



Failure Analysis of Spillway Gate of a Hydro Project - A Metallurgical Perspective

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Abstract. The spillway gate plays a crucial role in ensuring the safety and structural integrity of a dam in any hydroelectric project, as it regulates the reservoir's water level to prevent it from exceeding its maximum capacity. Understanding the mechanism and causes of spillway gate failures is essential for enhancing their safety and improving reliability of the gate. The present case study investigates the analysis of a spillway gate failure of a hydropower plant in which the girder plate cracked in between the spindle support flanges. In-depth metallurgical analysis along with macro-study were carried out to identify the cause of failure and further preventive action plan was proposed. Microstructural analysis revealed that repair welding was carried out at the failed location which compromises the structural integrity of the component. The findings highlight the need to strengthen the quality assurance management and fabrication procedures for spillway gates to ensure their reliability and performance.

Keywords: Spillway gate, girder beam, microstructure, weld structure

1 Introduction

A spillway is a critical structure in a dam or reservoir designed to safely discharge excess water downstream during times of high inflow, such as during heavy rainfall or rapid snowmelt. The spillway ensures that the water level in the reservoir does not exceed its maximum capacity, thereby protecting the dam structure and preventing downstream flooding. A spillway gate is a mechanical structure installed on a spillway to control the flow of water released from a dam or reservoir [1–3]. It is a crucial structure on spillway for flood management, reservoir level control, and operational flexibility in hydropower and water management projects. It can be of different types depending on their construction and operation mode such as radial (Tainter) gate, vertical lift gate, flap gate, sliding gate, sector gate, rolling gate etc [4–6]. A flap gate on a spillway is a hinged gate designed to control the flow of water over a spillway crest. It is typically hinged at the bottom and operates by tilting backward or forward to regulate water discharge. Flap gates are commonly used in spillways where flexibility in flow control is required. They are particularly effective in low to medium head applications [6]. A key structural component of the flap gate is the girder beam, which plays a crucial role in bearing and distributing the substantial mechanical loads

acting on the gate. It is basically a primary horizontal support beam that spans over the entire length of the gate. To accommodate the spindle shaft, which facilitates the gate's movement, flanges were fabricated at both end of the front panel of the girder beam for support and alignment of the spindle shaft.

Failures of spillway gates have occurred worldwide due to various reasons. Failure of Folsom dam is a well-known example of spillway gate failure. The incident occurred in the year 1995 where the spillway gate failed due to fatigue cracking and corrosion [7–9]. Another incident occurred at Oroville dam at California in 2017. In this case the erosion of the main spillway takes place during high discharge [10]. Moreira et al. investigated the failure of piston rod in spillway floodgate. The piston was made up of AISI 410 steel which failed because of improper heat treatment leading to stress corrosion cracking [11]. In general, the common causes of spillway gate failure are material degradation, design inadequacies, operational error, inadequate maintenance and natural disasters [4,12,13]. In general, material degradation includes corrosion, fatigue or ageing of structural component whereas operational error includes delay in opening of gates or incorrect gate operation during emergencies. Inadequate maintenance indicates lack of regular inspection, repair of gate components, hinges, seals and hydraulic systems.

While these general failure modes are well-documented, however it was observed that there was limited literature available specifically addressing failures involving critical structural elements such as the girder beam particularly in flap gate designs. Notably, no published studies were found on the failure of the girder beam in flap gates. The present case study was taken from a hydropower project in which the girder beam plate between the spindle support flanges observed to be fractured. This fracture led to the failure of one of the spillway gates while other gates remained operational and did not result in any operational disruptions or casualties. This article presents a metallurgical failure analysis of the spillway gate of a hydropower project using visual observation, microstructural and mechanical analysis.

2 Methodology

2.1 Visual observation

Site visit was conducted to understand the failure, where it was observed that the failure had occurred on the spillway gate of a hydropower project. It has a chute type spillway consisting of six gates. The failure occurred in one of the spillway flap gates during operation. The flap gate suddenly fell down and became inoperative. Visual observation was carried out at failure site and on failed component and documented with several photographs which is shown in figure 1 and 2. The failure was observed in the girder plate between both the flange joint. The flange was taken from the site and cut using gas cutter into smaller parts for laboratory analysis which is shown in fig.2. One side of the girder plate has flange joint while the other side of the girder plate has shown weld spatters at the crack line.

