Analysis and Treatment of Cracks in the Francis Turbine Runner of a Hydropower Station

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Abstract. This paper presents a statistical analysis of the occurrence of cracks in the runner of mixed-flow turbine in three units of a factory over a continuous period of five years. Due to the complex shape of the blade outlet connection resulting from welding processing and the high residual stress after welding, this area is prone to cracking. Most cracks show a trend of convergence after treatment, but some cracks do not converge after repair welding. This paper conducts a comprehensive analysis of various factors such as runner design, operating conditions, and repair processing techniques, and finds that welding processes and operating conditions have a significant impact on crack formation. To address the issue of repeated crack occurrence, this paper incorporates requirements for the operable area of the runner into the operating regulations and strictly controls the on-site welding process of the runner, focusing on quality control in every step such as preheating, stress relief, insulation, and linear grinding. Ultimately, the problem of repeated crack occurrence in the runner is successfully resolved, achieving effective control over runner cracks.

Keywords: Water turbine cracks; Convergence; Strength; Resonance; Operating conditions; Welding technology

1 Introduction

The turbine, as the core equipment in a hydropower station, primarily functions to convert the kinetic and potential energy of water flow into mechanical energy, which then drives the generator to produce electricity. However, during the long-term operation of turbines, the issue of cracks in the runner, a critical component, has been a focal point of concern in the industry. In recent years, with the expansion of hydropower station construction and continuous technological advancements, significant improvements have been made in turbine capacity, efficiency, and specific speed. Simultaneously, the design of runner blades has become increasingly complex, with larger sizes and thinner profiles, to adapt to varying hydraulic conditions and enhance power generation efficiency. Unfortunately, these design changes have also increased the risk of cracks developing in the runner blades during operation. The occurrence of cracks not only reduces the structural strength of the runner, increases the risk of failures, but also may shorten the equipment's service life, seriously affecting the stability and safety of

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hydropower stations. Therefore, research on cracks in turbine runners holds important practical significance and engineering value. This article takes a hydro-generator set in a hydropower plant as an example for analysis. A hydropower plant is equipped with three 150 MW vertical shaft mixed flow turbine generator sets, with a rated head of 80 m, a nominal diameter of 4.8 m, 14 blades and a rated speed of 142.9 r/min. During the operation of the three units, the runner blades all had cracks of varying degrees, with crack lengths ranging from 10 to 230 mm, some of which were through cracks. After multiple treatments during maintenance, the number of runner cracks did not decrease significantly, and at the same time, cracks repeatedly appeared in the same parts of some blades. If the cracks cannot be effectively cured, continued development during operation will bring greater safety hazards to the unit. A detailed analysis is required to avoid frequent cracks in the runner.

2 Analysis of the Causes of the Runner Cracks

There are many reasons for cracks in Francis turbines, such as deficiencies in runner design, processing and welding, operating conditions, and repair processes, which can all lead to cracks during operation. The cracks in the runner may be caused by one of these factors, or by the superposition of several of these factors. It is necessary to analyze each one of them, find out the main factors, and treat them in a targeted manner [1].

2.1 Analysis of Crack Occurrence

Crack Situation of Unit 1. The figure 1 shows the crack situation of each blade of the runner of Unit 1 from 2015 to 2019. From the statistics, it can be seen that the number of blades with cracks is large and the cracks are universal. Among them, blade 12 has experienced penetrating cracks for two consecutive years and blade 13 has experienced penetrating cracks for three consecutive years, and the penetrating cracks have no trend of decreasing and converging.

The figure 2 shows the statistics of the cracks in the runner of Unit 1 based on the location of occurrence. From the statistics, it can be seen that the cracks mainly occur at the upper crown end corner, lower ring end corner and fillet weld (flow channel) of the runner outlet. The cracks in the upper crown account for about 60%, and the cracks in the lower ring account for about 27%. The crack length is between 8~135 mm. Among them, the No. 12, No. 13, and No. 14 blades have crack defects in the same location.

