FAILURE ANALYSIS OF COMPONENTS USED FOR POWER SECTOR APPLICATIONS

Dr. Vilas Gunjal and Dr. Uday Puntambekar
Electrical Research & Development Association (ERDA)

1. Introduction

There is a substantial increment in installed generation capacity in India to meet the increased demand of electricity. The generation plants and utilities strive to operate at higher efficiency to meet the supply requirements of consumer. However, failure of components at power generation plants and at transmission and distribution lines pose major concern in meeting the demands. The component failures lead to plant shut-down, repair and replacement which cause tremendous cost to utilities. In this regards, analysis of failure is essential tool to avoid or delay the failure.

Failures in the form "Fracture" are considered to be the most serious failures and are given immediate attention. However, distortions, corrosion and erosion are also important, and sometimes lead to fracture.
The failure analysis is a cross-disciplinary activity which cuts across the entire gamut of the engineering and mathematical sciences. Further, once the cause of the failure has been determined, it immediately becomes possible to identify and formulate remedial strategies to ensure prevention of similar failures in future.
In this paper, overview on failure analysis methodology is presented. Apart from this, various failure types commonly observed in power sector across generation plants and transmission utilities are also discussed.

2. Classification of Failures

Failures are characterized either on the basis of the types of "failures modes" or the type of "service conditions" in which failures has taken place. The failure mode based characterization takes into account classical modes of material failure in different conditions, while the service condition based characterization of failures considers only the type of environment the component has experienced before failure. The failure of engineering component mostly occurs in two mode based on nature of failure: instantaneous loading failure and progressive failure as shown in Figure 1.

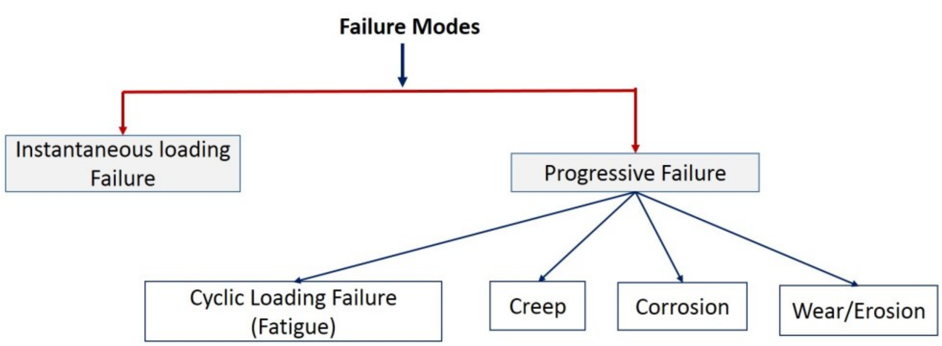

Figure 1. Various failure modes observed in engineering components

3. Failure Analysis Methodology

Failure analysis involves a systematic approach to identify possible causes and utilizes analytical techniques to pinpoint the exact cause(s). A failure investigation should determine the cause of a failure and based on that corrective action should be initiated to prevent the similar failures in future. A complex investigation usually requires the services of experts in several branches of engineering and the physical sciences. A four-phase approach generally followed for failure analysis is as below:

I) First phase –

a) Obtaining an overview of the failure.

b) Collection of background data / history and selection of samples.

c) Review of design specifications.

II) Second phase –

Detailed investigation which typically includes-

a) Fractography (Optical & SEM)

b) Material Composition Analysis (Conventional / EDAX /XRD)

c) Macro & Microscopic examination

d) Mechanical & Physical Property Evaluation

III) Third phase –

Advanced analysis, including

a) Stress Analysis / Fracture Mechanics

b) Testing Under Simulated Service Conditions

c) Reliability Analysis

IV) Fourth phase –

a) Synthesis of Results of Investigation

b) Formulation of Conclusions

c) Recommendations / Remedial Measures

4. Failures of Components Observed in Power Sector

The commonly observed failures of components in power sector (generation plants and transmission lines) are discussed below;

4.1 Failures at Power Generation Plants

Premature failure of boiler tubes located in various zones such as water walls, superheater, repeater, economizer, condenser etc. is one of the common phenomena observed in the power generation plants. These tubes mostly have finite life because of prolonged exposure at elevated temperature, stress and aggressive environments.

