Assessment of Remaining Life of A Control Stage Blade With Solid Particle Erosion Damage

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Abstract

Unscheduled replacement of HP control stage blades due to solid particle erosion can be avoided if the structural integrity of the eroded blade has not been compromised, and the risk of an in-service failure is shown to be minimal. An analytical approach is presented which was used to evaluate whether blades with SPE damage could remain in service until the next convenient outage, in order to provide the plant engineers with specifications to assist them in determining the need for replacement based on further observed erosion damage. A three-dimensional fracture mechanics model was applied to study the propagation of cracks caused by erosion, and to assess when rupture was likely to occur. The results of the study are presented as a model for plant operators to use in scheduling the repair or replacement of HP blades.

1. Current Industry Practice

In 1990, the Electric Power Research Institute concluded that solid particle erosion is costing utilities at least $150 million dollars per year in reduced efficiency, lost power generation, and maintenance of damaged components [1]. EPRI's condition assessment guidelines reaffirmed that for HP turbines, erosion of the airfoils remains the number one problem, with damage occurring to the root, tenon and shroud regions [2].

A number of solutions are currently being sought through EPRI sponsored programs to eliminate or correct the conditions which result in SPE damage. However, because solid particle erosion increases the likelihood of blade failure, current maintenance practice is to immediately repair or replace damage blades. The consequence to the plant is often an additional loss of unit availability due to turn-around repair time, or substantial penalty charges to expedite the delivery of replacement parts. For some operators, these unplanned outage extensions and expediting charges can outweigh the cost of lost turbine performance due to blade profile degradation. A utility might opt to continue running with the eroded blades if the risk of failure was minimal.

2. Experience with Evaluation of SPE damage

Since 1989, a limited number of high and intermediate pressure turbine blades, and stationary components have been investigated. Objectives of these studies were:

- To determine whether an analytical approach could be used to characterize the observed erosion damage
- To assess if the observed damage had compromised the structural integrity of the original design
- To assess whether assumed rates of continued erosion damage would significantly changed the risk of component failure before the next planned inspection.

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
Cincinnati, Ohio — May 24–27, 1993
General observations drawn from this experience to date are:

1. If erosion damage is uniformly spread over a large portion of the vane, and no notches or stress singularities are formed, then blade integrity can be assessed based on crack initiation life caused by low cycle fatigue (start-up/shut-down cycles). The rate of fatigue damage due to centrifugal and steam bending stress will increase as the erosion advances. However, the analyses performed to date indicates that well designed high pressure and intermediate pressure rotating and stationary blades can withstand a severe degree of uniform erosion before the risk of catastrophic failure becomes significant.

2. Erosion may also form notches, causing a stress singularity at the front of the notch. If the notch-crack occurs in the blade vane or cover, then an assessment of the blade’s structural integrity requires the application of fracture mechanics to estimate the crack propagation, and assess the remaining life of the blade.

3. Parametric increases in the magnitude of SPE damage can be used to examine the effect of further erosion on the predicted life of the damaged blades (assuming that they are returned to service). In lieu of detailed inspection records which indicate the progression of the erosion, an annual increase in erosion rate was roughly estimated by dividing the total SPE damage observed at the time of inspection by the number of years the blades had been in service. This assumed annual rate was then applied to the blade model to assess the impact of further erosion in terms of changes in stress and/or fatigue life which might occur before the next planned inspection outage.

4. In both the observed and assumed conditions of SPE damage which were studied, (uniform erosion and notching), changes in vane steady stresses, blade natural frequencies, and blade mode shapes were generally found to be minimal. The influence of these changes was also found to be inconsequential in terms of the estimated fatigue life for the blades.

5. For the limited number of observed and assumed conditions of SPE damage where notching (cracks) was analyzed, stresses from centrifugal and steam bending loads were predicted to cause the crack to propagate during each start-up/shut-down cycle of the turbine. However, because the cases studied were operated in base-load machines, the cumulative low cycle fatigue damage was predicted to be minimal. Crack growth due to low cycle fatigue was therefore not considered to be a determining factor in assessing the risk of in-service failure for these cases.

6. In both observed and assumed conditions of SPE damage on the HP and IP blades which were studied, dynamic stresses resulting from harmonic forces at per-rev excitations and nozzle passing wake were also generally found to be inconsequential as a source of fatigue damage. Dynamic stresses were calculated to be below the material limits for initiating or propagating cracks in eroded regions on the vane.

