PREDICTION OF FATIGUE CRACK PROPAGATION LIFE IN SINGLE EDGE NOTCHED BEAMS USING EXPONENTIAL MODEL.

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Mechanical Engineering

(Specialization: Machine Design and Analysis)

By

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DEPARTMENT OF MECHANICAL ENGGINEERING

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CERTIFICATE

This is to certify that the thesis entitled, "**Prediction of fatigue crack propagation life in single edge notched beams using exponential model**" submitted by **Mr. Avaya kumar baliarsingh** bearing **Rollno-211ME1344** in partial fulfillment of the requirements for the award of Master of Technology in **Mechanical Engineering** with **Machine Design and Analysis** specialization during session 2011-2013 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela, is an authentic work carried out by him under our supervision and guidance.

To the best of our knowledge, the matter embodied in this thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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ABSTRACT:

Metal beams are extensively used in structures, automobile sectors and machine components. Some of their applications include connecting rod of IC engine, shafts, axles, and gears, structures members of bridges and also components of machines. Most of them experience fluctuating or cyclic load condition in their service life's such loading conditions may initiate a crack and cause fatigue crack growth. The monitoring and modeling of fatigue crack growth are necessary for the stability and safety of machines and structures. In the present investigation an attempt has been made to develop a fatigue life prediction methodology by using an Exponential Model in single edge notched (SEN) cracked beams. The predicted results are compared with experimental crack growth data. It has been observed that the results obtained from the models are in good agreement with experimental data.

Keywords: -Beams, crack profile, fatigue crack propagation, constant amplitude loading, life prediction, exponential model.

CONTENTS

LIST OF FIGURES:

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NOMENCLATURE:

C	Compliance (mm/N)
V	Displacement of COD gauge (mm)
P	Applied load (N)
a	Crack depth / length (mm)
B	Specimen thickness (mm)
W	Specimen width (mm)
L	Specimen length (mm)
F (g)	Geometrical factor
σ_{max}	Maximum stress in a cycle (MPa)
σ_{min}	Minimum stress in a cycle (MPa)
σ_a	Stress amplitude(MPa)
σ_r	Stress range(MPa)
R	Stress ratio
μ	Poisson's ratio
E	Young's modulus (MPa)
a_i	initial crack length (mm), for exponential model
a_j	final crack length (mm), for exponential model
A, B, C, D	curve fitting constants
da/dN	crack growth rate(mm/cycle)
K	stress intensity factor (MPa$\sqrt{m}$)

K_C	fracture toughness (MPa√m)
ΔK	stress intensity factor range (MPa√m)
m	specific growth rate
m_{ij}	specific growth rate in interval j-i
N	number of cycles
$N^P{}_j$	predicted fatigue life using exponential model
P	population
P_o	initial population
$P\ (t)$	population at any time
R	load ratio
t	thickness of specimen(mm) exponential model
σ_b	bending stress (MPa)

CHAPTER -1

INTRODUCTION

INTRODUCTION

1.1Background

Failure due to repeated loading, that is fatigue, has accounts for at least half of this mechanical failure. No exact data is available, but many books and articles have suggested that between 50 to 90 per cent of all mechanical failures are due to fatigue, most of this is unexpected failures [1]. In many situations a beam experiences fluctuating loading conditions. This may initiate and propagate a crack. The monitoring and modeling of fatigue crack growth is more significant for the stability and safety of machines components, bridges, aircraft and structures. In this project (EN8) medium carbon steel beam is used. In fatigue fracture the stress is generally below the yield stress. In general ductile material deforms before fracture and gives warning before failure of a component but in case of fatigue failure the ductile materials fails suddenly. This becomes more significant when failure is related to automobile sectors or machinery parts in which heavy loads or continuous work being done. In a dynamic world, however, failure occurs at stresses much below the material's ultimate strength or yield strength. This phenomenon, failing at relatively low stresses, came as quite a surprise to most engineers in the early years of metal component design and manufacturing. The other frustrating aspect is that the material exhibited no sign of its tiredness or fatigue and could fail without much warning. This could be more dangerous if proper selection of design criteria is not selected and validation of those criteria with experiment is not done. There are many areas where the fatigue criteria should be in mind before designing the component.

1.2 Objectives

The objective of present work is: To develop compliance correlation of a-N data and estimation of fatigue crack propagation life by using exponential model.

1. To conduct fatigue crack propagation test of supplied (EN8) medium carbon steel under constant amplitude loading condition with different stress ratios.

2. To propose an exponential model to predict fatigue crack propagation in single edge notched cracked beam.

1.3 Thesis structure

The concept of present investigation is presented through six chapters. The first chapter presents an introduction of present work, 2nd chapter presents a brief review of literature. Chapter-3 describes the details of experimental procedure. Chaper-4 describes generation of crack profile and calibration of COD gauge, Chapter-6 describes the formulation and validation of proposed exponential model under constant amplitude loading condition with different stress ratios. Chapter-7 and Chapter-8, describes conclusion and possible future work respectively.

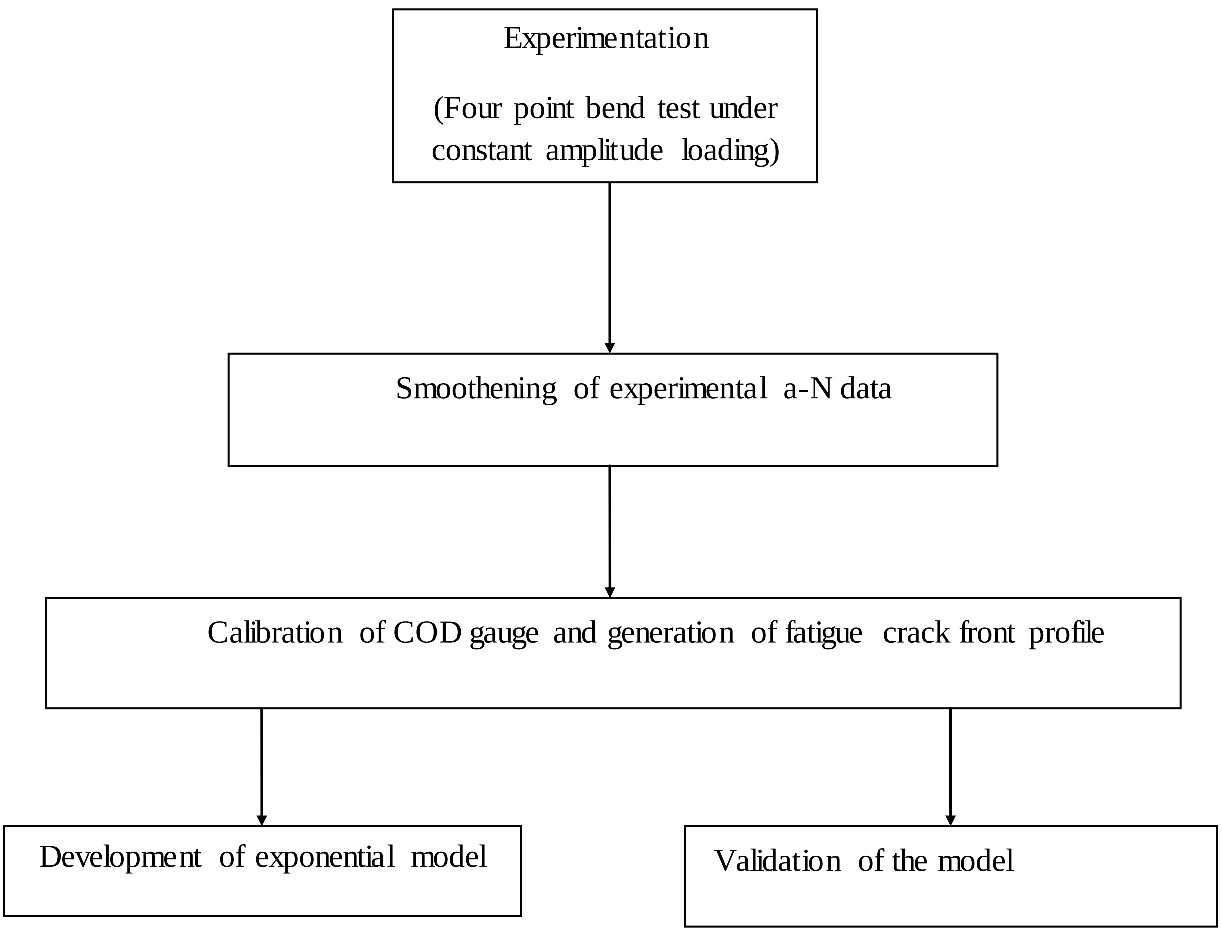


Fig. 1.3.1 Plan of work

The crack initiation starts in a point where the stress concentration is high. This stress concentration may be due to abrupt change in cross section or due to defect present within the system. The change of the cross section can do in such a way that the stress concentration will be lower. But the defect due to manufacturing process cannot be eliminated completely because of the complex nature of manufacturing and human interference.

Detection and measurement of fatigue cracks and damage can, in general terms, be classified into the following two groups according to their areas of application: laboratory methods and field service assessment methods. Numerous approaches and techniques are available to specify crack initiation and measure crack size for laboratory and field applications are summaries in table1.1. The fatigue damage can be measured as the progressive development of a crack from the sub-microscopic phases of cyclic slip and crack initiation, followed by the macroscopic crack propagation stage, to the final distinct fracture. These three stages are important in defining the fatigue life of specimen and structural components. In many situations, crack initiation can, however, be the primary event for life estimation and design analysis , such as the applications of σ (applied stress) versus N (fatigue-life cycle) curves. Crack initiation is the originator of fatigue failure. If the early stage of crack initiation can be identified, the mechanisms of crack initiation can be better understood and fatigue failure may be banned. When selecting a method or technique for fatigue crack detection or monitoring and measurement, sensitivity or crack size resolution plays an important role. The selection of crack measurement technique depends on loading type, specimen type, material, environment, crack initiation site, crack detection method, and sensitivity [2].

For example, loading condition could be bending, axial, reverse bending, tension, and mode II loadings. Specimen types could be plate, bar, welded plate, cylindrical bar, compact-type (CT) specimen, blunt-notched specimen, and three-point bend bar, four points bend specimen etc. The environmental condition could be air, water, vacuum, hydrogen, helium, and oxygen.

CHAPTER -2

LITERATURE REVIEW

2.1 Literature review

Several experiments and models have been proposed till date in order to predict fatigue crack propagation with load control method under constant amplitude loading conditions with different stress ratios with the help of INSTRON-8800. Generally crack length is measured by travelling microscope determined by mathematical modeling of standard specimens or by empirical relationship or by experimental investigation. We are here doing the experimental procedure to find out the crack length for beams. Generally compliance crack length relationship and four point bend test are used for determination of crack growth. The objective of present work is to develop compliance correlation of *a-N* data and estimation of fatigue crack propagation life by using exponential model.

Cyclic fatigue involves the microstructural damage and failure of materials under cyclically varying loads. Structural materials, however, are rarely designed with compositions and microstructures optimized for fatigue resistance. Metallic alloys are generally designed for strength, intermetallics for ductility, and ceramics for toughness; yet, if any of these materials see engineering service, their structural integrity is often limited by their mechanical performance under cyclic loads. In fact, it is generally considered that over 80 percent of all service failures can be traced to mechanical fatigue, whether in association with cyclic plasticity, sliding or physical contact (fretting and rolling contact fatigue), environmental damage (corrosion fatigue), or elevated temperatures (creep fatigue). Accordingly, a large volume of literature has been amassed particularly over the past twenty-five years, dealing with the mechanics and mechanisms of mechanical fatigue failure [1, 2].

