

# Corrosion Fatigue Crack Growth Studies in Ni-Cr-Mn Steel

Chinnaiah Madduri and Raghu V. Prakash\*

**Abstract**—This paper presents the results of corrosion fatigue crack growth behaviour of a Ni-Cr-Mn steel commonly used in marine applications. The effect of mechanical variables such as frequency and load ratio on fatigue crack growth rate at various stages has been studied using compact tension (C(T)) specimens along the rolling direction of steel plate under 3.5% saturated NaCl aqueous environment. The significance of crack closure on corrosion fatigue, and the validity of Elber's empirical linear crack closure model with the ASTM compliance offset method have been examined.

Fatigue crack growth rate is higher and threshold stress intensities are lower in aqueous environment compared to the lab air conditions. It is also observed that the crack growth rate increases at lower frequencies. The higher stress ratio promotes the crack growth. The effect of oxidization and corrosion pit formation is very less as the stress ratio is increased. It is observed that as stress ratios are increased, the Elber's crack closure model agrees well with the crack closure estimated by the ASTM compliance offset method for tests conducted at 5Hz frequency compared to tests conducted at 1Hz in corrosive environment.

**Keywords**—Corrosion fatigue, oxide induced crack closure, Elber's crack closure, ASTM compliance offset method.

## I. INTRODUCTION

**M**ECHANICAL parts of nuclear power systems, steam and gas turbines, aircraft, marine structures, pipelines, and bridges, offshore drilling jigs, boilers, pressure vessels, are frequently subjected to cyclically varying loads under aggressive chemical environments. Even when the structural members are operated close to the operating loads, failure happens at lower load levels due to the synergetic effect of both corrosion and cyclic loads. Due to sustained environment effect and cyclically varying load, an initial damage (such as defect or void) present in a component experiences accelerated damage resulting in faster crack growth rate that finally leads to permanent failure of the structure. The failure or initiation of crack in structural members in the corrosive environmental depends on several mechanisms, the loading conditions, and the environment. The mechanisms which involve in corrosion fatigue or stress corrosion cracking are typically hydrogen embrittlement, film rupture, enhanced localized plasticity (corrosion pits and residual stresses), pitting corrosion, film cleavage mechanism

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and the combination of the above mechanism [1]. It is very difficult to analyze the active governing mechanisms, which plays a major role in initiation and advancement of the fatigue crack in real time situations.

## II. EXPERIMENTAL DETAILS

### A. Experimental setup review stage

The test setup consists of 810 Material Test System (MTS) 100 kN servo hydraulic test system (Figure 1) and an interfacing computer with test software. A travelling microscope was used to measure the fatigue crack growth manually. Corrosion fatigue crack growth experiments were done by presetting a threshold applied stress intensity factor of  $15\text{MPa}\sqrt{\text{m}}$ . The mechanical variables, load and the frequency were manually entered in the computer interface which is connected to the MTS. CT specimens were pre-cracked to a crack length of  $\sim 10\text{ mm}$  prior to crack growth testing. The tests were carried out at constant amplitude fatigue loading in load control mode. The load is read from the load cell which is inbuilt to the MTS.

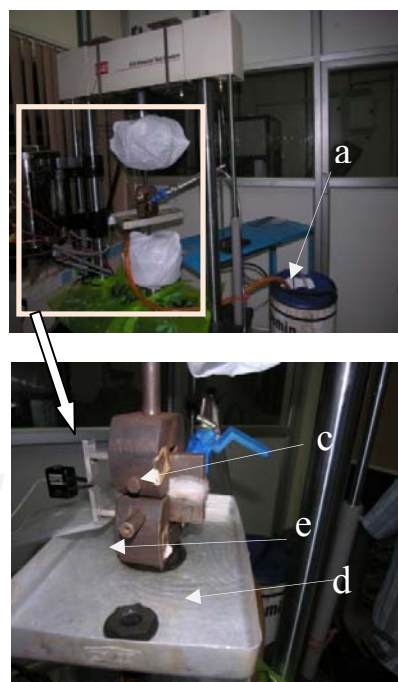
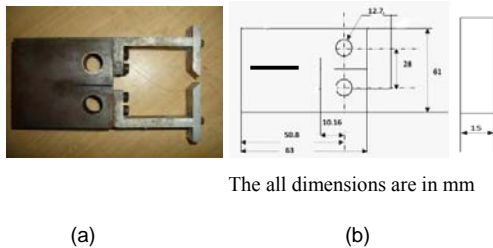