7. The analyses did indicate that the control stage turbine blades fatigue cracks might initiate and/or propagate under certain assumed conditions of partial admission load operation. A fracture mechanics approach was then adopted to assess the crack growth process under partial arc operation for an observed condition of erosion damage.

8. For cases where notches were starting to form, the risk of crack propagation was minimized by using the analytic model to specify alterations to the notch region of the vane to reduce the stresses and stress intensity factor at the notch (crack) tip.

9. Blade erosion is often traceable to nozzle erosion. Repairs to the nozzles might also be considered as a beneficial or positive step toward minimizing the harmonic excitation in advance of the blade.

10. For cases where cracks had already initiated from the trailing edge, a fracture mechanics approach was used. By assuming three crack front configurations, the stress intensity factor was computed to assess if an initial crack would stall as it progressed into the blade vane, i.e. would the crack tip stress intensity factor decrease below the threshold value. Without further erosion, the analytical model indicated that crack propagation would arrest after a small amount of growth. If the erosion reduced the net section of the vane so that stress intensity factor along the crack front exceeded the threshold value, growth would begin again. The results imply that the rate of fatigue crack growth will be governed by the rate of erosion.

In summary, STI’s limited experience has suggested that a systematic approach is necessary to analyze and assess the risk of returning a unit to service with blades that have SPE damage. A combination of finite element analysis and life prediction techniques were able to provide utilities with technical guidance on whether to continue operating with damaged blades until a future inspection outage.
3. Conditions Used and Assumptions Made for the Analysis of SPE damage.

After approximately seven years of service, a row of control stage blades, shown in figure 1 were inspected and found to be damaged by solid particles in the steam flow. On the trailing edge of the eroded blade, a sharp notch was formed. A crack appeared in the notch, near the cover, and propagated under operational loads. It was recommended by the OEM to replace these blades to avoid the possibility of catastrophic failure. However, the high cost of materials, and the unscheduled downtime involved in replacing the HP blades argued for keeping the blades in service until the next convenient outage. To examine the risks associated with this alternative strategy, the following studies were performed:

- Steady stresses of an undamaged and damaged blade were calculated and compared.
- Dynamic stress due to partial arc admission and nozzle passing excitation were calculated.
- Stress intensity factors were calculated for a blade with a 0.275 inch notch to examine the crack growth rate and trajectory under partial arc operation of the stage.

The control stage consisted of 72 blades arranged in groups of four. Each blade group is held together by a cover band, and fixed in place with two blade tenons. Each control stage blade has an integral cover. Solid particle erosion occurred mainly underneath the integral cover, on the concave side of the vane section.

SPE influences the inherent structural reliability of the HP turbine blades by changing the design of the original blade vane profile, cover or tenons. The geometric alterations were modeled in order to reflect the consequences of the damage as changes in operating stresses (steady, dynamic) and natural frequencies, which in turn may influence the initiation and/or propagation of cracks in the erosion damage zone.

To facilitate the examination of blade stresses, the EPRI BLADE-ST program was used to generate the majority of the finite element model. BLADE (Blade Life Analysis for Dynamic Evaluation - Steam Turbine) provided many of the functions and routines needed to quickly model the blade vane, root and cover geometry. [3] [4]. However, the commercially available version of BLADE is currently designed to handle low pressure blade geometries. Features specific to the HP blade problem such as the integral cover/double tenon and shroud arrangement, and adjustments to the vane to represent the solid particle erosion damage were therefore added to the original BLADE model using the preprocessor of the general purpose finite element program ANSYS [5].

The model consisted of a cover, vane, blade attachment root and disk segment. A single blade was comprised of 593 three-dimensional isoparametric elements having a total of 3624 degrees of freedom. By applying a matrix condensation technique, the single blade was reduced to a super element, and used to generate a four blade group model. For the purpose of the study only one blade group with the most extreme condition of erosion damage was analyzed. Coupled displacement boundary conditions were applied to the two faces of the disk sector to represent a cyclically symmetric, 360 degree bladed-disk. The model of the eroded blade is shown in Figure 2.
The control stage blade material properties used in the analysis are similar to Crucible 422SS. Material properties used in the calculation of stresses and natural frequencies are shown in Table 1.

