PREDICTION OF FATIGUE CRACK PROPAGATION IN A CRACKED BEAM SPECIMEN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY

IN

MECHANICAL ENGINEERING

By,

ASISH KUMAR SENA

ANSUMAN MAHARANA

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CERTIFICATE

This is to certify that the thesis entitled "**Prediction of Fatigue Crack Propagation In A Cracked Beam**" submitted by **Asish Kumar Sena (Roll No.110ME0332)** and **Ansuman Maharana (Roll No. 110ME0302)** in partial fulfilment of the requirements for the award of Bachelor of Technology degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my supervision and guidance.

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

Date: 12/05/2014

Prof. P. K. Ray

Department of Mechanical Engineering

National Institute of Technology, Rourkela

ACKNOWLEDGEMENT

We wish to express our deep sense of regard and extreme indebtedness to Prof. P.K. Ray, Department of Mechanical Engineering, N.I.T Rourkela, for introducing this project and for his inspirational guidance, constructive ideas and valuable suggestion throughout our project work.

We also extend our sincere thanks to Mr. Ajith Kumar for his constant support during the project work. We would also like to thank Cornell Fracture Group, Cornell University, for making the software CASCA and FRANC2D available free of cost.

Date: 12/05/2014

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Place: Rourkela

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ABSTRACT

In day to day our life, Various types of loads are acting on beams, columns, studs etc. These forces may be tension, compression, internal pressure, bending or any combination of all. These different types of loading situation may initiate and propagate a crack. This becomes more significant if the beams carry are used in large construction works. In this project Aluminium alloy beam is considered for study of propagation of an existing crack. A finite element based two dimensional crack propagation simulator software FRANC2D and a pre-processor software for this simulator CASCA developed by Cornell Fracture Group of Cornell University was used for simulation of crack propagation in two dimensional beam. Four point bending test experiment is carried out on aluminium beam and crack growth propagation behaviour is observed. These two observations i.e. from FRANC2D and experiment are compared.

KEYWORDS: FRANC2D, Four Point Bend Test, Crack, Beam, Propagate, CASCA

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CHAPTER 1

INTRODUCTION

Beams are used in factories and industries for support and to give strength to various elements. It is important to predict fatigue crack growth to obtain flaw acceptance criteria for an existing initial planar notch. Many experiments are performed to study the crack growth behaviour of beams containing initial surface notch under different loading condition [1,2]. Practical methods are not often used to study fatigue crack growth as these require a lot of time and money and are destructive in nature. So analytical methods are used to solve this problem based on finite element method and fracture mechanics. Analyses of three dimensional partial circumferential cracks need complex computational work to keep pace with the mesh pattern and large computer storage memory. Hence it is essential to have two dimensional analysis of the beam for ease of study. Thus a three dimensional beam is converted to a two dimensional beam having same thickness. For conversion a method has been proposed based on equating deflection of both the pipe specimen and the beam. Four point bending test experiment is performed by taking a bar made of aluminium material having a initial crack at one edge. A mesh generation program software CASCA is used and then for crack propagation simulation , a finite element based program FRANC2D software is used. Values of C and m (constants of Paris model) obtained from both the process are compared.

CHAPTER 2

LITERATURE REVIEW

When a metal is subjected to a repetitive or cyclic stress it fails at a stress much lower than that required to cause fracture or failure on a single application of load. These failures which occur under closures of dynamic loading are known as fatigue failures. Fatigue failures occur when a metal is subjected to a repetitive, cyclic or fluctuating stress (load) and will fail at a stress much lower than its tensile strength. This kind of failure occurs without any plastic deformation. The appearance of the fracture surface, which shows a smooth region, due to the rubbing action of a crack propagated through a rough section, where the member has failed in a ductile manner at a point when the cross section was no longer able to carry the load. Three basic factors are necessary to cause fatigue failures. These are:

1. A high value Maximum tensile stress,
2. A large variation in fluctuation on the applied stress, and
3. A sufficiently large number of cycles of the applied stress.

Coming to the processes involved in the Fatigue process:

1. *Crack initiation* – fatigue damage is developed and that can be removed by thermal annealing.

2. *Slip band crack growth* – involves the deepening of the initial crack on high shear stress planes. This frequently is called stage I crack growth.

3. *Crack growth on planes of high tensile stress* –this involves growth of well-defined crack in a direction perpendicular to maximum tensile stress. Usually called stage II crack growth.

4. *Ultimate ductile failure* – this occurs when crack reaches sufficient length so that the remaining cross section cannot support the load.

The relative proportions of the total failure that are involved with each stage depend on the test conditions and the material. However, it is well established that a fatigue crack can be formed before 10 percent of the total life of the specimen has elapsed. In general, larger proportions of the total cycles to failure involves the propagation of the stage II cracks in low-cycle fatigue than in long-life fatigue, while stage I crack growth comprises the largest segment for low-stress, high-cycle fatigue. If the tensile stress is high, as in the fatigue of sharply notched specimens, stage I crack growth may not be observed at all [3].

2.1 FATIGUE CRACK PROPAGATION

A component containing a crack, when loaded statically, no crack growth is seen as long as the crack length or the loading remains below a critical value. If the loading is oscillating crack growth in small steps can be observed for loading amplitudes far below the critical static load. This type of crack growth is called *fatigue crack growth.* Usually fatigue crack growth is specified by the *crack growth rate* (da/dN), where N is the number of load cycles [4].

Fatigue crack propagation behaviour for metals can be divided into three regions. The behaviour in Region I exhibit a fatigue-threshold cyclic stress intensity factor range, ΔK_{th} below which cracks do not propagate under cyclic stress fluctuations.

Region II represents the fatigue crack propagation behaviour above ΔK_{th} which can be represented by [5],

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

Where, a = crack length;
N = no. of cycles;
ΔK = stress intensity factor range,
'c' and 'm' are material constants.

The fatigue crack growth per cycle in region III is higher than that for region II.

Region wise following characteristics are shown by the metal.

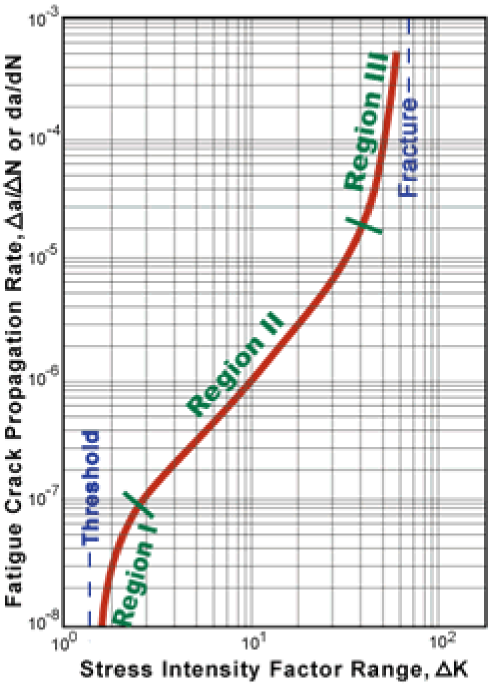


Fig [1]: fatigue crack propagation rate vs. stress intensity factor range [6]

Region.I:

The stage I propagate initially along the persistent slip bands. This stage is a non-propagating stage or very slow propagating stage with around 1 nm per cycle. The crack growth here is largely influenced by mean stress, microstructure and environmental factors.

