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FINITE ELEMENT AND FRACTURE ANALYSIS OF COMPRESSOR DISC OF AN AERO ENGINE

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Abstract: Fracture analysis is widely used to predict component failure caused by preexisting small cracks, allowing one to take precautions to prevent further crack growth or to determine the remaining life of the structure or component. To obtain the fracture damage, stress intensity factors (SIFs) must be evaluated accurately by Displacement Extrapolation Method. In this work Computation Fracture Mechanics (CFM) approach is used to analyze failure of fifth-stage aero engine compressor disc. Later, calculation of the stress concentration factor is done. Then analysis of the compressor disc with a crack has been performed. It is observed that for the crack length of 15-19 mm in the compressor disc, the crack becomes unstable and propagates rapidly and hence leads to the catastrophic failure of the 5th stage compressor disc of an aircraft engine.

Keywords: Aircraft engine, Compressor disc, Fracture analysis.

I. NTRODUCTION

Cracks and flaws occur in many structures and components, sometimes leading to disastrous results. The predictions of crack propagation and failure are made by calculating fracture parameters such as Stress Intensity Factors(SIF) in the crack region, which could be used to estimate crack growth rate. During design or after a structure is placed into service, fracture mechanics can be used to perform what is called a damage tolerance analysis. Damage tolerance analysis is actually an integral part of any good fracture control plan. This requires an understanding of how the structure will respond in the event of a sudden brittle fracture (member loss) and/or the likelihood of crack growth due to fatigue and the time required for growing cracks to reach a critical size (i.e., the size at which brittle fracture would occur).

The interaction of both creep and fatigue mechanisms is the other main cause of failure in compressors and turbines of aero engines. Creep damage is a thermally activated and time dependent mechanism which results from structural changes leading to continuous reduction in the strength of the material [5,6]

Compressor blades are within the most affected components for two main different reasons: either by the ingestion of debris, such as birds or sand, causing "Foreign Object Damages" (FOD) or by typical degrading mechanisms resulting from cyclic loading and high temperature environments (creep-fatigue interaction). In the former case, the impact of small debris induces nicking of the blades which, in turn, will act as stress raisers prone to crack initiation [1,4]. Parallel to this, the damage caused by FOD tends to compromise the mechanical balance of the rotating components and also alters the aerodynamic flow over the blade airfoil leading to significant vibration or flutter which can promote crack propagation due to fatigue which, in turn, is a common cause of component breakage [2,3].

II. GEOMETRIC DETAILS

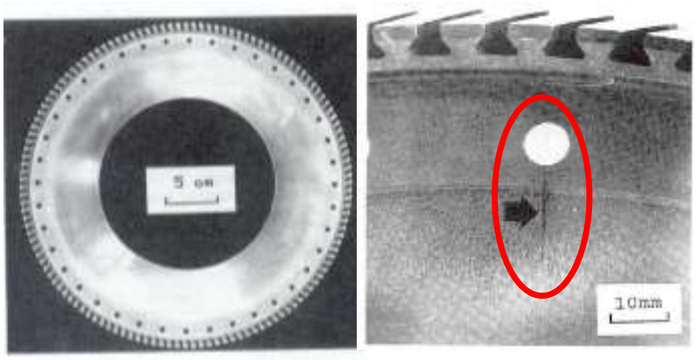


Figure 2.1(a): Compressor disc and micrograph showing 19mm long crack

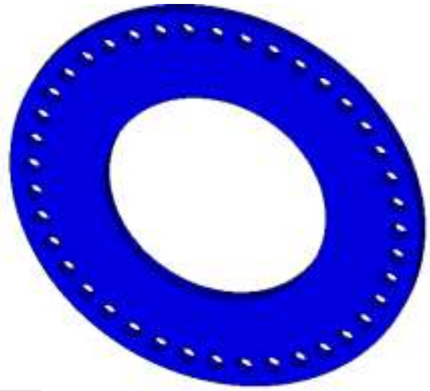


Figure 2.1(b): Geometric model for structural and crack analysis

Figure 2.1(a) shows the photograph of the fifth stage compressor disc. The disc contains 40 equally spaced tie bolt holes. Regions containing these bolt holes are known to be fracture-critical location. In some discs, cracks as long as 19mm were found.

