Analysis of Fracture on Turbo Expander Blade Tip to determine the Effect of Stress Intensity Factor by using Finite Element Method

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Abstract— This paper outlines the study of Stress and Modal behaviour of cracked compressor blade of high speed turbo machine. The compressor operates close to their failure stress due to high rotational speed of Turbo expander. Crack present in rotating part enhances the failure effect. The presence of crack can decrease the life; hence it becomes very necessary to study the fracture behaviour of the turbo expander parts. Creo modelling software is used to model the compressor and fracture analysis is performed in static structural module of ANSYS. The analysis and conclusion presented by the author will help the engineering society of the world to analysis, design and fabricate turbo machinery for better reliability and efficiency.

Key words: Turbo Expander, Fracture Analysis, Stress intensity factor.

A detailed survey about the history of turboexpander and its development has been presented by Collins and Cannaday [2] and Sixsmith [3]. Lord Rayleigh was the first to use the concept of using a turbine in refrigeration process in 1988. He explained the critical functionalities of a cryogenic expansion device, i.e. low temperature generation instead of getting mechanical work done. Followed by this suggestion, a number of patents were published on cryogenic expansion turbine. In the year 1939, a Russian scientist Peter Kapitza demonstrated that a low pressure (4-5 bar) liquefier using an expansion turbine would outperform a high pressure liquefier using a reciprocating expander. Besides having thermodynamic superiority, the low-pressure plant would be less expensive [4]. During the World War II, standardized turbines were needed. Hydraulic machine concept was applied. Impeller parameters like specific speed (ns) and flow coefficient (φ) etc. became the criteria for selection of turbines. The centrifugal inflow geometry thus became the usual configuration for small and medium sized cryogenic turbines [5].

During the period of 1960s and 70s, demand of helium increased. Hence, the demand for energy efficient liquefiers and refrigerators based on turbines increased. The volumetric flow rate in case of helium turbines is low due to low fluid temperature and large pressure ratio. World's first viable turbine-based helium liquefier was built by BOC for the Rutherford Laboratory in Oxford. By the end 1950s, England based company "Lucas company" had developed a large number of gas lubricated inward flow turbines for PDC (Petrocarbon Development Corporation) [6].

By the 1980s, the design of turboexpanders with gas bearings as its support became almost popular in Europe and USA. They built two models of small turbines, one for helium liquefiers and another for small air separation units. Naka Fusion Research Centre affiliated to the Japan Atomic Energy Institute [7] modelled a very large size He turbo-expander. Ino et al. [8] developed a He turbo-expander for a 70 MW superconducting generator. The work of Kapitza, paved the way for the Russian Turbine industries to use both oil and gas bearings to support turbo-expander. This has continued through the 90s [9]. Small turboexpanders for microcryogenic systems have also been developed by the Mikrokryogenmash company in Russia [4]. The development in the field like the micro turbines and application of bearings of a turboexpander are among various modern developments. A tiny version of the of the turbine for cryo-cooler was built by Sixsmith[10] in collaboration with Goddard Space Flight Centre of NASA.

Generally various types of turbo machines are used for various types of application. Depending on size they can be categorized as small, medium and large turbo machines. Various works has been done by Linde AG of Germany, Creare Inc. [10] USA. Generally shaft, expansion turbine and brake compressor are taken for analysis of stress and deformation, as the whole assembly is kept in housing, there is a probability that due to high speed rotation of the Turboexpander, the various elements of it may grow radially decreasing the clearance between the housing and turbo expander. This may cause catastrophic damage to the housing and the turbo expander and also to the bearings. There are sharp edges present in shaft; brake compressor, turbine wheel, and those are major areas of stress concentration. As turboexpanders are very delicate and costly, it is imperative to analyze each and every part carefully before putting it into application. Rotor is the rotating part of machine. Various types of rotor are turbine rotor, electric rotor, helicopter rotor, turboexpander etc. Above all high speed rotation is required in case of Turboexpander for cooling purpose. Turboexpander is also known as expansion turbine. It is having rotor, turbine and compressor. The fluid/gas expands through the turbine where it releases its energy to the turbine as rotational energy, this energy is used at the other end to compress another fluid/gas. The expansion is isentropic process i.e. entropy remains constant throughout the process i.e. the change in entropy is zero. Refrigeration industries generally use turboexpander in their various processes as the extraction of the gases like ethane and NGLs (Natural Gas Liquids). The gas at very high pressure enters into the turbine through various piping, into the plenum of the housing and after that into the nozzle. The gas exit from nozzle at very high speed and strikes the impeller radially. The high speed gas gives torque to the rotor. Generally converging-diverging nozzle is used where the pressure of the gas decreases and velocity of the gas increases at the exit. In this nozzle the pressure energy is transformed into the kinetic energy. The energy always remains conserved according to the first law of thermodynamics. As pressure energy converts into the kinetic energy the temperature of the gas decreases. Torque is generated by the force transmitted from high speed streams that strike against the blade. The alignment between the nozzle and the blades are made in such a way that the effect due to sudden changes in flow direction and loss of energy can be avoided.