Fig.1: Experimental test set up for corrosion fatigue crack growth experiments  
(a) NaCl solution reservoir (b) COD gauge

(c) Specimen (d) Water collecting chamber  
(e) Fixture

The specimen dimensions were 63.5X61X15 mm as shown in Figure 2(b). The specimens were mirror polished so as to get a smooth surface for visual observation of crack growth for initial calibration test as per the ASTM E647. Knife edge extension members as shown in Figure 2(a) are attached to the end of the specimen to maintain crack opening displacement gauge (COD) away from the corrosion fluid during corrosion fatigue crack growth test.



The all dimensions are in mm

Fig. 2-(a): CT specimen with extended knife edges to mount the COD gauge. (b): Compact Tension specimen dimensions

The compliance values were calculated from crack tip opening displacements at the crack tip by using COD gauge which is connected to data acquisition program. The loads are read from the load cell which is inbuilt to the MTS. The crack front region is surrounded by a cotton wicked swab to create artificial soaking of corrosion medium during the crack growth experimentation. Crack length measurement under corrosion environment during fatigue loading was made by compliance method at a stress ratio 0.1 @ 15 Hz; a block loading sequence consisting of stress ratios of 0.1, 0.7 @15Hz was applied to beach mark the specimen at stress intensity factor ranges above the threshold stress intensity range of 15 MPa√m. Corrosion fatigue tests were done at stress ratios 0.1, 0.4 and 0.6 at 1Hz and 5Hz frequencies respectively.

The chemical composition of the test sample is calculated from energy dispersive X-ray spectroscopy. The major composition of sample by weight percentage is tabulated below.

TABLE I CHEMICAL COMPOSITION OF MATERIAL

| (Weight percentage) |      |      |      |      |
|---------------------|------|------|------|------|
| Fe                  | Mn   | Ni   | Cr   | Ti   |
| 96.55               | 2.15 | 0.78 | 0.31 | 0.21 |

### III. RESULTS

#### A. Crack length-Compliance Correlation

A fifth order polynomial is fitted to the curve drawn between normalised crack lengths against non dimensional compliance and the same is shown in figure 3(a). The plot between the compliance and the crack length for the test at stress ratio 0.1 at 15 Hz frequency and threshold stress intensity of 15MPa√m is shown in figure 3(b). Compliance is function of crack opening displacement [ASTM E647].

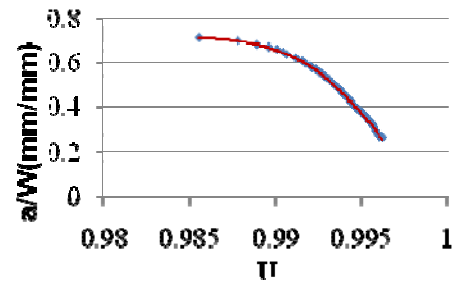


Fig. 3(a): Plot between the normalized crack lengths and non dimensional compliance for R=0.1 at 15 Hz frequency with 15 MPa√m threshold stress intensity range

Normalized crack length as function of normalized compliance is given below:

$$\frac{a}{W} = C_0 + C_1U + C_2U^2 + C_3U^3 + C_4U^4 + C_5U^5 + C_6U^6$$

where  $U$  is non dimensional compliance given by

$$U = \frac{1}{\left(\frac{BEV}{P}\right)^{1/2} + 1}$$

$B$  –Thickness of the specimen (mm)

$E$ -Young's modulus  $\left(\frac{N}{mm^2}\right)$

$V$ -crack opening displacement (mm)

$P$ -load (N)

$$\frac{a}{W} = 0.5489 \times 10^{10} U^5 - 2.7176 \times 10^{10} U^4 + 5.3812 \times 10^{10} U^3 - 5.3277 \times 10^{10} U^2 + 2.6373 \times 10^{10} U - 5.222 \times 10^{10}$$