Subcritical crack growth can occur at stress intensity K levels generally far less than the fracture toughness Kc in any metallic alloy when cyclic loading is applied ($\Delta K_{TH}/Kc$ *is nearly equal to* 0.1 – 0.*4*). In simplified concept, it is the accumulation of damage from the cyclic plastic deformation in the plastic zone at the crack tip that accounts for the intrinsic mechanism of fatigue crack growth at K levels below Kc. The process of fatigue failure itself consists of several distinct processes involving initial cyclic damage (cyclic hardening or softening), formation of an initial 'fatal' flaw (crack initiation), macroscopic propagation of this flaw (crack growth), and final catastrophic failure or instability. The physical phenomenon of fatigue was first seriously considered in the mid nineteenth century when widespread failures of railway axles in Europe prompted Wohler in Germany to conduct the first systematic investigations into material failure under cyclic stresses Wohler, 1860 [3]. However, the main impetus for research directed at the crack propagation stage of fatigue failure, as opposed to mere lifetime calculations, did not occur until the mid-1960s, when the concepts of linear elastic fracture mechanics and so-called 'defect-tolerant design' were first applied to the problem of subcritical flaw growth (Paris et al., 1961; Johnson and Paris, 1967). Such approaches recognize that all structures are flawed, and that cracks may initiate early in service life and propagate subcriticaly.

This paper [4, 5] presents the fatigue crack growth analysis on the perforated wide flange I-beam which is subjected to constant amplitude bending loadings. I-beam of grade steel is widely used in building and other structural constructions. The detailed geometries according to the size and weight have been standardized such as ASTM, ISO etc. Since I-beam has a significant contribution in building and other structural constructions, careful considerations has to be taken if defects or cracks are present in the beams. Many researchers have reported the behaviors of beam. Dunn et al.have introduced closed-form expressions for stress intensity factors for cracked square -beams subjected to a bending moment. GAO and Herman [6] have estimated the stress intensity factors for cracked beams. Most structural components are often subjected to cyclic loading, and fatigue fracture is the most common form of failure. In general, fatigue process consists of three stages: initiation and early Crack propagation, subsequent crack growth, and final fracture. The fatigue crack growth rate, da/dN, which determines the fatigue life of the cracked components, has extensively been investigated experimentally and theoretically. Stephens et al. [7] reported that fatigue crack growth curve for constant amplitude loading consisting of the crack growth rate (da/dN) versus the stress intensity factor range (ΔK) in the log–log scale typically includes three regions. Region-I is the near threshold region and indicate the threshold (ΔKth) value which there is no observable crack growth. Microstructure, mean stress, frequency, and environment mainly control Region I crack growth. Region II corresponds to stable macroscopic crack growth that is typically controlled by the environment. In Region III the fatigue crack growth rates are very high as they approach to instability. In Region III crack growth is often ignored in practice due to the insignificant fatigue life remaining upon entering the region. Structural engineers have been utilizing numerical tools/ software packages of Finite

Element Method or Boundary Element Method to assess their designs for strength including crack problems. BEM has emerged as a powerful alternative to Finite Element Method (FEM) for cases where better accuracy is required due to situations such as stress concentration (as in the case of a crack), or an infinite domain problem. Since BEM only requires discretization of surfaces (in case of 3D problems) and discretization of lines (in case of 2D problems), it allows modeling of the problem becoming simpler. Aliabadi [8] reported various applications of BEM to solve solid mechanics problems. Boundary element formulations for modeling the nonlinear behavior of concrete were reported by Aliabadi and Saleh [9]. Fatigue crack growth is required for the assessment of residual fatigue life, or for a damage tolerance analysis to aid structural design. In this paper fatigue crack growth of corner crack in wide flange I-beam under constant amplitude bending loading are presented. A quarter-elliptical corner crack in a prismatic solid is analyzed as benchmarking model for the available analytical solution [10] prior to making further modeling of the cracks.

This paper [11] examines the fatigue crack growth histories of a range of test specimens and service loaded components in Aircraft structures and Joint failures. The crack growth shows, as a first approximation a linear relationship between the log of the crack length or depth and number of cycles. These cracks have grown from; semi- and quarter elliptical surface cuts, holes, pits and inherent material discontinuities in test specimens, fuselage lap joints, welded butt joints, and complex tubular jointed specimens' .This application of exponential crack growth are discussed. The stress intensity factor range, ΔK has for many years been known to have a significant correlation with the crack growth rate, da/dN. The first paper making this correlation was published in 1961 by Paris, Gomez and Anderson [12], who adopted the K-value from the analysis of the stress field around the tip of a crack as proposed by Irwin in 1957 [13]. The results of the constant-amplitude crack growth tests by Paris were expressed in terms of da/dN (where N is the number of fatigue cycles) as a function of ΔK (which is K_{max} - K_{min}) on a double log scale. Plotting such data shows a region of growth where a linear relation between log (da/dN) and log (ΔK) appears to exist. This paper examines the Compliance crack length relations for the four-point bend specimen geometry in the laboratory. Crack lengths can be measured by direct and indirect means. While direct methods of crack length measurement, e.g. by travelling microscope, are tedious and prone to human error, the indirect methods are not only superior in these respects but are also amenable to automation and therefore useful for computer-controlled fatigue testing. The simulation and analysis process is done at various locations in four point bend test. A beachmarked fatigue fracture is produced under 4PB loading. The crack length at each beachmark obtained by optical measurements and compared with that obtained by the crack mouth CCL relation developed [14]. This paper examines the life prediction methodology by adopting an 'Exponential Model' that can be used without integration of fatigue crack growth rate curve. The predicted results are compared with experimental crack growth data obtained for 7020-T7 and 2024-T3 aluminum alloy specimens under constant amplitude loading. It is observed that the results obtained from this model are in good agreement with experimental data and cover both stage-II and stage-III of fatigue crack growth curve [15]. The aim of developing a fatigue crack growth model is to predict a safe operating life while designing a structure/component subjected to cyclic loading. The service life of a structure/machine component under cyclic loading can be estimated by integrating the rate equation of the Paris type. However, direct integration becomes robust and complicated as the geometrical factor 'f (g)' in the expression of ΔK varies with crack length. Therefore, fatigue life may be estimated by numerical integration using different values of 'f (g)' held constant over a small crack length increment [16]. To overcome this difficulty, the authors have attempted to introduce a life prediction procedure by adopting an 'Exponential Model'. The model can predict the fundamental a–N curve to calculate life without integration of FCGR curve. It is worth mentioning that an exponential model is often used for calculation of growth of population/bacteria, etc. In this paper, the fatigue cracks propagate in longitudinally reinforced concrete beams without stirrups. The experimental program has been designed to investigate the influence of the shear span-to-depth ratio on diagonal crack propagation and load carrying capacity of tested beams under four point bend test. The obtained test results were compared with numerical results made on the basis of Finite Element Method [17].In this paper, Fatigue crack growth tests were conducted on double cantilever beam bonded specimens with the aim to characterize an adhesive for structural applications. The tests were conducted in lab air at two different load ratios, and at two different loading frequencies, Crack propagation was monitored using the compliance method by three point bend test and FE model was used also [18].

2.2 Review on fatigue progressive fracture

Fatigue is defined as the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses at some point or points and that may culminate in cracks or complete fracture after certain number of fluctuations [19]. The stress value in case of fatigue failure is less than ultimate tensile stress and may be below yield stress limit of the material.

2.3 Review on cyclic stress history

Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio. Depending on the complexity of the geometry and the loading, one or more properties of the stress state need to be considered, such as stress amplitude, mean stress, biaxiality, in-phase or out-of-phase shear stress, and load sequence[20].

The related terminology is as under:

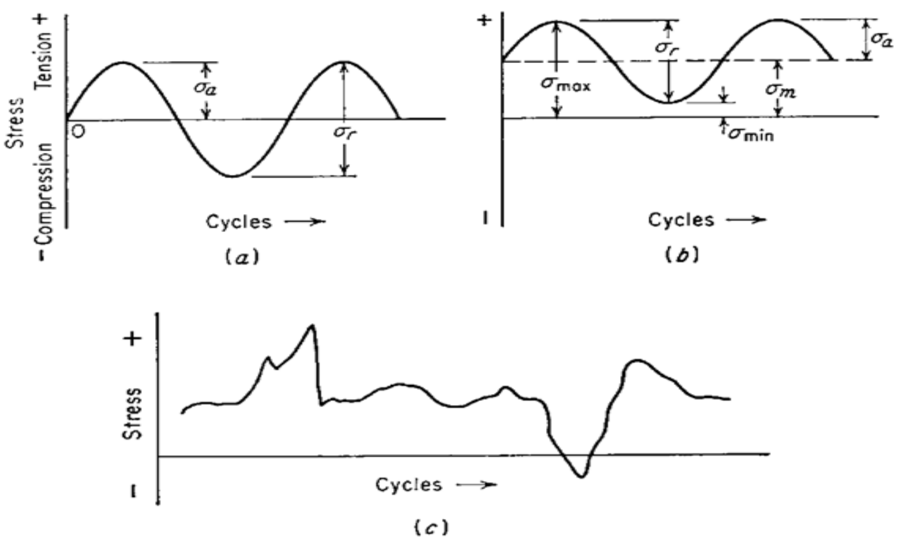


Figure 2.1 **Typical fatigue stress cycles. (*a*) Reversed stress; (*b*) repeated stress; (*c*) irregular or random stress cycle.**

Fig 2.3.1; cyclic stresses

Mean stress: $\sigma_{mean} = (\sigma_{max} + \sigma_{min})/2$

Range of stress $\sigma_r = (\sigma_{max} - \sigma_{min})$

Stress amplitude $\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min})/2$

Stress ratio(R) $= \sigma_{min}/\sigma_{max}$

Where σ_{max} and σ_{min} are maximum and minimum cyclic stress respectively

2.4 Review on modes of loading

There are three types of loading that a crack can experience as shown in figure 2.2 Mode I loading, where the principal load is applied normal to the crack plane, tend to open the crack. Mode II corresponds to in-plane shear loading and tends to slide one crack face with respect to the other. Mode III refers to out-of-plane shear. A cracked body can be loaded in any one of these modes, or a combination of two or three [21].

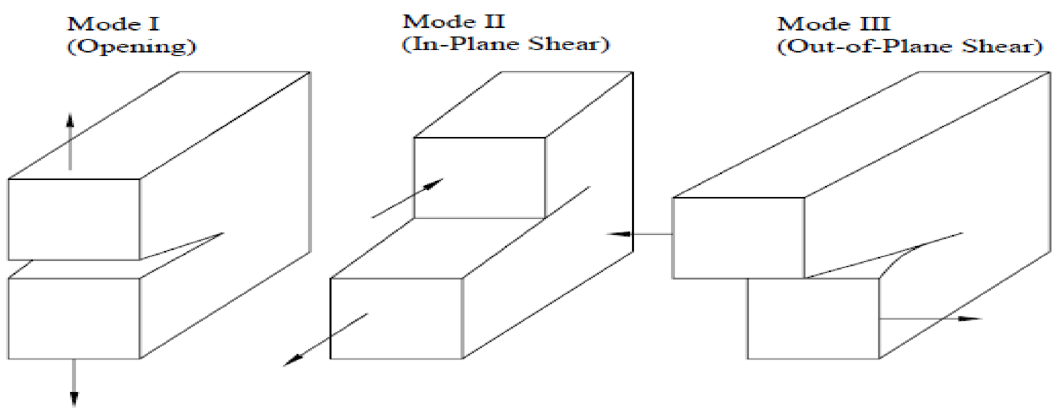


Figure 2.4.1; Three modes of loading that can be applied to a crack

2.5 Review on compliance method

The compliance method is based on the principle that when a test piece or specimen is loaded, a change in the strain and displacement of the specimen will occur. These strains and displacements are changed by the length of the initiated crack. From remote strain and displacement measurements, crack length can be estimated. However, each specimen and crack geometry requires separate calibration. This calibration can be done either experimentally or theoretically. The methods used to measure changes in compliance include crack-opening displacement (COD), back-face strain, and crack-tip strain measurements.

