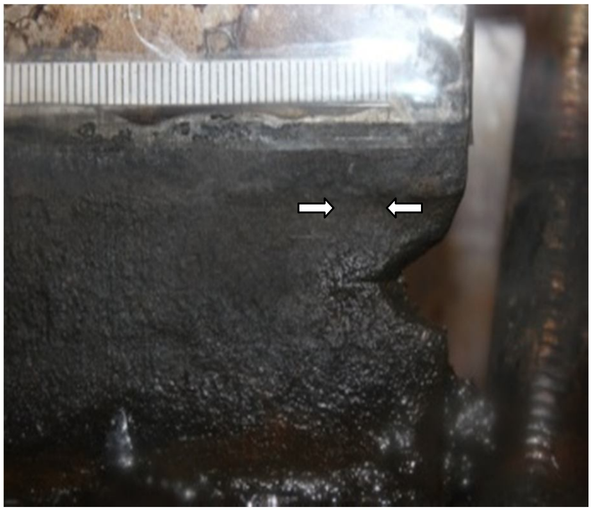
(a). 80,000 cycles



(b). 1,10,000 cycles

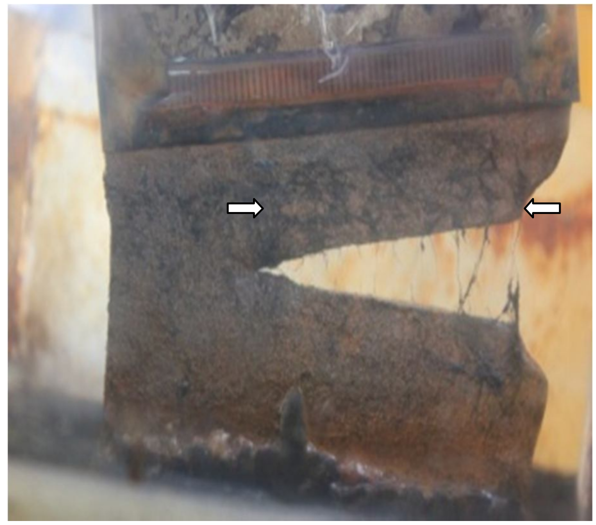
Crack length: 1.88 mm

Crack length: 4.49 mm



(c). 1,55,000 cycles

Crack length: 7.52 mm



d). 2,02,859 cycles

Crack length: 41.5 mm

Fig. 7 Crack growth images of the specimen IS/CFCG8-6AC

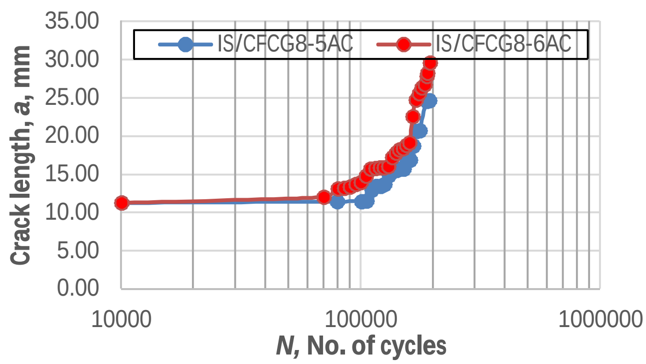


Fig. 8 Crack growth in ESE(T) specimens

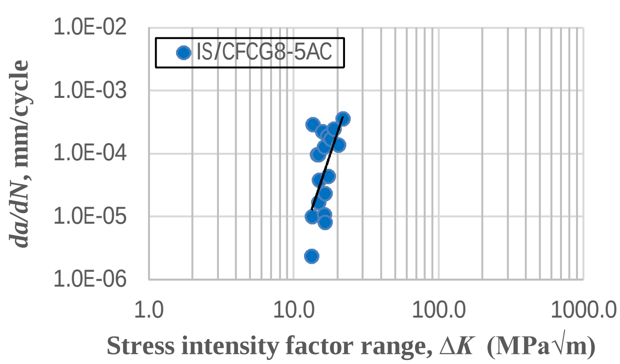


Fig. 9 Crack growth rate vs. stress intensity factor range for the specimen IS/CFCG8-5AC

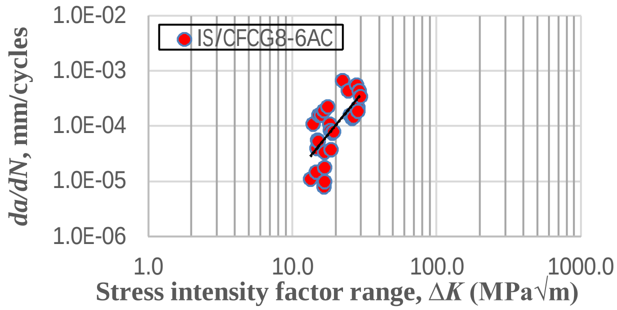


Fig. 10 Crack growth rate vs. stress intensity factor range for the specimen IS/CFCG8-6AC

VI. SUMMARY AND CONCLUSIONS

Corrosion fatigue crack growth studies were carried out on two ESE(T) specimens of IS 2062 steel in salt water environment. The tests were conducted under constant amplitude loading by using a ±250 kN capacity fatigue rated UTM. The corrosion process was accelerated by applying a constant direct current of 0.1 A and 0.3 A. The loading frequency was 0.375 Hz and the stress ratio was maintained as 0.1. From the test results, it is observed that crack growth rate increases with the increase in corrosion current. During the CFCG tests, the notch location was continuously monitored to determine the number of cycles to crack initiation. Thereafter, CFCG was measured at regular intervals of fatigue load cycles. The crack growth data are valid till the ASTM elastic check validity criterion is satisfied. Based on the corrosion fatigue crack growth data, FCG parameters C and m were determined. The corrosion rate of steel structures in sea water environment was 0.0635 mm/yr. On comparing this value with the corrosion rate obtained for the specimens, it shows that the actual corrosion process is accelerated by 730 times on the application of external DC current for IS/CFCG8-6AC and 250 times for IS/CFCG8-5AC. The present experiment forms a part of the studies being carried out at CSIR–SERC to evolve an accelerated corrosion fatigue methodology to simulate real life corrosion fatigue damage for this steel.

VII. ACKNOWLEDGEMENT

The first author thanks the Director, CSIR-SERC for the opportunity provided to her to carry out her post-graduate project work at the Fatigue & Fracture Laboratory, CSIR-SERC. The authors from CSIR–SERC thank the Director and Advisor (Management), CSIR–SERC for the constant support and encouragement extended to them in their R&D activities. The assistance rendered by the technical staff of FFL, CSIR-SERC in conducting the experimental investigations is gratefully acknowledged. This paper is published with the kind permission of Director, CSIR-SERC.

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