Other critical components commonly found failed at power plant includes turbine blades, shafts and other structured components such as bearings, bolts and flanges etc. The major failure mechanisms responsible for the rupture of these components are creep, fatigue, erosion and corrosion. Figure 2 shows the schematic representation of component failure mechanisms observed at generation plants.

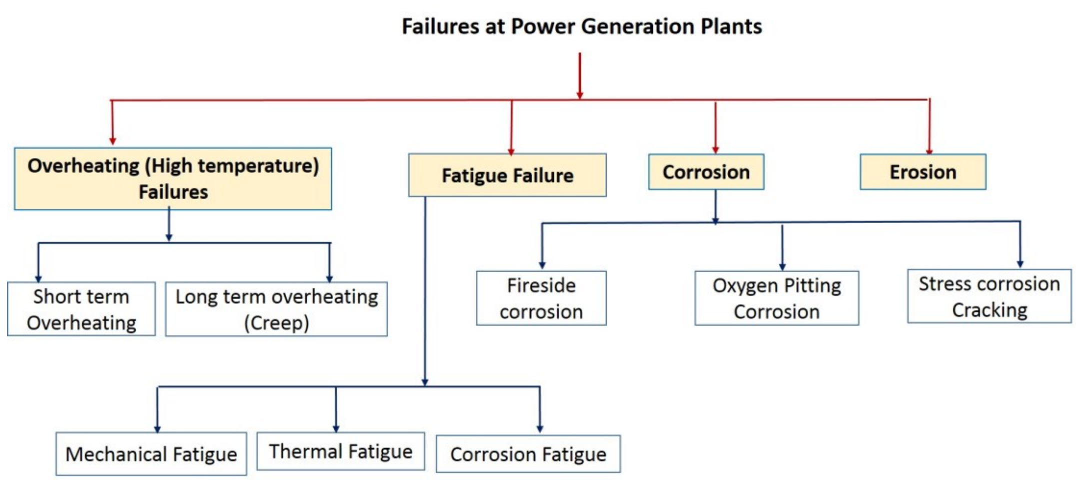

Figure 2. Schematic representation of failures types observed in power generation plants

4.1.1 High Temperature Failures

The exposure of boiler tubes above the design temperature results in overheating. The rise in temperature above design temperature can occur because of multiple factors such as increase in heat flux, internal deposit build up, reduced steam flow, non-uniform steam flow and improper burner adjustments etc. There are mainly two mechanisms associated with boiler tube overheating failure; 1) Short term overheating and 2) Long term overheating.

1) Short term overheating

Short-term overheating occurs when boiler tube is heated most probably locally to well above design temperature of the tubing material. This failure is also termed as thin lip rupture due to its appearance as shown in Figure 3. Thin lip rupture is a characteristic of stress rupture failure that is initiated by localized bulging and excessive tube wall thinning. The exposure of tube at very high temperature results in decrease in strength. Then, rupture of tube occurs when the stress on the tube wall (Hoop stress) is higher than material strength at that high temperature.

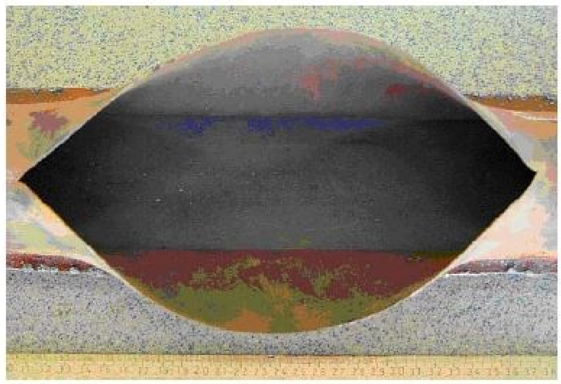

Figure 3. Boiler tube failure due to Short term overheating [1]

2) Long term overheating (Creep failure)

Time dependent deformation of component due to prolonged exposure at higher temperature and stress is known as creep. At high temperature, softening phenomena which are controlled by diffusion phenomena such as dislocation climb, dislocation annihilations, grain boundary diffusion and sliding, structural degradation such as spheroidization, primarily dominates the deformation and rupture behavior of material. In comparison to short term overheating, creep failure (long term overheating rupture) usually takes a much longer time in the order of five to twenty years because the temperature of boiler tube is slightly above the design. Long-term overheating damage usually occur with a small amount of creep deformation and results in thick lip rupture appearance as shown in Figure 4.

