Investigations on fatigue curves in dependency of water quality for nickel-martensitic steels

B Leibing¹, F von Locquenghien¹, D Rückle², G Schellenberg²

¹Voith Hydro Holding GmbH & Co. KG, Alexanderstraße 11, 89522 Heidenheim, Germany
²Materials Testing Institute University of Stuttgart, Pfaffenwaldring 32, 70569 Stuttgart, Germany

E-Mail: Benjamin.Leibing@voith.com

Abstract. With the need for flexible operation, Francis runners are exposed to various operating conditions outside the traditional operating range. To grant sufficient fatigue life, a deep knowledge of both loads and material behavior is mandatory. With the change in operation diverse stress amplitudes and number of cycles have to be considered for the comparison with fatigue curves. Hydro power turbines are exposed to possible corrosion attack due to the surrounding water environment, which is a relevant impact on the fatigue curves. Therefore an overview of parameters that influence the corrosivity will be given. From an evaluation of a database that contains water quality data of worldwide hydro power projects, different water qualities are defined to perform fatigue tests with the influence of a corrosive medium. For selected water qualities, preliminary material test results will be presented.

1. Introduction

To ensure a safe and reliable power supply with a minimum environmental impact in the future, hydro power plants will be exposed to an increasing number of starts and stops as well as a higher amount of part load operational hours with the purpose to counterbalance fluctuations in the electricity grid due to a growing share of volatile renewable energies (photovoltaics and wind turbines). Therefore, current R&D activities of various actors in the hydro power industry focus on a detailed assessment of the mechanical stresses in hydro power components for all operational modes. The determined stresses at critical spots are then subsequently incorporated in modern fatigue assessment concepts in order to proof sufficient safety against fatigue failure of the components for a given load universe. At Voith Hydro, for example, a sophisticated Operation Cycle Concept for the fatigue life prediction of Francis runners was established within the last years [1].

For a precise fatigue assessment of a hydro turbine runner, a solid and reliable material database covering different loading conditions as well as environmental influences (e.g. corrosion effects) is required. Typically, the material characteristics are implemented into the fatigue assessment procedure in terms of a so-called Haigh-Diagram (allowable stress amplitude vs. mean stress) which is derived from corresponding SN-curves with different mean stress levels or different R-ratios. Hereby, the R-ratio is defined by the lower stress ($\sigma_u$) and the upper stress ($\sigma_o$) or alternatively by the mean stress ($\sigma_m$) and the stress amplitude ($\sigma_a$), respectively, see equation (1).
\[ R = \frac{\sigma_u}{\sigma_0} = \frac{\sigma_m - \sigma_a}{\sigma_m + \sigma_a} \]  

(1)

2. Background and Scope of the Investigation

The majority of hydro runners are manufactured out of nickel-martensitic stainless cast steels with 13 % Chromium and 4 % Nickel (GX4CrNi13-4, 1.4317 acc. to DIN EN 10283 or CA6NM acc. to ASTM A743, abbreviated as 13-4 steels in the following). Originally, these steels were developed in the 1960’s and further improved and studied in the decade thereafter. With special regard to hydro power applications, a rather large program was executed in the 1980’s under participation of various hydro power equipment manufacturers, hydro power station operators and independent institutions to investigate the corrosion fatigue properties of the cast 13-4 steels, see e.g. [2, 3].

The results that were generated back in these days still form a solid basis for current fatigue assessments of hydro runners. However, the range of covered load levels and cycles is limited to the mid-cycle HCF-regime (approx. 1.0E+06 to 2.0E+07 cycles). Within today’s fatigue assessment approaches, the complete load cycle of a runner from start to standstill are of interest and hence fatigue data covering the LCF-, HCF- and preferably also the VHCF-regime are desired. Moreover, processes in material manufacturing were further developed and improved since the 1980’s. Nowadays, the 13-4 steel melts are typically treated using secondary metallurgical processes such as Argon Oxygen Decarburization (AOD) or Vacuum Oxygen Decarburization (VOD) that lead to steel batches with high purity and homogeneity (low content of tramp elements), relatively low Carbon contents and well-balanced alloy elements. The concrete impact of these factors to the available fatigue databases and their interactions have been considered only on a spot-light basis within the last years. A complete and extensive fatigue testing program of state-of-the-art 13-4 steel for hydro power applications has not been carried out in the last 20-30 years. Hence, the material investigations within the FrancisPLUS research project at Voith Hydro (VH) are intended to address the limitations described above and provide a reliable database for state-of-the-art fatigue assessments. As a prerequisite, water quality evaluations and corrosion test results are outlined within this paper before the fatigue testing setup and selected results of the corrosion fatigue tests will be presented.

