

# Investigation of Fatigue Crack Growth in Aerospace Bracket Using FEA

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**ABSTRACT:** Fatigue performance of structures is greatly affected by the presence of stress raisers such as fastener holes, manufacturing errors, corrosion pits, and maintenance damage which serve as nucleation sites for fatigue cracking. During service, sub-critical cracks nucleate from these sites and grow till catastrophic failure takes place when the crack length reaches a critical dimension. A structure cannot be retired from service simply on detecting a fatigue crack.

The objective of a Fracture Mechanics analysis is to determine if these small flaws will grow into large enough cracks to cause the component to fail catastrophically. The main goal of this project is to estimate the stress intensity factors along the crack length by using Paris law and by using fracture mechanics theories i.e. LEFM approach, applied to two dimensional objects such as plates and shells etc.

The aim of this study is to estimate numerically behaviour of crack in 2-dimensional. 7075-T6 aluminum alloy plate with hole using the finite element method. An observed the change in stress intensity factor along the crack length by using Paris law with help of FRANC-2D/L simulation software. The results are plotted by varying crack lengths are compared with the simulation results and theoretical results. The obtained results are found to be satisfactory.

**KEYWORDS:** Fatigue, Fracture Mechanics, LEFM approach, Paris law, Finite element method.

## I. INTRODUCTION

### Linear Elastic Fracture Mechanics (LEFM)

Linear Elastic Fracture Mechanics (LEFM) first assumes that the material is isotropic and linear elastic. Based on the assumption, the stress field near the crack tip is calculated using the theory of elasticity. When the stresses near the crack tip exceed the material fracture toughness, the crack will grow. In Linear Elastic Fracture Mechanics, most formulas are derived for either plane stresses or plane strains, associated with the three basic modes of loadings on a cracked body: opening, sliding, and tearing. Again, LEFM is valid only when the inelastic deformation is small compared to the size of the crack, what we called small-scale yielding. If large zones of plastic deformation develop before the crack grows, Elastic Plastic Fracture Mechanics (EPFM) must be used.

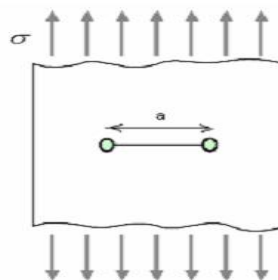


Fig 1.1 Linear elastic crack in tensile specimen

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In case of Linear Elastic Fracture Mechanics (LEFM) we use Stress Intensity Factor K or Stress Release Rate G.

Most metallic alloys and thermo set polymers are considered isotropic, where by definition the material properties are independent of direction. Such materials have only two independent variables (i.e. elastic constants) in their stiffness and compliance matrices. The two elastic constants are usually expressed as the Young's modulus E and the Poisson's ratio  $\nu$ . However, the alternative elastic constants K (bulk modulus) and/or G (shear modulus) can also be used. For isotropic materials, G and K can be found from E and  $\nu$  by a set of equations, and vice-versa. Three basic modes of loadings on a cracked body: opening, sliding, and tearing There are three basic modes of crack tip deformation, the opening (Mode I), the in-plane shear (Mode II), and the out-of-plane shear (Mode III):

Mode I (Tension, Opening)

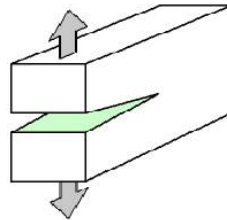


Fig 1.2 Opening mode of deformation

Mode II (In-Plane Shear, Sliding)

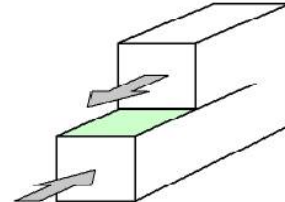


Fig 1.3 Sliding mode of deformation

Mode III (Out-Of-Plane Shear, Tearing)

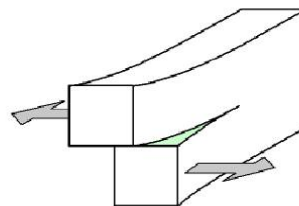


Fig 1.4 Tearing mode of deformation

## Stress Intensity Factor and Crack Tip Stresses

Crack tips produce a  $\frac{1}{\sqrt{r}}$  singularity. The stress fields near a crack tip of an isotropic linear elastic material can be expressed as a product of  $\frac{1}{\sqrt{r}}$  and a function of  $\theta$  with a scaling factor K:

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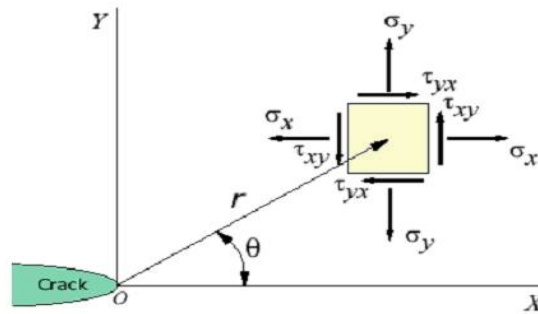


