FATIGUE PROPAGATION ASSESSMENT OF TURBINE BLADE CRACKS

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ABSTRACT

This paper describes a fracture mechanics assessment of a leading edge crack, on a low pressure turbine last stage blade, 36 millimetres in length. The blade had been replaced prior to the investigation, however, due to the prevalence of cracks on other blades in the Unit and the likelihood of more cracks occurring on blades in this and other similar units, the investigation was undertaken.

The findings are that the crack propagates, firstly through the suction side stellite erosion shield, by stress corrosion cracking, then through the pressure side weld and the blade material by high cycle fatigue cracking. The condition for the onset of blade cracking is when the erosion shield is totally cracked through. A single mode, the second mode of vibration(first axial), has been identified as the mode which drives the fatigue crack propagation.

The major result of the fracture mechanics calculations is that the time between inspections has been quantified - for a given crack size of 5 to 7 mm, inspections should be carried out every 4000 hours. If the crack is shorter than 5 mm, a time of 6000 hours between inspections is recommended. Other remedial action has been recommended for cracks longer than 7 mm on the pressure side of the blade.

KEYWORDS

Finite Element Model, high cycle fatigue propagation, harmonic dynamic analysis.

INTRODUCTION

This research describes a fracture mechanics assessment for a last stage blade with a 36 mm crack on the blade's leading edge, 180 mm from the blade tip, on a low pressure rotor on a 660 MW Power Station Unit. The prevalence of cracking on the blades in the unit called in to question the integrity of blades on this and all similar units.

The blade leading edge consists of a Stellite erosion shield attached to the blade by two weld runs, one on either side of the blade. The pressure side weld is 5 to 7 mm from the blade leading edge while the suction side weld is approximately 20 mm from the leading edge. The blades are connected in packets of five and six.

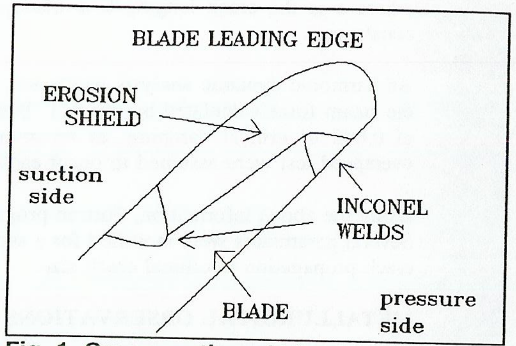

Fig. 1. Cross-section of blade leading edge

The aim of the research was to understand the initiation and propagation mechanisms of cracks on the last stage blades on the low pressure rotors on the Unit and apply the findings to all similar units where the need arises.

PROCEDURE

A review was made of all metallurgical observations and reports to gain insight as to how the blade cracks should be modelled and what the pattern of behaviour was for the cracks.

Two mechanisms of crack growth were proposed. Firstly, the crack propagates through the erosion shield by stress corrosion cracking(constant stress cracking), then secondly, through the pressure side weld and blade by high cycle fatigue cracking.

Material data for a full analysis required four components:

(i) Stress corrosion initiation data for the heat affected zone of the weld(the cracking initiates on this area of the suction side weld).

(ii) Stress corrosion propagation data for erosion shield material.

(iii) Fatigue crack propagation data for weld(on the pressure side) material.

(iv) Fatigue crack propagation data for blade material.

Comprehensive stress corrosion data, items (i) and (ii), were unable to be obtained, although the manufacturer has provided some threshold data. In this situation, metallurgical observation should be used for crack growth rates for propagation through the stellite erosion shield.

Fatigue crack propagation data was found for the weld and blade material. The manufacturer has supplied data for the blade material and weld material data was found in the database of the fracture mechanics program, FractuResearch.

For fatigue crack growth analysis, the alternating and steady Stress Intensities must be found for the crack as it grows to critical size. Stress Intensity, **K** is given by the following formula:

$$K = \beta\sigma\sqrt{\pi a} \quad (1)$$

where, β is the Geometry Factor of the crack, σ is a stress level of the "uncracked reference structure" related to the crack, π is Pi and **a** is the crack length.