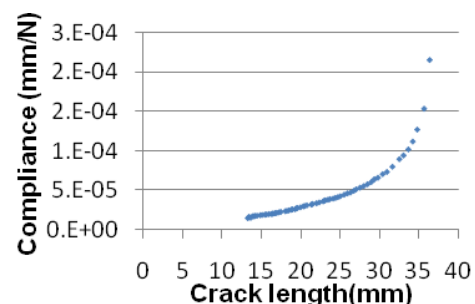


Fig. 3(b): Plot between compliance and crack length for R=0.1 at 15Hz frequency with 15MPa√m threshold stress intensity range

Figure 4(a) shows the plot between load (N) and crack opening displacement (mm) is drawn over a range between  $0.95P_{max}$  and  $0.5P_{max}$ . Inverse of the slope of linear least square fit between the above mentioned is parameters is taken as the compliance, and the same is used in estimation of crack length using the compliance calibrated polynomial equation. Figure 4(b) shows that the observed crack length by travelling microscope and the estimated crack length from the compliance calibration equation in block load sequence; there is a good agreement between estimated crack length and

physical measurement. The curves between the crack length and compliance for different tests are shown in figure 5.

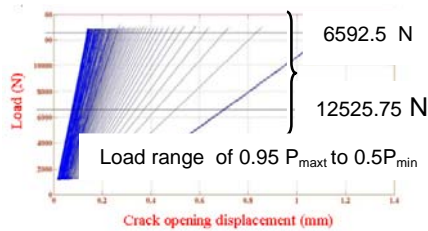


Fig. 4(a): Load (N) Vs crack opening displacement (mm) for R=0.1, 5Hz frequency under 3.5%NaCl environment.

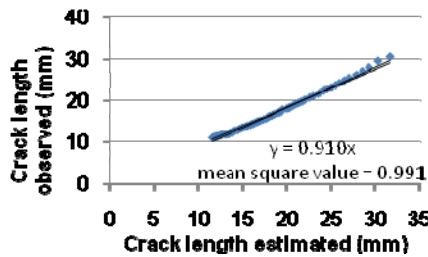


Fig. 4(b): Comparison between the observed and estimated crack length in block loading sequence

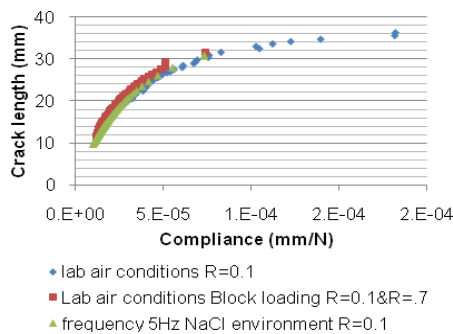


Fig. 5: Comparison of curves between the crack length and compliance

Fatigue crack growth rate in the corrosion medium is observed to be more than in lab air conditions. Comparison between the fatigue crack growth rate in lab air and in the presence of 3.5% NaCl solution is shown in the figure 6.

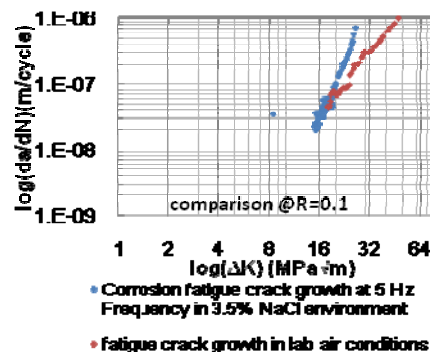


Fig. 6: Comparison between the fatigue crack growth rate and corrosion fatigue crack growth rate

For every increment in the crack, fresh material will be subjected to corrosion medium, which results in reduced load required to break the bonds. It is evident that the life of material is decreased under corrosion medium [20]. The pumping of the liquid environment near the crack tip ensures reaction with fresh material.

