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PROBABILITY DISTRIBUTION OF FATIGUE STRENGTH OF ROTOR BLADES (PROFAR)

Publishable Final Report
EU JOULE III Project JOR3-CT98-0266

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Abstract

In the period June 1997 – July 2001 the EU funded project 'Probability Distribution of Fatigue Strength of Rotor Blades – PROFAR' was carried out. The main objective of this project is to get a deeper understanding of the blade to blade variation of the fatigue strength of rotor blades and to determine the statistical distribution function by which this variation can be described. Furthermore the project aimed at the determination and quantification of the correlation between the measured fatigue strength of rotor blades and coupon data.

To achieve the project objectives 37 small-scale blades have been tested both static and in fatigue. Next to these blades, a number of coupons of identical material as that of the blades has been tested statically and under fatigue loading. The tests served two main purposes, finding the scatter in the blade properties and relating the coupon test data to actual failure of real blades. In order to serve these purposes the two different sets of test were done. One set aimed at failure in the prismatic outboard section of the blade in the parent glass fibre material, while the other aimed at failure in the geometrically complicated root section of the blade where failure of the bonding line, collapse of the spar or other mechanisms can be observed. These latter tests were done both in edgewise and in flapwise direction. The fatigue tests have been carried out at different stress levels. Besides fatigue, other failure modes like ultimate load are incorporated in the test sequence.

The tests have been performed at three laboratories, the Stevin laboratory of the Technical University of Delft, The Netherlands; the test facilities of the Centre for Renewable Energy Sources, CRES in Pikermi, Greece; and a test facility at Risø National Laboratory, Roskilde, Denmark.

The results of the blade tests have been correlated with coupon data for similar material obtained from coupon tests performed within this project and with corresponding material obtained from the existing data base FACT. Based on this correlation, test load factors were determined.

The results of the tests show that:

- Although a serious attempt has been made to harmonise the tests within the different laboratories, the available equipment, the in house procedures and culture makes inevitable that differences in the tests occur between the different institutions.
- Ignoring the slight "laboratory influence" scatter is most pronounced for tests focussed on the prismatic (tip) section.
- The results of the coupon tests are in good agreement with the FACT results when divided by the *UTS* value of the relevant material.
- For the blade tests and for the coupon tests the slope of the *S*-*N* curves is close to 10, for $R = 0.1$ as well as for $R = -1$.
- The scatter in the results of the blade tests is of the same order of magnitude as the scatter found in the coupon test results.
- It is shown that the Goodman based curves are close to the data obtained from the tests and therefore are to be used for design of wind turbine blades.
- Elementary statistical analysis of the blade test results gives way to the assumption that a partial safety factor on the tests load to account for the scatter in blade properties seems to be appropriate.

TITLE

Probability distribution of fatigue strength of rotor blades

Acronym: PROFAR

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1. INTRODUCTION

Objectives

The fatigue strength of rotor blades shows some variation, among others due to the inherent scatter of the material properties and due to the inevitable scatter caused by the production process of the blades. To take into account these uncertainties a (partial-)safety factor for fatigue strength is prescribed in design codes. Likewise an additional test load factor has to be applied in full scale blade testing. To determine these factors in a rational manner the fatigue strength distribution of rotor blades is a prerequisite. As this distribution is not available at the moment the corresponding factors are determined empirically and a lot of uncertainty concerning the values used nowadays is present.

For this reason the JOULE-III project PROFAR was initiated with the following *main objectives*:

- Acquisition of a deeper understanding of the blade to blade variation of the fatigue strength of rotor blades and determination of the statistical distribution function by which this variation can be described.
- Determination and quantification of the correlation between the measured fatigue strength of rotor blades and coupon data.

Besides, the following *additional objectives* are defined.

- Formulation of a more generic methodology to determine the fatigue strength distribution of rotor blades based on the above-mentioned correlation.
- Definition of the test load factors to be applied in a full-scale blade fatigue test as function of the number of tests to be performed.
- Transfer of specific knowledge on the application of statistical techniques to characterise the fatigue strength of blades to certification bodies.

Partial safety factors

To apply structural reliability techniques three aspects have to be considered, viz. the distribution of the load, the distribution of the strength, and a limit state function. For fatigue problems the definition of the limit state function and the description of the statistical load distribution are considered in several national and international projects, for example the JOULE II and III projects EWTS-I (JOU2-CT93-0387), EWTS-II (JOR-CT95-0064) and PRODETO (JOR3-CT95-0026). However the main problem in applying the probabilistic method is the lack of fatigue data for full scale GFRP-blades, necessary to determine the strength distribution. Normal practice in wind turbine industry is to perform one or two tests on each new type of rotor blade, one static test and a fatigue test. As these tests are normally not continued till failure, only one or two lower bound values with respect to the static and the fatigue strength of the rotor blades are obtained and therefore give no clear indication of the blade to blade variation due to production quality. In practice, it is not realisable to derive the blade strength distribution from full-scale blade tests because a large number of blades should be tested. At the same time, it is not possible to derive the distribution from coupon test data straightforward. In case of a full-scale test the larger part of the blade is being subjected to a test load equivalent to the design load and many details and a large area are tested simultaneously. This is more or less comparable to the testing of a number of small specimens under similar conditions. Statistically this would mean that for the blade a lower mean with less scatter could be expected than for small-scale specimens. On the other hand, the damage accumulation in the blade can be slower due to stress redistribution. At the moment, it is not clear how to quantify these aspects. For this reason, insight has to be gained in the blade strength distribution and in the possibilities to derive the fatigue strength distribution of blades from coupon tests.

