Fatigue Failure of Structural Steel – Analysis Using Fracture Mechanics

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***Abstract*—**Fatigue is the major threat in service of steel structure subjected to fluctuating loads. With the additional effect of corrosion and presence of weld joints the fatigue failure may become more critical in structural steel. One of the apt examples of such structural is the sailing ship. This is experiencing a constant stress due to floating and a pulsating bending load due to the waves. This paper describes an attempt to verify theory of fatigue in fracture mechanics approach with experimentation to determine the constants of crack growth curve. For this, specimen is prepared from the ship building steel and it is subjected to a pulsating bending load with a known defect. Fatigue crack and its nature is observed in this experiment. Application of fracture mechanics approach in fatigue with a simple practical experiment is conducted and constants of crack growth equation are investigated.

***Keywords*—**fatigue, fracture mechanics, fatigue testing machine

I. Introduction

Fatigue is the phenomena of failing a component under cyclic loading prior to its ultimate stress. Theories of failure describe the condition for failure. When external stress exceeds a possible value of maximum tensile stress, maximum compressive stress or maximum shear stress the component will fail. In case of fatigue failure, the failure will happen much early to the maximum value of design stress. Fatigue implies changes in properties which can occur in a metallic material due to repeated application of stress and strains, specially to those changes which lead to cracking or failure.

Fatigue crack almost always grow from welds in steel welded structures. The reason is that the welding process invariably leaves metallurgical discontinuities of minute sizes in the welds cracks develop from these discontinuities. Welds are usually rough in toes of butt welds and toes and roots of fillet welds, there are sharp changes in curvature and hence have local stress concentration. Cracks may develop from these areas.

Corrosion in steel will accelerate the fatigue failure. Surface damage or scratch or surface cracks are also may be a crack initiation point provided it acts as stress riser while the component experiences a fluctuating loading.

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Methodologies for damage tolerant evaluation of structural components under fatigue loads are known. Towards achievement of objectives of damage tolerant, namely, residual strength and remaining life, stress intensity factor has been computed accurately for the fatigue loading. The remaining life prediction has been carried out by employing Linear Elastic Fracture Mechanics (LEFM) principles.

II. Fracture Mechancanics

A. History

Fracture mechanics is solid mechanics of cracked bodies. Quantifying effects of crack-like defects was first taken by C E Inglis [1], a professor of Naval Architecture, in 1913; he published stress analysis of an elliptical hole in an infinite linear elastic plate loaded at outer boundaries where a crack-like discontinuity results by making the minor axis of the hole much smaller than the major axis. The equations are formulated which are then further modified by Griffith [2]

B. Basic equations

As pointed out by the HSE(2001), the use of fracture mechanics may be recommended for case where the standard S-N procedure is inappropriate, in particular for cracked joints difficult to repair, unusual structural details not covered by experimental S-N curve, definition of the periodicity of in-service inspections and assessment of the remaining life of cracked joints.

Even though the stress range, stress ratio, mean stress and amount of damage are the main parameters contributing to the fatigue crack growth [4,5,6,7]. In Linear Elastic fracture mechanics (LEFM) the stress intensity factor 'K' is the key parameter in the calculation of the fatigue damage. The distribution and intensity of stress and strains in the vicinity of a crack is obtained using either the LEFM or the Elastic Plastic Fracture Mechanics. LEFM, which is the most currently used approach, is based on the assumption that the plastic zone occurring at the crack tip is too small to significantly modify the stress distribution. There are three different basic modes of cracking, the opening, sliding and tearing modes

The stress intensity factor K depends on the loading, external geometry, and crack size and shape and may be expressed by the following general equation.

$$K = \sigma\sqrt{\pi a}\,Y \tag{1}$$

The IIW (1996) proposes a more elaborate expression for K with explicit differentiation between membrane and bending stresses:

$$K = \sqrt{\pi a}\left(\sigma_m Y_m M_{k,m} + \sigma_b Y_b M_{k,b}\right) \tag{2}$$

Many proposals (for example, Newman and Raju (1981) and (1983) are available in the literature for calculation of the correction functions Y_m and Y_b, accounting for various geometrical and loading configurations. Moreover, particular methods of calculation, including the superposition and influence function methods, have been developed for more complex cases not given in the literature. As an example, in the superposition method the actual case is decomposed into basic cases that have known solutions for Y and then combined linearly to obtain the actual solution. They can also be calculated using semi-analytical methods such as weight functions or the finite element method (FEM). The correction factors M_k can be found from Maddox et al. (1986) and Hobbacher (1994).

