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Root cause analysis of failure of 40th stage moving blade of single cylinder condensing turbine

Kumar R K*, Janardhana M* and Bhaskar Sharma K V**

Blade failures in steam and gas turbines are quite a common occurrence. The last stages of steam turbines are designed to have the lowest possible fluid temperature. In view of the longest blade length in the last stages, the blades are subjected to highest bending moment forces and susceptible for erosion-corrosion phenomenon owing to the low service temperature environment. The failure analysis of last stage blade of 54 MW direct condensing type gas turbine are presented. The blade was made of martensitic grade stainless steel. Detailed analysis of the blade surface, lacing wire hole as well as the fracture morphology was analyzed using SEM-EDX. The probable reason for the failure of the blade was brought out based on the detailed investigations of the failed blade as well as the vibration signature analysis at the time of failure incidence.

***Keywords** : Failure analysis, gas turbine blade, vibration frequency, fractography*

1.0 INTRODUCTION

The failure of rotating blades of steam turbine has been recognized as a leading cause for the unavailability in thermal plants. The blades of the steam turbine are exposed to severe operational conditions of centrifugal stresses in combination with erosion-corrosion environment [1-2]. The service life of the blade is affected by different factors including fatigue, the corrosion-fatigue, and stress corrosion fatigue mechanisms. The Low Pressure (LP) stage blades are designed to have the longest length and are subjected to highest bending moment forces. The susceptibility to failure of the blades in the last row of blades is the LP stage is predominant. The investigation of corrosion fatigue and vibration problems in steam turbine blade is widely reported [3-7].

In the present paper, a case of fracture of a steam turbine blade at the damping wire hole of 54 MW condensing type turbine of the barge-mounted power plant during service was investigated. The fracture of the blade has occurred at the smaller radius of the damping wire hole in the 40th stage of LP turbine and cracking and fracturing of sleeve joint used for connecting the ends of damping wires was also observed. The failure has been observed at the blade forming the end of the packet.

The material and design specification are ;

Blade Material : X20CrMo-13

Process Fluid : Wet steam at 40 – 60 °C

Total No. of stages : 40

*Joint Director, Central Power Research Institute, Bangalore -560080, India. E-mail: rkkumar@cpri.in, janardhana@cpri.in
**Sampoorna Rotor Dynamics Consultancy, Bangalore-560040, India. E-mail: bhaskar.sarma@smprdcindia.com

The number of blades in the 40th stage are 62 and it is divided into 3 segments. Each segment comprises of 20, 20 and 22 blades and supported by lacing wires with sleeve joints at the ends. The lacing wire diameter was 7 mm and passes through the set of blades having the hole diameter of 7.2 mm. The three lacing wires are connected with sleeves. Titanium alloy was used as the damping wire material.

2.0 FAILURE HISTORY AND DETAILS OF STEAM TURBINE:

The steam turbine of captive power plant is operated through a Distributed Control System (DCS) and equipment start-ups and shutdowns are fully automated with ramp-up and ramp-down logics provided by OEMs. These automations ensure operation of plant without much of human intervention. Alarms and trips are provided in DCS to immediately notify the operator about abnormality in the field parameters, if any. The set was commissioned in 2001 and had limited operational hours since this was being operated as peaking power generation unit.

The set experienced high vibrations of 13.67 mm/s on August 2012 and machine got tripped due to high vibrations.

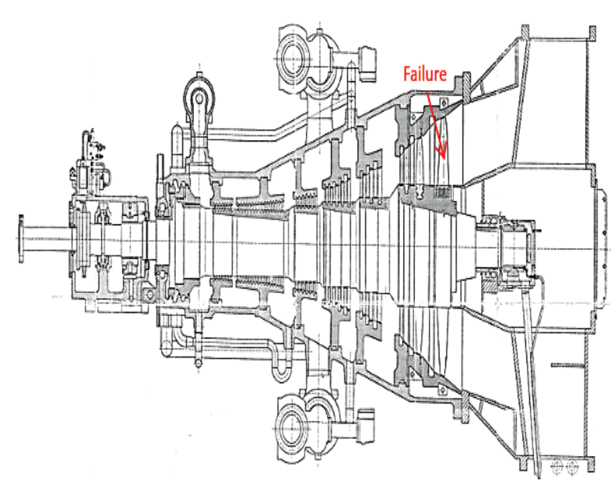


FIG. 1 GENERAL LAYOUT OF THE GAS TURBINE INDICATING THE FAILURE LOCATION

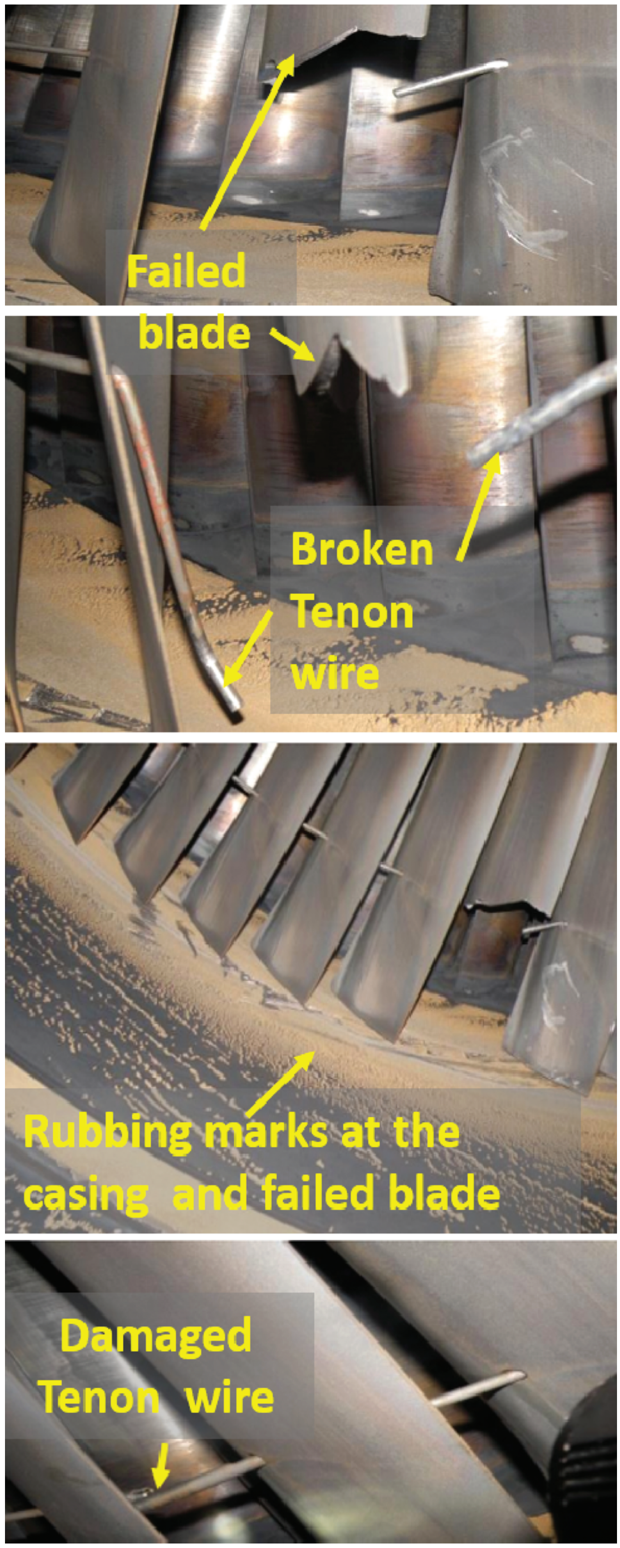


FIG. 2 GENERAL LAYOUT OF THE GAS TURBINE INDICATING THE FAILURE LOCATION

- It was found that the 36th blade of LP last stages were broken at the damping wire hole plane while in the 16th blade, long crack has been developed on inactive side. Both the blades are front and last blades in the packet

