Abstract
Safety critical plant such as turbine blades are exposed to various damage mechanisms including stress corrosion cracking, fatigue and creep. Damage accumulates throughout the life of these components, which manifests as cracking, and has to be managed to ensure safe operation as well as a high level of availability. Life predictions of these components are complicated by large scatter in material properties, variations in operating conditions and complex stress-strain histories. An alternative management strategy is to inspect these components with specifically engineered NDT techniques with high levels of reliability. Part of this approach requires a detailed description and characterisation of all likely cracking that can be expected. This specification is referred to as a flaw specification. Finite element analysis is used to determine locations of highest steady and dynamic stress as well as stress gradients and allowable crack sizes. If available, information generated from relevant failure investigations are used to augment this. This paper describes the typical process followed to generate a flaw specification as well as a case study.

Keywords: Flaw specification, turbine blades, finite element analysis

1. Introduction

With an installed capacity of more than 40GW, state owned South African utility Eskom is globally ranked as one of the 10 largest. At present it generates, transmits and distributes ~95% of the country’s power and ~45% of the power on the African continent. Although the energy mix includes nuclear, hydro, pumped storage, wind and gas the largest contribution (~83%) is from coal fired power stations.

Many of the 81 turbo-generator sets (including 2 nuclear) have reached or are fast approaching design life. To ensure power availability and reliability in a capacity constrained environment, optimum management of aging plant components such as steam turbines are required. Although reliability of steam turbines is generally high and mean time between failures low, consequences of failures can be significant in terms of cost and downtime. Failures can be catastrophic with severe implications for personnel and plant safety and must be avoided at all cost.

As part of the strategy to manage steam turbines, including last stage blades on low pressure (LP) turbines, Eskom has adopted a policy that requires the in-situ inspection of these components by qualified nondestructive testing (NDT) techniques at predetermined intervals to detect and/or monitor the evolution of damage mechanisms. In some cases where no known active damage mechanism has been identified this is done in a proactive mode. Where a damage mechanism has been identified to be active, in-situ inspections are used as part of a specifically developed strategy to manage the damage mechanism in the component to the end of life or until such time that it can be refurbished or replaced.

To ensure a high level of performance and reliability as well as an acceptable false call rate it is a requirement that NDT techniques be qualified. For safety critical components, such as last stage LP turbine blades, the qualification process consist of a technical justification, open trials and blind trials. As part of the technical justification process a detailed flaw specification is required.
The flaw specification provides detail information on the expected flaws as well as the required performance of the NDT technique to be applied.

This paper discusses typical information required in a flaw specification as well as the required performance level of the NDT technique. A case study based on a last stage LP turbine blade is also presented.

2. Degradation of turbine blades and requirement for inspections

Failures of turbine rotating and/or stationary components are generally contained within the casings thereof. In the event of such failures units can be controlled in a predictable manner and brought to rest with consequences being limited to cost and availability, which could be significant none the less. Notable exceptions include failures of last stage LP turbine blades. In these cases catastrophic failures can occur with consequential loss of life and destruction of complete units.

Last stage LP turbine blades, also referred to as L0 blades, have various root designs including axial entry fir tree, pinned fork, inverted T and straddle root. The vibration response of L0 blades has to be controlled to ensure resonance and resultant fatigue cracking does not occur at running speed. Mechanisms used to attain this may include lacing wires, arc bands or integral shrouds. In some cases none of these mechanisms are required and the blades are said to be freestanding. Various blade root designs exist which are used to attached blades to rotors and rotor discs. Two of the most common designs are presented in Figure 1.

![Figure 1: Pinned fork and axial entry fir tree root type designs.](image-url)

The most common damage mechanisms that affect the long term life and structural integrity of last stage LP turbine blades are stress corrosion cracking (SCC) and fatigue. Both of these mechanisms can lead to cracking in the blade roots of L0 blades where the highest steady as well as cyclic stress occurs. Both mechanisms initiate on the root surface, however, these areas are not accessible for direct surface inspection (e.g. Magnetic Testing, MT) during planned outages. Although dis-assembly for direct surface inspection is an option the time required for this operation is significant and will lead to extended outages especially for pinned, inverted T and straddle roots. Axial entry fir tree root design L0 blades are relatively simple to remove depending on the damping mechanism design.