The saturated aggressive chemical environment accelerates the crack to propagate in addition to the loads acting at the crack tip [5]. Unlike in the plain fatigue testing, the synergetic actions involved in the mechanics of corrosion fatigue make the damage accumulation at faster rates once the crack is initiated. Due to the interaction of saturated chemical solution present at the crack tip with the metal surface oxide film is produced resulting in formation of corrosion pits at the metal surface. These corrosion pits are the primary cause further crack initiation. Usually, this oxide film would act as a protective layer and prevent further corrosion of the metal. However, cyclic loading causes localized cracking of this layer, which exposes fresh metal surfaces to the corrosive environment. At the same time, corrosion causes localized pitting of the surface, and these pits serve as stress concentrations to promote the further damage. It is investigated that in the corrosive environment the threshold stress intensity for crack initiation is less compared to the lab air conditions [20].

Increase in the stress ratio results in a rise in the corrosion fatigue crack growth rate. Figure 7 presents the comparison of corrosion fatigue crack growth rates curves for different stress ratios and frequencies.

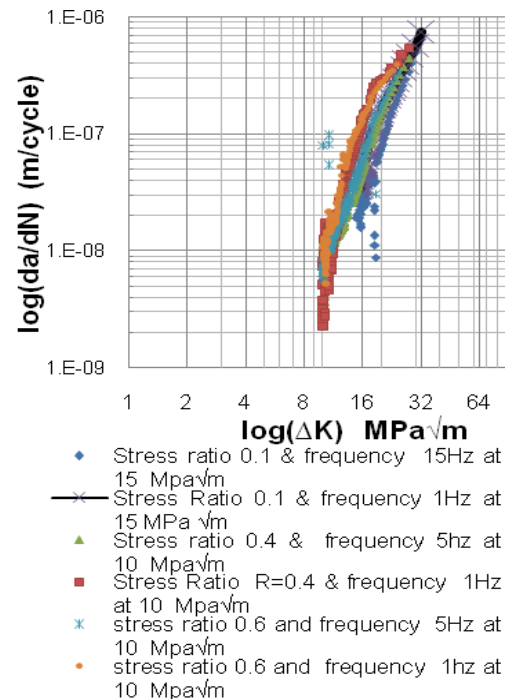


Fig.7: Comparison of corrosion fatigue crack growth rate curve for various Stress ratio and frequencies

Tests conducted at a stress ratio of 0.1 with a threshold stress intensity range of 15 MPa√m at 1Hz and 5Hz are

shifted little right away from that of the test done with stress ratio at 0.4, 0.6 at threshold stress intensity range of 10 MPa√m at 1Hz and 5Hz. Pre-cracking of test specimen is done at 5 Hz for the test done at 1Hz with stress ratio of 0.4 and 0.6 to reduce the time required in initiating the crack. At low frequency of operation of the test, the time required to interact the chemical solution with metal surface is high which results in reduced load requirement in propagation of the crack. Higher stress ratio results in an increase in the corrosion fatigue crack propagation rate. At lower frequencies, the rate of generation of hydrogen will allow the material to interact with the diffused hydrogen at higher concentrations permitting crack to accelerate.

It can be seen that the crack growth rates increases as the stress ratio increases. The curves are sensitive to the threshold stress intensity range and for different R ratio. The curves representing the lower  $\Delta K_{th}$  are bunched together. The corrosion fatigue crack growth rates are more predominant at low threshold stress intensity range compared to growth rate at higher stress intensity range values.

Due to the enormous time available for the aqueous medium to interact with surface at the crack tip, breakage of the bonds takes place, which accelerates crack growth. This effect will be more predominant as the frequency reduces to the decimal range [23]. It can be observed that the crack growth at the 1Hz frequency is nearly one order greater than that at a frequency at 5Hz.

Figure 8 presents the corrosion fatigue crack growth rates vs. effective stress intensity range after accounting for crack closure.