Region.II:

This is widely studied stage among all the stages of fatigue crack propagation. This is also stable stage fatigue crack propagation process. Continuous behaviour, striations or transition from non-continuous behaviour with,

(a) Large influence of certain combinations of environment, mean stress and frequency,

(b) Small to large influences of microstructures, depending on material.

Region.III:

In this stage unstable fatigue crack growth occurs which followed by failure. Static mode of behaviour is shown by the object. In this stage there is a large influence of microstructure, mean stress and thickness but a little influence of environmental changes, inter-granular and dimples affects this stage of crack growth.

2.2 Stress analysis for members with cracks- fracture mechanics approach.

For analysing fracture and fatigue behaviour of sharply notched structural members (cracked or flawed) fracture mechanics is the recommended engineering method to be used in terms of stress and crack length. So as to analyse stress in vicinity of a well-defined crack or a sharp crack, stress concentration factor and stress intensity factor are the main factors to be observed at these points respectively.

Stress concentration Factor is used for analysing stress at a point in vicinity of any well-defined notches. The discontinuities in structural components like holes, notches, fillets etc. when have a well-defined geometry, the value of stress intensity factor, K_t can be determined [7]. This Stress Concentration factor gives an important relationship between applied nominal stress and local maximum stress. However when the stress concentration goes severe, like while approaching a sharp where the radius of the crack tip is nearly zero, an analytical method which is different from the stress concentration is needed to analyse the behaviour of that structural component containing imperfections.

The parameter Stress Intensity Factor (K) which is related to both nominal stress level in the member and length of crack (a) and it has a unit of ksi$\sqrt{in}$ (MPa$\sqrt{m}$). To establish methods of stress analysis for cracks in elastic solids, it is surely defined in three types of relative movements of adjacent crack surfaces. The displacement modes (fig 2) represents the local deformation ahead of a crack. The opening mode I is characterised with local displacements which are symmetric with respect to x-y and x-z planes. The two fractured surfaces displace perpendicularly to each other in opposite directions. Mode II, is skew-symmetric with respect to the with respect to x-z plane and is symmetric with respect to x-y plane. The sliding surfaces slide over each other in the direction which is perpendicular to the line of crack tip. Mode III, the tearing mode is associated with the local displacement which are skew symmetric with both x-y and x-z planes. Here the two fracture surfaces slide over each other in the direction parallel to the crack front line. Each of these modes of deformation corresponds to a basic type of stress field which is in the vicinity of the crack tips [8].

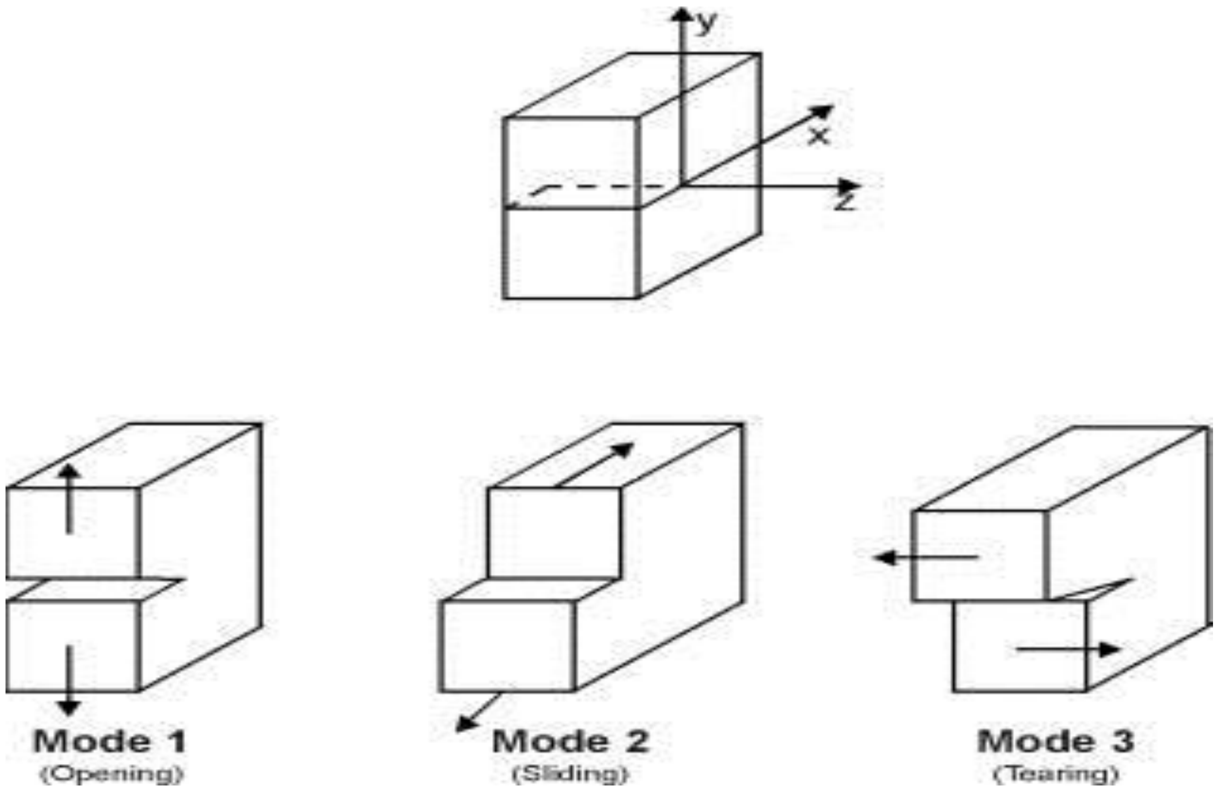


Fig [2] Three Modes of Crack Surface Displacement [9].

CHAPTER 3

EXPERIMENAL DETAILS

3.1 Specimen Details

.Chemical and mechanical properties are of the alloy are given in the following table.

3.1.1 Chemical Properties

Chemical Element	% Present
Manganese(Mn)	0.50 max
Iron(Fe)	0.40 max
Magnesium(Mg)	2.60 – 3.20
Silicon(Si)	0.40 max
Aluminium(Al)	Balance

Table {1}: Chemical Properties of Aluminium 5754[10].

3.1.2 Mechanical Property

Mechanical Property	Value
Yield Strength	276 MPa
Shear Strength	160 MPa
Ultimate Strength	580 Mpa
Poison's ratio	0.34

Proof stress	185-245 MPa
R(σ_{min}/ σ_{max})	0.3

Table {2}: Mechanical Properties of Aluminium 5754[11].

3.2 EXPERIMENTAL SETUP

3.2.1 MACHINE USED

An Ultimate Testing Machine (UTM) was used for the purpose of four point bend test. The four point bend test was done for a span length of 300 mm. The crack determination was done by visually using a travelling microscope where the parallax error was tried to diminish up to an acceptable level, this machine is manufactured by BISS (Bangalore Integrated System Solution).

