Finding the ideal strategy:  
Full-scale fatigue testing of wind turbine rotor shafts

T Rauert\(^1\), J Herrmann\(^1\), P Dalhoff\(^1\) and M Sander\(^2\)

\(^1\) Institute of Renewable Energy and Energy Efficient Systems, Hamburg University of Applied Sciences, Hamburg GER  
\(^2\) Institute of Structural Mechanics, University of Rostock, GER  
E-mail: thes.rauert@haw-hamburg.de

Abstract. For the purpose of a light weight design of rotor shafts, fatigue testing is necessary. Since full-scale fatigue tests of these large components are time consuming, costly and have not been done before, much effort has to be put into the implementation of a suitable test strategy. The paper presents the boundary conditions that have to be considered to determine the finite life regime of the component S/N-curve. A statistical simulation shows how much the derived S/N-curve is influenced by the specific test procedure.

1. Introduction
The design of a machine, in this case a wind turbine, starts with the requirements on the system level. In the next step, the requirements for the system integration level are derived. This procedure goes all the way down to the requirements for the materials. Subsequently, the requirements shall be tested on every level.

In [2] it is stated that today’s test facilities mainly focus on the operating performance of sub systems like the drive train, but only a few investigate the fatigue strength of components like blades or bearings. Furthermore, the necessity of developing new component fatigue testing procedures is emphasized. Currently the requirements for the rotor shaft of a wind turbine are not tested on the component level, sparing uncertainties especially about the fatigue behaviour in the design process, see figure 1.
In the case of the rotor shaft, these uncertainties are mainly concerning its fatigue behavior. To consider these uncertainties, material strength properties are reduced, the component S/N-curve is lowered and the accepted total damage sum over the component’s life must be below 1, e.g. 0.5, according to [3]. This approach leads to components that are heavier than they might need to be. A full-scale fatigue test of rotor shafts could reduce those uncertainties and therefore lead to a more efficient use of material. In addition, the applicability of prediction methods for fretting fatigue (wear between the main bearing inner ring and the rotor shaft) is investigated.

Since no full-scale fatigue tests of wind turbine rotor shafts have been conducted so far, there are not many relevant experimental data to consult. Thus a fatigue test will have to deliver basic scientific results about the fatigue behavior of the rotor shaft.

Due to the limited number of six specimen and the scatter of fatigue tests, the detailed test strategy has to be carefully developed, especially with regard to its statistical significance. The need for a statistical evaluation of a fatigue test procedure and statistically justified safety factors for the test results is described in [4].

In addition, it has to be ensured that only the material fatigue is causing the rotor shaft to fail during testing. Fretting fatigue between the rotor shaft and the main bearing inner ring must therefore not exceed a critical limit.

2. Rotor shaft loads

The loads at the rotor shaft originate from gravity and the aerodynamic loading of the rotor blades. The resulting forces on the rotor shaft are an axial force and a shear force. In addition, a torsional moment and a rotating bending moment act on the rotor shaft. The rotating bending moment however is contributing by far the biggest share to the total damage of the component. According to [5], calculations have shown that the damage from the rotating bending moment for an exemplary turbine life is approx. $10^7$ times higher than the damage from the torsional moment. The bending moment is resulting from the own weight of the rotor and the vertical and horizontal wind shear. A more in depth explanation of the loads on the rotor shaft can be found in [6].

The cumulative frequency distribution of the nominal bending stresses at the bearing seat of the rotor shaft is presented in figure 2. The blue line shows the deterministic characteristic of the stresses that result from the rotating bending moment from the own weight of the rotor. The bending moment from the aerodynamic loads are less predictable and contribute a triangular shape to the cumulative frequency distribution.

![Cumulative frequency distribution of nominal bending stresses at the bearing seat of the rotor shaft](image)

**Figure 2.** Cumulative frequency distribution of nominal bending stresses at the bearing seat of the rotor shaft (blue and green lines are presented qualitatively)

The load cycles (respectively stress cycles) of the rotating bending moment add up to a number of approximately $6 \cdot 10^8$ for 20 years of turbine life.
3. Fatigue life estimation

In order to estimate the lifetime of a rotor shaft, a fatigue life calculation needs to be carried out. This is usually done by a linear damage accumulation, based on the cumulative frequency distribution of stresses (figure 2) and the component S/N-curve (figure 3).