In this present work, we consider a generic problem as an annular disc with inner radius, Ri = 87.5mm, outer radius Ro = 162.5mm, and thickness h = 10mm, bolt hole diameter, d = 12.5mm and crack length a is variable. The pitch circle diameter of the tie bolt holes is Dp = 145mm the maximum speed is10,000 rpm.

III. REFERENCE MODEL FOR MODE I SIF EVALUATION FOR ROTOR

A rotor of radius 30cm is rotating as 10,000 rpm. A suspected radial crack of length 38mm became unstable and damaged the rotor. Calculate the fracture toughness of the rotor material.

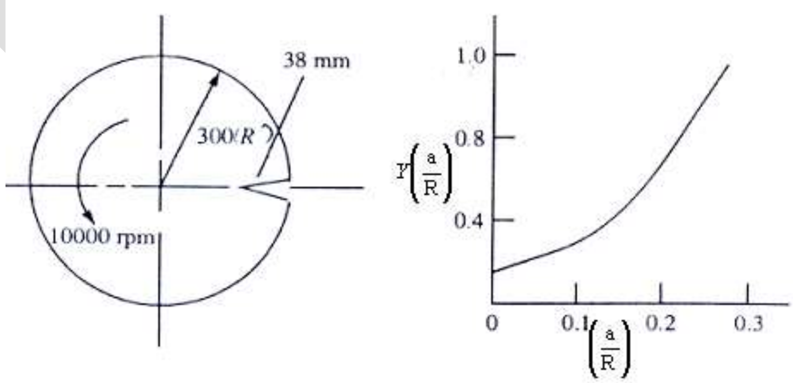
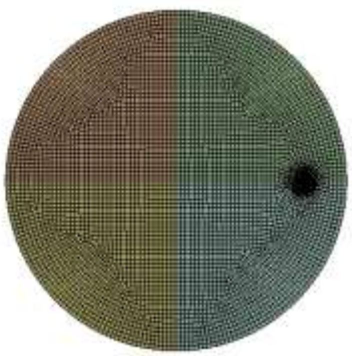


Figure 3.1: Geometric model along with graph

3.1 Material model and load applied

Material used	:	Precipitation-hardened AM355 martensitic stainless steel
Young's Modulus	:	2 e11 N/m2
Density	:	7900 kg/m3
Poisson's ratio	:	0.3
Element used	:	PLANE82
Load applied	:	10,000 rpm (angular velocity, 1046 rad/s)



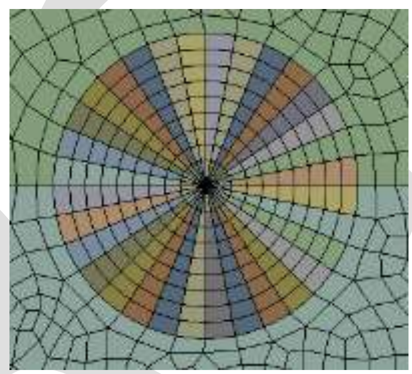


Figure 3.2: Reference FEA Model

Figure 3.3: Stress distribution around crack tip

From the Fringe plot it can be seen that the crack tip zone stress value I= 3.48E+9N/m^2 is very high compared to the stress away from the tip and hence the crack propagates from the crack tip until it became stable by losing the potential energy which is induced either due to internal stress or from the external loading.