Crack Situation of Unit 2. The figure 3 shows the crack situation of each blade of the runner of unit 2 from 2015 to 2019. Similar to unit 1, 9 blades of unit 2 have cracks, including through cracks in blades 1, 3, 4, 6, and 14. Blade 3 has had through cracks for 5 consecutive years, and blade 6 has had through cracks for 4 consecutive years. There is no obvious convergence trend in the number and severity of cracks.

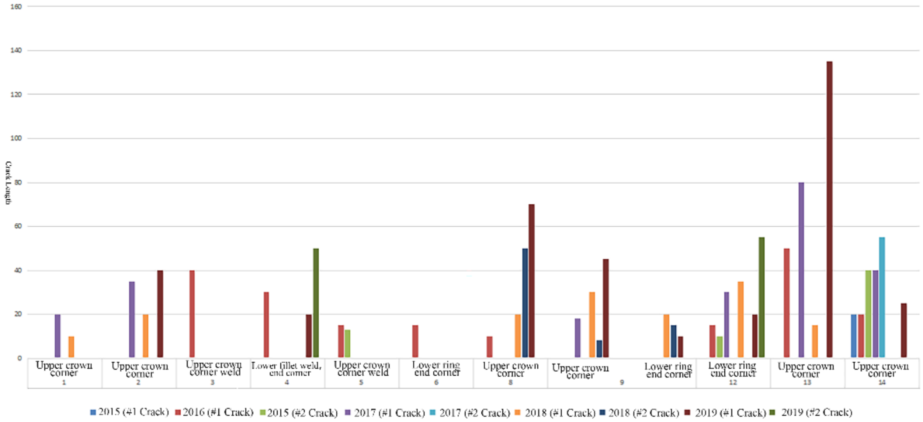

Fig. 1. Crack statistics of Unit 1 from 2015 to 2019

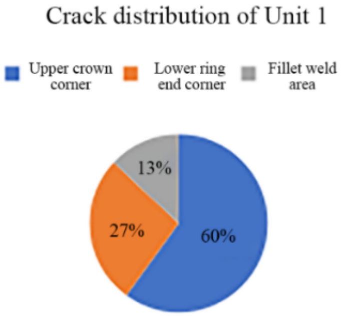

Fig. 2. Crack location statistics of Unit 1

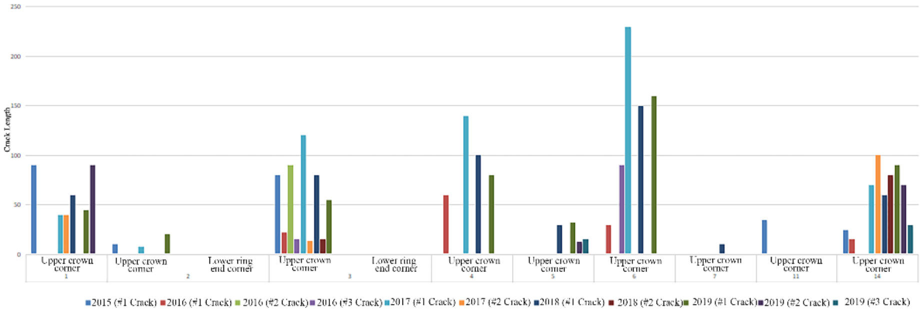

Fig. 3. Crack statistics of Unit 2 from 2015 to 2019

The figure 4 shows the statistics of the cracks in the runner of Unit 2 based on the location of occurrence. The cracks are also mainly distributed at the upper crown end corner and the lower ring end corner of the runner outlet. The cracks in the upper crown account for about 90%, and the cracks in the lower ring account for about 10%. Among them, 5 blades have crack defects in the same location continuously.

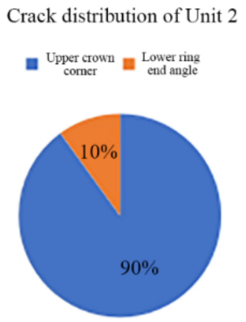

Fig. 4. Crack location statistics of Unit 2

Crack Situation of Unit 3. The crack situation and distribution of the blades of the runner of unit 3 from 2015 to 2019 are similar to those of the previous two units (Figure 5). Ten blades of unit 3 have cracks with a crack length of 10~100 mm, and three blades have penetrating cracks, which is slightly better than that of units 1 and 2. The cracks occurred at the upper crown end corner and the lower ring end corner, with the upper crown accounting for about 64% and the lower ring accounting for about 36%. Among them, five blades had crack defects in the same position continuously.