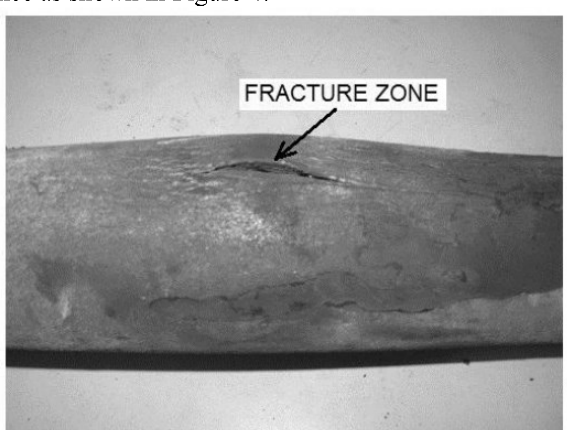

Figure 4. Boiler tube creep failure due to long term overheating [2]

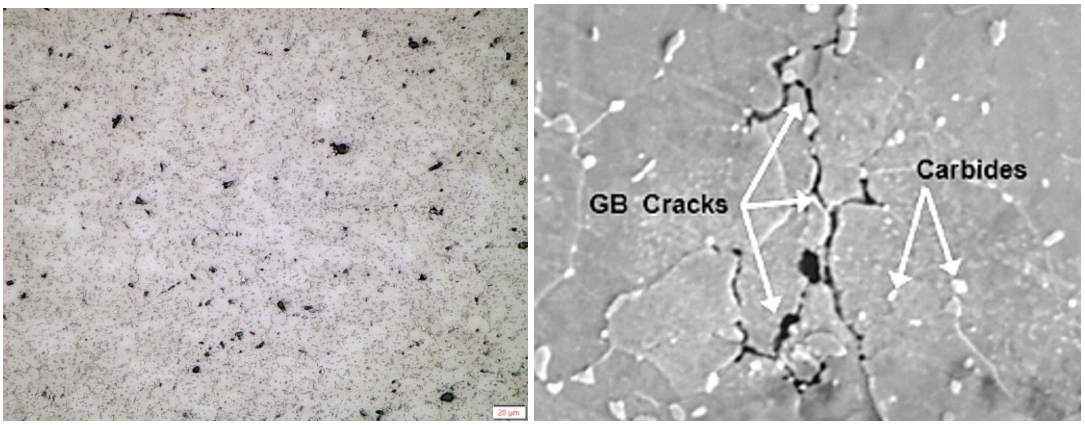

Figure 5. Microstructures of long term overheating failed tube (a) Optical micrograph; (b) SEM micrograph indicating presence of significant spheroidization and void formation during failure [3]

4.1.2 Fatigue failure

Fatigue failure of engineering components and structures occurs through progressive damage due to presence of fluctuating cyclic stresses. Although, fatigue is progressive damage over time, the final fracture occurs instantaneously without any prior indication. The fatigue fracture occurs in three steps: crack initiation, propagation and final fracture. The cracks mostly initiate at the surface due to fluctuating loading and unloading. Then propagates inside the material forming striations, beach marks and finally fracture occurs when material's load bearing capacity decreases below critical stress limit. Figure 6 shows the fracture appearance of fatigue failure indicating characteristic features of fatigue such as ratchet marks (crack initiation sites), beach marks, striations in propagation zone and final smooth/fibrous fracture zone.