For predicting crack growth a lot of mathematical and experimental investigation has been carried out. The well-known Paris and Ergodan [3] equation describes the crack growth rate in the intermediate region:

$$\frac{da}{dN} = C_0 (\Delta K)^m \tag{3}$$

This equation can be used for finding the life of the component or number of fatigue cycles the component will withstand to fail.

$$N = \int_{s_0}^{a_f} \frac{da}{C(\Delta K)^m} \tag{4}$$

There are many equation based on the studies of Paris and Erdogan [3] in the region of use full service time of the component under fatigue loading

TABLE I
LIST OF SYMBOLS

Symbol	Quantity	Description / unit
Y	Shape factor	Depends on the specimen geometry
N	Number of Cycles	number of stress reversal on specimen
a & b	Half length of the crack	Measured on surface width & thickness direction
m &C	Constants of Paris equation	Depends on material
σ_m σ_b	Nominal membrane and shell bending stress	Newton's per mm square
Y_m Y_b	correction function	Membrane and bending stress intensity factor
σ	stress	Newton's per mm square
da/dN	Crack growth	Millimeter per minute
K	Stress intensity factor	
G	Strain energy release rate	
$M_{k,m}$ $M_{k,b}$	correction factor	for the local membrane and bending stress concentration due to the weld profile
ΔK	Change in stress intensity factor	
E	Young's modulus	
dU	Strain energy	
dA	Area of fatigue crack	

III. EXPERIMENTATION

A simple experiment with strips of ship building steel may reveal some of the characteristic of pulsating bending cyclic loading. A strain controlled machine can be constructed for this purpose. Fatigue crack growth evaluation can be done with this machine by using a constant displacement type fatigue loading. The machine/test rig is simple and efficient at the same time it is cost effective also. Cantilever beam specimens cut out from ship building steel and commercially available MS plates are used to conduct the experiment.

Fig. 1 photograph of the Test rig

The test rig consists of
1. A clamping device suitable for fixing specimen with rectangular cross section.
2. Loading device to apply fluctuating load.
3. Recording system and
4. Power unit

The details of experimental setup are given in figure 1. The power unit consists of an induction motor with a speed reduction unit. The loading device consists of a 35mm steel shaft fitted with an eccentric cam assembly with heavy duty bearing to apply pulsating transverse load to the cantilever beam. Other end of the steel shaft is connected to mechanical counter through gear wheels to count the number of cycles of load or rotation of the shaft.

The experiments are conducted at a speed of around 350 rpm. A number of steel specimens are pre-cracked at low strain loads with side notches. The pre-cracked specimens are then machined to predetermine size, having initial cracks (quarter elliptical). They are subjected to fluctuating pulsating loads and resulting crack propagation in depth and length directions where recorded. The residual strength of specimens at intervals is assessed by load displacement plots.

IV. Results and Discussions

A. Observation of fatigue crack

The pre-cracked specimens subjected to pulsating bending loading will produce a hitting sound because of the loss of strength due to the increased size of the fatigue crack. The period of crack initiation is very short relative to the crack propagation period. A number of specimens of both MS and Ship building steel are used for conducting the experiment. The specimens are then dip in liquid nitrogen for sufficient time to make it brittle so that it can brake into two at the crack plane. The true shape of the crack can be observed at the cross section of the specimen. One of the observed fatigue crack photo graphs are displayed (figure 2)

Fig. 2 Quarter elliptical shape of crack observed

B. Method to find crack growth constants

In fracture mechanics the crack growth curve is plotted as a sigmoid curve which is started at the threshold of crack initiation and proceed to the crack propagation region and finally to a faster rate of crack growth. The figure 3 shows a typical crack growth sigmoid curve.

