

HIGH-CYCLE FATIGUE BEHAVIOUR OF
DARLINGTON UNIT 2 GENERATOR ROTOR MATERIAL

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A test program was undertaken to determine the high-cycle fatigue behaviour of material from a failed Darlington Unit 2 generator rotor shaft. There were no significant differences between the test results obtained in two different laboratories. Prediction methods, including the normal distribution, the Weibull distribution, and the arc sine function, were used to estimate the fatigue endurance limit. All distributions showed good correlation between the applied fatigue stress and the percentage of specimen failure. A fatigue strength of 410 MPa at 100°C, $R = -1$ for a smooth surface finish was used as a guideline for the new design modifications, which ensure that the component, with an appropriate factor of safety, operates well below this value.

INTRODUCTION

During the commissioning of Darlington Unit 2, a CANDU type of nuclear reactor with 936 MW generating capacity, excessive vibration in the generator rotor led to the discovery of a crack in the shaft end of the rotor. The crack was initiated by fretting and propagated under the influence of cyclic bending stresses. Details of the failure analysis have been reported elsewhere(1,2). In a joint program ABB and Ontario Hydro succeeded in resolving the problem in only 3 months by introducing a modified design that eliminated any risk of crack initiation by fretting. However, the cyclic bending stress was still present because of the rotor's dead weight and had to be taken into account in the assessment of the modified design. Therefore, Ontario Hydro and ABB established an intensive material test program to determine the high-cycle fatigue behaviour of the rotor steel that was taken from the failed shaft end.

The two laboratories obtained similar results; several statistical schemes were used to predict the fatigue strength from the test data. This value was then used to establish an appropriate factor of safety to ensure an infinite operating life for the modified generator rotor.

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DESCRIPTION OF EXPERIMENTAL SET-UP

The high-cycle fatigue tests on the failed rotor material were carried out at room temperature and at 100°C on servo-hydraulic or electro-mechanical frames designed for axial push-pull loading. In general, the test procedures followed the recommended guidelines in the ASTM standards(3,4). Hour-glass fatigue specimens, with the loading axis parallel to the longitudinal axis of the rotor, were machined from material close to the failure site. The measured chemical compositions and mechanical properties all conformed to the design specifications:

1. Composition: C, 0.22-0.32%; Mn, 0.2-0.5%; Si, 0.3% max.; Ni, 3.2-4.0%; Cr, 1.2-1.8%; Mo, 0.3-0.6%; V, 0.05-0.15%; P, 0.015% max.; S, 0.018% max.
2. Yield strength, 751 MPa; ultimate tensile strength, 855 MPa at room temperature.

The fatigue tests were conducted using load control and a sinusoidal waveform. The test matrix, with 165 specimens, included the following parameters: two R-ratios of -1 and 0, and two types of surface finish (N6, 0.8 μm and N9, 6.3 μm). The test specimen was called a run-out when the total number of fatigue cycles reached 10 million.

RESULTS

Figures 1 and 2 show all the S-N data, the number of fatigue cycles (N) is plotted against the fatigue stress amplitude (S), which is one half of the difference between the maximum and the minimum applied stress. There was good agreement of S-N data between the two laboratories. The S-N data plots showed that for N6, R = -1 and N9, R = 0 the data points obtained by Ontario Hydro appear to have a slightly lower correlation than ABB's data points. However, no such scatter was observed in the other test conditions (N6, R = 0 and N9, R = -1), which essentially used the same test procedures, suggesting that this was not an experimental problem. With little systematic error in test procedure, all results were therefore combined into a common data pool for evaluation.

Data Analysis

Since it is not economically feasible to test for a long period such that all test specimens will be run-out, multiple tests at relatively high stress amplitudes were used to determine the relationship between the fatigue strength and the percent of failures. Many schemes for fatigue-strength prediction are available; this analysis considers the normal distribution, the Weibull distribution, and the arc sine $\sqrt{p'}$ distribution.