Full scale tests
As a full scale fatigue test has to be performed in a relatively short time, say between 2 and 6 months while the design life is in the order of 20 - 30 years, a test load spectrum has to be applied instead of the design load spectrum. The general procedure for the conversion of the design load spectrum to a test load spectrum is as follows: A large number of small load variations is omitted while the range of a number of the remaining load cycles is increased to compensate for the cycles that were omitted. Another reason to increase the test load is to compensate for partial safety factors on the strength side, which are not applicable in a laboratory environment. Further, a test load factor has to be applied in a full-scale blade test to deal with the blade to blade variation. As no data for the blade strength distribution are available this test load factor has to be determined empirically and therefore a lot of uncertainty exists about the test load factor to be used.

2. TECHNICAL DESCRIPTION

To achieve the project objectives, 37 small-scale blades have been tested both static and in fatigue. Next to these blades, a number of coupons of identical material as that of the blades has been tested statically and under fatigue loading. These tests served two main purposes, finding the scatter in the blade properties and relating the coupon test data to actual failure of the real blade. In order to serve these purposes the two different sets of test were done. One set aimed at failure in the prismatic outboard section of the blade in the parent glass fibre material, while the other aimed at failure in the geometrically complicated root section of the blade where failure of the bonding line, collapse of the spar or other mechanisms can be observed. These latter tests were done both in edgewise and in flapwise direction. The fatigue tests have been carried out at different stress levels. Besides fatigue, other failure modes like ultimate load are incorporated in the test sequence.
The tests have been performed at three laboratories, the Stevin laboratory of the Technical University of Delft, The Netherlands; the test facilities of the Centre for Renewable Energy Sources, CRES in Pikermi, Greece; and a test facility at Risø National Laboratory, Roskilde, Denmark.
The results of the blade tests have been correlated with coupon data for similar material obtained from coupon tests performed within this project and with corresponding material obtained from the existing data base FACT [2].

The work has been carried out in three tasks, which are summarised below.
1. Design and testing of the blades and coupons;
2. Evaluation of test results;
3. Determination of test load factors.

3. RESULTS AND CONCLUSIONS

3.1 Testing

3.1.1 Design of test blade

For the test blades a small commercially available blade has been selected and modified for the purpose of the project. The main characteristics of a standard blade and of the modified version are given in Table 1.

Table 1: *Characteristics of the test blade.*

Property	**Standard blade**	**Test series**
Length (mm)	3380	3380
Mass (kg)	25.5	21.1
Centre of gravity (mm)	1035	1011
Outer diameter at root (mm)	172	190
Thread of embedded bushes	M12	M16
Tip chord (mm)	150	150
Twist (degrees)	18.8	18.8

The blade is a 3.4 m long blade for turbines in the range of 5 to 15 kW, produced by hand lay-up from glass fibre reinforced polyester. A rigorous quality assurance program was defined including traceability of all materials and workshop survey's by DNV.

In order to meet the requirements of the project, the blade has been modified in the root part, the lay-up and the geometry of the spar. A larger bolt size was used and some layers of glass were removed because the fatigue strength of the bolt connection was considerably lower than that of the blade itself. Next to that, an additional layer has been added on the compressive side of the blade and the width of the spar has been increased to have a smaller unsupported panel width in the trailing edge of the blade. Both in order to prevent failure of the blade due to buckling. After a pilot test, it appeared necessary to use an additional support during the outboard section testing, and at the location of this support, an additional layer of chopped mat has been placed.

3.1.2 Stress analysis

As support for the design and as preparation for the tests and the evaluation of the results, several stress analyses of the blade have been made. In the preliminary phase of the project, analytical tools have been used to assess the strength of the blade and the bolt connection. The buckling resistance of the blade has been assessed with the use of panel based methods as developed by ECN within the BUCKBADE project [1]. Both CRES and ECN prepared a finite element model of the blade and TUD modelled the blade in their beam model tool. A picture of the model used in the ECN FEM analysis is given in Figure 1. In this figure, also an impression of the shape and dimensions of the blade can be seen.

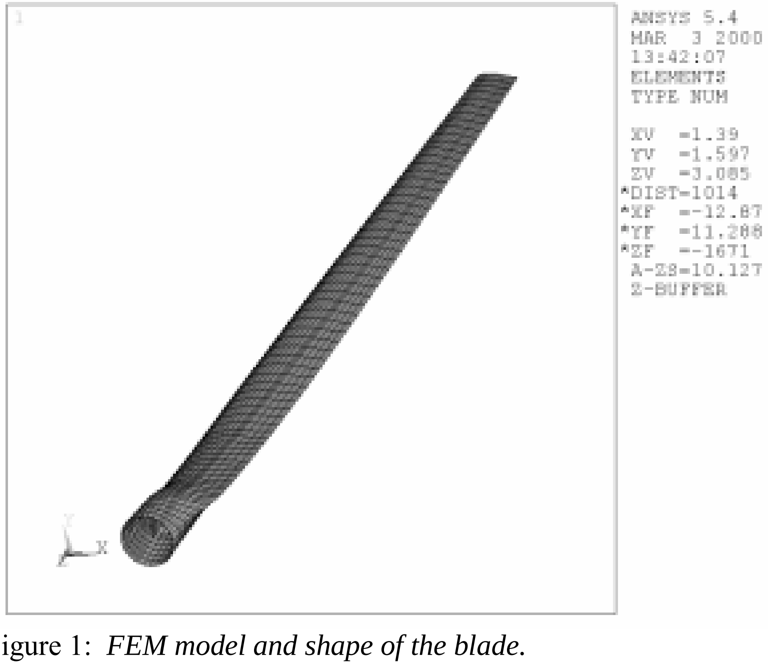


Figure 1: *FEM model and shape of the blade.*

3.1.3 Coupon data

FACT Database

In order to correlate data from existing coupon tests with the results of this project the FACT database [2] has been used to find coupon data for similar materials as used for the test blades. From the FACT database, a total of 52 tests provide useful information for the PROFAR project. However, the data only allows for linear regression analysis. Good estimation of Sendeckyj lines requires test data over a wide range of cycles. For the high cycle ratio, the linear regression lines are the most important.