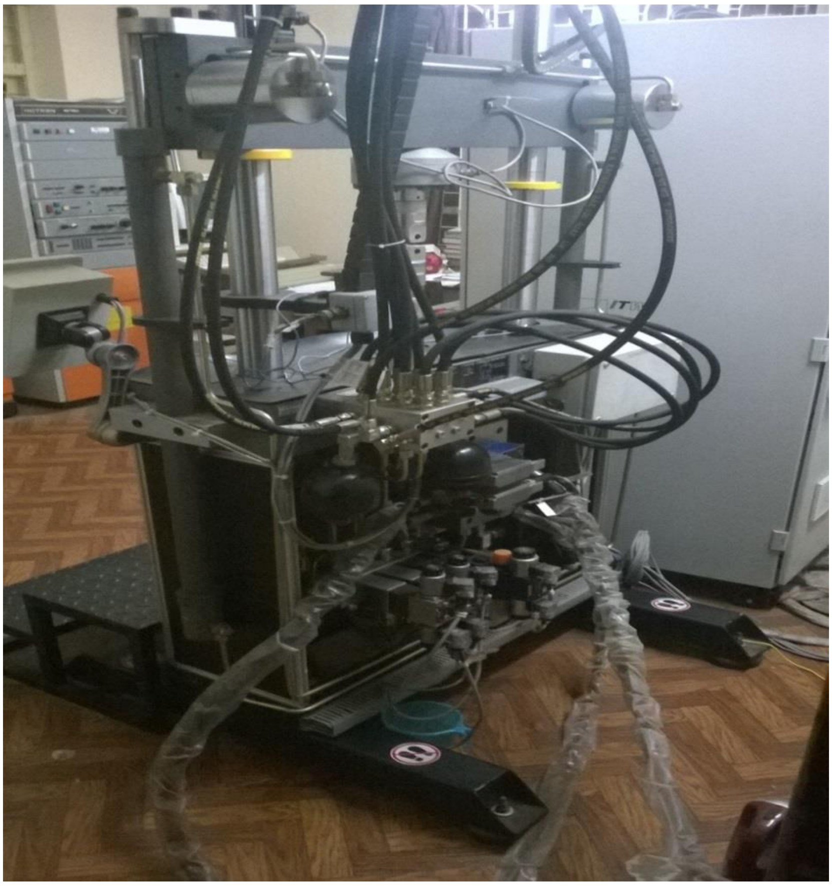


Fig [3]: view of the machine

3.2.2 DETAILS OF BEAM SPECIMEN

A 25×25 mm^2 cross section single edge notched beam made of aluminium 5754 material was used for our experiment. The beam specimen had initial planar notch at one plane of having length 2.69 mm. The notch was machined by wire EDM machining process. The notch was straight and at the middle along its length. The details of the beam specimen are given in Table 3.

Elements	Values (mm)
Length	300
Depth	25
Height	25
Initial Crack Length	2.69

Table {3}: Notch Dimension of Beam

For simulation in FRANC2D, four point bending test was done. In this type of loading the mid-section of the specimen i.e. the location of the notch is subjected to loading and that to pure bending. The schematic diagram is given in fig[4].

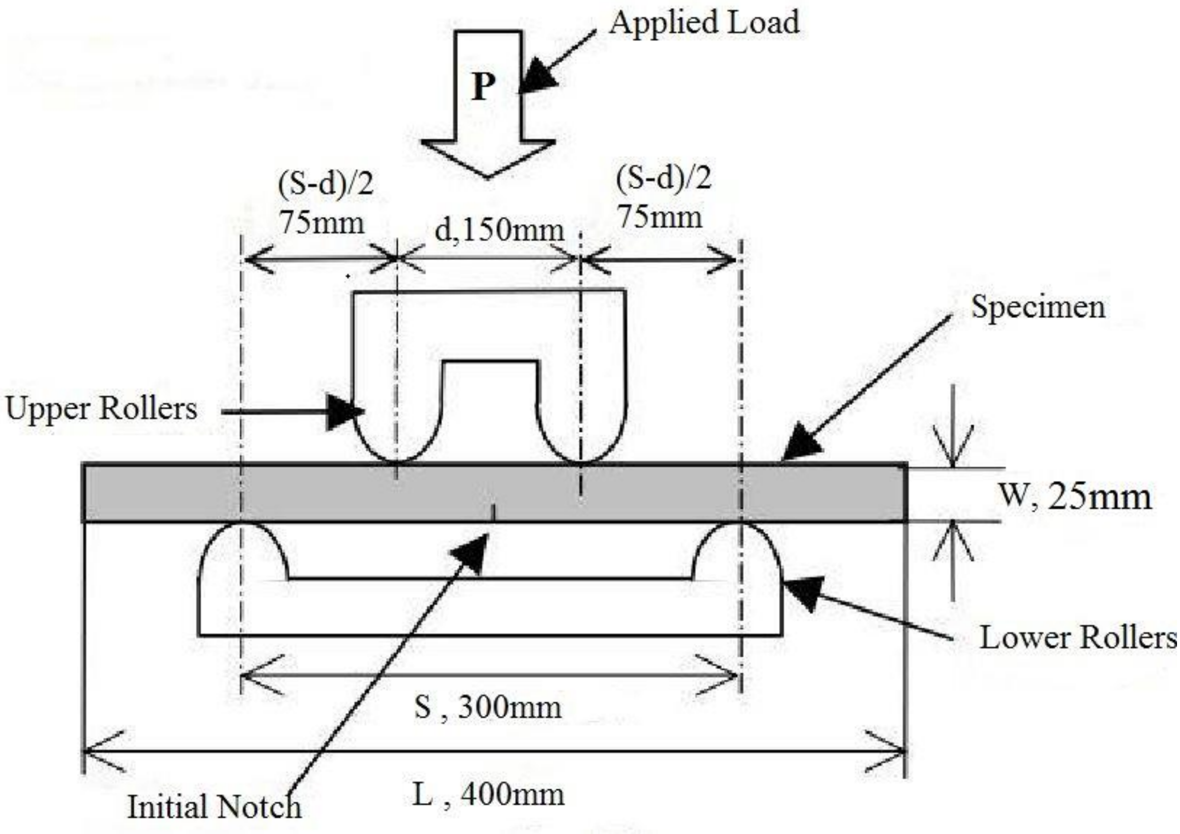


Fig [4]: Schematic Diagram of Experimental Setup [12].

Here the span length is 300mm beam test arrangement constituted of loading the beam under four point bending up to large scale plastic deformation with periodic significant loading and unloading so that a beach mark will be created on the cracked surface. The load was given in the form of sinusoidal wave. The load range taken for the four point bending test was of the order of 7.8 KN which was at a level below the yield strength of the beam material corresponding to considered notch dimensions [12]. This ensures that the crack growth is in gross elastic state. The load 7.8 KN taken so as reduce the no of cycles and time consuming for a corresponding value of stress intensity factor and R value i.e. 0.3.

3.3 FRANC2D SOFTWARE

FRANC2D is a two dimensional, FEA (finite element analysis) based program for simulating curvilinear or planar crack propagation in planar (plane stress, plane strain, and axisymmetric) structures. Before the use of FRANC2D, CASCA is used for mesh generation of the desired element. So it works as a simple pre-processor for FRANC2D. Other two dimensional finite element based programs can be used as a pre-processor for FRANC2D provided that the saving data file in the pre-processor can be converted to inp format FRANC2D input [13]. This FRANC2D and CASCA software is developed and distributed free of cost by Cornell Fracture Group, Cornell University, Ithaca, New York .