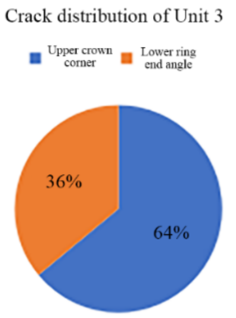

Fig. 5. Crack location statistics of Unit 3

Overall Situation and Explanation of Cracks. The number of runner cracks (Figure 6) and cracked blades (Figure 7) of the three units were counted each year. From the trend chart, it can be seen that the number of runner cracks of the three units is on an upward trend, and there is no year-on-year decrease or convergence trend. This shows that the cracks in the runners of the three units are universal and are not caused by special reasons of a certain unit. At the same time, there is no convergence trend, and further analysis is needed from other influencing factors.

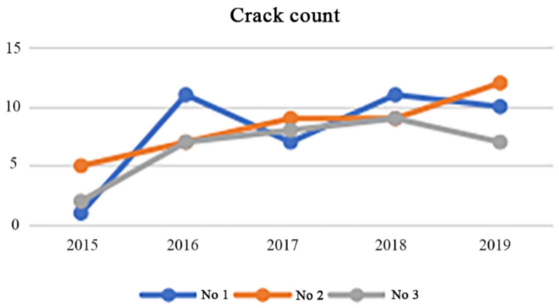

Fig. 6. Crack statistics of three units

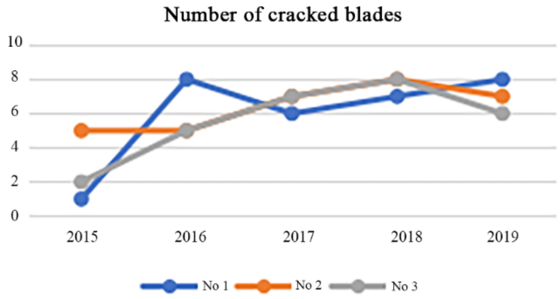

Fig. 7. Statistics of cracked blades in three units

From the locations where cracks occurred in the three units, it can be seen that they are mainly distributed in the upper crown end corner and lower ring end corner areas at the water outlet of the runner, and the two areas account for 96% (Figure 8). Since the runners of the three units are made of martensitic stainless steel, the runner blades are welded to the upper crown and lower ring. Martensitic stainless steel has high strength, low plasticity and toughness, and insufficient thermal conductivity [2]. At the same time, the shape of the blade outlet joint is complex, and the residual stress after welding is large. After a period of operation, the cracks of the mixed flow turbine are mostly generated here [3-4]. Therefore, from the proportion of crack occurrence locations, the crack location of the runner is consistent with the manufacturing characteristics of the mixed flow turbine, which is related to the large residual stress of welding. However, cracks occurred again after on-site treatment, and there was no trend of decreasing year by year. Further analysis is needed from the aspects of runner design strength, operation, and welding repair process [5].

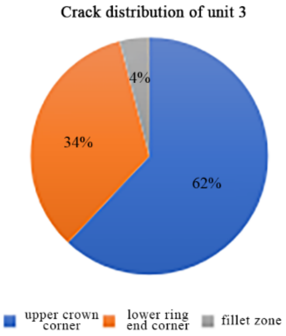

Fig. 8. Crack location statistics of three units

2.2 Runner Strength Analysis

Since cracks are common in runner blades and cracks appear repeatedly in the same part, the runner strength needs to be reviewed and analyzed to see whether resonance or quasi-resonance occurs with the water body during operation.

