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Investigation of Fatigue Crack Growth under Pure Mode-I and Mixed Mode

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Abstract— **It is very difficult to find out the exact failure and fracture mechanism in complex devices. An attempt is made to predict the fatigue crack growth using finite element analysis to design a body against fatigue failure. In the present study, Pure Mode-I and Mixed Mode fatigue crack are analyzed and experimented by using simple fixture which assembles the specimen to machine. Fatigue crack growth test in Mixed Mode carried out for several load ratio on IS 2062 Grade A (E-250) with 5 mm thickness. The tests were performed in standard Servo-hydraulic Machine. The fatigue crack path obtained by ABAQUS software was compared with experimental data. Based on experimental and simulation work, it is found that as inclination angle of crack increases, it requires more load for initiation of the crack so it will increases the fatigue life.**

Keywords—Mixed-mode Loading, Fatigue Crack growth rate, Fatigue Crack Path

I. INTRODUCTION

Fatigue crack growth is the most common failure mechanism in mechanical structure or component since they are usually subjected to cyclic loads.

In the past, many investigators have carried out research on sub critical propagation in metallic material. This was primarily motivated by need of fatigue crack growth rate data for their reduction of services live for structure subjected to cyclic stresses, especially for structure that contained fabrication imperfection. The study of fatigue crack propagation examines how fatigue grows under cyclic load [12].

The majority of the fatigue crack growth is usually performed under mode-I loading condition. In many practical cases are not normal to the maximum principal stress condition prevails at the tip of such crack. This type of loading is very commonly encountered when crack deflection occurs during crack growth [10].

Many ship-building components, marine structure, turbine shaft, and railways track etc have complex parts which are often subjected to combined loading such as bending, torsion, and tension. These parts always go under variable loads so if there is crack in the material; it will be mixed mode fatigue crack [11].
Many different specimen geometries have been used to produce different combination of mixed-mode loading under different test condition, in the real situation defects/cracks which is present in the structure or components are not necessarily in mode of opening. They may be in the mixed condition such as mode (I+II), mode (I+III), or Mode (I+II+III). The need for adopting new methods of damage assessment incorporating the effect of mode of loading is being increasingly recognized. Therefore, suitable FCG rate (Paris Type) law is require predicting the life of the component or structure under mixed mode loading [1].

Fatigue life has been considered to be composed of three phases:-

1) Crack Initiation
2) Stable Crack Propagation
3) Final Failure (Rapid Fracture)

A. *TYPES OF FATIGUE*

There are mainly three commonly recognized forms of fatigue:-

- High Cycle Fatigue (HCF)
- Low Cycle fatigue (LCF)
- Thermal Mechanical Fatigue (TMF)

High Cycle Fatigue (HCF):- HCF is characterized by low amplitude high frequency elastic strain. An example would be an aero-foil Subjected to repeated bending. One source of this bending occurs as a compressor or turbine blade passes behind a stator vane. When the blades emerge into the gas it is bent by high velocity gas pressure. Change in rotor speed change the frequency of blade loading [4].

Low Cycle Fatigue (LCF):- LCF is the mode of material degradation when plastic strains. For example if we pull the beam of the tuning fork apart until they are permanently bent we have imparted one half of an LCF [4].

Thermal Mechanical Fatigue (TMP):- In the case of TMF (present in turbine blades, vanes and other hot section components) large temperature changes result in significant by thermal expansion and contraction and therefore significant by thermal expansion and contraction. This strain are reinforced or countered by mechanical strains associated with centrifugal loads as engine speed changes. The combination of these events causes material degradation due to TMF [4].

B.DIFFERENT MODE FOR CRACK LOADING

There are mainly three mode of the Crack Loading

- Mode-I: - This mode of loading knows as crack opening Mode or Tensile. The crack surface moves directly apart. It is most common type mode encounter in most of engineering design.
- Mode-II: - This mode knows as in plane shear mode. Where the crack surface slides over one another in a perpendicular to leading edge of the crack.
- Mode-III: - This mode knows as out of the plane shear mode. Where the crack surface slides over one another in a perpendicular to leading edge of the crack.