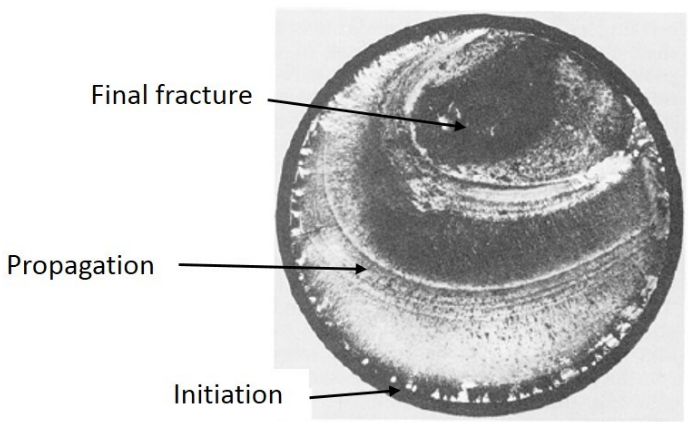

Figure 6. Fatigue fracture characteristics: Initiation, Propagation and Final fracture zones [4]

4.1.3 Corrosion Failures

Corrosion of boiler tubes on external wall surface and internal wall surface is one of the reasons for failure. Various corrosion mechanisms such as fireside corrosion (ash corrosion), flue gas corrosion, oxygen pitting corrosion, caustic corrosion, stress corrosion cracking (Sulphur, chloride environment) are observed in boiler components. Corrosion sites can act as a crack initiation sites for stress assisted cracking of boiler tubes.

i) Fireside corrosion:

Fireside corrosion of superheater, reheater and water wall tubes is high temperature corrosion in fossil fuel combustion boilers. It is mainly caused due to presence of Sulphur, alkali metals and chlorine in the coal, oil or natural gas. During combustion of fuel sodium sulphate and oxides (such as V_2O_5) are formed which are known as ash deposits. These low melting point deposits formed on the surface of superheater and reheater tubes dissolve metal protective oxide layer on the fire side of a tube which is known as fire side corrosion of tube.

Figure 7. Photograph of superheater tube surface with thick deposits due to corrosion [5]

ii) Oxygen pitting corrosion:

The pitting corrosion at internal wall of boiler tube mostly occurs due to dissolved oxygen in water. The localized corrosion pits formation (Figure 8a) occurs when protective layer (magnetite/Cr oxide) breaks down at internal wall surface. These pits acts as a fatigue crack initiation sites (Figure 8b) and are responsible for corrosion fatigue/stress assisted corrosion failure.

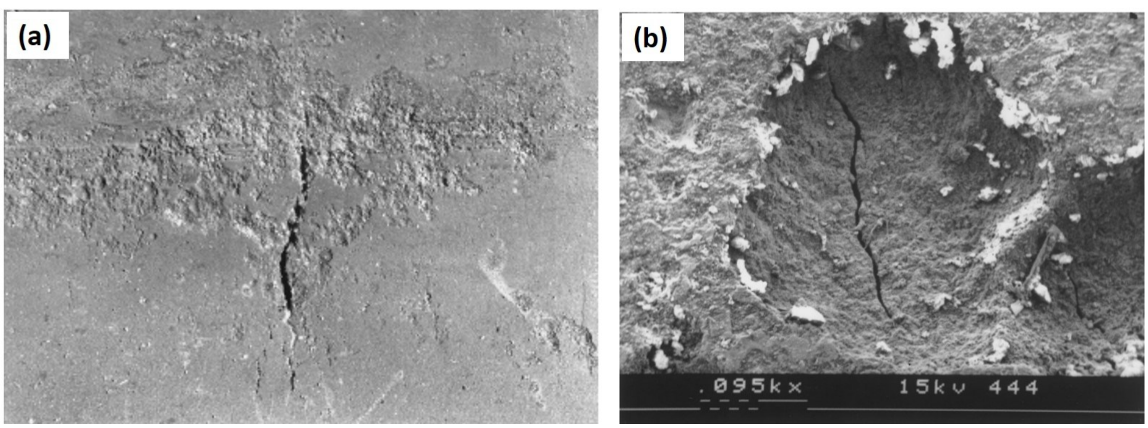

Figure 8. (a) Photograps of oxygen pitting (b) SEM mcirograph indicating fatigue crack initiated at the bottom of pit [6]

iii) Caustic Corrosion:

The caustic corrosion of tube surface is the thinning of tube caused by caustic soda attack. It results in irregular deposit of whitish sodium carbonate (residue of caustic soda reacting with carbon dioxide in air). Solid deposits from water such as calcium and magnesium salts, silica, manganese and iron can form scale in a boiler. Under these scales, sodium salts are trapped which cause corrosion and remain unseen until you remove the scales.