To overcome the time limitations during planned outages whilst adhering to the requirement for inspections, in-situ Ultrasonic Testing (UT) inspections are used in most cases.
3. Inspection technique qualification procedure

Due to the known possibility of the damage mechanisms discussed above to occur in L0 blades and the likely consequential damage in the event of a failure it is policy to inspect these blades during planned outages to detect the presence, or not, of active damage mechanisms. Eskom standards also require all inspection procedures for level 1 components to be qualified. Level 1 components are defined by Eskom as all components with significant replacement cost or that is safety critical or could lead to significant un-availability, amongst others. NDT procedure qualification for these components consist of input data, a technical justification, open trials and blind trials.

A technical justification requires a detailed flaw specification and includes a qualitative and quantitative assessment of the NDT systems (i.e. procedure, equipment and operator) ability to detect and size (if required) the flaws specified. This will require modeling, laboratory studies, assessment of empirical data and practical trials amongst others.

Open trials are conducted to test the capability of the developed procedure and equipment used to detect and size flaws as specified. After an inspection procedure and equipment has been demonstrated to be capable to perform as required then blind trials are conducted to test the capability of individual NDT operators. Final approval, i.e. qualification, of a procedure is attained upon successful completion of these three steps.

Figure 2: Typical NDT procedure qualification process.

4. Turbine blade flaw specification

A flaw specification may be based on empirical failure data i.e. information on actual cracks identified and investigated and/or based on experience with similar blades elsewhere and analysis. The following points are typical information required in a flaw specification but are not considered to be exhaustive.

4.1 Detail description of component

The physical component is described in detail in terms of design type, geometry, dimensions, and material of manufacture. This description must include any relevant modifications as well as the operating experience from the utility fleet and manufacturer. Limits of accessibility that would be experienced during the inspection must be described as this will affect the equipment selection,
procedure design and techniques to be used as well as operator performance during the inspection. Naming conventions to avoid confusion should also be included here.

4.2 Stress analysis

In most cases a linear-elastic 3D finite element analysis is required to calculate steady and cyclic stress distributions in the blade root as well as a modal analysis to determine vibration modes and possible resonance speeds. Results are used to identify local areas of highest steady stress (SCC risk) and cyclic stress (fatigue risk). Results can also be correlated with empirical crack data to confirm areas of high risk that has to be inspected.

4.3 Active and/or expected damage mechanisms

Active and/or expected damage mechanisms for the specific case are identified. Where mechanisms are known to be active further information on the case specific characteristics e.g. position and orientation can be supplied. In cases where no damage mechanisms are known to be active most likely mechanisms and typical characteristics are described.

4.4 Fracture mechanics assessment

Stress intensity calculations are conducted to assess the risk of exceeding SCC and fatigue threshold levels (defect tolerance assessment) as well as to determine allowable and critical crack sizes. This information is also required in developing a safe inspection interval.

4.5 Specific flaw details

Details of the actual or expected flaws are described in terms of position, orientation and extent. The likelihood of multiple initiation sites and overlapping cracks must be stated as well as the change in nominal propagation direction, if any.

4.6 Flaw morphology

Flaw morphology descriptions include aspects such as inter or trans granularity and extent of branching if any. For active damage mechanisms this can be established directly by failure investigations if samples are available. Alternatively the most likely morphology for the expected damage mechanisms from previous or similar designs can be used.

4.7 Flaw roughness

If actual samples are available this can be measured directly. Typical roughness ranges for SCC and high cycle fatigue is 8 to 200 and 8 to 212 µm respectively. Average roughness has been quoted in sources to be approximately 68 and 15 µm for SCC and high cycle fatigue respectively.

4.8 Tilt and skew of flaw

Geometric variations, including degree of tilt and skew, of flaws can significantly affect the performance of the NDT system. It is important that expected/known variances be stipulated so that it can be incorporated in the design of the inspection procedure.
4.9 Aspect ratio of flaw

The aspect ratio of a flaw is the ratio of the depth to length dimension. In most cases for the damage mechanisms discussed here aspects ratios less than 0.2 is expected.

4.10 Required performance of inspection technique

Clear requirements in terms of required detection size as well as tolerances for flaw depth and length must be stated. In addition the acceptable false call rate must also be specified. Over conservative specifications can lead to costly, time consuming and impractical NDT systems whereas in-complete or too relaxed specifications could lead to non-detection and component failure.

5. Case study

The following flaw specification for a L0 blade with a curved axial entry fir tree root design has been summarised and is presented to illustrate a typical flaw specification.

5.1 Component Details

The L0 blade has a curved axial entry root design. The root has a total of 5 serrations which are numbered from the lowest radial position as 1 (bottom) to the highest radial position 5 (top). A zig-zag rod type arrangement is used for vibration.