- Rubbing marks were observed on the casing in the direction of rotation.
- No damage marks were observed on the adjacent blades.

The location of the failure and the fractured condition of lacing wires observed is shown in Figures 1 and 2.

The operational history and vibrational data used for the analysis are given below.

- The natural frequency of blades as per the records are 200 HZ for LP1, 136 Hz for LP2 and 102 Hz for LP3.
- The number of guide blades is 80. The critical speeds are 1680 rpm and 5040 rpm for the turbine, 1431 rpm and 1616 rpm for the generator.
- The torsion critical speeds are 19.1 Hz and 144.8 Hz
- No of hours of service during the last 11 years period : ~ 45000 hours
- No. of start-up and shut down : 600
- The bearing pressure is of the order 1.25 MPa on bearings and the bearing clearances are 0.15% as per design and the existing one 0.175%. The bearings are the cylindrical type.
- The existing run outs are within permissible limits.
- The normal vibration values are less than 2 mm/sec RMS on bearing pedestals and shot up to 13.67 mm/sec during failure.
- Vibration levels on bearings are normal at all loads.
- The plant water quality data indicating conformance to the specific requirement in terms of pH and conductivity values.

3.0 DETAILS OF LABORATORY INVESTIGATIONS AND ANALYSIS CARRIED OUT

Two good blades on both sides of the failed blade No. 36 (i.e blade no. 35 and 37) was collected. Also, a small portion of the fractured tail end piece of the blade 36 and blade No. 16 which has shown crack around the damping wire hole were collected for laboratory investigations. The laboratory and field investigation conducted includes the following.

- Visual observation of two un-failed blades for surface degradation studies.
- Analysis of damping wire hole inner surfaces for possible pitting and corrosion issues through EDX analysis
- Fractography analysis of the cracked blade no. 16 and failed blade sample 36.
- Rap test on different stages viz. 37, 38 and 39 to identify the variations in their natural frequency linked to the damages experienced in service.
- Analysis of vibration data and coast down signal during the failure incidence

3.1 Visual Examination

The surface condition of the blades on either side of the failed blade in the 40th stage viz. blades 35 and 37, have been visually examined for possible pitting during extended service. The view of the un-failed blades considered for analysis is shown in Figure 4. The surface of the blade did not show any abnormalities in terms of change of surface finish in the vicinity of the damping wire hole. The fretting marks were observed on the ID side of the damping wire hole

