

ORIGINAL RESEARCH PAPER

Stress Concentration and Fatigue Crack Propagation at the Fir-Tree Root of Gas Turbine Disks Caused by Interconnection Tube Failure between Blades

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Abstract

Industrial gas turbine blades operate under severe thermo-mechanical conditions such as high temperature, corrosion, erosion, and cyclic loading, which make them highly prone to stress concentration and fatigue failure. This study investigates the failure mechanism of the interconnection tube connecting the first-stage blades of a gas turbine used in the oil industry. A combined experimental and numerical approach was employed, including hardness testing, chemical and structural analyses, visual inspection, macro- and micro-fractography, and finite element modeling. Fractographic analysis revealed clear fatigue striations on the fracture surface of the interconnection tube, confirming a fatigue-induced failure initiated at corrosion pits and eroded regions. The finite element results showed severe stress concentration at the fir-tree root region of the turbine disk, coinciding with the actual fracture zone observed in the failed component. Failure of the interconnection tube increased the transmitted stress to adjacent blades and led to an approximately 22% reduction in the fatigue safety factor at the fir-tree root, as determined by Goodman diagram analysis. The strong correlation between numerical and experimental results confirms that stress concentration, combined with corrosion, erosion, and vibration effects, plays a dominant role in accelerating fatigue crack initiation and reducing the structural reliability of the rotor assembly.

1. Introduction

Currently, aero-derivative gas turbines can stand a thermal efficiency of 25% higher than industrial gas turbines. This leads to a 3% increase in the total thermal efficiency of the plant. Aero-derivative gas turbines appear to be a good choice to decrease greenhouse gases. The disadvantages of these turbines are maintenance costs and less reliability compared to industrial

gas turbines. However, over time and with increased number of turbines in operation, the maintenance costs and reliability can be improved [1].

Key safety elements like the blades of a turbine need routine checks to ensure the system's safe operation. Gas turbines must undergo shut-down and start-up operation (start-stop cycles) to meet the fluctuating demand. The immense centripetal acceleration of the blades in operation and shut down causes heavy cyclic

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stress at localized areas of concentrated stress like fire-tree root fillets. The nucleation of cracks also happens at surface defects like voids (e.g., corrosion pits), inclusions, scratches developed by machining marks, and other macroscopic or microscopic specifications[2]. The multi-packet bladed disk's fatigue life characteristics are a higher level of complexity compared to a bladed disk that does not have bladed packets, which is a significant field of studies [3-6].

Holst [7] performed the first analysis of group blade dynamics through lumped-parameter modeling of blades using shroud connections modeled as spring elements. The response of forced vibration was obtained through the Holzer method. Turbine defects are caused by the degradation of materials because of unstable harmonics, flow, imperfections in the minimum throat, and so on [8]. The low pressure blades are the key elements of all types of turbines and have a key role in the power generation [9]. These blades suffer damages in operation and these damages change the stiffness of blade-packet assembly and the modal spectrum, which may bring it close to a possible resonance condition. The problem of fatigue fracture of pocket blades of the low pressure turbine was described by Tsai [10], Kubiak et al.[11], Poursaiedi et al.[12], Bhagi et al.[13], Rodríguez et al.[14], Chatterjee and Kotambkar [15], Saxena et al.[16], Segura et al.[17], Rivaz et al.[18], Sameezadeh et al.[19]. Indeed, it is imperative to prolong the service life of these parts given the heavy cost of producing or repairing and the losses caused by the shutdown of the power generation system. As to the damage and the reasons, fatigue is the most common mechanism of failure due to cyclic stresses [20]. In addition, due to the high working condition and exposure to corrosive materials, the mechanism of fatigue is usually mixed with tearing and corrosion which intensifies the rate of crack formation and propagation[21]. Das et al. [22] studied the damage in a 220MW low pressure steam turbine blade of 410 stainless steel. They reported that the failure happened on the airfoil of the blade. Analyses of the microstructure of the airfoil region indicated that Si caused very small voids. In addition, the tests on the holes and notches in these regions indicated the presence of chloride as the key factor in corrosion and initiation of cracks.

The primary aim of this study is to identify and analyze the root causes of failure in the interconnection tube connecting the first-stage blades of an industrial gas turbine after approximately 40,000 hours of operation. Unlike previous works that mainly focused on individual blade or disk failures, the present investigation concentrates on the degradation and fracture behavior of the inter-blade connection tube and its consequential impact on the fir-tree root region of the turbine disk. The novelty of this study lies in combining experimental characterization (hardness testing, chemical and structural analysis, macro- and

micro-fractography) with finite element stress analysis to establish a clear correlation between erosion-corrosion damage, stress concentration zones, and fatigue crack initiation. Through this integrated approach, the study quantitatively demonstrates how interconnection tube failure intensifies stress at the fir-tree root, leading to premature fatigue crack propagation and a significant reduction in the fatigue safety factor compared to the original design expectations.