3. Cast Material for Experimental Investigations

For material investigations within the FrancisPLUS project, inter alia, a block featuring three stages with different thicknesses representing the Francis runner blade shape was cast in the VH foundry. The composition of the cast material (GX4CrNi13-4+QT1) is in accordance with the above-mentioned standards, selected values of the chemical analysis are summarized in Table 1. The 13-4 steel batch was melt in an electric induction furnace with subsequent refinement in a separate AOD-Converter. After casting, the steel block was quenched and tempered using parameters that are also compliant with DIN EN 10283. The values of the basic material tests (Yield Strength, Ultimate Tensile Strength, Elongation, Reduction of Area and also Impact Strength) lie well above the given minimum values in DIN EN 10283 for heat treatment class +QT1. A comparison to Francis runner parts of selected projects realized by Voith Hydro in the recent past showed a good accordance of the basic material properties. Generally, in order to generate fatigue results with significance to real hydro runners, the specification for the test material was on purpose derived from actual runner manufacturing documents.

| Table 1. Chemical composition of the 13-4 steel cast block |
|----------------------------------------------------------|
| % C  | % Cr  | % Ni  | % Mo  | % Mn  | % Si  | % P   | % S   |
|------|------|------|------|------|------|------|------|
| DIN EN 10283 | < 0.06 | 12.0 – 13.5 | 3.5 – 5.0 | < 0.7 | < 1.0 | < 1.0 | < 0.035 | < 0.025 |
| Cast block actual | 0.03 | 12.0 | 3.66 | 0.44 | 0.69 | 0.36 | 0.030 | 0.005 |
4. Water Quality Evaluations

The majority of corrosion fatigue data that is available from the investigations performed in the past was derived using tap water; detailed information from water quality databases with relation to real hydropower projects was either not available or has not been considered. As a result, this makes the evaluation and comparison of the data challenging as the test conditions are not completely comparable.

The corrosion resistance of the 13-4 steels is highly dependent on several factors as the properties and composition of the surrounding medium, e.g. regarding pH-value, concentration of aggressive ions and oxidants. It is well known that the most failures on stainless steels due to pitting corrosion are caused by halides and especially Cl-ions which are relatively small anions with a high diffusivity that tend to form deep pits. This type of corrosion can act as local initiation point for corrosion fatigue cracks if mechanical load is present. While the risk of pitting corrosion increases with higher chloride concentrations, this tendency is not as clear for higher sulfate concentrations. Since sulfate ions are not as small as chloride ions, they might be absorbed at the passive film but do not induce a local breakdown because they prevent chloride absorption by forming some kind of barrier. However, the inhibiting effect of sulfate on the nucleation of pitting corrosion is strongly dependent on the sulfate/chloride ionic ratio and even synergistic effects of both, chlorides and sulfates were observed. Several failures of pitting corrosion pertaining to the described interactions were reported [6].

With regard to the above-mentioned parameters, a database containing water quality parameters of over 100 Voith-related hydropower projects all over the world has been evaluated. Naturally, the chloride, sulfate and calcium carbonate contents were of primary interest; nevertheless, also the dependent parameters electric conductivity and pH-values were evaluated.

As can be seen from Figure 1 and Figure 2, the chloride and sulfate content for the majority of the projects is relatively low as the Median values lies well in the left third of the diagrams. The Median value represents the 50 % quantile of the data set, i.e. 50 % of the projects lie below and 50 % above. In addition, it can be seen that there is a comparatively low number of projects that exhibit medium to high chloride and sulfate contents in the available water analyses. Based on the VH-database evaluations, two distinct water qualities have been defined for fatigue testing within the FrancisPLUS project. The parameters for water quality 1 (WQ 1) were defined in a way that more than 95 % of the projects are covered (i.e. the 95 % quantile). This water quality is subsequently used for the majority of the fatigue tests and serves as a reference and basis. In addition, a second water quality (WQ 2) has been defined representing the 75 % quantile of the projects. For selected R-ratios, supplementary fatigue tests with WQ 2 are carried out in order to assess the influence of different water quality parameters. It has to be emphasized that the water qualities have been defined based on river or reservoir water from the database, sea water qualities were not considered in the assessment.