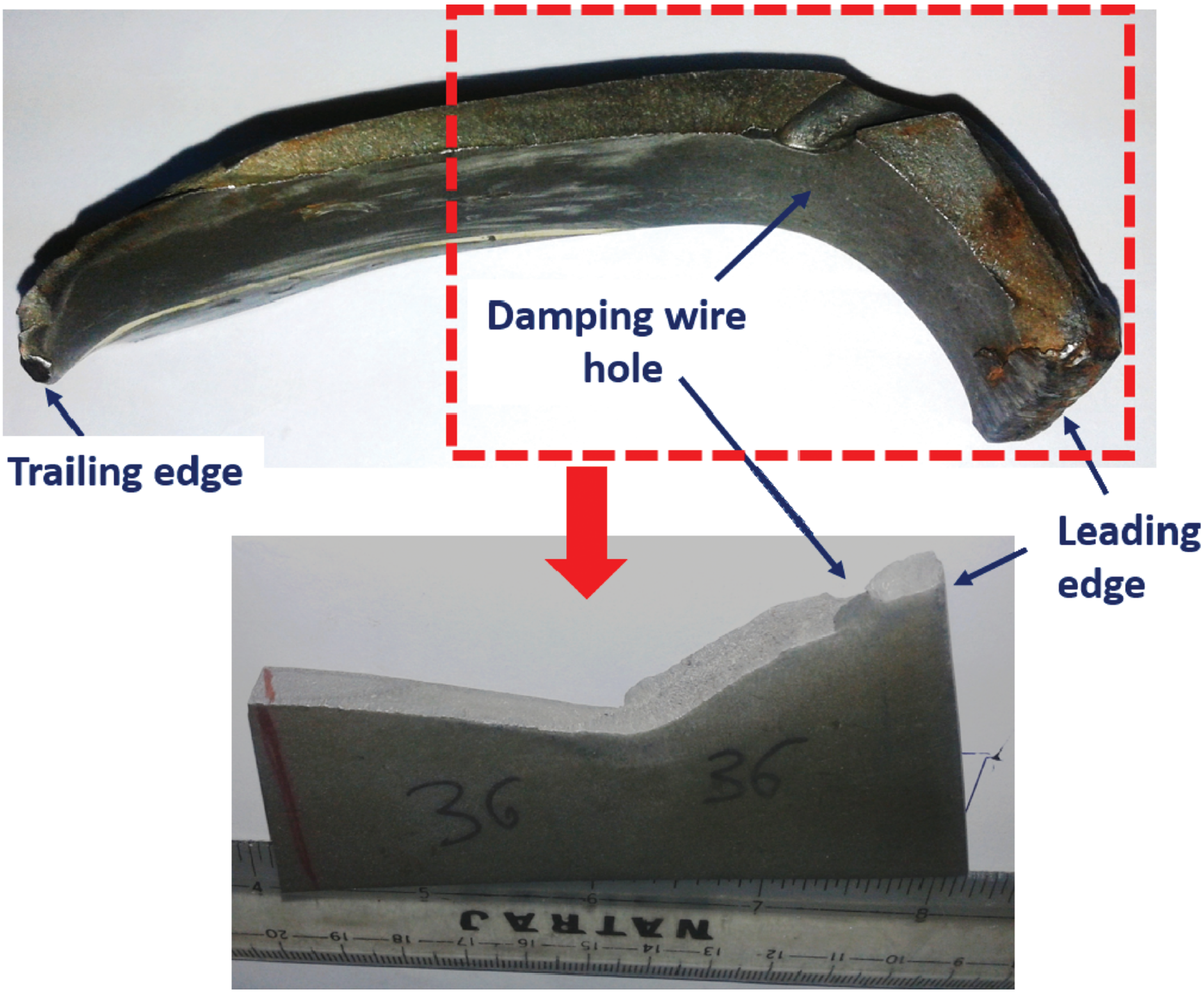


FIG. 3 FAILED BLADE 36 SHOWING THE FRACTURE SURFACESON THE CROSS SECTION

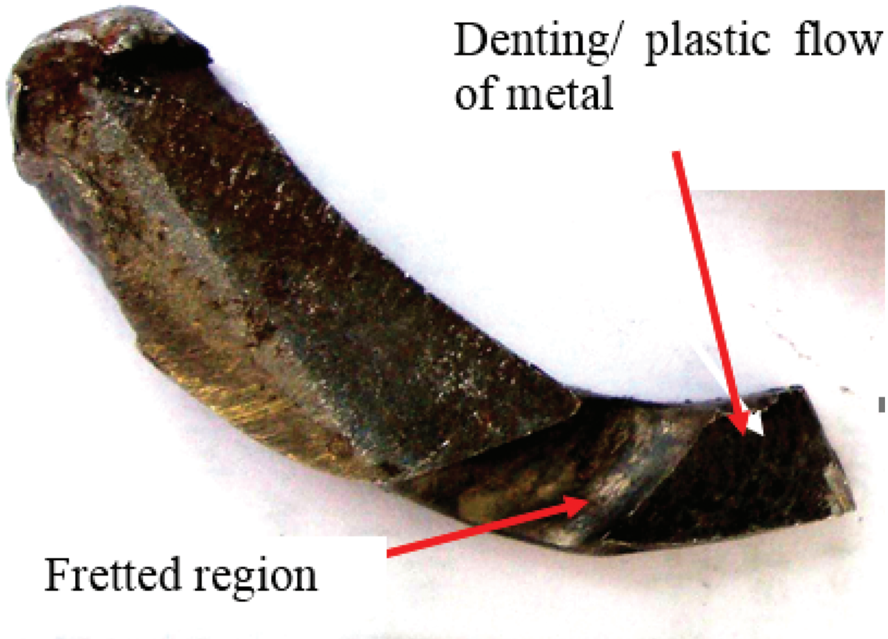


FIG. 4 VIEW OF FRETTED REGIONS OF DAMPING WIRE HOLE AND LOCALIZED DEFORMATION IN THE ADJASENTREGION

indicating that the effectiveness of damping wire in controlling the vibration of the blade during normal operational conditions.

The fractured blade (#36) had plastically deformed bend region close to the trailing end in the counter direction to blade rotation (suction side to the pressure side). The ID surface of the damping wire hole had shown localized rubbing/fretting marks close to the pressure side. In addition, ridges /steps like regions could be seen along the pressure side of the blade fracture surface.

The occurrence of these ridges is generally attributed to the torsional loading conditions of typical rotating components like a blade. In the present case, this is due to combined effect of possible steam hammering/fluttering of the blades and torsional loading. The suction side of fracture surface has shown typical of fine fracture indicating the final stages of the fracture process. The surface of the blade (along the blade length) did not show any abnormalities in the vicinity of the damping wire hole.

The fretting marks were observed on the ID side of the damping wire hole indicative of the fact that the blade was subjected to self-excitation.

3.2 Analysis of the damping wire hole inner surfaces through Scanning Electron Microscopy coupled with Energy Dispersive X-ray elemental analyzer

A small specimen of the blade around the damping wire hole has been cut by EDM on from both the blades 35, for assessment of the corrosion induced damages and the extracted specimen is shown in Figure 5. The EDM cut sample was subsequently cleaned in acetone ultrasonically. The complete region all along the bolt hole thickness directions have been analyzed through EDX. The EDX spectrum indicating various elements observed over different regions of the damping wire hole ID surface are shown in Figures 6 and 7.

The compositional analysis indicated that the ID surface consisted predominantly the oxides of iron and titanium with alower amount of chromium, aluminum and silicon. Elements vanadium is observed in trace amounts in isolated regions. The observed titanium, aluminum and vanadium peaks are indicative of the fact that the titanium alloyed damping wire were effectively rubbing at the damping wire holes during the process of dampening of the blade vibrations.

The analysis was carried out bot on the pressure and suction side surfaces of the blade and the average of six location compositional results were reported. The range of oxide composition observed on the ID side of the damping wire hole is given in Table 1.

TABLE 1

CONCENTRATION OF OXIDE COMPOUNDS OBSERVED ON THE ID OF DAMPING WIRE HOLE (%)

Fe_2O_3	TiO_2	Cr_2O_3	SiO_2	V_2O_5	Al_2O_3
49 to 82	4.8 to 26	10 to 14.5	1.5 to 4	1.5	1.3 To 4.9

The above analysis confirm that the prevalence of corrosion or cavitation on the ID surface of damping wire hole has not occurred.

3.3 Fractography of the failed blade # 36

The fracture surface analysis of the cracked and failed blade in the region away from the damping wire hole and towards the tail end has been carried out. The view of the fractured blade received for analysis is shown in Figure 3 and the fractographs obtained close to the edge of the hole are shown in Figure 8. The fracture morphologyc lose to the damping wire hole has shown features of severe localized fracture of the metal (Figure 8a and 8b). The growth of striations in the adjacent regions could be seen in multiple directions (Figure 8c to 8e). As the hairline crack approached the pressure side of the blade, the final fracture has occurred with predominant and sudden ductile tearing (Figure 8f).