Statistical Evaluation Schemes. The normal distribution method to determine the fatigue strength was well documented by R.E. Little(5). The formula most widely used in normal distribution(6) is:

$$p = (1 - 3/8)/(n + 1/4) \\ \text{or} \\ (1 - 3/8)/(n + 1/4) \text{ if no specimen failed} \quad (1)$$

where p = percent of specimen failures
i = number of failed specimens
n = number of test specimens

The percentage of specimen failure at each stress level is then expressed as a probability value (between 0 and 1); the 50% failure point is equivalent to 0.5 probability.

For the Weibull distribution(6), the equation for the percent of failure is:

$$p = (1 - 1/2)/n \\ \text{or} \\ (1 - 1/2)/n \text{ if no specimen failed} \quad (2)$$

The two parameter Weibull function used to fit the data is:

$$P = 1 - \exp [-(\sigma/\alpha)^\beta] \quad (3)$$

where P = probability of failure
 σ = fatigue stress amplitude
 α = scale factor
 β = shape factor

As for the arc sine $\sqrt{p'}$ distribution(7), the formula used was:

$$p = i/n \text{ or } 1/(2n) \text{ if no specimen failed} \quad (4)$$

The experimental fatigue stress amplitudes were correlated with the percentages of failures using the following equation:

$$\sigma = A + B (\text{arc sin } (\sqrt{p'})) \quad (5)$$

where σ = fatigue stress amplitude
A = intercept, fatigue strength at zero percent of failure
B = slope of straight line fit
p' = experimental percent of failure/100
arc sin = function expressed in radian

The results are shown in Table 1 and Figure 3.

TABLE 1 - Results of Probability Analysis

TEST CONDITIONS	NORMAL			WEIBULL			ARC SINE \sqrt{p}		
	$P_{0.01}$	$P_{0.5}$	r	$P_{0.01}$	$P_{0.5}$	r	P_0	$P_{0.5}$	r
N6, R = -1	410	457	0.85	396	460	0.84	428	452	0.82
N6, R = 0	312	355	0.95	302	358	0.96	320	354	0.96
N9, R = -1	272	319	0.84	260	321	0.86	286	316	0.85
N9, R = 0	234	278	0.73	225	280	0.71	252	275	0.74

The column $P_{0.01}$ represents the fatigue stress amplitude at 0.01 probability of failure; r is the correlation coefficient for the least-squares fit.

DISCUSSION

For engineering application, a designer normally applies the appropriate safety factor to the fatigue endurance limit and the choice of safety factors depends on the industry. With sufficient test data the B-10 level, which represent 10% failure, can be used.

Since the uncertainty decreases with the square root of the number of tests, therefore, a large number of tests is required. A large test matrix is essential, but expensive and time consuming. For example, to describe accurately the behaviour at any part of a normal distribution, a weighted Probit least-squares analysis would require about 50 specimens per test condition(8).

The problem to be resolved is: What is the reasonable limit for extrapolation from a data base that is heavily centred at the high-stress end without jeopardizing safety and meeting both the financial and scheduling limitations?

The difference in the fatigue strength between the normal (which is often used in North America), the Weibull, and the arc sine \sqrt{p} distribution (German practice) became notable only at low probability of failure. The differences between the 0 and the 0.01 probability strengths are of the order of up to 30 MPa. For the same strength value, different probability of failure was obtained, depending on the type of distribution. This difference may be the result of a small sample size, which influences the accuracy of the extrapolation. For the 50% fatigue strength, the range of values is of the order of less than 10 MPa between different distributions.

It is possible that the strength distribution flattens out below the 0.01 probability value in the normal distribution, which is an open distribution; at sufficiently low stress, no specimens should fail. Recent Japanese work(9) successfully applied the normal distribution to the data gathered from research over the past 20 years. Most of the data were within the 10 to 95% failure values. The fatigue strengths with no failures were found to be 10 MPa below the fatigue strength at 0.01 probability.