![Figure 1. Chloride Content Distribution](image1)

![Figure 2. Sulfate Content Distribution](image2)
5. Corrosion Characteristics

To investigate the corrosion susceptibility of the cast 13-4 steel in both selected water qualities, electrochemical analysis were performed. All steel samples were ground prior to the experiments using SiC grinding paper until grit size 600. A platinum wire counter electrode and an Ag/AgCl reference electrode were used for performance of the experiments. The electrodes were coupled to a potentiostat (Gamry Interface 1000) that is connected to a personal computer for data acquisition and analysis.

First, the open circuit potential (OCP) of the samples was measured for 30 minutes in the different water qualities, Figure 3. As can be seen, the open circuit potentials of the cast 13-4 steel after 30 minutes of immersion vary slightly from -100 mV in WQ 2 and -130 mV in WQ 1.

![Figure 3. Open Circuit Potential (OCP) for WQ 1 and 2](image)

![Figure 4. Polarization Curves for WQ 1 and 2](image)

Subsequently, cyclic polarization curves were recorded with a scan rate of 0.2 mV/s starting at a value that is 300 mV more negative than the determined OCP, Figure 4. In both water qualities the polarization curves show the typical active/passive behavior for stainless steels and quite similar corrosion potentials (approx. -100 mV) as well as passive current densities in the range of 6.0E-07 to 9.0E-07 A/cm² (horizontal course of the curves in the forward scan). In water quality 1, at a potential of +430 mV a sudden increase in corrosion current density is observed. This leap indicates a breakdown of the passive layer and the formation of stable pitting corrosion at this potential. In water quality 2, no pitting potential can be identified in the polarization curves. During microscopic analysis after electrochemical characterization, on both samples pitting corrosion could be observed. Hence, the formation of stable pits in WQ 2 must have occurred during the backwards polarization scan, leading to a shift of corrosion potential compared to the forward scan. As expected, the corrosion analysis clearly shows that water quality 1 is more corrosive than water quality 2.

6. Corrosion Fatigue Testing Setup

In order to cover a wide range of cycles, the corrosion fatigue tests within the FrancisPLUS project are carried out in the Low Cycle Fatigue (LCF) as well as in the High Cycle Fatigue (HCF) regime. Hence, load cycle numbers between 1.0E+03 and 1.0E+08 are covered. Smooth specimens with cylindrical cross section and thread clamping are used for all tests. The specimen are fully submerged in the corrosive medium for all tests. For this purpose, a test setup as shown in Figure 5 and Figure 6 had to be developed. All parts which are in contact with the corrosive media are manufactured of identical material in order to ensure that no electrochemical potential formation can occur which would possibly influence the test results. The corrosive medium is in constant circulation and is replaced for
each test. In addition, the water quality parameters are randomly checked to ensure reproducible conditions. Since a local enrichment of pitting corrosion-promoting ions is subordinate in a constant, flown-through Francis runner, pre-test aging was not applied to the fatigue specimen. However, this influence parameter will be addressed in a later stage of the project.

For LCF-experiments under strain control, a special linear variable differential transformer extensometer for exact displacement measurement is used. In order to record all stress-strain hysteresis directly on the specimen, the extensometer is also completely immersed in the medium (Figure 6). Since the test frequency can play a role in the presence of corrosive processes, the HCF-tests are performed on a servo-hydraulic test system with a frequency of 25 Hz. This lies in the range of typical gate passing frequencies of Francis runners. In order to be able to investigate the range of higher load cycle numbers (up to 1.0E+08) in a reasonable time, a resonance pulser with max. 160 Hz test frequency is also used. Naturally, the LCF-tests have to be performed at comparatively low frequencies (range of 0.1 Hz) due to the large displacements.

The test data of all test types are continuously recorded and evaluated with regard to different crack initiation criteria. Finally, all specimens are loaded until break in order to perform a post-mortem failure analysis of the fracture surface for casting defects, shrink holes etc. In the end, an extensive database containing fatigue data is expected. This database will be very valuable for evaluations, comparisons and material classifications of runners that will be realized at Voith Hydro.