The blades manufactured from 12% CrNiMoV steel and have a mass of approximately 24 kg and are approximately 945 mm long. Seventy eight blades are fitted to each side of the double flow turbines. Blades will be assembled on the rotor which will be installed in the bottom casing.

5.2 Cyclic and dynamic stress distribution

It was calculated that peak cyclic stresses occurs towards the ends of the 5th serration on the concave side as well as in the centre of the convex side. These areas will be more sensitive to fatigue cracking. Steady loads are higher on the concave side than the convex side which implies that the concave side is more susceptible to SCC. These findings correlate well with available empirical data.

5.3 Damage mechanism/s

SCC is known to have occurred in the 5th serration on the concave side. Intermittent high cycle fatigue (IHCF) have occurred in the 5th serration on the convex side. Initiation is nominally in the
centre of the blade and propagates initially at a steep angle but tends to turn after approximately 7 mm in a direction parallel with the rotor centre line.

5.4 Fracture mechanics assessment

The SCC threshold can be expected to be exceeded in the 5th serration for flaws of 200 µm depth. Based on available material toughness it was calculated that significant crack depths can be tolerated. It is estimated that cracks with depths less than 12mm do not have associated stress intensities high enough to cause accelerated growth due to K-dependence. Based on a maximum allowable crack depth of 12 mm, an inspection interval of 25kh and estimated SCC propagation rates an initial crack depth (detection capability) of 3 mm is found to be acceptable. Low rates of propagation are expected due to the intermittent high cycle fatigue.

5.5 Specific Flaw Details

SCC induced flaws are expected to be in the 5th (top) serration on the concave side. The calculated stress distribution indicates that the full length of the concave side is at risk and has to be inspected. Depending on the local conditions, SCC in the center of the convex side (5th serration) cannot be excluded and should also be inspected. The complete convex side up to 50mm from each end must be inspected for SCC. Multiple initiation sites can be expected in the affected areas. A volume up to a depth of 5 mm from the surface must be inspected.

IHCF cracks develop in the centre of the 5th serration convex side and propagate towards the inlet side. Based on the calculated stress distribution cracking towards the outlet side is also possible. Multiple initiation sites can be expected along the 5th serration. Initiation can be in any position in the corner radius. The full radius as well as 2mm either side must be inspected. (see Figure 6).

Figure 5: Combined extent of inspection.

Figure 6: Extent of inspection in radius.

Figure 7: Volumetric extent of inspection.
Multiple initiation sites and overlapping cracks can be expected in affected areas for SCC as well as IHCF. The nominal propagation rates are depicted in

![Nominal SCC propagation direction.](image1)

![Nominal IHCF propagation direction.](image2)

### 5.6 Flaw morphology

SCC cracks are expected to be intergranular and branched in the depth and length direction. IHCF cracks are expected to be transgranular with no branching. Note that overlapping cracks can occur due to multiple initiation sites in both cases.

### 5.7 Flaw Roughness

Intergranular stress corrosion cracking is expected to have a relatively rough surface. Surface roughness can vary from 8 to 200 µm with an average of approximately 68 µm.

IHCF cracks have relatively smooth fracture surfaces when ‘new’. Some degradation (increase) in roughness can occur due to oxidation. Surface roughness can vary from 8 to 212 µm with an average of 15 µm.

### 5.8 Flaw Tilt and Skew

For both SCC and IHCF a tilt of ±10° and a skew of ±10° can be expected.

### 5.9 Flaw Aspect Ratio

For both SCC and IHCF an aspect ratio of less than 0.5 is expected. In most cases it should be less than 0.2.

### 5.10 Required Inspection Performance

Due to the criticality and significant consequences of failure a high level of performance is required and all flaws ≥ 3 mm must be detected. A volumetric inspection technique must be capable to detect flaws with a depth and length of 3 and 6 mm respectively in the areas of inspection as described above. Flaws must be sized to within ±1 mm in the depth direction and ±6
mm in the length direction. False calls should be kept to a minimum. A false call rate of not more than 5% is required.

6. Conclusion

In an environment of aging plant where key components are reaching end of life due to damage mechanisms such as SCC and fatigue yet high levels of availability is required to ensure adequate capacity levels and uninterrupted supply, risk based management approaches are required. NDT of these components form an integral part of these strategies. Moreover, the criticality of these components and consequences of failure require NDT systems to be of the highest standard. To this end NDT systems are engineered, tested and qualified based on a detailed description of the expected flaws and the required performance level of the systems i.e. a flaw specification. Typical parameters that have to be supplied in a flaw specification are discussed in this paper and an illustrative case study is discussed.

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