FATIGUE ANALYSIS OF PLATE IN DIFFERENT MODES EXPERIMENTALLY AND USING FE ANALYSIS

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Abstract:Different metals are used with different geometrical cutouts in different industrial products; like aerospace, automobile, etc. this metallic components undergoes cyclic loading of (fatigue) condition from so many years. A lot of research work has carried out for the solution of fatigue. In this project work, we will try to identify the different parameters affecting\influencing the operational parameters, which directly or indirectly affect fatigue. In this work, our objective is to find out the Fatigue Crack Growth (FCG) on IS 2062 Grade A (E-250) plate. Fatigue Crack-Growth of plate had performed on Servo Hydraulic Machine. In this study, to find the fatigue crack growth of plate constant amplitude load is used. There is mainly two modes first opening or tensile mode and second in plane shear and mixed of these two modes were experimented for fatigue crack growth-rate. In addition, FE analysis has done for study of fatigue crack-growth propagation.

***Keywords* - Fatigue analysis of plate, crack growth analysis of plate, mixed mode analysis of plate, fatigue analysis of plate in cyclic loading.**

I. INTRODUCTION TO FATIGUE:-

Materials fails under the fluctuating stresses at a stress magnitude, which is lower than the ultimate tensile strength or yield strength of the material. Fatigue failure is also defined as time delayed fracture under cyclic loading. About 80% of failure of mechanical components is due to fatigue failure resulting from fluctuating stresses. These failures are dangerous because they occur without any warning. The phenomenon of decreased resistance of the material to fluctuating stresses is main characteristic of fatigue failure. These failures occur in both metallic and non-metallic materials [1]. Fatigue is “the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations”[2]. The fatigue is defined as the deterioration of a component caused by the crack. Initiation or by the growth of a crack. Basic different between failures due to [3]:-

1) Static load.
2) Fatigue.

1) The failure due to static load of the component by the simple tension test. In this case, the load is gradually applied and there is sufficient time for the elongation of fibre.
2) Fatigue failure begins with a crack at some point in the material.

- Crack is more likely to occur in the following regions:

1. Regions of discontinuity, such as Oil holes, Keyways, Screw threads etc.
2. Regions of irregularities in machining operation, such as Scratches on the surface, Stamp mark, Inspection marks etc.
3. Internal cracks due to defects in materials like blowholes.

Examples of parts in which the fatigue failures are common: transmission shaft, automobile crankshaft, connecting roads, gears, vehicles, suspension springs, and ball bearing, jet engines, turbines, mostly aircraft wings, power plants, ships, etc.

W. A. J. Albert [4] found that fatigue is not depending on the overload but the number of repeating loaded cycles, which refer to fluctuating loading. There is commonly recognized that a material failure may happen even the maximum stresses are well below the ultimate tensile stress limit. It has long been confirmed that fatigue is one of the primary reasons for the failure of structural components. In fact, 80% to 95% of all structural failures occur through a fatigue mechanism, Adarsh Pun.

There are mainly three modes of the crack loading:-

1) MODE – I: - This mode of loading known as crack opening mode or Tensile. The crack surface moves directly apart. It is most common type mode encounter in most of engineering design.
2) MODE– II: - This mode known as plane shear. Mode where the crack surface slides over another in a perpendicular to leading edge of the crack.
3) MODE – III: – This mode known as Out of plane shearing. Where the crack Surface relative to one another and parallel to the leading edge of crack.

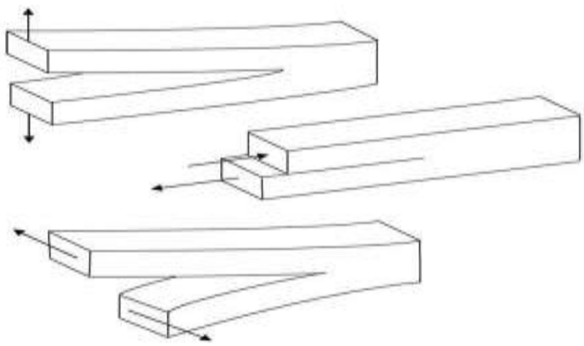

Figure 1Modes of Failure.[5]

The process of fatigue is characterized by the three stages [6]:-

1) Crack Nucleation (Crack Initiation):- Fatigue cracks start following the nucleation of a crack on a persistent slip bend (PSB). The initial crack propagates parallel to the slip bands. The crack propagation rate during stage is very low, on the order of 1 nm per cycle, and produces a practically featureless fracture surface. The crack initially follows the slip bands at approximately 45 degree to the principal stress direction.
2) Fatigue Crack Growth (Stable Crack Nucleation):-This is the number of cycle required to grow the crack in stable manner to a critical size, generally controlled by stress level. The Stress Intensity Factor has used in fracture mechanics to predict the stress state near the tip of a crack caused by a remote load. It is denoted by K.

STRESS INTENSITY FACTOR (K):-

$$K = \beta * \sigma * \sqrt{a \quad \pi} \text{................1)}$$

3) Rapid Fracture (Unstable Crack Propagation):-Very Rapid critical crack growth occurs when the cracklength reaches a critical value.The Fracture Toughness KIC of the material is the primaryfactor for rapid fracture prediction or Design against fracture.Maximum value of stress intensity-factor, which the partcan sustain, is known as Fracture Toughness, It is denoted byKIC.

FRACTURE TOUGHNESS (Kic):-

$$Kic = \beta * \sigma * f * \sqrt{a \quad \pi} \text{..................2)}$$

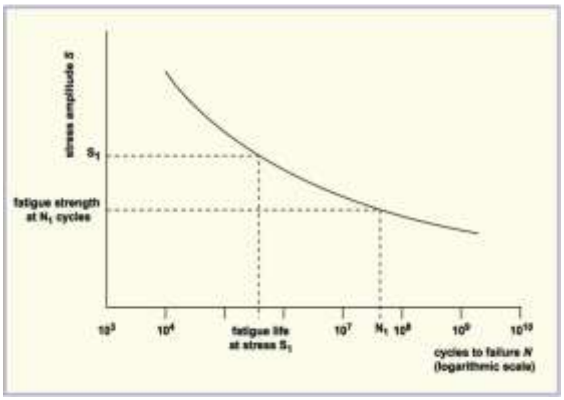

Figure 2S-N Curve

There are two region of this Fatigue Curve are [6]:

1) LOW – CYCLE FATIGUE: Any fatigue failure when the numbers of stress cycle are less than 1000 is consider as Low Cycle Fatigue. Ex: Failure of studs on truck wheels, Failure of setscrew for locating gears on shaft.

2) HIGH –CYCLE FATIGUE: - Any fatigue failure when the numbers of stress cycle are more than 1000 is called High Cycle Fatigue. The failure of machine components such as Springs, Ball Bearing or Gears that Subject to fluctuating stresses are the example of high cycle fatigue.

Joel schubbe (2009) [7] evaluate the fatigue life and crack growth rates in 7050-T7451 Aluminum plate for T-L and L-S oriented failure under truncated spectra loading. An accurate numerical determination of the stress field and stress intensity variation through the thickness of a central cracked plate was first carried out in order to evaluate three-dimensional effects in FEA analysis ABACUS software is used.

L.P. Borrego, F.V. Attunes, J.M. Costa (2006) [8] experimented mixed mode fatigue crack growth behavior in aluminum alloy. Experiment has done by different loading angle crack-growth paths for several loading angles. Observed that fatigue crack growth direction changed immediately from the initial notch.

Eugenio Giner, Mohamad Sabsabi (2010) [9] analyzed numerically and correlated experimentally the orientation and propagation of crack in fretting fatigue problem by use the extended finite element method (X-FEM).

J.B.Esnaulta, V.Doquet.a, P.Massin (2013) [10] had studied the three dimensional analysis of the fatigue crack paths in thin metallic sheets, they reported that Tests in air or in salt water produced different crack paths for similar mechanical conditions, shear lips being reduced by the corrosive environment, in the aluminum alloy as well as in steel.