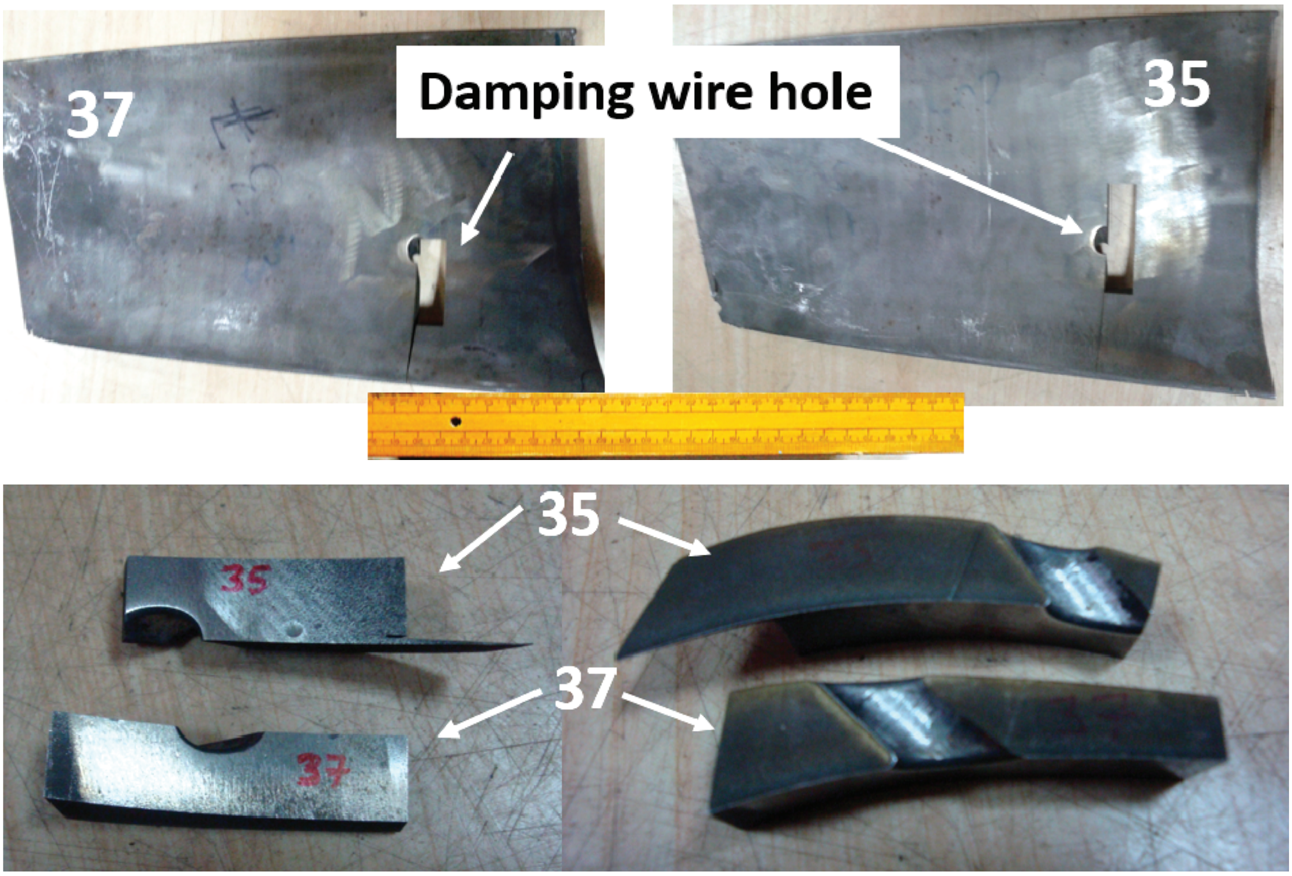


FIG. 5 BLADES 37 AND 35 RECEIVED FOR LABORATORY ANALYSIS AND EXTRACTED SPECIMEN ALONG DAMPING WIRE HOLE CENTRAL LINE BY EDM OF DAMPING WIRE HOLES

It may be noted that the two halves of the fractured component will have the features same in the sense that one of the fractured component will have projections and the other will have corresponding depressions in the fracture plane. In the present case, the nature of fracture plane is near horizontal without much undulations, the analysis of one fracture component is considered more than necessary and the same is followed as a standard practice in all failure investigations.

A small portion of fractured blade sample has been cut from the leading edge and upto a length of approx. 10 mm after the damping wire hole, for the fracture surface analysis. Scanning Electron Microscopy (SEM) observations have been made all along both edges of damping wire hole to identify possible regions of crack origin. The fractographs were taken along the full thickness of the blade to get insight into the possible crack initiation region. The stitched SEM fractography indicating the complete thickness of the fracture region covering both edges (suction and pressure side) of the damping wire hole is shown in Figure 9 and 10. Also, the region away from the edges has been observed for fracture morphology and is shown in Figure 1.1.

It has been observed that both sides of hole edges corresponding to the fracture plane have not indicated any ridges and other surface discontinuities. The localized mechanical damage (plastic flow/denting) at the end of the hole could be seen. The fracture region ahead of the local denting did not show the characteristic features of fatigue striations and hence this denting is attributable to possible secondary damage. The observed ratcheting marks on the suction side all along the length of the blade is indicative of the torsional loading of the blade prior to failure. The SEM analysis of the fracture region away from the hole edge has shown features typical of mixed mode fracture viz. cleavage and ductile tearing regions along with striation like regions and cracking at isolated locations. The presence of cracks as observed in isolated locations on the fracture surface (Figure 12) is suggestive of the fact that the magnitude of stresses during the blade vibration during the continued service upon failure of lacing wire, is in excess of the yield strength of the material.

3.4 Measurement of resonant frequency

The bump test was carried out on the 37, 38 and 39^{th} stage blades to ascertain any degradation of the blade due to the pitting or another corrosion phenomenon. The natural frequency values of stage 37 and 38 blades were observed to be 139 Hz, which is matching with that of the values recorded prior to failure. In respect of stage 39, the natural frequency of blades randomly selected were observed to be 139 Hz, which is slightly higher than the recorded value of 134 Hz.

The natural frequency of blades as per the records are 200 Hz for LP1, 136 Hz for LP2 and 102 Hz for LP3. The fundamental natural frequency of the blade is close to 2^{nd} harmonic of rotation. But the overall vibrations are well within limits. The design value of torsional natural frequencies of the turbine is quite far away and thus considered adequate against torsional vibrational failure. The torsional critical speeds are 19.1 Hz and 144.8 Hz. The normal vibration values are less than 2 mm/sec RMS on bearing pedestals and shot up to 13.67 mm/sec during the incident of failure.

In view of the above, there is no evidence of any significant degradation of the adjoining blades on either side of the fractured 40^{th} stage blade and hence the possibility of any pitting and another corrosion phenomenon related failure can be ruled out.

3.5 Analysis of Vibration signature data

The operational data and on analysis of turbine vibration data, the following points were noted.

The eddy circulation with negative damping created aflutter in the blade, which generates self-excited vibrations with uncontrolled amplitudes due to negative damping. The cause of the eddy currents could be because of a combination of many reasons. The most probable reason could be due to Condensate/steam hammering or Flutter during low flow conditions.