Fig 1.5 Stress field near crack tip of an isotropic linear elastic material

$$\lim_{y \rightarrow 0} \sigma_{ij}^{(I)} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}^{(I)}(\theta)$$

$$\lim_{y \rightarrow 0} \sigma_{ij}^{(II)} = \frac{K_{II}}{\sqrt{2\pi r}} f_{ij}^{(II)}(\theta)$$

$$\lim_{y \rightarrow 0} \sigma_{ij}^{(III)} = \frac{K_{III}}{\sqrt{2\pi r}} f_{ij}^{(III)}(\theta)$$

Where the superscripts and subscripts I, II, and III denote the three different modes that different loadings may be applied to a crack. The factor K is called the Stress Intensity Factor.

## FATIGUE

Failures arising under conditions of dynamic or alternating loading are called *fatigue failures*, apparently because it is generally observed that these failures happen only after certain period of time and service. Fatigue failure usually occurs at stresses below those required for yielding or in some cases above the yield strength but below the tensile strength of the material. A fatigue failure can usually be recognized from appearance of the fracture surface, which shows a smooth region due to rubbing action as the crack propagated through the section and through a region, where the member has failed in a ductile manner when cross section was no longer able to carry the load. The progress of the fracture is indicated by a series of rings or beach marks, progressing inwards from point of initiation of failure [1].

Fatigue process involves [1]:-

1. Crack initiation – This includes the early development of fatigue damage which can be removed by a suitable thermal anneal.
2. Slip band crack growth – This involves the deepening of the initial crack on planes of high shear stress. This is called stage-I.
3. Crack growth on planes of high tensile stress-involves growth of well-defined crack in a direction normal to maximum tensile stress. Usually it is 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 applied load.

Factors that affect fatigue are:

- There are several factors affecting fatigue life, among which the most important are:

1. The mean stress value
2. The shape of the component
3. The surface roughness value
4. The stress gradient and the dimension of the component

• There exist other factors, such as frequency, temperature, environment, but they are usually less important and dependent on peculiar applications.

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## FATIGUE CRACK PROPAGATION:

Usually, fatigue crack propagation can be divided into 3 stages-

1. Region I (short cracks),
2. Region II (Long cracks),
3. Region III (final fracture).

### Description of Region I

Once initiated, the fatigue crack propagates along high shear stress planes (45 degrees). It represents the early development of a fatigue crack and the crack growth rate. This is a slow crack growth process which is related to non-continuum mechanisms.  $da/dN$  is normally of the order 10<sup>-6</sup> mm/cycle or smaller. This region is very sensitive and it is largely influenced by the microstructure features of the material such as the mean stress of the applied load, grain size, the environment present and the operating temperature. Region I is bounded by a threshold value  $\Delta K_{th}$  below which there is no observable fatigue growth. At stresses below  $\Delta K_{th}$  cracks behave as non-propagating cracks.  $\Delta K_{th}$  occurs at crack propagation rates of the order of 0.25 nm/cycles or less. [2]

### Description of Region II

Stage II initiates when the slip starts to develop in different planes close to the crack tip and the stress intensity factor  $K$  increases as a consequence of crack growth or higher applied loads. Propagation in stage II is perpendicular to the load direction, while stage I is orientated 45 degrees in relation to the applied load. An important characteristic of stage II is the presence of surface ripples known as striations; these are visible with the aid of a scanning electron microscope. The region II represents an essentially linear relationship between  $\log da/dN$  and  $\log \Delta K$ . [3]

$$\frac{da}{dN} = C(\Delta K)^m \quad (\text{Paris law})$$

Where,  $a$  = crack length;  $N$  = no. of cycles;  $\Delta K$  = stress intensity factor range

$$\Delta K = K_{max} - K_{min}$$

The crack growth rate is typically on the order of 10<sup>-6</sup> to 10<sup>-3</sup> mm/cycle. 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 and usually results in closely spaced lines parallel to each other. The mean stress effect is greater for some material than others. [2]

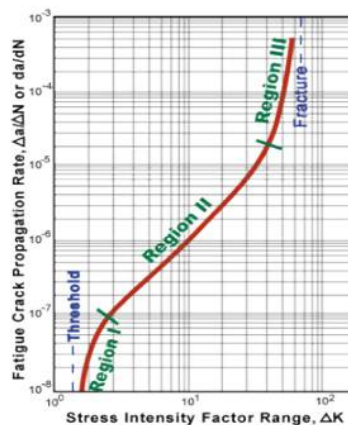


Fig.1.6 Fatigue crack growth vs. Stress intensity factor

### Description of Region III

This is a region of accelerated crack growth which is unstable as  $K_{max}$  approaches  $K_{IC}$ , the fracture toughness of material. Crack growth is controlled by static modes of failure and is very sensitive to the load ratio, microstructure and stress state (plane stress or plane strain loading). Region III represents the fatigue crack growth at very high rates,  $da/dN > 10^{-3}$  mm/cycle due to rapid and unstable crack growth just before the final failure. The  $da/dN$  versus  $\Delta K$  curve is not gradual and asymptotically approaches the fracture toughness  $K_C$  for the material. 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 that the fatigue crack growth rates are very high and little fatigue life is involved. [2]

