

# An investigation about preventing cavitation damage and fatigue failure in Derbendikhan power station

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## Abstract

During periodic inspections of unit 2 in Derbendikhan hydropower station, cavitation damages and fatigue cracks were observed in the runner and draft tubes. Operation data (field data) between 1997–2002 were taken from the station; these data included head and output. The Prototype performance curve was obtained from the model test data and drawn by using the available equations, charts and tables from the literature and catalogs. The results showed that the unit 2 in Derbendikhan hydropower station operated abnormally which led to cavitation damages and fatigue cracks. For simulating the effect of overloading procedure on fatigue cracks in the runner, laboratory measurements were performed using martensitic stainless steel notched specimens. Four modes of overloading procedure are accomplished which were tension (T), compression (C), tension-compression (TC) and compression-tension (CT). For each overloading mode four different load values 150N, 200N, 250N and 300N were applied. The results showed that the beneficial effect (crack retardation) was observed under certain values for each overloading mode.

*Keywords: cavitation damage, fatigue, hydropower station, overloading.*

## 1 Introduction

The major problems in operating the hydraulic turbines are the occurrence of cavitation and fatigue failures. Cavitations are the formation of water vapor and air bubbles in the water due to the reduction of pressure below the vapor pressure corresponding to the temperature of the water. The cavity bubbles collapse close to a solid surface at regions of higher pressure, which generates highly localized stresses. Repetition of this phenomenon for a large number of times causes local



surface fatigue failure and subsequently detachment or flaking off of pieces of material and causing material loss and produces a strong characteristic noise.

Specific speed, level of turbine blades with respect to level of tail water, speed of runner, shape of the runner blade and their finishing are all factors which affect the occurrence of cavitation. [1-4].

Decades of operating time causes turbine runner to develop fatigue cracks in areas, where stress concentration and material defect coincide. The failure mechanism is due to the combination of low-cycle (start-stop cycles) and high-cycle (hydraulic load fluctuations) fatigue. Cracks become critical, when the stress intensity range due to vibration loading exceeds the threshold for fatigue crack growth [1, 5].

The application of an overload cycle introduces various plastic zones ahead of the crack tip. Cyclic hardening in the plastic zone and crack closure effect causes a significant reduction in fatigue crack growth rate (FCGR). The crack retardation zone may be characterized by parameters,  $a_D$  (overload affected total crack length) and  $N_D$  (delay cycles) and is represented in fig. 1 [6-8].

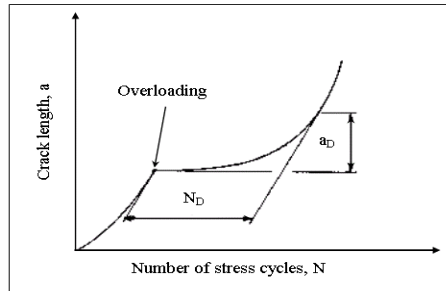


Figure 1: Schematic representation of the response of fatigue crack growth on overload application [6].

## 2 Derbendikhan Hydropower Station

Derbendikhan Hydropower Station is constructed in Iraq about 230 km northeast of Baghdad; Basic characteristics of the power station are as follow [9]:

Type of turbine	Francis turbine
Rated head	80 m
Turbine output and discharge at rated head	83000 kW, 113 m <sup>3</sup> /s
Rated speed	187.5 rpm
Runner inlet diameter	3 m

Periodic inspections have been done for the unit 2 of the Derbendikhan hydropower station. One inspection completed at February 2002. In this inspection the runner was subjected to six fatigue cracks, in the other side the runner and draft tubes surfaces are subjected to cavitations, as shown in fig. 2.

### 2.1 The operational data

The operational Data is divided in to two parts, the first part is the model test data, which includes the operational parameters of the model, and used to

develop the data for the prototype. The second part represents the operational condition of the life Derbendikhan Hydropower station for the period from 3/5/1997 to 18/2/2002.



Figure 2: Cracks in the runner, cavitation damage on the blades surface, and cavitations on the draft tube surface.

### 2.1.1 Model test data

Experimental Laboratory of TAKASAGO Technical Institute performed the model tests; Mitsubishi Heavy Industrial, Ltd. Model test data includes the measurement of rotational speed ( $n$ ), head ( $H$ ), discharge ( $Q$ ), load ( $P$ ), and efficiency ( $\eta$ ).