The optimum procedure employs the use of high speed digital data acquisition and processing systems, but low-speed autographic equipment can also be used to record the force and displacement signals. Depending on the data acquisition equipment and cyclic force frequency, it may be necessary to lower the frequency during the period of data acquisition.

The compliance method typically has a crack-length detection sensitivity of 10 μm. The strain gauge method is more suitable than the crack-opening displacement measurement in high-frequency fatigue tests. The unloading elastic compliance method is applicable for both short and long crack measurements [22].

The various compliance methods have its own merits and demerits. For example, the crack opening displacement (COD) method is less expensive, the specimen need not be visually accessible, and it provides an average crack-length outline. However, separate calibration tests are required in many cases.

The COD method has the following advantages: it can be used from nonaggressive to aggressive environments and for various geometry configurations that behave in an elastic manner. It is available in lower cost for room-temperature, air tests to moderately expensive in high-temperature aggressive environments. It can be used as a remote method and is easily automated and it produces an average crack-length outline where crack-front curvature occurs. The COD method, however, has its limitations: separate calibration tests are required in some instances, and it is used for specimens where time-dependent, time-independent, and reversed-plasticity effects are small. The back-face strain method has the following advantages: It is available in low cost for room-temperature tests to moderately higher cost for high-temperature tests. It is remote method and crack increment of 10 μm can be resolved by this method. However, this method could be used only for specimens where time-dependent, time-independent, and reversed plasticity effects are small [22].

The crack tip strain measurement is applicable to various specimen geometries. It can detect crack initiation even in a large-scale plasticity conditions. However, it cannot be used for big specimens where the surface behavior is not the same with the crack growth in the interior. Under linear elastic conditions for a given crack size, the displacement, v, across the load points or at any other locations across the crack surfaces is directly proportional to the applied load (P). The compliance, C, of the specimen is defined as

$$C = \frac{v}{P}$$

The relationship between dimensionless compliance, *BEC*, where *B* is the thickness and *E* is the elastic modulus, and the dimensionless crack size, *a*/*W*, where *W* is the specimen width, is unique for a given specimen geometry [8]. Thus:

$$BEC = f\,(\frac{a}{w})$$

The compliance of an elastically strained specimen is determined by measuring the displacement along, or parallel to, the load line. The more deeply a specimen is cracked, the greater the amount of, v, measured for a specific value of tensile load.

Theoretical compliance expressions for standard test specimens like the compact, C(T), the middle tension, M(T), and the eccentrically-loaded single edge crack tension, ESE(T) can be easily find out. Selection of displacement measurement gauges, attachment points and methods of attachment are dependent on the test conditions such as frequency, environment, stress ratio, and temperature. Gauges must be linear over the range of displacement measured, and must have sufficient resolution and frequency response.

All compliance-crack size relationships are applicable only for the measurement locations on the specimen for which they were developed. In the basis of an analytically derived compliance relationship, it is possible to empirically develop a compliance curve for any type of specimen used in fatigue crack growth rate testing. Such curves are not limited to displacement measurements alone and can involve strain related quantities.

The compliance of structure tends to increases in the presence of crack .The compliance of structure is strongly linked to the crack tip fracture mechanics parameter. The measurement of this compliance is very sensitive. And is depends on the position and location of displacement gauge.

Compliance gauges can be divided into two main classes: Gauges which are placed closed to the crack tip and the gauge which are placed remotely from the crack tip. The main aim of the remote gauges is to measure the crack length and to monitor the crack closer response. And near tip gauges are very sensitive to the change of specimen compliance associated with crack closure. But it can be used for determining absolute crack length as calibration becomes sensitive to the gauge location.

Crack mouth gauges are clips across the notch mouth of the specimen such as compact tension specimen. It can be clipped across the mid-point in a Centre cracked specimen. This crack mouth gauges are made from a single cantilever or from double cantilever. The displacement is measured via strain gauges on the arm of the gauges [23]. The single cantilever gauge suffers from a drawback that it is delicate and difficult to mount on the test piece but it is more sensitive. Sullivan and cooker [24] have measured experimentally crack opening displacement (v) at the mouth of the compact tension specimen as a function of crack length (a). A quadratic regression analysis of their data may be used to give a calibration function for this geometry:

$$\frac{\mathrm{EvB}}{P} = 65.351 - 298.06\left(\frac{\mathrm{a}}{\mathrm{w}}\right) + 630\left(\frac{\mathrm{a}}{\mathrm{w}}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$; 0.3 \leq \frac{\mathrm{a}}{\mathrm{w}} \leq 0.6$$

Where E is the young's modulus, B is the specimen thickness, P is the load applied and w is the specimen width.

The back face strain gauge can be used for bend specimen such as four point bend specimen and compact tension specimen. For compact tension specimen, this gauge shows more hysteresis and is more sensitive and is less influence by loading pin mechanical noise than the crack mouth gauges. Richards and Deans [25] have found experimentally the relation between back face strain (ε) and specimen aspects ratio (a/w) for the compact tension specimen. Quadratic regression analysis can be used to express their result in closed form

$$\frac{\varepsilon \mathrm{EvB}}{\mathrm{P}} = 13.841 - 72.506\left(\frac{\mathrm{a}}{\mathrm{w}}\right) + 138.45\left(\frac{\mathrm{a}}{\mathrm{w}}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$; 0.3 \leq \frac{\mathrm{a}}{\mathrm{w}} \leq 0.6$$

Where E is the young's modulus, B is the specimen thickness, P is the applied load, w is the width of the specimen and ε is the back face strain.

In case of four points bend test or pure bending case, f (a/w) can be calculated in given formula;

$$f(a/W) = \frac{6\sqrt{2\tan\left(\pi a/2W\right)}}{\cos\left(\pi a/2W\right)}\left[0.923 + 0.199\left\{1 - \sin\left(\pi a/2W\right)\right\}^4\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where f (a/W) is called as geometrical correction factor, W is the width of the specimen. In my experiment, this formula is used T.l Anderson [21].

In the present investigation calibration of COD gauge for EN8 medium carbon steel beams have been done with single edge straight notched at Centre so that the fatigue crack growth study can be done in future also.

2.6 Review on crack front profile

Different classical solutions have been done on past for evaluating the stress intensity factors of elliptical surface defect or flaw in a beam under the action of pure bending moment and plates under the action of pure tension. Through-the-thickness crack having constant geometry factor but a straight crack front, part-through cracks do not have a constant geometry factor. And therefore, do not present a constant stress intensity factor along the crack front. But for ellipse with low diameter ratio, the maximum value of the stress intensity factor is at the Centre of the crack front. The Centre of the crack front is the deepest point of the crack through the wall thickness of a beam or plate with an elliptical crack front. Anywhere along the crack front, when the value of the stress intensity factor becomes equal or greater than the fracture toughness, fracture would occur at that point.

Taking into account the fact that a through-the-thickness crack is restraint by the thickness of the material, in this situation the plane strain fracture toughness criterion would be acceptable. When the crack tip has a circular shape, the stress intensity factor is the same all along the crack front, and the fracture occurs at the same time along the crack tip. However, in cases of low ellipse diameter ratio, the stress intensity at the end of the crack tip is considerably lower than that at the Centre of the crack front. Therefore, until the stress intensity factor attains largest value at the Centre of the crack front, more crack growth would take place in a certain cycle at the deepest location along the crack front as compare to other points in the crack front. This would progressively force the crack front to change its shape closer to a circular form, which means an ellipse with a diameter ratio, equal to unity. Many researchers have observed that a value of 0.85 for diameter ratio of ellipse, the stress intensity factor values at different points along the crack front are nearly the same [26]. In case of thumb nail type, in which the difference of maximum to minimum value of y-axis is taken as the crack length of a specimen. Crack front shape strongly depends on initial flaw shape, size and loading situations. But the actual shape of the crack front is complex in nature. In the present investigation the crack front shape is experimentally evaluated also.

2.7 Review on fatigue crack growth curves

A typical fatigue rate curve, commonly referred to as a *da/dN* versus ΔK curve, is illustrated by Figure 2.8.1. The curve is defined by Regions A, B and C which is commonly referred to as region I, II and III respectively.

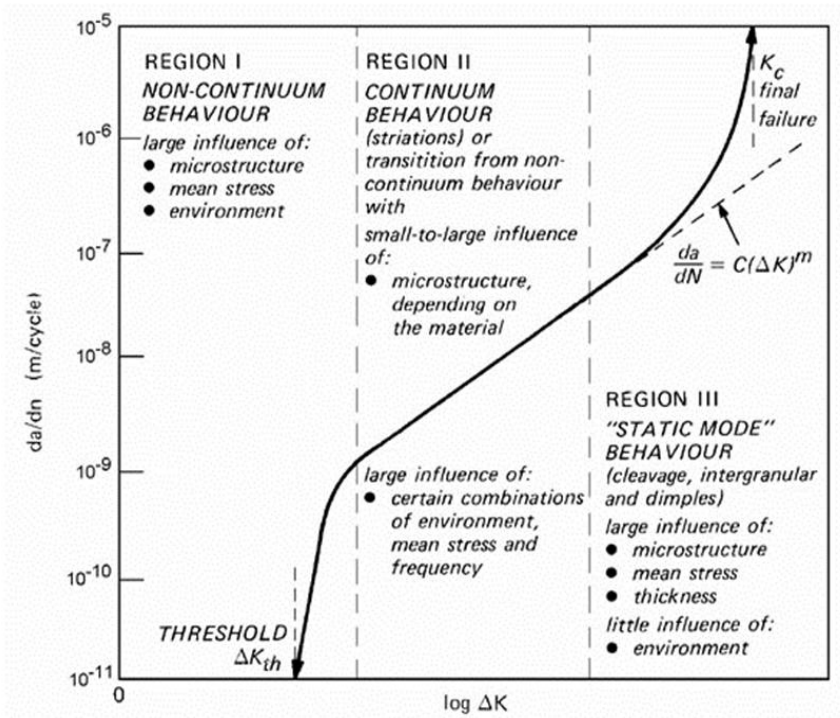


Fig. 2.7.1; Typical *da/dN* versus log (ΔK) curve [40]

Region I

Region I represents the early development of a fatigue crack and the crack growth rate. This region is extremely sensitive and is largely influenced by the microstructure features of the material such as grain size, the mean stress of the applied load, the operating temperature and the environment present. The most important feature of this region is the existence of a stress intensity factor range below which fatigue cracks should not propagate. This value is defined as the fatigue crack growth threshold and is represented by the symbol ΔK_{th}.

Region II

Region II represents the intermediate crack propagation zone where the length of the plastic zone ahead of the crack tip is long compared with the mean grain size, but much smaller than the crack length [27]. The use of linear elastic fracture mechanics (LEFM) concepts is acceptable and the data follows a linear relationship between log *da/dN* and log ΔK. This region corresponds to stable crack growth and the influence of microstructure, mean stress, ductility, environment and thickness are small. The influence of the mean stress is probably the most significant.

Region III

Region III represents the fatigue crack growth at very high rates due to rapid and unstable crack growth just prior to final failure. The *da/dN* versus ΔK curve becomes steep and asymptotically approaches the fracture toughness K_c for the material. The corresponding stress level is very high and causes a large plastic zone near the crack tip as compared with the specimen geometry. Because large scale yielding occurs, the influence of the nonlinear properties of the material cannot be ignored. The mean stress, materials microstructure and thickness have a large influence in this region and the environment has little influence. Fatigue crack propagation analysis is very complex in this region but often ignored because it has little importance in most fatigue situations. The reason is the fatigue crack growth rates are very high and little fatigue life is involved.

2.8 Review on fatigue crack growth models

The study of fatigue crack growth is always been a matter of research among scientists and researches all around the world. For designing any structure, the fatigue crack behavior has been an important parameter. Numerous attempts have been made in developing fatigue crack growth models for constant amplitude loading [28]. Every model has its own merit and demerits and applies to specific loading condition. Most of the proposed models are based on integration of crack growth rate equation in order to determine fatigue life. However complicated numerical integration limits their applicability.