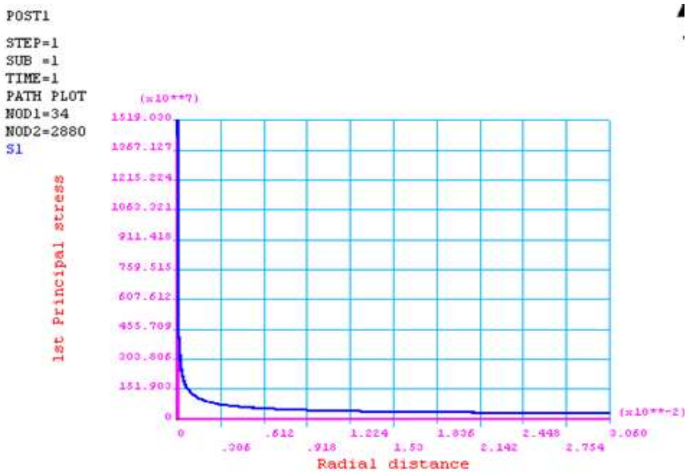


Figure 3.4: Plot of 1st principal stress along radial distance from crack tip towards center

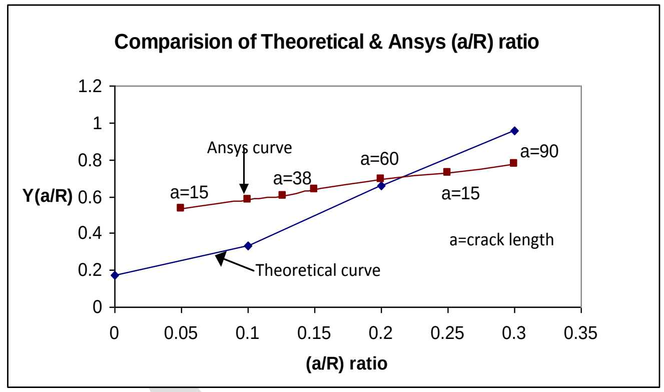


***Figure 3.5:** Comparison of the theoretical and Ansys data for different crack length*

The stress intensity factor defines the amplitude of the crack tip singularity. That is, stresses near the crack tip increases in proportion to 'K'. Moreover, the stress intensity factor completely defines the crack tip conditions. From the plot it can be concluded that the stresses at the crack tip is asymptotically high and it keeps on decreasing as one moves from the crack tip towards the centre of the disc.

Comparison of the theoretical and Ansys data for different crack length. For crack length of a = 60mm it is observed that the Ansys and Theoretical value are matching as verified by Ansys calculation and can be viewed from the graph.

Parameter	**Target Solution**	**Ansys Solution**
$Y\left(\frac{a}{R}\right)$ ratio	0.66	0.65

IV. STRUCTURAL ANALYSIS OF A COMPRESSOR DISC

Critical components like compressor discs are subjected to cyclic stresses during flight maneuvers. The cyclic stresses can exceed the yield strength of the material at stress-concentration sites, such as bolt holes and bores and thus lead to low-cycle fatigue cracking.

Structural analysis of the compressor disc operating at 10,000 rpm is analyzed for the stress-concentration factor at the bolt holes and bore and their implications are ascertained.