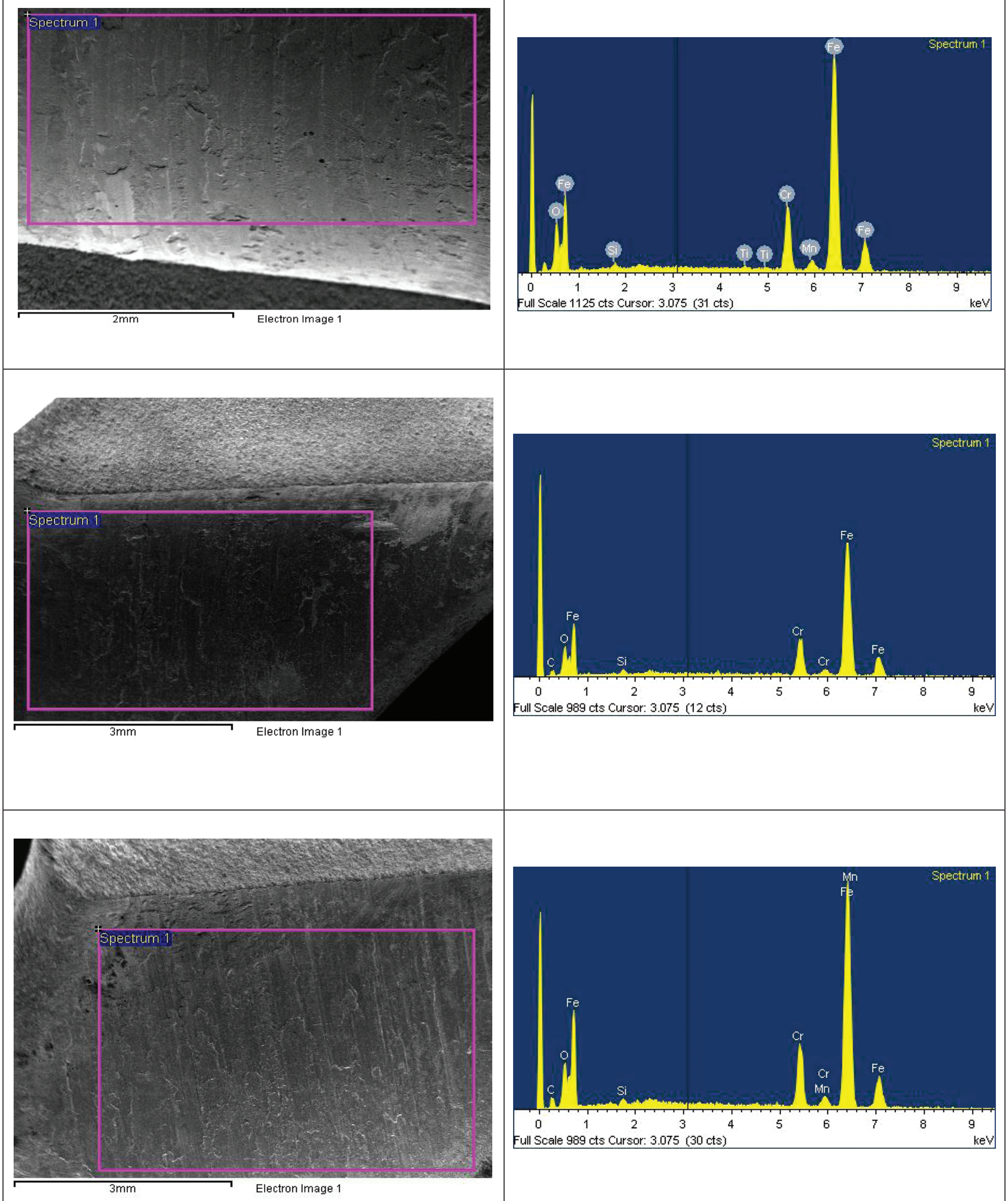


FIG. 6 ELEMENTAL MAPPING OF DAMPING WIRE ID HOLE SURFACES OF BLADE 35

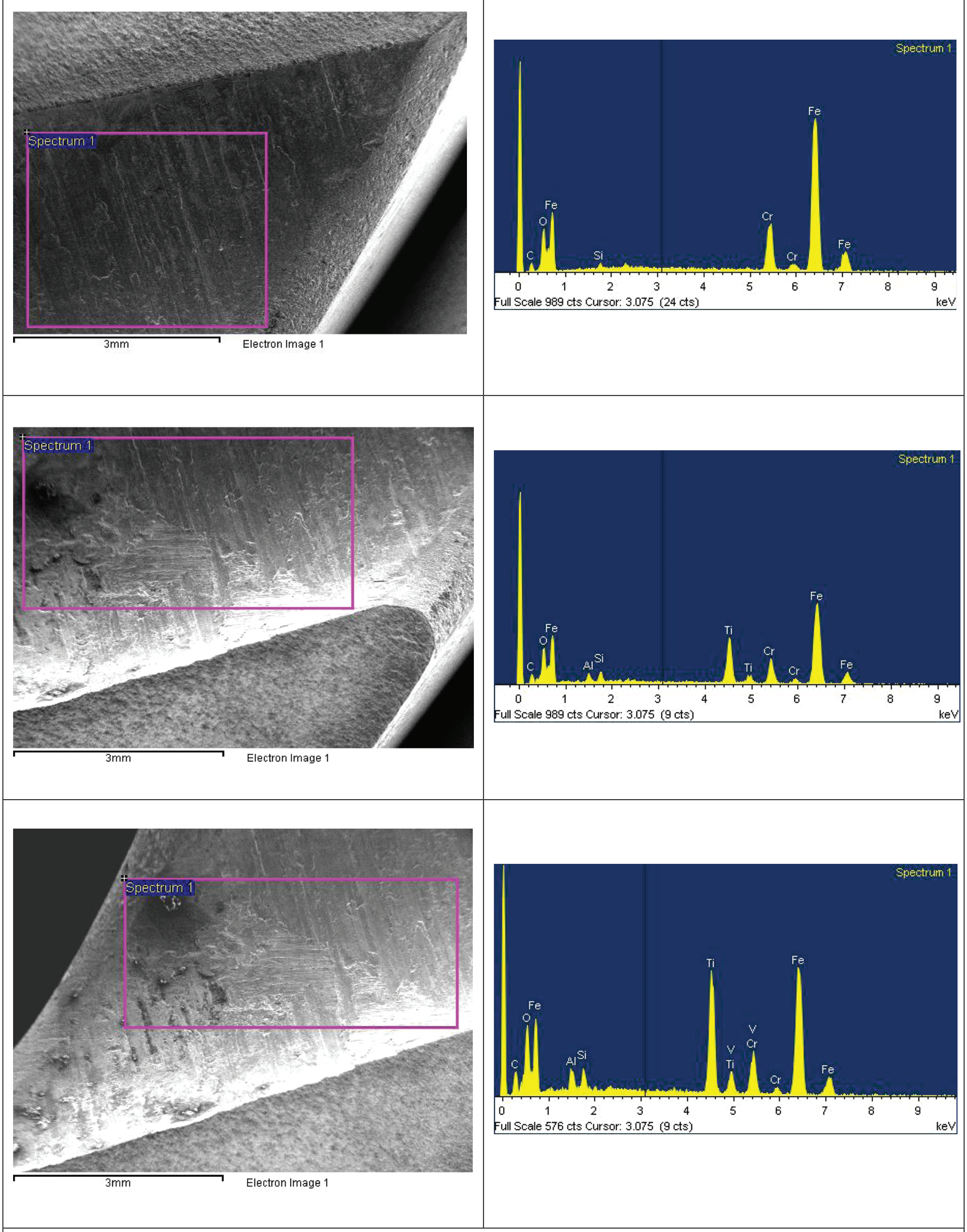


FIG. 7 ELEMENTAL MAPPING OF DAMPING WIRE ID HOLE SURFACES OF BLADE 37

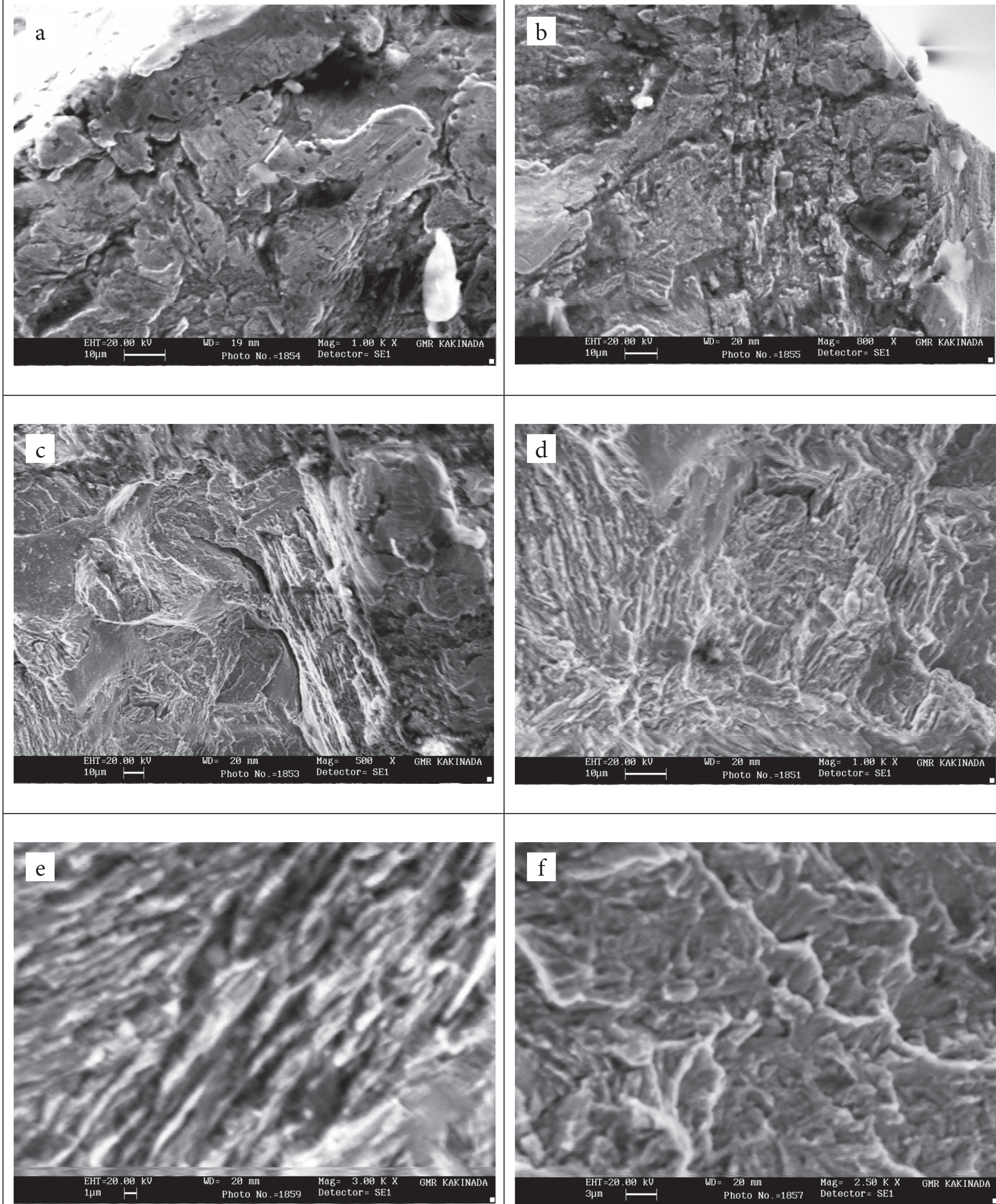


