International Journal of Engineering Science Invention
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org Volume 2 Issue 5 ǁ May. 2013 ǁ PP.61-68

Idealization of a Foreign Object Damaged Compressor Blade of an Aero Engine to Rectangular Plate to determine the Stress Concentration Factor using FEM

Mohammadrafi nadaf[1], sharan shegedar[2]

[1] *(Department of mechanical engineering, college of engineering, ambajogai, India)*
[2] *(Department of mechanical engineering, appa institute of technology, Gulbarga India)*

ABSTRACT ***:*** *Foreign object damage from objects ingested into jet engines can have a detrimental effect on the fatigue strength of fan and compressor airfoils. It can result in immediate failure of the components and reduction of high cycle fatigue life of the components. Foreign object damage does not always lead to sudden catastrophic failure, yet such damage can dramatically reduce the lifetime of components subjected to cyclic fatigue stresses. . In spite of rigorous control exercised in the airfield maintenance foreign objects do enter the turbine engines. Hence the blades are designed in general to sustain certain levels of damage due to the impact of foreign objects. The typical standards followed in the industry stipulate a Stress Concentration Factor of 2.0 to 3.0 for the blades. As the blades operate at higher levels of stress and temperature, the damage caused could alter the stress and vibration patterns on the blade. The impactor geometry being irregular, the resulting damage can be a nick, dent or a crack. However designer has a requirement of arriving at a specific shape and size of cutout on the blade airfoil which can generate a known Stress concentration factor. By doing so it would be possible to map out certain damage shapes that can be declared safe.*

In this paper a simplified blade in the form of a cantilever plate is studied with variation of cutout geometry simulating various Stress concentration factor. Finite Element analysis is carried out to study the overall stress profile with and without cutouts. The study is then extended to a typical aerofoil. This study presents the influence of the geometric parameters of the cutout and its relative position on the airfoil on the stress pattern and Stress concentration factor.

Keywords - *Rectangular plate, Stress Concentration Factor, Finite Element Method*

I. INTRODUCTION

The ingestion of foreign objects into aircraft jet engines can also lead to severe structural damage of the fan and/or compressor airfoils. Reports have shown that foreign object damage is a prime reason for maintenance and repair of military jet engines. Indeed, the damage induced by small hard objects of millimeter size in conjunction with the typical load spectra experienced by airfoils can lead to non-conservative life prediction and unexpected fatigue failures.

Foreign object damage by hard-particles mostly occurs during motion of the aircraft on the airfield, during takeoff and during landing. Typical objects ingested are stones and other debris, sizes in the millimeter regime, from the airfield. The worst case condition is experienced during takeoff; maximum engine thrust leads to maximum impact velocity. Typical impact velocities are in the regime of 100 – 350 m/s, depending on the specific engine, the impact location on the blade and other things. Foreign object damage causes expensive, significant damages every year to many aircrafts, and regularly causes death and injury.

1.1 Foreign object analysis

The common failures mechanisms in gas turbine blades are discussed and illustrated by Tim J Carter in [1]. He elaborated different mechanical damages, high temperature exposures and damages, creep, fatigue and corrosion failures of the gas turbine engine blades in this presentation. He illustrated about the mechanical damage, high temperature failures of the gas turbine blades are due to Foreign object ingestion into the gas turbine.

The J.O. Peters, etal [2] study is focused on the role of such foreign-object damage in influencing fatigue crack–growth thresholds and early crack growth of both large and small cracks in a fan blade alloy, Ti-6Al-4V. Foreign object damage, which was simulated by the high-velocity (200 to 300 m/s) impact of steel spheres on a flat surface, was found to reduce markedly the fatigue strength, primarily due to earlier crack initiation. Nowell, etal [3] presented stress analysis of V-notches with and without cracks with application to foreign object damage. In their explanation, small hard particles ingested into the gas turbine engines take the sharp V-notches in the leading edge of blades. Prediction of initiation and propagation behavior of fatigue cracks is presented. Authors use the dislocation density approach to solve the 2-D elastic problem of a V-notch with reduced root. Stress concentration factors are found for the notch itself, and stress intensity factors are determined for cracks growing away from the notch for cases of applied and residual stress distributions. Comparisons are made with existing notch solutions from the literature.

