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Fatigue crack growth simulation in a first stage of compressor blade

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ABSTRACT

A first-stage rotary compressor blade of a Model GE-F6 gas turbine failed due to vibration in early March 2008. Initial investigations showed that pitting on the pressure side of the blade caused micro cracks, leading to larger cracks due to high cycle fatigue. To assess this failure, a series of experimental, numerical, and analytical analyses were conducted. Fractography of the fractured surface of the blade indicated that two semi-elliptical cracks incorporated and formed a single crack. In this study, static and dynamic stress analyses were performed in Abaqus software. Moreover, fracture mechanics criterion was accomplished to simulate fatigue crack growth. This was carried out using a fracture analysis code for 3-dimensional problems (Franc3D) in two states. Firstly, stress intensity factors (SIFs) for one semi-elliptical surface crack and then SIFs for two semi-elliptical surface cracks were taken into account. Finally, the Paris and Forman–Newman–De Koning models were used to predict fatigue life. Since stress level and crack shape in both conditions are the same and the SIF at the crack tip reaches the fracture toughness of the blade, SIFs results indicate that insertion of a second crack has no effect on the final SIF, however, the second crack facilitates the process of reaching the critical length. So, fatigue life in two-crack condition is less than in the one-crack state.

1. Introduction

A gas turbine is a type of internal combustion engine that has an upstream rotating compressor coupled to a downstream turbine, and a combustion chamber in-between. A compressor is one of the main components of the gas turbine. The main role of the compressor is to compress air, which is used in the combustion process. The blade and disc of the compressor work mostly in low temperatures and are subjected to high rotational velocity, which causes large centrifugal forces in discs and blades. During permanent work of the engine in the corrosion and erosion environment, the first component that can suffer damaged is the compressor blade [1]. Corrosion of compressor blades occurs when moisture containing salts and acid collects on the parts. During operation, the humid air may be condensed at the compressor inlet [2]. Compressor blades mainly fail due to the initiation and propagation of fatigue cracks. The initiation of fatigue cracks in blades is greatly influenced by surface defects in the form of nonmetallic inclusions, corrosion pits, and dents [3]. High speed rotating compressor components are susceptible to many types of problems. One of the problems is failure due to high cycle fatigue (HCF). HCF is the fatigue of rotating components generally brought on by dynamic forces caused by vibration. HCF is always concerned

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with rotation of an unbalanced shaft or compressor/turbine disc. Moreover, the HCF condition also occurs during passing of blades by the non-uniform stream of air produced by the blade cascade [4]. A review of previous blade analysis papers implies a serious problem in different types of blades, for example, erosion, stress corrosion cracking (SCC), fretting fatigue, and HCF.

Murakami and Nemat-Nasser [5] found that crack tip stress was greater where cracks are deeper.

Heath and Grandt [6] investigated planner cracks interaction. Results showed that interaction effects increased by decreasing of distance between cracks and the coalescence effect in accordance with the ratio of crack length and coalescence depth.

Lin and Smith [7] assessed a number of planner cracks on a plane exposed to tension and bending. They analyzed crack growth behavior during three steps of growth, pre-coalescence, coalescence, and post-coalescence, by integrating the Paris model equation.

Barlow and Chandra [8] analyzed fatigue crack growth (FCG) in the generator fan blade of an aero engine. Their crack growth simulation was done in Franc3D and assessed all fracture modes.

Shokrieh and Rafiee [9] performed a series of experimental and numerical analysis on rotor fan blades in a wind turbine. They concluded that the blades fractured due to fatigue mechanisms. Also, they performed a finite element analysis and realized that cracks nucleated at the maximum stress region.

Poursaeidi and Salavatian [10,11] showed that the rotor fan blade failed due to the HCF mechanism. They did a series of experimental, numerical, and analytical analyses to identify stresses on blades and revealed that bending stresses due to resonance in the first mode of vibration caused this failure. Also, they simulated FCG in Franc3D and assessed the fatigue life of blade.

Witek [12,13] analyzed the stress state of the blade without defects and also with V-notches during the first mode of transverse vibration. He showed that the life mainly depends on both blade vibration amplitude and radius of the notch. Also, he was used a dual boundary element method to calculate SIF of semi-elliptical crack in the blade.

Poursaeidi et al. [14,15] presented an experimental and numerical analysis to investigate failure analysis of an axial compressor first row rotating blades. They showed that the blade failed due to HCF. Also, they evaluated effects of natural frequencies on this failure and concluded that the resonance of the blade under the first and second natural frequency modes is the primary reason for the fatigue fractures of the blade.

Following of last paper of first author [15], this manuscript simulates the fatigue crack growth in the blade by numerical method and a simplified analytical model. The first part of this manuscript investigates the fracture surface and fatigue phenomenon with concentration on finding the initial crack shape and size. Then briefly, reviews the stress analysis that needed for modeling of crack growth.

In the second part of this manuscript, the FCG is modeled in Franc3D for two states, one-crack and two-crack. For both states, the blade life has been calculated by Paris model equation [16,17] and Forman–Newman–De Koning (FNK) model equation [18] under analyzed stress. Moreover, calculation of the mode I SIFs (K_I) by a simplified analytic model has been done.

Various criteria to govern the direction and growth rates of cracks in mixed-mode situation have been developed. Some of these criteria are the maximum tangential stress criterion, the maximum energy release rate criterion, the minimum strain energy density criterion, the vanishing mode II SIF ($K_{II} = 0$) on the crack extension criterion, the maximum stress triaxiality criterion, etc. [19]. Since the mode II SIF (K_{II}) can be neglected in comparison with the mode I SIF (K_I), so maximum tangential stress criterion has been selected in this simulation.

2. Fractography

Initial observations of fractured surfaces showed that the crack nucleated on the pressure side and extended to the trailing edge, causing separation of the upper half of the blade. When crack length achieves critical size, leads to a rupture of that part. The blade had worked for 30,895 h before failure. Airfoil in the leading edge shows fatigue signs (Fig. 1a). As shown in Fig. 1a, final fracture has occurred in a plane with the angle of 45° which is the plane of maximum shear stress. Hence, in the final fracture area, shear stress is dominated. Collision between the upper half and final fracture area is shown in Fig. 1a. The fracture occurred at approximately 62 mm from the hub (Fig. 7). The material of the blade is AISI Custom 450, also called GTD-450 [15]. A chemical analysis by a scanning electron microscope (SEM) revealed that sulfur, sodium, and chlorine existed in the pitting sites. Fig. 1b shows that two semi-elliptical cracks are recognized and implies that the cracks extended from two different co-directional crack fronts. Also, beach marks are evident in this figure. Fig. 2 shows the striations in the middle section of the large semi-elliptical crack.

3. Finite element stress analysis

In order to investigate the failure analysis and prevent similar occurrence, a stress analysis of the blade was performed. To reach this aim, finite element analysis of the blade was done in Abaqus software. Because fillet with small radius existed on the blade, a quadratic tetrahedron element that has 10 nodes (C3D10) was used in this analysis (Fig. 3a). The blade has a rigid joint on its root, therefore, displacement and rotation of the blade root was constrained in all directions. According to the