FATIGUE CRACK PROPAGATION AND ENDURANCE LIMIT OF THE WELD BOND REGION IN STRUCTURAL STEEL

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ABSTRACT

The fatigue crack growth in structural steel types welded joint were investigated. A particular attention, is emphasized on fatigue crack growth of cross bond type crack, where crack is intended to take place in two different regions, one of which is the weld metal region and the other is the parent metal region. During cyclic loading local plastic flow may take place under the influence of stress concentration which can lead to fatigue crack initiation. On the otherhand, if initial crack are presented before testing, it means that crack propagation will start and observed on specimens fatigued under rotating bending test. The condition of crack propagating cracks in welded joints will control the fatigue limit of the joint itself. Fatigue limits tends to fall from the average level when other factors of steel properties and dimensions are included. Fatigue limit results were analysed in relation to the threshold ΔK-J on the basis of non linear fracture elastic-plastic principals.

INTRODUCTION

Extensive number of researches have studied the fatigue crack propagation in welded joints. Most of them were concerned with the effect of residual stresses, micro structures and heterogeneity in mechanical properties. However, in most of these studies attention was focussed only on cases of homogeneous properties along the crack front (1,2). Another group of studies were concerned with crack propagation through bond regions of different type of groove weldment where properties and micro structure along crack front are usually inhomogeneous (3,4). The growth rate of the weld metal specimen or parent metal are clearly studied with respect to residual stress distribution and effective stress intensity range. In the present study the crack growth rate is studied together with the stress intensity concept defining fatigue limit as the lower stress intensity limit for cyclic dislocation activity. Therefore the traditional S-N curve is obtained for welded specimen subjected to a definite state of stress induced during rotating bending test. The crack growth rate of different weld joints through weld metal or parent steel as well as cross the bond weld interface are measured and monitored. Moreover the relationship between crack growth rate and effective intensity range ΔK_{eff} are plotted. The effective intensity is calculated by using the load range from the crack opening load to the maximum load. The C.O.D. is measured from the lack of straightness of the rotating bend specimen.

Thus for most cases of weld shape the S-N curve may be obtained from the summation of crack increment up to the critical crack length. The number of cycles to fracture should be equal to that causing crack propagation from initial crack size a_o to critical size a_{cr} at the monitored test stress. The observed fatigues limit is equal to the stress at which transition from elastic to plastic strain will take place. The crack initiation period is normally short and the life time is consumed in propagating of cracks. Therefore for certain flaw size, the number of cycles to fracture decreases and the effective fatigue stress limit is lowered in accordance with the threshold stress intensity ΔK_{th} (1).

EXPERIMENTAL

Specimens were made from mild structural steel and low carbon steel having 0.15 % carbon. Specimens are welded according to, the resulting grain size after annealing was 40 μmm. The specimen cross section diameter is 10 mm. Fatigue tests were carried out at 4 point bending using a support span 88 mm. The middle of the specimen where joints are presented intended to suffer the greatest cyclic stress, notches are bored around the cylindrical specimens to serve as crack starters, notches either 6 mm or 7.5 mm notch depth with a root radii of about 0.2 mm or 1.5 mm. Two types of notches were examined, the shallow notch at the cross bond region is intended to have an elastic stress concentration factor equal to 1.04 was machined in the middle of the gage length, while deep notches were bored through the weld or parent metal at which stress concentration factor is designed to have a factor equal to 1.5 due to hardenability of that type of cracks and its high compliance to start propagation. The straightness measure reliably giving a measurement accuracy of 0.05 mm as crack opening displacement during crack growth. Tests are conducted on rotating fatigue bending machine at frequency of 20 HZ and 50 HZ, see Figures (1,2) for experimentation conduction and specimens of welded cracks.