Since in the project the strain to failure for a given number of cycles has to be predicted, average values will be used, and the relation:

$$\varepsilon_{max} = 3.52 \cdot N^{-0.082}$$

seems to be the most appropriate. The linear regression lines for glass fibre reinforced polyester (GP) with $R = 0.1$ is shown in Figure 2.

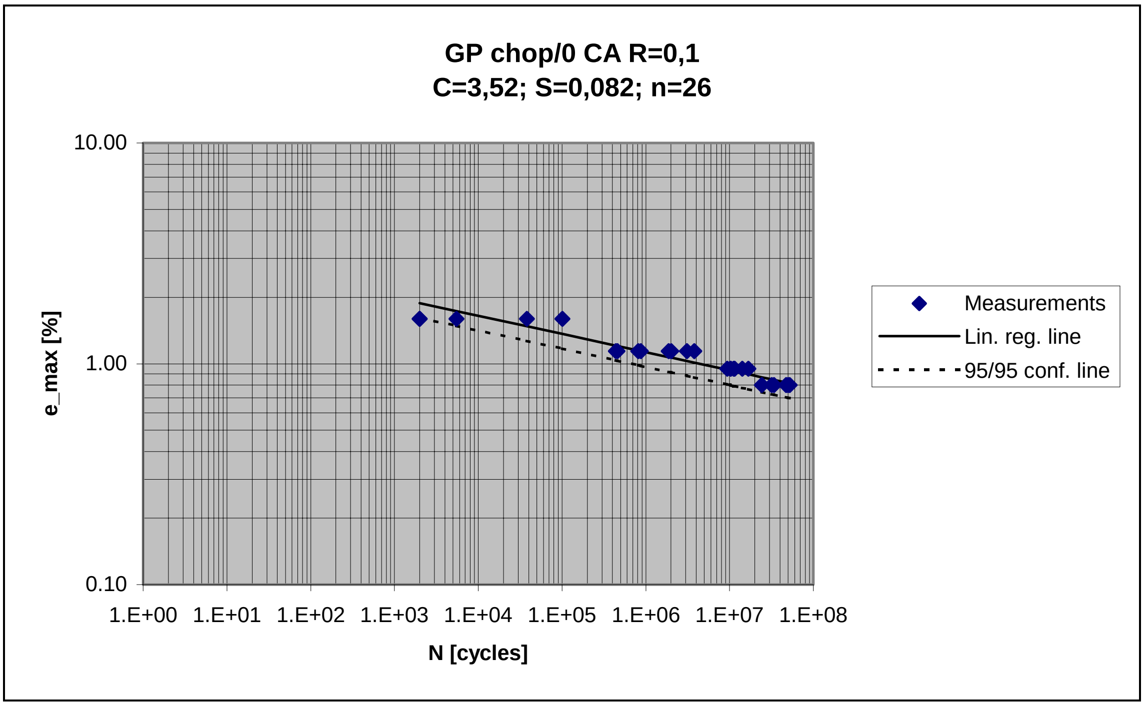


Figure 2: *Result FACT database*.

Coupon tests

The coupons tested within the project were of identical material as the test blades and with a lay-up that was comparable to the lay-up at the location of the blade where failure was to be expected for the prismatic section tests. A total number of 35 coupons have been tested.

- CRES: 4 static test and 8 fatigue tests with an R value of 0.1;
- TUD, 4 static tests, 11 fatigue tests at $R = 0.1$ and 8 fatigue tests at $R = -1.0$.

The results of the coupon tests are depicted in Figure 3.