2.9 Constant amplitude loading models

The fatigue crack propagation analysis for constant amplitude loading condition is simplest because no loading history is required. There are several models available for fatigue crack propagation. However, they vary in the factors and the number of curve fitting parameters required. The following literature introduces various fatigue crack propagation models for constant amplitude loading condition.

Paris Model:-

Paris *et al.* [29-32] proposed that the fatigue crack propagation is power law and describes by eq. as:

$$\frac{da}{dN} = C\left(\Delta K\right)^{n}$$

Where C and n are material constants and ΔK is the stress intensity factor range given by $K_{\max} - K_{\min}$ .The Paris law is simple and it requires only two curve fitting constants to define fatigue crack propagation. The limitation of Paris law is that it capable of describing fatigue crack propagation in region II. However it cannot be applied to other regions where accelerated growth occurs. Also Paris law does not consider the effect of stress ratio; however it depends upon material used.

Walker model:-

Walker et. al [33] included stress ratio (which has ignored by Paris) in fatigue crack propagation equation which is described as

$$\frac{da}{dN} = C_b[(1 - R)^{c_1} K_{max.}]^{n_b}$$

Where R; is the stress ratio for constant amplitude loading.

Forman model:-

Although Walker improved the Paris model by taking account of the stress ratio, neither models could account for the instability of fatigue crack growth when the stress intensity factor approaches its critical value. Forman improved the Walker model by suggesting a new model which is capable of describing region III of the fatigue rate curve and includes the stress ratio effect. The Forman law [34] is given by this mathematical relationship given as:

$$\frac{da}{dN} = \frac{C_F\left(\Delta k\right)^{m_y}}{\left(1-R\right)K_C - \Delta K} = \frac{C_F\left(\Delta K\right)^{m_y}}{\left(1-R\right)\left(K_C - K_{\max}\right)}$$

Where; K_c is the fracture toughness for the material and thickness of interest. The above eq. indicates that as $K_{\max}$, *approaches* K_c then *da/dN* tends to infinity. Therefore, the Forman equation is capable of representing stable intermediate growth (region II) and the accelerated growth rates (region III).

McEvily model: McEvily proposed a model that relates the crack advance per cycle in the striation mode to the crack tip opening displacement and to include the threshold effect, which leads to this relationship [35].

Frost and Pook model:-

Frost and Pook [36] proposed that the crack growth occurs under cyclic loading not as a consequence of any progressive structural damage but merely because unloading reshapes the crack tip at each cycle and this sequence is responsible for the formation of striations [37]. Therefore the increment of crack growth in each cycle can be related to the changing crack tip geometry during its opening and closing and a simple model based on.

Zheng model:-

Lal and Weiss [38] proposed a static fracture model, that the crack was advanced by a distance (during each cycle) over which the maximum normal stress exceeded the critical fracture stress of the metal. Their model was moderately successful in predicting fatigue crack growth except it did not account for the crack tip blunting phenomena and their model used material constants that had no physical significance. However Zheng [39] improved the La1 and Weiss model by modifying the static fracture portion and obtained material constants that are defined by the tensile properties of the metal. Briefly, Zheng found that upon loading the crack opens elastically and the crack tip becomes blunt, which occurs at a stress intensity threshold denoted as K_{th} .

Wang model:-

Wang et al. [40] proposed a damage accumulation theory, which considers the plastic component of the J integral as a damage factor resulting in a simple formula for the fatigue crack growth rate. The proposed damage accumulation theory assumes:

1. The total plastic strain energy density absorbed by the material is a constant prior to reaching its ultimate state. This constant is a parameter that can be determined by tests.
2. The elastic strain energy density stored by the material does not cause damage and is released upon unloading.

Dowling and Begley Mode1:-

For situations of fatigue crack growth under large scale yielding conditions, where the stress intensity factor is no longer valid, Dowling and Begley [41, 42] suggested to use the ΔJ integral as the fracture parameter.

The investigation of a pipe subject to bending moment with an equivalent plate subject to tension has been carried out by Mohammad Iranpour and Farid Taheri [43]. This study is done to avoid the complexity usually involved with experimental crack growth investigations of pipes with initial defect or surface flaws. This approach also minimizes the use of more complicated monitoring instruments, thereby offering important expenditure savings. This equivalency has been done for both finite element analysis and experimental investigations. A number of finite element analyses were carried out to both verify the values of the stress intensity factor (K) and verify the results of the interpolation function used in the computational simulation. Based on the FE simulations, crack front follows a semi-circular shape during its growth. Dimensionless relationship between stress intensity factor (K) of a pipe under bending moment and that of a plate under pure tension has been introduced. Numbers of experiments were performed to verify the validity of the proposed computational simulation. The analysis shows the acceptability of replacing a pipe subject to bending moment within equivalent plate subject to tension is good enough.

Most of the models have been developed for SENT, CT specimens and very little information is available for fatigue life prediction of pipe specimens. This is due to their geometrical factors (as stress intensity factor is widely depends upon geometry of specimen and notch) and complexity of experimentation (monitoring of COD gauge readings).

CHAPTER -3

EXPERIMENTAL INVESTIGATION

Experimental Investigations

3.1 Introduction

The fatigue crack propagation tests were conducted on (EN-8) medium carbon steel beams. All the tests were conducted in a servo-hydraulic dynamic testing machine (Instron-8800) using through cross-sectional of cracked beam specimen under load control mode. A four point bend fixture was fabricated for conducting fatigue crack propagation tests. Before conducting the test, COD gauge was calibrated for single edge straight notched cracked beams specimens. All the tests were conducted in air and at room temperature.

3.2 Four Points bend Method

Four point bending (FPB) is a cornerstone element of the beam flexure portion of a sophomore-level mechanics of materials course. The FPB lecture has traditionally developed the theory from body diagram through beam deflection, with related homework problems providing analytical practice. In FPB method Beam flexure represents one of the three most common loading categories for mechanical systems. As such, it is on the syllabi of nearly all sophomore-level mechanics of materials courses, including the mechanical engineering technology course under consideration here. Within the lecture setting, FPB theory is developed from free-body diagram through beam deflection. This theory is reinforced by analytical practice solving related homework problems. By this FPB the result to experimentally and analytically verify and Validated beam flexure theory. According to the convention specified in ASTM D6272-00 transverse vertical loads are applied to horizontal beams such that a constant bending moment results between the two inner load locations. Figure below shows the corresponding loading diagrams, from free-body to bending moment.

The major difference between the three point and four point flexural tests is the location of bending moment. The four point bending method allows for uniform distribution between the two loading noses, while the three point bending method, stress is located under the loading nose. But in four point bending test, no shear force acts in between two inner spans, while in case of three point bending test maximum shear force act a loading nose.

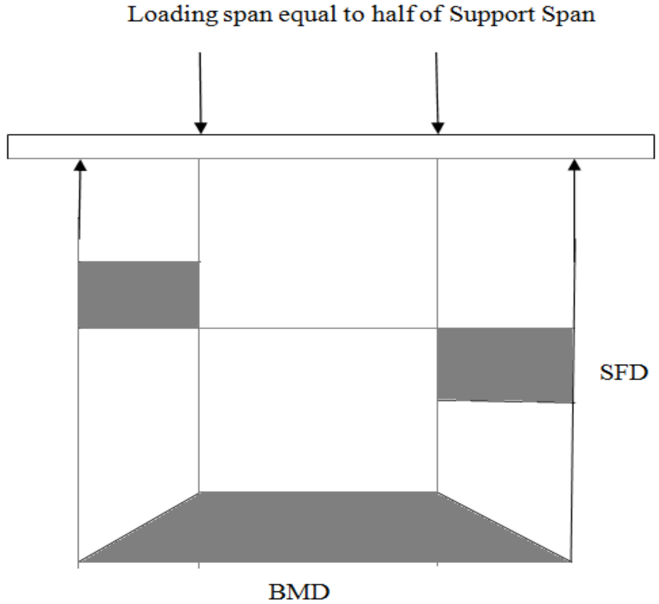


Fig.3.2.1; Four points bend method

3.3 Beam materials

EN8 is an unalloyed medium carbon steel with good tensile strength, which is readily machinable in any condition. It is normally supplied in cold drawn or as rolled. Tensile properties can vary but are usually" between "500 to 800 N/mm^2.It is available from stock in bar, square, flat plate, and hexagon, etc. It is used for shafts, stressed pins, studs, keys, nuts, bolts, axles, and gears etc. Fatigue crack growth behavior depends on the stress state at the notch tip, the geometry of the component, the shape and size of the notch and loading conditions. The medium carbon steel beams used in automobiles, machine shop etc. Corrosion occurs due to presence of Iron and oxygen in the atmosphere. It can be protected metals by painting. The Tensile property of specimens was determined by using in accordance with the ASTM EN8 standards and is presented in table. Summarizes the average values of the mechanical properties data (e.g. stress-strain diagram, yield stress, UTS, % elongation, % reduction in area and young's modulus) measured, that would be used in the fatigue crack propagation mechanics evaluation of the experiments. The chemical composition of the beam materials, EN8 D (080A42) medium carbon steel in structure presented by ASTM EN8 and EN8M (212A42) specifications. These data are used to normalize the results in such a manner so that the proposed correlation becomes independent of the material parameters.

3.4Tensile test of specimen

Tensile testing, in which a sample is subjected to controlled tension until failure. The Tensile properties of beam specimens were tested as per ASTM EN8 standards and EN8M (212A42) specifications. It is given in Table 3.1.2. The LLD (load-load line displacement) diagram is shown in fig. 3.4.3. Summarizes the average values of the mechanical properties data (e.g. stress-strain diagram, yield stress, UTS, % elongation, % reduction in area and young's modulus, Poisson's ratio) measured, that were used in the fracture mechanics evaluation of the experiments results. The chemical composition of the beam material is also shown in the table 3.2.

Fig 3.4.1; Tensile specimen

Table 3.1; Dimension of tensile specimen of EN8

SL No.	*Mean Diameter(mm)*	*Length(mm)*
1	*6.84*	*25*
2	*6.66*	*25*

Fig 3.4.2; Tensile testing (Instron-1195)

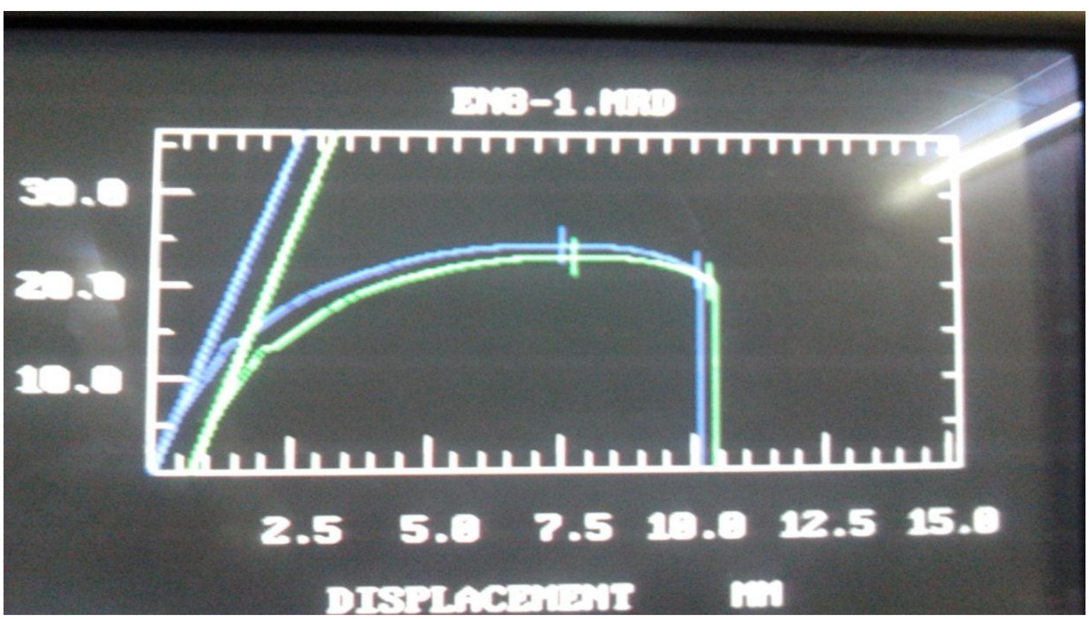


Fig. 3.4.3.; Experimental results of Load vs. Load line displacement

Table 3.2; Mechanical Properties of EN8

Young's modulus	205 MPa
Poission's ratio	0.3
Yield stress	530MPa
UTS	660MPa

Table 3.3; Chemical composition of EN8

Elements	Alloy(% by weight)
Carbon	0.40
Silicon	0.25
Manganese	0.80
Sulphur	0.05
Phosphorus	0.05
Iron	Bal.