The region II of fatigue cracking may pronounce plastic component of deformation under constant amplitude of loading. Therefore range of ΔJ integral are substituted by range of stresses $\Delta\sigma$, the crack length growth rate is presented against the J integral range. In region II where high crack growth rate is attained, the Paris law is adapted to:

$$\frac{da}{dN} = C\left(\frac{\Delta J}{\Delta J_o}\right)^n \tag{1}$$

where J is the integral in the crack field at the elasto-plastic region where large crack may take place

J_o is the integral in the crack field without precrack where small crack are susceptible. (2)

Two stress amplitudes close to the fatigue limit were chosen 20 HZ and 50 HZ where the amount of plasticity is very low in the 20 HZ, and thus ΔJ is nominated as ΔJ_o and its value was calculated from the relation

$$\Delta J_o = \Delta K^2 / E \tag{2}$$

CYCLES TO FATIGUE FRACTURE FUNCTION

The rate of crack growth is not significantly affected by variations in proof stress or ultimate tensile strength within the range of low alloy steels used for general structural purposes. These properties only affect the initiation period, which, being negligible in welds, results in little influence on fatigue life. This beha contrasts with the fatigue of non-welded details w increased mechanical strength generally results improved fatigue strength and life serv consequently crack growth rate, particularly at stag in steels subjected to fatigue loading described by following relation (Paris, Erdogaer, 1963)

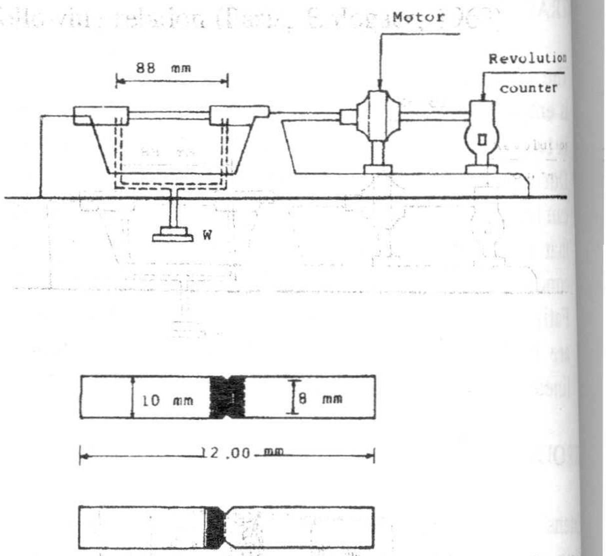


Figure 1. Lay out of testing machine and weld specimens.

$$\frac{da}{dN} = A(\Delta K)^m \quad ($$

Where da/dN fatigue crack growth rate

ΔK fatigue stress intensity range of propagati threshold.

A and m are constants that depend on materi environment, frequency, stress ratio and temp. (3)

In Figure (2) data are presented relating to da/dN v ΔK for low carbon and high tensile local produ steels. Simplicity necessitates using L.E.F.M princip for evaluation of stress intensity range as,

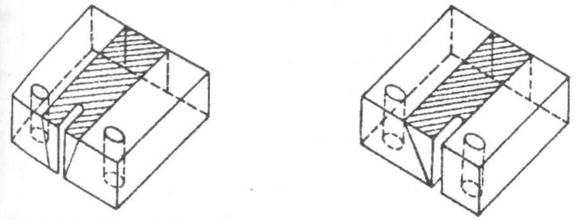
$$\Delta K = \Delta\sigma\sqrt{\pi a} \quad ($$

Where $\Delta\sigma$ fatigue stress or amplitude of stress range

a crack length

Substituting 4 in 3 then;

$$\frac{da}{dN} = A(\Delta\sigma)^m \pi^{m/2} a^{m/2}$$



Crack through weld metal only C.T. Spec.

Crack Crosses Weld metal and parent metals

Figure 2.