FIG. 8 FRACTOGRAPHY OF THE FAILED BLADE SAMPLE AT DIFFERENT REGIONS FROM THE DAMPING WIRE HOLE MINOR RADIUS

FIG. 9 STITCHED FRACTOGRAPHOF THE LACING WIRE HOLE EDGE –SIDE 1 (TOWARDS TRAILING END)

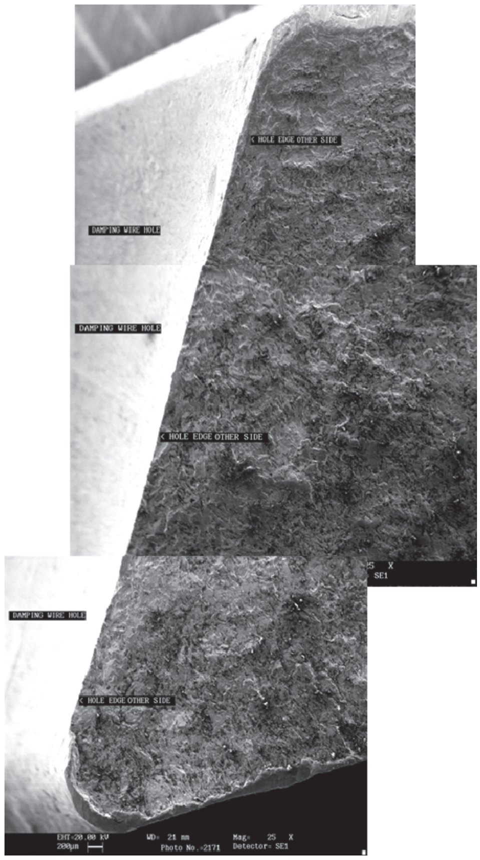


FIG. 10 STITCHED FRACTOGRAPHY OF THE LACING WIRE HOLE EDGE–SIDE 2 (TOWARDS LEADING EDGE SIDE)