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## FINITE ELEMENTS:

### Isoparametric, Quadratic Singular Elements

A fundamental difficulty when modelling Linear Elastic Fracture Mechanics (LEFM) problems using the finite element method is that the polynomial basis functions used for most conventional elements cannot represent the singular crack-tip stress and fields predicted by the theory. This means that as the mesh is refined the finite element solution will initially begin to converge to the theoretical solution, but eventually will diverge. This difficulty was recognized and demonstrated relatively early in the development of the finite element method. A number of researchers investigated special finite element formulations that incorporate singular basis functions or stress intensity factors as nodal variables.

A significant advancement in the use of the finite element method for LEFM problems was the simultaneous, and independent, development of “quarter-point” elements by Henshell and Shaw (1975) and Barsoum (1976). These researchers showed that the proper crack tip displacement, stress, and strain fields are modelled by standard quadratic order isoparametric finite elements if one simply moves the element's mid-side node to the position one quarter of the way from the crack tip to the far end of the element. This procedure introduces a singularity in the mapping between the element's parametric coordinate space and Cartesian space.

Henshell and Shaw described a quadrilateral quarter point element, illustrated in figure 1.7 (a).

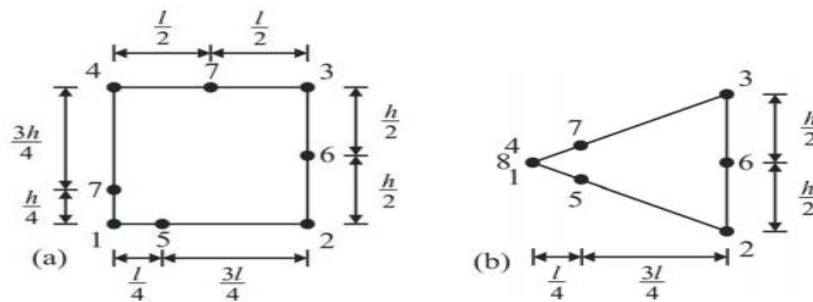


Fig 1.7 Quadrilateral (a) and Collapsed Quadrilateral (b) quarter point elements

Barsoum proposed collapsing one edge of the element at the crack tip. This is shown in fig, where the crack tip nodes (1, 4, and 8) are constrained to move together. The discovery of quarter point elements was a significant milestone in the development of finite element procedures for LEFM. With these elements standard and widely available, finite element programs can be used to model crack tip fields accurately with only minimal pre-processing required.

## II. RELATED WORK

The objective of our project is to illustrate the process of finite element program to compute the stress intensity factor histories accurately so that they can be used for fatigue crack growth (FCGR) and life predictions.

The problem is a relatively common structural detail, modelled as a plane stress problem, as shown in fig.2.1

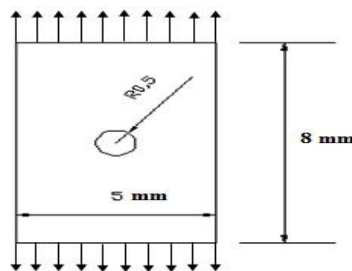


Figure 2.1: Schematic of Plate with Hole

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This figure shows a simple plate with hole under symmetric loading. Let us consider half portion of the fig (considering the right half). The traction load is applied on the top and bottom edges of the plate. A crack is initiated at the location of high effective stresses, and allows it to propagate in a straight line manner. FRANC 2D/L (Cornell Fracture Group, 2002) is used as the finite element solver.

The plate is modelled by using CASCA software. CASCA is an interactive program for the creation of two-dimensional continuum finite element meshes. Its capabilities include three and six-noded triangles and four and eight-noded quadrilaterals.

The coordinate system used within the program is always fixed so that the x-coordinate is horizontal; increasing to the right and the y-coordinate is vertical, increasing going up. CASCA was originally developed by Paul Wawrzynek and Louis Martha at Cornell University as a test bed for a hierarchical data base that was later implemented in FRANC3D. However, it has proven to be a useful tool, so it has continued to live beyond its initial application.

The fact that CASCA was originally written in 1987 is reflected in the menu structure. The menus were designed for display using low level X Windows commands.

The solution phase consists of two stages; modelling and analysis. Modelling is done by using CASCA. The analysis is done by using FRANC2D/L.

FRANC2D/L is a highly interactive program for the simulation of crack growth in layered structures. It is possible in FRANC2D/L that the representation of layered structures such as lap joints or bonded repairs. In addition, a linear bending option is available to account for the eccentricities of the layers when appropriate. The coordinate system used within the program is always fixed so that the x and u coordinates are horizontal, increasing to the right. The y and v coordinates are vertical, increasing going up.