Strength Analysis. Ansys software boasts powerful multi-physics analysis capabilities, enabling it to simulate the complex working environment of hydraulic turbines under different operating conditions. This includes the interaction of multiple physics fields such as fluid dynamics, structural mechanics, and thermal stress, thereby more accurately reflecting the force conditions of hydraulic turbine runners during actual operation and providing more comprehensive data support for crack analysis. Since the turbine runner is a periodically symmetrical structure, a fan-shaped area including a complete blade is selected for calculation. The analysis selects two working conditions: the maximum head and maximum output conditions with greater stress during operation and the runaway condition at the extreme of the fault (Figure 9 and 10) [6]. The calculation results are shown in the following table 1. By calculating the maximum stress of the runner at the maximum head and maximum output, the maximum stress at the runaway condition is 98.3 MPa, and the maximum stress at the runaway condition is 113 MPa, both of which are less than the design strength of 100 MPa and 360 MPa. The stress strength during operation does not exceed the design range, and the design strength meets the requirements, so this factor can be excluded.

Table 1. Calculation Results Table

Working conditions	Maximum displacement (mm)	Maximum stress (MPa)	Maximum stress position
Maximum head, maximum output	4.52	98.3	The connection between the water outlet edge of the blade and the lower ring
		96.4	The connection between the front of the blade and the upper crown

		74.7	The connection between the water outlet edge of the front of the blade and the upper crown
Escape	3.94	113	The back of the lower ring blade close to the water edge

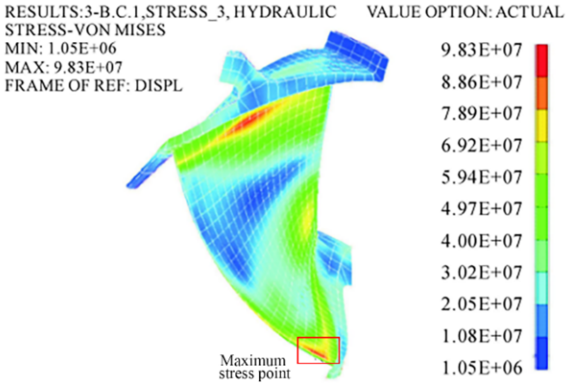

Fig. 9. Calculation of maximum head and maximum output conditions

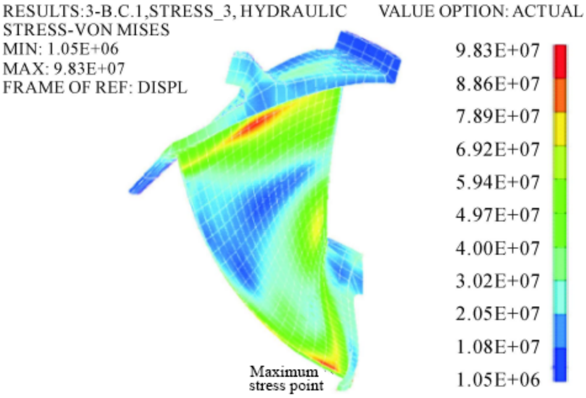

Fig. 10. Calculation of runaway conditions

Resonance Analysis. I-DEAS (Integrated Design, Engineering and Analysis Software) leverages advanced numerical methods and efficient algorithms to swiftly tackle intricate computational tasks, significantly enhancing design efficiency. During the computation process, the software adeptly handles various complex boundary conditions and material properties, ensuring the accuracy of the results and providing a solid foundation for the design of hydraulic turbine runners. Using I-DEAS software, a complete impeller is selected as the analysis model (Figure 11), and the Block Lanczos method is used to analyze the natural frequency of the impeller(Figure 12). The calculation results are shown in the following table 2. From the calculation results, it can be seen that the natural frequency of the impeller in water can avoid the product of the rotation frequency and the number of guide vanes, and there is no resonance. This factor can be excluded.