4.1 FE meshed model

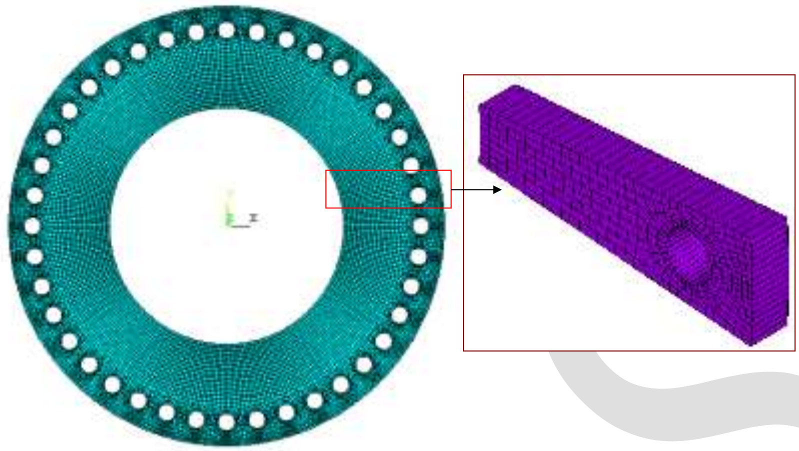


Figure 4.1: FE model for structural analysis

Boundary condition is applied by giving Cyclic Sector, which utilizes the advantage of the cyclic symmetry of the problem on hand.

4. 2 Principal Stress distribution plots

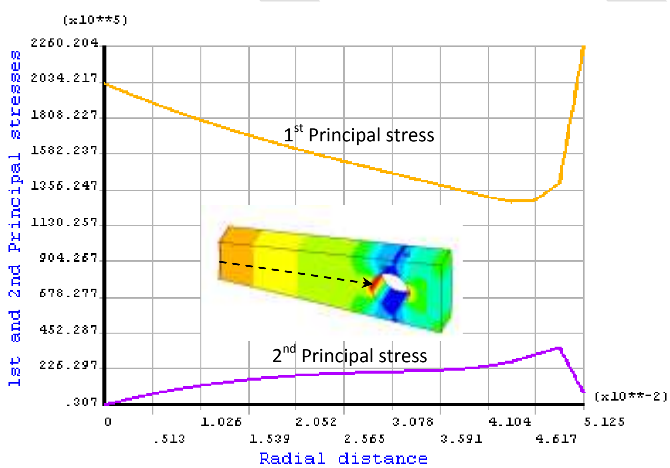


Figure 4.2(a): Principal stress plot

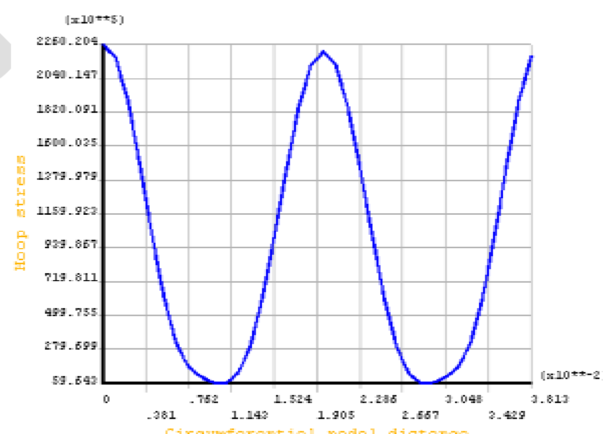


Figure 4.2(a): Hoop stress distribution around

The principal stress plot which indicates the stress at the crack tip is very high and the slope decreases drastically in the immediate vicinity of the crack tip due to reinforcement (presence of material) and then the slope has the steady rise towards the bore of the disc. The hoop stress distribution about the circumference of the bolt hole. It can be observed that the hoop stress at the crack tip is very high and further proceeding around the circumference it fluctuates and never reaches the highest value of stress.

4.3 Calculation of Stress Concentration Factor (SFC)

The discontinuity in geometry causes high stresses in very small regions of the disc and these high stresses are called as the Stress Concentration Factor (SFC). By Saint-venant's principle, Stress Concentration Factor,

$$\text{SFC}=\frac{\sigma_{\max}}{\sigma_{nomin\,al}}=\frac{Maximum\ stress\ at\ crack\ tip}{No\min al\ stress}$$

$$\textbf{Stress Concentration Factor (SFC)} = \frac{\text{Maximum hoop stress at the bolthole}}{\text{Mamimum hoop stress at the disk bore}}$$

$$=\frac{226\,MPa}{203\,Mpa}=1.113$$

As the stress intensity factor is more than one, it implies that the structure will undergo crack at this region, which will propagate with time and will lead to the failure of the compressor disc.