In 1958 in one of the earliest investigations B.D Blackwell [4] presented on foreign body damage on the axial compressor blades. To study the effects of impacts on blades, a start was made using an air gun to shoot steel balls at stationary blades made of aluminum and steel. To simulate the effects ball velocities of 100ft/sec and 1000ft/sec were used. Fundamental experiments were made with strip specimens mounted as cantilevers. The technique used photography to reveal the dynamic displacement of the cantilever and the subsequent vibration. Unexpected consequences of the different laws occurred for different blade materials and ball velocities. The objective of the work carried by J.O. Peters and R.O. Ritchie in [5] is to provide a rationale approach to define the limiting conditions for high-cycle fatigue in the presence of foreign-object damage. This study focused on the role of simulated foreign object damage in affecting the initiation and early growth of small surface fatigue cracks in a Ti-6Al-4V alloy, processed for typical turbine blade applications. Using high-velocity (200±300 m/s) impacts of 3.2 mm diameter steel spheres on the flat surface of fatigue test specimens to simulate foreign object damage, they found that the resistance to High cycle fatigue is markedly reduced due to earlier crack initiation.

An overview from the industry perspective, highly empirical approach for assessing the High cycle fatigue capability in aircraft gas turbine was presented by B.A. Cowles [6]. Typical compressor blade foreign object damage and corresponding impact on High cycle fatigue, approximated by V-notched titanium blade tests are explained. Airfoils are designed assuming reduced High cycle fatigue capability in foreign object damage susceptible areas. Nick and blend limits to repair damages are set empirically, based on blade fatigue tests. Complicating factors that must be addressed which affect the engine High cycle fatigue capability are also described. Future directions which would improve the high empirical approach are outlined, emphasizing incorporation of fracture mechanics.

Predictive Study of Foreign Object Damage to Aero Engine Compressor Blades [7] by P. Duo, etal explains the predict loss of fatigue life resulting from Foreign object damage on blades. This literature describes a continuing programme of work using representative "blade-like" specimens and ballistic impact damage in order to closely reproduce service conditions. Finite element modeling is carried out using an explicit code and the effect of damage size on the residual stress distribution is investigated. Graham Clark [8] mentioned about the failures in military aircraft. He presented a wide range of failure modes and explained many factors, which influence those failures for components in military aircraft. He mentioned that the failure of different components of military aircraft due to foreign object damage is one of the causes. These show good agreement with the stress-relieved results. In [9] P. Duo, etal a design methodology for compressor blades to resist Foreign object damage is presented. Experimental results on 'blade-like' specimens have been conducted using a ballistic facility, which is considered the best method of reproducing realistic damage. The specimens were subsequently fatigue tested by a step loading method.

1.2 Blade repair

The repair of gas turbine blades is a complex area of manufacture and existing process are both manually intensive and costly. Solutions are developed to improve the blade repair technology, including vision-assisted blade build up technology and contact probe assisted welded blade machining process. Integrated blade repair is the solution to automate the repair process, improve the repair efficiency and reduced repair cost. Paul S. Prevéy etal [10] had done case studies of fatigue life improvement using low plasticity burnishing in gas turbine engine applications. Surface enhancement technologies such as shot penning, laser shock penning, and low plasticity burnishing can provide substantial fatigue life improvement. However, to be effective, the compressive residual stresses that increase fatigue strength must be retained in service. Dynamic blade-test method in both fatigue and vibration was given by R.F. French [11]. Earlier test techniques developed for determining blade vibration and fatigue characteristics were satisfactory for stationary blades, but without providing the centrifugal field needed for rotor-blade tests. This literature describes a test technique and facility on which blades are tested in their actual centrifugal environment.