The turbine wheel that is used in Turboexpander is of radial or mixed flow type. The radial or mixed flow turbines are those where the flow enters the wheel radially and exists axially. While larger units are generally shrouded, smaller wheels are open, the turbine housing acting as the shroud. When the high speed flow of gas strikes the blade of the turbine, it loses its velocity and the energy of the fluid decreases after the strike. The energy which is lost is transmitted to the turbine wheel i.e. work is extracted as the gas expands in turbine. This work extracted can be used to compress some other gas at another end or generate electricity etc. Due to the loss of energy the gas at exit is having very low temperature below -1400C or less. These gases can be used in cryogenic applications like liquefaction of gases. That’s why cryogenic industries use high speed turboexpander for their applications.

II. FRACTURE ANALYSIS

Fracture analysis deals with the computation of fracture parameters. Fracture analysis assumes the presence of a crack in the structure. Fracture analysis is typically carried out either using the energy criterion or the stress-intensity-factor criterion. When the energy criterion is used, the energy required for a unit extension of the crack (the energy-release rate) characterizes the fracture toughness. When the stress-intensity-factor criterion is used, the critical value of the amplitude of the stress and deformation fields characterizes the fracture toughness.

There are three modes of Fractures studied during fracture analysis as shown in Fig 2.

Mode I – Opening or tensile mode

Mode II – Shearing or sliding mode

Mode III – Tearing or out-of-plane mode

III. FRACTURE ANALYSIS OF COMPRESSOR

Stress and deflection analysis have been carried out by using ANSYS fem solver.

1) First of all the model i.e the compressor blade and compressor are modelled using Creo software. The model is then saved in *.iges/*.igs format (iges stands for initial graphics exchange specification, which is a neutral data format file that helps in digital exchange of data among various CAD software).

2) This model is then imported to ANSYS.

3) Meshing of the solid model is generated by using the meshing function of the ANSYS finite element solver package.

4) Then various boundary conditions are applied to the model and solved for stress and deflection.

5) Crack is generated for studying the fracture behaviour of the compressor.

6) Modal analysis and Fracture analysis is studied for the model with and without crack.

A. Boundary condition

The compressor is applied to the fixed support at the hub to restrict its motion along any axis.

1) Load

- Centrifugal force is applied along Y-axis (Clockwise) to the rotor.
- Earth gravity is applied about Y-axis in negative direction.

2) Analysis and Results

- Element type -3D solid element (Tetrahedron mesh)
- Number of element- 5057
- Number of nodes- 2497

3) Material used – Aluminium Alloy

- Density: 2700 kg/m3
- Young's Modulus: 68.3 GPa
- Poisson,s ratio : 0.33

4) Loading

 Centrifugal load is applied to the compressor along Y-axis (Clockwise) having angular velocity ω = 14660 rad/s.

 Earth gravity is applied about Y-axis, g = - 9806.6 mm/s2.

B. Nomenclature

- Ω - Angular velocity (rad/s)
- ρ - Density of the material (kg/m3)
- G - Acceleration due to gravity (m/s2)
- E - Young`s modulus (GPa)
- M - Mass of the rotor (kg)
- ν - Poison's ratio (dimensionless)
- N - Revolution per minute (rpm)

IV. RESULT & DISCUSSION

After the fracture analysis the value of three SIF was obtained for varying crack length. Table I shows the values of SIF obtained with respect to varying crack length. Table II and Table III shows the different values of Von Misses stress and Stress intensity respectively with respect to varying crack length.