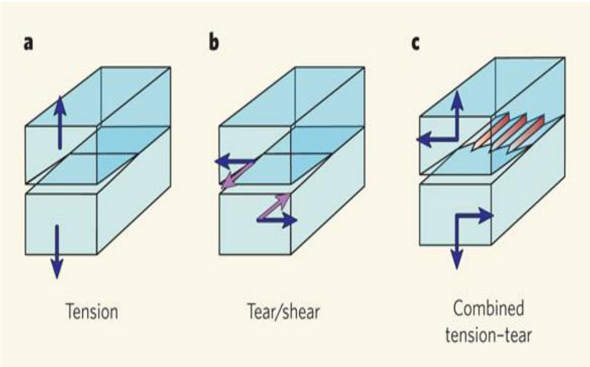

Fig:-1 Three Different mode of Crack Loading

II. LITERATURE REVIEW

M. Nani Babu had work done on the evaluation of FCG behavior of SS316L (N) under mixed mode loading condition. The FCG data for mixed mode have been compare with pure mode-I. The crack length measurement was carried out using a suitably calibrated direct current potential (DCPD) system. They concluded that when the loading angle is increase the fatigue crack growth decrease. At loading all three models appear successful [1].

Rohinkumar I. Patel and Chetan Jadav had been presented the investigated of the fatigue crack growth rate of thin plate. For find out crack growth path under the constant amplitude loading. Further FEA analysis is done by XFEM based algorithm available in the finite element code ABAQUS is explored with respect to its performance in estimating crack growth Paths [2].

H.A. Richard had an overview about theories, experiments and simulation of crack and crack growth under mixed loading condition. They have been described some concept and theories for two dimensional and three dimensional crack in mixed mode situation. Experiments for 3D mixed mode problems are very difficult to perform. Based on the theoretically and experimentally results are compared. For crack growth simulation three dimensional programs ADAPCRACKD used [3].

Nirepesh vikaram and Raghuvir Kumar had been focused on crack propagation in fatigue and its numerical analysis using Fem published since 19^{th} century and identified new research lines. Based on the literature review they conclude that the fatigue crack growth rate equation expressed in term of the stress intensity factor range K deepened on the R-ratio. They observed that some researcher have found that U is a function R only, and is independent of other parameters for a material. Specimen geometry and material properties are found to affect crack growth rate. Nowadays also crack closure was still considered to be the leading mechanism to arrive at effective in stress range [4].

Rahman Seifi and Naser Omidvar had been focused on the fatigue crack growth affected by some parameters such as inclination angle, pre-crack length, load ratio and thickness. The crack growth path, fracture surface and stress intensity factor along crack front are studied by the numerically and experimentally. Based upon the experimental work and numerical calculation found that FEM will be accurate for study of mixed mode fatigue crack growth. Fatigue lives increase by increasing the crack angle and decreasing the pre crack length. The stress intensity factor for all modes increases when the length of pre-crack increases and by increasing the thickness and loads ratio, the SIF values decreases for all modes [5].

Pukar T. Sanjay and Pathak Sunil had focused on the capability and limitation for predicting the crack propagation trajectory and the stress intensity factor value under linear elastic fracture analysis. In this work the main purpose of serving optimum design of structure against fatigue failure and the fatigue crack path. Circular hole in rectangular plate and double notched plate were consider under mode-I loading using and adaptive mesh finite element strategy. Finally they concluded numerical finite element analysis with displacement exploration method have been successfully employed for linear fracture mechanics problem [6].