3.3.1 SIMULATION IN FRANC2D

The simulation procedures in FRANC2D are as follows [12]:

1. Geometrical layout of the beam of specified dimension was created using CASCA pre-Processor.
2. The element's layout then divided into a number of segments followed by mesh generation.

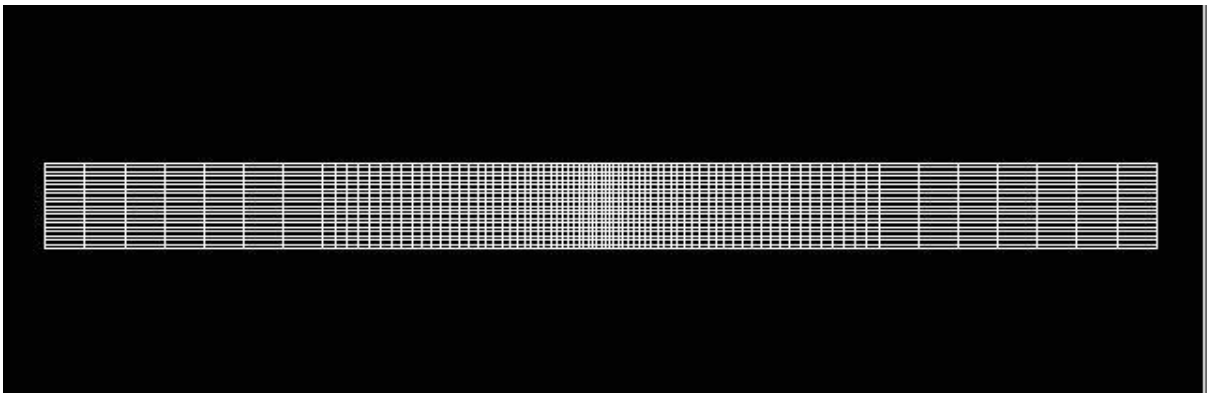


Fig [5]: Mesh Generated In CASCA

3. The generated mesh in CASCA was then saved as inp format so that it can be reopened in FRANC2D for simulation process.
4. Then the file was saved and CASCA was closed, FRANC2D was opened. The mesh file saved in inp format was opened in FRANC2D.
5. Then problem type was set to plain stress condition and appropriate material properties were given for the pipe material considered as per command sequence

PRE-PROCESS -> PROBLEM TYPE ->PLANE STRESS.

To set material property, MATERIAL command was selected. Young's modulus, Poisson's ratio, thickness values were given by selecting E, NU and THICKNESS options respectively. Our material is aluminium AA5754 H24 . Its material properties were entered using table .

6. Then it is important to reformulate the element stiffness Matrices which was done by selecting ELEM STIFF option. Thus the file was saved

7. The next step the boundary conditions specification. This was done by selecting PRE-PROCESS and then FIXITY option. Two nodes or ends were fixed appropriately in X or Y direction or in both the direction. The size of the box containing the node can be adjusted using the tolerance window given at the left hand below corner.

8. Now it's time for the loads turn. Loads were given by selecting

LOADS -> POINT LOAD.

Then the corresponding values of load were entered at specified location of the beam.

9. Before crack initiation stress analysis is must which was done by selecting

ANALYSIS -> LINEAR -> DIRECT STIFF

This provided a little report that summarized the size of the model and the time required for the analysis.

10. After the analysis was done, to see whether boundary conditions were properly given or not we selected DEFORMED MESH option. Then POST-PROCESS option was selected, followed by CONTOUR option to view various color stress contours which indicate principle tensile stress(SIG 1) , effective stress(EFF STRESS), shear stress(TAU MAX) etc.

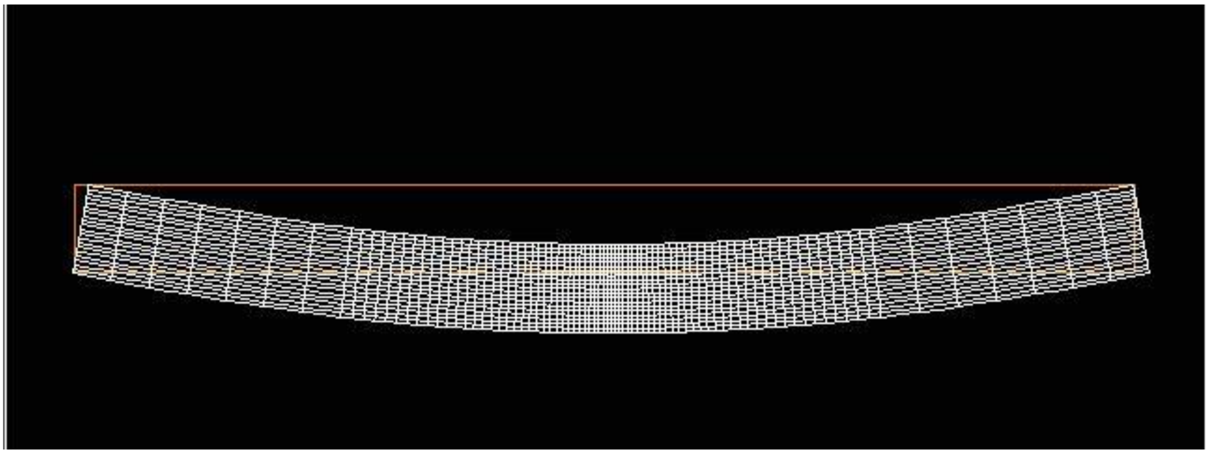


Fig [6] Deformed Mesh After Applying Boundary Condition And Load.

11. Now we initiate an initial crack in the beam which was done by selecting

MODIFY -> NEW CRACK -> NON-COHESIVE -> EDGE CRACK.

The location of the notch was at the middle of the beam. The crack length was then entered as 0.098425 inch and the minimum no. of elements along crack extension was taken as 3. Then ACCEPT option was selected. Re-meshing of nodes took place.