1.3 Stress concentration factor

A number of investigations have determined Stress concentration factor for certain classical type of notches, giving results, which are more or less in agreement with one other. However, there is very little information on the stress concentration which is caused by a notch on one side of a plate in tension, photo elastic determination of stress concentration factor caused by a single U-notch on one side of a plate in tension is given by A.G. Coles and A.F.C. Brown [12]. Interpolated curves of photo elastic data is given in this technical note. In this report for comparison of Finite element method this photo elastic data is used for different sizes of semicircular notch and U-notches. F.G. Maunsell [13] calculated an approximate solution for stress in a notched plate under tension by introducing bipolar coordinates in stress function. The result that the maximum concentration of stress is very nearly 3 times of the applied tension and suggested 3 times applied tension accurate value in [13]. The X-ray method contribution in the field of stress analysis for calculating the stress concentration in elastic, partly elastic and plastic stage for a notched flat bar was given by J. T. Norton and Rosenthal [14].

II. SOLUTION TYPES

Fan and early stage compressor blades are prone to High cycle fatigue failure initiating from foreign object damage on or near the leading edges. The impact being a chaotic phenomenon and as the impactor geometry being irregular, the resulting damage can be a nick, dent or a crack. Foreign object damage is usually distributed along the leading edge of the blades ranging from the platform toward the tip, with a higher concentration of foreign object damage near the higher velocity tip. A complex and irregular distribution of minor indentations covers the surface, including leading edge impacts. The foreign object damage prone blades are extremely difficult to repair by conventional methods. Automated laser welding and plasma based welding are permanent repairing technologies employed widely on the blade tips.

When the aircraft needs to run in an emergency conditions or when the repairing techniques are readily not available for the aircraft in the operating areas, then maintenance section must go for instant remedies to run the aircraft. The quick-fix solution to run the aircraft in urgent needy conditions with the foreign object damaged blades with edge fractured and irregular shaped notch damage is to grind a semicircular or U-shaped edge notch depending on type, shape and size of damaged region. Low speed grinding machines are not suitable for grinding the foreign object damage damaged blades. High speed grinding machines are preferred for grinding the cracks, irregular notches geometry to notches of regular known geometry because of good surface finish and less damage to the blades in grinding. By grinding to a semicircular the crack is arrested and the stress concentration and intensity factors are reduced. So we are converting the stress intensity i.e. dynamic fracture mechanics problem to a regular shaped cutout stress concentration fail safe design structural analysis problem. However designer has a requirement of arriving at a specific shape and size of cutout on the blade aerofoil which can generate a known Stress concentration factor. By doing so it would be possible to map out certain damage shapes that can be declared safe.

2.1 Idealization of the compressor blade to cantilever plate

The damage caused by foreign objects often in the form of a geometric discontinuity like a notch. The presence of residual stresses, sub-structural damage in regions adjacent to the notch and complex 3-D geometry of aerofoils prohibit the use of simple notch analyses. Finite element analysis is used to estimate the stress concentration effect of the geometry of the notch. For this purpose, the compressor aerofoil blade is idealized into simple rectangular cantilever plate for Finite element method study. The complexity of the problem is reduced by assuming the aerofoil section to a flat rectangular plate as shown in fig.1. Furthermore, the methodology using Finite element method is applied to simpler problem of rectangular plates to aster the correctness of analysis with the empirical solutions and experimental solution in the literature. Then this methodology used for cantilever plates both in static and rotating conditions. To analyze the stress concentration effect of foreign object damage, different notches are made by varying the notch dimensions viz. depth, radius of the notch and the location of the notch from the fixed end on the leading edge of the rectangular plate.