The caustic treatment is commonly used to prevent failures of hydrogen damage and acid phosphate corrosion. In case of improper monitoring and control of boiler water pH, excessive amount of NaOH in boiler water can result in inevitable caustic gauging [7, 8].

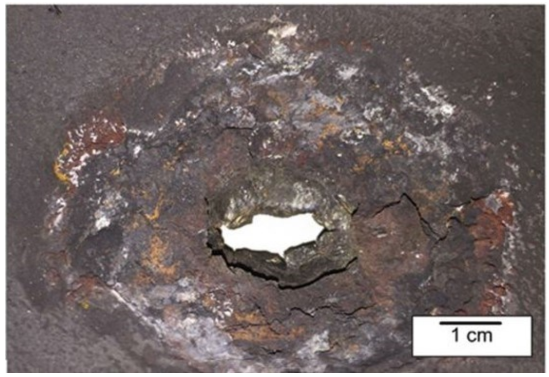

Figure 9. Caustic corrosion failure of tube. It shows white color deposits near the rupture [9]

iv) Stress corrosion cracking:
Stress corrosion cracking (SCC) commonly observed in stainless steels is the failure in presence of stress and corrosive environment. In case of austenitic stainless, sensitization (Prolonged heating of in ~415-810 ºC sensitization temperature regime) results in chromium depletion in the vicinity of carbides precipitation at grain boundaries making it susceptible to intergranular corrosion or intergranular stress corrosion cracking (Figure 10a). The failed component exhibit brittle, thick edged failures without any significant deformation. The crack propagation in SCC leads to branching as shown in Figure 10b. The stresses responsible for cracking can be thermal stresses due to restraint, hoop stress due to water/steam pressure, residual welding stress etc.

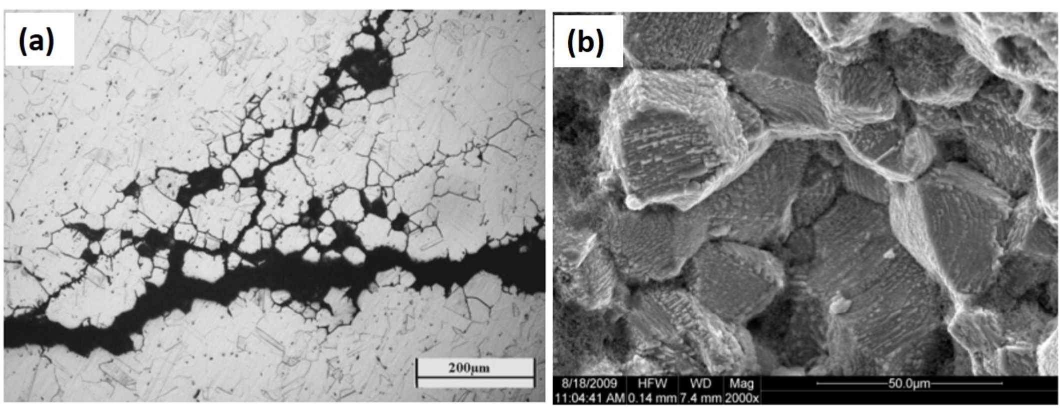

Figure 10. Microstructure of SCC (a) Optical micrograph (b) SEM micrograph of fracture surface indicating intergranular cracking [10]

4.1.4 Erosion
The erosion is a wear failure of tube which results in thinning of tube by material removal by the action of solid particles impinging on it. The combustion products of coal contain fly ash particles, soot blow, which impinge on boiler tubes and erode them. Figure 11 shows the tube failure due to erosion. It indicates significant thinning of external wall surface due to erosion. The reduction in strength of material due to thinning causes rupture of tube.