Y. S. Upadhyaya and B. K. Sridhara (2012) [11] studied fatigue crack initiation and propagation life prediction of materials". Fatigue life is predicted for a smooth (un-notched) specimen in the strain amplitude range of 0.3 % to 0.7 %, in room temperature at stress ratio of -1. The inputs required for both the models have been determined by conducting monotonic, cyclic, fracture toughness and fatigue crack growth tests.

M. Sander, H.A. Richard (2005) [12] had studied the finite element analysis of fatigue crack growth with interspersed mode I and mixed mode overloads. They studied the fatigue crack growth under variable amplitude loading in a real structure is modelled using an elastic-plastic finite element analysis. They reported that due to an overload depending on the overload ratio R and the mode I/mode II ratio plastic deformations occur. They conclude that due to a mode I overload plastic deformations along the crack surfaces occur.

J.R. Yates, M. Zanganeh, R.A. Tomlinson, M.W. Brown, F.A. Diaz Garrido [13] studied experimentally crack path under mixed mode loading. They compare the cyclic stress intensity factors obtained from these experiments with Numerical simulations using finite element analysis.

II. EXPERIMENTAL FACILITY:-

2.1.) Fatigue testing machine: In this study, the experiment of fatigue crack has done by using Servo Hydraulic Fatigue Testing Machine, MTS 810. This hydraulic machine used to give the different loading condition at different frequencies on the specimen for the test of specimen. Figure of this Servo Hydraulic Fatigue Testing Machine shown below:

Figure 3Servo Hydraulic Fatigue Testing Machine

2.2.) Machine specification /*Test loading conditions/parameters for fatigue testing:*

Specification of machine used in this test given below:

1.) Frequency = 100Hz.
2.) Loading Capacity = 100 KN.

Test loading conditions:

1.) Tension – Tension.
2.) Tension – Compression.
3.) Compression – Compression.

Parameters for fatigue testing:

1.) Frequency
2.) Load
3.) Stress ratio or R-ratio

Stress ratio or R-ratio defined as the maximum stress experienced during cycle to maximum stress experienced during cycle. Stress value can be positive (Tensile stress) or Negative (Compressive stress).

2.3.) Material and Dimension of plate (specimen):

Material of plate: - IS 2062 A(E-250)

Dimensions of plate:

Table 1Dimension of plate.

Length (mm)	115
Width (mm)	50
Thickness (mm)	5
Length of Crack (Pre-Crack)(mm)	15
Thickness of Pre-Crack (mm)	0.36

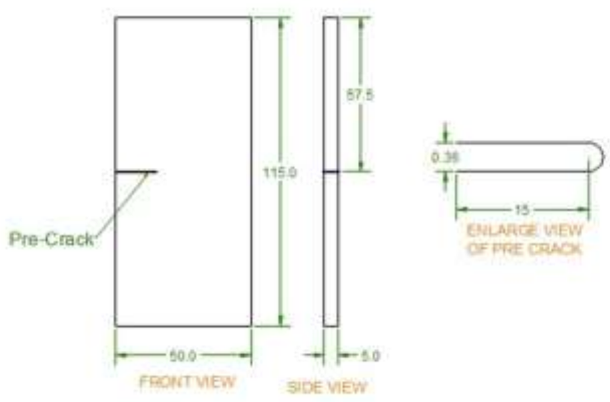

Figure 4Test Specimen of Plate for Pure Mode-I.

2.4). Material Property:

IS 2062 GRADE A (E-250)

Table 2Chemical Composition of IS 2062 Grade A (E-250)

Element Details	C % Max	Mn % Max	S% Max	P% Max	Si % Max	CEV % Max
Weight (%) Balance	0.260	0.430	1.550	0.050	0.050	0.420
Observed Value (%)	0.149	0.148	1.034	0.021	0.012	0.328

Table 3Mechanical Properties of IS 2062 Grade A (E-250)

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

2.5.) Experimental Parameter:

I.)Loading Condition: Fully Reversed Loading
(Load Ratio R= -1and -0.8)

II.) Stress Ratio:

Table 4Stress Ratio

Different Mode	Compression (KN)	Tension (KN)	Frequency (Hz)
Plate-1 (Mode-I)	20	20	22
Plate-2,30° (Mode-I+II,30°)	20	20	22
Plate-2,45° (Mode-I+II,45°)	25	25	22

2.6.) Procedure to perform Experimental work:

During the experiment, first remove the surface roughness, scratches, void for that first operation to make smooth surface using surface grinding machine.

Figure 5Clean plate surface with Surface Grinder Machine.

After the smoothing of surface, cut the specimen of plate with accurate dimension without damage edges. For precise dimension has achieved by Wire Cut Machine without damage of edges. The accuracy of Wire Cut Machine is 0.20 Micron.

Figure 6Load Part in to Wire Cut Machine.

After cut the plate accurately in desire dimension. The Pre -crack is also created by the Wire Cut Machine because requirement of small crake as possible without any damage. Thickness of wire is 0.18 mm and it will be spark both sides so Pre-Crack generated at 0.36 mm.

Figure 7Wire Cut Machine Create Crack on Plate

Create Mark with the help of marker on plate Specimen at equally at 2 mm. These marks will be start after the Pre -Crack. That mean Pre Crack length is 15 mm so the First Mark Come at 17mm next mark is at 19 mm…onwards.

Figure 8Create Marks on the Plate

After the mark on the plate, fixed the hydraulic chuck in to servo hydraulic machine. Hold the plate specimen on hydraulic ch uck.

Figure 9Hold the Specimen of Plate in Hydraulic Chuck

Input the Experiment parameter in Computer. Given inputs:

1) Length.
2) Width.
3) Thickness.
4) Load.
5) Load Ratio.
6) Frequency.

Apply Run Command on the computer and machine will start to perform the experiment. For measurement of crack growth along crack length the traveling microscope used.

III. MODELIND AND FEA SIMULATION:-

Create a model required for FE analysis of fatigue crack growth rate in plate. Some steps of modeling has shown below:

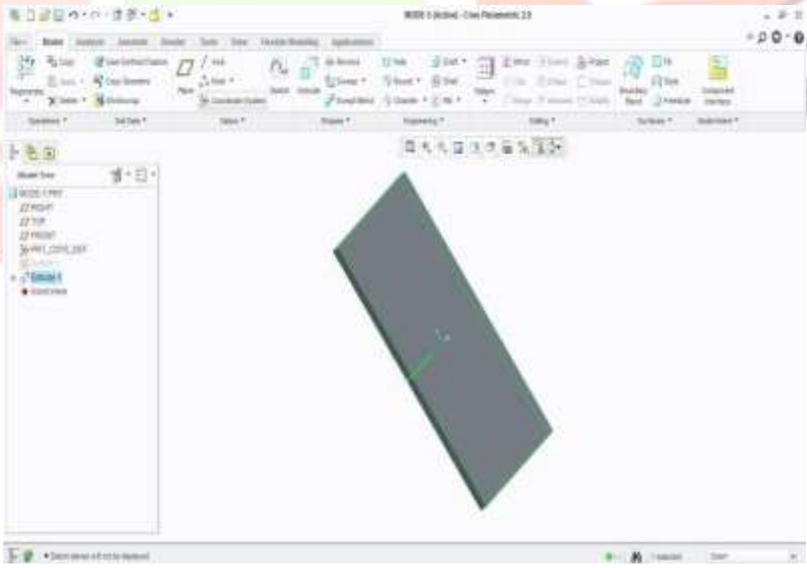

Figure 10 Modeling of Plate for Pure Mode–I.