Table 1: Properties of Crucible 422SS at 950 F

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus</td>
<td>22,500 ksi</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>177 ksi</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>131 ksi</td>
</tr>
<tr>
<td>Elongation</td>
<td>12%</td>
</tr>
<tr>
<td>Reduction of Area</td>
<td>43%</td>
</tr>
<tr>
<td>Fatigue Strength</td>
<td>38 ksi</td>
</tr>
<tr>
<td>Threshold Stress</td>
<td>3.1 ksi/in*</td>
</tr>
</tbody>
</table>

* defined at growth rate 10^-8 in/cycle. R = 0.5, where R is the stress ratio, defined as the ratio of minimum stress to maximum stress.

In the initial step of the overall evaluation, blade stresses were calculated for centrifugal and steam bending loads. During operation, the control stage runs at 3600 rpm. Centrifugal force acting on the blade can be calculated as a body force. The force vector for each element is determined as:

\[ F = \int r \rho \omega^2 dv \]

where:
- \( r \) is the radial vector from the shaft to the element
- \( \rho \) is the mass density
- \( \omega \) is the rotational speed
- \( v \) is the element volume

Table 2: HP Turbine Steam Inlet Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam flow rate</td>
<td>2,301,000–6,200,000 lbm/hr</td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>3,500 psia</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>1000 F</td>
</tr>
<tr>
<td>Inlet enthalpy</td>
<td>1421 Btu/lbm F</td>
</tr>
</tbody>
</table>

Steam conditions at the inlet of the HP turbine are given in Table 2. The force in the tangential direction was estimated to be 700 lb per blade, and in the axial direction 250 lb per blade. In a partial arc mode of operation, the pressure difference across the control stage could be as much as 100%-200% higher than in the normal mode of operation. Operation under partial arc admission was therefore anticipated to represent a significant potential source of high cycle fatigue damage in the control stage blades. A forcing function due to partial arc admission is difficult to characterize without resorting to experimental measurements using a device such as the rotating water table [6]. Therefore, for the purpose of this study a 60 hz. dynamic force with a 150% stimulus ratio was assumed to calculate the dynamic response of the control stage blade group. Since a one-per-rev forcing is much lower than any fundamental mode frequency of the blade group, results from these dynamic stress calculations were used to represent the transient response of the blade group to partial arc steam admission.

Another type of dynamic forcing in the control stage is caused by nozzle wake excitation. In this case, 104 nozzles created a dynamic force at 6,240 hz. For the purpose of this evaluation, forcing amplitude at nozzle passing frequency was assumed to be 10% of steady steam bending load. Damping in the control stage was considered to be mainly due to material damping, estimated at less than 0.2%. Since the forcing frequencies are not close to any natural frequencies, the effect of damping on dynamic response is not expected to be significant. Based on earlier blade damping tests performed on behalf of EPRI, a uniform modal damping of 0.2% was used to calculate blade dynamic stresses [7].

4. Comparison Of Results

Figure 3 shows an example of the stress plots used to identify and compare the equivalent stresses in the original and damaged blades. Tables 3 and 4 reflect the change in stress and blade frequencies which result when the erosion damage to the blade is confined to the vane trailing edge, and no notch is formed.
5. Analysis of Crack Propagation in Vane Trailing Edge Under Partial Arc Admission

After approximately 40,000 operating hours notches, notches typically 0.1-0.2 inches in depth appeared in the trailing edge of the blades. In one sample blade, a 0.4 inch crack was found. Stress due to up-down cycling was calculated to be about 18 ksi. This crack would be expected to propagate during each start-up of the unit. However, only a few such cycles would occur in any given year. Under this type of operating scenario, the crack would not be expected to grow rapidly, and risk of fatigue-failure was considered to be minimal.

However, the units these blades came from did operate in a partial arc steam admission mode at low load for approximately 25% of the total operating time. Assuming the units run 2000 hours per year in the partial arc admission mode, the total number of cycles experienced by the blade would be:

\[
2000 \text{ hours} \times 3600 \text{ sec/hr} \times 60 \text{ cycles/sec} = 4.3 \times 10^8 \text{ cycles}
\]

If the stress intensity factor at the crack tip formed in the notch reaches its threshold value, the crack would be expected to grow rapidly under partial arc admission.

At the per-rev forcing frequency of 60 hertz, the cumulative number of cycles experienced by the blade in one hour would be over 200,000. Assuming the initial value of \( K_I \) exceeds the threshold value under partial arc admission, a 0.2 inch crack could double in length within a few hours of operation. The risk of failure before the next outage would be considerable.