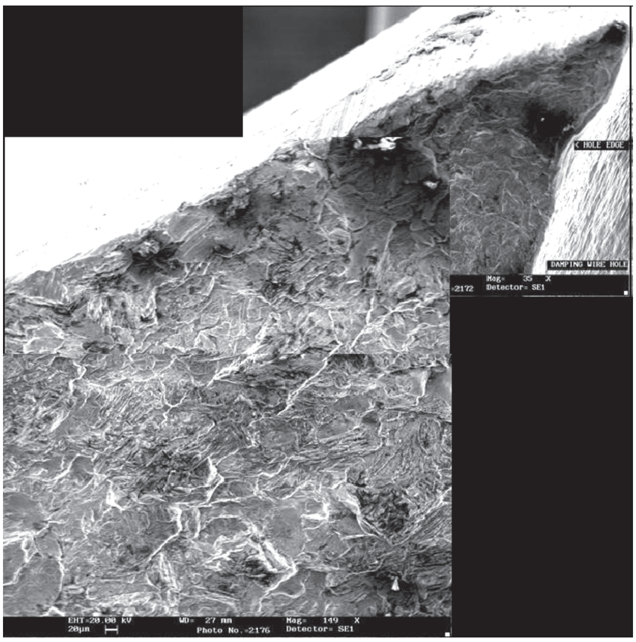


FIG. 11 FRACTURE MORPHOLOGY AWAY FROM THE DAMPING WIRE HOLE

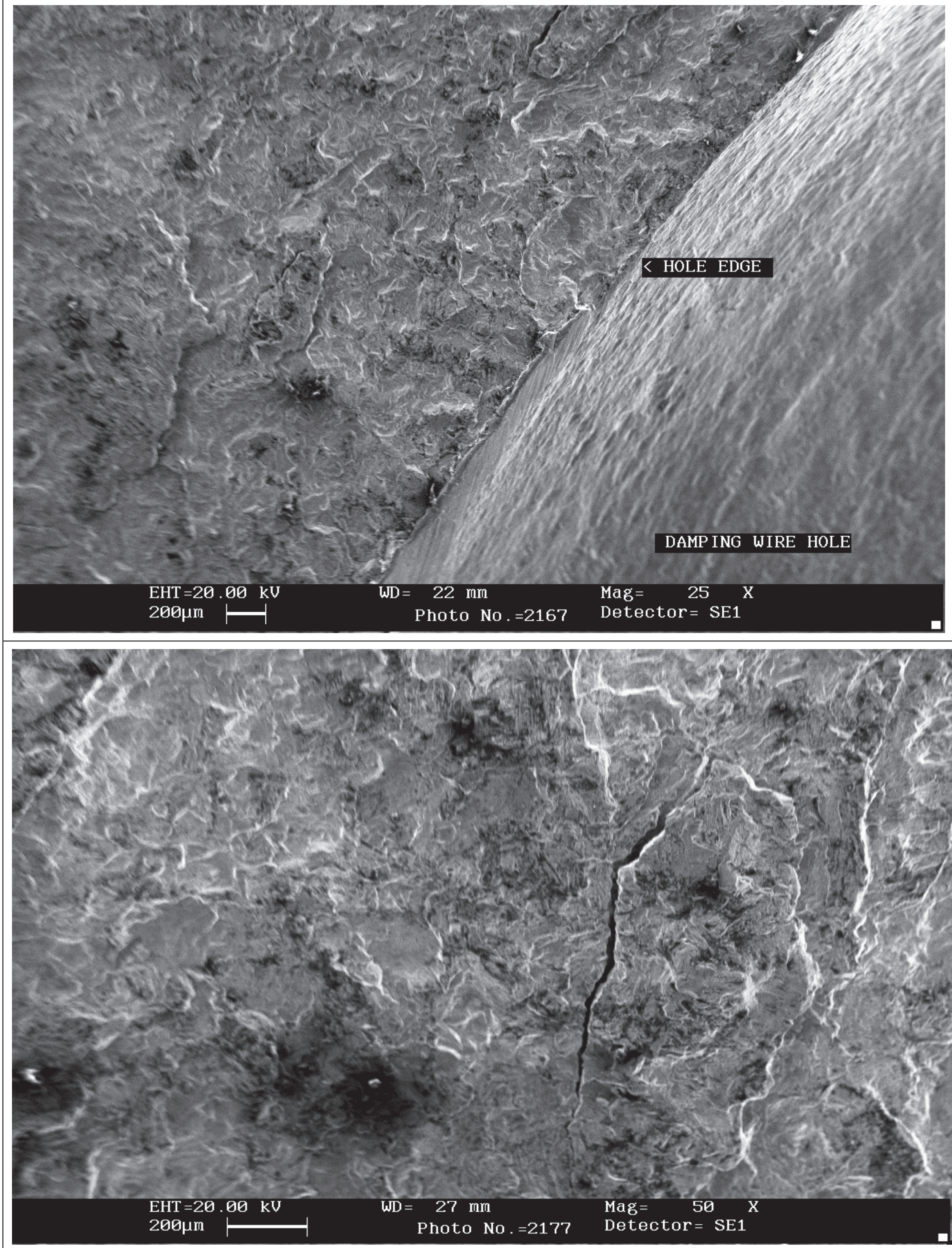


FIG. 12 FRACTURE MORPHOLOGY AWAY FROM THE DAMPING WIRE HOLE (CLOSE TO TOP END OF HOLE) SHOWING CRACKS AT ISOLATED REGION

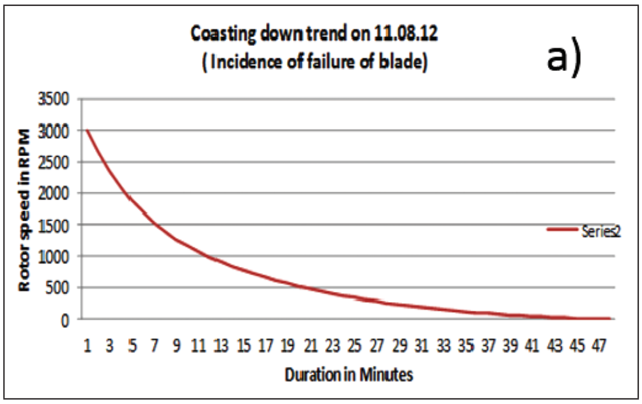
These vibrations have resulted in snapping of the blade damping wire and sleeve resulting in a crack. This will cause unbalance and further loss of positive damping. This resulted in excessive vibration levels from 0.8 to 13.67 mm/sec.

3.6 Coasting down signal analysis

The coasting down signal at the time of failure incidence was compared with other tripping conditions and the analysis results are shown in Figures 13 to 16. With the alarm, the machine tripped on load and took 47 minutes to stop. The coasting down of the turbine is smooth and if any damage would have occurred earlier, coasting downtrend would have shown disturbances. The comparison of coast down plots indicate that there is no friction/rubbing effect until the machine came to near halt. All last stage blades of condensing turbines will have fundamental natural frequencies of coupled bending and torsion. Unless there is an unsteady flow, the blade cannot vibrate. The metallurgical observations indicate that the blade has atorsional sign of failure.

At the time of machine tripping, the blade piece above the damping wire did not get released from the blade #36. This piece appears to have detached from the blade when the machine was about to stop. This is based upon circumstantial evidence of rubbing marks over a short length of approx. 1.5 meter of the casing, rather than the complete circumference.