2. Background

A gas turbine converts the thermal and kinetic energy of hot gases into mechanical rotational power, commonly referred to as brake horsepower. In configurations where the power turbine is mechanically coupled to the gas generator through a transition duct, the power turbine expands the combustion products exiting the gas generator over one or two stages, thereby extracting the remaining available gas energy before discharge to the exhaust system.

The generated shaft power is transmitted to the driven equipment through mechanical couplings. Fig. 1 illustrates a cross-sectional view of a 15 MW industrial gas turbine package employed to drive a centrifugal pipeline booster for natural gas compression. In this configuration, the exhaust gas from the hot section of the gas generator serves as the working fluid for the power turbine, with an inlet temperature of approximately 600 °C.

Fig. 2 presents the general assembly of the power turbine considered in this study. The power turbine consists of two stages, each comprising 42 blades. The first-stage blades are interconnected via an interconnection tube and arranged into six groups of six blades and two groups of five blades. The blade roots are of fir-tree type, designed to accommodate the high centrifugal and thermal loads encountered during operation.

The nominal rotational speed of the power turbine is 4960 rpm, with a maximum continuous operating speed of 5200rpm. The defined overspeed condition corresponds to 5500rpm. According to the original equipment manufacturer (OEM) specifications, the first-stage turbine blades are manufactured from the nickel-based super alloy Waspaloy, while the interconnection tube is made of IN718. The operating conditions of the power turbine include a typical metal temperature of approximately 550 °C, an operating pressure of about 0.2 bar, and a rotational speed range between 4900 and 5200rpm.

During the overhaul of the power turbine rotor, a defect was identified in the interconnection tube associated with one of the six-blade groups. The blade selected for detailed evaluation has an overall length of 250 mm. An initial macroscopic assessment of the

failed interconnection tube was conducted by means of systematic visual inspection and photographic documentation. The fractured interconnection tube is presented in Fig. 3. The damage was confined to the six-blade group and was specifically located at the left and right sides of the fifth blade within this group. No other visible damage was observed in the remaining blade groups at this stage of the inspection.

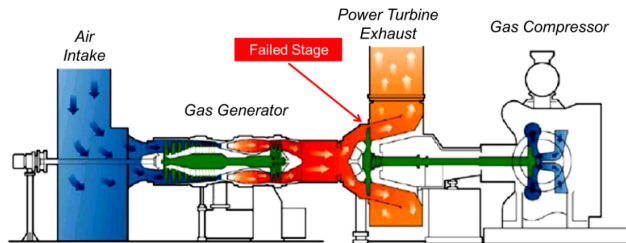


Fig. 1. Gas turbine and power turbine schematic.



Fig. 2. View of an undamaged power turbine.

3. Numerical Simulation

Given the findings based on fractographic inspection which supported erosion and corrosion signs and fatigue beach marks, the finite element analysis was carried out on the blade groups to identify the critical regions.

The computational mechanics procedure used in this work consisted of digitizing a single blade to obtain a file with the geometric dimensions and building

a solid CAD model of the blade. The 3D assembly of group blades, disk, and interconnection tube was converted to a FEM. The modeling process is shown in Fig. 4. 10-Node quadratic tetrahedron (solid 187) elements were employed to mesh the model. Then, the key mechanical properties were defined in the software according to Table 1.

When a crack initiates on a metal surface, it expands beyond a specific size to become a fully formed crack. Once a crack is formed, its propagation is a function of the external stress. Thus, when a crack starts to form and a large enough cyclic tensile load is induced to propagate the crack in the metal, the final rupture becomes inevitable. The main reason for the failure is determined through how and where the crack is initiated and nucleated.

ANSYS was used to obtain the bending stress caused by the pressure profile on the airfoil and the tensile stress caused by centrifugal force while rotating.

The reason for using static stress analysis was to determine how tensile stress forms on the fractured surface where crack is formed. The majority of this tensile stress is due to centrifugal load. Fig. 6 indicates equivalent von Mises stress distribution while group blades are connected to the interconnection tube. Clearly, the highest stress of 686 MPa is less than the yield strength IN718 (Table 1). Therefore, the system can sustain the forces under static conditions with no major crack.