Table 2 – Variation of Von Misses stress w.r.t crack length

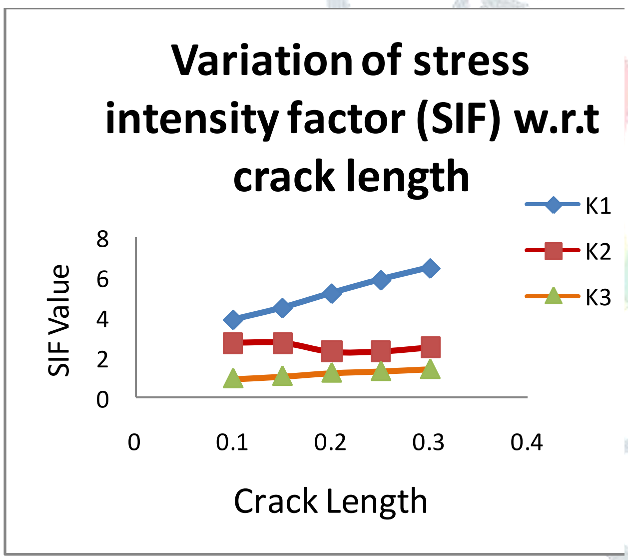
Crack Length (mm)	**Von Misses stress (MPa)**
0.1	9.41
0.15	8.19
0.2	7.87
0.25	7.16
0.3	6.82

Table 3 – Variation of stress intensity w.r.t crack length

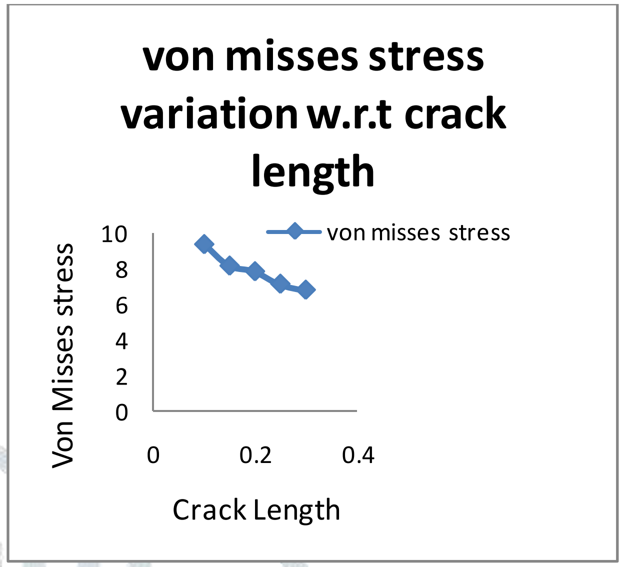
Crack Length (mm)	**Stress Intensity (MPa)**

0.1	9.42
0.15	8.22
0.2	7.88
0.25	7.17
0.3	6.83

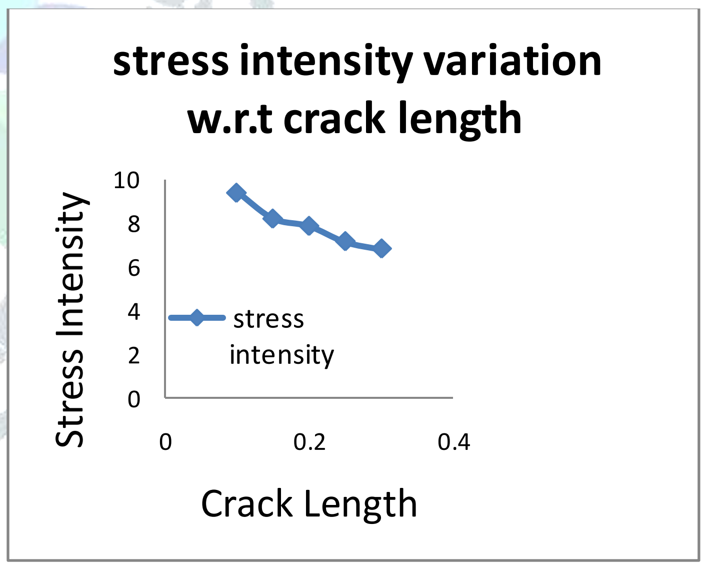
Table 1, 2 and 3 shows the variation of stress intensity factors, Von Misses stress and stress intensity with respect to crack length. The same is can be seen in the graph 5.7, 5.8 and 5.9 respectively.