Therefore for an initial crack of length a_o, the number of fatigue cycle required to extend the crack length from a_o to a will be

$$N = \frac{1}{A}\int_{a_o}^{a} \frac{1}{\Delta\sigma^m\ (\pi a)^{m/2}}\, da$$

Where,

$N = N_a - N_o$

N_a = Number of cycles up to crack length a

N_o = Number of cycles to initiate an initial crack a_o

$$\begin{aligned} N &= \frac{1}{A(\Delta\sigma)^m\pi^{m/2}}\int_{a_o}^{a} a^{-(m/2)}\, da \\ &= \frac{1}{A(\Delta\sigma)^m\pi^{m/2}}(a^{1-m/2} - a_o^{(1-m/2)}/(1 - m/2) \\ &= \frac{a_o}{A(\Delta\sigma)^m\pi^{m/2}}\left(\frac{2}{2-m}\right)\left[\left(\frac{a}{a_o}\right)^{1-m/2} - 1\right] \end{aligned}$$

Substituting ΔK of equation 4, therefore number of cycles N VS stress intensity ΔK will be,

$$N = \frac{a_o}{A(\Delta K_o)^m}\frac{2}{2-m}\left[\left(\frac{a}{a_o}\right)^{1-m/2} - 1\right] \qquad (5)$$

$$\text{for } m > 2$$

OR

$$N = \frac{a_o}{A(\Delta K_o)} \ln\left(\frac{a}{a_o}\right) \qquad (6)$$

$$\text{for } m = 2$$

FATIGUE CRACK GROWTH AND STRESS INTENSITY LIMIT THRESHOLD CRACKING ΔK_{th}

The fatigue growth rate in a benign environment may represented by the Paris, Erdogan equation in 1963 within the region II of fatigue cracking as follow, (4)

$$da/dN = A(CK + K_R^T)^m \qquad (7)$$

Where, da/dN fatigue crack growth rate

k	stress intensity range for cracked specimen.
K_R^T	sum of stress intensity due to residual strains.
c,m	constant that depend on material properties, frequency, stress ratio and environment.

$$k_R^T = \Delta\sigma\sqrt{\pi a} \qquad \& \qquad \Delta\sigma = k(\epsilon p)^n \qquad (8)$$

Therefore,

$$k_R^T = k(2\epsilon p)^n\sqrt{\pi a} \qquad (9)$$

Where,

n strain hardening exponent of material in the experimental stress-strain relation in equation (8)

2 ϵp cyclic plastic strain of Figure (3) and Figure (4). Recent experimental studies carried out by Hickerson in 1982 (3) given the following relation between constants A and m during region II of fatigue cracking as follow,

$$\text{Log } A = a + bm \qquad (10)$$

Where a and b have the same values for the same material regardless of specimen shape or dimensions, therefor it was one of the purposes of this work is to establish definite values for a,b in case of Egyptian structural steel to be adequate for fatigue studies by using the rotating fatigue bending facility.

EXPERIMENTAL RESULTS

The material used in this study were specimens of local product low carbon steel. The chemical composition and mechanical properties are given in Table (1) and (2). The specimens of crack growth were cut out from a steel plate of 12.5 mm thickness, in such a manner that the loading direction coincided with the direction transversal to the rolling direction. While fatigue specimens are selected from rebars of 13 mm and rounded to 10 mm diameter for testing. The welded Joint's were carried out by using SMAW with the weld conditions indicated in Table (3).

Table 1. Chemical composition.

	C	Si	M_n	S	P
ASTM G 60 Rebars	0.25	0.30	0.60	0.05	0.06
AISI G 400 Sections	0.15	0.25	0.96	0.033	0.017

Table 2. Mech. Properties

	T.S. kg/cm^2	Y.P. kg/cm^2	% EL	% R.A.	k t/m^2
Rebar	6300	4200	10	30	2500
Plate	5200	3600	12	40	2200

Table 3. Welding conditions.

Weld electrode	E 80 xx
Welding current	120 amp.
arc volt	25 volt
weld speed	15 cm/min
number of pass	5 + 1

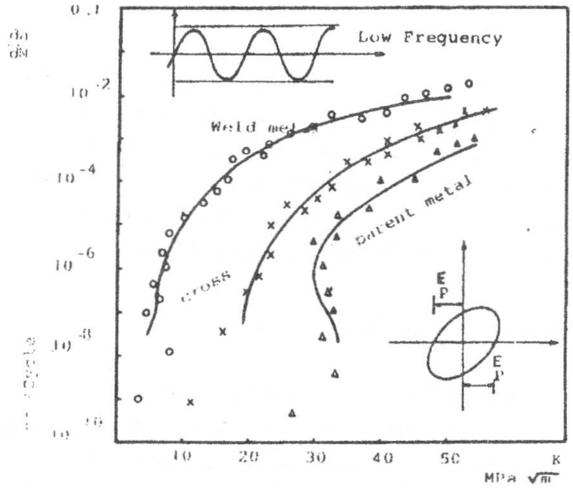


Figure 3. Crack growth rate VS stress intensity.