In the area of stress concentration, despite the presence of holes, microcracks are created under the effect of gas pressure fluctuations, and these microcracks gradually grow. It can be concluded from Fig. 7 that the tube failure occurs first at location A and then at location B from the end of the blade. The reason why the stress value is higher at the ends of the tube is that the end blade is more deformed than other blades under the effect of centrifugal force and gas pressure.

Fig. 8 shows the subsequent damage observed on the power turbine rotor assembly after the interconnection tube failure. As shown in Fig. 8a, fatigue fracture occurred at the fir-tree root of the first-stage disk due to increased stress concentration and vibration amplitude following the disconnection of the inter-blade tube. Fig. 8b presents severe blade tip rubbing against the casing, resulting from excessive radial displacement and unbalanced vibration. In Fig. 8c, contact marks and wear are visible on the labyrinth seals on the shaft, indicating axial and radial misalignment during operation. Finally, Fig. 8d shows metal-to-metal contact at the journal bearing seating area caused by shaft vibration and loss of oil film integrity. These cumulative damages confirm the propagation of stress concentration effects throughout the rotor assembly after the interconnection tube failure.

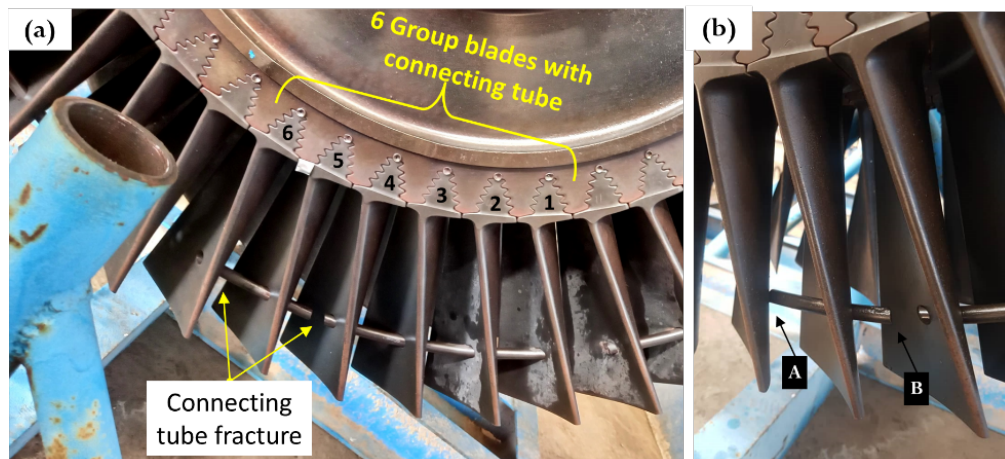


Fig. 3. Photographs showing the positions which a) interconnection tube is failed. b) Location A and Location B.

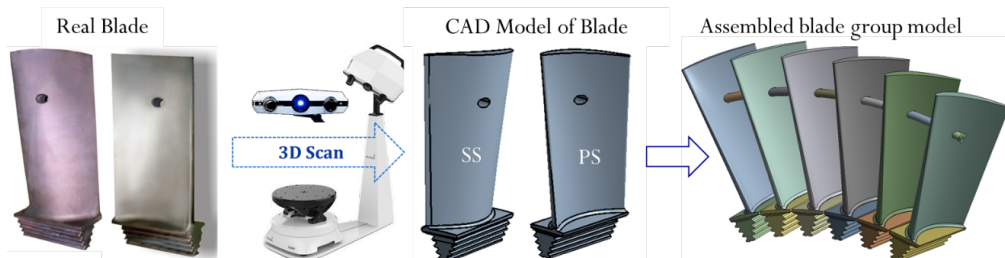


Fig. 4. 3D scanning procedure of the blade and assembly group blade with interconnection tube.