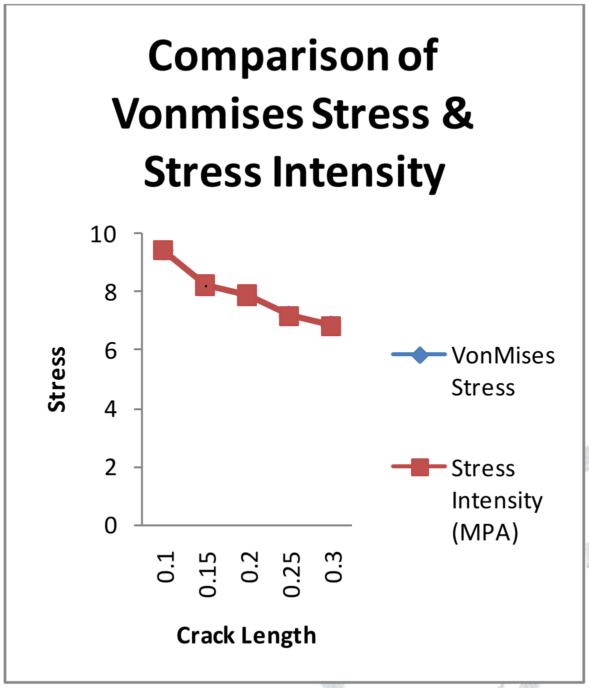
Figure– Variation of stress intensity Factors w.r.t crack length



Figure– Variation of Von Misses stress w.r.t crack length



Figure– Variation of stress intensity w.r.t crack length

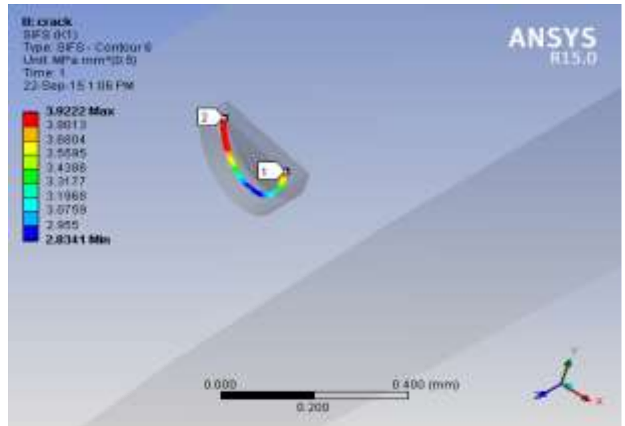


Figure– Comparison of stress intensity & Vonmises stress w.r.t crack length

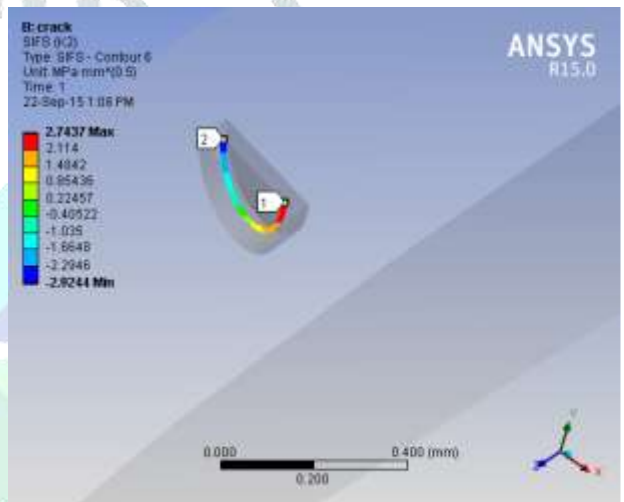
The variation of stress intensity factor with respect to crack length is shown in Figure 5.9. The variation of Von-Misses stress and stress intensity at crack with respect to crack length is shown in Figure 5.10 respectively.

Figure 5.11 to Figure 5.13 and Figure 5.14 shows the stress intensity and Von- Misses stress variation with respect to crack length respectively.