2.2 Chemical composition

The chemical analysis was carried out using Optical Emission Spectrometry (OES) method (Make: M/s Thermofischer Scientific, ARL 3460). The analysis was performed at a flat location on the girder plate. Prior to the analysis, the sample surface was ground using emery paper to prepare a flat area with minimum dimensions of $12 \times 12 \text{ mm}^2$.

2.3 Microstructural analysis and mechanical testing

For the microstructural study, small specimens were extracted from selected locations of the sample based on the area of interest using a precision abrasive cutting machine and proper precaution was taken to avoid heating of the sample as marked in Figure 2(f). All the selected specimens were then mounted ensuring proper edge retention for further metallography study purpose. The mounted specimens were subjected to multiple stages of grinding and polishing process to obtain a mirror-finish surface. The final stage of the polishing operation was carried out using a specific cloth suitable for $0.5\text{--}1 \text{ }\mu\text{m}$ diamond paste. These metallographic specimens were examined under an optical microscope in both unetched and etched conditions to understand different microscopic features of the failed sample. Etching of the sample was performed using a 2% Nital solution. After the metallographic study, the molded samples were taken for microhardness measurement using a Vickers microhardness tester with a load of 0.5 kgf and a diamond indenter. The sample was prepared for tensile analysis from the region adjacent to the flange for mechanical tensile testing. The tensile specimen was prepared and tested as per the standard IS 1608:2005 [14].

3 Results and Discussion

3.1 Visual observation

During site visit it was observed that one of the spillway flap gates was fell down. Fig. 1(a) showed one of the operational spillway gates. It is to be noted that in the figure, it has two lifting spindles shaft (or lifting bracket) which support the girder beam of the gate. During flap gate operation, the flap gate suddenly fell down and went inoperative. The failed spillway gate was shown in fig 1(b). It showed the shearing of the front plate of girder beam in between lifting bracket shaft which is shown in fig. 1(c & d). At one end of the lifting bracket, the shaft was found detached, while at the other end, the front panel (or plate) of the girder beam was observed to be hanging. The thickness of the girder beam plate was 14 mm. The front panel of the beam failed in between flange area across the 400 mm width of the plate as can be seen from fig 2(a). The bottom part in between the flange was bend inward. The rear surface of the plate showed weld deposits on the fracture edge just below the top surface which was shown in fig 2(d). Keeping the crack part safe, the flange joints were cut using gas cutter for further analysis (fig. 2(c)). The samples for metallurgical sample were prepared as shown in the fig 2(f).

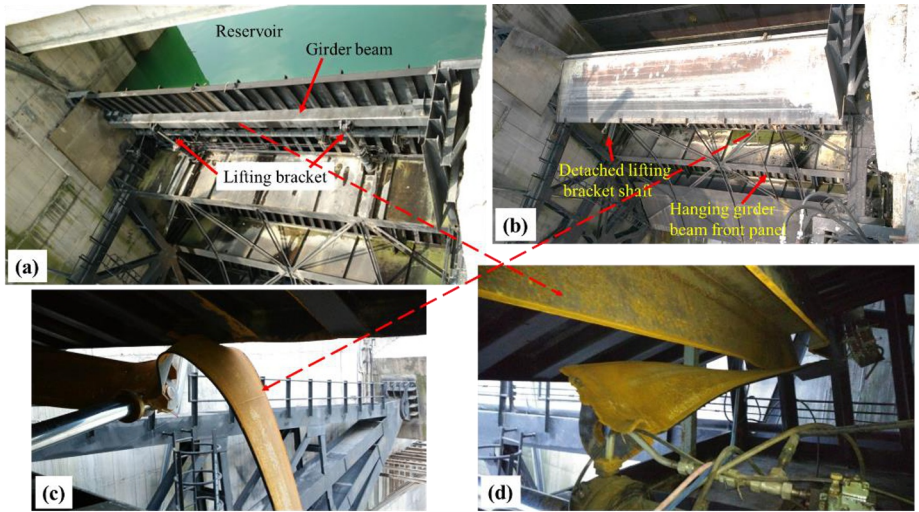


Fig. 1. (a) Image showed the operational spillway gate (spillway side view). It showed the normal condition of girder beam and lifting bracket with two spindles on both side of the gate; (b) Image showing the failed spillway gate. It showed detached lifting bracket shaft and hanging front panel of box beam (indicated by arrow); (c) Bending of front panel of girder beam at one side of the gate; (d) Other side of the gate showed failed flange part and tearing of front panel of girder beam.