7. Selected Fatigue Test Results
Since the beginning of the FrancisPLUS project, over 100 HCF-tests and more than 60 LCF-tests were performed with the cast 13-4 runner material. The corrosion fatigue tests were executed under different R-Ratios to include the mean stress influence in the test results. For the R-Ratios 0 and 0.5 (i.e. the pulsating tensile stress range), a preliminary comparison of the test results for both water qualities is shown in Figure 7 and Figure 8. In the diagrams, the normalized stress amplitude is plotted against the number of cycles to failure (SN-diagram). As can be seen in Figure 7 for R = 0, the slope of the mean lines is quasi identical for both water qualities. The scatter (\(T_N\)) is calculated according to DIN 50100, see equation (2), where \(s_{STD}\) is the standard deviation [8].

\[
T_N = 10^{2.564 \cdot s_{STD}}
\]

(2)
The results show a typical scatter that can be expected for a cast material. It seems to be somewhat larger for WQ 1, however, less data is available for WQ 2 and only failed specimen were used for the evaluation of $T_N$ and the slopes. Comparing the mean lines in Figure 7 that represent a 50% survival probability of the specimen, it is obvious that the mean line for WQ 2 is shifted slightly to the right giving a factor $F_N$ of 1.68 in cycle direction or a factor $F_\sigma$ of 1.10 in stress amplitude direction. This means that specimen tested in WQ 2 withstand either a higher number of cycles at constant stress amplitude (factor $F_N$) or a higher stress amplitude at a certain number of cycles (factor $F_\sigma$). Indeed, for the data sets shown in Figure 7, the line representing 90% survival probability of WQ 2 corresponds to the mean line representing 50% survival probability of WQ 1. Hence, the less corrosive WQ 2 results in somewhat beneficial fatigue properties for $R = 0$ compared to WQ 1. However, this picture is not so clear for the $R$-Ratio of 0.5 in Figure 8. For WQ 2, a larger slope exponent was found compared to WQ 1. As a result, the mean lines are not parallel and no constant factors can be derived. Especially for higher number of cycles ($> 1.0E+07$), the data points of WQ 2 seem to support the findings described for $R = 0$.

It has to be emphasized that these considerations are preliminary as the testing program is still running. Especially for $R = 0.5$, only scarce data is yet available for WQ 2. Moreover, in the current state of the project selected specimen have been chosen for further examination of the fractured surfaces e.g. in the scanning electron microscope. These examinations allow a more distinct evaluation of outliers and may lead to revisions of the diagrams presented. Further specimens have to be tested and will improve the database. A complete picture will be first available when all tests are finished and the overall evaluation is complete.

![Figure 7. Results of HCF-Tests at $R = 0$ for WQ 1 and 2 (preliminary)](image1)

![Figure 8. Results of HCF-Tests at $R = 0.5$ for WQ 1 and 2 (preliminary)](image2)

8. Summary

Within the paper at hand, the general approach and a number of results from the materials testing program within the FrancisPLUS project at Voith Hydro (VH) are presented. Beyond the claim of significantly enlarged operational horizons for hydro runners, reliable and up-to-date corrosion fatigue data of the runner material is required for accurate fatigue life calculations. In a first step, corrosiveness of water qualities which are contained in an in-house database was evaluated. Based on this evaluation two water qualities are defined that cover 95% and 75% of the VH-related projects. Corrosion tests showed that aggressiveness of the 95% water is higher as a distinct pitting potential could be observed. This was not the case for the less aggressive 75% water. However, the 95% water was chosen as major water quality for the fatigue tests in order to add a certain conservatism to the fatigue database. The
corrosion fatigue tests are carried out as Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) tests in order to cover a wide range of load amplitudes and number of load cycles. In the end, preliminary fatigue results are presented comparing both water qualities. Whereas at a R-Ratio of 0 a benefit is obvious for the less corrosive water, data situation is not sufficient yet for final evaluation of the R-Ratio of 0.5, but similar results as for R = 0 are expected.

With increasing requirements to the fatigue life of Francis runners it is inevitable to increase the knowledge about both material and loads. A profound database of material testing that includes different aspects of the runner materials and the boundary conditions is the foundation to build reliable and robust designs. A small selection of results with the focus on water quality has been presented within this paper for the cast steel CA6NM. Additionally the corresponding forged material (X3CrNiMo13-4 or F6NM) is under investigation to complement a comprehensive picture for flexible hydro operation in the future.

Acknowledgments

The authors acknowledge the financial support by the Federal Ministry for Economic Affairs and Energy of Germany in the project FrancisPLUS (project number 03EE4004A).

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