Table 2. Self frequency analysis

Natural frequency of the rotor	Frequency in air (Hz)	Frequency in water (Hz)	The product of the rotation frequency and the number of guide vanes
Torsional Vibration	40.9	35.58	57.16
Swing (pitch diameter = 1)	52.12	41.7	
Swing (pitch diameter = 2)	60.13	42.09	
Swing (pitch diameter = 3)	97.55	69.26	

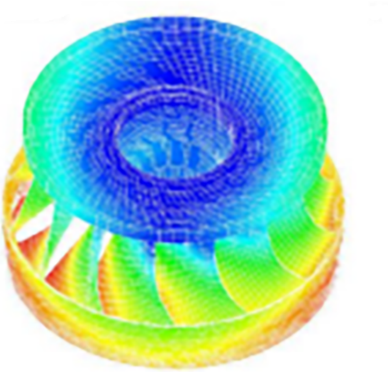

Fig. 11. Finite element meshing of runner dynamic characteristics

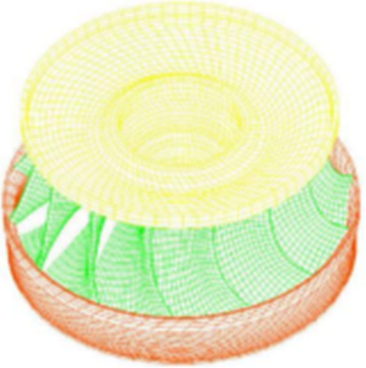

Fig. 12. Vibration shape of runner pitch diameter = 1

2.3 Operation Analysis

Français turbines generally have vortex pressure pulsation in the intermediate load area. When operating in this area, the flow-through parts and units of the turbine vibrate greatly. According to relevant research on turbine fatigue and reliability, the extended operation time in the low-load area of the vortex will accelerate the fatigue and life loss of the turbine. According to the turbine model test results and unit stability test data of the plant, the turbine has obvious pressure pulsation in the tailwater cone of the turbine in the no-load and partial-load areas. The pressure pulsation is the largest in the load range of 40%~54% of the extreme maximum head, the load range of 40%~45% of the rated head, and the load range of 40%~66% of the extreme minimum head. Therefore, the unit has obvious vibration below 60% load, and it is not recommended to operate for a long time [7].

The load distribution of the units under different water levels in the two years of the plant was counted (as shown in Figures 13 and 14). It can be seen from the figure that the three units operated below 60% of the rated output for a certain period of time in the two years; at the same time, under the rated head of 80m, the load carried by the units in some periods exceeded the guaranteed output range of the runner, and there was a certain degree of overload operation.

The above two situations have a certain impact on the turbine, which will accelerate the fatigue of the blades and cracks. This factor is one of the factors affecting the cracks in the runners of the three units. During operation, it should be avoided as much as possible to operate under bad conditions for a long time. If the recurrence of cracks can be reduced by changing the operating conditions, no further structural optimization of the runner can be done.