Lichun Bian and Farid Taheri had been observed the crack initiation and propagation in rectangular and theoretically. Based on the different criteria, a detailed analysis of fatigue crack initiation and propagation under mixed mode loading condition as commonly encountered in encountered in engineering structure. They consider that the Z-criterion is effective and offers acceptable estimation in predicting the mixed mode fatigue crack propagation [7].

Ki-Jeong Seo was investigate on the fatigue crack growth with/without a circular micro defect under the mixed mode loading condition is through experiments and analyzed by linear elastic finite element (FE) analysis. In this work simulated crack path observed through experiment. In this studied three loading angle and two cases of the sample with circular micro defect are selected. Based on the experimental work, they concluded that the crack growth rate increases when the crack entre in to micro-defect. On the other side when the crack does not entre the micro defect, the effective rang of stress intensity factor can be a better parameter for explaining the crack growth rate [8].

J.M. Alegre was work done on the modeling of crack propagation through a finite element mesh under mixed mode condition and the effect of mesh size in the crack path estimate also analyzed. The effect of initial crack angle on the experiment results showed that development of the crack propagation [9].

Luca Susmel and David Taylor had done work on the non-propagating crack were generated under different Mode-I and mode-II stress components. They concluded that crack length tended increase as the mode-II contribution to fatigue damage increased. They used linear elastic stress analysis, are useful tool for the prediction of fatigue limit under mixed mode in phase loading condition [10].

L.P. Borrego was presented work on the correlation of the equalient value of effective stress intensity factor with crack growth rate. They have been concluded when load direction modified the fatigue crack growth rate direction change immediately from the initial notch orientation. Under the mixed mode loading condition the crack closure increase compare to mode-I loading condition. From the experiment they have been concluded that the lower crack closure level are obtain by the elastic-plastic finite element analysis relatively to measure value at high load direction angle mainly due to roughness induced closure [11].

M. Sander and H.A. Richard gave an idea about fatigue crack growth under variable amplitude loading in real structure is modeled using elastic-plastic finite element analysis. Based on the numerical and simulation study it can be concluded that the crack closure is very important factor for the fatigue crack growth. By a mixed mode overload the crack deformation become asymmetrical and smaller [12].

III. EXPERIMENTAL AND FINITE ELEMENT ANALYSIS

Modeling was done with Cre-o and analysis was carried out using ABAQUS, a commercially available FE analysis programed. The material used in this study was one of commercial-grade hot-rolled Mild steel (IS 2062 Grade-A E-250) which is popularly used in Boiler, Furnaces and Automobile parts. Physical parameters of plate, material properties and Chemical composition of material are given below.

A. *Physical parameters of component*

Table:-1

1.	Length (mm)	115
2.	Width (mm)	50
3.	Thickness (mm)	5
4.	Length of Crack (mm)	15
5.	Thickness of Pre-Crack (mm)	0.36

B. *Material properties of IS 2062 Grade-A (E-250)*

Table:-2

Yield strength (MPa)	250
Elongation	23
Poisson's ratio	0.30
Tensile Strength (MPa)	410

C. *Chemical composition of IS 2062 Grade-A (E-250)*

Table:-3

C %	Mn %	S %	P %	Si %	CEV %
0.149	0.148	1.034	0.021	0.012	0.328

D. *Experiments*

For experimental work the sample specimen surfaces are first clean with the help of surface grinder machine to remove the surface roughness, voids, Scratches. After that Wire cut machine is used for to achieve the exact dimension with higher accuracy. Crack is created using wire cut machine. The crack created is equal to diameter of wire. The diameter of wire is 0.38 mm. As Shown in Fig.2 for Pure Mode-I crack is created at 0° with Horizontal plane, Mixed Mode-I+II Crack at angle 30° and 45° and mixed mode-I+III Crack angle at 30° and 45° are considered for the study.

Fig. 2 Details of Specimen (Front View & Side View)

Two test conditions are taken for Pure Mode-I, Mixed Mode-I+II, 30° and Mixed Mode-I+III, 30° the load ratio (R) of -1 with loading frequency is 22 Hz. For Mixed-Mode I+II, 45° and Mixed-Mode I+III, 45° load ratio(R) of -0.8 with loading frequency is 22 Hz.