Paris Law data was used for the crack propagation. Paris' Law states

$$\frac{da}{dN} = C(R)\Delta K^{M} \quad (2)$$

where **da/dN** is the rate of crack growth per cycle, **C** and **M** are constants and **C** is a function of **R**, the ratio of minimum stress to maximum stress for the cycle.

From the formulae, β and steady and alternating σ must be found as the crack grows. Stress intensities and stresses were found using Abaqus Finite Element software and the modelling software used was Ideas.

The quantity, calculated by Abaqus, is termed J, the J-Integral. For the plane stress propagation, as is occurring with the blade, the conversion to **K**, stress intensity is:

$$K = \sqrt{EJ} \quad (3)$$

where **E** is Young's Modulous. A total of nine cracks at different stages of development were modelled to obtain stress intensities. Below are diagrams of the 20 mm length crack model. The left diagram is a "free face" diagram of the model.

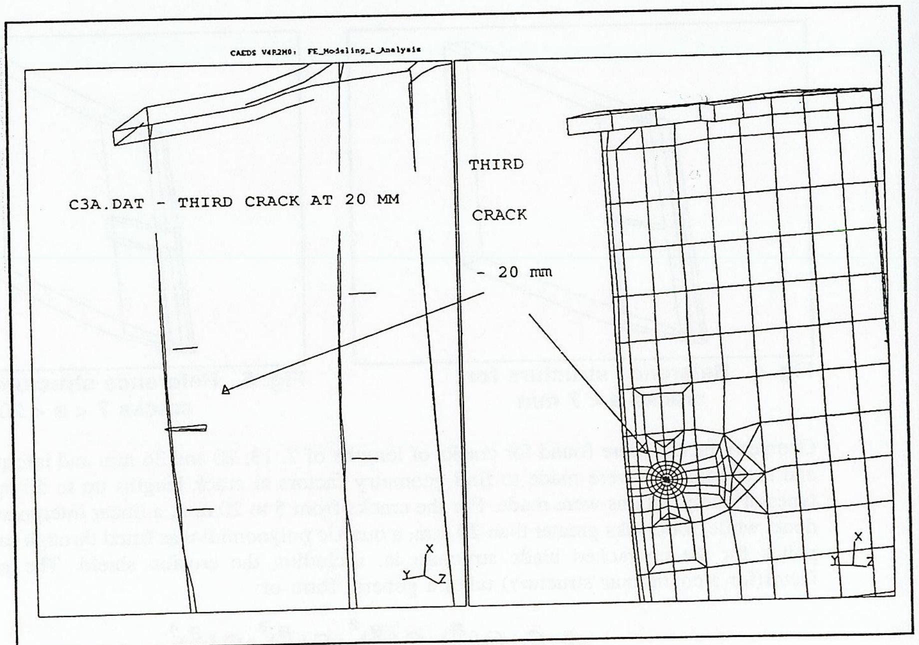

Fig. 2. Finite Element Blade Model of 20 mm crack

The fatigue crack growth consists initially of propagation through a "discontinuous" thin section of the blade and weld from about 5 to 20 mm, then propagating through the full thickness of the blade.

Observation has shown the fatigue cracking through the pressure side weld and blade occurs after the erosion shield is fully cracked through and this is assumed for conservatism in the analysis.

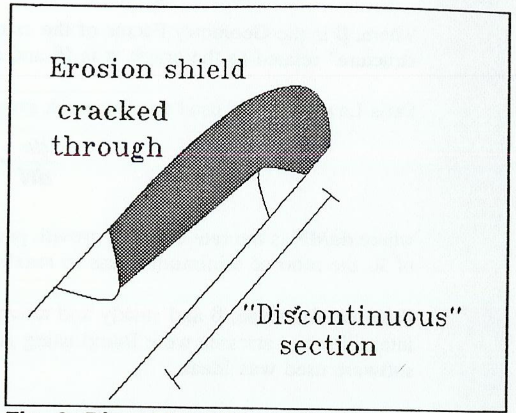

Fig. 3. Discontinuous section for cracks 5 to 20 mm in length.