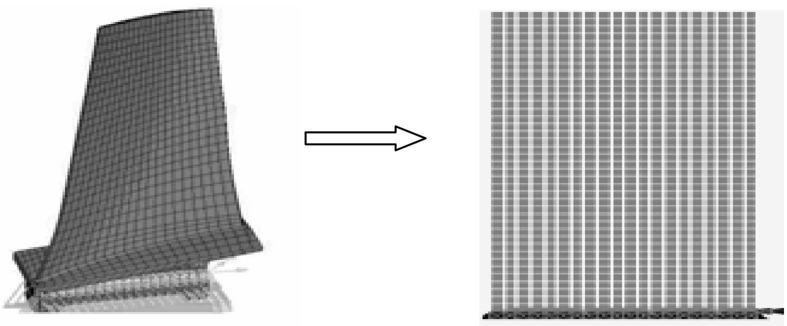


Fig.1 Idealization of the compressor blade to cantilever plate

2.2 Geometry taken for analysis

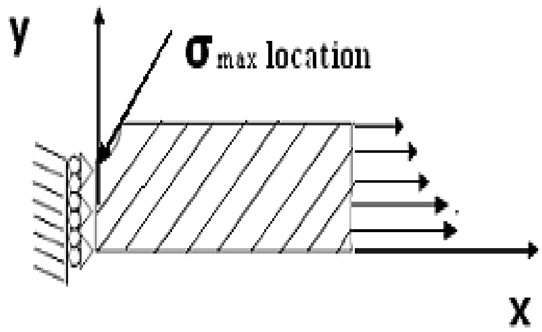


Fig.2 half the plate with applied boundary conditions

Owing to the geometric symmetry about Y-axis of the member under study and the type of applied boundary conditions, only one half of the plate was used as delimited by the shaded area as shown in fig 2. The left boundary was entirely restricted in the horizontal direction but allowed to move in the vertical direction. This two dimensional model under plane stress condition is meshed using the standard four node quadrilateral isoparametric element to compute the maximum stress.

2.3 Relations for equivalent applied boundary pressure and stress concentration factor

Basic strength of materials equations [15] are used for converting the tensile load to equivalent bending stresses for correctness of the solution, when the load acting is away from the centre of the gravity.

Let the load is at an eccentric distance 'e' from the x-axis. The section of the plate is subjected to direct and bending stresses.

The load P produces a direct stresses

$$\sigma_{direct} = \frac{P}{A_{norm}} \tag{1}$$

Due to the eccentricity o f the load, the section of the member is subjected to moment

$$M = P.e \tag{2}$$

At any distance y from the neutral axis XX or centre of gravity, the bending stress due the moment M is given by

$$\sigma_{bending} = \pm \frac{M}{I} y \tag{3}$$

This stresses due to bending may be compressive or tensile depending on the situation of the point with respect to the neutral axis. Hence the resultant stresses at any point distance y from the neutral or centre of gravity axis is given by

$$\sigma_{resultant} = \sigma_{direct} \pm \sigma_{bending} \tag{4}$$

For the rectangular plate case the resultant stresses are given by

$$\sigma_{resultant} = \frac{P}{A} \pm \frac{M}{Z} \tag{5}$$

Where Z=I/y, A=D*h and Z=I/y=hD²/6

$$\sigma_{resultant} = \frac{P}{D.h} \pm \frac{P.e}{\left(h.D^2/6\right)}$$

$$\sigma_{resultant} = \frac{P}{D.h}\left(1 \pm \frac{6.e}{D}\right) \tag{6}$$

The resultant stresses at any distance from the neutral or centre of gravity axis is given by

$$\sigma_{at(y)} = \frac{P}{h.D}\left[1 + \frac{12.e.y}{D^2}\right] \tag{7}$$

y is positive above the neutral or centre of gravity axis and y is negative below the neutral or centre of gravity axis.
Equivalent boundary bending stresses applied at the different nodes of meshing are calculated by

$$\sigma_n = \frac{P}{(h.D)}\left\{1+\frac{12e(C.G-Y_{n)}}{D^2}\right\} \tag{8}$$

Stress acting in the element is taken as the average of the stress of two nodes of the element and replaced on to the side edge elements of meshed plate where the load P acting.