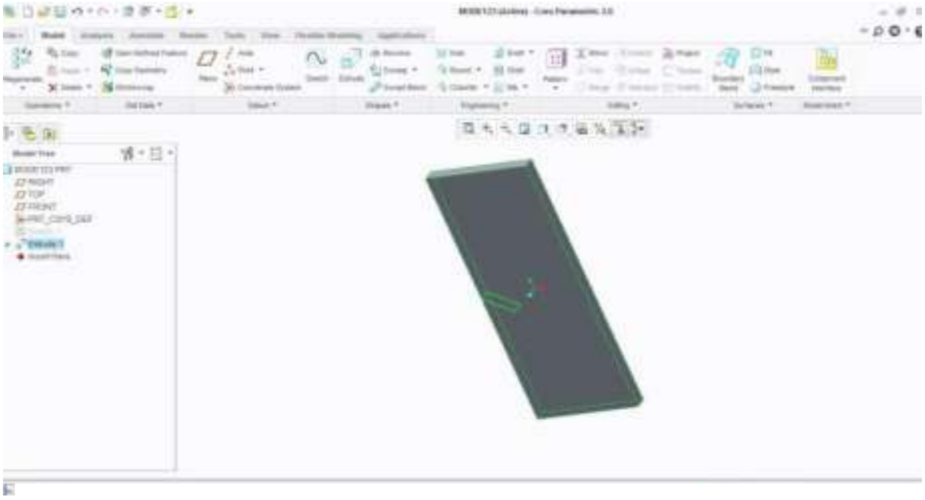

Figure 11 Modeling of Plate for Mixed Mode- I+II, 30°

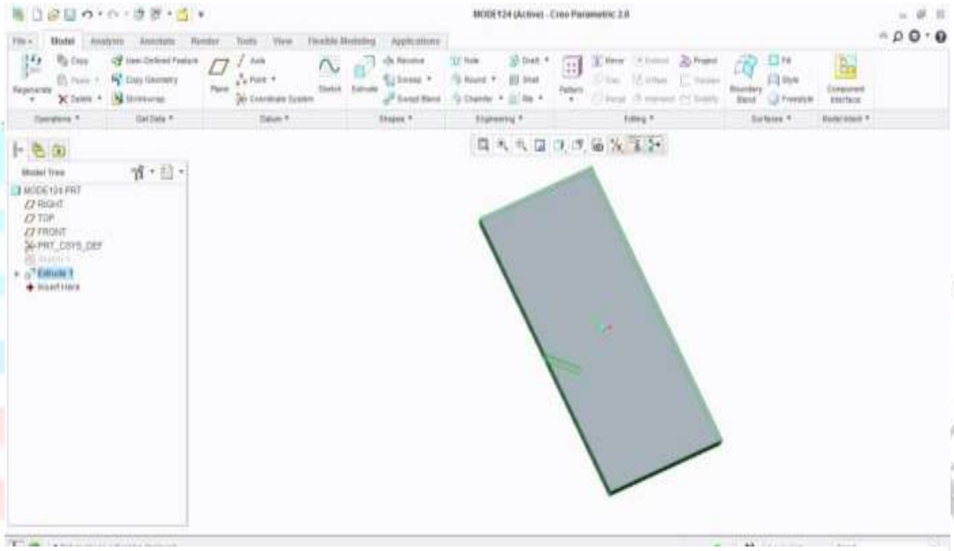

Figure 12 Modeling of Plate for Mixed Mode-I+II, 45°

After modeling of plate geometry, import this geometry in the analysis software. Input the material property for specify the part in to software.
After that select the sectional categories for the plate which homogenous.

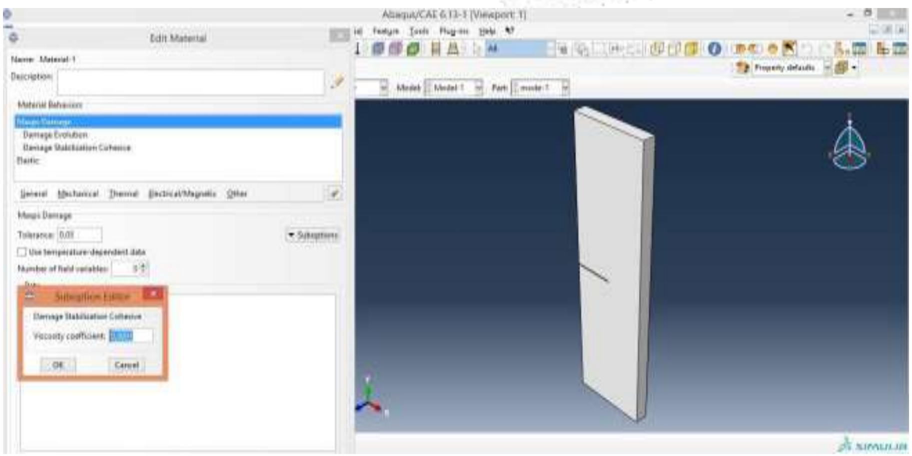

Figure 13 Input Material Properties

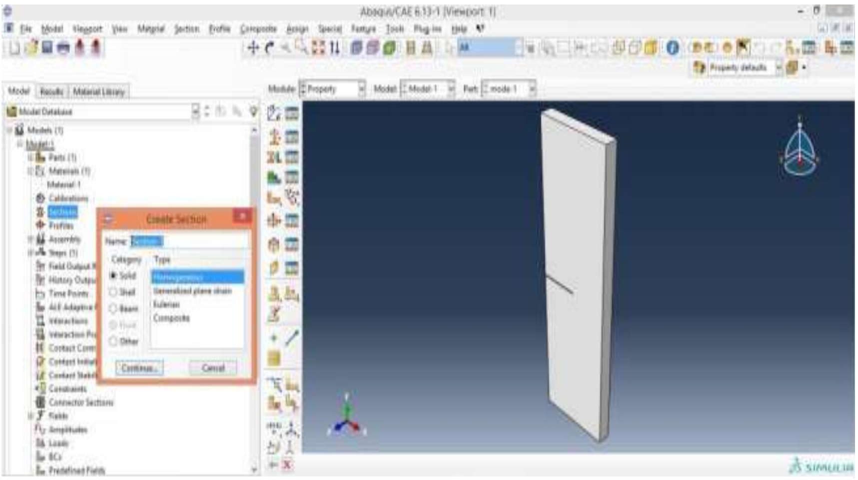

Figure 14Select Sectional Categories for Plate.

After that, create the dependent mesh on the part.

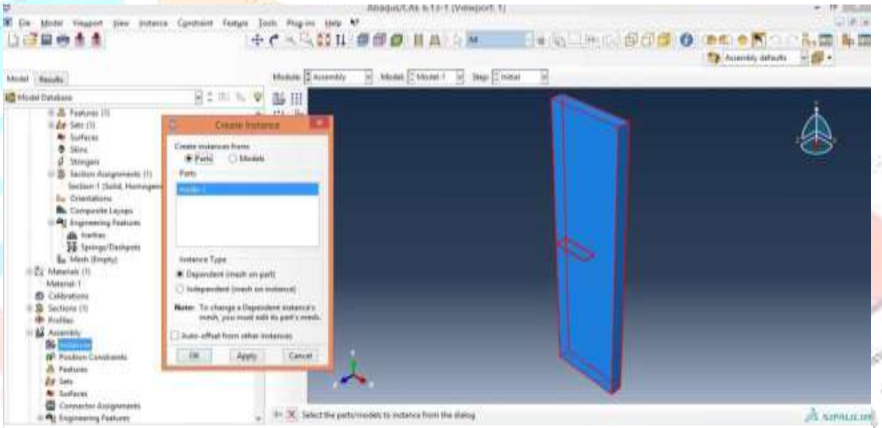

Figure 15Create Instance on Plate.

After this, create the crack location in the geometry and by following the some other procedures make the final model for the FE analysis of crack growth rate in plate.