S/N-curves correlate the stresses in the component with the corresponding number of load cycles which can be sustained. Therefore, S/N-curves are a central element of fatigue life assessment. They can either be obtained by performing fatigue tests of material or components or can be estimated analytically. Detailed information can be found in [7], [8] and [9].

To derive an S/N-curve from a test procedure, multiple specimen have to be tested. Each specimen is tested under a certain loading which is oscillating between two fixed load levels. The number of cycles, until an initial crack can be detected, is counted. Finally, the number of cycles and the according stress level are plotted in a chart with logarithmic scale (lin-log or log-log). The more specimen are tested on multiple levels, the better the accuracy of the S/N-curve is. Since fatigue tests underlie a large scatter, the results have to be statistically evaluated and S/N-curves with different probabilities of failure can be derived.

\[
N_D = \frac{N_{90\%}}{N_{10\%}}, \text{ endurance limit } \sigma_{aD}
\]

\[
N_1 = C \cdot \sigma_a^{-k}
\]

\[
N_i = N_D \left( \frac{\sigma_{aD}}{\sigma_{a1}} \right)^{-k}
\]

In the high cycle fatigue regime, a logarithmic normal distribution of the lifetime can be assumed. Therefore, a linear regression can be performed in a log-log plot to determine the parameters C and k of the following equation from [11]:

\[
N_1 = C \cdot \sigma_a^{-k}
\]

C is the theoretical number of cycles corresponding to a stress amplitude \(\sigma_a = 1\) and \(k\) is the slope of the S/N-curve in the high cycle fatigue regime. \(N_1\) is the corresponding number of cycles till failure for a cyclic stress amplitude of \(\sigma_{a1}\).

Usually the S/N-curve in the high cycle fatigue regime is represented in the following way:

\[
N_i = N_D \left( \frac{\sigma_{aD}}{\sigma_{a1}} \right)^{-k}
\]

\(N_D\) is the cycle number at the endurance limit \(\sigma_{aD}\). The derived function describes the P50 S/N-curve. Meaning that 50 % of all specimen reach more cycles than defined by the S/N-curve. However,
it still has to be statistically corrected, depending on the number of tested specimen, to be within a desired confidence range.

4. Test strategy
As stated before, a full-scale fatigue test series will be done in order to reduce uncertainties in the fatigue life estimation of the rotor shaft. Therefore, an extensive investigation has been carried out to determine the most adequate test strategy for the given boundary conditions, which facilitate a scope for the test series of six full-scale fatigue tests. The results are shown in figure 4. By means of a morphological analysis, the test strategy has been divided into ten aspects and several implementations have been proposed for each aspect. A detailed explanation of the morphological analysis can be found in [5].

![Morphological analysis of the test strategy, final strategy is highlighted in red [5]](image)

The final test strategy is highlighted in figure 4. In terms of classic S/N-testing, the rotor shaft will be loaded with a constant rotating bending moment. For this reason, variable amplitude loading is not possible. However, in future tests an investigation of the effects of variable amplitudes would also be valuable. To achieve a higher statistical significance of the derived S/N-curve, all six shafts will be used for the determination of one S/N-curve. Therefore, all six shafts have the same design and are made from the same material. For this reason, only shafts from forged steel can be tested. The test bench design itself is providing an installation of the specimen that is very close to the situation in the real turbine. The original main bearing is utilised. A substitution structure is used to support the shaft at the rear end, replacing the gearbox.
The shaft is loaded with a constant rotating bending moment during testing. A shear force is induced, as shown in section 5.1. The goal of the tests is to determine the S/N-curve in the high cycle fatigue regime. A detailed investigation of the distribution of the specimen on selected load levels is presented in section 5.3.

In order to generate a crack in the rotor shaft in a reasonable amount of time, the magnitude of the bending moment is increased well above the normal bending moment of regular turbine operation (above 3MNm). Also the loading frequency will be increased to 1 Hz.

5. Rotor shaft fatigue-testing

In the following sections, the fatigue test bench and the boundaries of testing are presented. Based on a statistical simulation and evaluation of S/N-tests, recommendations for the detailed test plan are given.

