CHAPTER 8

CONCLUSIONS

The objective of a successful structural integrity was met and the result of the case study favours continued use of the component. A rigourous process was followed to account for most known influencing factors including:

- Calculation methods.
- Industry experience.
- Material properties.
- Mechanical loads.

The outcome of investigating the above proved that it is of vital importance that the analyst is familiar with the calculation methodology to apply it with confidence. Many factors proved critical in the outcome of the assessment.

Incorrect assumptions on material properties or mechanical loads can easily lead to the wrong conclusions. The influence of the frictional stress was of particular importance to the case study, but many problems are likely to have their unique load categories that need to be quantified before analysis can be performed and concluded.

Non-destructive testing (NDT) plays an important role in identifying the presence of cracks in a component and quantifying the magnitude thereof. The analysis is in favour of continued use of the component, but shows the potential for crack extension so that future risk still needs to be managed. While NDT can be used to monitor the evolution of the cracks, especially while they are well below the predicted high cycle fatigue limit, on-line monitoring is of paramount importance to prevent the potential of catastrophic failure.

It was also shown that minor changes in the operating parameters will reduce the severity of the problem drastically and have the potential of nullifying the degradation for the rest of the components operating life.

8.1. DISCUSSION

The results of the assessment shows concludes that crack propagation will take place during barring operation, but that short cracks (smaller than the high cycle fatigue threshold) will not propagate during normal operation at 1500 rpm. This is supported by the experience of the OEM who has many identical rotors in operation.

The fatigue threshold is influenced by multiaxial loading and differs from LP to LP depending on the torque that it carries. The fatigue threshold for the rotors are met when the crack sizes are 72, 82 and >100 mm for LP1, LP2 and LP3 respectively.

Frictional force is released during operation. This is deduced by the fact that the inclusion of frictional force in the analysis gives the result that cracks will propagate during normal operation resulting in rapid crack extension and failure which is in contradiction to industry experience. The release of frictional force was also measured and confirmed in an experiment on a similar rotor assembly.

The analysis also shows that, for this case, fracture assessment based on axisymmetric analysis will give incorrect results. The crack opening displacement results in a release of the shrink fit stress and eliminates the mean K_I resulting in changes to the stress ratio. This is also supported by industry experience since a crack would not be able to grow beyond the influence of the stress concentration effect around the key (figure 6.9). 3D finite element analysis confirms that this is the case and that K_I reduces to zero with crack extension, opposed to the 2D analysis that indicates negative values for cracks larger than 30 mm.

While LP3 can tolerate the deepest crack before high cycle fatigue takes place, it has the highest effective stress intensity. This means that LP3 has the smallest critical crack size. A large crack will result in dynamic loading, a fact that is supported by the detectability of cracks by vibration monitoring. Since such dynamic loads are indeterminate a crack cannot be allowed to grow to its critical size for the known static loads. A crack that extends halfway through the rotor was demonstrated, with conservative assumptions with regard to the material toughness, to be well below the critical crack size for fracture.

8.2. RECOMMENDATIONS

The following recommendations are made with regard to the case study:

- The turbines can be returned to service.
- Consult with the OEM to investigate the influence of lowering the barring speed from 70 rpm to 20 rpm and implement the change if feasible. Although no problems can be foreseen for this modification, it cannot be blindly implemented
- Perform additional validation studies to quantify and increase the accuracy of non-destructive testing. Some ultrasonic techniques, like time-of-flight diffraction, have proven to determine the size of cracks accurately. Application of the techniques to the rotor in the case study has some complications because of the long distance from the rotor ends and the influence of shrink interfaces.
- Ensure that appropriate on-line vibration monitoring equipment is installed and that it has crack detection capabilities. The end-user has the responsibility of ensuring plant safety and has to ensure a thorough understanding of the equipment, the crack detection scheme employed and its detection capabilities. First efforts in this regard should already try to detect the presence of the cracks found in the rotors.
- Obtain representative material test pieces and perform multiaxial fatigue tests to verify the material properties under the prevailing environment. The results will play an important role in making structural integrity decisions if further crack extension takes place.
- Non-destructive testing should be performed during each maintenance outage to trend crack extension.
- Crack detection by vibration monitoring is more sensitive in the coast down approach and must be performed every time the rotor train coasts down.

8.3. FUTURE WORK

Some aspects of the assessment are still indeterminate and leave scope for future work. They are:

- Crack front changes during transitions from barring to normal operating speed. It is postulated that the crack propagates during barring operation, but arrests during normal operating speed because of load changes.

  Load changes are associated with a decrease in K_I due to centrifugal lifting of the disk and the introduction of K_{III} as a result of torque. The torque has a branching effect on the crack front which together with crack face interaction effects leads to arrest. This process describes a crack blunting effect.

When the operating mode changes from normal operation to barring, the crack front must go through a phase of sharpening to become an active propagating crack. The opposite is also true so that some crack extension is possible when the operation changes from barring to normal operating speed. Hence the caution and strong requirement for on-line monitoring.

These effects can only be quantified by material testing. Future work in material testing can be performed to simulate load interactions, as discussed above, and environmental effects.

- Assumptions were made with regard to the crack shape. Although the assumptions are based on cracks observed in actual rotors, only the final crack shape is known. It is possible, with the correct models, to also predict the shape into which a crack will grow.

  Such an analysis will required an extensive numerical analysis, recording fracture parameters for each point along the crack front. In practice, the assessment performed in this dissertation must be performed for a number of points along the crack front, the fracture parameters must be extracted, the crack growth must be predicted and the crack shape must be updated. This process must be repeated through the whole range of crack sizes under investigation.

- It was mentioned in chapter 6 that conservative assumptions were made with regard to the bending moments. These stem from the shaft end conditions. The applied bending moment was calculated based on a freely supported shaft under the weight of the rotor. In reality the ends of the shaft are coupled to the rest of the rotor train and are supported in bending.

  Accurate assumptions around the bending moment can only be made if the whole rotor train is modelled. Knowledge about the stiffness of the bearings, the shaft line assembly and the coupling stiffness is required for this.

- A number of studies can be performed to model and quantify the vibration characteristics of a cracked rotor shaft. The model would have to include the full rotor train as discussed in the previous bullet point.

  Of particular interest to the author are the dynamic forces that would be imposed on the bearings by a "breathing" crack. A "breathing" crack would result in additional deflection of the shaft when the crack is at the bottom. This deflection would cause rotation of the shaft ends and should produce a force on the bearings of the adjacent rotors through the lever created by the cracked rotor's bearing supports. When the rotor rotates, the force would be cyclic and may serve as a detection mechanism.