The FRacture ANalysis Code (FRANC2D) was originally developed by Paul Wawrzynek at Cornell University. FRANC2D represented a significant step in the development of discrete fracture analysis programs because of its modular software design and topological data structure.

Initially we have modelled the fig with the default dimensions as given in fig. Crack has been initiated as discussed above and the graph has plotted between  $da/dN$  Vs  $\Delta K$  stress intensity factor. The standard graphs are available, which have plotted from the theoretical results. Then the graphs obtained from FRANC-2D/L are compared with these graphs.

Material is used for an analysis is 7075-T6 aluminium alloys.

7075-T6 aluminium alloys .Fined extensive application in transport industries, aerospace industries, and defence and for consumer durables due to their higher strength to weight ratio, corrosion resistance and high ductility.

Chemical composition of 7075-T6 Aluminium alloys

Alloy	Al	Cr	Cu	Mg	Zn	Other
7075-T6	91.4	0.18	1.2	2.1	5.1	0.2

Table 2.1 Chemical composition of 7075-T6 Aluminium alloys

## 2.1 The Input Parameters for the problem

### Plate dimension

Radius of the hole (r) = 0.5mm

Width of the plate (2b) = 5mm

Height of the plate = 8mm.



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## Material Properties

Material	Young's modulus (E)	Poisson's ratio ( $\nu$ )	Thickness of the plate (t)	Paris Constant	
				C	m
AA 7075-T6	10.28E6 Psi	0.33	0.04mm	1.10E-10 mm/cycles	3.45

Table 2.2 Material Properties

### Assumptions are:

Material is linearly isotropic,

The problem is modelled as a Plane stress condition.

The solution processor is discussed in the next chapter. The next chapter describes the processor to be followed in detail. The fig shown here are obtained for considering the values as shown in fig. In the remaining analysis, the dimensions will be different, but the same procedure is followed.

Sometimes an image may contain text embedded on to it. Detecting and recognizing these characters can be very important, and removing these is important in the context of removing indirect advertisements, and for aesthetic reasons.

Our system aims at the automatic detection of text. This is done by the algorithm. Fig. 1 shows the flow diagram of text detection algorithm. The algorithm steps are summarized as follows.

1. An efficient edge detection scheme is applied to the greyscale image. The image I is blurred (to reduce false edges and over-segmentation) using open-close and close-open filters. The final blurred image Ib is the average of the outputs of these filters. The 3 x 3 8-connected structuring element of type 'square' is used here. Next, the morphological gradient operator is applied to the blurred image Ib resulting in an image G as follows:  
$$G = \text{Dilation (Ib)} - \text{Erosion (Ib)}$$

The Morphological gradient is an edge-strength extraction operator that gives symmetric edges between foreground and background regions.

The resulting image is then thresholded to obtain a binary edge image. Global thresholding technique is used for that.

2. Closed edges in the binary edge image are grouped by dilation using eight- connected structuring elements. Then small connected components in the dilated image are filtered using erosion. The output is a binary image that contains text candidate regions.
3. Connected component labelling is performed to label each object separately.
4. After applying connected component labelling, the first set of criteria is applied which eliminate all objects whose area is greater than 10000 and filled area is greater than 8000. One more criteria namely major axis length is used which is used to retain the text region alone. All objects, whose major axis lengths are in between 20 to 3000, are considered to be text. To eliminate small objects, connected component labelling is applied to the resultant image and the second set of criteria is applied which eliminates all the objects whose area is less than 300 and filled area is less than 500.

After applying all these 4 steps, we get a filtered image that contains only text regions.

