CHAPTER 1

INTRODUCTION

Many structural components throughout industry fall in a class that is capital intensive, has high safety risks and has high reliability expectations. In cases where the integrity of such a component is at risk, the risk has to be evaluated by analysis and theoretical predictions with regard to structural degradation. Once the risk is evaluated, a decision can be made on the future use of the component.

The quality of solutions is very important when theoretical assessment studies are performed, because errors can be costly in terms of capital and human life. Where exact details like material properties and system loads are not available, the analyst is forced to revert to a conservative approach. Some conservatism can be removed through refined analysis, provided the underlying theoretical approach is justified and well understood by the analyst.

Most structural degradation mechanisms like stress corrosion cracking (SCC), fatigue, high temperature creep, manufacturing anomalies etc. eventually manifest in the form of propagating cracks. The presence and propagation of a crack impose increasing constraints on the material. When the crack reaches a critical dimension, the material can no longer withstand the loads and the component will fail.

Fracture mechanics deals with the analysis of cracked structures. The theory of fracture mechanics is strongly based on the theory of elasticity. Many empirical solutions to simple problems have been derived by researchers for general use. General application of empirical solutions requires simplification of the actual problem to match the empirical basis, often leading to uncertainty in the accuracy.

Exact solutions can be obtained by application specific analysis, but due to complexity, rely heavily on numerical analysis. It is of paramount importance that the analyst has a thorough understanding of the theory of elasticity, fracture mechanics and its application through numerical methods to understand its integrated application and the inherent potential errors.

This dissertation explores the theory of elasticity, the development of fracture mechanics and its application through the finite element method with the aim of defining limitations and errors in its general application. The methods are then used in a case study of transverse cracking in a large steam turbine spindle.

This chapter gives a general perspective on steam turbines, with specific reference to the case study. The research objectives are listed, in the context of the case study to restrict the relevant theoretical fields to the problem at hand.

1.1. STEAM TURBINES

Steam turbines are critical components in the power generation industry. Catastrophic failure of turbine shafts is associated with the destruction of the surrounding plant at very high costs and risk to human life. For this reason, the safe operation of steam turbines must be ensured at all times.

Steam turbines suffer from a number of degradation mechanisms including low cycle fatigue, creep, stress corrosion cracking etc [P1,T1]. Initiation of cracks can never be ruled out, but turbines are designed to be resistant to high cycle fatigue. If the primary crack growth mechanism is slow, the cracks will be detected during routine maintenance by non-destructive testing (NDT) so that corrective action can be taken before crack growth moves into a high cycle fatigue regime.

Only a few incidences of catastrophic rotor bursts occurred in the history of power generation [P1]. Incidences of cracking are higher, but still surprisingly low considering the number of rotors in operation. Several rotors are retired annually to forestall the possibility of catastrophic failure, usually on recommendation from the manufacturer. It is important that utilities obtain adequate knowledge of the factors influencing the remaining life of critical components to protect their capital investments.

Another safeguard against catastrophic failure is vibration monitoring. The presence of a crack causes an imbalance in the rotor stiffness, resulting in changes in the dynamics of the rotor. The presence of a crack is detected by changes in the vibration characteristics as measured on the bearing housings.

In spite of the industry experience that rotor bursts do not readily occur, a rotor with an incipient crack cannot automatically be assumed to comply to the general case. Safety of operation must be demonstrated by justifiable analysis techniques for the short and long term operation of the component.

1.2. PROBLEM DESCRIPTION

A specific incidence of transverse cracking in a turbine rotor occurred in the Eskom fleet [U1]. The problem is regenerated for the purposes of this study with the exclusion of information relating to the identity of operators and equipment manufacturers, the specifics of which can be obtained from reference U1.

This aim of the case study is to apply fracture mechanics to a low pressure (LP) turbine, with shrunk on disks, to predict the crack growth behaviour of transverse cracks. Transverse cracks develop mainly on the surface of rotors with shrunk on disks [P1]. The results and methodologies can be used to avoid failure of turbine shafts and to derive life extension strategies.