IV. RESULTS OF EXPERIMENTAL AND SIMULATION:-

4.1. RESULTS OF EXPERIMENTS:

4.1.1 FOR PLATE-1 LOAD (20,-20) FOR PURE MODE-I:-

Load =20 KN
Ratio = -1
Frequency = 22 Hz
Pre Crack Length = 15 mm

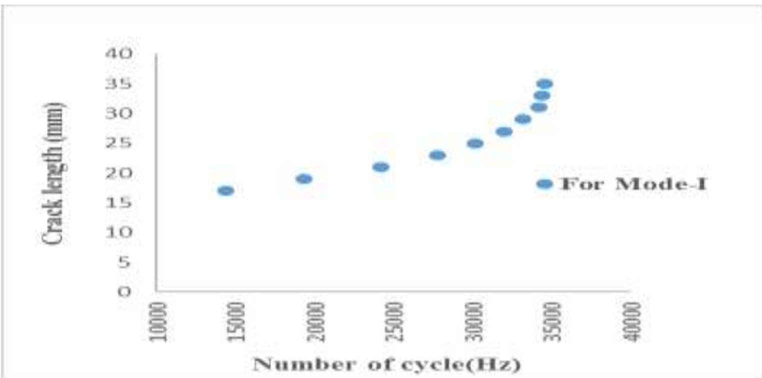

Figure 16Crack Growth rate for Pure Mode-I.

Figure 16 shows the crack growth rate Vs Number of cycles for the pure mode I. crack length increases as the number of frequency increases at constant loading 20 KN. The Fracture of plate occurs at the number of frequency reaches the 35283 plate will fracture completely.

4.1.2 FOR PLATE -2 LOAD (20,-20) FOR MIXED MODE -I+II, 30˚:-

Load =20 KN
Ratio = -1
Frequency = 22 Hz
Pre Crack Length = 15 mm

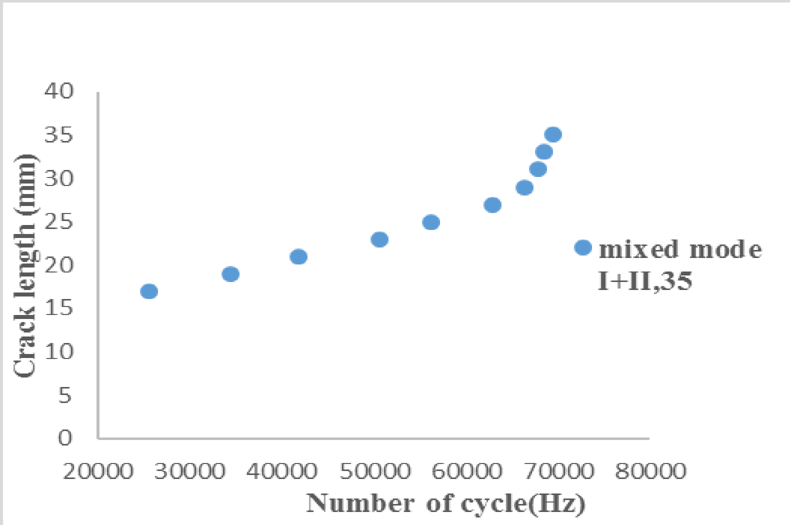

Figure 17Crack Growth rate for Mixed Mode-I+II, 30˚.

Figure 17 shows the crack growth rate Vs Number of cycles for the mixed mode I +II, 30˚. Crack length increases as the number of frequency increases at constant loading 20 KN as it in case of pure mode. However, the Fracture of plate occurs at the number of frequency reaches the 71668 plate will fracture completely, which is higher than the pure mode.

4.1.3 FOR PLATE -2 LOAD (25,-20) FOR MIXED MODE -I+II, 30˚:-

Load =25 KN
Ratio = -0.8
Frequency = 22 Hz
Pre Crack Length = 15 mm

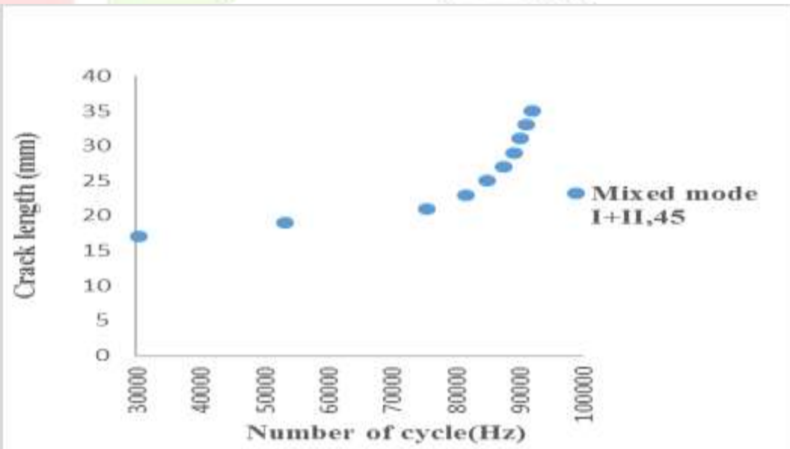

Figure 18Crack Growth rate for Mixed Mode-I+II, 45˚.

Figure 18 shows the crack growth rate Vs Number of cycles for the mixed mode I +II, 45˚. Crack length increases as the number of frequency increases at constant loading 25 KN,- 20 KN. However, the Fracture of plate occurs at the number of frequency reaches the 91986 plate will fracture completely , which is higher than the both pure mode and mixed mode I +II,45˚.

4.2 PLATE BEFORE EXPERIMENT:-

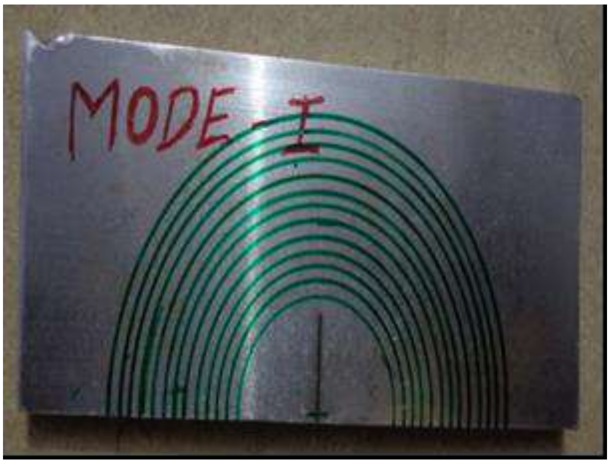

Figure 19Pure Mode-I plate before failure.

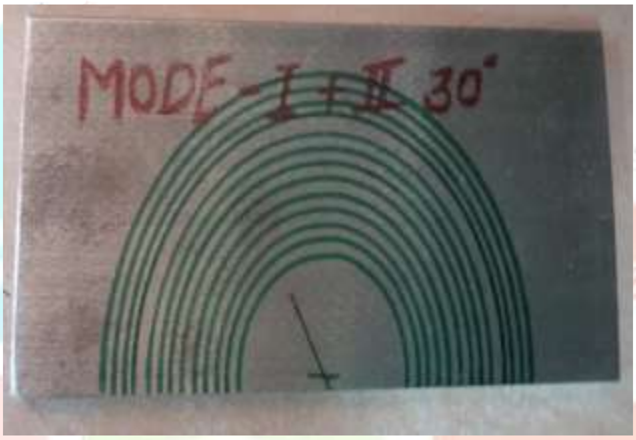

Figure 20Mixed Mode-I+II with 30° plate before Failure

Figure 21Mixed Mode-I+II with 45° plate before Failure

A.3 PLATE AFTER EXPERIMENT:-

Failure of plate in observed servo hydraulic machine. Below figure shows crack follows different path in different mode like mode I crack follows nearly linear path.

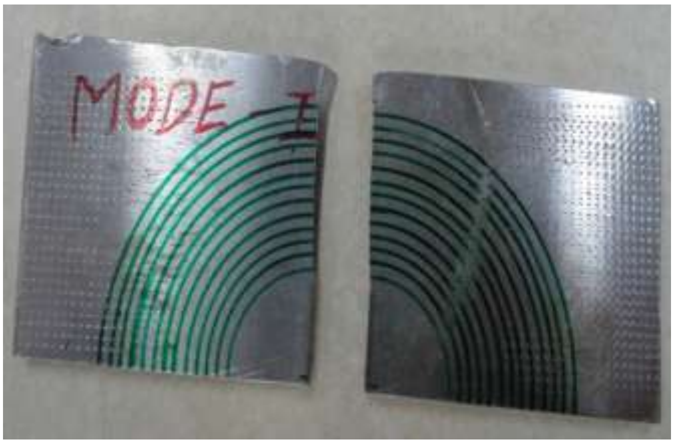

Figure 22For Pure Mode-I plate after Failure.