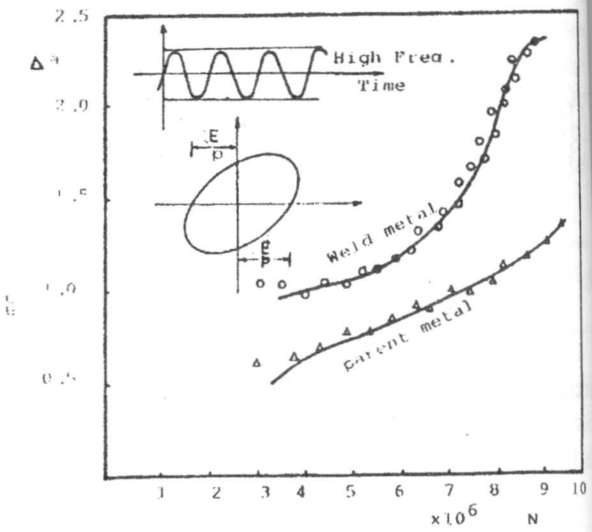


Figure 4. Crack length VS no. of cycles for hi rotating specimens.

The threshold stress intensity test was carried out o a manual tensile grip, that can be adjusted to perfor a straining rate of 5 (10^{-3})/sec, in the same order a which the fatigue bending machine is adjusted. Th rotating bending machine produce a similar rate whil fluctuating at frequency from 20 HZ to 50 HZ.

Fatigue crack growth rate as a function of th effective stress intensity range keeping a constant strai rate are plotted for parent metal (plate) and weld meta (electrode) in Figure (3).

The rotating bend specimens crack length wer measured at interval of times and the results are plotte in Figure (4), for parent metal (Rebar) and weld meta (electrode) constants of equation 7 and 8 are obtaine from data obtained in Figure (3) and Figure (4) an given in Table (4).

Table 4. Material constants.

Parent Metal	Weld Bond Region
a = 6.738	7.505
b = 1.037	0.966
n = 0.504	0.388
$\epsilon p = 8.5(10)^{-6}$	$7.9\ (10)^{-7}$

Table 5. Cracking threshold constants.

m	0.5	1	2	3	4
A for rebars	$1.80(10^{-7})$	$5.956(10^{-7})$	$6.495(10^{-8})$	$7.073(10^{-9})$	$7691(10^{-10})$
A for plates	$9.727(10^{-7})$	$2.958(10^{-8})$	$2.735(10^{-9})$	$5.529(10^{-10})$	$2.338(10^{-11})$

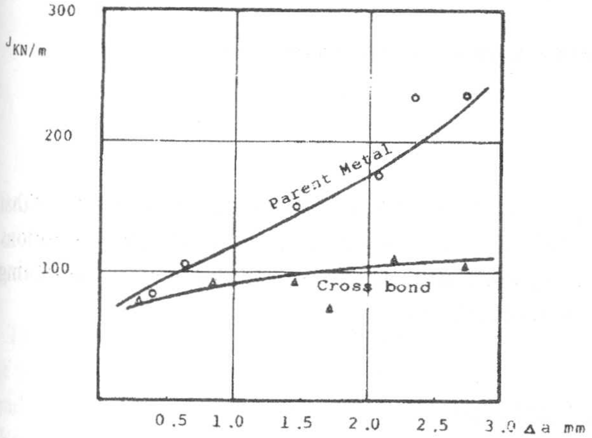


Figure 5. Integral J VS crack length.

