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Idealization of a Gas Turbine Compressor Blade to a Rectangular Plate and Analyzing the Variation of Stress Concentration Factor for U-Notches

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ABSTRACT
Aircraft turbine engines routinely experience the ingestion of debris resulting in 'foreign object damage' FOD. The ingestion of foreign object into aircraft engines leads to severe structural damage of the fan or compressor blades. Foreign object damage by hard particles mostly occurs during motion of the aircraft on the airfield, during take-off and during landing. Typical objects ingested are stones and other debris; sizes in the millimeter regime form the airfield. The worst case condition is experienced during take-off maximum thrusts leads to maximum impact velocity. Typical impact velocities are in the regime of 100 – 400m/sec, depending on the types of engine and impact location on the blades. Foreign object damage does not always lead to sudden catastrophic failure, yet such damage can have a detrimental effect on the fatigue strength of fan and compressor aero foils. However complex stress fields and geometry of the aerofoil make it difficult to use of simple notch analysis. For finding the stress concentration factor on the notches grinded on the typical aerofoil FOD damaged gas turbine compressor blade closed form solutions are difficult proportion. In this paper a finite element analysis is carried out by idealization of the typical aerofoil to rectangular cantilever plate with single edge U-notches for finding the stress concentration factor and is then compared with the standard stress concentration data by R.E.Peterson. The study can then be extended to a typical aerofoil.

***Keywords* –** Stress Concentration Factor, U-Notches, Foreign Object Damage, Compressor Blade

I. INTRODUCTION

The ingestion of foreign objects into aircraft jet engines can also lead to severe structural damage of the fan and compressor airfoils. 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 – 400 m/s, depending on the specific engine, the impact location on the blade. FOD does not lead to sudden catastrophic failure, yet such damage can dramatically reduce the lifetime of components subjected to cyclic fatigue stresses. Compressor blades are susceptible to debris strikes and also experience significant fatigue loading. The ingested FO can cause damage that can vary from near microscopic to large tears, dents or gouges the form of a geometric discontinuity like a notch, cracking, nick dent, distortion or airfoil surface defects etc on the gas turbine compressor blade. However the complex stress fields and geometry of the airfoil makes it difficult to use of simple notch analyses.

The impact being a chaotic phenomenon and as the impactor geometry being irregular, the resulting damage can be a nick, dent or a crack. FOD is usually distributed along the leading edge of the blades ranging from the platform toward the tip, with a higher concentration of FOD near the higher velocity tip. The quick-fix solution to run the aircraft in urgent needy conditions with the FO damaged blades with edge fractured and irregular shaped notch damage is to grind a U-shaped edge notch depending on type, shape and size of damaged region. By grinding to a U-notch the crack is arrested and the stress concentration and intensity factors are reduced. By doing so the designer has a requirement of arriving at a specific shape and size of cutout on the blade airfoil which can generate a known SCF.

II. FOREIGN OBJECT DAMAGE (FOD)

This includes any damage done to aircraft, helicopter, launch vehicles, engines or other aviation equipment by hard body (usually) foreign object debris entering the engines flight controls or other operating systems.

Enormous literature is available regarding FOD and prevention and repair of FO damaged blades. In the NATO **[1],** FOD news **[2],** FOD Control Corporation **[3],** national aerospace FOD preventing incorporation **[4]**, DTIC **[5]** different authors presented about the problem, different definitions and effects of FOD on the aircraft gas turbine engine, different components failures of the aero engines due to FOD, engine blade damage definitions, performance, structural and cost effects on aircraft due to FOD, FOD awareness and controlling programs, preventing techniques, tool control to prevent FOD, and various equipments used in airfields and the engine design that avoids FOD. At the 2004 Atlanta conference **[2],** George A. Morse made an elaborate presentation of the impact damage characteristics and photo presentation on FOD.

2.1 FOREIGN OBJECT DAMAGE ANALYSIS

Blade fatigue failures by mechanical analysis and examination of failed blades are investigated and presented by **Jianfu Hou, etal [6].** A series of mechanical analysis were performed to identify the possible causes of the failures by examining anomalies in the mechanical behavior of the turbine blade. A non linear finite element method was utilized to determine the steady state stresses and dynamic characteristics of the turbine blade. An investigation by visual inspection and finite element analysis on failure of gas turbine first bucket was presented by **Jung-Chel Chang, etal [7]**. The failure mode of a major bucket cooling passage was a critical cause of the separation of a bucket segment and caused micro-structural deterioration of the neighboring regions by serious thermal loads. Surface damage of the bucket such as cracks is investigated by visual inspection and FEM analysis after coat stripping.