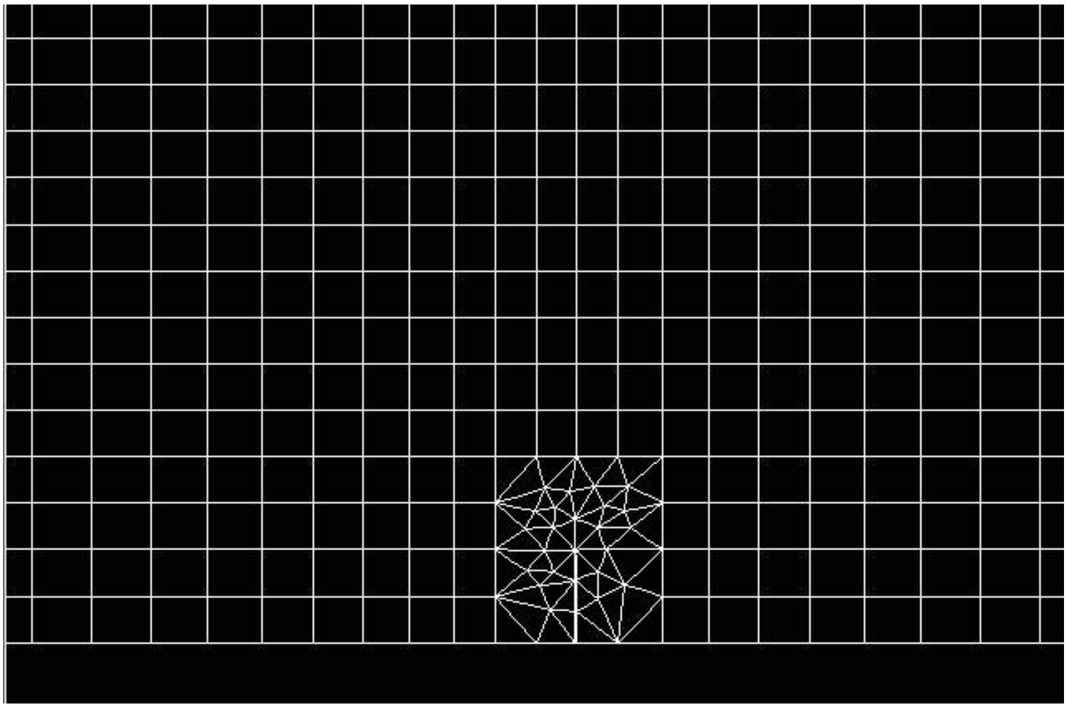


Fig [7]: Crack Initiation.

12. For this new structure, new analysis was performed by selecting

ANALYSIS -> LINEAR -> DIRECT STIFF.

A report on the mesh was generated showing total work required.

13. Then we went to PRE-PROCESSOR -> FRACT MECH to get the cycle plot between crack length and no of cycles and the stress intensity factors were computed using displacement correlation technique (DSP CORR SIF).
14. Now the crack was propagated along the width from the crack tip. This was done by entering

MODIFY -> MOVE CRACK -> AUTOMATIC -> PROPAGATE

To give the specified amount of crack growth at each step CRACK INCR option was chosen and crack increment value per step was specified. STEPS option was then used to set the no. of propagation steps at each propagation. Then PROPAGATE option was selected to begin crack propagation.

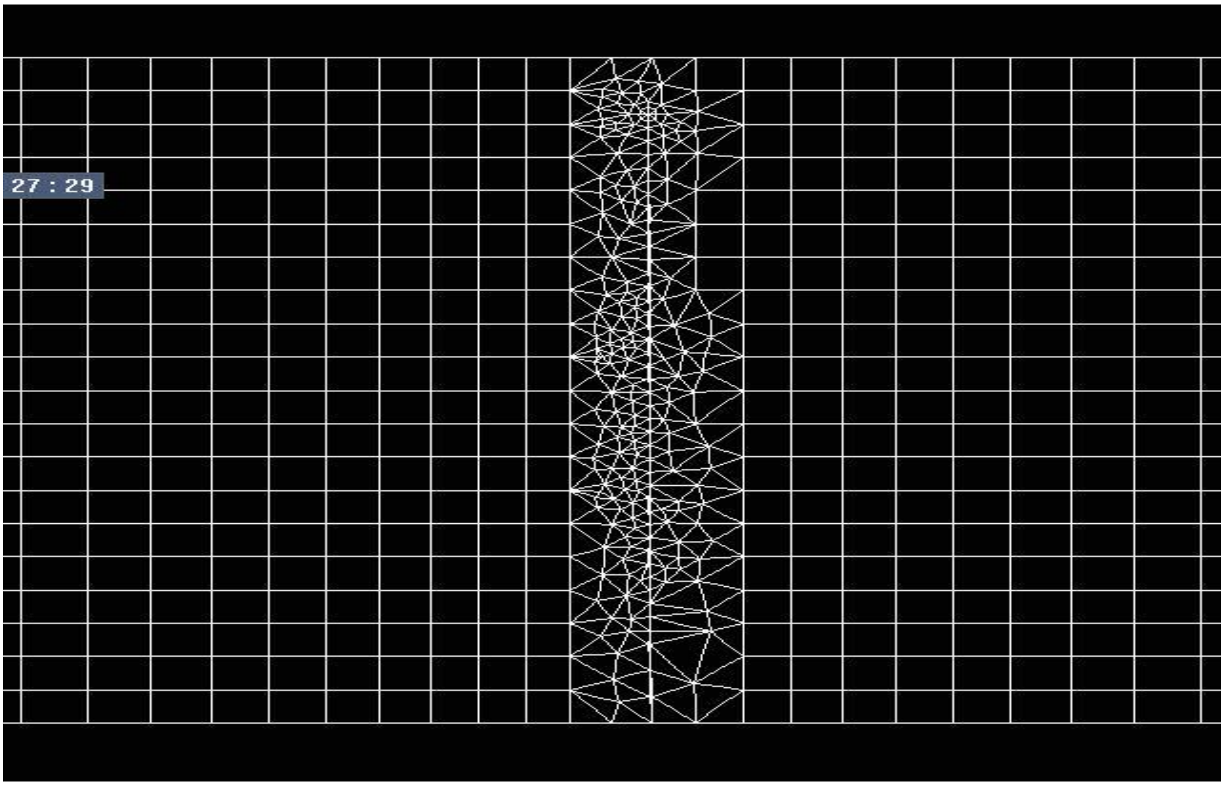


Fig [8]: Crack Propagation.

15. Then the file was saved using WRITE option.
16. Now the fatigue crack growth analysis was done by selecting POST -PROCESS and FRACT MECH options. The stress intensity factor history was found using SIF HISTORY option. A KI vs. crack length graph was generated. Here KI is stress intensity factor.
17. Now, by using the FATIGUE PLTS option, fatigue analysis was done. Since it is based on Paris model, constants C and m are provided using SET C and SET m option. Then the CYCLE PLOT option created a plot of the number of load cycles as a function of crack length.

CHAPTER 4

DATA ANALYSIS

4.1 EXPERIMENTAL DATA ANALYSIS

Four point bending test performed on the beam and different data are recorded. No of cycles, coordinates of crack at each step noted down. From these data crack length calculated and a graph was plotted between crack length and no of cycles. Similarly da/dN is calculated for each step and stress intensity factor computed from a complex formula. Again a graph was plotted between these two. Information about the crack growth in the beam is given in the table below.