Because of the discontinuity, three different "uncracked structures" were required from which to derive β. The "uncracked structures" are reference structures used to obtain reference stresses for the stress intensities. They consist of two similar models, one for crack lengths of 7 mm and under, the other for crack lengths between 7 and 20 mm and the third, for cracks of length greater than 20 mm. The first two reference structure models, in "free face form", are shown in the following diagrams, the third reference structure is simply the uncracked blade.

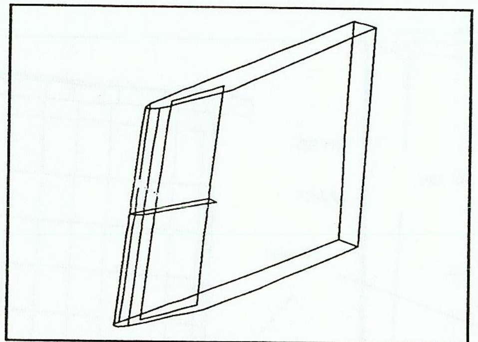

Fig. 4. Reference structure for cracks a < 7 mm

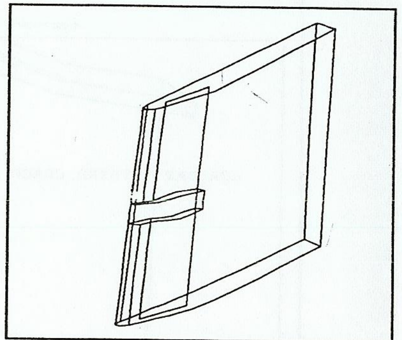

Fig. 5. Reference structure for cracks 7 < a < 20 mm

Geometry factors were found for cracks of lengths of 7, 13, 20 and 36 mm and interpolations and extrapolations were made to find geometry factors at crack lengths up to 50 mm. Two types of interpolations were made. For the cracks from 5 to 20 mm, a linear interpolation was done, while, for cracks greater than 20 mm, a quartic polynomial was fitted through calculated points for the uncracked blade structure ie. including the erosion shield. The geometry factor(for a continuous structure) takes a general form of:

$$\beta = C_1 + C_2\left(\frac{a}{T}\right) + C_3\left(\frac{a}{T}\right)^2 + C_4\left(\frac{a}{T}\right)^3 + C_5\left(\frac{a}{T}\right)^4 \qquad (4)$$

where **a** is the crack length, **T** is blade width minus the crack length and $C_{i,\ i=1\ to\ 5}$ are constants.

An harmonic dynamic analysis was made, to find alternating stress, using three per cent of the steam force calculated by the STI "Blade" program as a stimulus, with a damping ratio of 0.002 of critical damping, as recommended by "Blade". Seventeen startups and one overspeed test were assumed to occur each year of operation.

Using the above information, Fortran programs were written to determine the crack growth. Several parameters were modified for a sensitivity analysis to obtain an estimate of time for crack propagation to critical crack size.

METALLURGICAL OBSERVATIONS

Four major surveys were made of the blades. Firstly in February 1990, secondly in May 1992, thirdly in December 1992, and finally in February 1994, when the blades had been replaced in the turbine. A survey was done on blades on the generator ends of both low pressure rotors on October 1992.

Some of the major findings and outcomes of the surveys and metallurgy reports were:

The crack of interest was observed to grow from 8 mm to 36 mm between the first and second survey. This growth occurred over approximately 15000 hours service.

Many cracks did not grow at all after the second survey.

All the longer cracks surveyed agreed with the finding that the suction side must be cracked substantially before cracks will grow in length on the pressure side. The metallurgist states in conclusion that cracks propagate completely through the shield by stress corrosion cracking prior to cracks propagating into the blade material by high cycle fatigue.

The high cycle fatigue crack propagation through the blade showed the growth on the pressure side was accentuated with respect to the suction side of the blade as in Fig.6.

Most cracks were situated between 170 mm and 250 mm from the blade tip.