5.1. Test setup

The test bench has been developed and constructed by Fraunhofer IWES in Bremerhaven and is shown in figure 5. The support (gearbox substitution structure and original main bearing) is similar to the situation in the real wind turbine (Suzlon S88), as required from the test strategy. The rotor shaft is connected to a 5.5 m load lever. A cross force is applied to the end of the load lever, producing a bending moment in the rotor shaft. An electric motor rotates the shaft, leading to a rotating bending moment. As described before, the applied load is kept constant over the whole testing time. During the test, 20 strain gages, evenly distributed across the circumference of the rotor shaft, monitor its condition at the most fatigue critical area. In addition, the displacements and temperatures are logged. An initial crack shall be detected by an increasing total displacement of the load application, visual inspections and a changing strain state at the hot spot. In total six shafts from forged steel (42CrMo4) are tested with different load levels.

Figure 5. Setup of rotor shaft fatigue test bench (image provided by Fraunhofer IWES)

The rotor shaft design had to be altered, to reduce testing time. More precisely, the notch radius in the critical area of the shaft has been reduced to create a higher stress concentration. This change in the notch effect has to be regarded when transferring the test results to the usual or other shaft designs.

5.2. Boundaries of testing

Determining the S/N-curve in the high cycle fatigue regime is the goal of the experimental investigations. Therefore, an upper and lower load level needs to be defined for the fatigue tests.

5.2.1. High cycle fatigue regime. The lowest load level is basically determined by the endurance limit (see figure 3). From further material investigations the endurance limit $\sigma_{\text{end}}$ can be estimated. The lowest load level should be sufficiently higher than the endurance limit. The highest limit of the high cycle fatigue regime corresponds to a cycle number of approximately $5 \cdot 10^4$. In case that no experimental data are available, a synthetic S/N-curve can be calculated according to [8]. Depending on the reliability
of the available material and component data, the distance to the low cycle and very high cycle fatigue regime has to be chosen.

5.2.2. Fretting wear at bearing seat. Due to high bending moments at the rotor shaft, relative movements between the rotor shaft and the main bearing inner ring occur. These relative movements can lead to the undesirable phenomenon of fretting fatigue. The contacting surfaces are deteriorating and the fatigue strength of the shaft is reduced unnoticed. Under this condition surface cracks can develop in the shaft. In case of high local stresses in the area of fretting wear, these cracks can grow and lead to an early failure of the component [6].

![Assumed initial crack and Hotspot](image)

**Figure 6.** Stress distribution on the rotor shaft, assumption of an initial crack at the position of the edge of the inner ring of the main bearing resulting from a bending moment.

The occurrence of a growing crack from fretting wear has to be excluded for the fatigue test. A rotor shaft, which fails due to fretting fatigue, is not usable for the determination of an S/N-curve.

In terms of a conservative approach an analytical crack growth calculation, based on the NASGRO-equation [12] from FORMAN and METU is done. According to [6], an initial crack depth of 2 mm is supposed at the beginning of the test and therefore used as an input parameter for the crack growth calculation, see figure 6. Finite element calculations have shown that nominal bending stresses can be assumed in the area of fretting wear at the main bearing seat for the regarded rotor shaft design.

This means that nominal bending stresses on the shaft surface must not exceed the threshold stresses for crack growth in that area for an initial crack depth of 2 mm. An evaluation with the analytical crack growth simulation software NASGRO leads to the following result: In the regarded case, cracks do theoretically not grow below a stress amplitude of 175 MPa. However, crack initiation due to fretting is possible.

A nominal bending stress amplitude of 175 MPa is caused by a bending moment of 5.8 MNm. This however leads to a hotspot stress of approximately 556 MPa. This stress amplitude is already in the low cycle fatigue regime of the component S/N-curve. Thus, a fretting induced surface crack is not expected to grow during a fatigue test in the high cycle fatigue regime and will therefore not lead to a failure of the rotor shaft.