2.4 Stress Concentration Factor

As is well known the theoretical stress concentration factor is defined according to [16].

$$\mathrm{Kt} = \frac{\sigma_{max}}{\sigma_{nom}} \tag{9}$$

Where σ_{max} is the maximum localized stress in the model at varying section and σ_{nom} is the nominal stress.

2.5 Finite Element Procedure

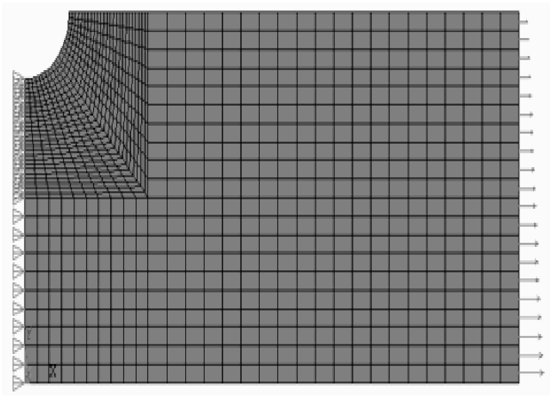
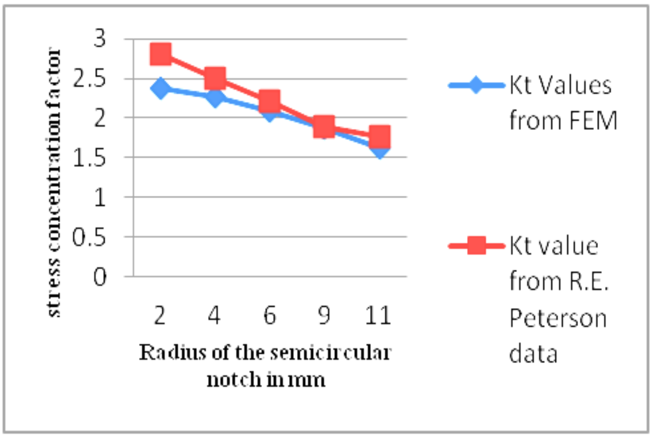


Fig.3 Finite element model with applied boundary conditions.

Dimensions and Material Properties for the rectangular plate are as follows
Length of the plate, L =200mm (only 100mm is considered because of symmetry
Width of the plate, W=50mm
Thickness of the plate, t=5mm
A tensile load of 5KN is applied
Young's Modulus = 2.1e5 MPa.
Density = 7850 Kg/mm^3
Poisson's ratio = 0.3
The material is assumed to be in linear isotropic elastic condition.

The finite element meshed model is fixed in x-direction and calculated averaged variable bending stresses from equation 8 are applied. The plate geometry shown in fig.3 is modeled and meshed by using ANSYS. The finite element meshed model is fixed in x-direction and calculated averaged variable bending stresses from equation 8 are applied as shown in fig.3. The stress concentration factor from finite element method result is compared with the standard stress concentration data available from R.E.Peterson stress concentration data [16]. By enhancing the mesh density in vertical direction for the respective notch radii size of r = 2, 4, 6, 9 and 11 mm keeping the loading edge side elements same. The maximum stress values are increased and converging towards the exact solution of the available stress concentration data.



Graph.1 Comparison of FEM data with R.E.Peterson stress concentration data For a mesh density of 1000 elements

Graph.1 is a plot of stress concentration factor obtained by finite element procedure and date from R.E.peterson with radius of the semicircular notch. By enhancing the mesh density in vertical direction for the respective notch radii size of r = 2, 4, 6, 9 and 11 mm keeping the loading edge side elements same. The maximum stress values are increased and converging towards the exact solution of the available stress concentration data. Hence finite element method can be adopted for the above analysis.