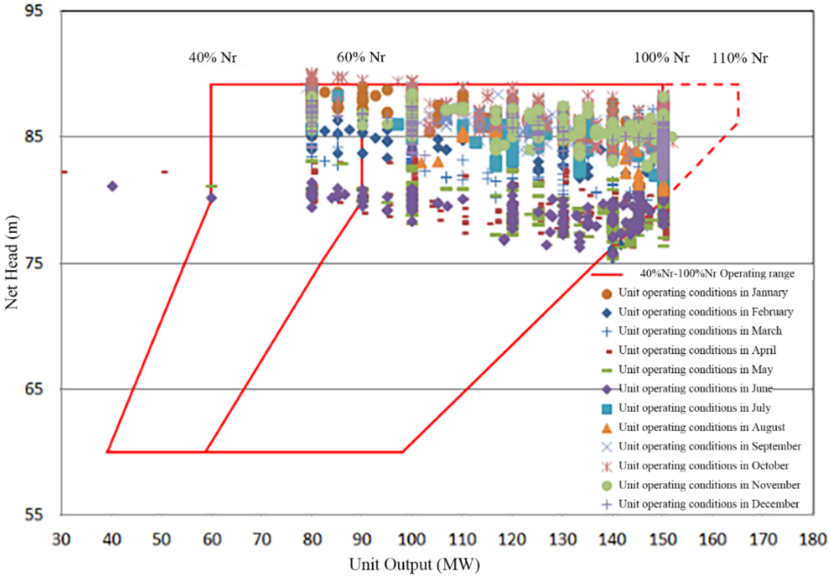

Fig. 13. Unit load operation statistics in 2017

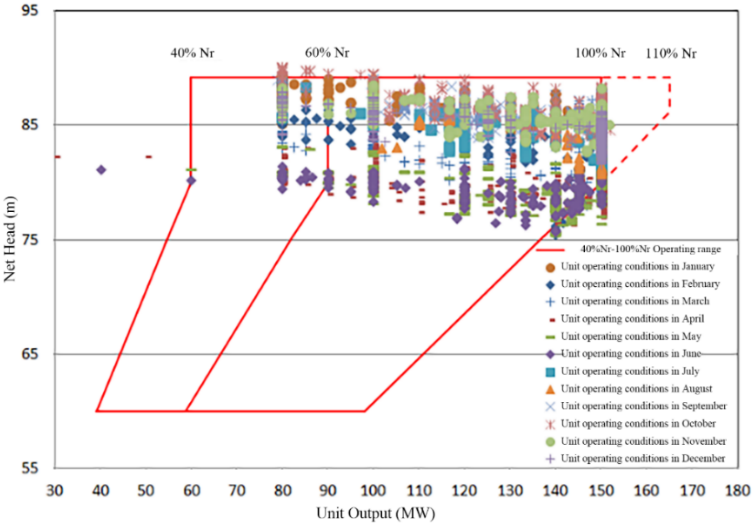

Fig. 14. Unit load operation statistics in 2018

2.4 Analysis of Runner Crack Repair Process

Cracks in mixed flow turbine generator sets that have been put into operation are generally repaired by on-site welding. After repair, the number of runner cracks and the trend of redevelopment of most turbines gradually decrease, showing a convergence state [8]. However, from the above statistics, it can be seen that with the increase of the repair treatment year, the number of cracks and the development trend have no convergence law, and the severity of cracks in some blades has even shown a worsening trend. The reasons for this are as follows through analysis of the welding process:

1.The quality of the runner welding repair process is poor. It can be seen from Figures 15 and 16 that some cracks have defects such as pores and pits after repair. During operation, cracks originate from these pores and pits and further expand. Cracks in areas with dense pores have the situation of extending in series along the pores.

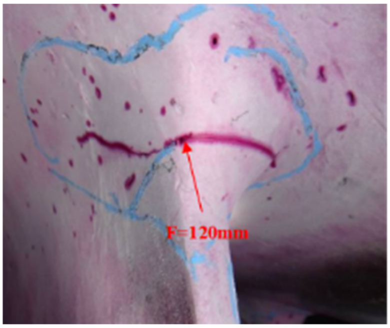

Fig. 15. Blade cracks

Fig. 16. Blade cracks

2. Poor grinding and shaping after repair welding. As can be seen from the figure 17, some cracks have angular surfaces and poor smoothness after repair and grinding, and there is no smooth transition. At the same time, the surface roughness of the repaired part is not good and does not meet the design requirements.

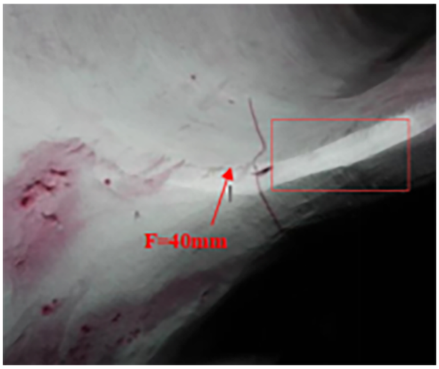

Fig. 17. Grinding after crack repair

3. Repeated welding leads to a decrease in the mechanical properties of the material. After multiple carbon arc gouging and welding, the heat treatment state of the material in the corresponding area is changed, making the material structure brittle, the hardness increased, and the plasticity decreased, increasing the probability of crack occurrence. At the same time, the 0Cr13Ni5Mo material wheel has low thermal conductivity and is prone to overheating. When the temperature exceeds 1150°C during welding, a coarse, brittle and hard martensite structure will be produced in the heat-affected zone, and repeated heating will further increase its brittleness [9].