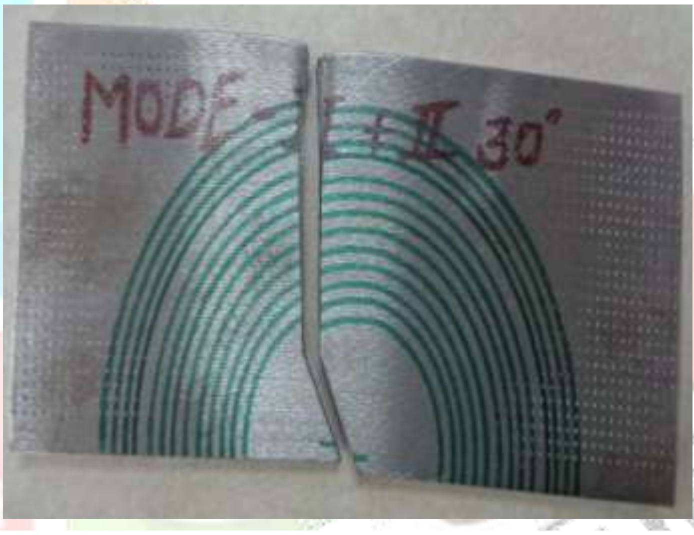

Figure 23For Mixed Mode I+II with 30° plate after failure.

Figure 24For Mixed Mode I+II with 45° plate after failure

4.4. RESULTS OF SIMULATION:

4.4.1 FATIGUE CRACK GROWTH UNDER PURE MODE-I:

Fatigue Crack growth start and its will increase with the number of cycle increases. Below figure 25 shows initiation of the crack.

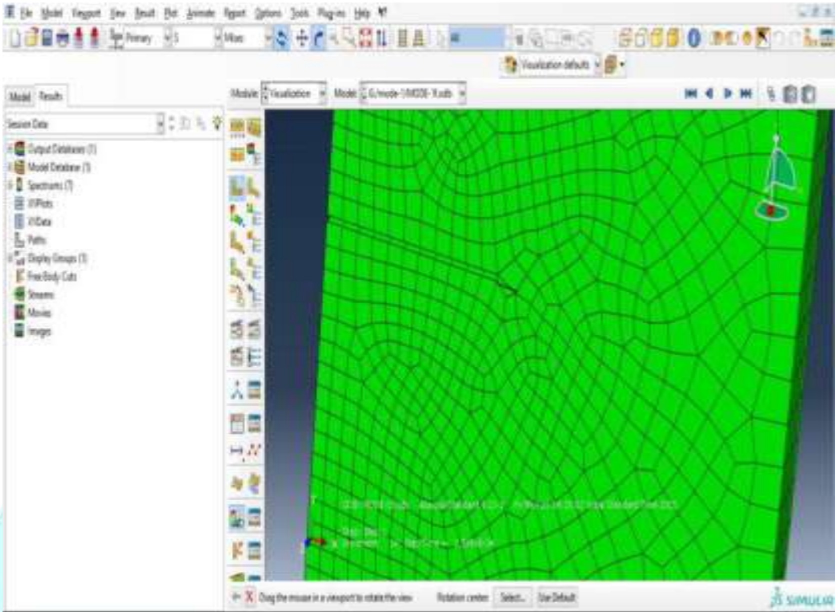

Figure 25Fatigue Crack Start for Pure Mode-I.

Figure 26 shows Contours on deformation shape of Specimen in Pure Mode-I.

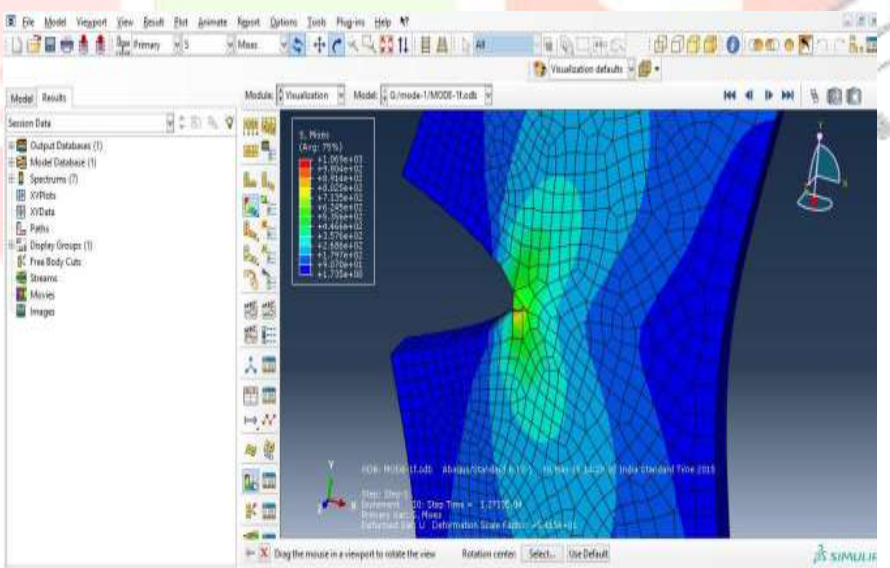

Figure 26Contours on deform shape for Pure Mode-I.

Crack growth start and it will reach near to the middle portion of the specimen. This analysis done for Mode-I, Crack path is approximately straight in linear direction.