3.5 Specimen geometry and accessories

A square beam whose length, breath and thickness are 505mm, 25mm, and 25mm respectively has been subjected to FBT tests. The middle position of the beam was made on straight- notched whose depth is 3 mm with help of wire EDM as shown in fig. From literature we have, the beam specimens with a surface notch are subjected to fatigue loading till the crack has grown through thickness. After this, fracture tests have been carried out through cross section of cracked beam produced by fatigue loading.

Fig.3.5.1; Test Specimen

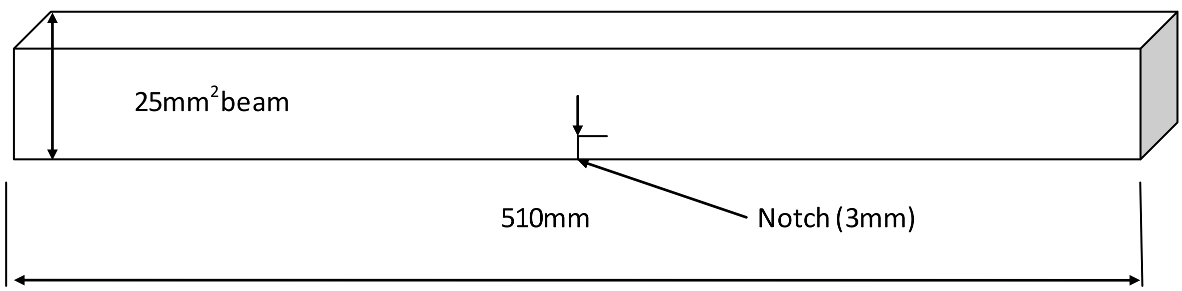


Fig. 3.5.2; Dimensions of test specimen

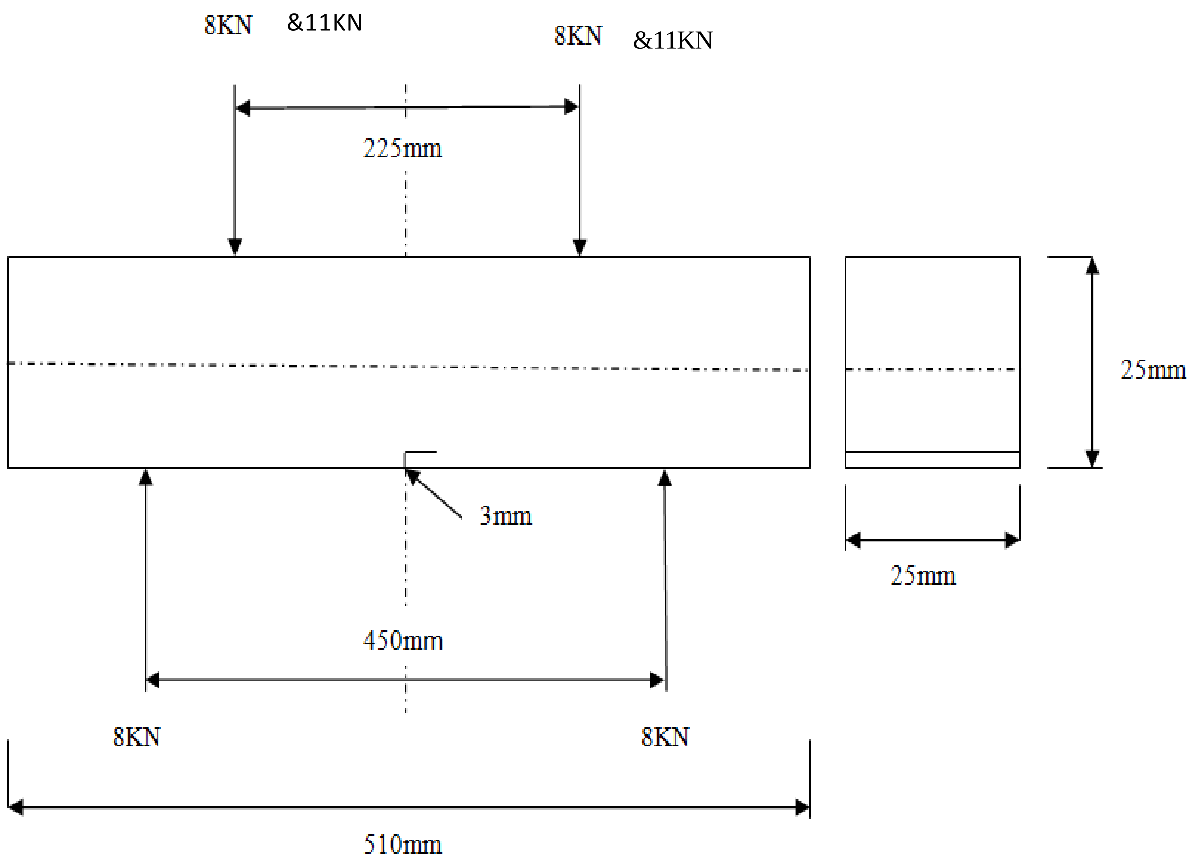


Fig 3.5.3; Dimensions of beam specimen with straight notch at center

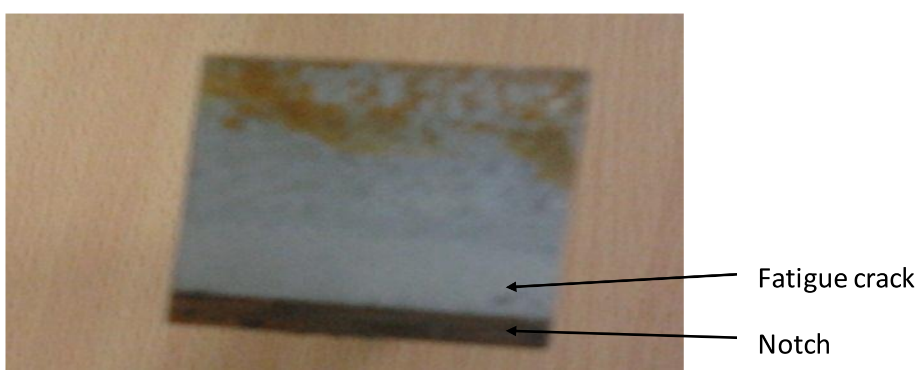


Fig. 3.5.4; Fatigue surface

Table 3.4; Specimen and notch dimension of beam

Specimen	Dimension (mm)
Length of beam(L)	510
With of beam(B)	25
Thickness of beam (*t*)	25
Notch length of beam(l)	3
Upper span length(S/2)	225
Lower span length(S)	450

3.6 Test setup and procedure

The test has been done on Instron 8800. It consists of a servo hydraulic loading system, support for the specimen and various instruments for measurement of data. A servo hydraulic controlled actuator of ±250 KN capacity and ±50 mm displacement has been used for loading. The support system consists of two pedestals with two rollers, at a span of 450 mm and a pair of inner loading rollers with a span of 225 mm, which provides four-point bending. The test specimen was gripped between rollers. The fig. 3.6.1 shows the four point bend arrangement for beam. This type of loading ensures that the mid-section of the specimen, where the notch is located is subjected to pure bending. The monitoring of crack was done using a COD gauge with data acquisition system, the data storage system is integrated with machine which stores data at every point of testing. Beam test arrangement constituted loading the beam under four point bending up to large scale plastic deformation with periodic significant unloading so as to create a beach mark on the crack surface. The actual beam test arrangement is shown in fig3.5.5. After the test, fractured surface is extracted by Power saw and it was cut in such a way that the crack surface is not damaged. Then the extracted crack length will be examined in scanning electron microscope (SEM) at various loading stages. The crack surface is again examined in travelling microscope. The loading is given in the form of sinusoidal wave.

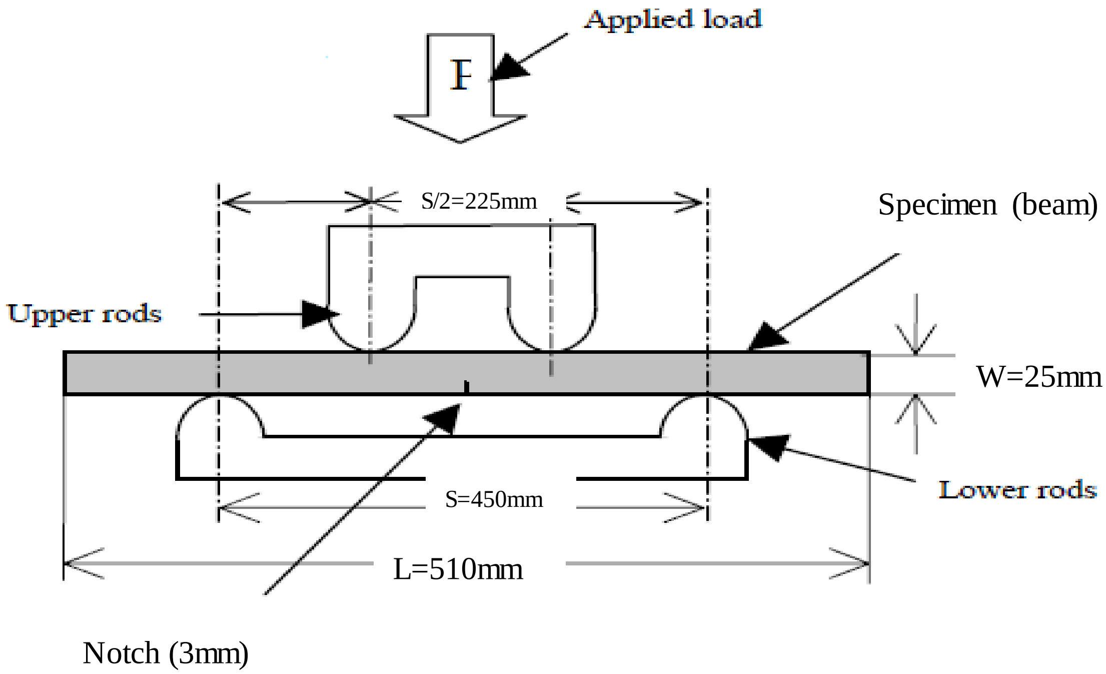


Fig 3.6.1; Schematic showing the four point bending test

The crack opening was measured by the means of a crack opening displacement gauge (COD) mounted on the Centre of the notch. The monitoring of crack was done using a COD gauge with data acquisition system, the data storage system is integrated with machine which stores data at every point of testing. Fatigue test arrangement constituted loading the beam under four point bending up to large scale plastic deformation with periodic significant unloading so as to create a beach mark on the crack surface.

The loads applied to the specimens were defined by either a constant stress range (σ_r) or constant stress amplitude (σ_a).