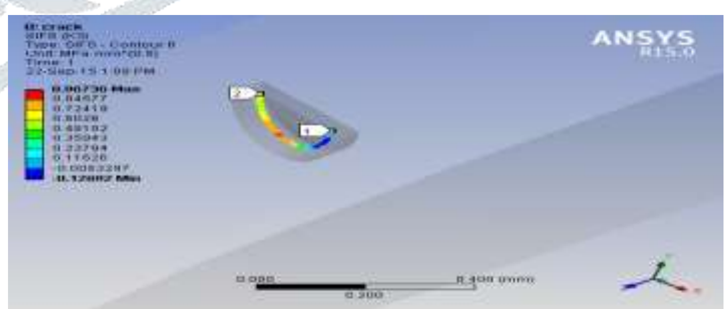
➢ **Crack depth – 0.1 mm**



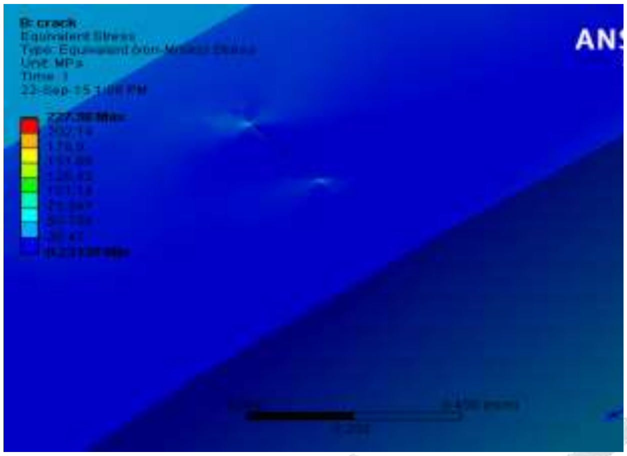
Figure– K1 variation



Figure– K2 variation



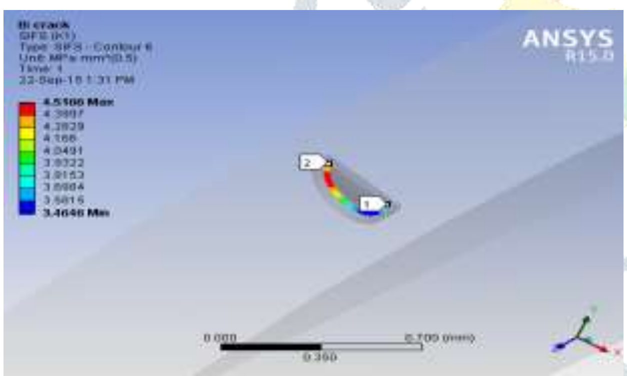
Figure– K3 variation



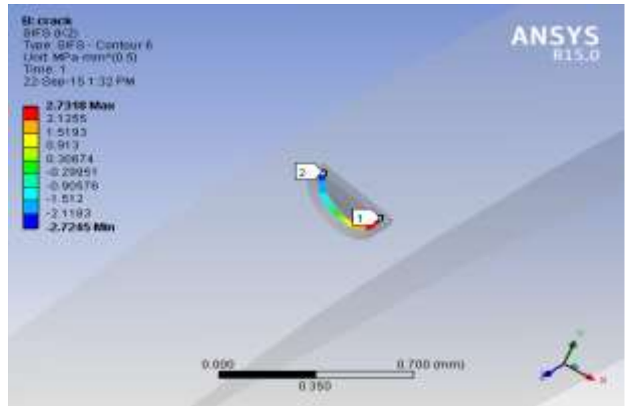
Figure– Von Misses stress variation

- **Crack 0.15 mm**

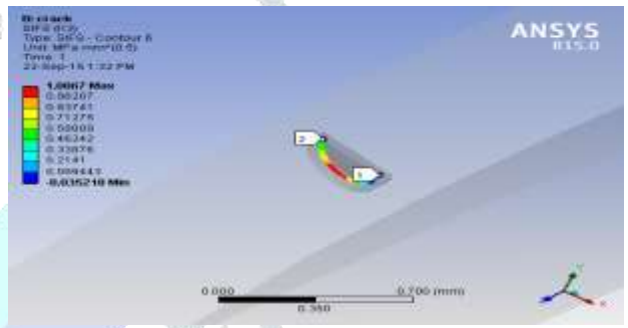
Figure 5.15 to Figure 5.17 and Figure 5.18 shows the stress intensity and Von- Misses stress variation with respect to crack length respectively.