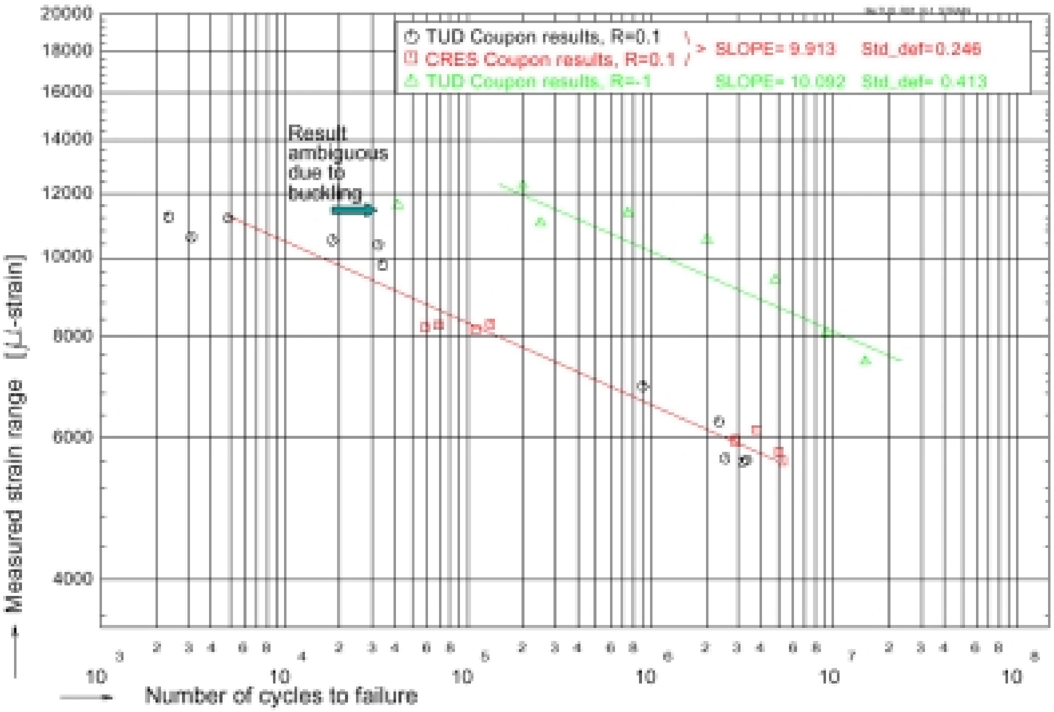


Figure 3: *Cycles to failure for the coupon tests.*

3.1.4 Generic properties of the blades

Before starting the destructive testing of the blades, generic properties such as mass, position of centre of gravity, natural frequencies and damping were measured. An overview of these properties is given in Table 2.

Table 2: *Generic properties of the blades.*

	Mass	**c.o.g. pos.**	**1st flap freq.**	**damp.**	**1st edge freq.**	**damp.**
	kg	m	Hz		Hz	
Average	20.80	1.01	5.21	0.64%	13.06	0.77%
Standard deviation	0.449	0.013	0.081	0.09%	0.295	0.05%
Coefficient of variation	2.16%	1.26%	1.55%	13.7%	2.26%	6.70%

The remarkably high variation in the measured damping is partly caused by the differences in measuring method. At Risø and CRES the damping is measured using relatively small displacements and accelerometers on the blade while the damping at TUD has been measured using larger displacements and linear transducers for measuring the displacement.

3.1.5 Blade tests

Design

A total of 37 blades has been produced for this project in two batches. The first batch consisted of three blades, which were shipped to the three laboratories for a preliminary test and for developing the test set-up. From these preliminary tests, it appeared that the deflection of the blade was unacceptably high. It would lead to very low test frequencies and hence too long test times, and not all laboratories had actuators with sufficient stroke available. Therefore, it was decided to use an intermediate support for the outboard prismatic section tests. In order to avoid damage at the location of this intermediate support, an additional layer of chopped mat was placed in the region 300 mm inboard to 300 mm outboard of this support, for the remaining 34 blades.

Due to the presence of the intermediate support, the loading in the inner part of the blade during the prismatic section tests was very low. This meant that the root section tests could be done on blades that were tested previously for failure in the prismatic section. Both CRES and TUD have taken this opportunity and performed additional tests in the root section on blades failed in the prismatic part.

The resulting test matrix is given in Table 3.

Table 3: *Test matrix.*

Load case	**Number of cycles (target)**	**Number of tests**			
		CRES	**RISØ**	**TUD**	**Total**
Preliminary test	10^5	1	1	1	3
Static ultimate load test	-	-	-	2	2
Largest cord flapwise	10^7	1	1	2	4
	10^6	1	1	6	8
Prismatic section flapwise	10^7	2	1	2	5
	10^6	4	4	5	13
Largest cord edgewise	10^7	1	1	3	5
	10^6	1	1	3	5
TOTAL		11	10	24	45

Test set-up

For the tests aiming at failure in the prismatic outboard section of the blade, the blade was tested in flapwise bending. The aerodynamic suction side was the mechanical compression side. The blade was clamped at the root using the standard mounting bolts. At a location 1780 mm from the root, the blade was clamped such that the movement in flap direction was prevented but that rotation and horizontal movement were free. For this clamp, a lined wooden clamp in the local profile shape was used, which was hinged to connecting rods.

For the tests aiming at failure in the root section the blades were only clamped at the blade root and the clamp at position 1780 was used to apply the load. These test were done both in flapwise and in edgewise direction.

An overview of the test locations is represented in Figure 4 - Figure 6.

At TUD and CRES the blades were loaded using hydraulic actuators and at Risø the loading was applied using an electric motor and a crankshaft mechanism. The tests aimed at fatigue under constant load conditions. However, due to the development of creep deformation and due to reduction in stiffness of the test blades during the test, the required stroke to reach a certain force does increase. Therefore, the stroke was updated in the course of each test at regular intervals such that the measured force was re-set to the value at the beginning of the test.