The rotors are of a typical dual flow LP turbine design with shrunk on blade carrier disks. Figure 1.1 shows a layout of the turbine construction. The turbine has a shrunk on centre ring that is keyed to the shaft with 3 equally spaced axial keys as shown in figure 1.2. The disks are in turn keyed to the centre ring, and to each other, by axial drive pins.

The LPs are connected in a 5 shaft 1000 MW generation train consisting of HP, LP1, LP2, LP3 and the generator rotors in that order. The LP shafts are geometrically identical for all practical purposes. Table 1.1 gives some general parameters of the turbine unit construction.

Power Rating of Unit	1000 MW
Power Rating of LP	231 MW
Operating Speed	1500 rpm
Barring Speed	70 rpm
Operating Time	90000 hr
Barring Time	9557 hr
Assembled Mass	140 ton
Span (Between Bearings)	2.7 m
Nominal Diameter	940 mm
Material	CrMoV

Table 1.1: General turbine parameters

General industry consensus is that the cracks develop by fretting on the edges of the centre ring key, as depicted in figure 1.3 [U1]. This prognosis is also advocated by the original equipment manufacturer (OEM). A number of ultrasonic techniques, including time of flight diffraction through the centre ring shrink fit, were used to confirm the incidence of cracking [U1]. The results indicate a maximum crack depth of 15.6 mm, extending to just below the bottom of the keyway.

Identical rotors in the OEM fleet are in operation with a maximum reported crack of approximately 95 mm in depth [U1]. Local experience is that the cracks initiate, but do not propagate by high cycle fatigue during normal operation.

It is postulated that crack propagation is only active during barring operation. Barring is a period of operation when a unit goes off load. The turbine train is rotated at relatively low speed (70 rpm) to let the disks and couplings settle while the rotor cools down.

If high cycle fatigue occurs during normal operation, it will lead to very rapid crack growth and subsequent failure of the shaft within approximately one month of operation if not detected by vibration monitoring. This is a direct result of the rapid accumulation of cycles. The crack will experience a rapid increase in length, even if the crack extension per cycle is low.