III. FINITE ELEMENT ANALYSIS OF A RECTANGULAR PLATE IN ROTATION BY VARYING THE RADIUS AND HEIGHT OF THE SEMICIRCULAR NOTCH ALONG THE LEADING EDGE

The Rectangular plate dimensions are length L= 200mm at distance of 250 mm from the x-axis (i.e. the radius of rotation is at 250mm from the x-axis) and width 50 mm and 5 mm thickness. The edge notches are located at a distance of 20, 50, 100, 120, 150, 180 mm in these regions from fixed end of the cantilever rectangular plate in rotation. The sizes of the semicircular notches at different regions are of radius r=2, 4, 6, 8 and 10mm. The plate is rotating about x-axis at N=15000rpm and gravity is acting in negative y-direction. The material properties remain same as assumed above.

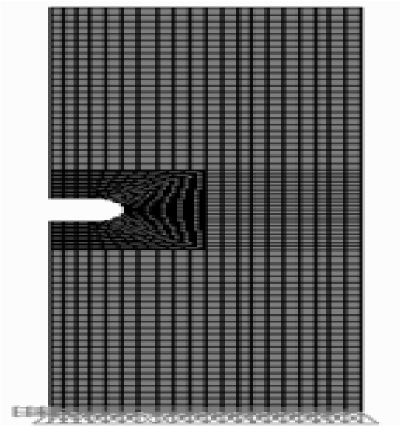


Fig.4 boundary conditions for a cantilever plate in rotation

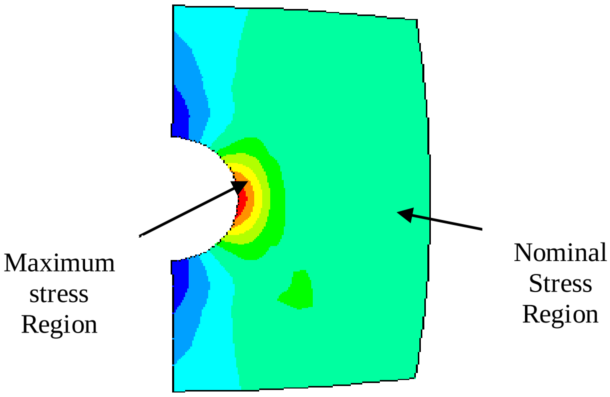
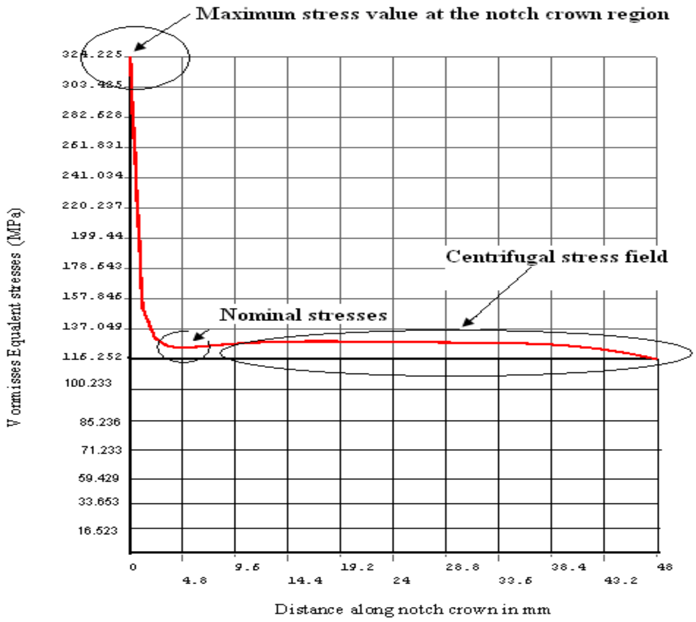


Fig.5 Plot shows the maximum and nominal stress regions at the enlarged portion of the notch