X axis	Y axis	Final Crack Length in mm	No Of Cycles(N)	a/w	f(a/w)	Δk	da/dN
2.319	0	2.69	114195.8	0.1076	1.473619	459213839	9.28086E-06
2.359	0.04	3.19	139917.9	0.1276	1.489343	505409797	1.06132E-05
2.409	0.09	3.688196748	164158.2	0.14758	1.509642	550851471	1.19723E-05
2.44	0.121	3.943735395	176053.8	0.15779	1.521932	574252170	1.269E-05
2.453	0.134	4.42227484	197349.2	0.17681	1.54854	618726727	1.40864E-05
2.474	0.155	4.896511068	217191	0.19586	1.579764	664185340	1.55558E-05
2.506	0.187	4.985953787	220792.5	0.19948	1.58622	672962740	1.58442E-05
2.51	0.191	5.586703319	243823.8	0.22348	1.63448	734025095	1.78921E-05
2.57	0.251	6.02715763	259428.8	0.24106	1.67558	781583054	1.95351E-05
2.604	0.285	7.02715763	290835.1	0.28106	1.788775	900946692	2.38341E-05
2.704	0.385	7.56166675	305331.2	0.30247	1.861855	972765737	2.65348E-05
2.755	0.436	7.666069815	307976.4	0.30663	1.87725	987556943	2.71012E-05
2.765	0.446	8.137768872	319168.3	0.32551	1.951683	1.058E+09	2.98379E-05
2.809	0.49	9.063511817	337520.1	0.36254	2.123324	1.215E+09	3.62027E-05
2.9	0.581	9.253511817	340694.5	0.37014	2.1632	1.25E+09	3.77011E-05
2.919	0.6	10.56732307	357126.9	0.42263	2.490525	1.538E+09	5.03898E-05
3.05	0.731	10.96782275	360218.5	0.43873	2.611065	1.643E+09	5.52553E-05
3.09	0.771	11.14670819	361309.9	0.44588	2.668544	1.693E+09	5.76137E-05
3.106	0.787	11.66670819	363467.4	0.46668	2.849661	1.849E+09	6.5207E-05
3.158	0.839	12.38670819	363961.2	0.49548	3.139665	2.099E+09	7.7875E-05
3.23	0.911	12.58670819	363584.5	0.50348	3.229467	2.177E+09	8.1923E-05
3.25	0.931	12.92670819	362431.2	0.51708	3.392557	2.318E+09	8.94232E-05

Table {4}: Crack Propagation Information

K is stress intensity factor which was computed from the formula [14] given below:

$$K = \frac{6M}{BW^2}\sqrt{\pi a}.\, f\left({}^{a}/_{w}\right)$$

$$f\left({}^{a}/_{w}\right) = 0.8 - 1.7\left({}^{a}/_{w}\right) + 2.4\left({}^{a}/_{w}\right)^2 + \frac{0.66}{\left(1-\frac{a}{w}\right)^2}$$

K value was calculated using the formula given above where,

M= max. bending moment
B= Depth of the specimen
W= width of the specimen
a= Crack length

And here, $f({}^{a}/_{w})$ is a polynomial function [15]. Its value of the polynomial obtained depends on the material characteristic properties and varies from one material to another.

