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Failure Analysis of a Kaplan Turbine Blade in Iraq's Haditha Hydropower Plant

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Conflicts of interest

The authors declare that there is no conflict of interest.

Authors' contribution

Undivided co-authorship.

Abstract. Kaplan turbines are widely used in low-water-head and large-capacity hydropower plants. The design of such systems is based on long-term performance. Nevertheless, many failures are reported in the industry, which lead to economic losses for the purpose of major repairs or replacement of a part of the system. Therefore, it is very important to know the failures, their causes, and finally provide useful solutions for their prevention or early treatment. In the present article, the authors focused on the failure detection of a Kaplan turbine blade in an Iraqi hydropower plant, and then, determined the direction of their future research. Quantometric test, tensile test, compression test, microhardness test, metallographic examination and study of the damaged surface were conducted from damaged runner blade. It was revealed that the raw material for manufacturing runner blade of Kaplan turbine was 304 stainless steel by employing cold drawing or rolling process. In addition, annealing treatment has also been done. In addition, it was found that the predominant damage in the studied part was severe cavitation.

Keywords: Hydropower plant, Kaplan hydro turbines, Runner blades, Failure, Cavitation

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Анализ неисправности лопатки турбины Каплана на иракской гидроэлектростанции Хадита

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Нераздельное соавторство.

Аннотация. Турбины Kaplan широко используются на маловодных и крупнотоннажных гидроэлектростанциях. Конструкция таких систем основана на долгосрочной производительности. Тем не менее в отрасли сообщается о многих сбоях, которые приводят к экономическим потерям с целью капитального ремонта или замены части системы. Поэтому очень важно знать сбои, их причины и, наконец, предлагать полезные решения для их предотвращения или раннего лечения. В настоящем исследовании авторы сосредоточились на обнаружении неисправности лопатки турбины Каплана на иракской гидроэлектростанции, а затем определили направление своих будущих исследований. С поврежденной рабочей лопатки были проведены квантовометрические испытания, испытания на растяжение, на сжатие, на микротвердость, металлографическое исследование и исследование поврежденной поверхности. Выяснилось, что сырьем для изготовления рабочей лопатки турбины Каплана была нержавеющая сталь 304, полученная методом холодной вытяжки или прокатки. Так же, была проведена обработка отжигом. Кроме того, установлено, что преобладающим повреждением в исследуемой детали является сильная кавитация.

Ключевые слова: гидроэлектростанция, гидротурбины Каплана, рабочие лопатки, отказ, кавитация

Для цитирования

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Introduction

The Haditha hydropower plant, which was built in the 1980s on the Euphrates River at the Haditha dam and whose embankment was designed by the Soviet Union's Ministry of Energy, is the largest fully operational hydroelectric facility in Iraq. Moreover, its power station and equipment were designed and built by various Yugoslavian companies. This unit has a total capacity of 660 MW, which contains six 110 MW vertical-type units of the Kaplan turbines, as shown in Figure 1, and is situated on the Euphrates River in Iraq. Table 1 presents the technical specifications of the studied HPP. Kaplan turbines commonly sustain damages from silt erosion [1–4], cavitation [5–7], and fatigue [8–11]. Also, erosion of material surfaces due to collisions of solid particles has been an old and vital challenge in the hydro-engineering field. Rivers all over the world are full of hard particles like quartz and feldspar, and as a result, typical hydroelectric power facilities are likely to experience several cavitation-related problems. This is because the pressure inside the hydro unit will frequently drop low enough to equal water's vapor pressure [12]. In vapor- or gas-filled cavities, bubbles might be generated in those regions, and they will have a strong influence on the flow stability and the hydro unit vibration behaviour [13]. Shock waves, micro jets, and noise emissions will be produced when