**2.1.1.1 Derived results of performances of the prototype turbine** Model test data can be used for determination of the quantities like efficiency ( $\eta$ ), output ( $P$ ), discharge ( $Q$ ), and net head ( $H$ ) of the prototype turbine by using the converting equations.

**2.1.1.2 Cavitation test** To determine the cavitation limit for prototype turbine the model was tested under homologous condition similar to the prototype. The test result showed that the cavitations limit (critical cavitation coefficient,  $\sigma_c$ ), is equal to 0.11 and 0.17[9].

### 2.1.2 Field data

The field data of Derbendikhan Hydropower Station are taken from 3/5/1997 to 18/2/2002 under different operating conditions for output and net head. In general, the output and net head for the station were registered for each hour.

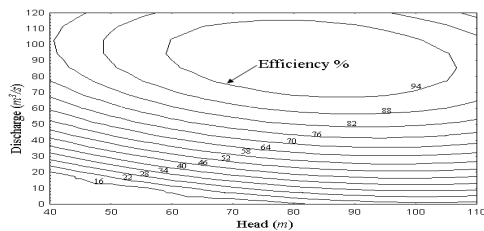


Figure 3: The relationships between the discharge, head, and efficiency of the prototype turbine.

### 2.1.3 Results and discussion of operational data

Figures 3 to 5 show the performance curves, which are constructed using a statistical software program. According to these curves the prototype turbine can

be operated for all specified power outputs and net head. But under specified values of these parameters the turbine and draft tubes are subjected to cavitations.

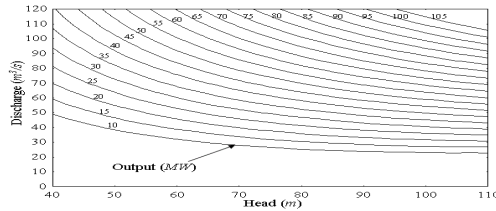


Figure 4: The relationships between the discharge, head, and output of the prototype turbine.

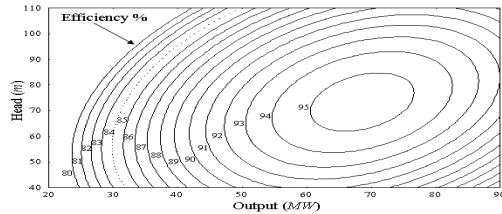


Figure 5: The relationship between the head, output, and efficiency of the prototype turbine.

**2.1.4 Model test cavitation**

Equation (1) is used to determine the specific speed  $N_s$  range with using the values of critical cavitation coefficient  $\sigma_c$  (0.11 - 0.17)[9]. In this case the specific speed range located between 186.28 to 231.58 rpm, which is defined as a limit of normal operation condition without significant cavitation [10].

$$\sigma_c = 0.0317 * \left( \frac{N_s}{100} \right)^2 \tag{1}$$

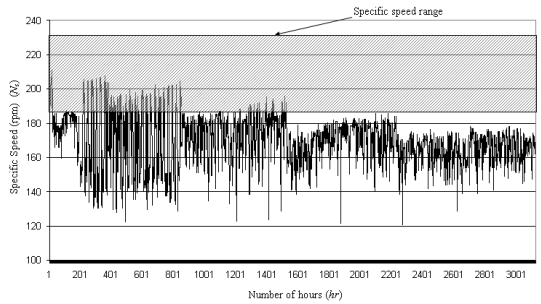


Figure 6: Specific speed values for each hour of operation of year 1997 under various conditions of head, and output.

**2.1.5 Turbine cavitation**

Equation (2) is used to determine the  $N_s$  value for each hour of operation under various conditions of head and output. Figures 6 to 11 show the values of  $N_s$  for all hours considered in this study. The shaded area represents the specific speed range of 186.28 to 231.58 rpm, which provides the normal operation conditions.

$$N_s = \frac{n\sqrt{P}}{H^{5/4}} \tag{2}$$

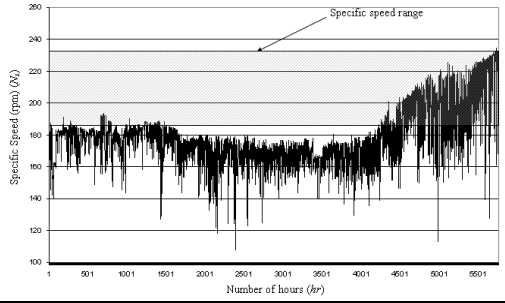


Figure 7: Specific speed values for each hour of operation of year 1998 under various conditions of head, and output.