Figure 4: *Test set up at CRES.*

Figure 5: *Test set up at TUD.*

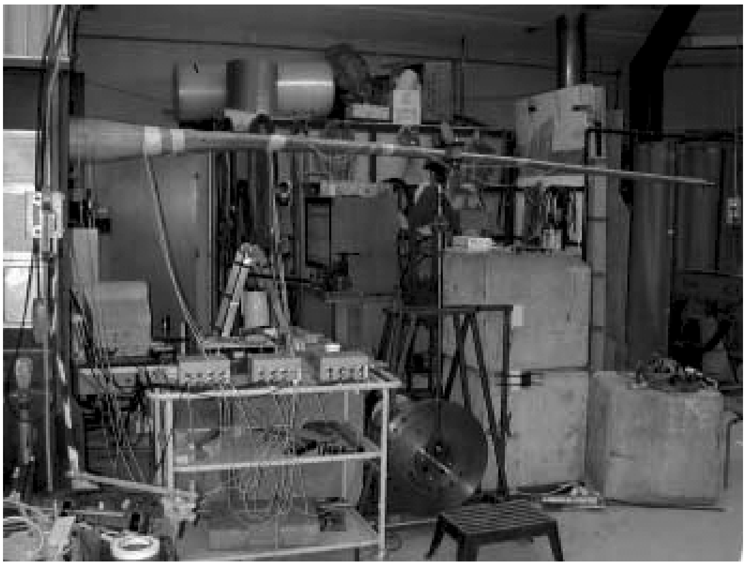
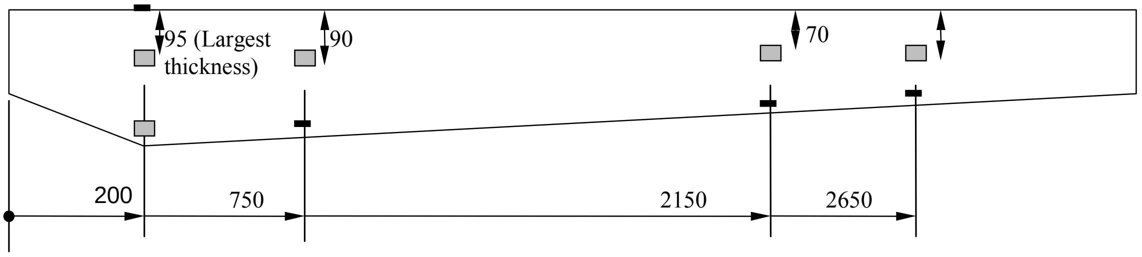


Figure 6: *Test set up at Risø.*

Strain gauge measurements

During the test, the blades were equipped with strain gauges at critical positions. These positions were locations of extreme strain determined from the analytical and FEM analyses and are depicted in Figure 7. In order to have comparable results in the different laboratories, markings have been applied in the mould such that hairline position markers are visible around the intended location for strain gauges on the finished blade. The strain gauges at the expected location of the highest strain have been used to determine the force required for each test.



▨ Strain gage on both sides of the blade, for flapwise tests

▬ Strain gage on nose and tail, for edgewise tests.
Strain gages on tail, mounted 20 mm from tail of section.

Figure 7: *Location of strain gauges.*

Test results

Because glass-fibre reinforced plastic blades show serious stiffness reduction during the fatigue life, blade failure has been defined as a reduction of the initial stiffness with 20%. Moreover the blades show creep behaviour, and therefore the stroke to reach the initial force range has to be re-established during the test at certain intervals. Figure 8 shows the occurrence of creep development and stiffness reduction for a typical prismatic section test.

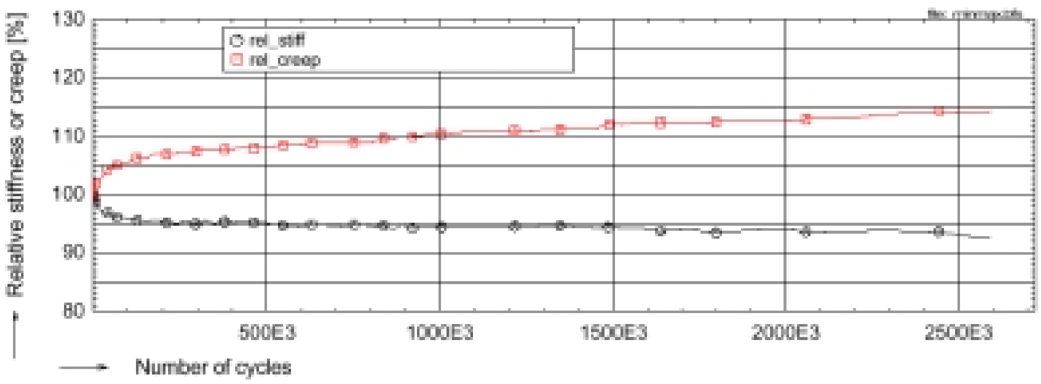


Figure 8: *Example of creep development and stiffness reduction for a typical prismatic section.*

For each blade tested the number of cycles to failure are depicted in Figure 9 as function of the maximum strain, for the strain gauge location where the failure is expected to occur.