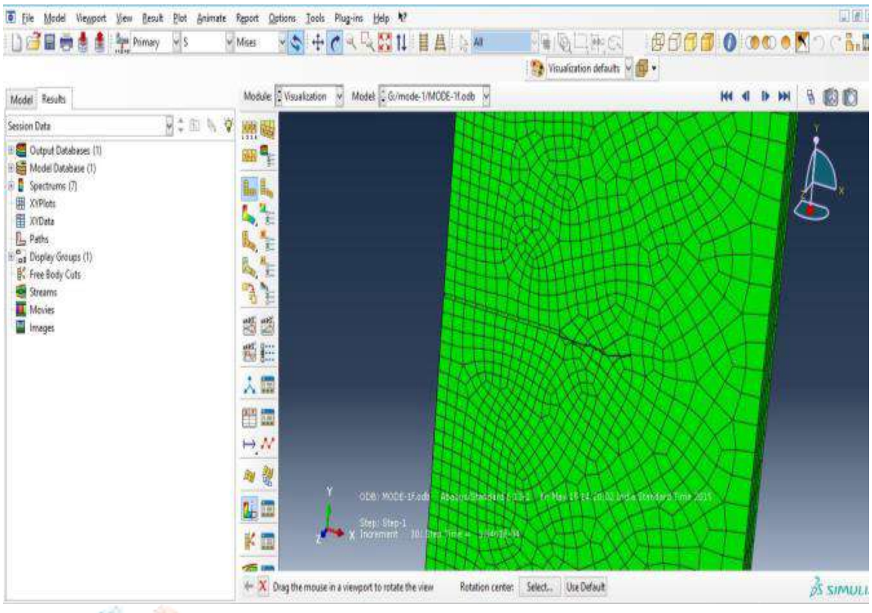

Figure 27Fatigue Crack Growth Increasing for Pure Mode-I

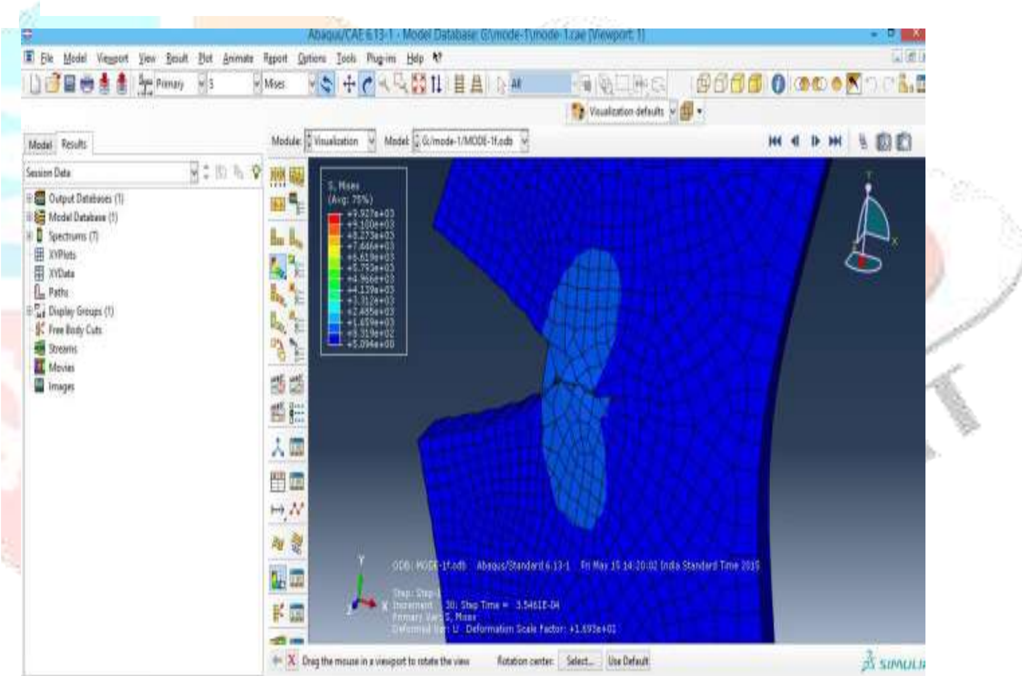

Figure 28Contours deform at middle part of plate forPure Mode-I.

4.4.2 FATIGUE CRACK GROWTH UNDER MIXED MODE-I+II, 30°:

The fatigue crack growth under Mixed Mode I+II, 30°. The first increment of the crack appears in below figure 29. As compare with Mode-I the first increment of crack required more number of cycles to appear the crack.

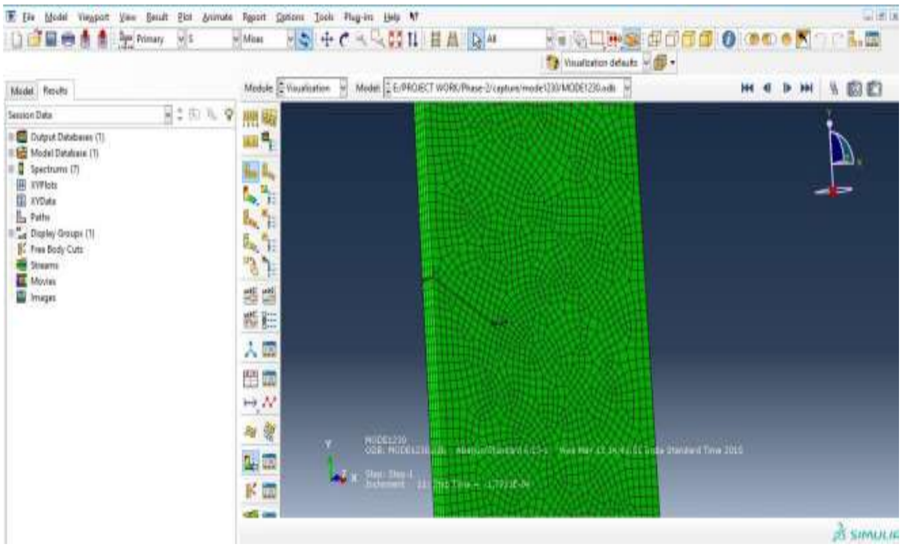

Figure 29Crack Growth Start for Mixed Mode-I+II, 30°.

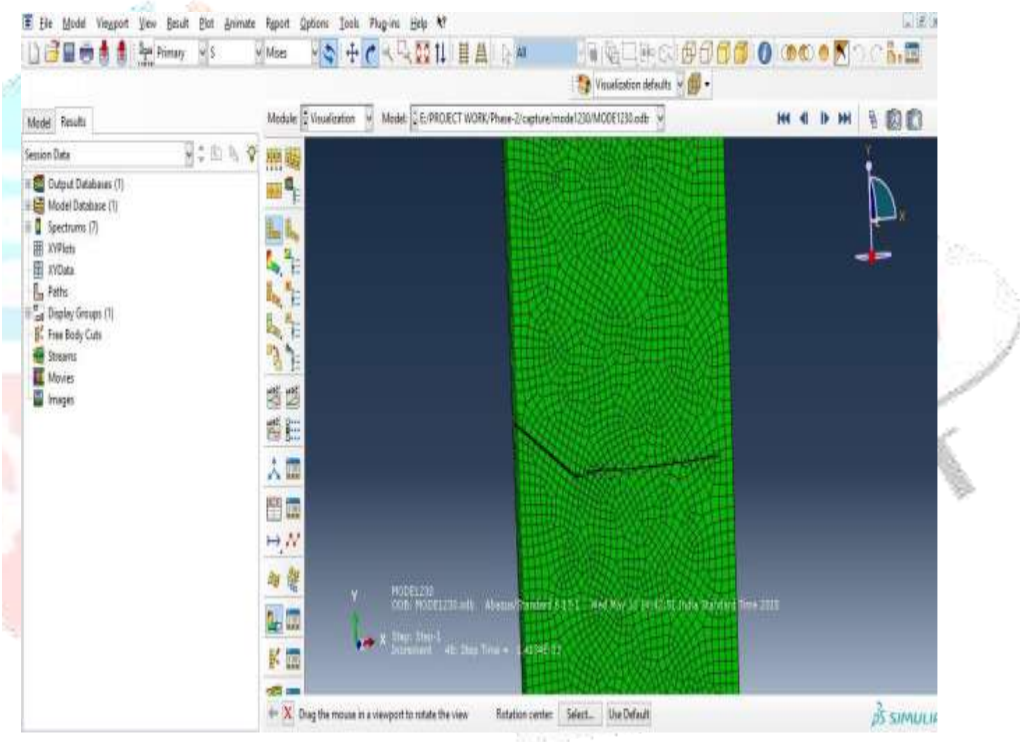

Figure 30Crack reach near to complete failure of plate Under Mode-I+II, 30 °.

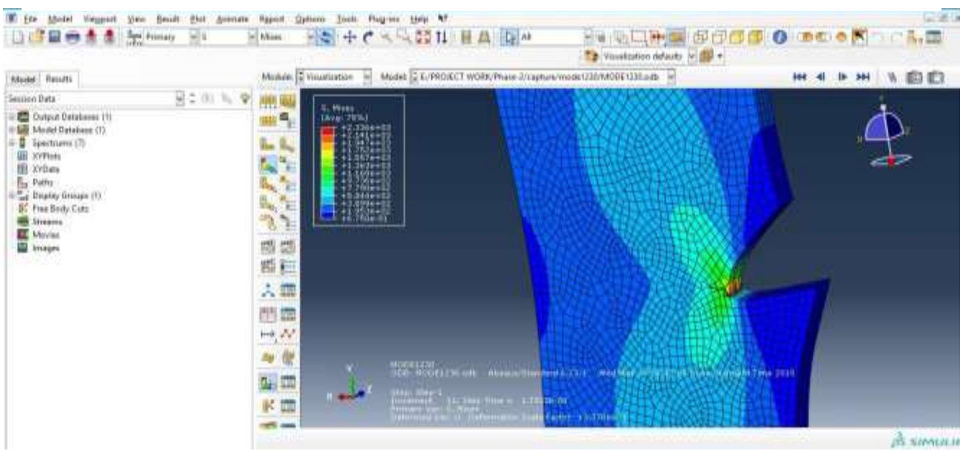

Figure 31Contour Deform Shape on Second Side of plate for Mixed Mode-I+II, 30°.