In summary, factors such as poor welding repair quality, unqualified post-weld grinding, and repeated repair of material mechanical properties will cause cracks in the same part to recur and further expand. Therefore, after strict welding quality control, the number and location of cracks should be further analyzed to see if they have converged.

3 Crack Repair and Treatment

3.1 Welding Process Control

In view of the shortcomings in welding quality and post-weld treatment, the welding repair process plan and operation control documents were re-formulated, and the manufacturer's welding personnel were invited to carry out the repair. The welding quality control was carried out well throughout the whole process, and the requirements for interlayer disinfection of welding were strictly implemented; the gouging area was preheated before carbon arc gouging, and the preheating temperature and interlayer temperature were strictly controlled during welding; after welding, it was immediately covered with insulation material and slowly cooled; the weld was polished, and stress concentration points were not allowed to exist, and pits and bosses with a depth of more than 0.5 mm were not allowed to appear on the flow surface of the blades [10].

3.2 Optimize the Unit Operation Area

According to the load plan, optimize the unit startup combination, and try to avoid operating in the vibration zone to reduce the dynamic load on the runner blades and reduce the possibility of fatigue cracks on the blades [11-12].

Strictly follow the guaranteed output operating range given by the manufacturer, ensure that the load meets the manufacturer's requirements when the water level is low, and avoid long-term operation at excessive output.

The above measures were adopted to repair the cracks in the runners of the three units again. After strict welding quality control and optimization of operating conditions, after three consecutive years of observation, the number of runner cracks has been significantly reduced, and no cracks have occurred after repair treatment. This problem has been effectively controlled.

4 Conclusion

The Francis turbine, being the core component of hydropower stations, plays a pivotal role in ensuring the overall safety and stability of the entire station. If cracks in the runner are not promptly addressed, they can lead to unit shutdowns or even accidents, inflicting significant losses on the hydropower station. Effective remediation measures can reduce downtime and maintenance costs caused by runner cracks, thereby enhancing the power generation efficiency and economic benefits of hydropower stations. As a crucial source of clean energy, the safe and stable operation of hydropower stations is instrumental in promoting energy structural transformation and mitigating environmental pollution. Addressing runner cracks contributes to enhancing the environmental and social benefits of hydropower stations. Additionally, the research on runner crack remediation can accumulate rich technical experience and data, providing valuable references for future turbine design and manufacturing. Based on the research content of this article, the following suggestions are offered:

1. Due to welding processing, the shape of the water outlet connection of the Francis turbine is complex, and the residual stress after welding is large. This area is prone to cracks after running for a period of time. After the cracks occur, the location and number of cracks should be counted, and their changing trends should be analyzed. Most of them will gradually decrease and converge after treatment.
2. If the runner cracks do not converge after repair welding, a comprehensive analysis should be conducted from multiple factors such as runner design, operating conditions, and repair treatment process. When there are no major defects in the design, the welding process and operating conditions have a greater impact on the cracks.
3. The requirements for the runner's operable area should be improved to the operating procedures to avoid long-term operation of the unit in the low-load area and operation beyond the design output.

4. During the design phase, thorough consideration should be given to the stress distribution of the runner blades. This can be achieved by optimizing blade shapes, increasing blade thickness, and enlarging the fillet radii at the welds between the blades and the upper crown and lower ring, thereby minimizing the occurrence of stress concentration phenomena.

5. Strictly control the on-site rotary wheel welding process, and try to have the manufacturer's welding process personnel perform the repair, and do a good job of quality control in each link such as preheating, stress relief, heat preservation, linear grinding, etc. Any link that is not properly controlled may cause cracks to reappear. Welding quality control is a key control factor.

6. Hydroelectric power stations should establish a regular maintenance and inspection system, strengthen the training and management of operators, and improve their understanding and response capabilities regarding runner crack issues. Conduct regular inspections and maintenance of the runner to promptly identify and address potential problems such as cracks.

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