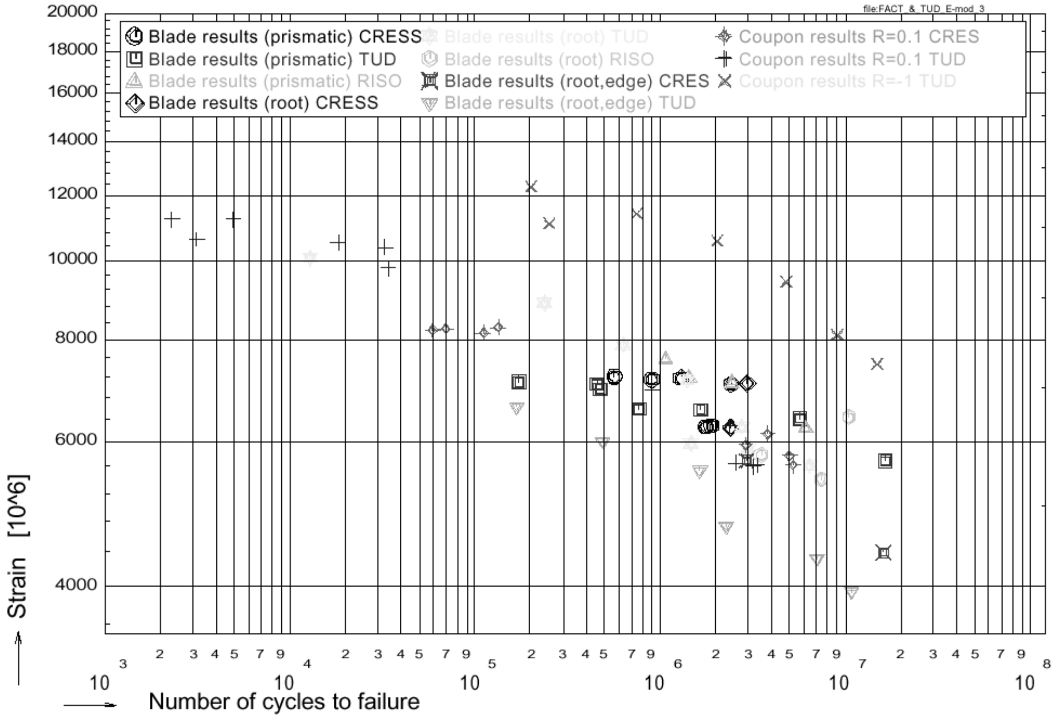


Figure 9: *Overview of all blade tests.*

3.2 Evaluation of test results

3.2.1 Correlation

Two different effects had to be taken into account in order to compare the results of the different laboratories and in order to compare the results with theoretical data. The procedure for updating the stroke was not identical in each lab, and due to the large displacement of the blade, the non-linear relation between the actuator force and the moment at the failed location had to be taken into account, see Figure 10.

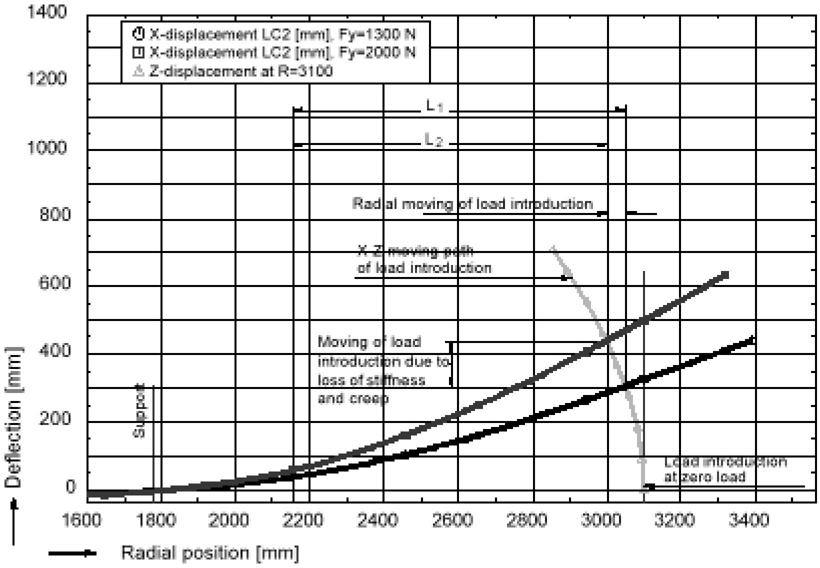


Figure 10: *Path of loading during flapwise test.*

These effects were corrected for by determining the actual moment as a function of the actuator displacement taking into account the change of position of the load application point due to large displacement of the blade and swivel of the actuator. These actual moments were rain-flow counted and an equivalent moment at the location of failure was determined with the use of an *S*-*N* line with a *k*-factor of 10. Since these were only relatively small corrections, the process it not sensitive to the actual value of *k*, as was checked with a concise sensitivity study.
The results for the prismatic tip section tests for the three laboratories are represented in Figure 11. In Figure 12 the results for the root section flapwise tests are represented and in Figure 13 the results for the root section edgewise tests are represented.