4.4.3 FATIGUE CRACK GROWTH UNDER MIXED MODE-I+II, 45°:

Fatigue crack growth under Mixed Mode-I+II, 45° is shown in figure below. In Mode-I+II, 45° the load on the plate is larger due to its resist mode fatigue strength and also required a more number of cycle with compare to Mode-I and Mixed Mode-I+II, 30° to first appear crack.

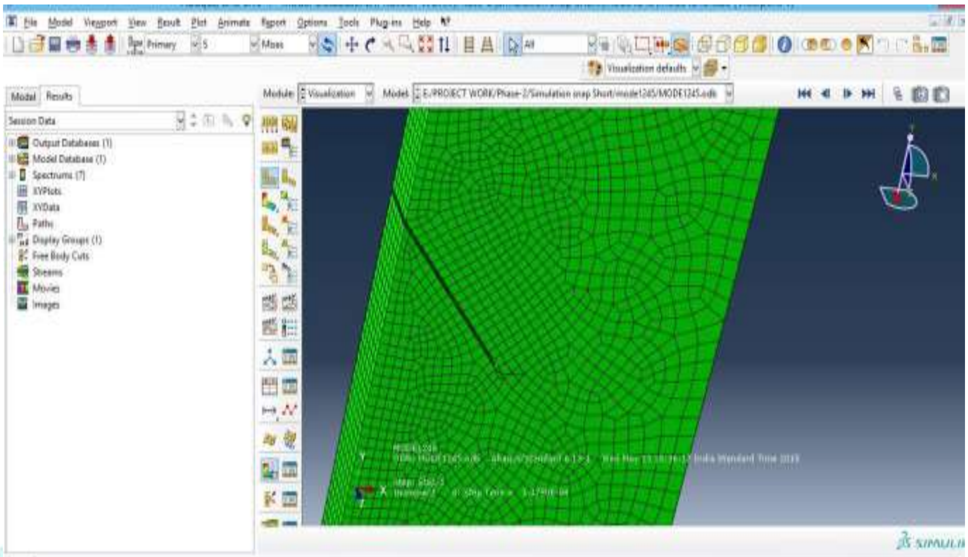

Figure 32Fatigue Crack Initiate for Mode-I+II, 45°.

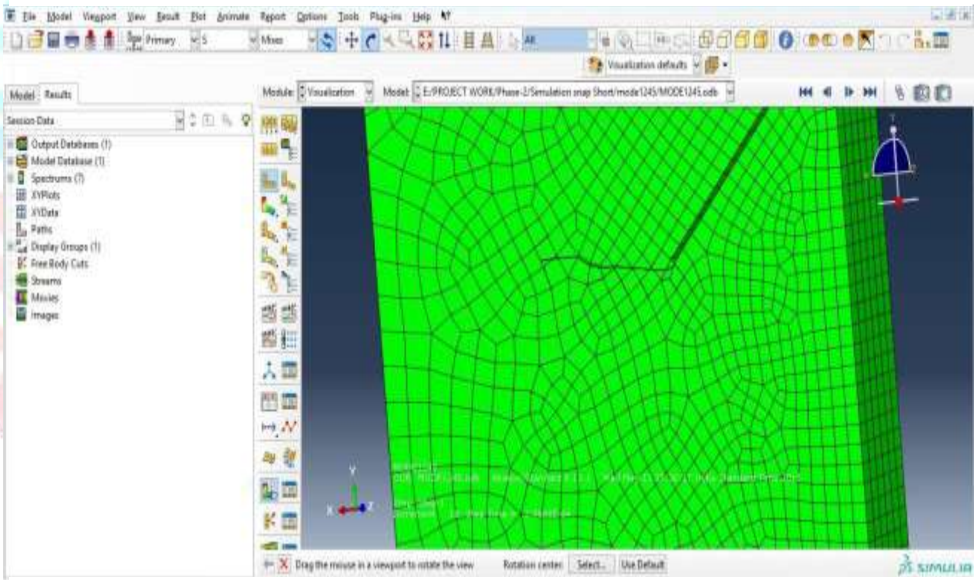

Figure 33Crack Increases and reach Middle of Plate for Mode-I+II, 45°.

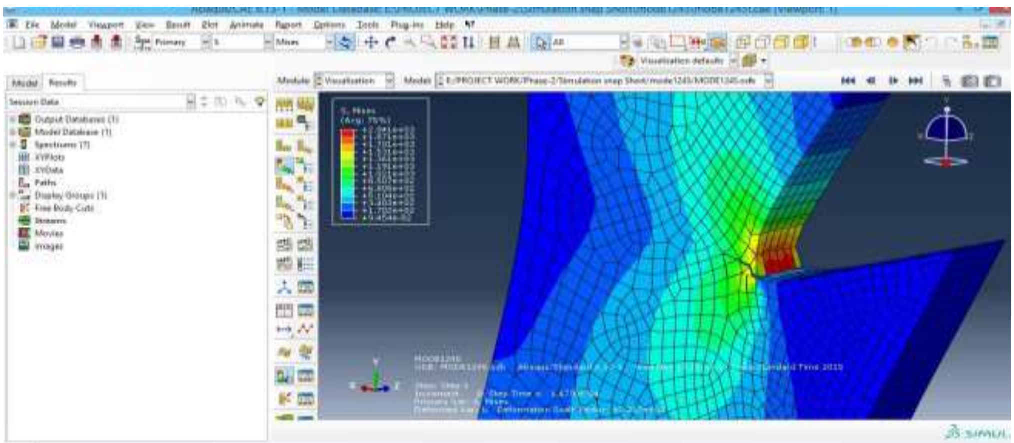

Figure 34Contour Deform Shape on Second Side of plate for Mixed Mode-I+II, 45°.

4.5. RESULT COMPARISION OF EXPERIMENTAL AND SIMULATION FOR CRACK DIMENSIONS IN X AND Y DIRECTION:

4.5.1 PURE MODE-I CRACK LENGTH IN X AND Y DIRECTION:

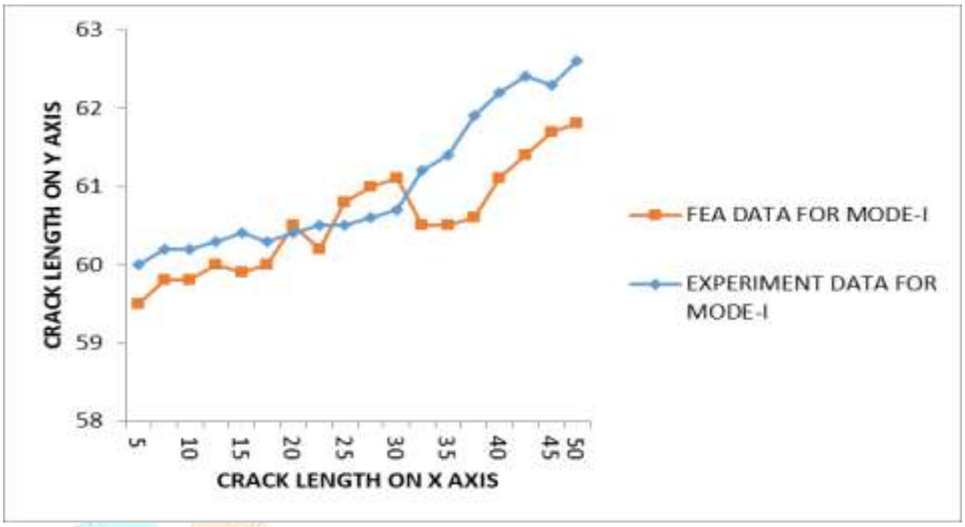

Figure 35comparison of experimental and simulation results of crack dimensions for pure mode-I.

Figure 35 shows the comparison of experimental results and the simulation results for the dimensional growth of crack in Y direction with respect to dimensional growth in X-direction. Figure 35 shows the same trend in both cases experimental and simulation. The result shows these lines are almost identical but having some negligible amount of difference.