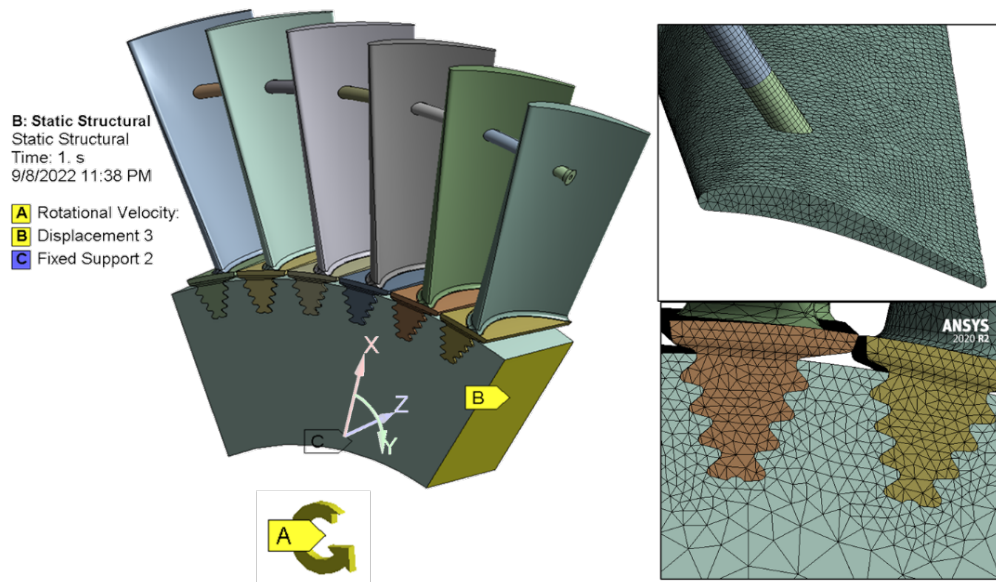


Fig. 5. Boundary condition and group blade meshing.

Table 1
Mechanical properties of Blade and Tube at room and operating temperatures.

Materials	Temperature [°C]	Elastic Modulus [GPa]	Density [g/cm ³]	Yield strength [MPa]	Ultimate strength [MPa]	% Elongation
Waspaloy [Blade]	21 650	211 171	8.19	1076 980	1441 1358	27 22
IN718 [Tube]	21 650	208 162	8.22	1172 1027	1407 1158	21 19

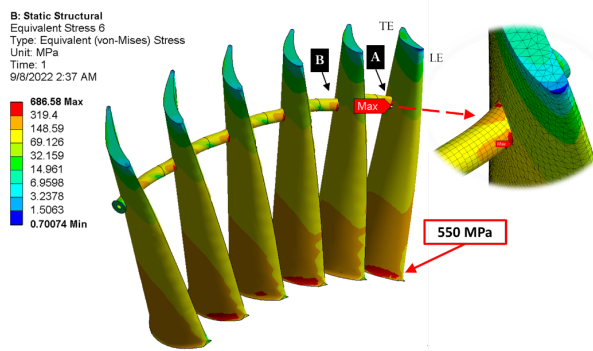


Fig. 6. Distribution of von-misses stress of the group blades under static loads.

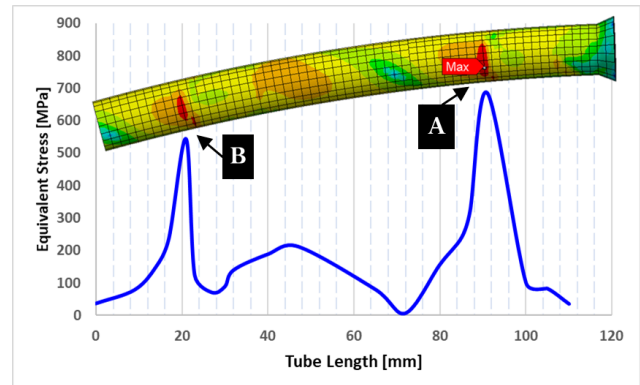


Fig. 7. Equivalent Von-Mises stress curves due to the static loads at the tube section vs. the tube length.