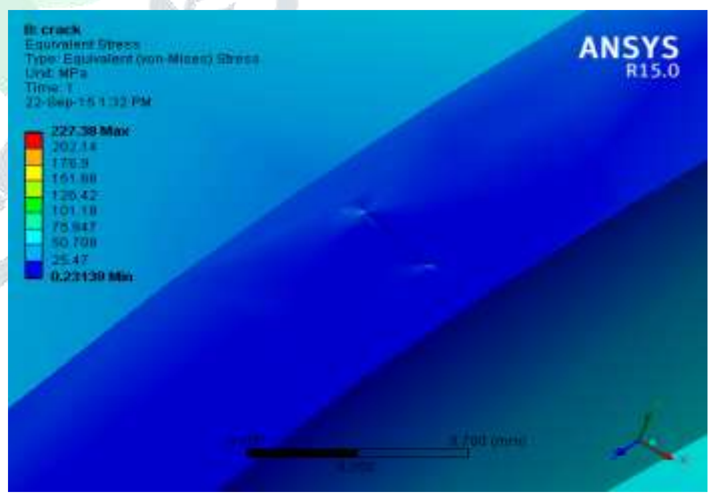
Figure– K1 variation



Figure– K2 variation



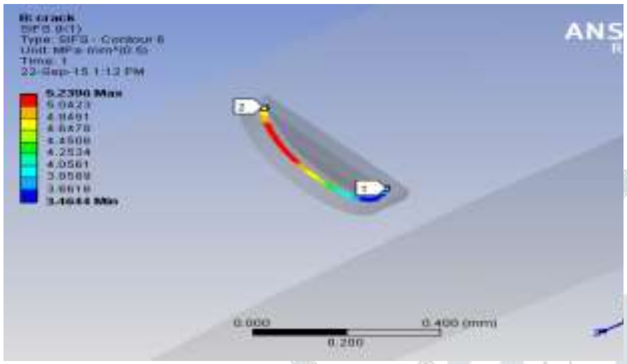
Figure– K1 variation



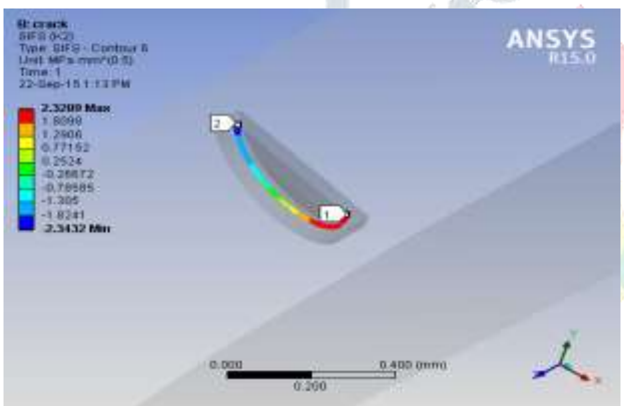
Figure– Von Misses stress variation

- **Crack 0. 2 mm**

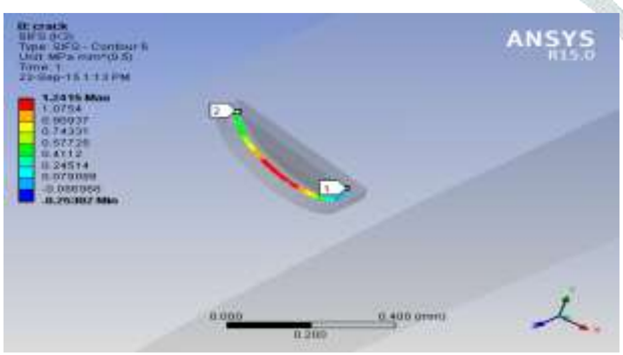
Figure 5.19 to Figure 5.21 and Figure 5.22 shows the stress intensity and Von- Misses stress variation with respect to crack length respectively.