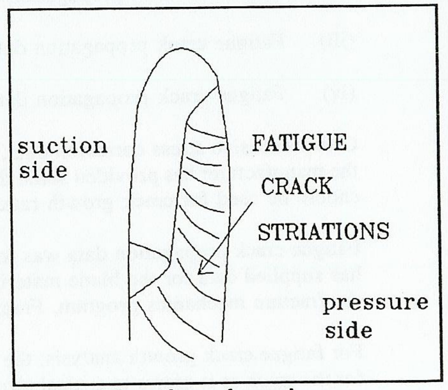

Fig. 6. Direction of crack propagation

GEOMETRY FACTORS

The geometry factors of the blade cracks were established using a result found for a simple planer, edge cracked specimen. This was investigated to account for the effect of the skew angle of the crack striations. The geometry factors were found for a crack, 21 mm in length, with the crack oriented at different angles in a similar manner to the observed crack propagation. The angle of the crack of the simple edge cracked specimen was varied to examine the effect this would have on the geometry factor, β. Superposition would then be used to adjust β for the blade cracks.

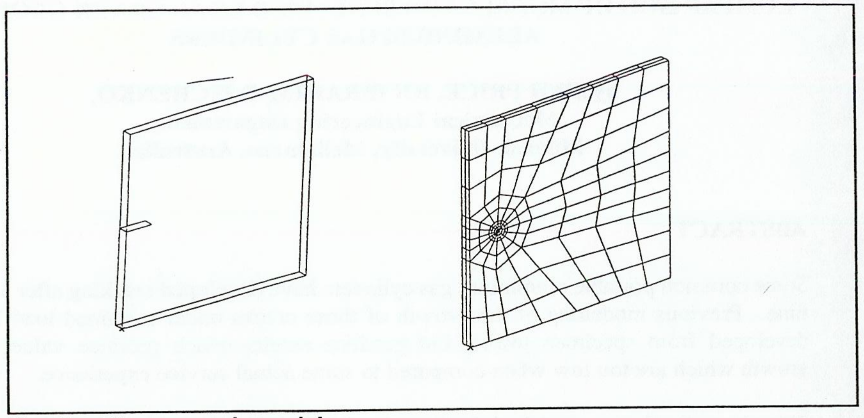

Fig. 7. Planer crack model

It was noted by varying the angle of propagation from 0 to 45 degrees, the value of the stress intensity at the crack centre and the average stress intensity across the crack front changed little and were of similar value. Using this observation, only the intensity values obtained in the central areas of the blade cracks modelled were relied on as accurate. It was also then assumed that this centre value of stress intensity was constant across the (blade)crack front - if the stress intensity did vary, the crack propagation would be such to correct any variation.

The geometry factor was found to be higher when the crack is small, due to this area being where the weld is attached at the gap between the blade and the shield. The load path changes prior to propagation through the remaining weld and the blade, causing higher stress intensities. The full compliance function in graphical form is:

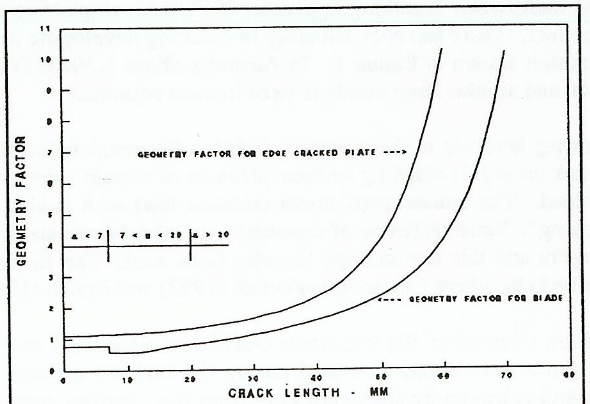

Fig. 8. Geometry Factor vs. Crack Length.

STEADY STRESS LEVELS

The steady stress levels, due to centrifugal force, are high on the suction side of the blade at 565 MPa with lower stress of 171 MPa on the pressure side.

The highest steady stress levels occur on the suction side weld exactly where the manufacturer predicted cracks to initiate, about 180 mm from the blade tip, and also where the 36 mm crack was found. Thus the stress analysis agrees with the metallurgist's conclusion that stress corrosion is the major component in initiating and propagating cracks at the suction side weld.

DYNAMIC STRESS LEVELS

The result of the harmonic analysis was that the second mode of vibration was identified as the mode shape which was driving the crack propagation. The second mode is the zeroth mode of axial vibration, ie. the blade packet vibrates uniformly in the axial direction. The stress plot for this mode shows high dynamic stresses occurring on the blade leading edge on the pressure side of the blade. This pattern corresponds to the pattern of crack striations on the pressure side of the blade.