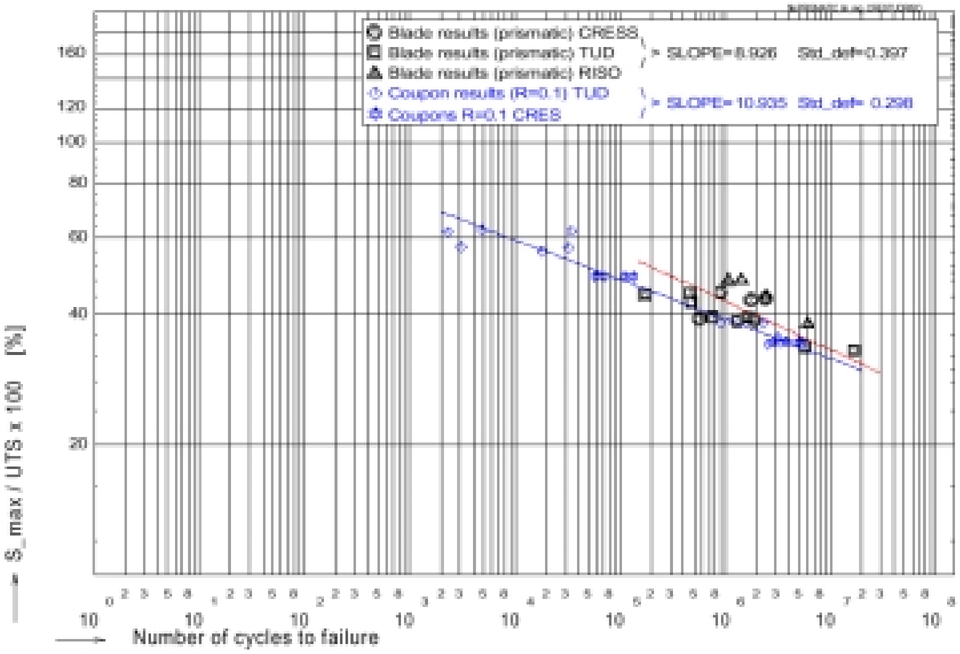


Figure 11: *Corrected results for the tip section tests.*

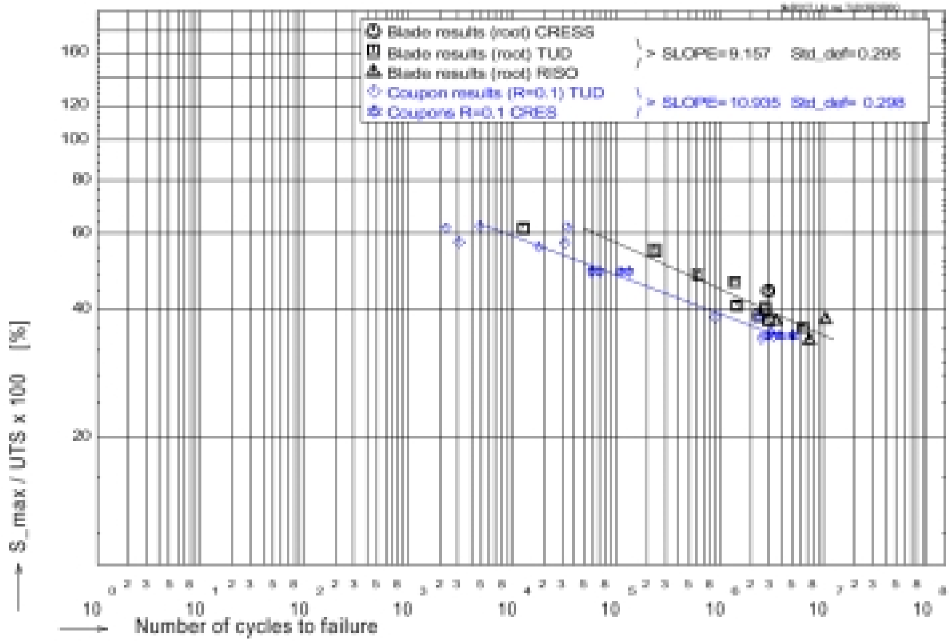


Figure 12: *Corrected results for the root section flapwise tests.*

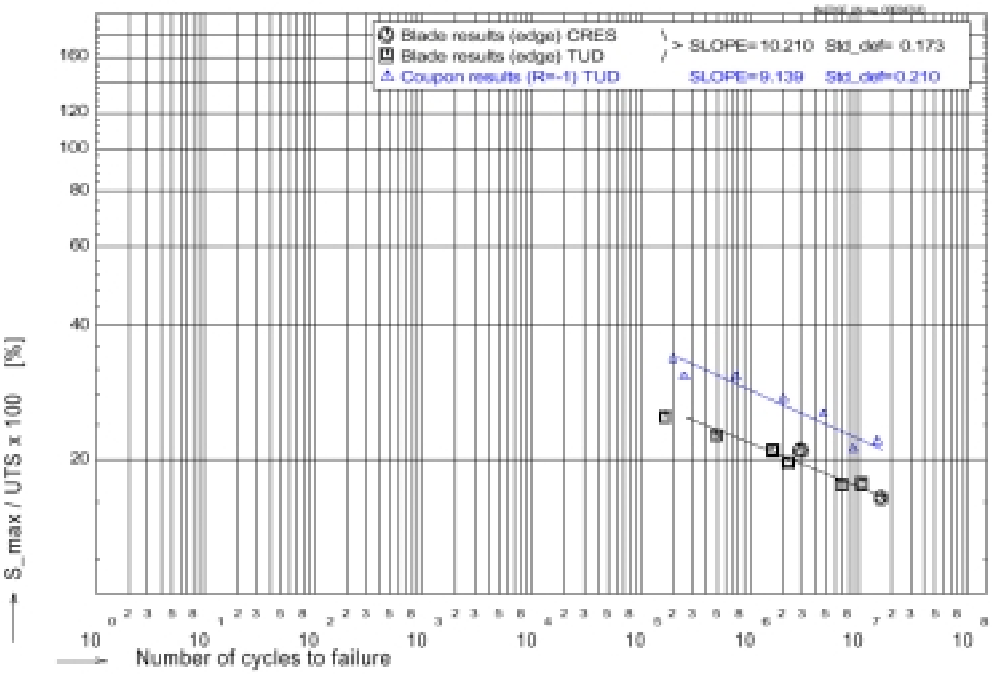


Figure 13: *Corrected results for root section edgewise tests.*

3.2.2 Strength model

The data obtained from the fatigue tests are compared with the representative fatigue life curve as stated in Dutch pre-standard for certification of wind turbines, NVN 11400-0:1998 [3]. In this standard the Goodman diagram is given as:

$$N = \left[\frac{\dfrac{UTS + |UCS|}{2} - \left| \sigma_{\mathrm{m}} - \dfrac{UTS - |UCS|}{2} \right|}{\sigma_{\mathrm{a}}} \right]^{10}$$

where

UTS : the ultimate tensile strength
UCS : the ultimate compressive strength
σ_m : the mean value of a stress cycle
σ_a : the amplitude of a stress cycle
N : the allowable number of cycles

A comparison of the *S-N* curves (characteristic curves 95% survival probability with 95% confidence) estimated from the fatigue tests and the Goodman diagram is made in Figure 14 for the flapwise tests with $R = 0.1$ and in Figure 15 the edgewise tests with $R = -1$.

For the flapwise tests it is clear from Figure 14 that the line according to the Goodman relation is conservative for data in the prismatic part of the blade. In the root section where the geometry is more complex and where much more scatter in the test results is present, the line is conservative for the high strain ranges, i.e. more than 4000µ strains, but too optimistic for strain ranges lower than 3000µ strains. In Figure 14 also the *S-N* curve as given by Mandell and modified by Appel and Olthoff [4] is shown, this curve is much too optimistic concerning the fatigue strength.