Stress amplitude (σ_a) = $\frac{\sigma_{max}-\sigma_{min}}{2}$

Stress range (σ_r) = σ_{max} - σ_{min}

Stress ratio (R) = $\frac{\sigma_{min}}{\sigma_{max}}$

From the bending moment equation; Ϭ/y=M/I=E/R

Where M=P*L

Stress intensity factor k = $Ϭ\sqrt{\pi a}\quad F(g)$

Stress intensity factor range Δk =$\Delta Ϭ\sqrt{\pi a}\quad F(g)$

Where F (g) is the shape factor related to the geometry of the component

Where F (g) = a/W

$$f(a/W) = \frac{6\sqrt{2\tan(\pi a/2W)}}{\cos(\pi a/2W)}\left[0.923 + 0.199\left\{1-\sin(\pi a/2W)\right\}^4\right]$$

3.7 Test Equipment

The servo-hydraulic dynamic testing machine (Instron 8800) having load cell of capacity 250 KN were used for fatigue test which is interfaced to a computer for machine control and data acquisition. Fig 3.6 shows a photograph of the test set-up along with the test specimen.

Fig. 3.7.1; Instron 8800

3.8 Test condition

The tests were conducted at room temperature and laboratory air environment under constant amplitude sinusoidal loading at stress ratio of 0.1 & 0.3 and frequency 3 Hz. The load range applied during the fatigue crack initiation and growth test was of the order of 8 KN and 11KN.

CHAPTER-4

GENERATION OF FATIGUE CRACK PROFILE AND CALIBRATION OF COD GAUGE

4.1 Introduction

The crack profile was measured and plotted with the help of optical travelling microscope and calibration of COD gauge was done using multiple specimen technique.

4.2 Crack profile

The crack profiles obtained by using multiple specimens are shown in Fig. 4.2.1 and Fig.4.2.2.From the crack profile it is clear that the crack propagates in lateral direction and parallel to the loading. From the profile it is also clear that the crack front profile is approximately thumb nail shape in nature. In case of nail shape, the difference of maximum to minimum value of y-axis is taken as the crack length of a specimen with help of travelling microscope. Crack front shape strongly depends on initial flaw shape, size and loading situations. But the actual shape of the crack front is complex in nature. In the present investigation the crack front shape is experimentally evaluated also.

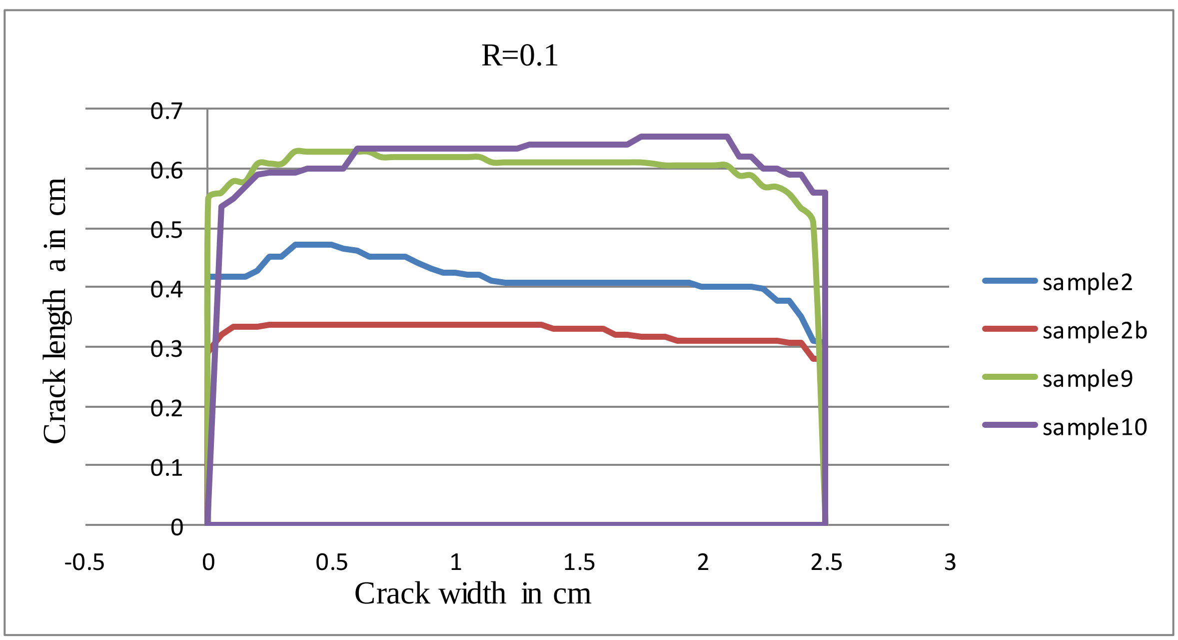


Fig 4.2.1; Crack profile with R=0.1

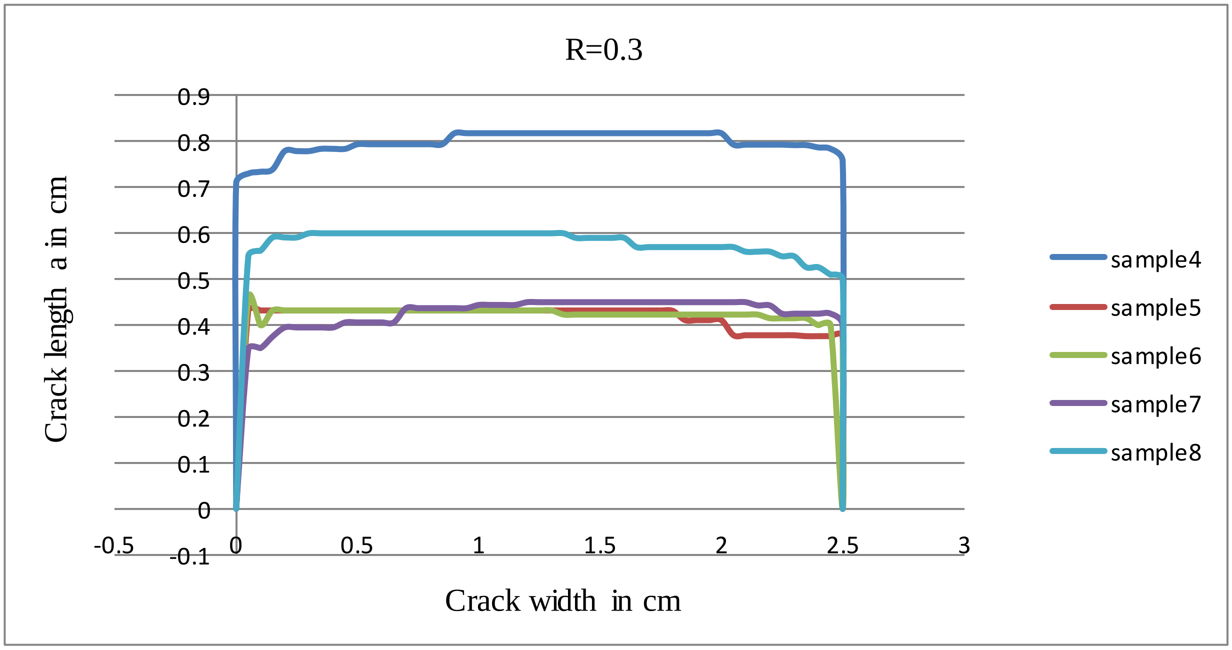


Fig 4.2.2; Crack profile with R=0.3

4.3 Calibration of COD gauge

Beams with straight notched at Centre were used for calibration of COD gauge. The COD calibration curve (Del. COD vs. measured crack length along the beam cross-section) is shown in Fig. 4.1. With constant loading of different R ratios such as R= 0.1 and R=0.3