V. CRACK ANALYSIS OF A COMPRESSOR DISC

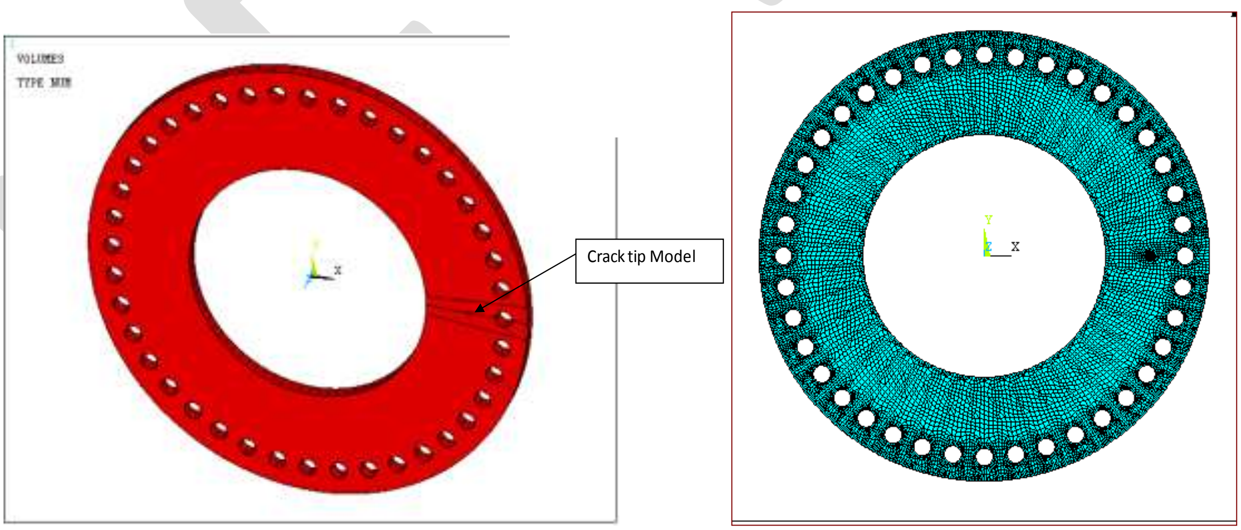
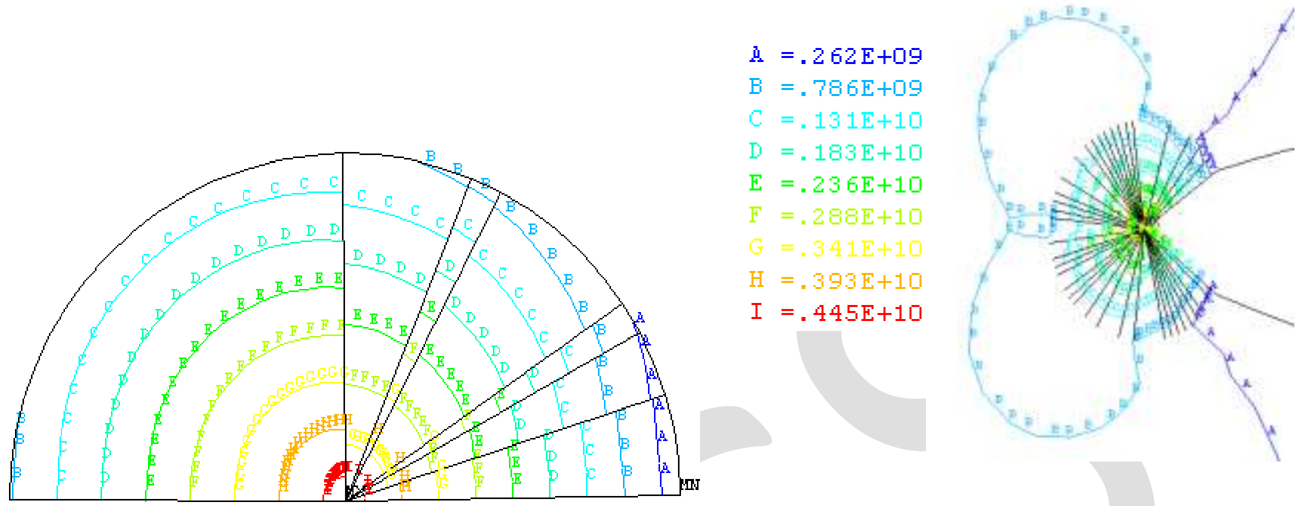