From Figure 15 it is clear that the line according to the Goodman relation is conservative with respect to the curve estimated from the fatigue tests of the blades in the edgewise direction with $R = -1$. In this figure the *S-N* curve as given by Mandell and modified by Appel and Olthoff is shown also, this curve actual fits well to the curve from the measurements.

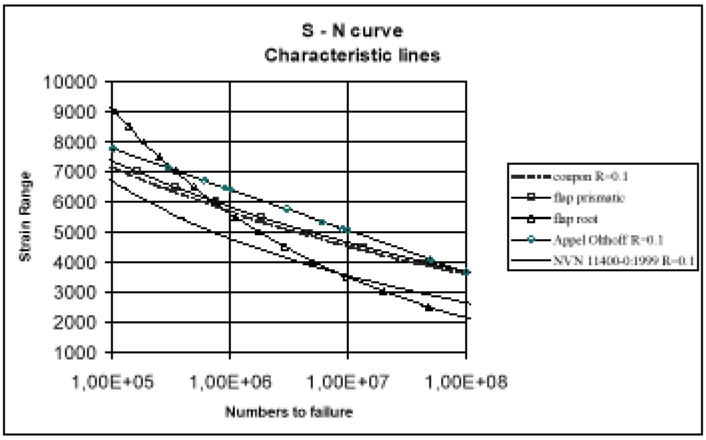


Figure 14: *Characteristic S-N curves for flapwise tests (95% confidence intervals and 5% fractile)*

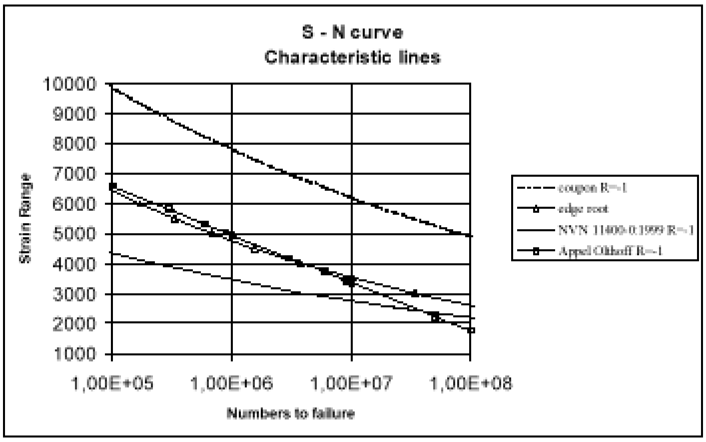


Figure 15: *Characteristic S-N curves for edgewise tests (95% confidence intervals and 5% fractile)*

3.3 Determination of test load factors

The spread in the results of the blade fatigue tests is of the same order of magnitude as the scatter in the coupon test results. For this reason it seems to be appropriate to apply a partial load factor on the test load for full scale blade tests in order to account for the scatter in the blade fatigue strength. The rigorous statistical analysis required to quantify the partial safety factor for the scatter of the fatigue strength to be applied in full-scale blade testing, could not be done within this project.

3.4 Conclusions

- With regard to the testing it can be concluded that although a serious attempt has been made to harmonise the tests within the different laboratories, the available equipment, the in house procedures and culture makes inevitable that differences in the tests occur between the different institutions.

- The results of the coupon tests are in good agreement with the FACT results when divided by the *UTS* value of the relevant material.
- For the blade tests and for the coupon tests the slope of the *S*-*N* curves is close to 10, for $R = 0.1$ as well as for $R = -1$.
- Ignoring the slight “laboratory influence” scatter is most pronounced for tests focussed on the prismatic (tip) section.
- The scatter in the results of the blade tests is of the same order of magnitude as the scatter found in the coupon test results.
- It is shown that the Goodman based curves are close to the data obtained from the tests and therefore are to be used for design of wind turbine blades.
- Elementary statistical analysis of the blade test results gives way to the assumption that a partial safety factor on the tests load to account for the scatter in blade properties seems to be appropriate.

4. EXPLOITATION PLANS AND ANTICIPATED BENEFITS

Each partner will use the results of the project and the knowledge gained within the project to the extent required for further R&D activities. Furthermore the results might be of great interest for third parties. For this reason the results will be disseminated through:

- Presentations at conferences and publications in scientific journals;
    - J.J. Heijdra, H. Braam, E.R. Jørgensen, D.J. Lekou, P.S.Vionis, J.L. van Leeuwen, D.R.V. van Delft *PROBABILITY DISTRIBUTION OF FATIGUE STRENGTH OF ROTOR BLADES, PROFAR*, to be presented at EWEC 2001, Copenhagen, 2 – 6 July 2001.
    - Hans van Leeuwen (corresponding author), Don van Delft; Delft, John Heijdra, Henk Braam, Eric Jørgensen, Denja Lekou and Pantelis Vionis, *Probability Distribution of Fatigue Strength of Rotor Blades, PROFAR,* to be presented at the ASME/AIAA 2002 conference, Reno, USA, 14-17 Jan. 2002.
- Contribution in expert meetings;

Although the test results are not evaluated fully yet, it is believed that the results and knowledge gained so far can be of significant benefit for the wind turbine industry, certifying bodies and standardisation committees as it provides underpinned information concerning:

- The scatter in fatigue strength of rotor blades that can be expected;
- Correlation of fatigue strength of rotor blades with coupons;
- Recommendations for test load factors.

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