Table 1

Haditha HPP technical specifications

Type of turbine	Kaplan model 6-K-50
Operating Head	H_{max} = 46.6 m H_{min} = 18 m
Unit Flow Rate	Q in case of H_{max} = 259 m^3/sec Q in case of H_{min} = 223 m^3/sec
Power	P_{max} = 110 MW P_{min} = 33.5 MW
Runner diameter	6600 mm
Number of blades	6

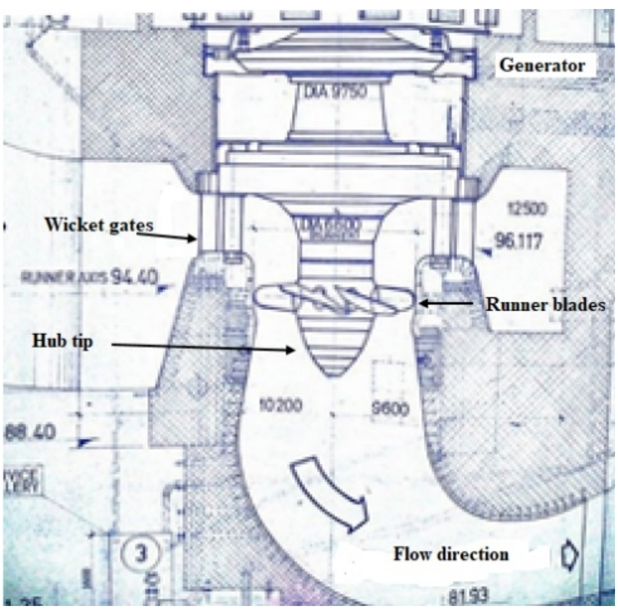


Figure 1. As-Built drawing of Haditha HPP.
Source: made by Ministry of Electricity, Iraq

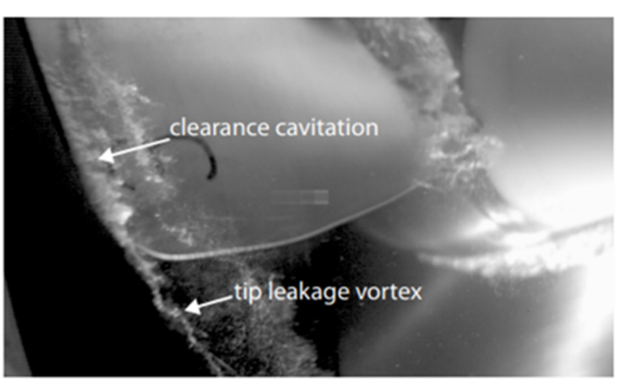


Figure 2. Various cavitation phenomena occurred in Kaplan turbine
Source: photo by [19]

these cavities collapse due to the energy released. The various bubble sizes will also cause a variety of loud noises and vibrations to be produced by their oscillation and collapse inside the flow [14]. The most common type of cavitation occurs at the blade tip clearance (the space between the blade tipand the stationary shroud wall casing). In fact, two types of cavitation occur in this region: 1-tip clearance cavitation and 2-tip vortex cavitation [15; 16]. Because of the high pressure difference between the pressure side and suction side of the runner blade, a leakage flow departs from the high-pressure region to the low-pressure region. The leakage flow has a very fast velocity, which causes the pressure at the tip clearance to drop. On the other hand, tip clearance cavitation typically happens when pressures fall below the saturation pressure. The leaking flow also contributes to the tip vortex cavitation.