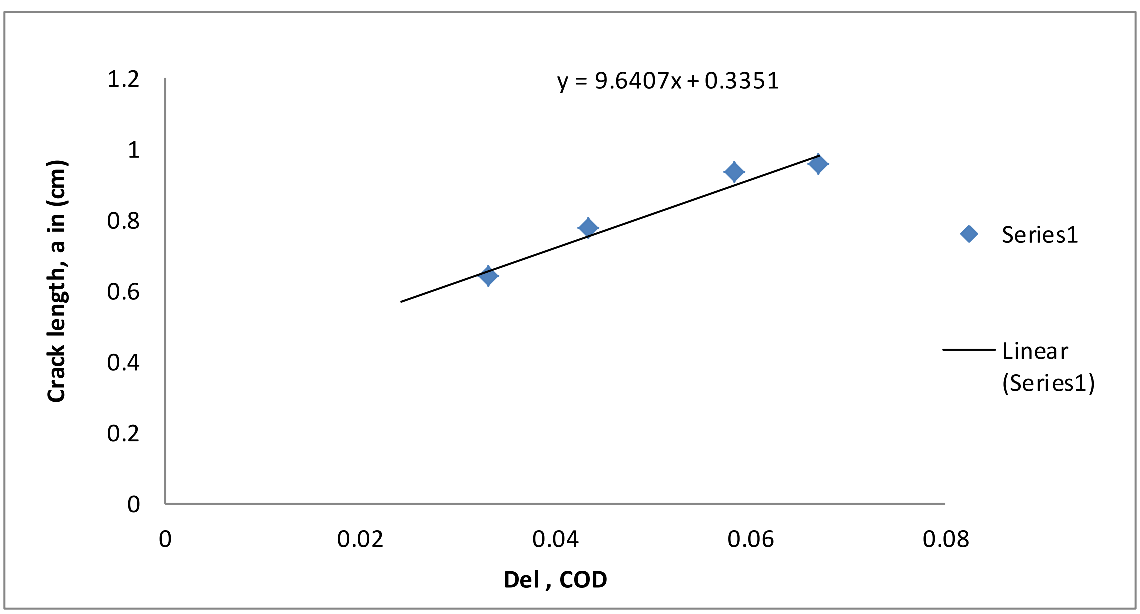


Fig. 4.3.1; Calibration of COD gauge with R=0.1

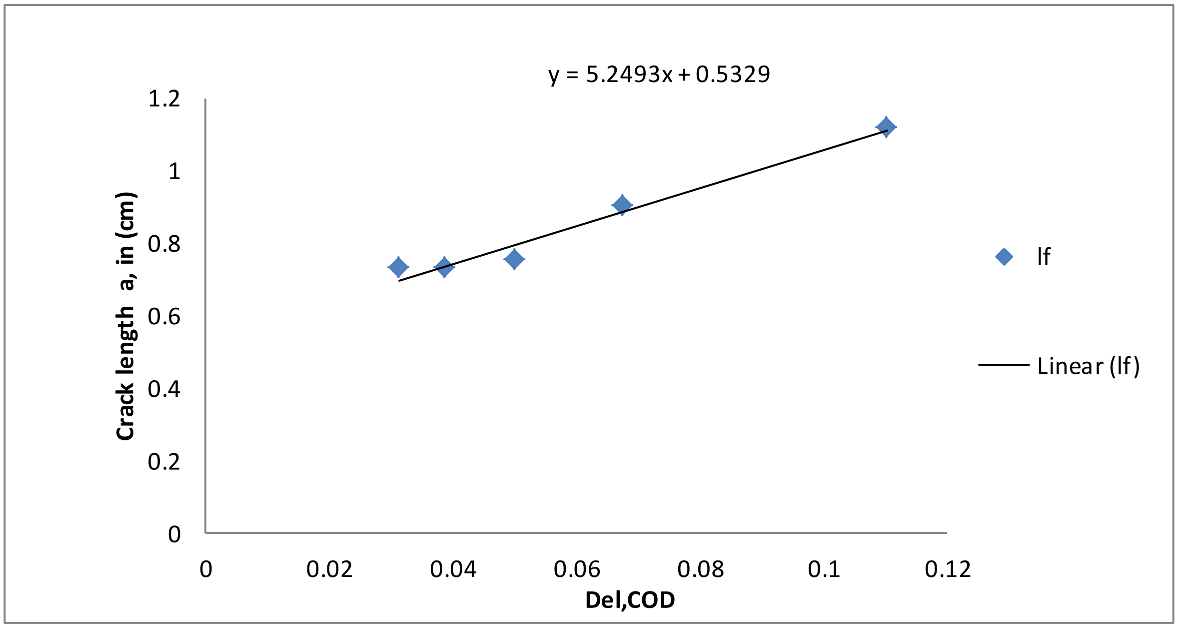


Fig. 4.3.2; Calibration of COD gauge with R=0.3

Table 4.3; Experimental Results of EN8 beams

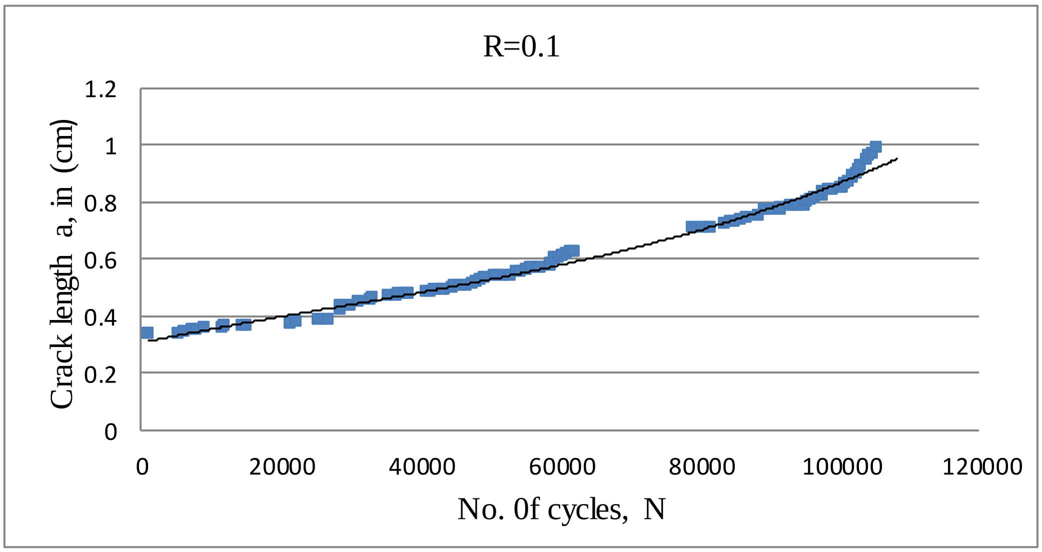
Sl no.	P_{max} In(N)	P_{min} In (N)	R	Max cod in mm	Min cod in mm	Del cod in mm	Crack length in cm	Total No.of cycles
1	8888.88	888.88	0.1	0.08147	0.0481	0.03337	0.637	78829
2	8888.88	888.88	0.1	0.07669	0.03308	0.04361	0.773	62203
3	8888.88	888.88	0.1	0.08577	0.02734	0.05843	0.928	108146
4	8888.88	888.88	0.1	0.08207	0.01494	0.06713	0.955	65685
5	11500	3451	0.3	0.18809	0.07785	0.11024	1.118	113799
6	11500	3451	0.3	0.07785	0.03894	0.03891	0.732	71410
7	11500	3451	0.3	0.06519	0.03376	0.03143	0.732	81174
8	11500	3451	0.3	0.010510	0.03789	0.06776	0.90	71863
9	11500	3451	0.3	0.09015	0.03991	0.05024	0.75	95825

CHAPTER-5

PREDICTION OF FATIGUE CRACK PROPAGATION USING EXPONENTIAL MODEL

5.1 Prediction of fatigue crack propagation using exponential model

Fatigue crack propagation, a natural physical process of material damage, is characterized by rate of increase of crack length (*a*) with number of cycles (*N*). It requires a discrete set of crack length vs. Number of cycle data generated experimentally. Unlike monotonic tests, fatigue test data are usually scattered. Therefore curve fitting of experimental *a-N* data was done which are usually scattered (Fig. 5.1).



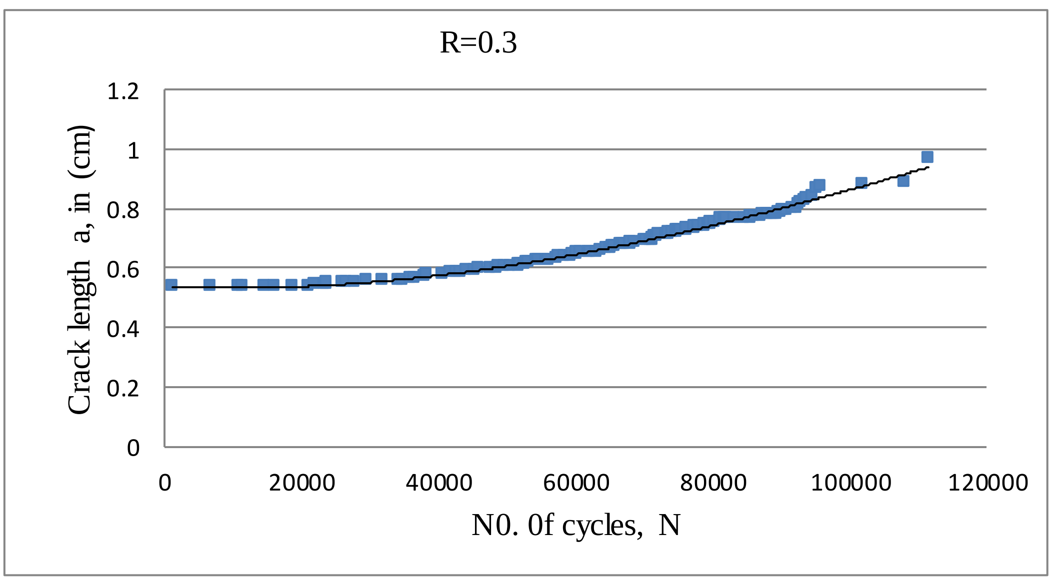


Fig. 5.1; Curve fitting of experimental data (crack length vs. number of cycles)

5.1Introduction

The exponential model was developed by Mohanty *et. al.* [44-47] for prediction of fatigue crack growth in SENT specimen for constant amplitude loading as well as variable amplitude loading. However, this model was not developed for beams specimens. In the present investigation an attempt has been made to use the exponential model for fatigue crack propagation life in cracked beams subjected to constant amplitude loading.

This model is based on the exponential nature of fatigue crack propagation with number of loading cycles. The exponent (known as specific growth rate) of the proposed exponential model has been correlated with various physical variables like crack driving parameters, crack resisting parameter, and material properties in non-dimensional forms. Finally the validation of the model has been done with experimental data in order to compare its accuracy in predicting fatigue life of cracked beams.

5.2Background and approach

Use of exponential model was first suggested by Thomas Robert Malthus (1766-1834) for the prediction of growth of human population/bacteria. He realized that any species could potentially increase in numbers according to an exponential series. The differential equation describing an exponential growth is

$$\frac{dP}{dt} = rP \quad \text{...} (1)$$

Where P is population, t is time and the quantity r in the above equation is the Malthusian parameter, also known as specific growth rate. The solution of the above differential equation is

$$P(t) = P_o\, e^{rt} \quad \text{...} (2)$$

This equation is called law of growth.

In our present research equation (2) is modified and form of exponential equation of the proposed exponential model is as follows:

$$a_j = a_i e^{m_{ij}} (N_j - N_i\,) \quad \text{..} (3)$$

The exponent, i.e. specific growth rate (m_{ij}) is calculated by taking logarithm of the above equation as follows:

$$m_{ij} = \frac{ln\left(\frac{a_j}{a_i}\right)}{(N_j - N_i)} \quad \text{... (4)}$$

In conventional differential equation model of Paris-Erdogan, there is a physical inconsistency when the constants of the crack growth rate equation are randomized as per dimensional analysis point of view [48]. In case of the proposed exponential model, this type of inconsistency does not arise as the specific growth rate m_{ij} is a dimensionless parameter. The specific growth rate m_{ij} is given by:

$$m = \left(\frac{\Delta k}{k_C}\right)^A \left(\frac{K_{Max}}{k_C}\right)^B \left(\frac{\sigma_{ys}{}^2 a}{k_C{}^2}\right)^C (1-R)^D \quad \text{.................... (5)}$$

Where m is correlated with two crack driving forces ΔK and K_{max} as well as material parameters K_c, R, σ_{YS} and is represented by equation:

5.3 Formulation and validation of model:

The modified exponential equation is given as:

$$a_j = a_i e^{m_{ij}} (N_j - N_i) \text{.. (5.3.1)}$$

$$m_{ij} = \frac{ln\left(\frac{a_j}{a_i}\right)}{(N_j - N_i)} \quad \text{... (5.3. 2)}$$

Here N_j and N_i represent number of cycles in ith step and jth step respectively, and a_j and a_i are the crack lengths in ith step and jth step respectively. m_{ij} is specific growth rate in the interval (j-i)

The specific growth rate m_{ij} is calculated for each step from experimental result of fatigue test *(a-N* data) according to equation (5.3.2)

The different m is fitted by $3rd$ degree polynomial. The predicted m values are calculated for different specimens by using formula:

$$m = \left(\frac{\Delta k}{k_C}\right)^A \left(\frac{K_{Max}}{k_C}\right)^B \left(\frac{\sigma_{ys}{}^2 a}{k_C{}^2}\right)^C (1-R)^D \qquad \text{.......................... (5.3.3)}$$

where A, B, C, and D are curve fitting constants whose average value for four specimens have been presented in the table 5.5.1.

From the bending moment equation; Ϭ/y=M/I=E/R

$Ϭ_{max}$ and $Ϭ_{min}$ are calculated according to our loads and specimen dimensions for four points bend test.

Stress range $(\Delta Ϭ) = \sigma_{max} - \sigma_{min}$

The stress intensity factor K_{max} has been calculated by following equation,

Stress intensity factor $k_{max} = Ϭ_{max}\sqrt{\pi a} \quad F(g)$ .... (5.3.4)

The stress intensity factor range ΔK has been calculated by following equation,

Stress intensity factor range $\Delta k = \Delta Ϭ\sqrt{\pi a} \quad F(g)$ .... (5.3.5)

Where F (g) is the shape factor related to the geometry of the component

Where F (g) = a/W

$$f(a/W) = \frac{6\sqrt{2\tan(\pi a/2W)}}{\cos(\pi a/2W)}\left[0.923 + 0.199\left\{1-\sin(\pi a/2W)\right\}^4\right] \qquad \text{......... (5.3.6)}$$

5.4 Validation of model

The predicted number of cycles or fatigue life is given by:

$$N_j^P = \frac{ln\left(\frac{a_j}{a_i}\right)}{m_{ij}} + N_i \quad \text{.. (5.4.1)}$$

The predicted values of specific growth rate (m_{ij}) of the tested specimen have been calculated by putting the average values of the curve fitting constants (for specimen no. 1, 2, 3, 4,) in equation

(5.3.3). For validation of proposed exponential model; fatigue life is calculated (for specimen no. 5 and 6) by using the equation (5.4.1)

5.5 Discussion

The basic aim of present work is to develop a fatigue crack propagation model for SEN beam without going through numerical integration process. The specific growth rate (*m*) is an important parameter of our model. The value of *m* is correlated with two crack driving forces (ΔK *and* K_{max}), and with material parameters fracture toughness (K_C), yield strength (σ_{YS}), stress ratio(R), and Young's modulus (*E*) by curve fitting. The experimental *a-N* data of four specimens were used for formulation of model, and its validation has checked for 5th and 6thspecimens. The average value of curve fitting constants for beams has been given in Table5.5.1. By using these constants fatigue life of a beam specimen can be predicted. The predicted result by using exponential model has been compared with the experimental result. The *a-N* curve obtained from proposed exponential model and that obtained from experimental data have been compared [Fig. 5.2]. The *da/dN* – ΔK curves are also compared [Fig. 5.3]. It can be seen that the predicted results are in good with the experimental data.