5.3. Statistics of fatigue testing

The fatigue life of a component is subjected to scatter. A large amount of specimen has to be tested to determine the fatigue life with high confidence. The reason for this is illustrated in figure 7. The red line shows the basic population with the true mean value M. Usually not enough specimen can be tested to determine this true distribution. A fatigue test with a small number of samples can lead to a non-conservative estimation of the mean value m (green line). This is why a statistical amendment, depending on the number of specimen, is necessary. This can be done by correcting the mean value (in the regarded case m is the number of load cycles $N_{50\%}$) from a small sample by equation (3) from [13].
Figure 7. Basic population and small sample, based on [10]

The risk factor \( j_{C,n} \) is defined as:

\[
j_{C,n} = 10^{u_c / \sqrt{n}}
\]  

(4)

\( u_c \) is the confidence coefficient and is chosen from the literature for a desired confidence level (e.g. \( u_c = 0 \) for a confidence of 50%, \( u_c = 1.282 \) for a confidence of 90%, according to [7]). \( s \) is the supposed standard deviation and \( n \) is the number of tested specimen. If the scatter range is available (see figure 3) instead of the standard deviation, the following equations can be applied according to [7]:

\[
s = \left( 1 / 2.56 \right) \log \left( 1 / T_N \right)
\]  

(5)

\[
j_{C,n} = \left( 1 / T_N \right)^{u_c / (2.56 \sqrt{n})}
\]  

(6)

Equations (3) - (6) can be applied for a single load level. Therefore, for a series of S/N-tests with different load levels, the results (cycle numbers) on each load level should be corrected accordingly.

There are different approaches towards determining an S/N-curve. One is to test one specimen per load level. In [14] this is called the method of discrete load steps. The alternative is the method of fixed load horizons. In this case, fatigue tests will be performed on fewer load levels with multiple specimen per load level. Also hybrid methods are possible. In which a series of specimen are tested, each on a separate load level. Afterwards one of the first load levels is selected for further tests on that level.

Taking into account the scatter of fatigue lifetime, it becomes clear that different methods of S/N-tests can provide S/N-curves of different accuracy. Hence, a close investigation of the influence of the methods on the accuracy of the derived S/N-curve is necessary prior to testing. To accomplish this, a simulation of S/N-tests is done. All necessary steps for this simulation are explained subsequently:

In the programming environment of Python a large number of fatigue experiments are being simulated. This is done by randomly generating logarithmic normally distributed numbers with a given mean value and standard deviation. For the regarded rotor shaft, a standard deviation of 0.15 has been determined by material testing. A basic population (50,000 random numbers) is generated.

A plausibility check is done by calculating the scatter range \( T_N \) (see formula in figure 3), the logarithmic standard deviation \( s \) and the logarithmic mean value \( N_{50\%} \) from the equations (7) and (8), according to [7] from this generated basic population. The results are shown in table 1.

\[
s = \frac{1}{n-1} \cdot \sum_{i=1}^{n} \left( \log N_i - \log N_{50\%_n} \right)^2
\]  

(7)

\[
\log N_{50\%_n} = \frac{1}{n} \cdot \sum_{i=1}^{n} (\log N_i)
\]  

(8)
Table 1. Plausibility check of random numbers

| Parameter | True value | Simulation |
|-----------|------------|-----------|
| s         | 0.15       | 0.149     |
| T_N       | 1/2.42     | 1/2.418   |
| N_50%     | 503.000    | 503.441   |

Table 2. Parameters of S/N-curve

| Parameter | Value       |
|-----------|-------------|
| N_D       | 2.073.000   |
| \( \sigma_D \) | 212 MPa    |
| k         | 5.12        |

The simulation can now be used to generate and evaluate the random numbers (load cycles) on multiple load levels and derive an S/N-curve as described in section 3. This is done by distributing the six available specimen across the high cycle fatigue regime.

Therefore, the six load levels for the simulation can be defined. Based on equation (2) and the S/N-curve parameters from table 2 the corresponding load cycles (mean values) are calculated.

For each load level, a defined number of values (cycle numbers) is generated (six in total) and the position and slope of the S/N-curve are derived by means of a linear regression. The position of the S/N-curve is defined as the corresponding load cycle number of the mean load level of the S/N-curve in the investigated range. This is repeated several times in order to get an information about the scatter range of the S/N-parameters.

To find out how many random S/N-curves have to be generated for one test series (specified load levels and corresponding number of specimen), an examination of convergence is done, see figure 8.