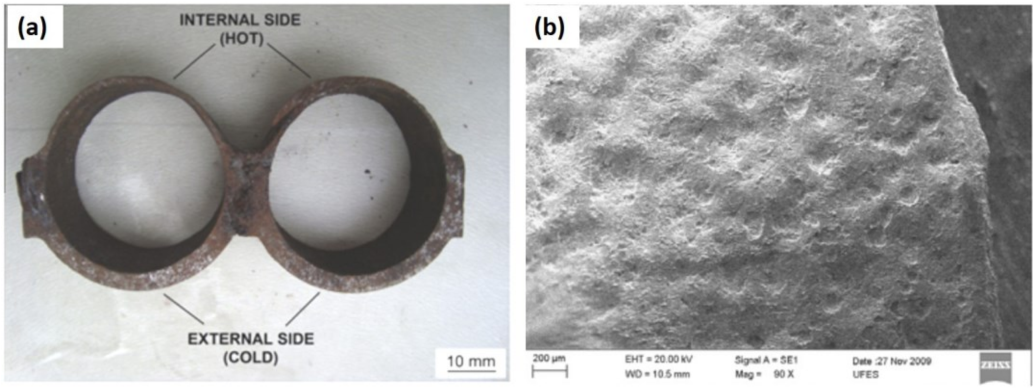

Figure 11. Erosion Failure (a) Photograph of boiler tube indicating erosion on fire side surface (b) SEM micrograph of eroded surface [11]

4.2 Failures at transmission and distribution utilities

Overhead transmission lines conductors carry electrical energy from generating stations to distribution stations and to consumer. These are bare conductors above the ground levels, supported between two towers and susceptible to failure due to extreme environmental conditions such as heavy wind in forest and hill areas, humid and corrosive coastal regions etc. The most deteriorating problems in conductors are mechanical fatigue and corrosion of conductor wires.

The fatigue failure of conductor strand mostly occurs due to aeolian vibration and wear, especially at devices such as spacers, clamps etc. which restrain its movements. The aeolian vibrations results in bending stress and clamping torque on the conductor to initiate the fatigue. The fatigue crack initiation mostly occurs due to fretting/wear near the contact and finally fails typically at 45° as shown in Figure 12.

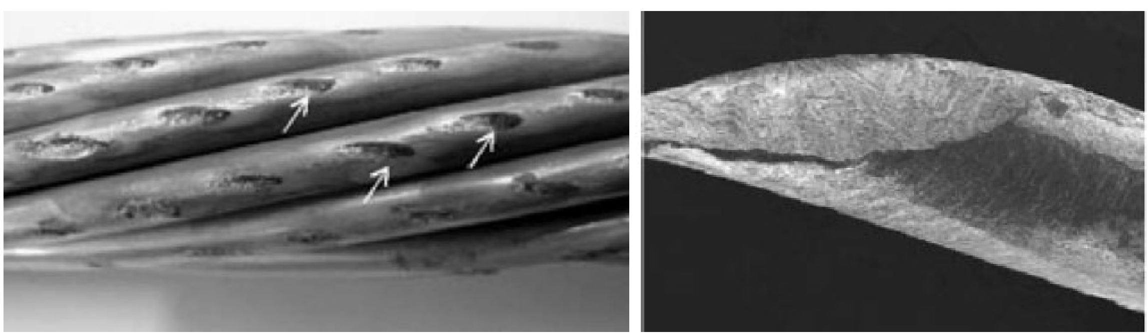

Figure 12. Photographs of fatigue failure of ACSR conductor. (a) Fretting marks on strands near clamp area; (b) failed strand indicating fracture at 45° [12]

The environmental factors such, as industrial pollution, marine salts, humidity in the air etc. are the reasons for corrosion of conductor strands. In case of ACSR conductors damage of preventive coatings (zinc coating) of steel core results in galvanic corrosion, making aluminum wires anodic, leading to aluminum strand failure. (Ref. Fig. 13)