ANALYSIS OF RESULTS

The analysis of fatigue crack growth data was carried out using the modified L.E.F.M. principal. The predictions are made using the crack growth equation (1). A threshold values of $\Delta\ k_{th}$ correspond to stress amplitude close to the fatigue limit are obtained. For these values of high stressing, amount of induced plasticity was found very low and integ. J is evaluated from Δk_{th} as given in Figure (5). Predicted lives for the L.E.F.M., and test results are given in Table (7) as predicted from the threshold compact tension test results revealed fracture stresses as indicated in Table (6).

The rotating bend test is conducted for each precracked specimen as a ΔK constant test since ΔK varies between 28 MPa $435474\sqrt{m}$ to 32 MPa $\sqrt{m}$. The relation between crack growth rate in Figure (3), only long through crack are represented, short cracks are scattered, simultaneously, because small cracks always have much greater tendency for closure, although the center region of the crack front remain open. Raising the frequency of applied load, increasing the crack opening, stress will delay the crack growth at the region. As the initial crack is larger than threshold one, the crack grows to the long crack regime, the total force at the tip may become tensile during the transition from elastic to elasto-plastic and integral J is used Figure (5).

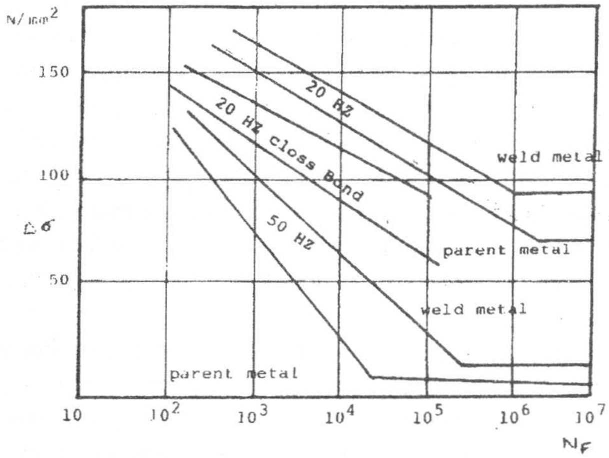


Figure 6. S-N for structural steel joints.

Table 6. Spectrum of crack threshold intensity of C.T. specimens.

Material Region	Initial Crack Length mm	Crack width mm	Stress Intensity Mpa m	Stress Amp. N/mm²
Weld Metal	10	2	40	100
	20	4	60	200
	30	3	50	180
Weld Cross region	10	3	80	150
	20	5	70	310
	25	4	50	240

Table 7. Spectrum test results.

Material	Notch C.S.A. %	Initial crack length mm	Stress amplitude N/mm^2	No of cycles x10^5	Expected lives x10^5
Rebar	30	1	50	80	60
Plate	40	3	60	40	50
Weld Material	20	2	80	25	20
Cross plate	30	4	120	10	12

CONCLUSION

The fatigue limits of a series of structural steel joints are discussed in relation to weld type, size and fracture toughness of material used in welded joints. The crack growth rate in the weld metal through weld direction rather higher than that crack propagate in the parent metal. The crack growth rate and behaviour at the cross bond region seemed to have an intermediate rate and behaviour of the two different regions of the weld metal or the parent metal to homogenize cracking behaviour in both weld material and parent metal, heat treatment is a must, particularly for weld details (weld lines and regions) to reduce the effect of residual stresses at weld zone.

Moreover crack growth rate and constants of Paris equation has to be determined accurately for good prediction of specimen lives. The following most important conclusions drawn from the life prediction of precracked welded joints:

1. Short cracks (exhibit a length $\leq$ threshold propagation length) sustained cyclic loads at low frequency what ever where the crack takes place first through metal or parent one.
2. Long cracks (having length > threshold length) reveal short life time only when crack propagate through weld metal inspite of the frequency. Long crack at parent metal will sustain much longer except the neighborhood of the threshold length.

Expected life based on L.E.F.M. description or the obtained from J integral at the elasto plastic regions agree very well with experimental data of rotating bend specimens.

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