Typically FOD is one of the factors causing reduction of blade life time under different damage mechanisms. The blade experiences the internal cooling hole cracks in different airfoil sections assisted by a coating and base alloy degradation due to operation at high temperature. A detailed analysis by **Z. mazur, etal [8]** of all elements which had influence on the failure initiation was carried out, namely loss of aluminum from coating due to oxidation and coating phases changing.

Nowell, etal [9] presented stress analysis of V-notches with and without cracks with application to FOD. 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.

Predictive Study of Foreign Object Damage (FOD) to Aero Engine Compressor Blades **[10]** by **P. Duo, etal** explains the predict loss of fatigue life resulting from FOD on blades. Foreign object damage (FOD) is a major cause of engine removal and repair, particularly from military aircraft. Manufacturers are seeking to improve the FOD tolerance of engines at the design stage and thereby reduce the (significant) costs of ownership. 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 modelling is carried out using an explicit code and the effect of damage size on the residual stress distribution is investigated. These show good agreement with the stress-relieved results. Application of this work to other geometries may provide useful insights for FOD problems, which confront the aviation industry. In **[11] P. Duo, etal** a design methodology for compressor blades to resist FOD 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

The objective of the work carried by **J.O. Peters and R.O. Ritchie in [12]** is to provide a rationale approach to define the limiting conditions for high-cycle fatigue (HCF) in the presence of foreign-object damage (FOD). This study focused on the role of simulated FOD 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 FOD, they found that the resistance to HCF is markedly reduced due to earlier crack initiation.

The **J.O. Peters, etal [13]** study is focused on the role of such foreign-object damage (FOD) in influencing fatigue crack–growth thresholds and early crack growth of both large and small cracks in a fan blade alloy, Ti-6Al-4V. FOD, 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. This is discussed in terms of four salient factors: (1) the stress concentration associated with the FOD indentation, (2) the presence of small microcracks in the damaged zone, (3) the localized presence of tensile residual hoop stresses at the base and rim of the indent sites, and (4) microstructural damage from FOD-induced plastic deformation.

2.2 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 [14]** had done case studies of fatigue life improvement using low plasticity burnishing in gas turbine engine applications. Surface enhancement technologies such as shot peening, laser shock peening (LSP), and low plasticity burnishing (LPB) 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 [15].** 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.

III. STRESS CONCENTRATION FACTOR

A number of investigations have determined S.C.Fs. for certain classical type of notches, giving results which are more or less in agreement with one other. Some of the literature regarding the stress concentration factor determination is given below. **F.G. Maunsell [16]** 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 **[16].** 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 [17]**. No results was published for the notched flat bar in tension in **[17]**.

The article described by **D. Dini** and **D. A. Hills** in **[18]** gives a quantitative comparison of cracks and notches, sharp and with rounding, semi-infinite and infinite bodies. The article has shown that the elasticity solutions for plane cracks and notches have properties in common. Asymptotic solutions for semi-infinite rounded features are introduced in this article. Sharp features have singular fields which have been compared quantitatively. Rounding locally the sharp feature of the crack changes the nature of the problem from one of a stress intensification to stress concentration. In this report on parametric studies on compressor blades, that’s what exactly done by grinding the crack feature to a semicircular notch on the airfoils of the blade.

Peterson’s handbook **[19]** is the compilation of the results obtained by hundreds of investigators using any available methods. Peterson compiles the results with the little or no reference to the methodology. It includes notches and grooves, shoulder fillets, holes in two and in three dimensional bodies, an appreciable number of structural components: shafts with key seats, splined shafts, gear teeth, shrinked fitted members, etc.

IV. METHODOLOGY OF SOLUTION

For finding the stress concentration factor on the notches grinded on the typical aerofoil FOD damaged gas turbine compressor blade closed form solutions are difficult proportion. Hence finite element methodology is employed for finding the stress concentration factor on the FOD damaged grinded compressor blade. First, the finite element methodology is compared with the standard stress concentration data by R.E.Peterson and Photoelastic data for the general flat plate in tension with the single edge U-notch of different dimensions. The methodology is then extended to the general cantilever flat plate with single edge U-notches in rotation for finding the stress concentration factor. Finite Element analysis is carried out to study the overall stress profile with and without cutouts.

4.1 IDEALIZATION OF THE PROBLEM

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 airfoils prohibit the use of simple notch analyses. FE 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 FEM study as shown in figure 1. The complexity of the problem is reduced to by assuming the aerofoil section to a flat rectangular plate. Furthermore, the methodology using FEM is applied to simpler problem of rectangular plates to aster the correctness of analysis vis-à-vis 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 FOD, 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.