4.1.1 Crack Length Vs No Of Cycles.

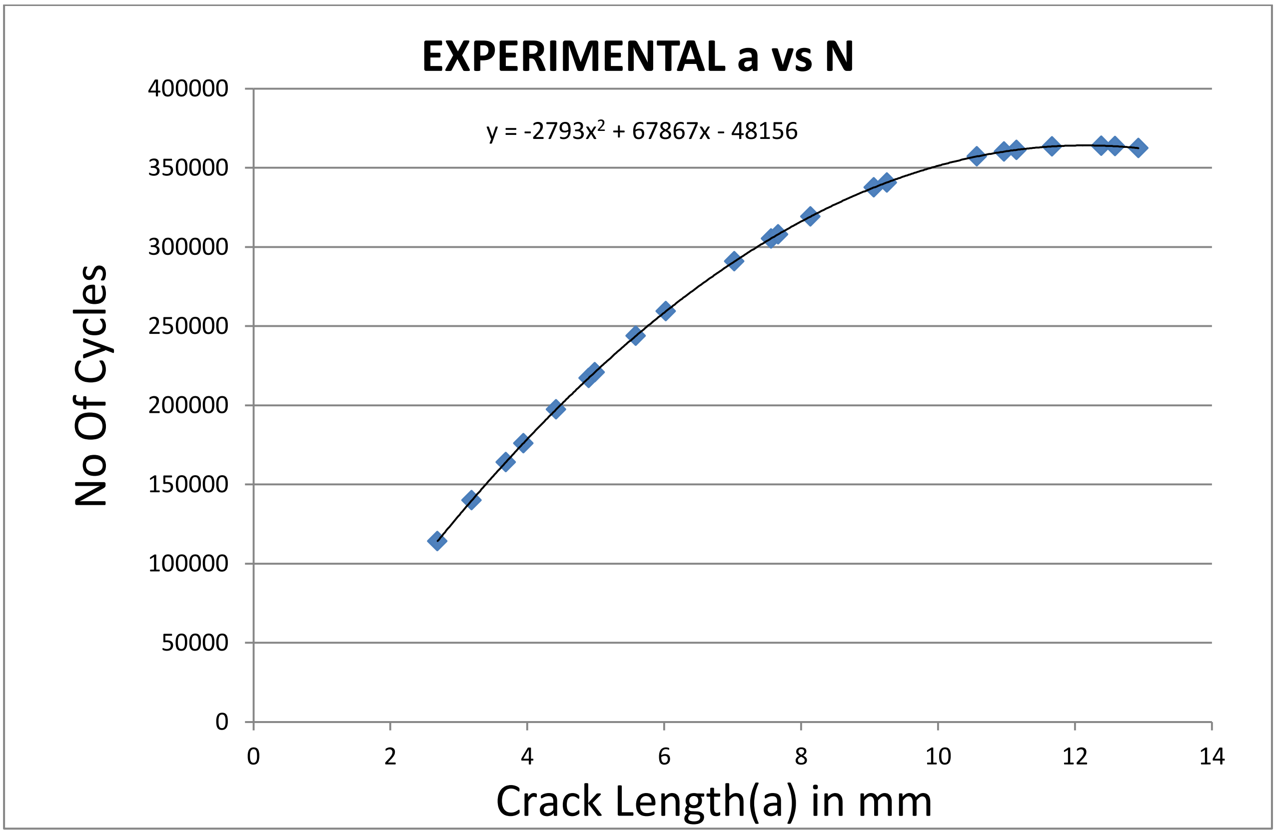


Fig [9]: Crack Length vs. No. of cycles

4.1.2 Stress Intensity Factor vs. da/dN

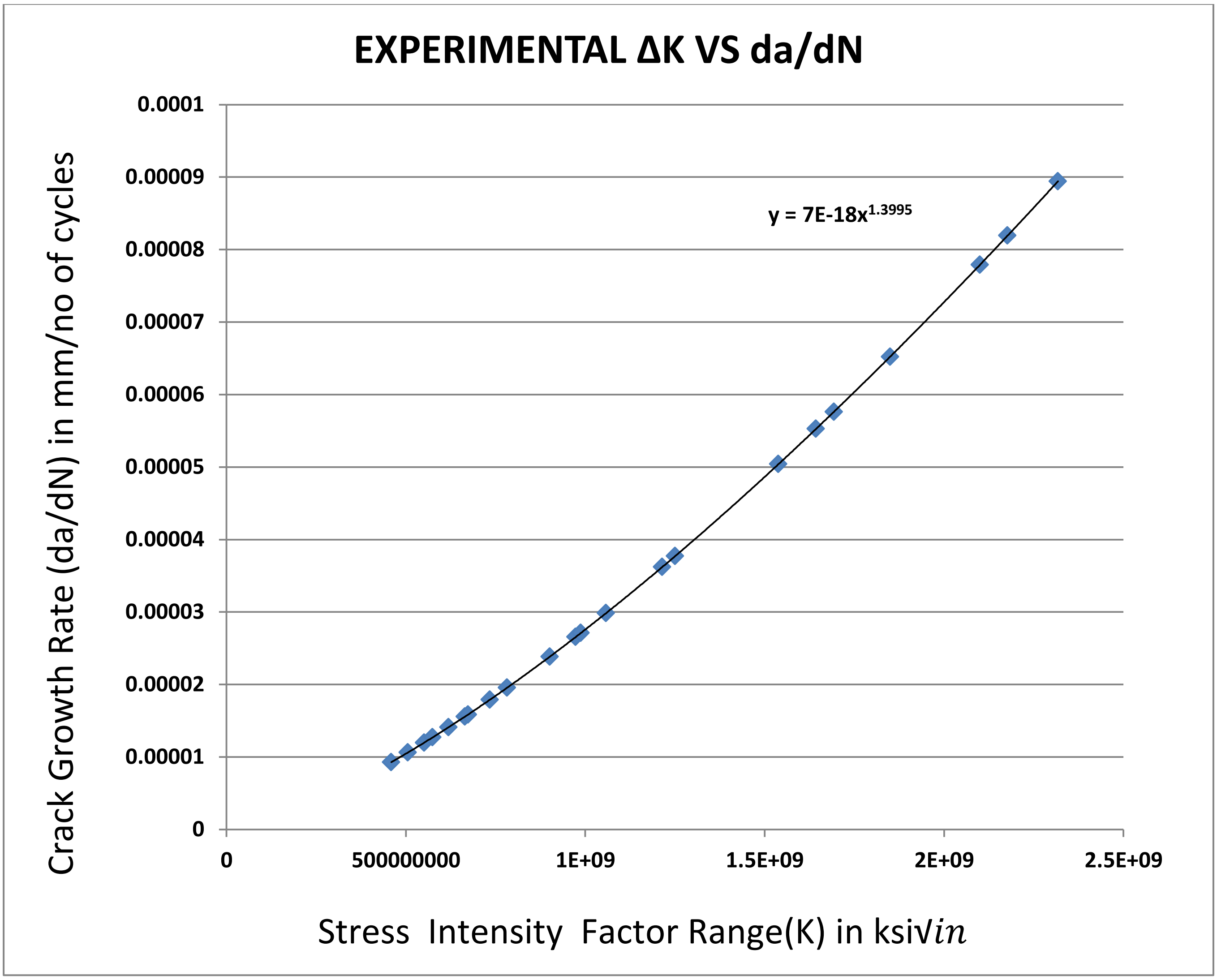


Fig [10]: Stress Intensity Factor Range Vs da/dN

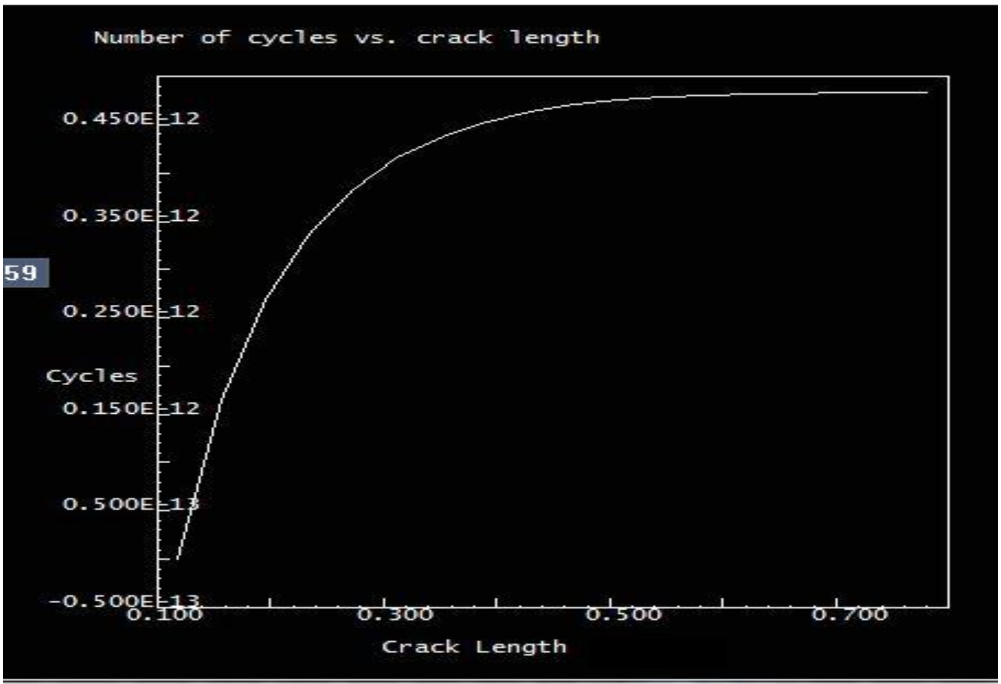
4.2 SOFTWARE DATA ANALYSIS

In FRANC2D, graph between crack length and no of cycles was generated by the software itself after the simulation process by selecting POST-PROCESS followed by FRACT MESH option. But the graph between stress intensity factor and da/dN was plotted manually. K(stress intensity factor), a(crack length), N(no of cycles) are noted at each step of crack propagation and graph will be plotted by using Microsoft Excel. For this we had to set the steps to1 first and then we gave crack increment.

Crack Length a in inch	*No Of Cycles N*	*da/dN*	*ΔK(Stress Intensity Factor Range)*
0.05	2.4E+11	3.57143E-13	0.095991
0.1	3.8E+11	6.33333E-13	0.112684
0.157	4.7E+11	9.5E-13	0.126209
0.195	5.1E+11	1.36667E-12	0.139716
0.236	5.4E+11	1.35E-12	0.139237
0.29	5.8E+11	2.63158E-12	0.167801
0.34	5.99E+11	5E-11	0.382198
0.39	6E+11	8E-12	0.228976
0.43	6.05E+11	2.5E-11	0.31487
0.48	6.07E+11	4E-11	0.359084
0.52	6.08E+11	#DIV/0!	0.401828
0.58	6.08E+11	#DIV/0!	0.407191
0.62	6.08E+11	#DIV/0!	0.410502
0.67	6.08E+11	#DIV/0!	0.414386
0.73	6.08E+11	#DIV/0!	0.418723
0.78	6.08E+11	#DIV/0!	0.422105
0.82	6.08E+11	1.34868E-12	0.139199

Table {5}: Crack Propagation data By FRANC2D

4.2.1 Crack Length Vs No Of Cycles.



Fig[11]: Graph Of Crack Length Vs No. of Cycles.

Crack Length (mm) In X axis and No of cycles in Y axis.