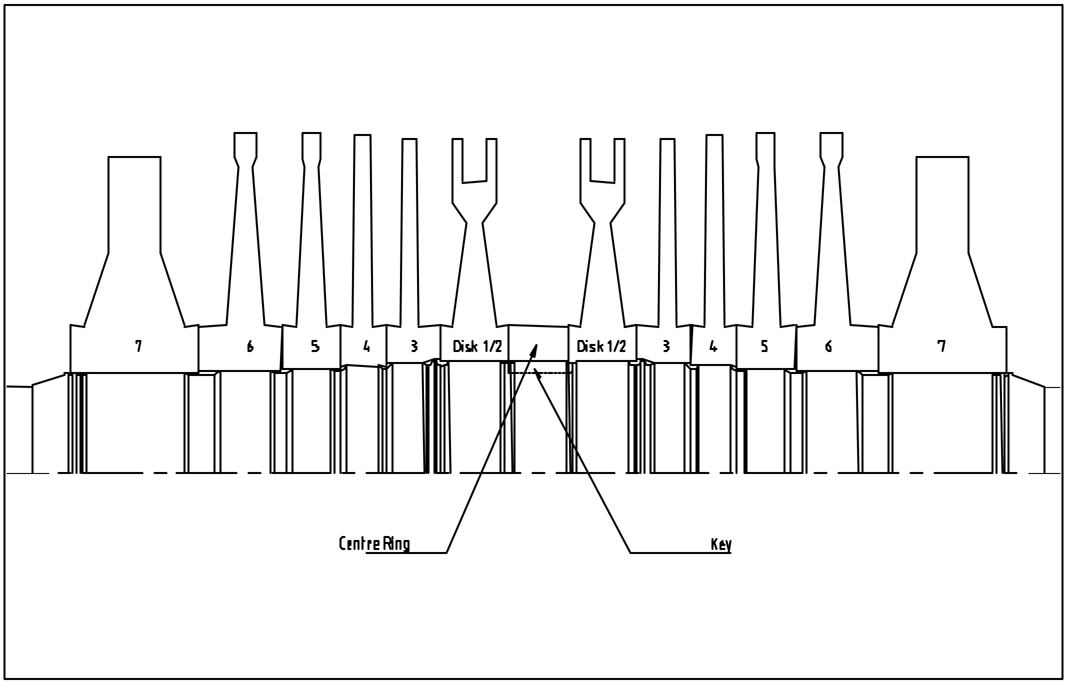

Figure 1.1: LP turbine layout

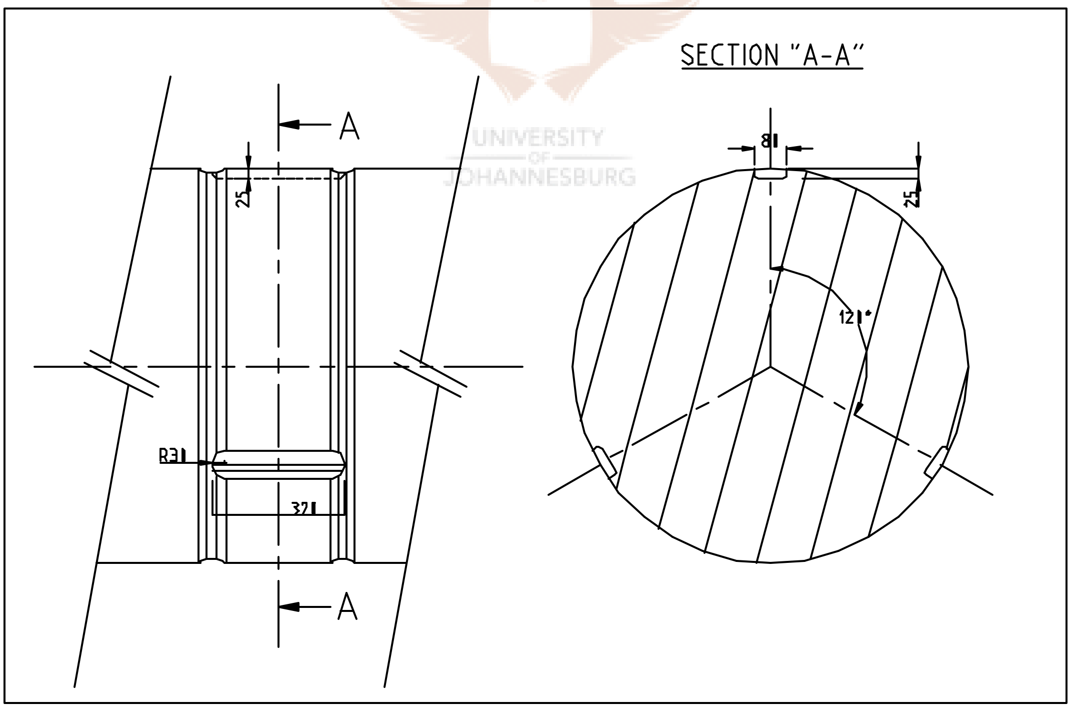

Figure 1.2: Details of key area (dimensions in mm)