After tripping, the rotor came to rest and it was put on barring gear for two days to cool down (78 rpm). No rubbing marks were observed on casing except for a short arc



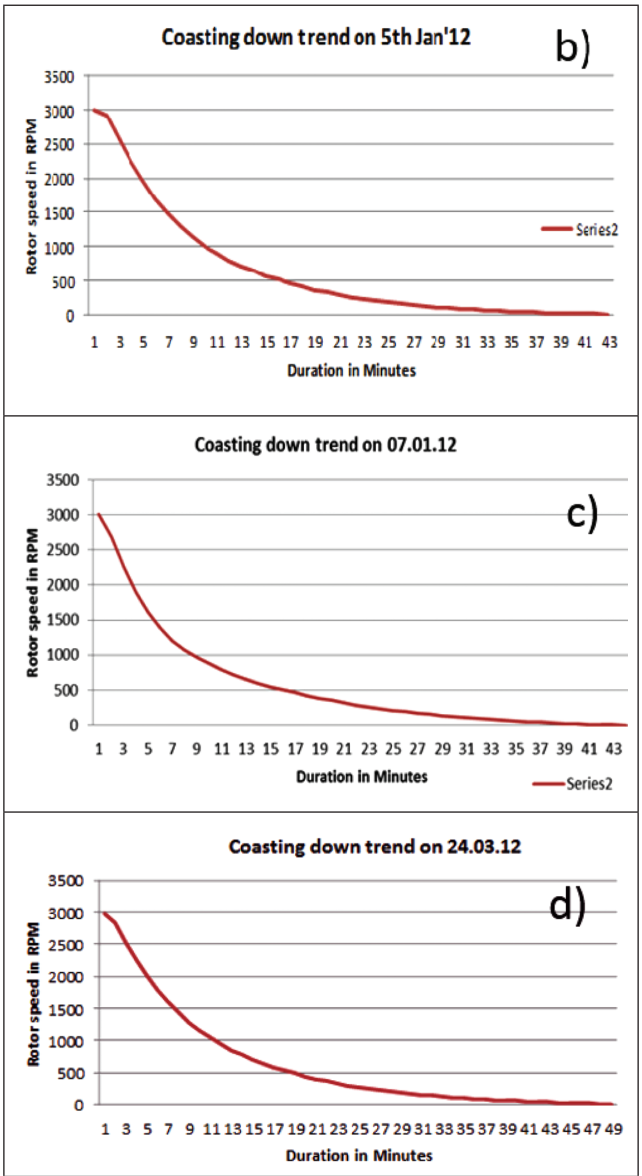


FIG. 16 COASTING DOWN TRENDS AT DIFFERENT TRIP CONDITIONS A) INCIDENCE OF FAILURE-AT 10 MW LOAD B) NORMAL TRIP CONDITIONS AT 17.5 MW C) 21 MW D) 23 MW LOAD

length of approx. 1.5-meter length. This is indicative of the fact that the snapping of fractured blade occurred just before the complete stoppage of the machine. Otherwise, the piece would have given rubbing marks around the periphery. The arc indicates that the possible speed of the rotor was approx. 25 rpm at the time of breakage of blade #36 and the broken piece was found.

During normal tripping conditions at 17.5 MW, 21 MW, and 23 MW load conditions, the coasting downtime was recorded to be ~43 to 48 minutes. The increased coasting down time during the blade failure load conditions of 10 MW, is mainly due to the fact that the machine got tripped under loading conditions (Figure 16a). The presence of a proportional quantity of steam present inside the turbine, in proportion to the load, provide additional inertia to the rotor.

4.0 DISCUSSION ON THE LABORATORY AND FIELD TEST RESULTS

Under the conditions of low part load conditions especially below 20% capacity, the occurrence of flow induced vibrations are prominent in the last stage of the turbine.

As per the data collected, the turbine was loaded close to 10 MW. The pronounced effect of steam churning occurring at these low load conditions will give rise to flow distortions and unsteady flow conditions during the operation of the turbine. Under continued operation would result in increased vibrations of the blade beyond the dampening capacity of the damping wire and lead to failure of the end joints of the damping wire initially followed by the sudden failure of the wire due to excessive bending stresses.

The ends of the damping wires in between the pockets act like a hinge due to coupling action. With the unsteady flow forces, when the coupling breaks, the damping wire will act like a cantilever on either side of the damping wire. Under the normal operational condition, the blade frequency will cross the resonant frequencies and the possibility of cracking becomes imminent especially at the damping wire hole corners where the stress intensity levels are maximum and thus vulnerable to initiation of hairline cracks.

The increased vibration values of close to 12 mm/s during the blade failure at the bearing against the normal vibration level of 2 mm/s are indicative of the blade subjected to abnormal vibration levels

The propagation of the hairline crack during the continued service under normal operating condition cause an increase in the gap between the damping wire hole and the wire. Under the conditions of sufficient gap, the top portion can acts like a heavy unbalance and the amplitudes of vibrations can raise very high and results into rubbing to the casing in the radial direction. This is being evidenced in the damage observed on the casing during the field visit.

As the evidence of pitting induced cracking is absent, the occurrence of failure is considered not directly related to corrosion since its extent was insignificant to play any role in the eventual failure of the blade.

The absence of both, the crack initiation region all along the edges of the damping wire hole and absence of characteristic fatigue features on the fracture surface is suggestive of the fact that the blade has not been subjected to prolonged fatigue-induced damage.

In summary, the key findings observed are:

- The analysis of failed blades did not show the occurrence of pitting both on pressure and the suction side of the blade surfaces.
- The fretting marks observed on the ID side of the lacing wire holes in both blades are typical of normal conditions indicative of damping provided by the lacing wires.
- The ultrasonically cleaned damping wire hole regions did not show any pitting marks and cracks and the surface chemistry observed on the damping wire hole did not show elements forming primary the corrosion deposits.
- The bump test carried on LP stage blades(except blade failed stage due to shaving off) randomly does not indicate any variation in the natural frequency.
- The torsional natural frequencies of the turbine generator are quite far away. Hence, torsional induced vibrations are not possible either due to resonance or due to frequency variation.
- The coast down signals and coast up signals are quite good. Hence the rotor bearing system cannot contribute to the failure of the blade.

- The evidence of pitting induced cracking could not be observed. The plant water quality data also lends support to this view (pH > 8). In the event of corrosion attack, its prevalence shall be observed throughout the steam flow circuit, which has not been observed in the present case.

Based on the laboratory examinations as well as the field data, the possible sequence of events leading to breakage of 40th stage, blade #36 was summarized as :

- The occurrence of self-excited vibrations with uncontrolled amplitude due to negative damping.
- These vibrations have resulted in snapping of blade damping wire and sleeve.
- Vibration levels in the machine rose from 0.8 mm/sec to 13.67 mm/sec.
- Machine tripped on high vibration and coasting down the sequence of the machine automatically initiated.
- In the absence of damping, the blade was continued to undergo vibrations at its natural frequency. In general, the last stage blades of the condensing turbine undergo combined torsion and bending vibrations. The synergistic effect of the failure of both damping wire and sleeve in combination with torsional and bending induced vibration caused the blade to fail in a short period of time (fast fracture). The observed ridges on the fracture surface lends support to this conclusion

5.0 CONCLUSIONS

From the metallurgical investigations, operational data and physical observations at the site, it is inferred that the blade has not failed due to corrosion or prolonged fatigue.

The probability of failure of the blade may be attributed to hairline crack initiation induced by the abnormal vibration level caused during low load unsteady flow operations

The occurrence of cracking in the anticipated most stress intensive lacing wire hole region of the blade as well as the pronounced overhanging effect of the damping wire onto the blade under the conditions of failure of sleeve suggestive of the fact that the blade has sheared due to sudden excessive vibration at the prevalent low load conditions during service.

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