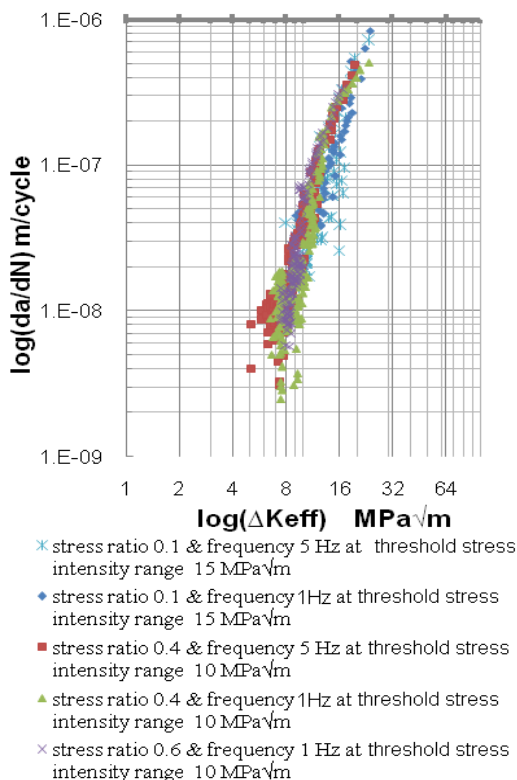


Fig. 8: Corrosion fatigue crack growth rate vs. effective stress intensity range

The oxidation which promotes the crack closure in environmental assisted crack growth is very less as the mean stress is increased [21]. The effect of corrosion pit formation will be less at higher stress ratios operation due to the insufficient exposure time at the crack tip. The crack surfaces will not come into closure sufficiently because of the higher crack mouth opening displacements at the crack tip due to the less effect of corrosion pit formation. At the higher stress intensity range, the effect of oxidized induced crack is minimized [19]. Figure 9 presents a comparison of corrosion fatigue crack growth rate after accounting for crack closure estimated by Elber's crack closure relation and by the ASTM compliance offset method.