4.2.2 Stress Intensity Factor Range VS da/dN

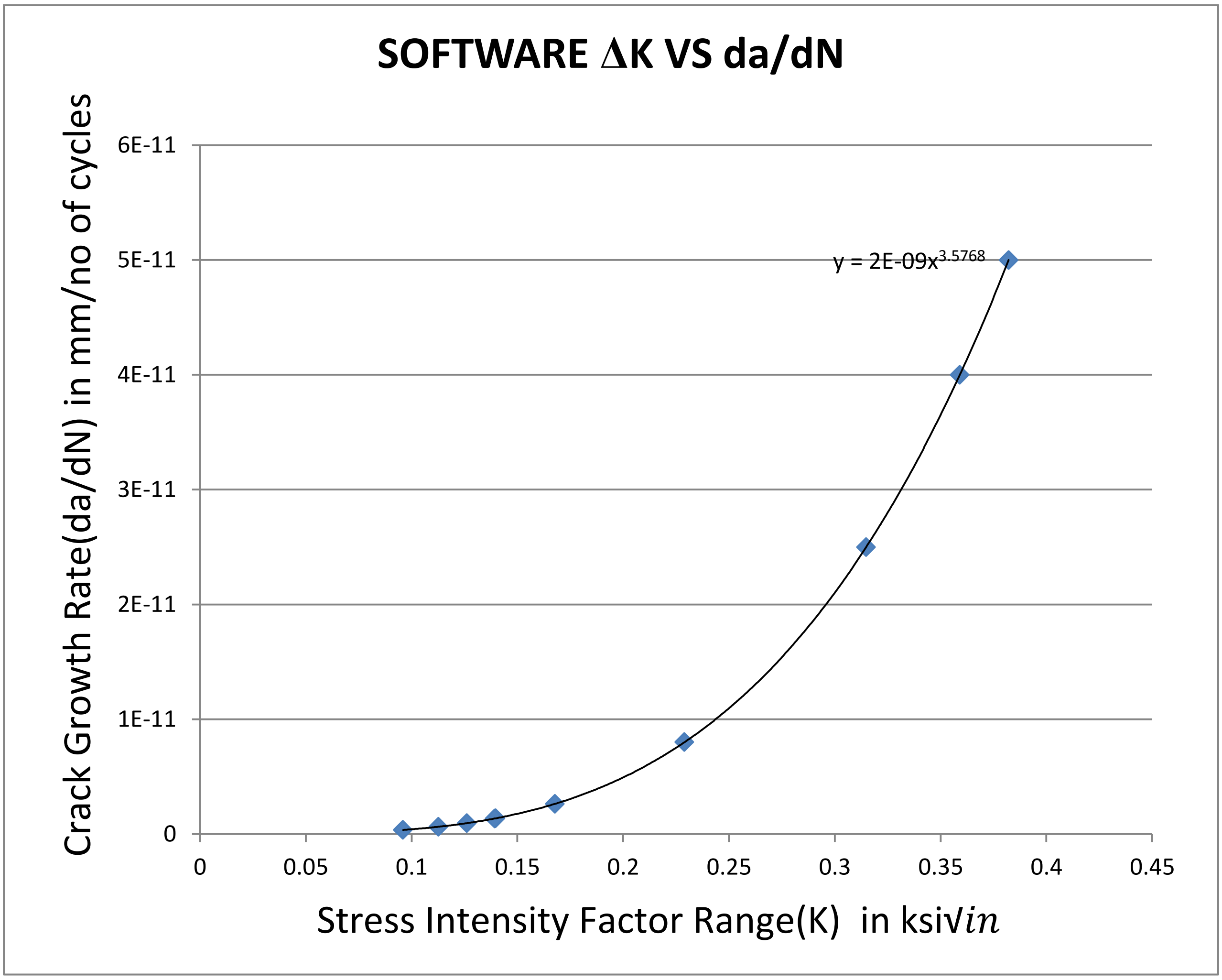


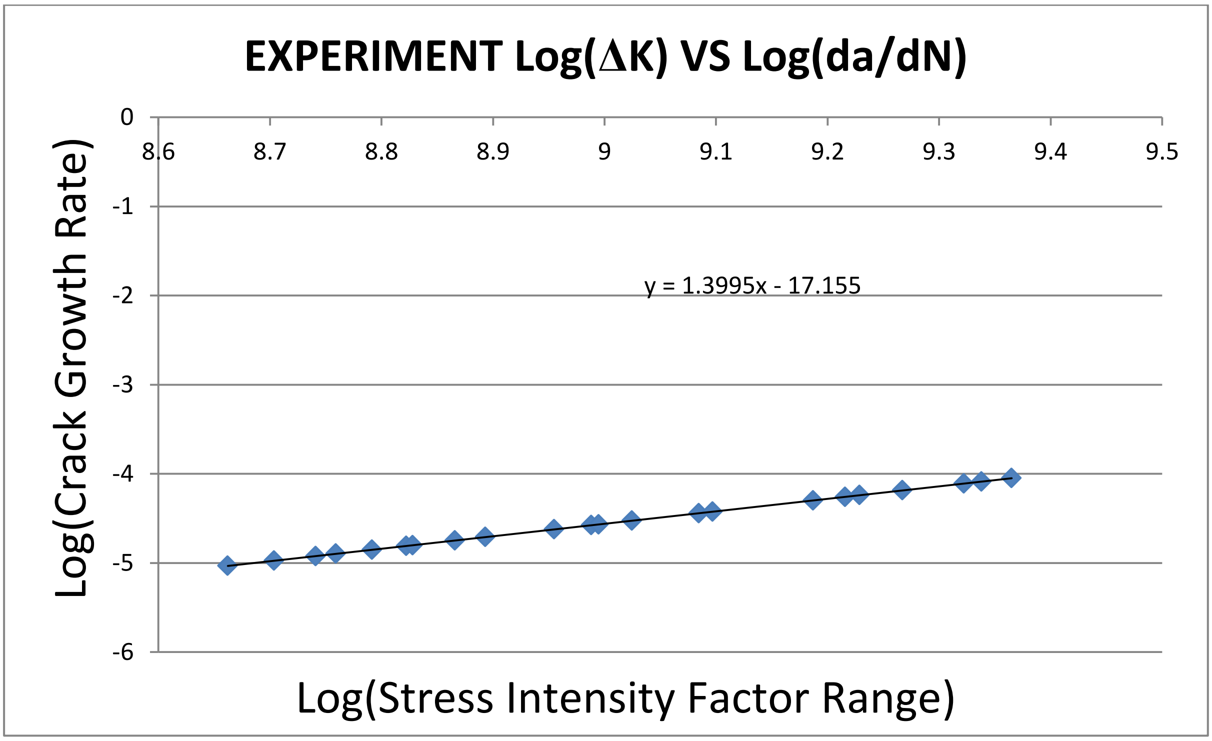
Fig [12]: Stress Intensity Factor Vs da/dN

In FRANC2D, the value obtained for c and m was 2E-09 and 3.577 respectively.

CHAPTER 5

RESULT AND CONCLUSION

In the experiment, the material constants i.e. ‘c’ and ‘m’ found out to be 7E-18 and 1.3995 respectively which is unlike to literature survey statistics. But the ‘c’ and ‘m’ value interpreted by software are 2E-09 and 3.5768 which is different from experimental value. The main reason for this being the value of stress intensity factor (K) which is responsible for the deviation, albeit the values of ‘c’ and ‘m’ as per software are in a permissible range. Possibly the equations used for determination of K may be the reasons for the discrepancy in “c” and ‘m’.



Fig[13]: LogΔk vs Log(da/dN)

From this we can conclude that the beam specimen material undergoing the four point bend test in the UTM (Universal Testing Machine) gives characteristics traits which follows the Paris Model of fatigue crack propagation and this is validated by the graph obtained in the result between the logarithm of rate of crack growth vs logarithm of stress intensity factor range, where slope is almost constant or slightly increasing and it suggests that it falls under the region II of the crack propagation.

CHAPTER 6

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