A jet flow is produced as the leakage flow exits the blade tip gap [17]. A tip vortex is created when the flow jet leaves the suction side and interacts with the freestream flow at a separation line [18]. In this regard, the flow rolls up to form the Tip Leakage Vortex (TLV), beginning at the leading edge, and is strongly influenced by the shroud wall confinement. TLV detaches the blade's suction side and develops downstream along the runner blade. A tip leakage vortex is destined to promote cavitation, leading to erosion, flow instabilities, or noise during operation [19]. In the Haditha HPP, the plant operation regime is typically outside of the optimal design point and frequently below the minimal required water head because of the high demand for energy and the low river flow rates. However, failures in turbine blades are frequently reported by the engineering team at various stages of periodic inspection. For example, Figure 2 shows the different cavitation phenomena occurred in the Kaplan turbine. But unfortunately, with all the research done in this field, the use of prevention techniques, and employing necessary instructions, there is a need in different industries to study each of the failures on a case-by-case basis to determine and implement appropriate and effective solutions for them. Therefore, the primary goal of this research is to identify the material of damaged turbine blade because the manufacturing factories do not provide complete information about the manufacturing process to the purchasing countries. Next step is to identify the dominant failure mode in this case study. Eventually, the subject of future research will be determined with the aim of helping this industry.

1. Experimental procedure

In the first step, it is necessary to have samples of the broken part along with its working conditions [20–21]. Then, its raw material is identified, and in this regard, similar materials are also categorized so that, if necessary, alternative materials can be used. For this purpose, various mechanical, material, and metallurgical tests should be performed [22]. After determining the material, the damaged surface should be studied, and the main reason/source should be found by considering different scenarios of failure causes [23]. Finally, based on the properties of the material and the source of damage, a logical and practical solution should be provided and the platform of its implementation in the industry should be provided. Hence, a piece of damaged runner blade in the turbine of Haditha HPP was studied as a case study. To fabricate standard samples for various tests, the real piece was modeled in 3D (Figure 3) and the location of different samples was determined on it.

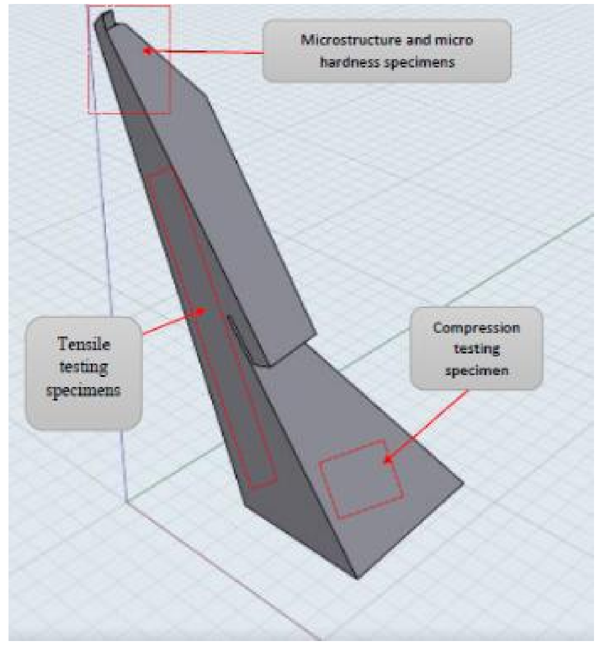


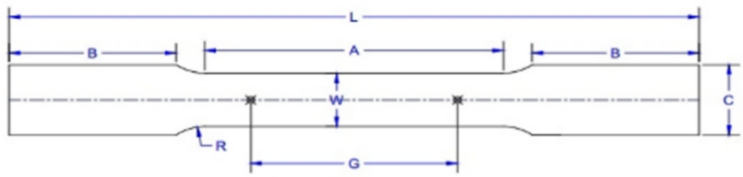
Figure 3. 3D model for the runner blade piece of turbine
Source: made by the authors

Next, the details of various tests performed in the current study are presented as follows:

1.1. Quantometric test. This test was conducted using the metal scanning device type ARUN 1650 (Figure 4) according to ASTM A240. The test was done at three different points so that more accurate results can be obtained.

1.2. Tensile test. This test was conducted using a 100KN computerized electromechanical universal testing device (Laryee), according to ASTM standard A370, for two samples with dimensions as shown in Figure 5.