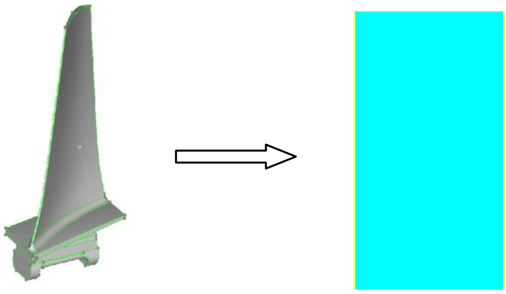


Fig.1. Idealization of the compressor blade to rectangular cantilever plate

Finally the FE methodology is applied on the typical compressor aerofoil blade to study the stress concentration factor effects by varying the dimensions of the notch viz. radius, depth, location of the notch from the base on the leading edge of contour section.

V. FINITE ELEMENT ANALYSIS OF RECTANGULAR PLATE IN TENSION

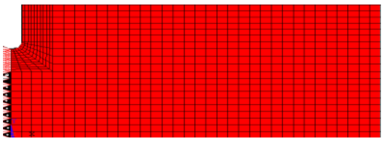


Fig.2. Finite Element Model of rectangular plate with U-notch

The figure 2 shows the flat tension bar considered for finite element analysis. 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 shown in figure 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.

5.2. EQUATIONS FOR APPLIED BOUNDARY PRESSURE AND STRESS CONCENTRATION FACTOR

Basic strength of materials equations**[20]** are used for converting the tensile load to equalent boundary pressure (bending stresses) for correctness of the solution, when the load acting is away from the C.G. 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 resultant stresses at any distance from the neutral or C.G. axis is given by

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

y is positive above the neutral or C.G. axis and y is negative below the neutral or C.G. axis.

Equalent boundary bending stresses applied at the different nodes of meshing are calculated by

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

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.

As is well known the theoretical stress concentration factor is defined according to **[20]**.

$$Kt = \frac{\sigma_{max}}{\sigma_{nom}}$$

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

VI. FINITE ELEMENT PROCEDURE

The analysis is carried out on the rectangular plate in tension with U-notch dimensions of depth d=33.33, 41.66 mm and radius r= 3, 4,5, mm For all the cases of rectangular plate with U-notches, a tensile load of 5KN is applied .The material taken for the plate is steel, have properties

Young's Modulus = 210 GPa.

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 (2) are applied as shown in figure 2. The analysis is carried out with course medium and fine mesh density and compared with the ref **[19]** for the U-notches.

Table 1. Comparison of stress concentration factor values from FEM with R E Peterson data for U-notches with depth d=33.33mm

Radius of the notch in mm	3	4	5
SCF values form FEM	2.436	2.231	1.972
SCF values form R.E.peterson	2.625	2.355	2.03

Graph 1. Comparison of SCF values of FEM result with R E Peterson data for U-notches with depth d=33.33mm

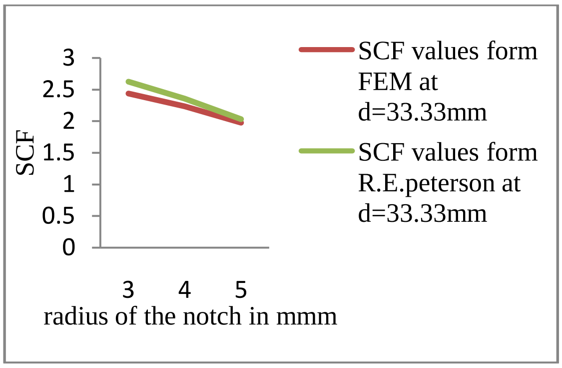
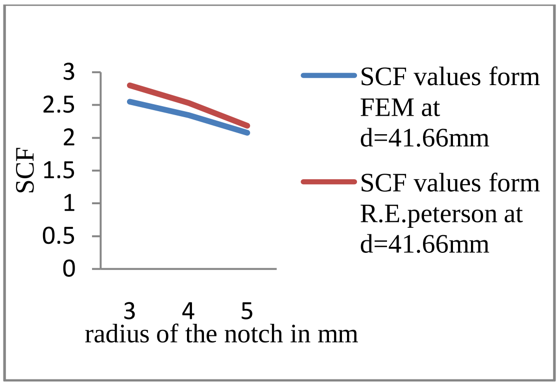


Table 2. Comparison of stress concentration factor values from FEM with R E Peterson data for U-notches with depth d=41.66mm

Radius of the notch in mm	3	4	5
SCF values form FEM	2.551	2.346	2.077
SCF values form R.E.peterson	2.8	2.53	2.18

Graph 2. Comparison of SCF values of FEM result with R E Peterson data for U-notches with depth d=41.66mm



Form tables 1 and 2 or graphs 1 and 2, the stress concentration factor values for rectangular plate with U-notches in the current study matches closely with ref **[19]** at higher notch radii and were found to be deviating from those values at lower radii. This can be due to the mesh density for all the notches. However it can be seen that the Kt values at lower radii also matches with those in ref **[19]** after the analysis was done with extra enhanced mesh density.