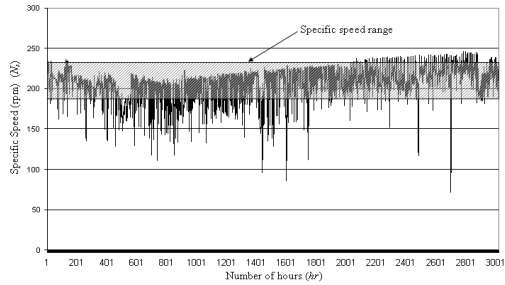


Figure 8: Specific speed values for each hour of operation of year 1999 under various conditions of head, and output.

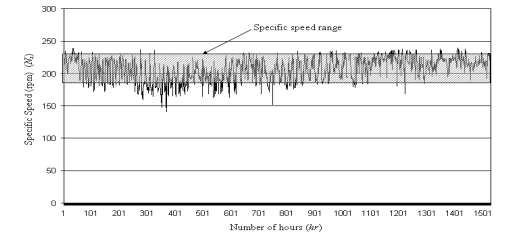


Figure 9: Specific speed values for each hour of operation of year 2000 under various conditions of head, and output.

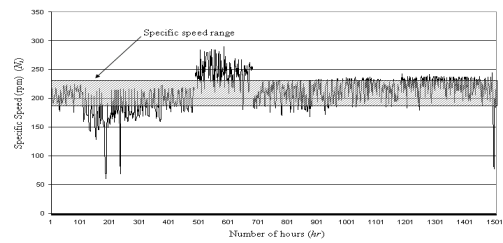


Figure 10: Specific speed values for each hour of operation of year 2001 under various conditions of head, and output.

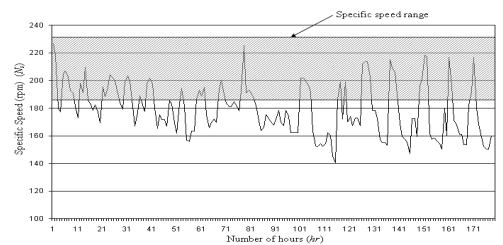


Figure 11: Specific speed values for each hour of operation of year 2002 under various conditions of head, and output.

Table 1: Total number of hours and number of hours under cavitation condition, for each year of operation for different specific speed range.

Specific speed range (rpm)		Critical cavitation coefficient ( $\sigma_c$ )		Number of hours under cavitation condition (hr) for each year						Percentage of its operating period with cavitation (%) for each year						Number of hours under cavitation condition (hr)	Percentage of its operating period with cavitation (%)
Lower value	Higher value	Lower value	Higher value	1997	1998	1999	2000	2001	2002	1997	1998	1999	2000	2001	2002		
186.28	231.58	0.11	0.17	2840	4630	598	292	592	115	0.912	0.806	0.199	0.192	0.397	0.65	9067	0.6024
180	235	0.11	0.175	2840	4630	532	265	502	115	0.912	0.806	0.177	0.175	0.336	0.65	8884	0.5903
180	240	0.11	0.183	2840	4630	454	233	418	115	0.912	0.806	0.151	0.154	0.28	0.65	8690	0.5774
180	245	0.11	0.19	2840	4630	417	233	392	115	0.912	0.806	0.139	0.154	0.263	0.65	8627	0.5732
180	250	0.11	0.198	2840	4630	414	233	375	115	0.912	0.806	0.138	0.154	0.251	0.65	8607	0.5719
170	235	0.092	0.175	1577	2048	323	78	338	64	0.506	0.356	0.108	0.051	0.227	0.362	4428	0.2942
170	240	0.092	0.183	1577	2048	245	46	254	64	0.506	0.356	0.082	0.03	0.17	0.362	4234	0.2813
170	245	0.092	0.19	1577	2048	208	46	228	64	0.506	0.356	0.069	0.03	0.153	0.362	4171	0.2771
170	250	0.092	0.198	1577	2048	205	46	211	64	0.506	0.356	0.068	0.03	0.141	0.362	4151	0.2758
160	235	0.081	0.175	789	613	234	45	274	30	0.253	0.107	0.078	0.03	0.184	0.169	1985	0.1319
160	240	0.081	0.183	789	613	156	13	190	30	0.253	0.107	0.052	0.009	0.127	0.169	1791	0.119
160	245	0.081	0.19	789	613	119	13	164	30	0.253	0.107	0.04	0.009	0.11	0.169	1728	0.1148
160	250	0.081	0.198	789	613	116	13	147	30	0.253	0.107	0.039	0.009	0.099	0.169	1708	0.1135
150	235	0.071	0.175	296	152	195	42	274	4	0.095	0.026	0.065	0.03	0.184	0.023	966	0.0642
150	240	0.071	0.183	296	152	112	10	190	4	0.095	0.026	0.037	0.009	0.127	0.023	767	0.051
150	245	0.071	0.19	296	152	75	10	164	4	0.095	0.026	0.025	0.009	0.11	0.023	704	0.0468
150	250	0.071	0.198	296	152	72	10	147	4	0.095	0.026	0.024	0.009	0.099	0.023	684	0.0454