Although the 50% failure fatigue strength is more accurate, its use does not give a clear picture of the true degree of safety. The fatigue strength is governed by the crack initiation process, which is a statistical process controlled by the distribution of local microstructure, and every statistical process is, by its very nature, subject to scatter. This scatter in fatigue strength can become considerably larger if all the influences of a machining operation, such as local roughness and residual stress, add to the crack initiation process. A 50% failure fatigue strength, is therefore just an indication of a 50% chance to jeopardize a machine's integrity.

To ensure infinite operating life of a component or machine design exposed to fatigue loading, a fatigue strength with low failure probability has to be used for the design evaluation. The results of this investigation indicate that the zero failure probability value of the arc sine \sqrt{p} distribution or the 0.01 failure probability value of the normal distribution are similar and represent suitable design values. For the assessment of the Darlington generator rotor modified design, the normal distribution value of 410 MPa at R = -1 together with a safety factor of 4 was obtained in the final design.

For any combination of fatigue stress amplitude and mean stress, the Smith diagram(10), which utilizes the Goodman and Gerber equations is often used by the designers. As shown in Figure 4, the experimental results from R = 0 fall within the Smith envelop.

SUMMARY

All the test laboratories generated similar fatigue test data. The normal distribution, which has been used extensively for many different materials, gave a 0.01 probability of failure for the zero failure fatigue strength based on the arc sine \sqrt{p} equation. However, the median fatigue strength is the same regardless of the distributions used. For design purpose, the fatigue strength of 410 MPa at R = -1 can be used when an appropriate safety factor is chosen during the design stage.

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REFERENCES

- (1) Clarke M. Metallurgical investigation of cracking in generator rotor shaft, Darlington NGS, unit 2. Ontario Hydro Research Division, Report no. 91-7-K, February 18, 1991.
- (2) Schollhorn K, Ebl G, Steigleder K. Fretting cracks in a 936 MW turbogenerator shaft: failure analysis and solution. Proceedings of VGB Congress, Karlsruhe, Germany, October, 1992.
- (3) ASTM E 468-82, 1990.

- (4) **ASTM E 606-80, 1990.**
- (5) **Little R.E., Jebe, E.H.. Manual on statistical planning and analysis for fatigue experiments. ASTM STP 588, 1975:54.**
- (6) **Weibull W. Fatigue testing and analysis of results. Oxford: Pergamon Press 1961:163,198-199.**
- (7) **Dengel D. Die arosin (P)-Transformation - ein einfaches Verfahren zur grafischen und rechnerischen Auswertung geplanter Wohlerversuche. Z.f. Werkstofftechnik/J. of Materials Technology 8. Jahrgang. Heft 8. August 1975:253-288.**
- (8) **Weibull W. Fatigue testing and analysis of results. Oxford: Pergamon Press, 1961:15-16.**
- (9) **Tanaka T, Sakai T, Iwaya T. Fatigue lives and fatigue strength of ferrous metals. In: Statistical research on fatigue and fracture. London, UK: Elsevier, 1987:125-157.**
- (10) **Weibull, W. Fatigue testing and analysis of results. Oxford: Pergamon Press, 1961:155.**