Figure 4. Metal scanning device model ARUN 1650
Source: made by the authors



DIMENSION		Subsie Specimen 1/4-in wide, mm		
G-	Gage length (Notes 1 and 2)	25.0	6	0.08
W-	Width (Note 3, 5 and 6)	6.25	6	0.05
T-	Thickness (Note 7)	–		
R-	Radius of fillet, min (Note 4)	6		
L-	Over-all length, min (Notes 2 and 8)	100		
A-	Length of reduced section, min	32		
B-	Length of grip section, min (Note 9)	32		
C-	Width of grip section approximate (Notes 4, 10 and 11)	10		

Figure 5. Shape and dimension of tensile testing sample
Source: made by the authors

1.3. Compression test. This test was conducted using a 100KN computerized electromechanical universal according to ASTM standard E9. A cylindrical sample with a length and diameter of 20 and 10 mm, respectively, was used for this test.

1.4. Microhardness test. A digital microhardness tester was used to measure hardness on three different points of the specimen according to ASTM E384.

1.5. Metallographic examination. A digital microscope was utilized in this test for one specimen according to ASTM A923. Before that, different preparation steps, including mounting, grinding, polishing, and etching by Nital (2 % HNO_3 + 98 % ethanol) were performed.

1.6. Study of the damaged surface. In this section, the damaged surfaces were examined, and the authors have tried to consider the visible characteristics of them such as cracks, the starting point of the cracks, etc. Finally, the main cause of failure in this case study was reported by considering different scenarios.

2. Results and discussion

The chemical composition, wt %, of the material as the results of quantometric analysis for three different point are presented in Table 2.

Table 2

The chemical composition, wt %, of the material as the results of quantometric analysis

Point No.	Fe	Si	Mn	Co	Cr	Cu	Mo	Nb	Ni	Ti	V	W
1	82.7	0.892	0.395	<0.20	8.10	0.143	0.231	<0.060	4.77	<0.100	0.0348	<3.0
2	78.5	0.988	0.254	<0.20	11.6	0.138	0.169	<0.060	5.68	<0.100	0.0259	<3.0
3	78.1	1.13	0.383	<0.20	12.2	0.138	0.156	<0.060	5.17	<0.100	0.0376	<3.0

Table 3

Microhardness results for three points on the specimen

Point No.	Testing force, N	Duration time, Sec	HV, N/mm^2
1	2.94	15	309.9
2	2.94	15	318.2
3	2.94	15	310.8
Mean	2.94	15	312.96

The results show that the main base of this material is iron. Also, it contains 8–12 % Chromium and 4–6 % Nickel. Therefore, so far it can be concluded that the primary material for manufacturing the runner blade of turbine was stainless steel and grade 304 in AISI standard. In addition, the tensile test results reported an average value of 702 and 825.5 MPa for the Yield Stress (YS) and Ultimate Tensile Strength (UTS) of the part, respectively. In comparison with the mechanical properties of 304 stainless steel, these values indicate that heat treatment such as annealing and then tempering has been done during the manufacturing process. This issue was confirmed by the results obtained from the compression test. Because the results were obtained about 3 to 4 times the compressive properties of 304 stainless steel. Next, the results of microhardness measurement are reported in Table 3. As it is clear, this material has an average hardness of about 313 HV. Therefore, its production method can be cold drawing, and on the other hand, there is not a tempering operation because it greatly reduces the hardness. Therefore, the material is made of 304 stainless steel and the manufacturing method is cold drawing along with annealing operation.

The results of examining the objective evidence on the damaged surfaces show that severe cavitation occurred due to very harsh working conditions, which resulted in high structural vibration due to dynamic loading, and finally, erosion damage of the runner blade occurred. Moreover, structural crack have been seen in the runner blades, and these problems are exacerbated as long as the units are operating against their intended specifications. This condition resulted in damage to the runner blades in the Kaplan turbine of Haditha HPP, as shown in Figure 7. In addition to the above-mentioned damage, excessive off-design operation causes blade damage, wear in various turbine parts, and eventually fatigue damage. Figure 8 demonstrates an example of the structural damages that Haditha plant turbines suffered.