### 2.1.6 The effect of specific speed range on the operational conditions

In order to determine the number of hours under cavitation condition for each year, some interval specific speed values are taken outside the range of the model operation namely from 150 to 180 rpm for the lower limit, also from 235 to 250 rpm for the upper limit as shown in table 1. This table shows that the number of hours under cavitation condition is decreased from 9067 to 684 hours (i.e.



decreasing the percentage of its operating period from 60% to 4.5%) when the specific speed range is increased from 186.28-231.58 to 150-250 rpm.

## 2.2 Experimental work of crack retardation

### 2.2.1 Material

Martensitic stainless steel type 410 AISI has been investigated in around shaft of 12.7 mm diameter.

### 2.2.2 Fatigue test device

Cantilever-type rotating bending fatigue test model WP 140 used to carry out the fatigue tests. This machine was taken at different stress level with zero mean stress, stress ratio equal to (-1) and frequency of 50 Hz.

### 2.2.3 Preparation of the specimen

Specimens of martensitic stainless steel were prepared as shown in fig. 12. A pre-crack (notch) was created in one side of the specimens by 1.2 mm length approximately, to increase the crack growth rate, to decreasing fatigue limit and fatigue life, and to limit the region under study.

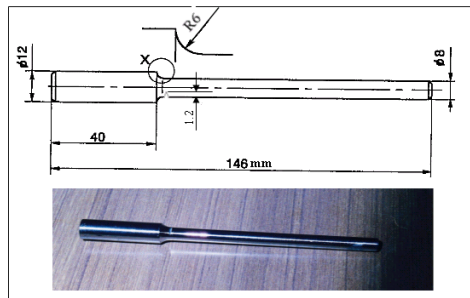


Figure 12: Specimen dimensions used in fatigue test.

### 2.2.4 Fatigue crack growth rate measurement

The crack propagation was monitored with the help of a low magnification power microscope (100X) the microscope mounted on the fatigue test machine by a fixture. The crack length was calculated from the crack length on the circumference [11].

### 2.2.5 Crack retardation modes

In order to investigate the effect of overloading procedure on the crack retardation (decreasing crack growth rate) different modes of overloading procedures are applied like tension, compression, tension-compression, and compression-tension. Each type of these modes is subjected to four overloading values 150, 200, 250, and 300 N.

### 2.2.6 Crack retardation procedure

The a-N curves are established when the fatigue test device rotate the notched specimen under constant amplitude loading of 80N till the fatigue crack extends

by approximately 0.5 mm. At this moment the device is stopped, then the selected overloading modes and values are applied on the specimen, after that the device is re-operated (applying 80 N), with increasing the crack length to a considerable amount for certain number of cycles, the device was stopped again, and the overloading procedure (under the first run value) re- applied, then the device re-operated, and so on till fracturing. For each time of stopping the device, both the crack length and associated number of cycles are recorded. For comparison purpose the same procedure is applied also for one specimen without overloading.

**2.2.7 Results and discussion of experimental work**

Fig. 13 shows the variations and relations between the crack length (*a*) and number of cycles (*N*) for specimens under a static load of 80N with overloading of 150N in (T), (C), (TC), and (CT).

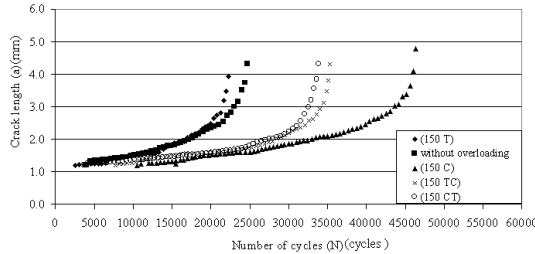


Figure 13: Relationship between the fatigue crack length and number of cycles for specimen with overloading of 150N.