Figure 5.1: Geometric model and FE model along with the crack tip

5.1 Stress distribution



A-A is the fringe plot of the crack

Figure 5.2: Stress distribution

From the Fringe plot it can be seen that the crack tip zone stress value I= 4.45E+9N/m^2 is very high compared to the stress away from the tip and hence the crack propagates from the crack tip until it became stable by losing the potential energy which is induced either due to internal stress or from the external loading.

Stress intensity Factor for varying (a/d) ratio (crack length) is obtained and graph is as obtained below,

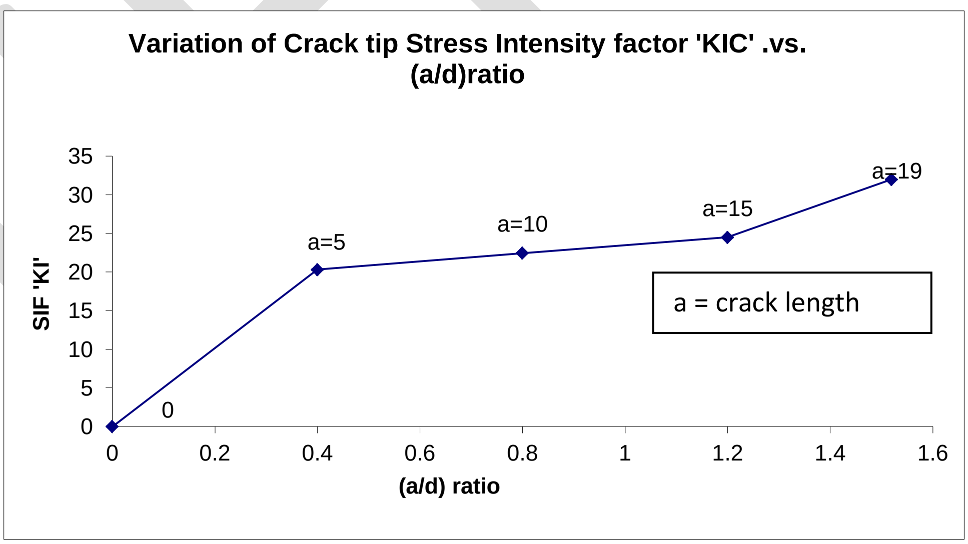


Figure 5.3: Stress Intensity factor plot for varying (a/d) ratio

It is observed from the graph that for the crack length of up to 5mm, Stress Intensity Factor at the crack tip is rapid but within the limit of component design strength and hence no failure of component occurs, but as the crack length increases from 5mm to 15mm, the Stress Intensity Factor propagates slowly but above 15mm crack length, the crack propagates rapidly and becomes unstable and hence fracture occurs.

VI. CONCLUSION

The compressor disc of an aero engine under investigation has analyzed using the theory of Computational Fracture Mechanics (CFM) and ANSYS software as a tool. The study reveals that for the crack length of 15mm up to 19mm (as observed from figure.) the crack becomes unstable and hence propagates very rapidly and leads to the catastrophic failure of the disc.

Thus it can be recommended that the inspection interval should be decided from the results obtained in order to avoid the propagation of crack to critical value.

'Damage-tolerance' based maintenance methodology can be effectively used to retire the cracked discs with little danger of catastrophic failures.

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