Figure 6 presents the Optic Microscope (OM) image of specimen with 10X magnification. From this Figure, the main phase is austenite. But there are numerous twins, which could be created by annealing or by rolling. In addition, parallel lines arose by the rolling during the technologic process.

Figure 6. The OM image of specimen with 10X magnification
S o u r c e: photo by the authors

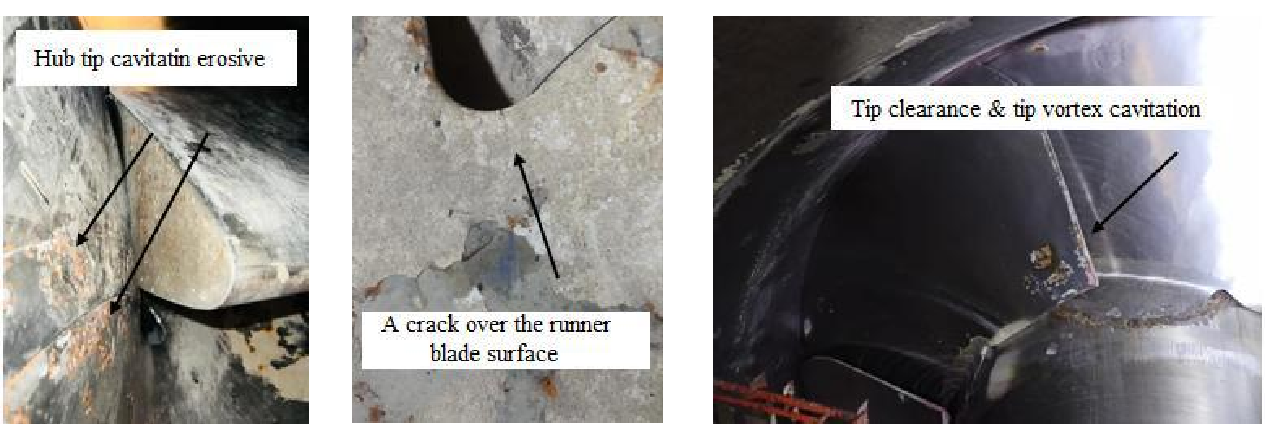


Figure 7. Cavitation and cracks of the Haditha HPP Kaplan turbine: image courtesy of the Ministry of Electricity, Iraq
S o u r c e : photo by the authors

Figure 8. Damaged runner blades of the Haditha HPP Kaplan turbine:
image courtesy of the Ministry of Electricity, Iraq
Source: photo by the authors

Conclusion

In the present research, a case study was conducted on the damaged part (runner blade) of Kaplan turbine in Haditha HPP from Iraq. After performing various tests and obtaining mechanical, material, and metallurgical properties of standard specimens, which are fabricated from damaged runner blade, it was proved that the raw material for manufacturing runner blade of Kaplan turbine was 304 stainless steel by employing cold drawing or rolling process. In addition, annealing treatment has also been done. To accurately determine the manufacturing steps, it is necessary to perform different tests and different thermal treatments on 304 stainless steel and compare the results with the data obtained from the damaged part. Furthermore, it was found that the predominant damage in the studied part was severe cavitation. In fact, cavitation is a phenomenon that occurs in a variety of turbomachinery applications and causes problems with those systems. Some of these downsides include damaging the components of the system, generating noise and vibration, and losing the turbine's efficiency over time. Thus, it is imperative to address the issue of cavitation to increase the life span of the equipment in addition to improving the system performance. However, for the high flow rate required by the Kaplan hydro turbine, which requires good cavitation erosion resistance, 304 stainless steel is the most suitable material for this type of application. Hence, the best solution is to strengthen this steel against cavitation. In summary, in their future research, the authors are looking for useful solutions (e.g., coating) to improve the properties of 304 stainless steel against cavitation, wear, and erosion phenomena.

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