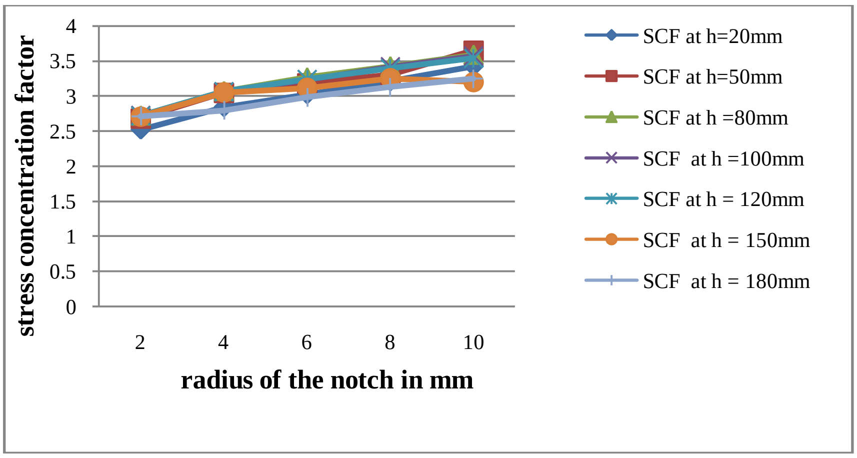


Graph.2 shows a plot of von misses stress Vs distance of the semicircular notch at a height of h=20mm and notch radius r=2mm along the leading edge

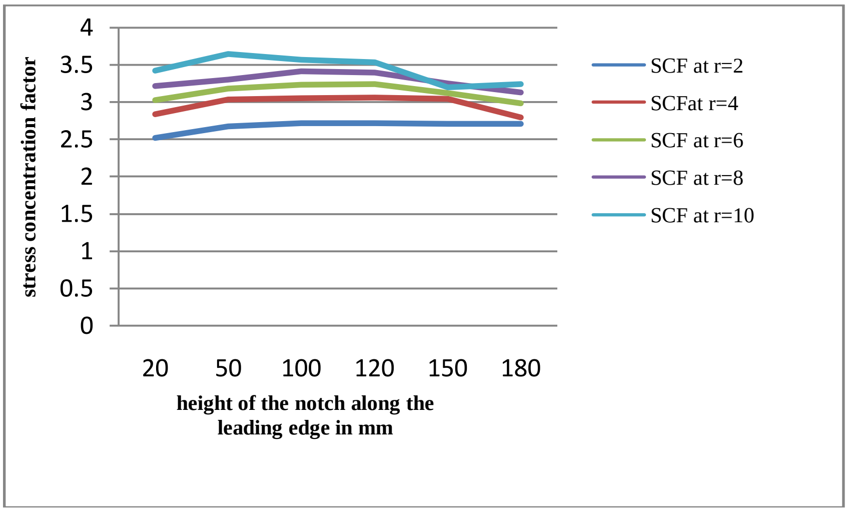
Fig.5 shows the stress fringes in the rectangular plate, the red region at the crown of the notch is the maximum stress region and the nominal stress is as indicated in the figure. Table. I shows the variation of the stress concentration factors calculated for different notch radii at varying height along the leading edge of the rectangular plate.

Table 1. Stress concentration factor values for different semicircular radii at varying height along the leading edge of the rectangular plate

Radius of the notch in mm	2	4	6	8	10
Stress Concentration Factor Kt at h=20mm	2.52	2.84	3.03	3.21	3.43
Stress Concentration Factor Kt at h=50mm	2.68	3.04	3.18	3.30	3.65
Stress Concentration Factor Kt at h=100mm	2.72	3.06	3.23	3.41	3.57
Stress Concentration Factor Kt at h=120mm	2.72	3.07	3.24	3.39	3.54
Stress Concentration Factor Kt at h=150mm	2.71	3.05	3.12	3.25	3.20
Stress Concentration Factor Kt at h=180mm	2.71	2.80	2.98	3.13	3.25



Graph.3 Stress concentration factor Vs radius of notch



Graph.4 Stress concentration factor Vs height of the notch along the leading edge of the rectangular plate.