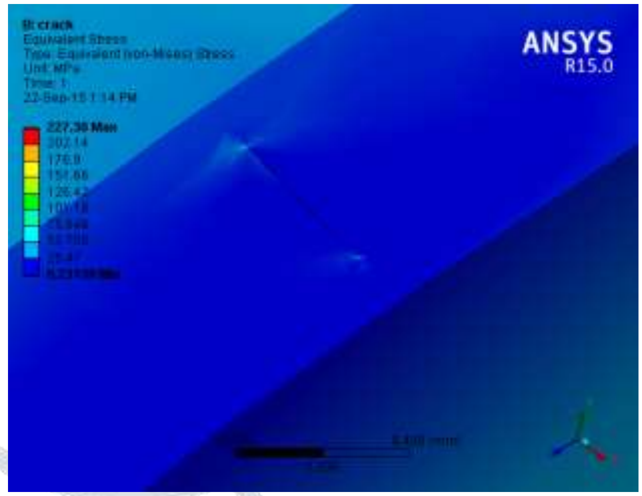
Figure– K1 variation



Figure– K2 variation



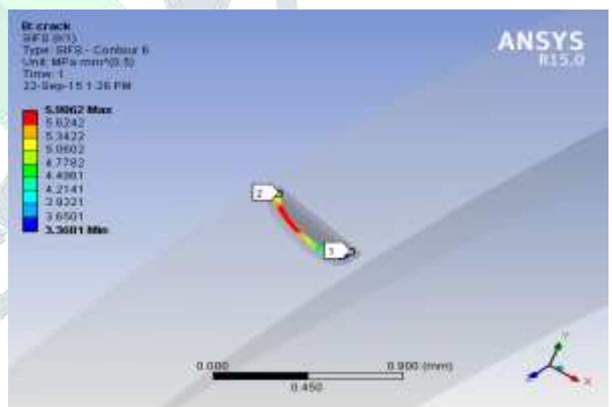
Figure– K3 variation



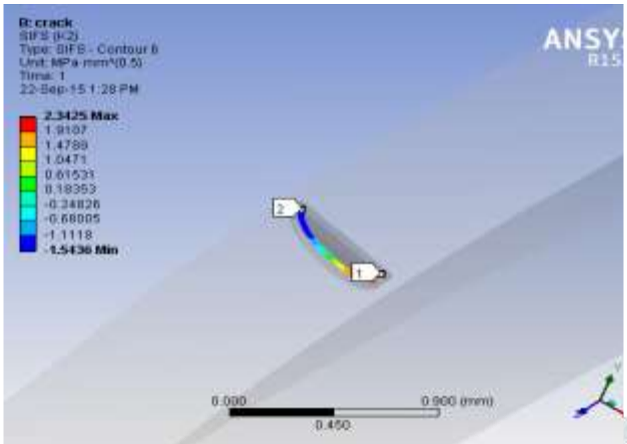
Figure– Von Misses stress variation

- **Crack 0.25 mm**

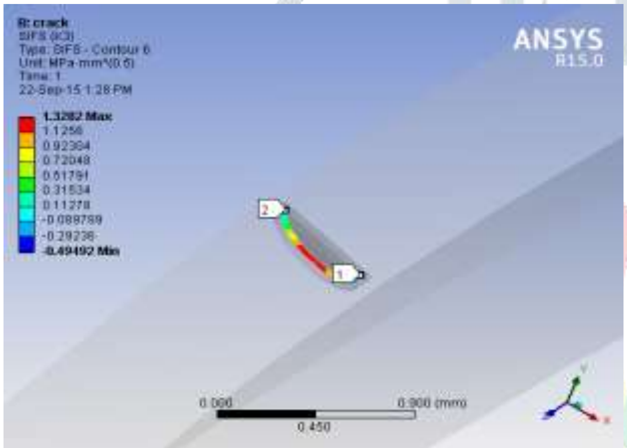
Figure 5.23 to Figure 5.25 and Figure 5.26 shows the stress intensity and Von- Misses stress variation with respect to crack length respectively.