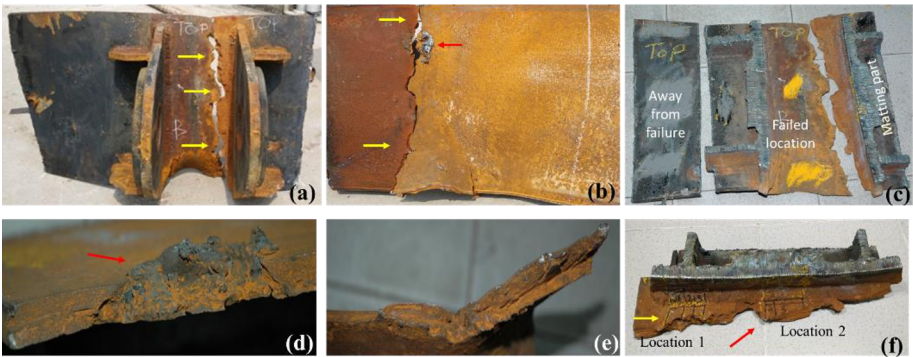


Fig. 2. (a) Image showed the crack in between the spindle support flange (marked in yellow arrow); (b) Rear side of the plate showed crack (marked in yellow arrow) and weld spatter (marked in red colour). It also showed bending at the bottom part; (c) The flange joint was cut for obtaining failure location: two mating parts of failure and one away from failure; (d) Fracture edge at mid-section showed blacking appearance weld material deposit; (e) Fracture edge at bottom side showed weld spatter; (f) Image showed the marking for metallurgical sample.

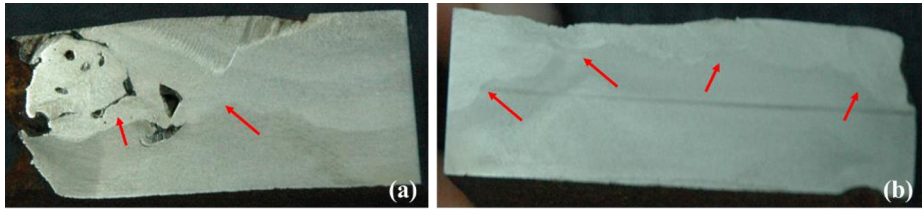


Fig. 3. (a) Cross-sectional view of polished surface at failed location shows metal deposit and weld porosity; (b) Cross-sectional view of the tube shows multiple welded structure.

3.2 Chemical composition

The chemical composition of the plate was carried out using Optical Emission Spectrometry (OES) method, was presented in table 1. The chemical composition of the plate conformed to be IS 2062 E410 (Fe540) Grade material. Here, CE in the table stands for carbon equivalent.

3.3 Microstructural analysis and Mechanical testing

Microstructural analysis was carried out at different locations as marked in fig. 2f. The macrostructure at fracture edge showed presence of weld porosity, multiple weld layers and inhomogeneity (fig 3a). Furthermore, a weld structure with varying layer thicknesses was observed on the surface of the plate. Weld build up was also observed in all the samples along the fracture edge as shown in fig. 3b. Thick oxide scale at the fracture edge was also observed.

Microstructure at fracture edge on flange side and rear side of girder plate showed welded structure (fig. 4 (a, b & d)) which indicated that a repair welding was carried out at that location. Repair welding is very critical part of operation and maintenance. If it is not done in proper way, it led to catastrophic failure of the component [15,16]. It also showed weld porosity with range varies from 0.8 mm to 1.25 mm. Magnified view (fig. 4c) showed the oxide scale penetration in to the material at fracture edge. Microstructure at mid thickness of the plate showed ferrite-pearlite structure. Microstructure at location 2 (fig. 5) showed sever inclusions in the material at fracture edge. Inclusion was also observed at the weld structure at flange side. The mid-section of the plate showed ferrite-pearlite structure.

Table 1. Details of the sample taken for case study

Steel grade	C	Si	Mn	S	P	CE
E410 (Fe 540) grade	0.20	0.45	1.50	0.045	0.045	0.44
As per IS 2062:20	max	max	max	max	max	max
Analyzed						
(base metal)	0.17	0.31	1.45	0.043	0.027	0.41