## III. EXPERIMENTAL PROCEDURE

### Creating Plate in CASCA.

Creating the Problem Outline for plate

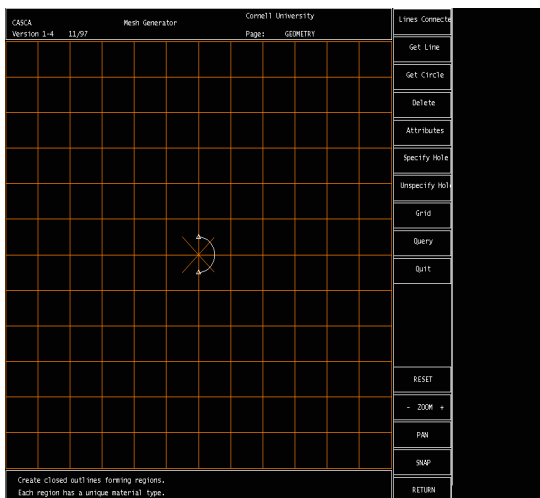


Fig 3.1 Circle border for plate

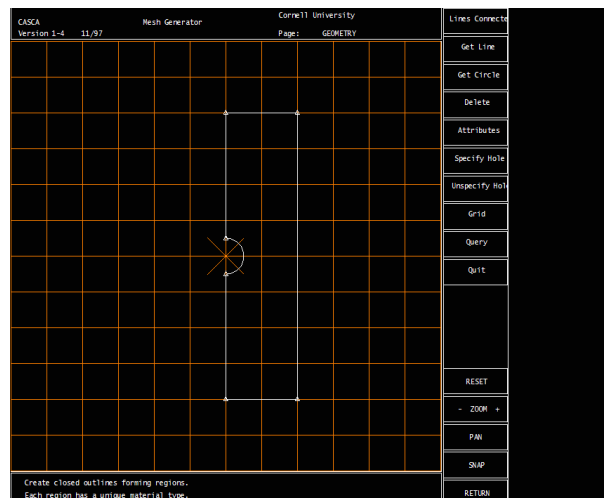


Fig 3.2 Plate border

### Adding Sub regions and Subdivisions for plate

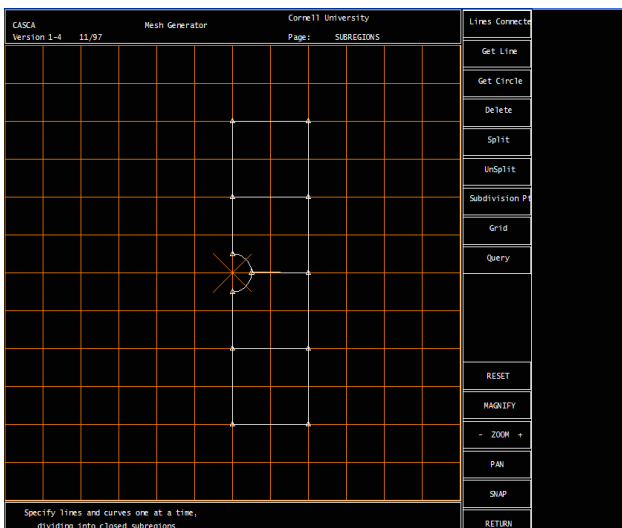


Fig 3.3 Sub regions added for plate

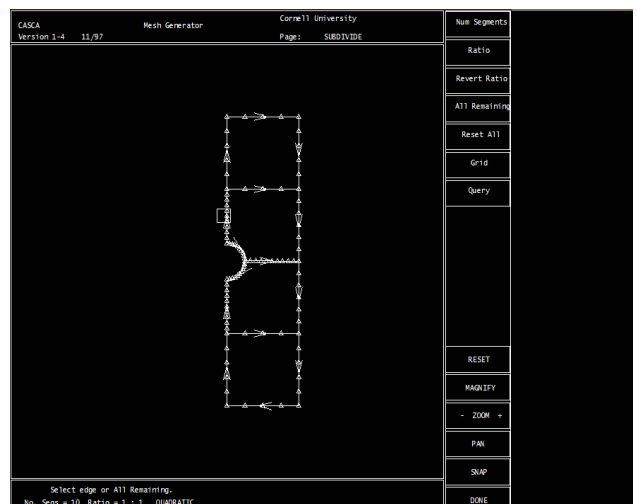


Fig 3.4 after line subdivision for plate



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## Mesh Generation for Plate

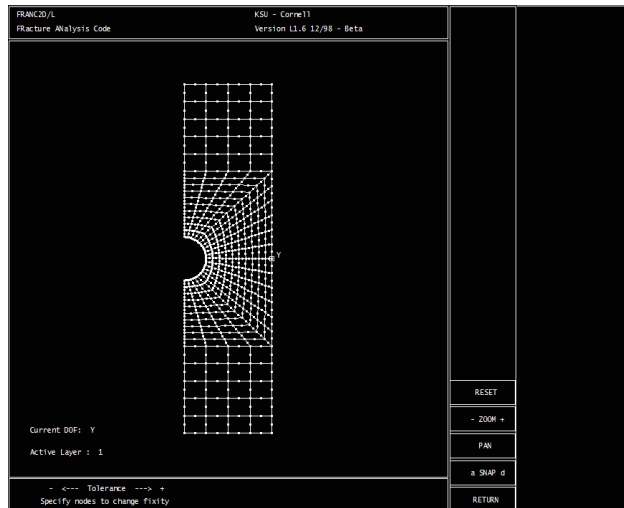


Fig3.5 Final Mesh for plate

The above figure's 3.1, 3.2, 3.3, 3.4, 3.5 shows how the model is created by using CASCA  
You should now run the **FRANC2D/L** program