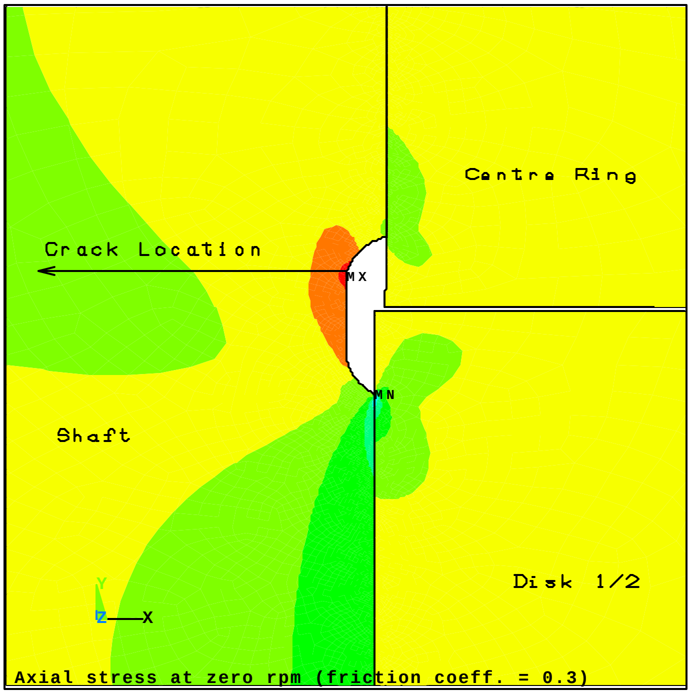

Figure 1.3: Crack Initiation Position (2-D Presentation) showing typical axial stress contours

1.3. RESEARCH OBJECTIVES

The objective is to demonstrate structural integrity assessment through a case study of an LP turbine shaft with transverse cracks. Structural integrity consists of many components including:

- Theoretical predictions of degradation mechanisms i.e. crack growth and fracture in this case.
- Fail safe management of the defected structure i.e. inspection and monitoring.

To this end the theoretical basis of the relevant theory of elasticity, its application to fracture mechanics and the numerical analysis thereof is conveyed as a precursor to the case study. The theoretical survey is followed by a literature survey that focuses on issues relating to the structural integrity assessment of the case at hand, followed by the analysis work and the assessment itself.

The objective is to demonstrate a successful structural integrity assessment of a critical component through the case study at hand. The focus is on critical influencing factors and of particular interest, in this case, are the frictional stress between the shrunk on components and the shaft and multiaxial loading.

1.4. OVERVIEW

Part 2 deals with a survey of the theoretical basis of fracture mechanics and its application through the finite element method (FEA). The aim is to define and evaluate all assumptions and to evaluate the resulting errors and its limitations of application.

Chapter 2 explores the relevant theory of elasticity in sufficient detail to follow the solutions that form the basis of stress intensity, K; an essential parameter in linear elastic fracture mechanics (LEFM). Fracture mechanics is an extension of analytical solutions, obtained from the theory of elasticity. Some insight is provided on the assumptions and restrictions of the analytical solutions.

Chapter 3 deals with fracture mechanics principles and uses the theory of elasticity to explore the influence of assumptions made in the basic solutions describing stress fields in the vicinity of a crack front discontinuity.

Chapter 4 extends the theory of elasticity solutions and the stress intensity solutions to a finite element formulation. Although the convergence behaviour is not explicitly discussed, the author has a demonstrated experience in this field [U1].

Part 3 deals with the structural integrity assessment of transverse cracking in an LP rotor. Although analytical prediction of the crack growth behaviour is the main focus, attention is also given to the fail safe management of the turbine for future use.

Chapter 5 is a literature survey to obtain the industry experience for the case study used. Inspection and monitoring techniques are explored in some detail. Chapter 5 concludes with a detailed survey of the mechanical properties of rotor steel.

Chapter 6 discusses finite element modelling considerations and gives an outline of the strategy followed for the case study. The chapter includes the progression of numerical analysis for the case study and reports the calculated parameters that are required for the assessment.

Chapter 7 deals with the structural integrity assessment. The calculated parameters are interpreted in terms of the material behaviour and predictions are made on the crack growth behaviour.

Chapter 8 is a discussion of the structural integrity assessment and includes potential future work, recommendations relating to the case study and a conclusion.