The FE analysis holds good for finding the stress concentration factor for finite width rectangular plate in tension. Since no data is available for cantilever plate U- notch in rotation, the FE analysis is carried out for finding the stress concentration factors for cantilever problem.

VII. STRESS CONCENTRATION FACTOR FOR ROTATING CANTILEVER PLATE WITH EDGE U-NOTCH

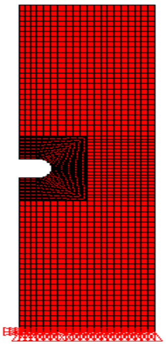


Fig.3. Meshing and Boundary Conditions of the cantilever plate in Rotation

Stress concentration factors are to be found for the cantilever plate with U-notches edge notches shown in figure 3. The Rectangular plate dimensions are length L= 200mm at distance of 250 mm from the x-axis and width 50 mm and 5 mm thickness. The U-notch dimensions are at depths of b=1,2 mm and of radius r= 2, 4, 6and 8 mm.

The plate is rotating about X-axis at N=15000rpm (1570.796rad/sec) and gravity is acting in negative y-direction. To simulate gravity by using inertial effects, accelerate the cantilever plate in the direction opposite to gravity. The cantilever plate is assumed to linear elastic isotropic material and the material specifications for the plate are same as that of steel given above in section 5.2.

Table 3. SCF value with depth b=1, and varying height and notch radius from fixed end

Radius of the notch in mm	2	4	6	8
SCF at h=20mm	3.015	3.107	3.204	3.330
SCF at h=50mm	3.204	3.391	3.463	3.544
SCF at h=80mm	3.253	3.430	3.491	3.645
SCF at h=100mm	3.252	3.420	3.537	3.641
SCF at h=120mm	3.247	3.419	3.522	3.596
SCF at h=150mm	3.237	3.390	3.373	3.355
SCF at h=180mm	3.165	3.135	3.265	3.389

Graph 3. SCF with depth b=1, varying height from fixed end and radius of the U-notch

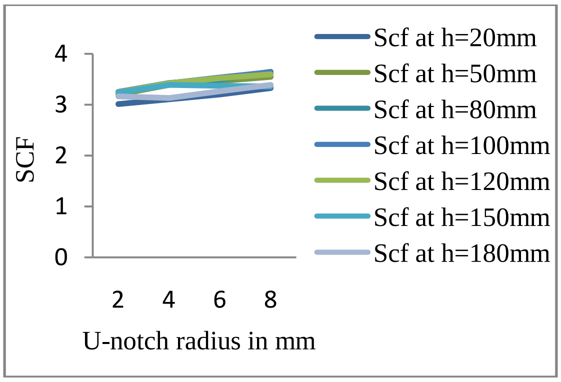
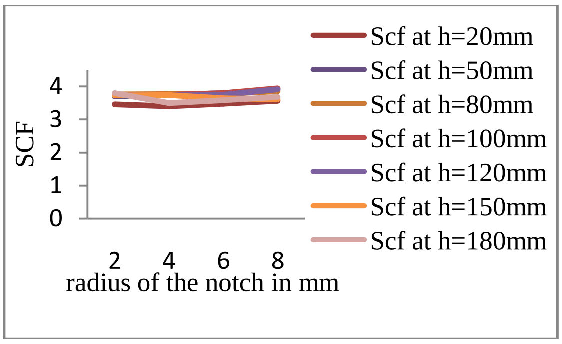


Table 4. SCF value with depth b=2, varying height from fixed end and notch radius

Radius of the notch in mm	2	4	6	8
SCF at h=20mm	3.453	3.393	3.471	3.565
SCF at h=50mm	3.695	3.739	3.790	3.905
SCF at h=80mm	3.753	3.767	3.777	3.852
SCF at h=100mm	3.741	3.748	3.793	3.942
SCF at h=120mm	3.741	3.720	3.748	3.910
SCF at h=150mm	3.728	3.73	3.636	3.607
SCF at h=180mm	3.794	3.491	3.575	3.672

Graph 4. SCF with depth b=2, varying height from fixed end and radius of the U-notch



The SCF shows an increase trend with increase in the depth of the notch as shown in tables 3 and 4 or graphs 3 and 4. The maximum stresses increases with increase in the depth of the notches.

VIII. CONCLUSION

Based on the analytical work carried out on 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.

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