Fatigue load were applied by Servo hydraulic machine. A simple fixture was used for assembling the specimen to the machine. A sample under load and its fixtures are depicted in Fig. 3. All tests were done at room temperature. The length of fatigue crack growth was measured along crack path by a traveling microscope. The crack length is measured in X and Y direction by profile projector.

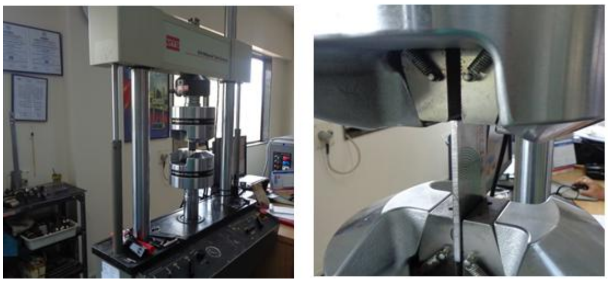

Fig. 3 A sample with proper fixture before test and during test

E. Finite element Analysis

A commercial FE analysis program ABAQUS is used for the computation of fatigue crack path. First, Model of plate with different modes is created using Cre-o software. ABAQUS software is used for analyzing different condition to get accurate results.

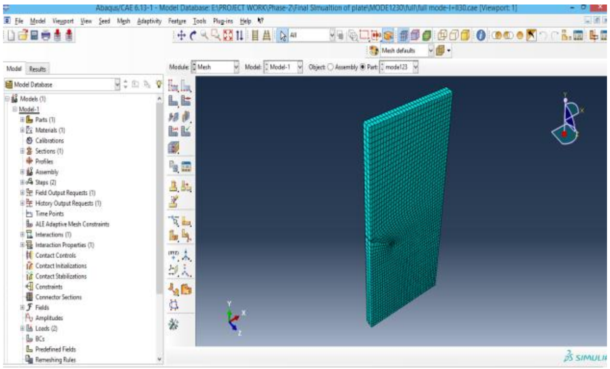

Fig. 4 Meshed View of plate for Mixed Mode-I+II, 30°

As shown in Fig.4 by increasing the number of elements, the fatigue path gets more accurate. In figure demonstrates a meshed blade with 12860 elements generated.

III. RESULTS AND ANALYSIS

In below figures, the comparison between the crack paths obtained by the experimental and FE analysis is shown for all cases are considered for carrying work.