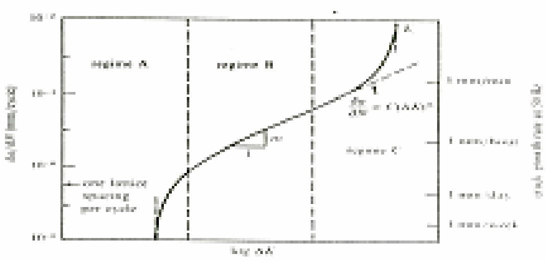

Fig. 3 a typical sigmoid curve

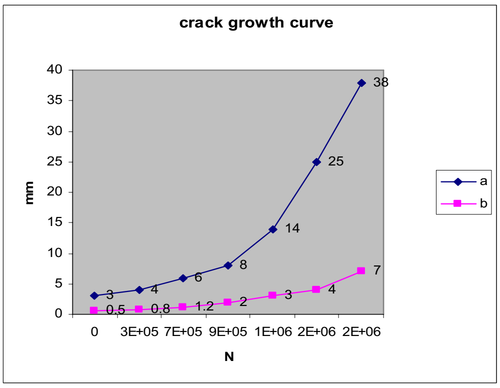

Fig. 4 crack growth curve

Figure 4 shows the change in rate of crack growth with the applied cycle. It can be observed that from the initial crack as the cycling proceeds increment in length is very little but towards the end of the experiment, the growth rate will become faster From the experimental results the crack growth rates in thickness direction are computed and plotted against stress intensity factor ranges using log scale resulting in fatigue crack

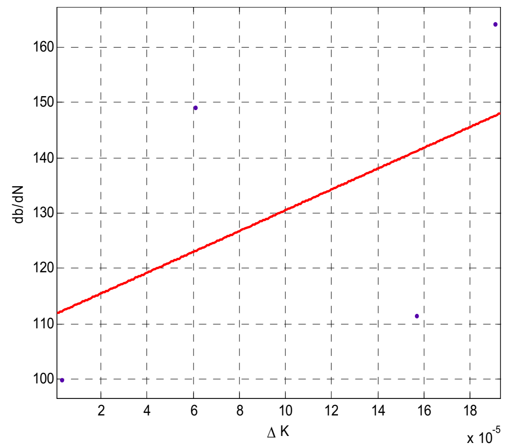

Fig. 5 crack propagation curve

propagation curve for mild steel as given in Figure 5. This curve will be useful to generate the fatigue crack propagation rate which in turn can be used to assess the life of a structure/ component made of mild steel with an initial crack.

Stress intensity factor range ΔK can be found by observing the load deflection curve at the beginning of the experiment and at the end of the experiment the area enclosed between the plot of load Vs. deflection (figure 6) with out crack and with crack (initial & final) will give dU strain energy and the corresponding area d/A can be directly measured form the specimen.

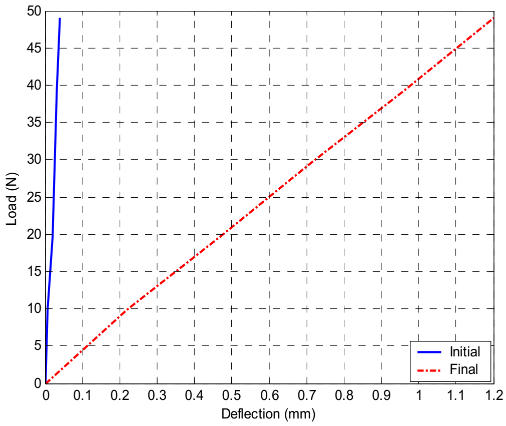

Fig. 6 load-deflection curve

The quantity dU/dA is the strain energy release rate G. Strain energy release rate G and stress intensity factor K can be related as $G=K^2/E$, where E is the Young's modulus of steel for a particular specimen from initial to final value of the crack, K can be considered to be ΔK

It may be observed that the crack propagation is strongly related to the parameter, stress intensity factor range. Once the plot of db/dN vs. ΔK is completed a suitable straight line fit can be done for the points to get the middle portion of sigmoid curve. Since the mid portion of the sigmoid curve follow Paris equation any two known points will give the values of two unknown constants in the equation

V. Scope of the Testing Machine

The testing machine can be used for the following purposes.

1) In order to conduct a fatigue test on a flat specimen. The length, width and thickness of the specimen on the testing machine can be standardized.
2) Change in fatigue crack growth under corrosive ambient and weld on structure can be examined.
3) The effect of higher amplitude stress cycle followed by lower amplitude stress cycle can be observed. Nature of crack growth on stress reversal can be studied.
4) Life of the specimen can be estimated. This can be used for predicting the total life span of the structure.
5) For an estimated fixed life span of the structure the maximum allowable defect can be found.

VI. Conclusion

Study of pulsating bending effect of ship building steel is carried out which may be use full in design of ship structural plate. If a probabilistic approach can adopt for random wave effect in real sea situation converted in to equivalent constant amplitude pulsating bending loads. The experiment will be very much valid. Since this can predict life of the component in constant amplitude pulsating bending loads.

Further work on composite materials, welded specimen and corrosion fatigue is in progress

Acknowledgement

The authors express their sincere thanks to the Institute of Human Recourse Development (IHRD) Thiruvananthapuram and Technical Education Quality Improvement Program me (TEQIP) for sponsoring this paper for presentation.

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