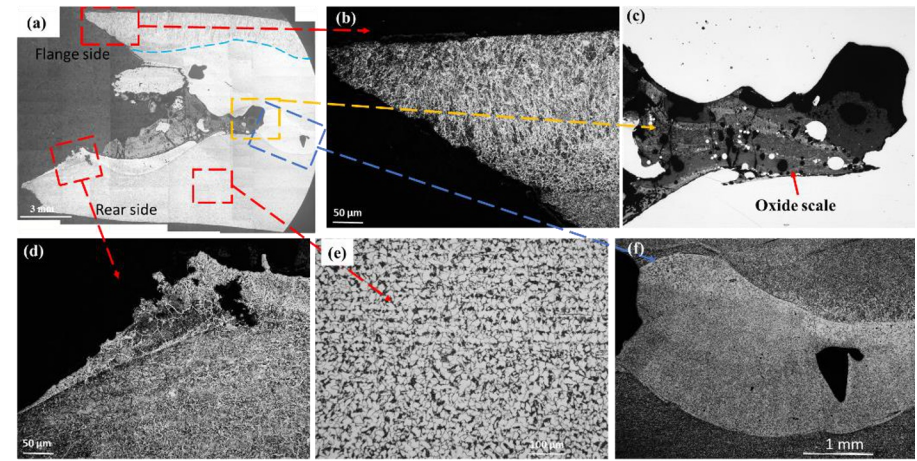


Fig. 4. (a) Microstructure showed weld structure and thick oxide scale; (b) Magnified view of the marked location indicated the weld structure (etched condition); (c) Magnified view at centre area showed oxide scale penetration (unetched condition); (d) Microstructure at rear side also showed weld structure with weld porosity (etched condition); (e) Microstructure at mid-section showed ferrite-pearlite structure (etched condition); (f) Microstructure at marked location showed weld porosity (etched condition).

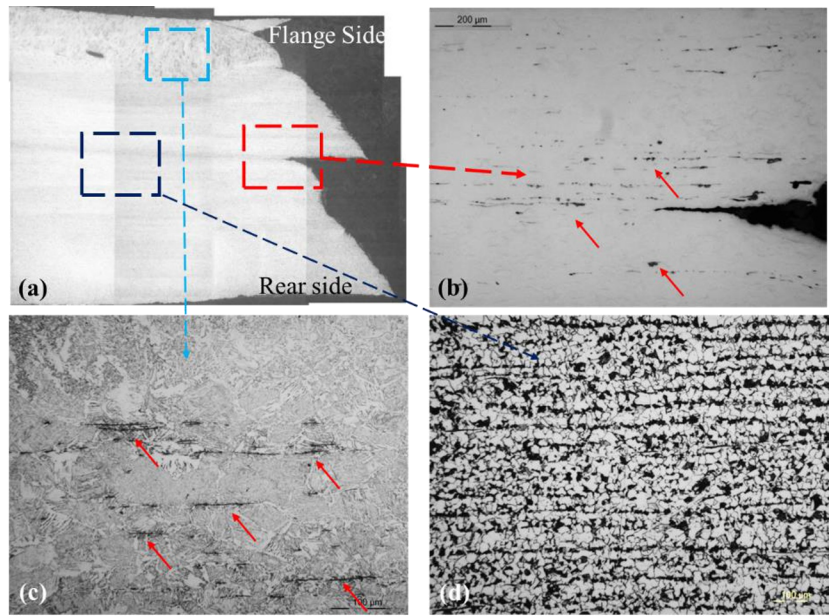


Fig. 5. (a) Microstructure at location 2 showed different structure at different location (unetched condition); (b) Microstructure in unetched condition showed inclusion at fracture edge; (c)

Microstructure at flange side showed weld structure and inclusion (etched condition); (d) Microstructure at mid-section of the plate in etched condition showed ferrite-pearlite structure.

The hardness of the sample at fracture edge having weld structure side was in the range of 269 – 280 HV0.5 while the hardness away from failure was in the range of 228 – 236 HV0.5 which is in accordance with the observed microstructure. The yield strength and ultimate tensile strength obtained from the tensile test are 468.2 MPa and 572 MPa respectively.

4 Conclusion

The failure analysis of the spillway flap gate sample was conducted through visual inspection, chemical analysis, microstructural examination, and mechanical testing. The conclusions drawn from the study are as follow:

- Chemical analysis showed that the material grade conformed to specified grade (E410 (Fe 540), IS 2062:20).
- Tensile analysis confirmed that the base material met the required strength as per the grade specifications.
- Microstructural study at the fracture edge showed evidence of weld deposits, inclusions, weld porosity, oxide scale, and multiple weld layers.
- These findings inferred that repair welding was carried out at the failure location and the quality of repair welding was not maintained properly. The weld repair procedure compromised the structural integrity of the component under operational load conditions.
- It is recommended to use new material as per the specification and avoid repair welding on structural members at load-bearing location to ensure reliability and safety of the components while operation.

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