However, as the crack propagates toward the center of the blade vane the crack front is extended. The stress field at the crack tip might decay as a consequence. The stress intensity factor would also be decreased. A fracture mechanics study was therefore performed to assess whether a 0.275 inch crack (worst observed condition) would propagate rapidly under partial arc steam admission conditions of operation, and/or whether the crack might arrest itself as it progressed further into the blade vane.

A major limitation of conventional linear fracture mechanics programs is their inability to simulate arbitrary crack shapes, or to account for changes which occur to the original geometry (and stress field around the crack tip) as the crack propagates. To study the crack growth for the conditions as described, a special purpose finite and boundary element based fracture mechanics program, FRANC-3D was applied [8]. The aim of the simulation was to examine how the stress intensity factors along the crack front change as the fatigue crack grows. The solid model description of the damaged blade was based on the finite element mesh prepared by BLADE. Only the cover and airfoil surface was used in the FRANC-3D model. The boundary element model mesh used to analyze the HP blade is shown in Figure 4.
The principle of superposition was used to compute stress-intensity factors along the crack fronts. The problem was loaded by applying tractions to the crack surfaces, and the surfaces where SPE damage had occurred. These tractions are equal in magnitude, and opposite in direction to those extracted from the BLADE finite element analysis at these locations. The boundary conditions give the proper crack opening profile, from which the stress intensity factors are computed.

Three crack-front configurations were analyzed, with nominal crack lengths of 0.07, 0.16 and 0.26 inches (as shown in Figure 5). The computed stress intensity factors for these three crack fronts are 4.8, 4.4, and 3.2 ksi/\(\sqrt{\text{in}}\) respectively.

Two important observations can be made regarding the computed stress intensity factor value:

1) The values are near the threshold values for fatigue growth in steels at this temperature (about 3-4 ksi/\(\sqrt{\text{in}}\))

2) The values decrease as the crack propagates.

These results suggest the following crack fatigue mechanism. The solid particle erosion reduces the net section, thus increasing the stress in the remaining material. Eventually, the stress intensity factor along an existing fatigue crack will reach a threshold value, and the crack will begin to propagate. The loading was assumed at 60 cycles per second, so the crack growth rate will be relatively rapid, even with such relatively small loads. It is apparent however, in the regime which was analyzed, that the stress intensity factor drops as the crack propagates, i.e. crack propagation will arrest after a relatively small amount of growth. This implies that the rate of fatigue crack growth will be governed by the rate of erosion.

A possible scenario is that the blade experiences some amount of erosion which, by reducing the net section, causes the stress intensity factors along the crack front to rise above the threshold. The fatigue crack will then begin to propagate. However, as shown in Figure 5, as the crack propagates, the crack becomes wider which lowers the stress intensity factors along the crack front, below the threshold value, and the crack arrests. This process will be repeated until the crack is sufficiently long enough that the stress intensity factors no longer fall below threshold, as when the crack propagates. At this point, one would anticipate rapid growth rates, due to the high frequency of loading, leading to failure of the blade.
6. Conclusions

The limited research undertaken and discussed within this paper suggests that under certain conditions and restrictions, blades with SPE damage can be returned to service while corrective measures are prepared. For plants which are willing to temporarily accept the performance losses associated with degradation of the vane profile, the ability to defer repair or replacement provides an alternative short term maintenance strategy. If BLADE-ST and FRANC-3D, models have been prepared in advance, the plant could update an original assessment in a systematic manner by recording the growth of the erosion damage at each subsequent inspection. The analytical results can also be used to define maximum tolerable limits of damage, to assist plant engineers when they inspect the HP and IP blades.

7. Considerations Regarding the Analysis of SPE Damage

Many of the features necessary to run an SPE damage analysis exist in the BLADE-ST and FRANC3D programs. The principal features which are not available within BLADE-ST include:

- A pre-processing tool for efficiently altering an existing blade vane profile to represent regional changes of erosion damage.
- A capability specifically designed to model crack growth in turbine blades using fracture mechanics.
- A solution routine for calculating transient dynamic stresses under partial admission loading.
- A post-processing routine which would automatically tabulate and compare stresses, frequencies and life for each SPE case studied against values obtained for the original

8. References


5. "ANSYS", Engineering Analysis System, Revision 4.2 (Issued June, 1985), Swanson Analysis Systems Inc., P.O. Box 65, Houston, PA