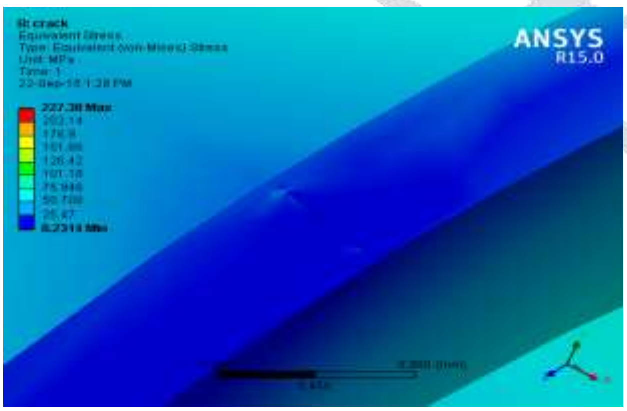
Figure– K1 variation



Figure– K2 variation



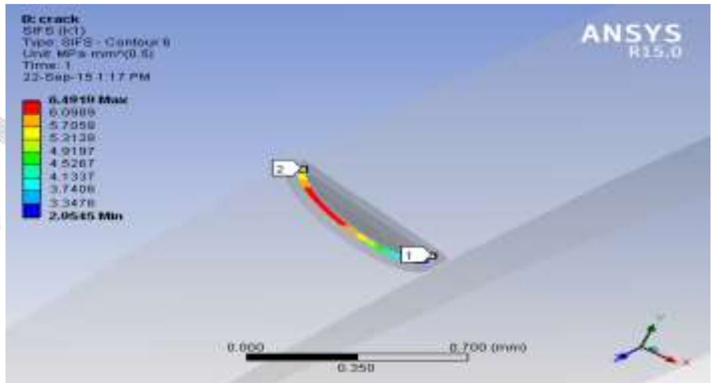
Figure– K3 variation



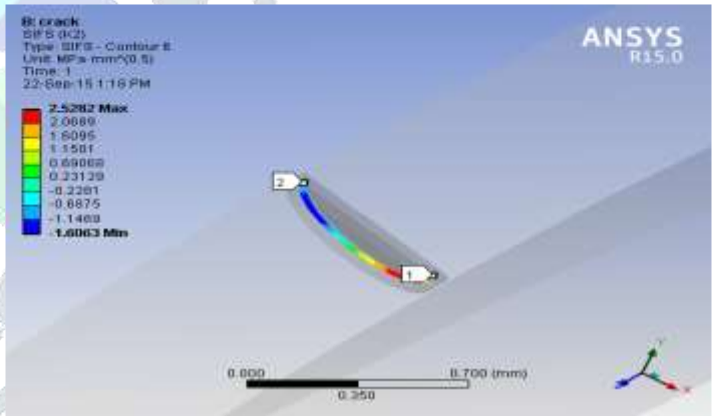
Figure– Von Misses stress variation

➢ **Crack 0.3 mm**

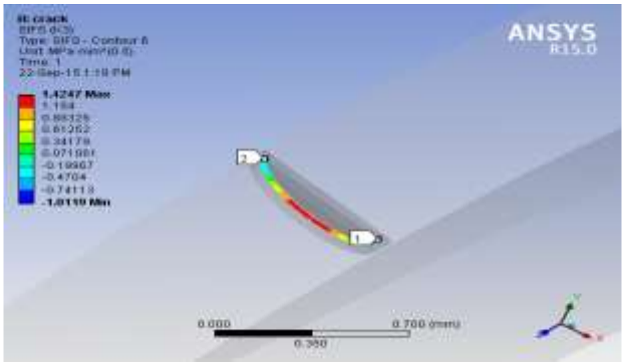
Figure 5.27 to Figure 5.29 and Figure 5.30 shows the stress intensity and Von- Misses stress variation with respect to crack length respectively.



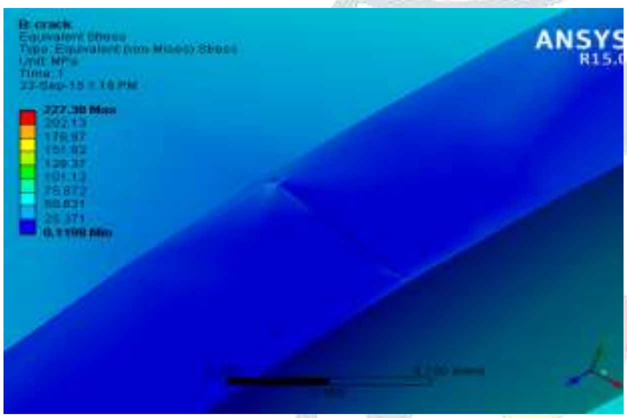
Figure– K1 variation



Figure– K2 variation



Figure– K2 variation



Figure– Von Misses stress variation

CONCLUSION

In the current investigation fracture analysis for compressor of turbo expander is done.

Below are the lists of observation from current analysis.

- First Natural Frequency for blade is found out to be 760.18 Hz which when validated with "L. Witek / Engineering Failure Analysis 16 (2009) 2163–2170" Table No.1 gives acceptable Error of 1.8 %.
- The maximum deflection for compressor is 0.059 mm at outer circumference.
- The maximum Von Misses stress is found out to be 227.38 Mpa near the hub of compressor.

Fracture Analysis

- K1 increases as crack length increases.
- K2 and K3 has negligible effect with crack length.
- Von Misses stress decreases in the crack vicinity as crack length increases.
- Stress Intensity decreases in the crack vicinity as the crack length increases

Future Scope

Current project can be very helpful to the design engineer of turbo expander, which is used mostly for cryogenic application. The analysis will be very helpful to the engineering society of world to analyze, design and fabricate small turbo machinery using ANSYS.

Below is the list of future scopes for the project:

1. All components of turbo expander namely rotor, compressor and expansion turbine can be combined together and a detail analysis can be done to study the critical areas using ANSYS.
2. An analytical analysis of high speed rotor, compressor and expansion turbine using Finite Element Method can be done and compared with the result obtained from the ANSYS software.
3. Bearings for such high speed turbo machines are critical parts, so analysis of bearings are needed to complete design of turbo machines.

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