These results show a detrimental effect following a (T) overloading. However, approximately similar beneficial effects (crack retardation) has been found in both the (CT) and (TC) overload, furthermore, the compressive (C) overloading was most effective than the other three cases. The crack retardation effect in (C) overload shows decreasing the crack growth into the half amount compared with (CT) and (TC) overloading.

Overloading in (T) case tend to accelerate the crack growth rate and this can be attributed in addition to tensile residual stresses, also to opening the crack tip mouth, therefore more crack displacement and more applied tensile stresses occur. In another word, with applying the (C) loads, the residual compressive increases and consequently cause to decrease the crack growth rate.

Fig. 14 shows the relation between the crack length (*a*) and number of cycles (*N*) for specimens under a static load of 80N with overloading of 200N in (T), (C) (TC), and (CT).

The result shows that the effect of crack retardation has been observed following a (TC) overload. Approximately both (CT) and (C) overloads have the same beneficial effects on fatigue life, however (T) overload was found to have a more beneficial effect. This result can be explained in terms that with increasing the tensile overloading the crack tip blunting operation takes place, thus the stress concentration factor decreases, consequently the fatigue life increases.

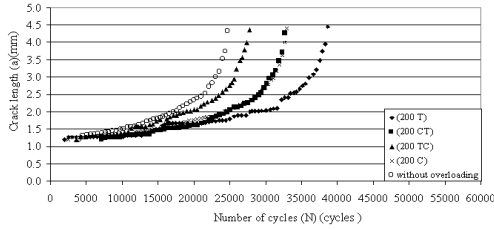


Figure 14: Relationship between the fatigue crack length and number of cycles for specimen with overloading of 200N.

Fig. 15 and 16 show the relation between the crack length ( $a$ ) and number of cycles ( $N$ ) for specimens under a static load of 80N with overloading of 250N and 300N in ( $T$ ), ( $C$ ) ( $TC$ ), and ( $CT$ ).

Fig. 15 and 16 demonstrate that with increasing the overloading value from 250N to 300N the beneficial effect for crack retardation increases at ( $CT$ ) overloading this is due to the increase in the amount of residual compressive stresses on the crack surface.

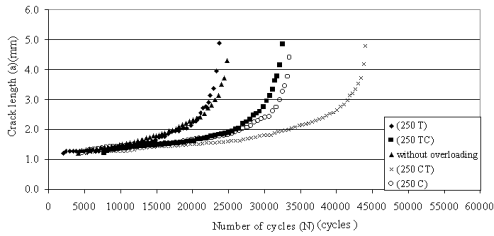


Figure 15: Relationship between the fatigue crack length and number of cycles for specimen with overloading of 250N.

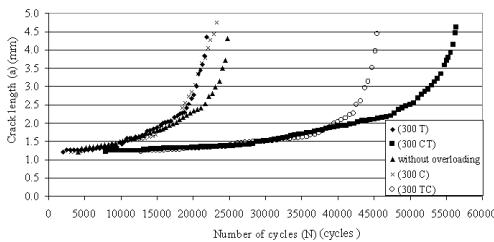


Figure 16: Relationship between the fatigue crack length and number of cycles for specimen with overloading of 300N.

**2.2.8 Conclusions**

**2.2.8.1 Cavitations in runner and draft tubes**

- 1- The specific speed range for normal operation is located between 186.28 and 231.58 rpm.
- 2- Unit 2 in Derbendikhan Hydropower Station operated under abnormal operation condition for more than 60% of its operating period.

- 3- Increasing the upper value of the specific speed range has no significant effect on decreasing the number of hours under cavitation condition.
- 4- The most sever effects of abnormal operation condition appears in 1997, It seems that the percentages of its operating period with cavitation is more than 90%.

#### 2.2.8.2 Fatigue cracks in runner

- 1- The runner of the turbine was subjected to high cyclic fatigue-HCF for more than 60% of its operating period, also the runner was subjected to low cycle fatigue-LCF due to start stop cycle loading for 1144 cycles.
- 2- The (CT) overloading mode gives the beneficial effect for crack retardation at 300N compared with other overloading modes.
- 3- With increasing the overloading values in (TC) and (CT) overloading modes the benefit of crack retardation increases.
- 4- The value 200N gives the maximum retardation in (T) mode overloading.
- 5- With increasing the loading values in (C) overloading mode, the crack retardation decreases.

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