## Boundary Conditions

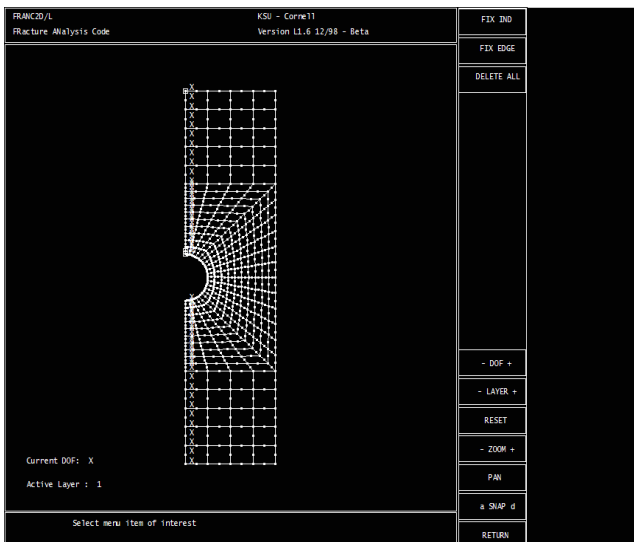


Fig 3.6 X Constraints

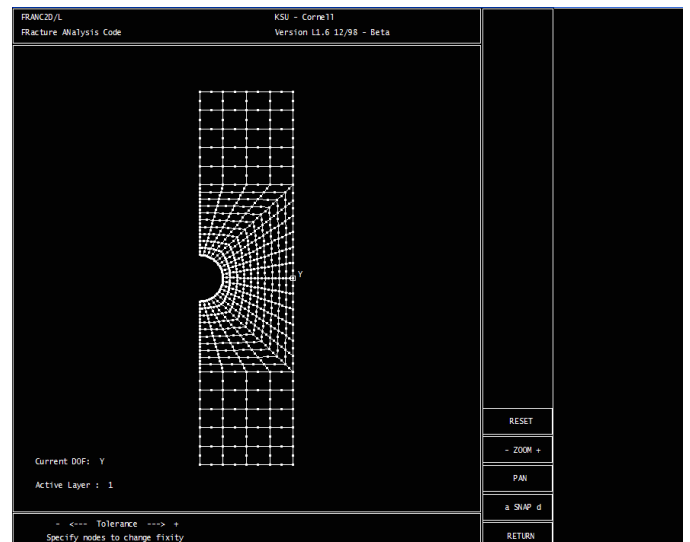


Fig 3.7 Y Fixity

## Stress Analysis and Post Processing

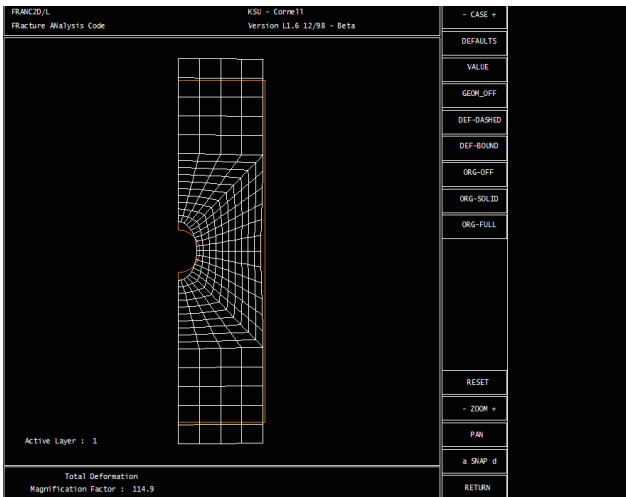


Fig 3.8 Deformed Mesh

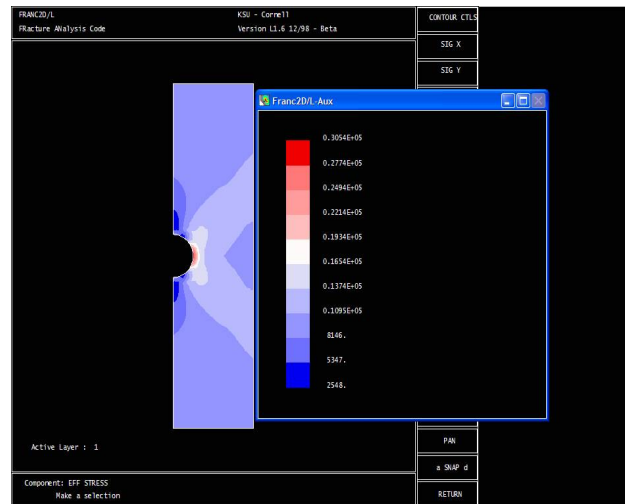


Fig 3.9 Stress contours

## Crack Initiation

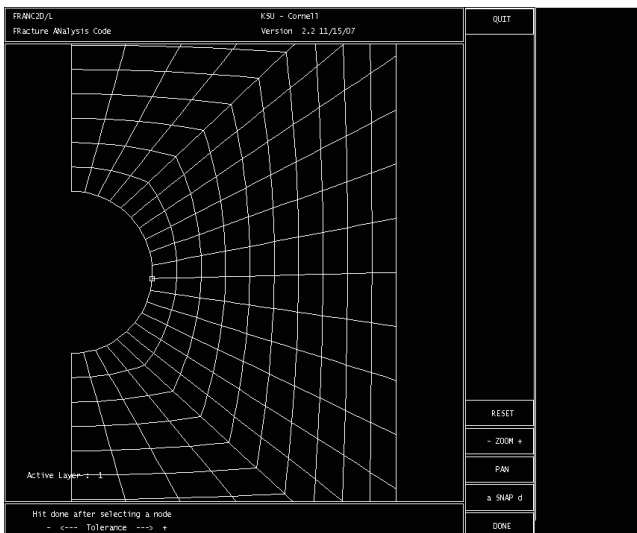


Fig 3.10 Selection of crack initiation point

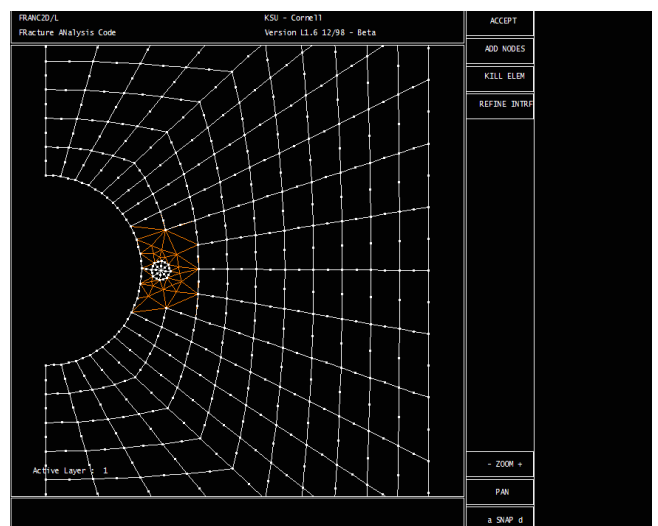


Fig 3.11 Mesh with crack

**Crack Propagation**

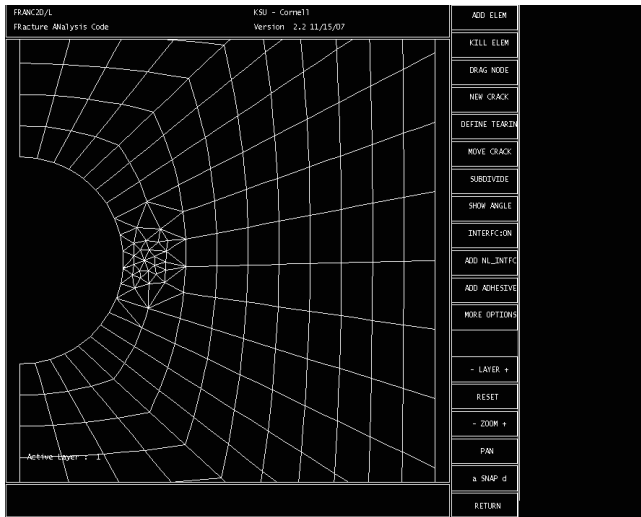


Fig 3.12 Mesh after growth

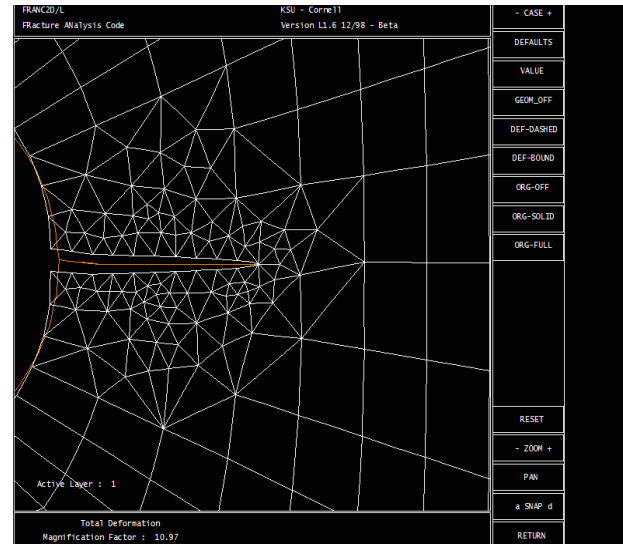


Fig 3.13 Displaced mesh

The above figure's 3.6, 3.7, 3.8, 3.9, 3.10, 3.11, 3.12, 3.13 shows the cracking occur with the fatigue load condition by using FRANC2D/L.

**Deformation modes and stress intensity factor:**

For mode 1 loading (see fig1.2) the stress intensity factor  $K_I$  characterizes the magnitude of stress in the vicinity of an ideally sharp crack tip in a linearly elastic and isotropic material. The stresses  $\sigma_x, \sigma_y,$  and  $\tau_{xy}$  are proportional to  $K_I$ .

$$\Delta K = \Delta\sigma * Y * \sqrt{\pi a} \text{ Psi} - \text{in}^{1/2}$$

The stress intensity  $\Delta K$  theoretically is calculated based on the following equation

$$\Delta K = f(\alpha) * \Delta\sigma * \sqrt{\pi a} \text{ Psi} - \sqrt{\text{in}}$$

$$\text{Where } f(\alpha) = 1.12 - 0.231(\alpha) + 10.55(\alpha)^2 - 21.72(\alpha)^3 + 30.39(\alpha)^4$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min}$$

$$Y = 1.12 \text{ (Geometrical Parameter)}$$

$$a = \text{crack length}$$

Thus, the Paris Law becomes:

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

Where,

C, m are Paris constants depends on materials.