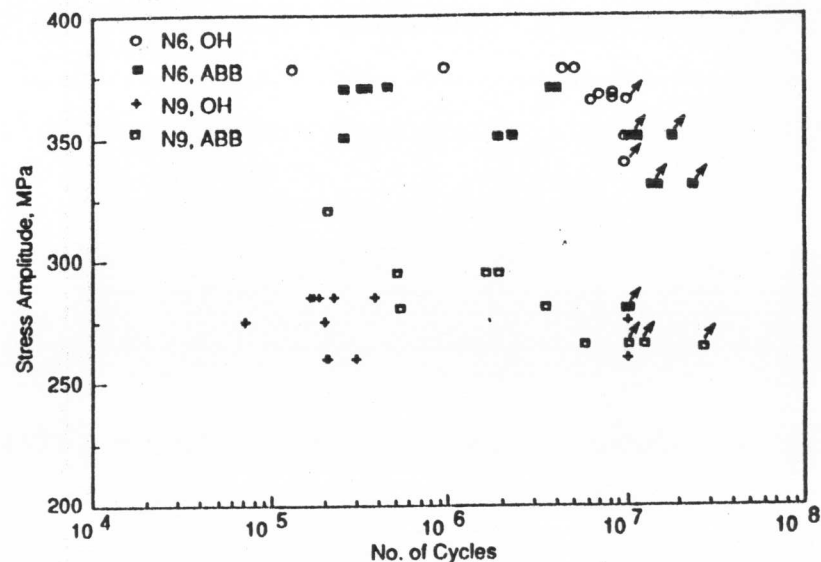


Figure 2 Combined fatigue data 100°C, R = 0

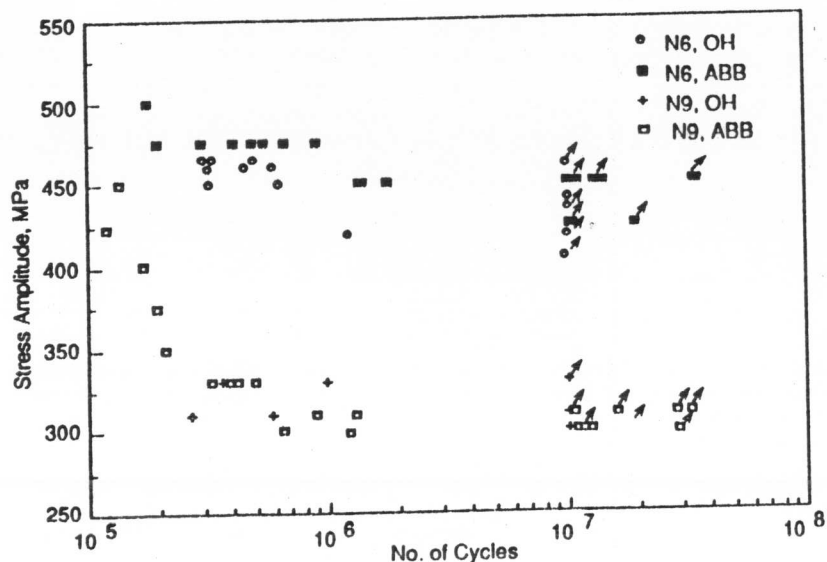


Figure 1 Combined fatigue data 100°C, R = -1

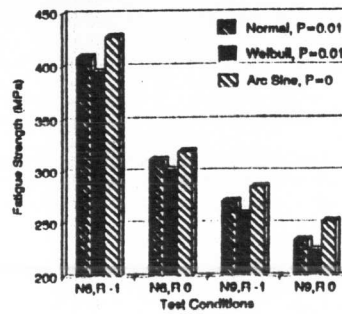


Figure 3 Comparison of three distributions

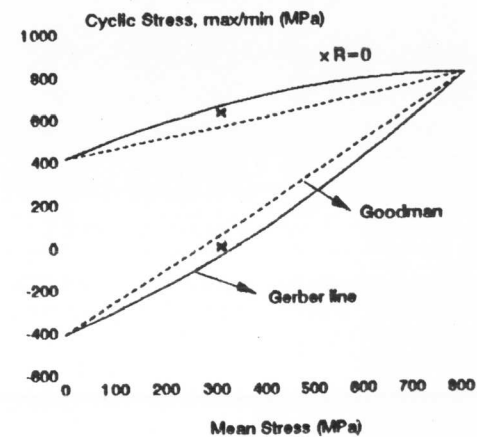


Figure 4 Smith diagram for N6 finish, 100°C