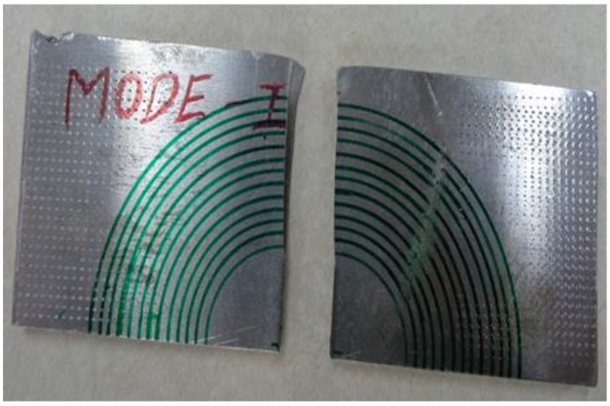

Fig.:- (a) For pure Mode-I after failure

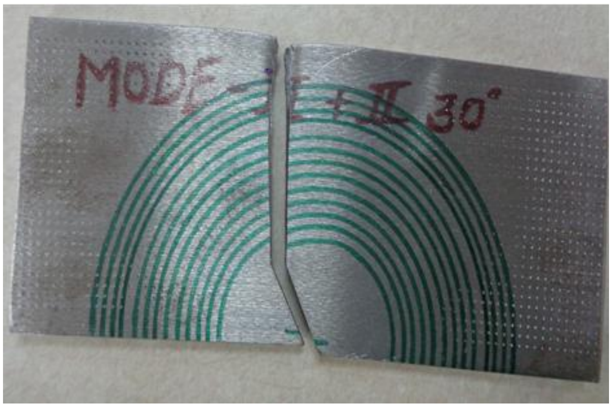

Fig.:- (b) For Mixed Mode-I+II, 30° after failure

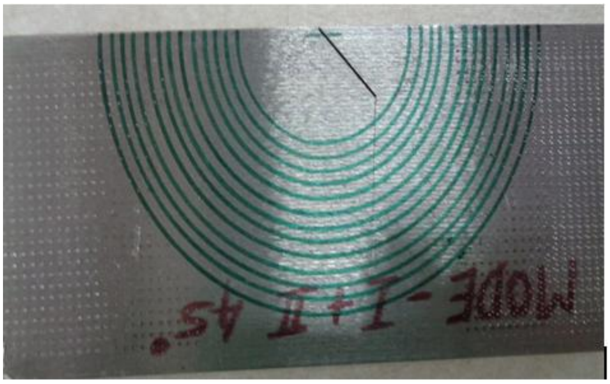

Fig.:- (c) For Mixed Mode-I+II, 45°

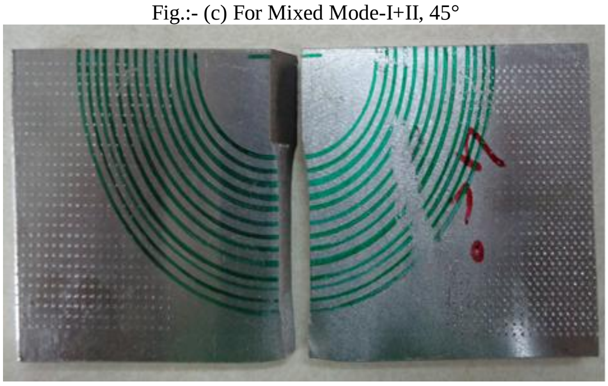

Fig.:- (d) For Mixed Mode-I+III, 30° after failure

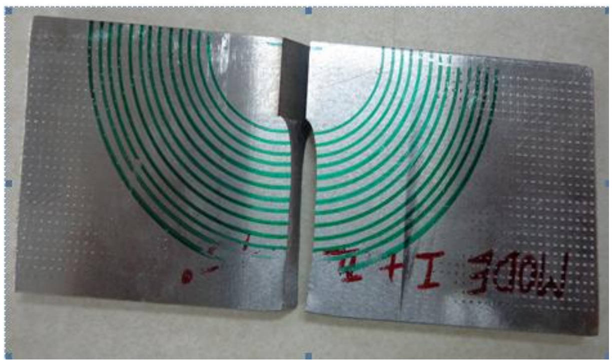

Fig.:- (e) For Mixed Mode-I+III, 45° after failure

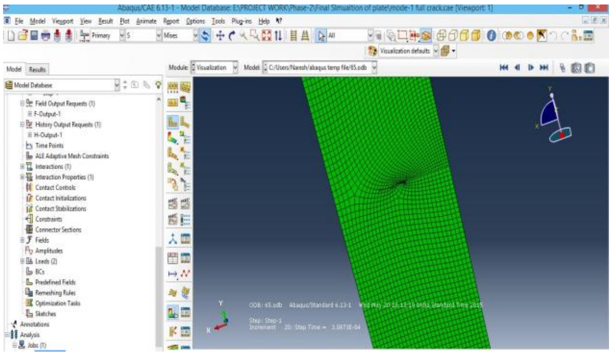

Fig.:-(f) Crack growth incrases for Mode-I

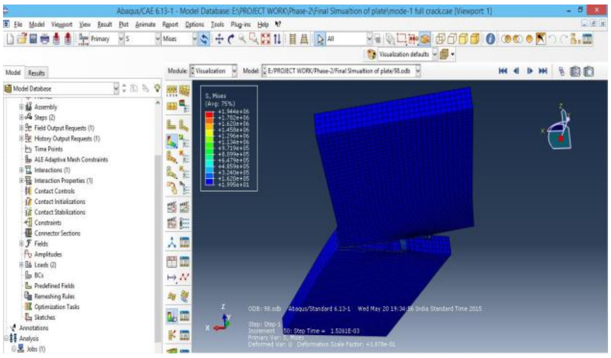

Fig.:-(g) Contours deform shape for Mode-I

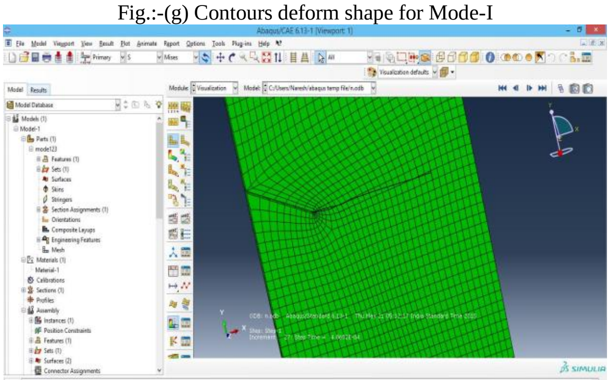