Table5.5.1; value of coefficients for exponential model

Material	A	B	C	D
EN8	7574.09	-8566.67	499.31	4.84

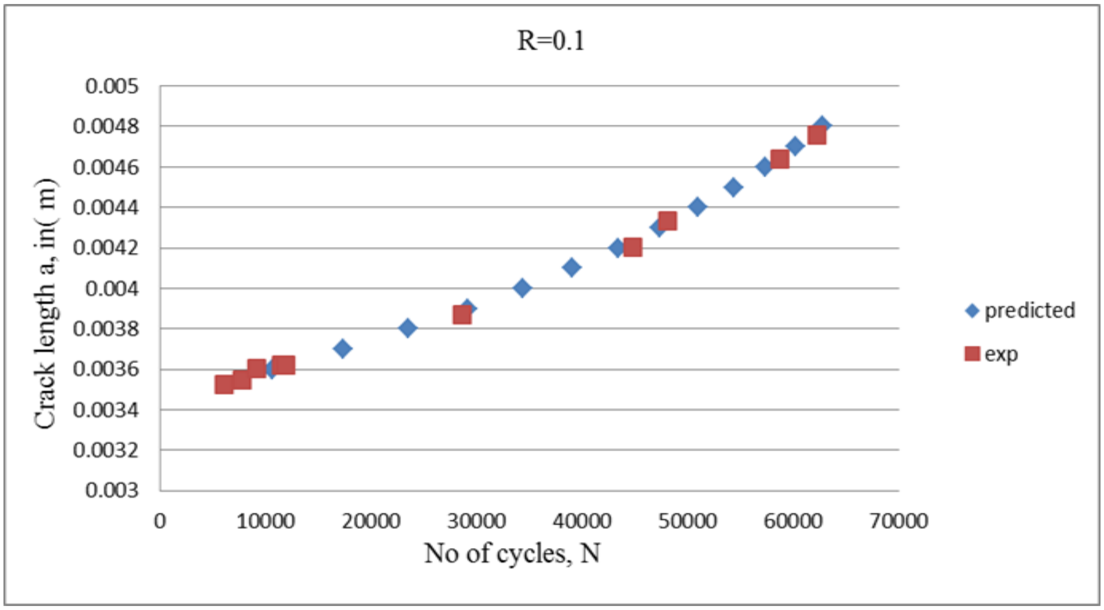


Fig. 5.5.1 ;(*a-N)* curve of EN8 medium carbon steel beam (exponential model)

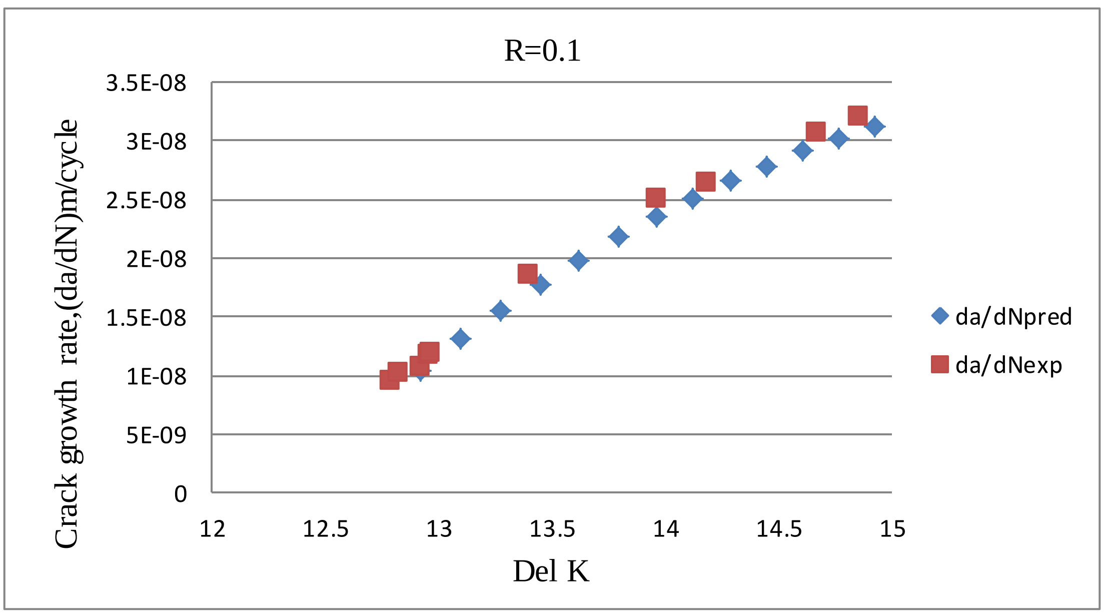


Fig 5.5.2; (da/dN-ΔK) of EN8 medium carbon steel beam (exponential model)

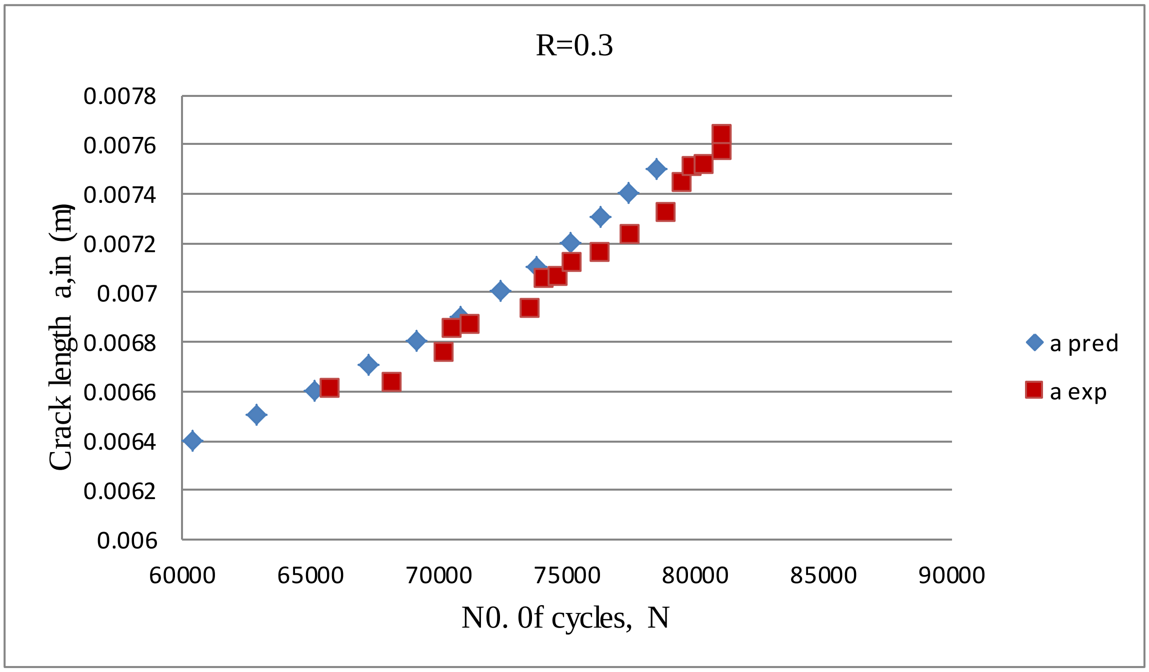


Fig. 5.5.3 ;(*a-N)* curve of EN8 medium carbon steel beam (exponential model)

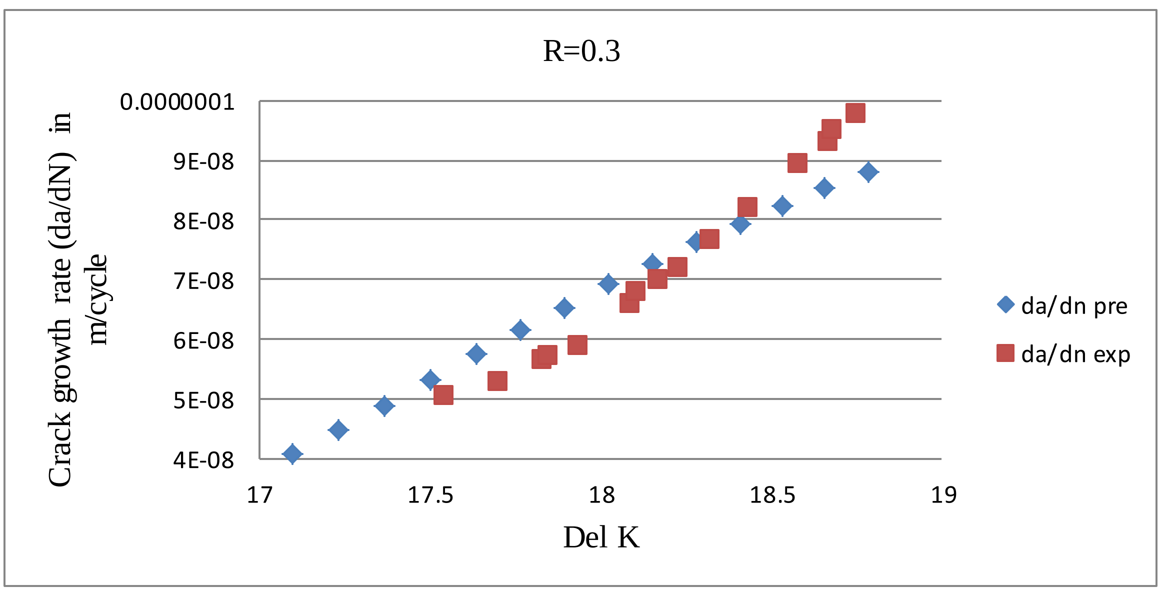


Fig 5.5.4; (da/dN-ΔK) of EN8 medium carbon steel beam (exponential model)

CHAPTER-6

RESULTS AND DISCUSSION

RESULTS AND DISCUSSION:

The basic aim of present work is to develop a fatigue crack propagation model for SEN beam without going through numerical integration process. The specific growth rate (m) is an important parameter of our model. The value of m is correlated with two crack driving forces (ΔK *and* K_{max}), and with material parameters fracture toughness (K_C), yield strength (σ_{YS}), stress ratio(R), and Young's modulus (E) by curve fitting. The experimental *a-N* data of four specimens were used for formulation of model, and its validation has been checked for 5th and 6th specimens. The average value of curve fitting constants for beam has been given found out by using these constants fatigue life of a beam specimen can be predicted. The predicted result by using exponential model has been compared with the experimental result. The *a-N* curve obtained from proposed exponential model and that obtained from experimental data have been compared with other figure. The da/dN – ΔK curves are also compared also. It can be seen that the predicted results are in good with the experimental data.

CHAPTER -7

CONCLUSIONS

CONCLUSIONS:

1. The calibration curve of COD gauge is found to be straight line, which shows linear relationship between COD gauge and crack depth of straight notched beam.

2. The crack front profile is approximately thumbnail shape in nature as the crack depth increases.

3. Exponential model of the form $a_j = a_i e^{m_{ij}} (N_j - N_i)$ has been used for other specimen geometries and can also be used to determine the fatigue life in beams without going through numerical integration.

4. Subsequently, to predict fatigue life, the exponent, m_{ij} (specific growth rate) has been judiciously correlated with crack driving parameters ΔK and $K_{\max}$ and material properties K_C (for specific specimen geometry) E, σ_{ys} and R in the form of dimensionless quantities.

5. The proposed exponential model may be used to predict fatigue crack propagation under constant amplitude loading condition with different stress ratios.

CHAPTER -8

FUTURE WORK

SUGGESTED FUTURE WORK:

1. The proposed models may be tested for other specimen geometries.

2. The soft computing methods may be used to determine the specific growth rate.

CHAPTER -9

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REFERENCES

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