Y= Constant depends on geometry

Exemplar based inpainting technique is used for inpainting of text regions, which takes structure synthesis and texture synthesis together. The inpainting is done in such a manner, that it fills the damaged region or holes in an image, with surrounding colour and texture. The algorithm is based on patch based filling procedure. First find target region using mask image and then find boundary of target region. For all the boundary points it defined patch and find the priority of these patches. It starts filling the target region from the highest priority patch by finding the best match patch. This procedure is repeated until entire target region is inpainted.

The algorithm automatically generates mask image without user interaction that contains only text regions to be inpainted.

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## IV. RESULTS

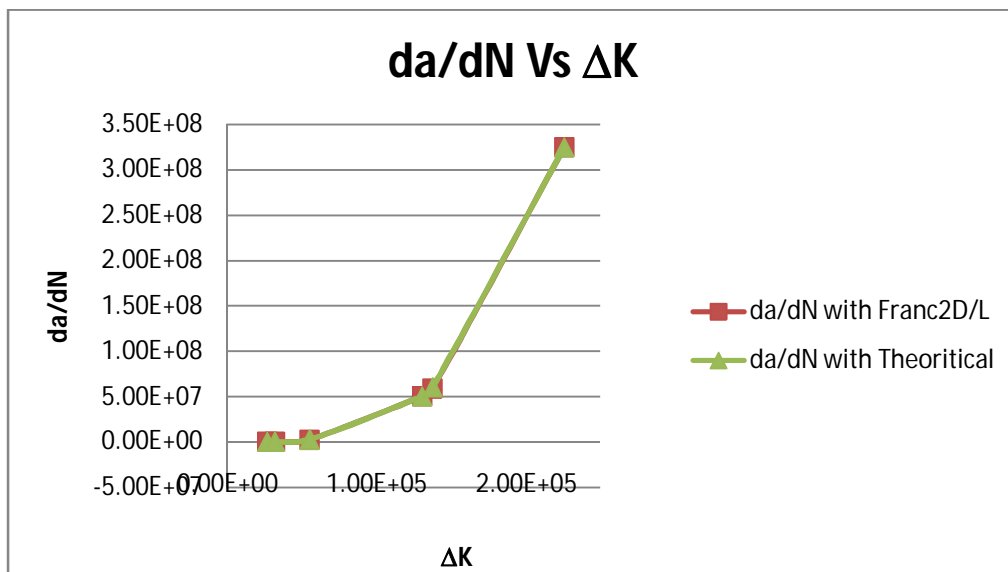
The table shown below shows the various **da/dN** values along various crack lengths. The **ΔK** values depend only on crack length and size of the discontinuity only.

The following table shows the value of **da/dN** and **ΔK** stress intensity factor (SIF) obtained for plate with hole

Sl. no	a mm	a/w= α	f(α)	S <sub>max</sub>	S <sub>min</sub>	Δσ	ΔK <sub>Franc2D/L</sub> Psi-√in	ΔK <sub>THEO</sub> Psi-√in	da/dN with Franc2D/L	da/dN with Theoretical
1	0.6	0.12	1.213	0.1763E+05	93.54	17.536E+05	26.96E+03	29.203E+03	212.50E+03	213.97E+03
2	0.9	0.18	1.325	0.1710E+05	90.37	17.009E+05	32.032E+03	37.895E+03	385.17E+03	387.86E+03
3	1.2	0.24	1.473	0.2549E+05	32.45	25.457E+05	55.35E+03	72.807E+03	2541.84E+03	2544.70E+03
4	1.5	0.3	1.66	0.3649E+05	13.10	36.476E+05	130.68E+03	131.442E+03	50223.83E+03	50237.2E+03
5	1.8	0.36	1.901	0.5175E+05	41.15	51.708E+05	137.71E+03	233.75E+03	58996.1E+03	59988.2E+03
6	2.1	0.42	2.221	0.7856E+05	63.58	78.496E+05	225.81E+03	447.79E+03	324942.5E+03	324954.6E+03

Values of **da/dN** and **ΔK** for plate with hole.

From the obtained values, graphs are plotted between **da/dN** Vs **ΔK** for various crack length. The values of **ΔK** are considered on X axis and **da/dN** values are considered on Y axis. The following graph has obtained.



Variation of **da/dN** and **ΔK** for various crack length

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## V. CONCLUSION

The problem is considered under mode-I conditions and  $K_I$  the Stress intensity factors are calculated from displacement correlation method. The results are plotted by varying crack length and are compared with the theoretical and Franc2D/L graphs. The obtained results are found to be satisfactory.

## VI. FUTURE SCOPE

In present project did not consider dynamic simulation can vary by applying dynamic load. Thermal stresses not taken it can be check by different material with different values of co-efficient thermal expansion. Similar work can be carried out for the mode II and for the mixed mode overloads. In these project only isotropic materials has taken for the analysis. But can be extended for orthotropic and anisotropic materials also. The analysis can be making for plane stain case also.

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