Fig.:- (h) Crack path for Mixed Mode-I+II, 30°

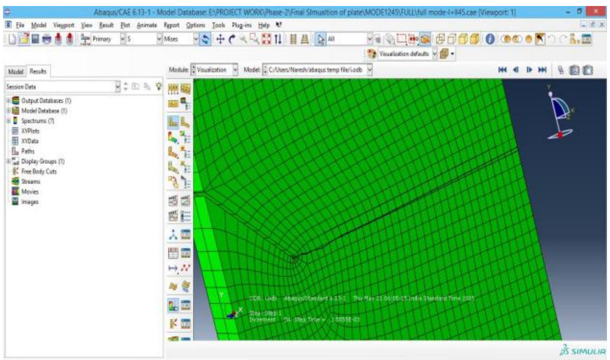

Fig.:- (i) Crack path for Mixed Mode-I+II, 45°

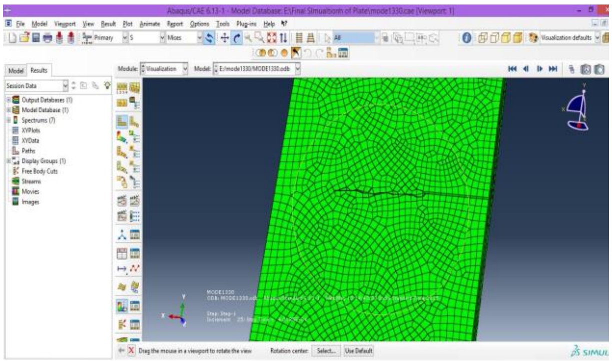

Fig.:- (j) Crack path for Mixed Mode-I+III, 30°

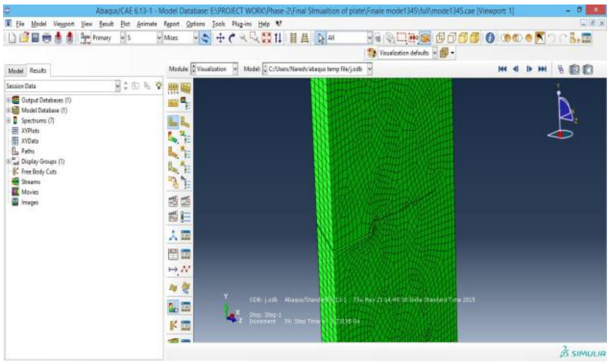

Fig.:- (k) Crack path for Mixed Mode-I+III, 4

A. Compare results of Experimental Vs. FEA Crack Length

Below graph shows the fatigue crack length on Y axis versus crack length on X axis. It is compare experimental data versus simulation data. In which the blue line indicate experimental data and red line indicate simulation data. The result shows these lines are all most identical but having some negligible amount of difference.