From the graphs 3 and 4 the stress concentration factor value shows an increasing trend with radius at a particular location and shows a constant trend for particular notch radii at different locations.

IV. CONCLUSION

Based on the analytical work carried out on semicircular and U-notches on rectangular plates and subsequently on rotating cantilever plate it can be seen that the methodology is and Boundary conditions are adopted are apt for this type of problems. The SCF values obtained by this analytical method compare well with the experimental and other methods. The analysis has been further refined with convergence studies. With this the analytical methods can be confidently adapted to 3-D aerofoil for which the standard analytical and experimental results are not available.

REFERENCES

[1]. Tim J Carter:"Common Failures in gas turbines", Engineering Failure Analysis, vol.12, 2005, PP 237-247.
[2]. J.O. Peters, O. Roder, B.L. Boyce, A.W. Thompson, and R.O. Ritchie: "Role of Foreign Object Damage on Thresholds for High Cycle Fatigue in Ti-6Al-4V", Metallurgical and materials transactions A, Vol.31A, June 2000, P 1571-1583.
[3]. D Nowell, D Dini, P Duó:" Stress analysis of V-notches with and without cracks, with application to foreign object damage", The Journal of Strain Analysis for Engineering Design, Vol. 38, No. 5 2003, P 429 – 441.
[4]. B D Blackwell: "Some Investigations in the Field of Blade Engineering", Journal of royal Aeronautical Society, Vol. 62, 1958, P633- 646.
[5]. J.O. Peters, R.O. Ritchie: "Influence of foreign-object damage on crack initiation and early crack growth during high-cycle fatigue of Ti-6Al-4V", Engineering Fracture Mechanics, Vol.67, May 2000, P 193-207.
[6]. B.A.Cowles: "High Cycle Fatigue in Aircraft Gas Turbines an Industry Perspective", Int. Journal of Fracture Vol. 80, 1996, P 147- 163.
[7]. P. Duó, D. Nowell, J. Schofield, A. Layton, M. Lawson:" A Predictive Study Of Foreign Object Damage (FOD) To Aero Engine Compressor Blades", 10th National Turbine Engine HCF Conference, 2005.
[8]. Graham Clark: "Failures in Military Aircraft", Engineering Failure Analysis, Vol. 12, 2005, P 755-771.
[9]. P. Duó, D. Nowell , J. Schofield: " Assessment of Foreign Object Damage (FOD) in Aero Engine Blades ", 10th National Turbine Engine HCF Conference, 2005
[10]. Paul S. Prevéy ,N. Jayaraman Michael Shepard, Timothy Gabb: "Case Studies of Fatigue Life Improvement Using Low Plasticity Burnishing in Gas Turbine Engine Applications", Proceedings of ASME Turbo Expo 2003, June 16–19, 2003, Atlanta, Georgia, USA,P1-10.
[11]. R.F. French: "Mechanical Evaluation of Gas turbine Blades in Their Actual Centrifugal Field", Experimental Mechanics, 1962, P 122- 128.
[12]. A G Cole and A F C Brown: "Photoelastic Determination of Stress Concentration Factors by a single U notch on One side of a plate in Tension", Journal of Royal Aeronautical society, Vol.62, 1958, P 597- 598.
[13]. F G Maunsell: "Stresses in a Notched Plate under Tension", Phil. Mag. 7 Vol.21, 1936, P 765-773.
[14]. J T Norton and D. Rosenthal: "Recent Contributions to the X-RAY Method in the Field Of Stress Analysis "Experimental Stress Analysis 1947, P 71-77.
[15]. O.C.Zienkiewicz: "The Finite Element Method", 3rd Edition, Tata McGraw Hill publications, 2005.
[16]. R E Peterson: "Stress Concentration factors, Charts and relations useful in making strength calculations for machine parts and structural elements", John Wiley & Sons, New York, 1973.