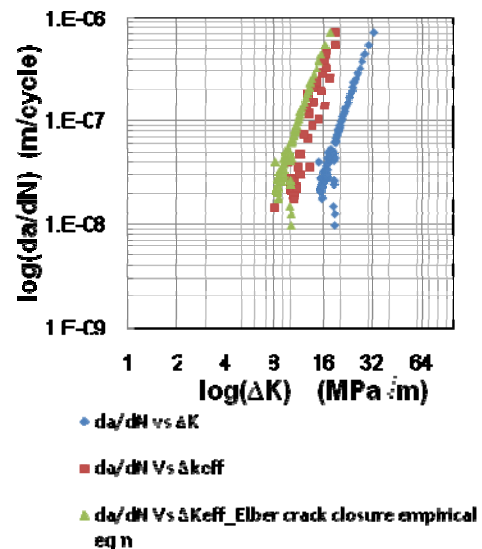


Fig.9: (a) Stress ratio 0.1 and frequency 5 Hz

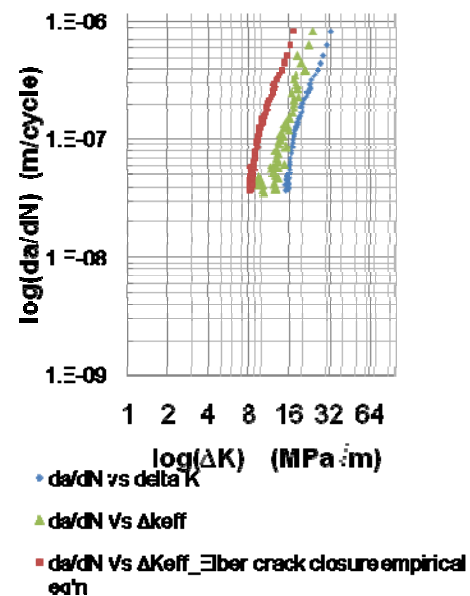


Fig. 9: (b) Stress ratio 0.1 and frequency 1 Hz

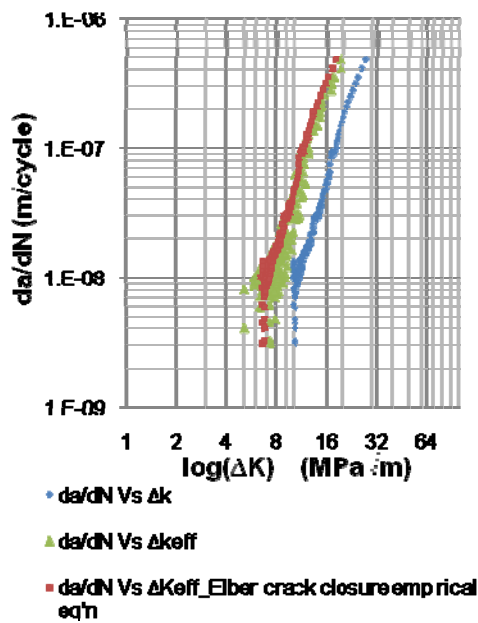


Fig.9: (c) Stress ratio 0.4 and frequency 5 Hz

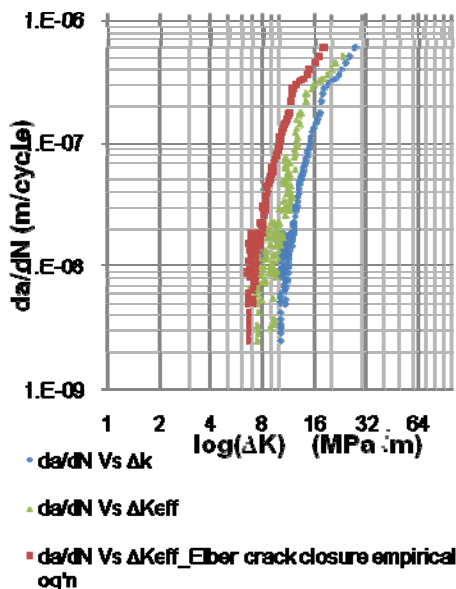


Fig. 9: (d) Stress ratio 0.4 and frequency 1 Hz

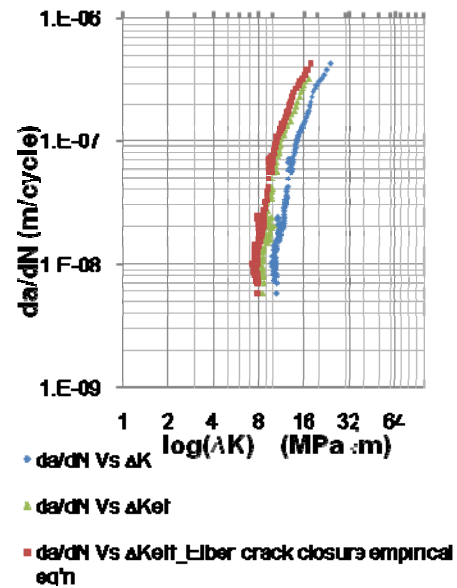


Fig. 9: (e) Stress ratio 0.6 and frequency 1 Hz

Fig. 9: Comparison of corrosion fatigue crack growth rate between Elber crack closure relation and ASTM compliance offset method

As the stress ratios are increased the Elber's crack closure approximation agrees well with the crack closure measurements estimated by ASTM compliance offset method; as the stress increases the effect oxide induced crack closure will not have much effect on the crack growth. The Elber's crack closure relation deviates at low frequencies operation from the ASTM compliance offset method, but at  $R=0.6$  and 1 Hz the well agrees with the above two methods.

#### IV. CONCLUSION

Based on this study the following conclusions can be made:

1. It is observed that there is an increase in the crack growth and reduction in the threshold stress intensity for the material when tested in 3.5% saturated NaCl environment compared to data obtained under lab air conditions.
2. It is understood that the crack propagation per cycle is very sensitive to stress ratio and the maximum stress intensity factor. At higher stress ratios, the mechanism by which crack propagation under corrosive environment is less compared to that of crack propagation due to the localized crack tip loads.
3. It is observed that, at lower frequencies the crack growth is accelerated due to the aqueous environment present at the crack tip.
4. It is also observed that crack closure is due to the both the plasticity around the tip and the oxide layer formation at the crack tip. At higher stress levels, the oxide layer formation will be less, so the plasticity induced crack closure will dominate. But at lower stress ratios both will show considerable effect on crack closure.



5. Due to the reduced available time for corrosion to interact with metal at the crack tip, the effect corrosion product crack closure decreases as the fatigue testing frequency increased. Due to the high frequency the corrosion products are ejected during the pumping of saline water at the crack tip.

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