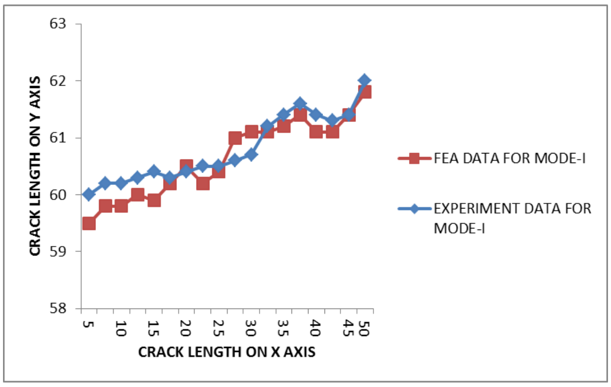

Fig. 5 Graphical Representation for Mode-I

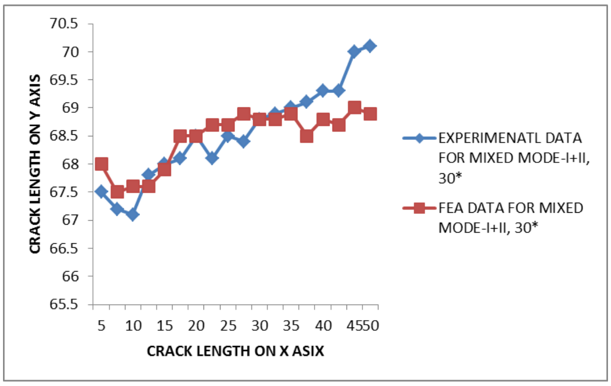

Fig. 6 Graphical Representation for Mixed Mode-I+II, 30°

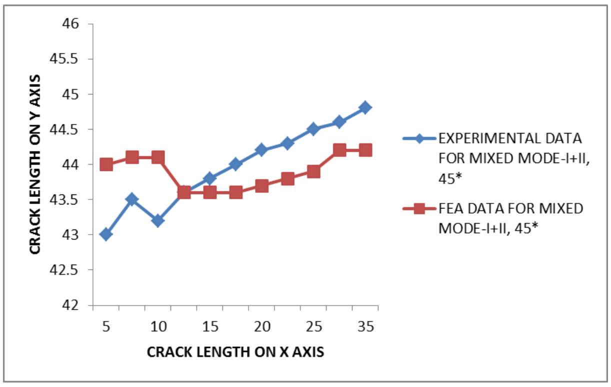

Fig. 7 Graphical Representation for Mode-I+II, 45°

Fig. 9 shows Compressions of the simulation data Vs experimental data. Experimental data taken as average both side cracks on plate.