4.5.2 MIXED MODE-I+II, 30° CRACK LENGTH IN X AND Y DIRECTION:

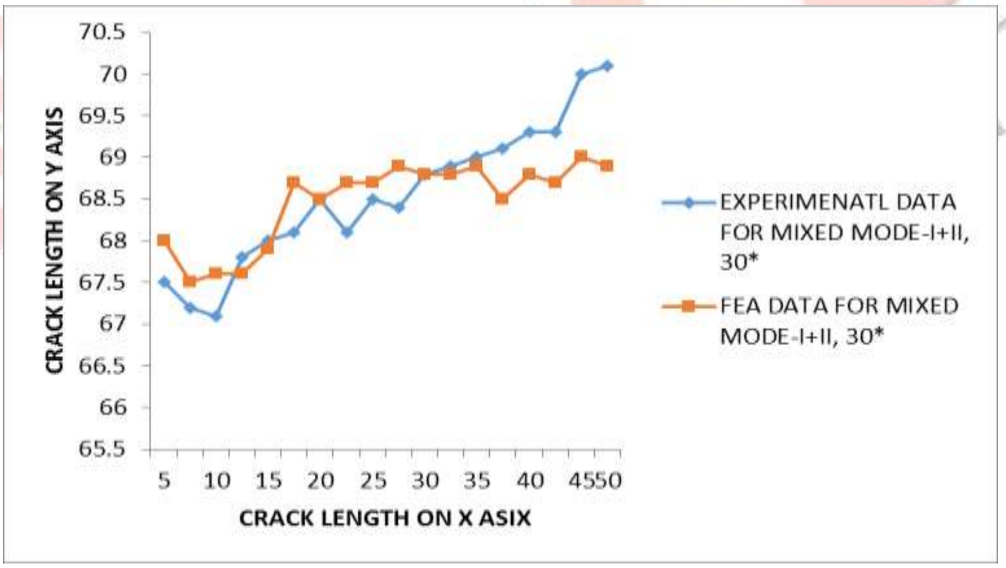

Figure 36comparison of experimental and simulation results of crack dimensions for mixed mode-i+ii, 30°

Figure 36 show the result for mixed mode I+II, 30° for experimental and simulation results and it shows that both results very nearly match to each other.

Load ratio = -0.8

Figure 37 shows the comparison of experimental and simulation results for the crack dimensions. The trend of graph of both the experimentation and simulation result were very much similar to each other.

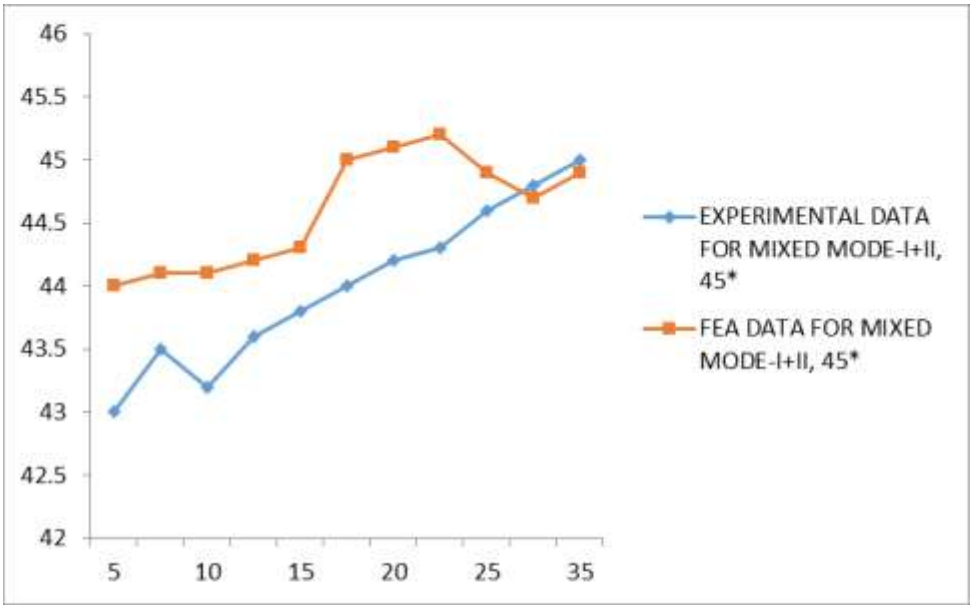

Figure 37comparison of experimental and simulation results of crack dimensions for mixed mode-i+ii, 45°.

Figure 37 shows the comparison of experimental and simulation results for the crack dimensions. The trend of graph of both the experimentation and simulation result were very much similar to each other.

4.6. Number of Cycle Vs. Crack Length:

For Pure Mode -I, Mixed Mode - I+II, 30˚, Mixed Mode-I+ii, 45°

In below figure, graph shows the comparison between Number of cycle and Crack length. Compare Mode-I to Mixed mode-i+ii, 30° and Mixed Mode-i+ii, 45°.For Mode-I and Mixed Mode load ratio is same -1 bur for Mixed mode-i+ii, 45° load ratio is -0.8. Here we see that when any part under Mixed mode-i+ii having angle more it will be required more number of cycle for complete failure.

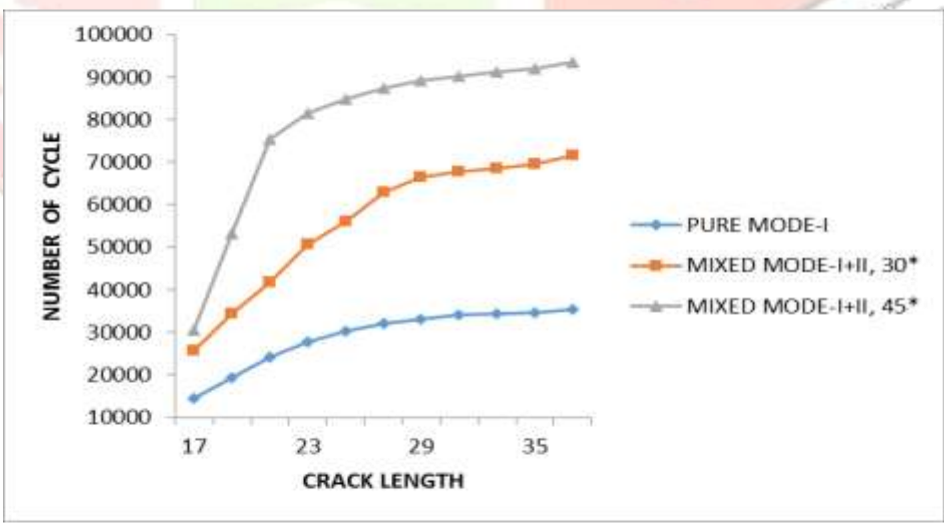

Figure 38Crack Growth for Pure Mode-I,

V. CONCLUSION:-

In this work, our objective is to find out the Fatigue Crack Growth (FCG) on IS 2062 Grade A (E-250) plate. Fatigue Crack Growth of plate is performed by Servo Hydraulic Machine. For finding out the Fatigue Crack growth of plate, Constant amplitude load is used. The fatigue crack path movement in X and Y direction are measured by a profile projector. The two test condition are taken for mode-I, Mixed Mode I+II-30° load ratio (R) of -1 with frequency 22 Hz and other one is Mixed Mode-I+II-45° load ratio (R) of -0.8 with frequency 22 Hz.

The conclusions of this study has summarized below:

1.) For the Pure Mode-I the fatigue crack growth requires less number of cycle for failure of material as compared to mixed mode-i+ii with same loading condition. Therefore, it has found that fatigue life increases by increasing the crack angle related to loading direction.
2.) As the number of cycle increases and as the crack reaches the middle portion of plate, Mode of failure changes from Mixed mode-i+ii to Pure Mode-I.

3.) In the Pure Mode-I load condition; the crack path is nearly perpendicular to load direction.

4.) The crack path follows Zigzag way from initiation of crack to final fracture of specimen.

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