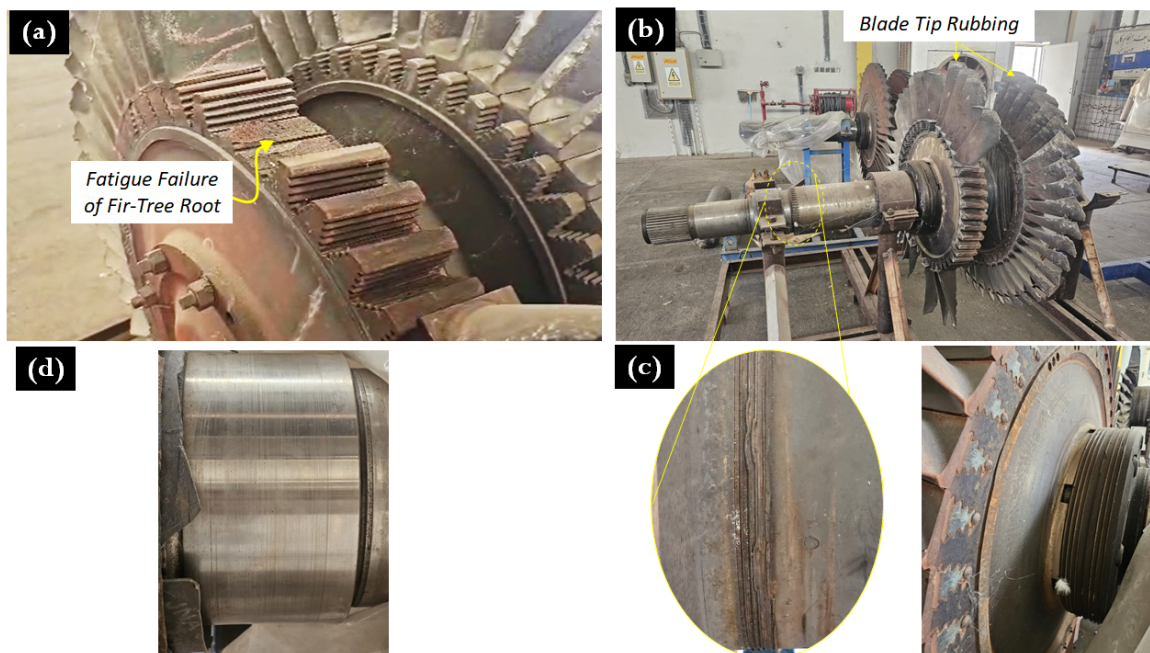


Fig. 8. Visual evidence of secondary damage after interconnection tube failure.

Fig. 8a illustrates the actual fatigue failure observed in the fir-tree root of the first-stage gas turbine rotor. The fracture occurred precisely at the contact region between the blade root and the disk, where cyclic loading and fretting stresses are concentrated. The visual evidence of material separation and surface oxidation indicates a long-term fatigue propagation rather than an instantaneous overload failure. The observed crack location in the failed fir-tree groove shows strong agreement with the stress concentration zone predicted in the finite element simulation (Fig. 9), confirming that the numerically identified high-stress region corresponds to the real fracture site on the disk. This correlation validates the accuracy of the FEM model and emphasizes the dominant role of stress concentration in initiating fatigue failure at the fir-tree root under combined mechanical and vibratory loading conditions.

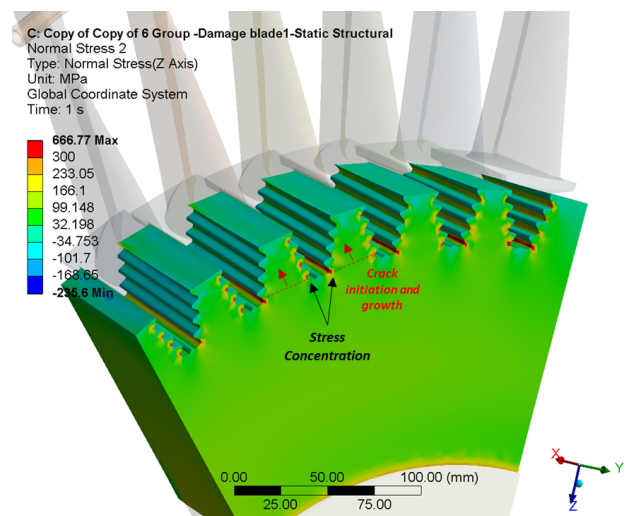


Fig. 9. Stress concentration on the turbine disk.

4. Conclusion

The failure analysis of the interconnection tube between the first-stage blades of an industrial gas turbine was conducted through detailed experimental and numerical investigations. The blades and interconnection tube were made of Waspaloy and IN718, respectively—both nickel-based superalloys. Several analytical methods, including chemical composition analysis, hardness measurement, and fractographic examinations, were employed to identify the dominant failure mechanisms. The main findings are summarized as follows:

- 1) The failure originated from surface degradation caused by erosion due to high-velocity gas impingement, which initiated localized pitting on the tube surface.
- 2) The presence of chloride ions and silicon oxides in the combustion environment accelerated corrosion, leading to the formation and growth of corrosion pits that acted as stress raisers.
- 3) Crack initiation occurred precisely at the stress concentration region identified in the finite element model, confirming that local stress intensification played a critical role in fatigue crack initiation and propagation.

In summary, the study demonstrates that stress concentration and surface degradation mechanisms, aggravated by environmental and vibratory effects, are the primary factors governing the fatigue failure of the interconnection tube and the subsequent damage to the fir-tree root in gas turbine blades.

Acknowledgments

The authors declare no conflict of interest.

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