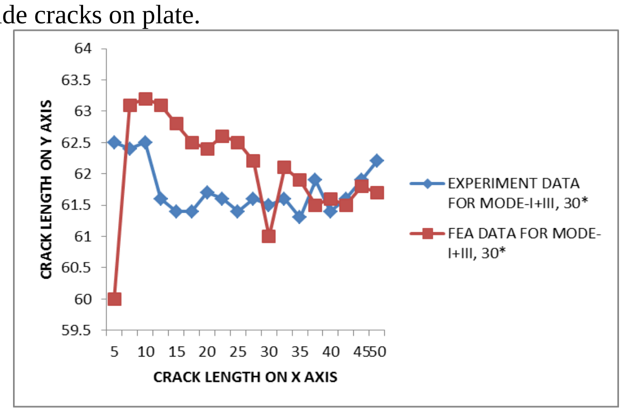

Fig. 8 Graphical Representation for Mode-I+III, 30°

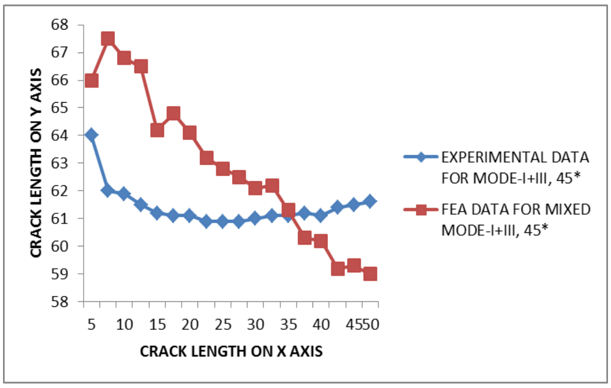

Fig. 9 Graphical Representation for Mode-I+III, 45°

B. Compare Fatigue Number of cycle Vs Crack Length

Below graph shows the comparison between Number of Cycle versus crack length. Compare Mode-I with Mixed Mode-I+II, 30° and Mixed Mode-I+II, 45°. For mixed Mode-I+II, 45° Load ratio is -0.8. A result shows that when any part under Mixed Mode and having more inclination angles with load direction it requires more number of cycles for crack initiation and complete failure of component.

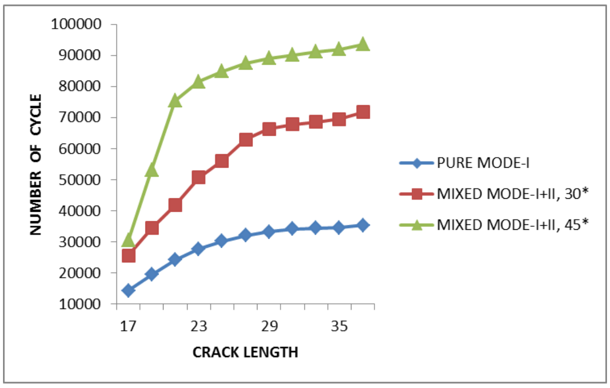

Fig. 10 Graphical represntation for Pure Mode-I with Mixed Mode-I+II, 30° and Mixed Mode-I+II, 45°

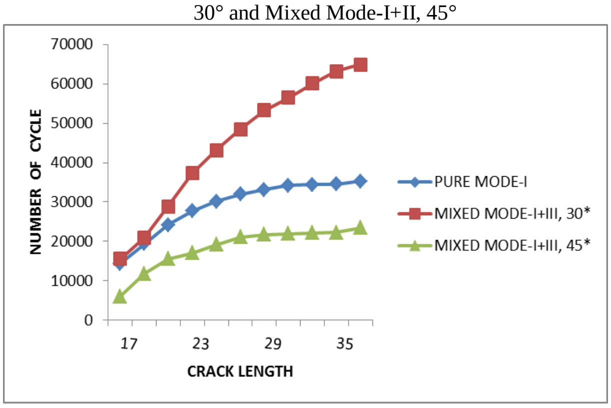

Fig. 11 Graphical represntation for Pure Mode-I with Mixed Mode-I+III, 30° and Mixed Mode-I+III, 45°

CONCLUSION

In this study, Fatigue crack Growth and fatigue path of IS 2062 Grade-A (E-250) is investigated through experiment and simulation. The CAD model was created in Cre-o and FEA is carried out using ABAQUS. Compare the experimental results with Simulation results. On the Bases upon these results, the fatigue crack growth life increases by increasing of a crack angle. As the number of cycle increases and as the crack length reaches near to the middle-portion of the plate, mode of failure changes from Mixed-mode-I+II to pure mode-I. In the Pure Mode-I load Condition; the crack path is nearly perpendicular to load direction. The Cracks Paths follows the Zigzag way from initiation of crack to complete failure of plate.

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