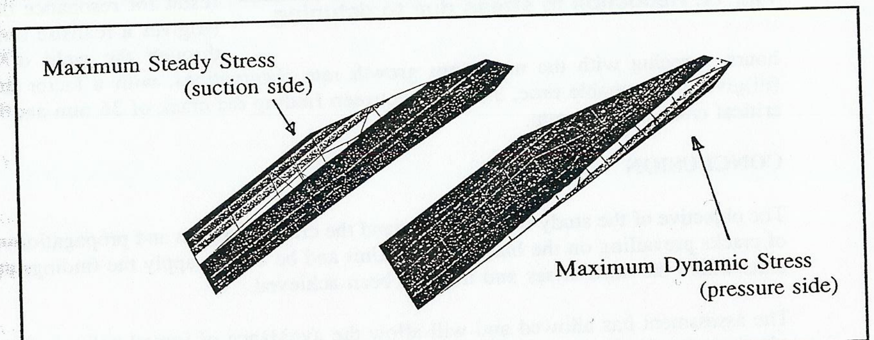

Fig. 9. Cut-plane Stress Plots

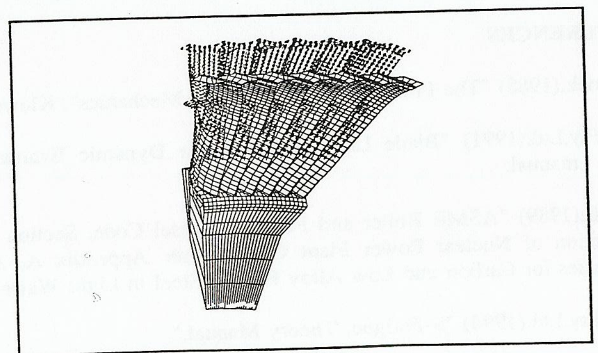

Fig. 10. First Axial Mode Shape

The fatigue crack propagation depends on the proximity of the resonant frequency to the excitation at 150 Hz(the closest multiple of the machine frequency of 50 Hz). Resonance was calculated at 157.1 Hz. A sensitivity analysis was done to compare results, taking resonance at 155.0,157.1, 160.0 and 165.0 Hz while also considering variable weld sizes.

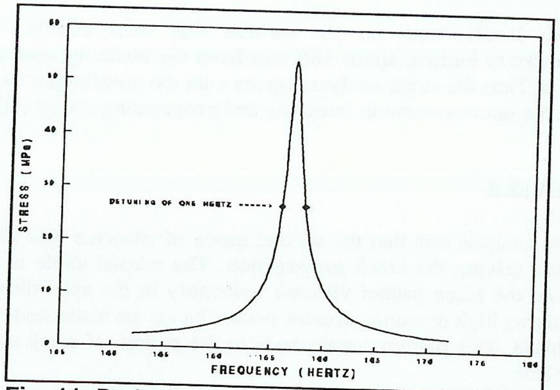

Fig. 11. Reduction in stress due to detuning.

The graph at left plots the response vs. frequency for a resonance at 157.1 Hz, showing that detuning of one Hz may reduce stress by one half.

From the sensitivity analysis, the result taken as the most accurate guide for crack growth was a result for 157.1 Hz, assuming a short weld of only 3 mm in length. The reasons for this choice are that the result (i)uses the actual calculated result for resonance of 157.1 Hz., (ii)gives a realistic time of growth through the weld of about 6000 hours, agreeing with the maximum growth rate observations, with a factor of safety and (iii)gives a reasonable time, 3.7 days, between finding the crack of 36 mm and reaching the critical crack size, 50 mm.

CONCLUSION

The objective of the study was to understand the crack initiation and propagation mechanisms of cracks prevailing on the blades on the Unit and be able to apply the findings to all similar units where the need arises and this has been achieved.

The assessment has allowed and will allow the avoidance of forced outages, the scheduling of appropriate inspection intervals and the implementation of blade-erosion shield replacement strategies in a cost effective manner.

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