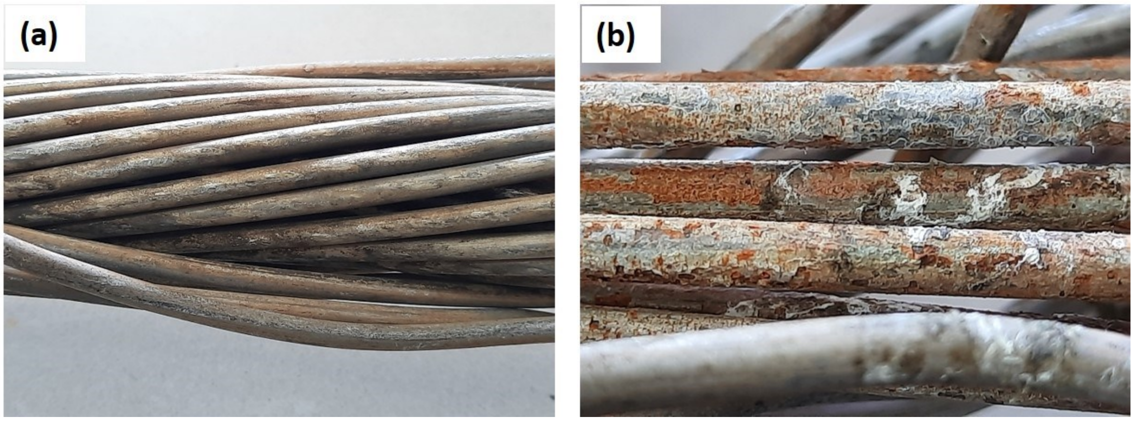

Figure 13. Photographs of ACSR conductor indicating corrosion of strands (a) Aluminum strands (b) steel strands

5. Closure

Failure Analysis is a systematic study involving various tools & techniques such as material characterization, design, fracture mechanics, etc. The science and technology of failure analysis are now well developed. Documented procedures / guidelines are available in various reference handbooks. It is suggested that the industry should make use of failure investigation not only for avoiding repetitive failures but also for gaining crucial inputs for their product development / improvement cycle.

References

1. Graham R. Lobley and Waleed L. Al-Otaibi, “Diagnosing Boiler Tube Failures Related to Overheating”, Advanced Materials Research, Vols. 41-42 (2008), 175-181
2. Atanu Saha and H. Roy, “Failure Investigation Of A Secondary Super Heater Tube In A 140 MW Thermal Power Plant”, Case Studies in Engineering Failure Analysis, Volume 8, April 2017, 57-60
3. Pramanick et al. “Failure Investigation Of Super Heater Tubes Of Coal Fired Power Plant”, Case Studies in Engineering Failure Analysis, 9 (2017), 17–26
4. ASM Handbook, Volume 11, Failure analysis and Prevention, page No 1498.
5. David N. French, “ Understanding Fireside Corrosion”, David N. French Metallurgists News Letter, 2015
6. A. M. Heyes, “Oxygen pitting failure of a bagasse boiler tube”, Engineering Failure Analysis, 8 (2001), 123-131
7. Srikanth S. et al., Phosphate induced stress corrosion cracking in a waterwall tube from a coal fired boiler. Eng. Fail. Anal. 10 (2003); 491–501.
8. Fatah et al., “Caustic Corrosion In A Boiler Waterside Tube: Root Cause and Mechanism”, Engineering Failure Analysis, 28 (2013), 69–77
9. Y. S. Kim et al., “Bulging Rupture and Caustic Corrosion of A Boiler Tube In A Thermal Power Plant”, Engineering Failure Analysis, 104 (2019), 560–567.
10. Shugen Xu et al., “The Stress Corrosion Cracking Of Austenitic Stainless Steel Heat Exchange Tubes—Three Cases Study”, Proceedings of the ASME 2010 Pressure Vessels & Piping Division / K-PVP Conference PVP2010, July 18-22, 2010, Bellevue, Washington, USA
11. S. S. M. Tavares et al., “Failure of ASTM A-106 Gr. B Tubes By Creep and Erosive Wear”, Engineering Failure Analysis, 26 (2012), 337–343
12. C. R. F. Azevedo and T. Cescon, “Failure Analysis Of Aluminum Cable Steel Reinforced (ACSR) Conductor Of The Transmission Line Crossing The Parana´ River”, Engineering Failure Analysis, 9 (2002), 645–664