Figure 8. Examination of convergence based on the calculation of the slope k for simulated fatigue tests to find the minimum number of fatigue tests that define a basic population

The examination of convergence is done by gradually increasing the number of repetitions of one test series. For each test series the slope k of the S/N-curve is determined. Then the mean slope of all repetitions of the test series is calculated. For more than 10,000 repetitions, the calculated slope over all repetitions is adequately close to the true value. It means that 10,000 repetitions are getting sufficiently close to a basic population.

The next step is to evaluate the accuracy of the testing method. Therefore, the scatter range T of the derived position and slope over all repetitions is calculated. For the assumption of a logarithmic normal distribution of the derived parameters, a probability is assigned to every derived slope and position of each test series. They are therefore sorted in a descending order and assigned an ascending order number j starting with 1. According to [15] the probability P is:

\[
P = \frac{3j - 1}{3n + 1}
\]  

The dedicated probability P for one specific value indicates that P [%] of all values are below this value. The results of such a calculation is shown in figure 9 for the position of the S/N-curve.

In analogy to the calculation of the scatter range T_N for single load levels (see figure 3), the scatter range T of the estimated position can be calculated to rate the accuracy of a derived S/N-curve. The
same is done for the slope. According to [4], the calculated scatter range can be used as a safety factor. When $T_N$ is calculated from the $P_{10}$ and $P_{90}$ value, 80% of all derived slopes and positions, will be under- or overestimated by a factor of $\sqrt{T}$. 

**Figure 9.** Quantiles and confidence range for the estimated position of the S/N-curve, 

The different testing methods can now be benchmarked, based on the scatter range. Figure 10 shows the results of this benchmark. Five different test methods are compared with regard to the scatter range of the estimated parameters of the S/N-curve for varying spreading values. The spreading is defined as the quotient of the cycle number of the lowest and the highest load level of the test series ($N_{low}/N_{high}$).

**Figure 10.** (a) Scatter range of estimated slope, (b) Scatter range of estimated position at center of rotation of the S/N-curve, (c) Scatter range of estimated position at lower limit of S/N-curve in the high cycle fatigue regime

It is evident that the spreading of the test series has by far the biggest influence on the scatter range (the accuracy of the derived S/N-curve). A spreading of 10 and higher must be a premier goal of the real fatigue tests.
The method of fixed load horizons (2 load levels each with 3 specimen) offers the best accuracy for slope and position estimation, as it offers the smallest scatter range of all test methods. However, in terms of test risks, the method of discrete load steps can be the method of choice. This is because this method offers the possibility of gradually increasing the spreading and this way increasing the accuracy of the derived S/N-curve. In case a closer investigation of the standard deviation of the fatigue lifetime is desired, the first three specimen could be used to create a large spreading ($N_{low}/N_{high} > 10$). The other three specimen could afterwards be tested on one of the first three load levels. In this case, the accuracy of the S/N-curve in terms of estimated position will be the best at the load level with four tested specimen.

In figure 10 b an influence of the spreading on the estimated position of the S/N-curve cannot be determined. The reason for this is that the scatter range of position estimation is done close to the center of rotation of the S/N-curve. The same evaluation for the lower part of the S/N-curve does yield a strong dependence on the spreading, see figure 10 c.

### 6. Conclusion

The test strategy for a full-scale fatigue test of the rotor shaft and the developed test bench are presented. In addition, the basics of the desired component S/N-curve are described. Subsequently, different test methods to determine the S/N-curve in the high cycle fatigue regime and the boundaries and influences on the test are introduced. A crack growth simulation for the fatigue critical area of the rotor shaft shows that an early failure of the rotor shaft due to fretting fatigue induced surface cracks can most likely be excluded, as long as the nominal bending stresses stay below 175 MPa.

A developed statistic simulation tool can be used after the fatigue tests, to statistically correct the component S/N-curve. This can be done by calculating the scatter for both position and slope of the S/N-test and using the square root of this scatter as statistically justified correction factors.

The statistic simulation of the S/N-test shows a strong dependency of the test results on the spreading of the load cycles. A spreading of 10 or higher should be achieved for the real test, since this strongly increases the accuracy of the derived S/N-curve. Depending on the used test procedure, the scatter of the estimated slope of the S/N-curve can be decreased by a factor of 2 to 3 when the spreading is increased from 2 to 10.

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